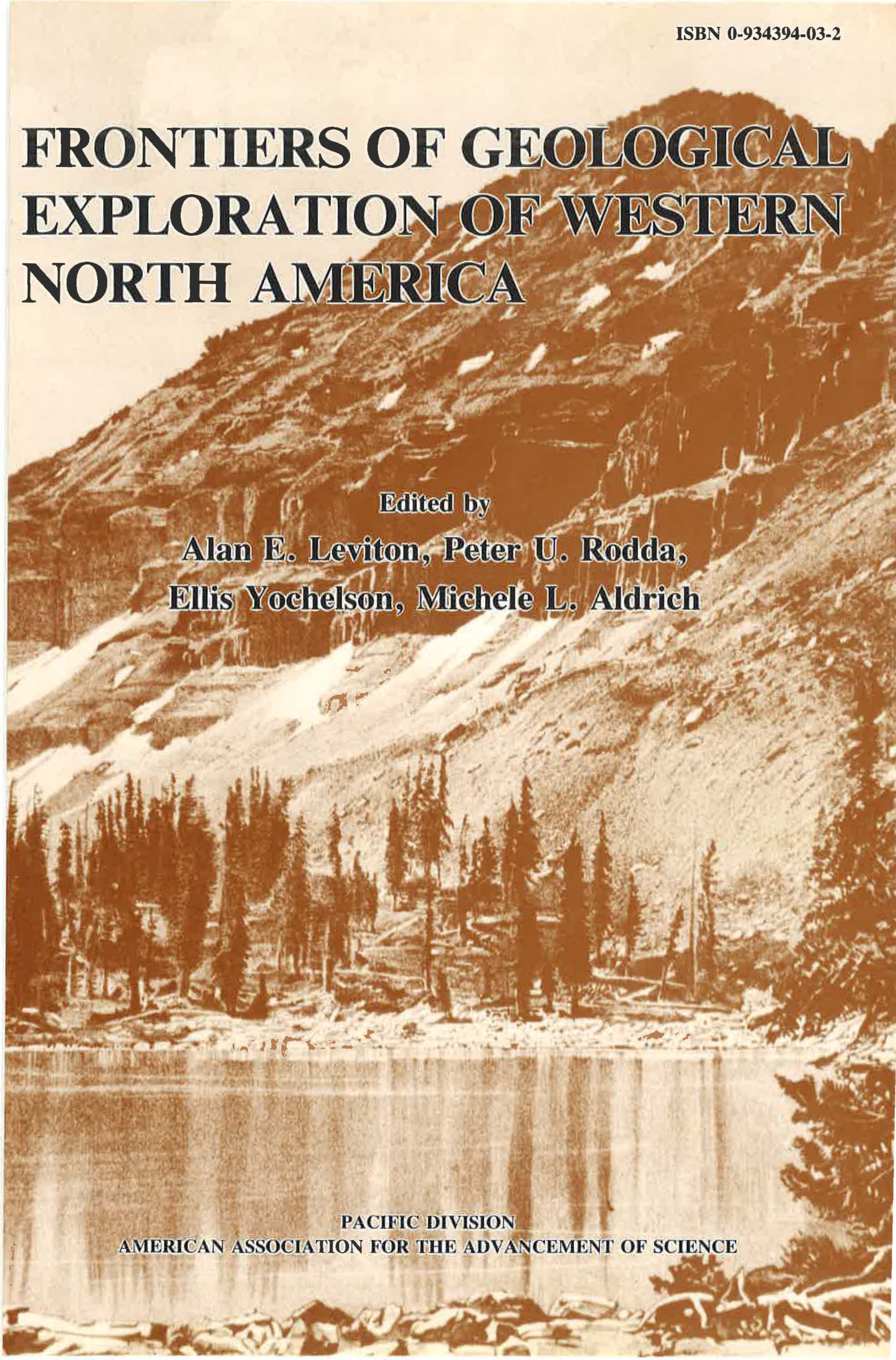

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FRONTIERS OF GEOLOGICAL EXPLORATION OF WESTERN NORTH AMERICA

Edited by

Alan E. Leviton, Peter U. Rodda,
Ellis Yochelson, Michele L. Aldrich

PACIFIC DIVISION
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

COVER: Mt. Agassiz, Uinta Range, Utah. Photograph by Timothy O'Sullivan. Reproduced in Clarence King, *Systematic Geology* (1878), plate 9.

FRONTIERS OF GEOLOGICAL EXPLORATION OF WESTERN NORTH AMERICA

SHOSHONE FALLS, FROM BELOW–IDAHO

Photograph by Timothy O'Sullivan. Reproduced in Clarence King, *Systematic Geology* (1878), plate 17

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American Association for the Advancement of Science, the School of Mines and Earth
Sciences, University of Idaho, and the Idaho Bureau of Mines and Geology
on the occasion of the 100th anniversary of the founding of the
United States Geological Survey

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American Association for the Advancement of Science

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PREFACE

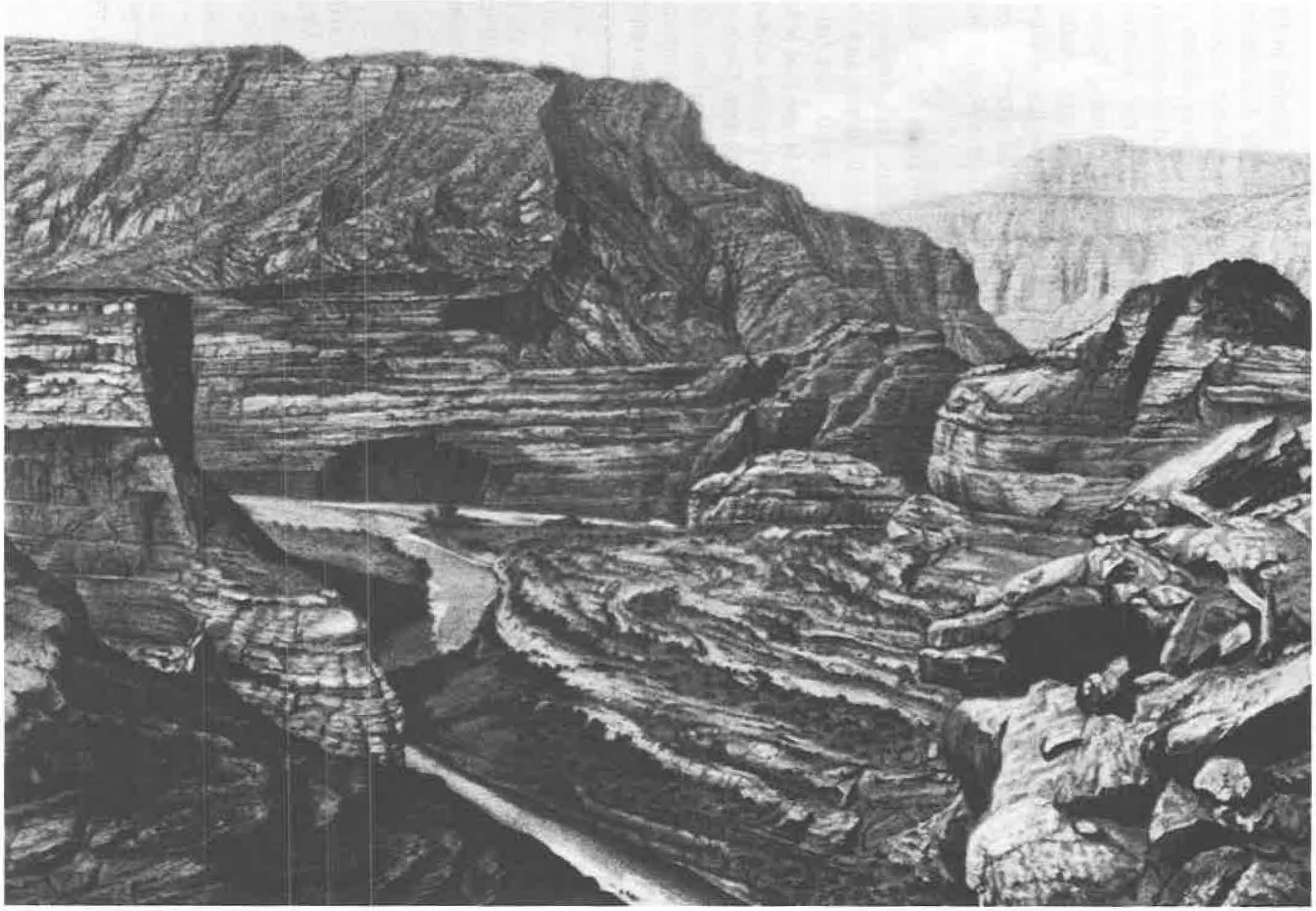
The Pacific Division, American Association for the Advancement of Science, became established as the first division of the American Association for the Advancement of Science in 1914. Prior to its affiliation with AAAS, the Pacific Division was known as the Pacific Association of Scientific Societies. It numbered among its affiliated charter members the Cordilleran Section of the Geological Society of America, the Pacific Coast Section of the Palaeontological Society, and the Seismological Society of America. From its founding, the Pacific Division had a commitment to the earth sciences, and this commitment continues to the present day through the activities of its Section E (Geology and Geography) and Section W (Atmospheric and Hydrospheric Sciences) and several of its affiliates. Thus, in 1978, when it was suggested that the Division conduct a commemorative program on the occasion of the centennial of the United States Geological Survey, the Division found the idea most appealing inasmuch as the origins of the USGS were so closely tied to the accomplishments of the territorial and railroad surveys in the Western United States that preceded the Survey's founding in 1879.

The sessions were organized through the good offices of Maynard Miller, Dean of the School of Mines and Earth Resources, and his associates at the University of Idaho, Jack Smiley and George Williams; Clifford Nelson and Ellis Yochelson, United States Geological Survey; and Peter Rodda, Department of Geology, California Academy of Sciences. Three symposia were held to commemorate the 100th anniversary of the USGS in recognition of the contributions that federal agency has made to the growth and development of geological knowledge, with special reference to Western North America. Papers from two of the symposia, "Frontiers of Western Geological Exploration" and "Geological Exploration in the Trans-Mississippi West by National and State Agencies from 1860-1900," are included in this volume. Papers presented at the symposium session "Late Cenozoic History of the Pacific Northwest" will be published as a separate volume.

The Pacific Division, AAAS, is immensely pleased to acknowledge the extraordinary contributions made by the United States Geological Survey during its first 100 years of existence. It is also pleased to have this opportunity to wish the Survey an equally productive second century.

This volume was authorized by the Executive Committee of the Pacific Division, AAAS. For assistance in its production, the Division wishes to express its appreciation to the California Academy of Sciences and to those individuals who served as reviewers of the various contributions.

Alan E. Leviton
Pacific Division, AAAS and
California Academy of Sciences
San Francisco, California
Michele L. Aldrich
American Association for the
Advancement of Science
Washington, D. C.
November 20, 1981



YAMPA CAÑON, UINTA RANGE, UTAH
Photograph by Timothy O'Sullivan. Reproduced in Clarence King, *Systematic Geology* (1878), plate 6

FOREWORD

To the nineteenth century geologist, trained in the East, western geology was of challenging complexity on an unprecedented scale. The West was a different kind of country–vast, rugged, and harsh. Although the terrain and climate provided many magnificent outcrops, accompanying logistical problems were formidable, and the early exploring expeditions provided only tantalizing samples of rocks, fossils, and structures. Later, more comprehensive reconnaissance surveys, by Hayden, King, Powell, Wheeler, and the Railroad and Canadian Boundary surveys, described broad scale features of the geology, geography, and natural history of major parts of the Cordillera. Most of the early geological efforts were related to surveys for transportation routes, and they were undertaken in the political and economic context of the westerward movement and the need for information to support the occupation and exploitation of this new frontier.

The end of the last century saw the end of the frontier and the final settling of the West. By then, organized governmental agencies, federal and state, had begun their systematic geological work of mapping, description, and interpretation, with emphasis in areas of economic mineral deposits. In California, for example, by 1900 the exploratory and reconnaissance phases (Trask, 1851-1856; Pacific Railroad surveys, 1853-1857; Whitney survey, 1860-1868[1872]) had ended, and the present California Division of Mines and Geology had been organized (in 1880 as the California State Mining Bureau). The mineral and agricultural wealth of the West provided the basis for political, economic, and intellectual growth.

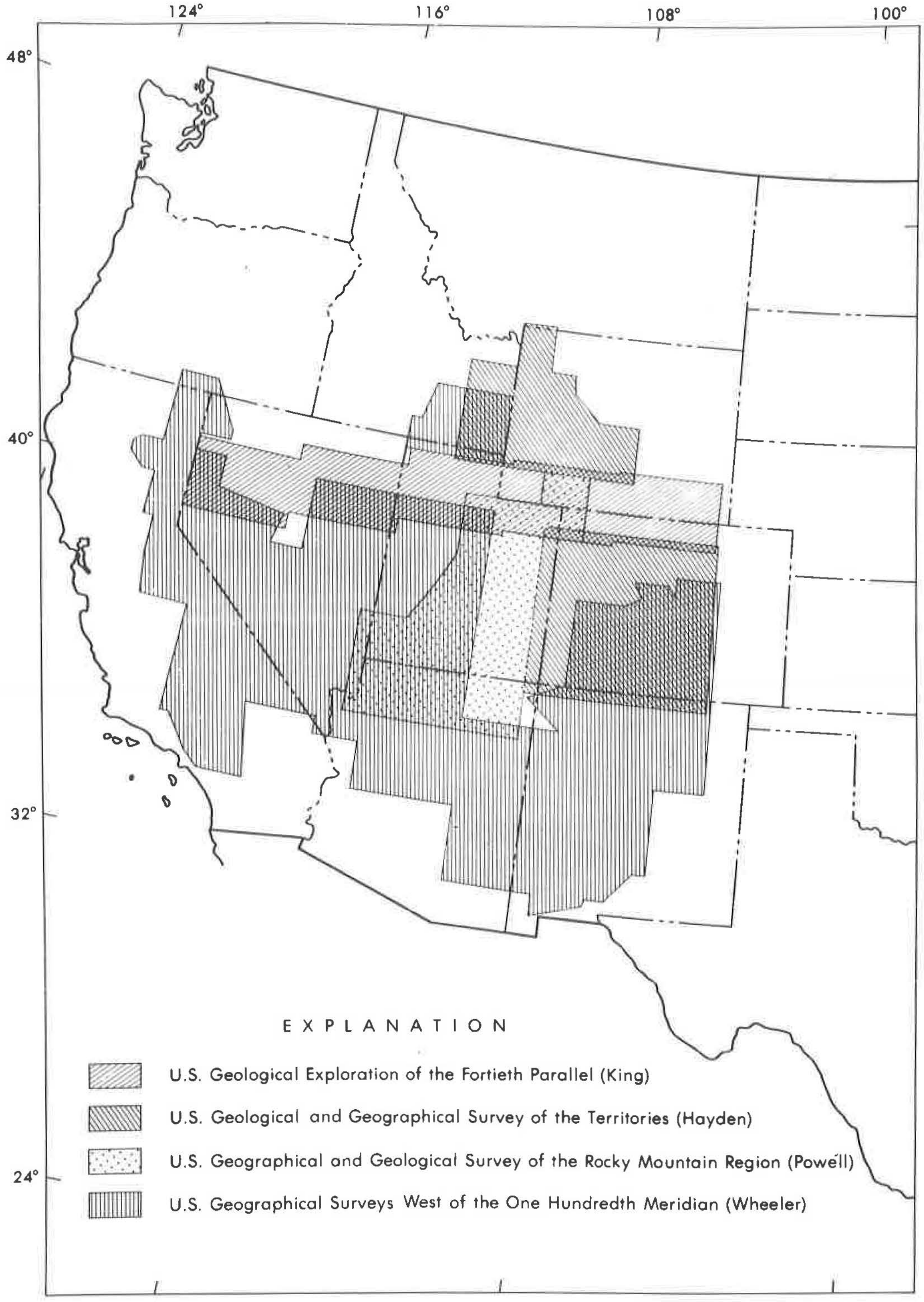
On March 3, 1879, the Congress of the United States passed and President Hayes signed into law a bill that included the provision that ". . . the Geological and Geographical Survey of the Territories, and the Geographical and Geological Survey of the Rocky Mountain Region, under the Department of the Interior and the Geographical Surveys West of the One-Hundredth Meridian, under the War Department, are hereby discontinued to take effect on the thirtieth day of June, eighteen hundred and seventy-nine." Thus ended the careers of Ferdinand V. Hayden, John Wesley Powell, and Lt. George M. Wheeler, as leaders of their own federally financed territorial surveys. A year earlier, Clarence King had submitted his final report of the Geological Exploration of the Fortieth Parallel (Rabbitt and Nelson 1979). The old cliche "the end of an era" applied well to 1879. The four territorial surveys had covered vast stretches of the Western United States (Fig. 1) and had established geology as a federal activity. They had produced scores of maps and linear yards of books, now yellowed with age and seldom read, and a few names scattered on the landscape remain to remind us of their travels (Yochelson 1971).

The newly founded U. S. Geological Survey took the best of the territorial surveys and built a permanent professional agency to study geology (Rabbitt 1979, 1980). No doubt the members of the Geological Survey of Canada, an agency nearly forty years older, took time to smile encouragingly at this new United States bureau.

The fledgling has survived more than a century, only one of seven U. S. government agencies to endure that long. Throughout its 100 years of ups and downs, the USGS has broken new ground and has set new standards in the earth sciences. In view of its record of contributions to basic and applied science, and the western origins of the USGS, it seemed appropriate that the Pacific Division of the American Association for the Advancement of Science note this anniversary.

At the 60th Annual Meeting of the Pacific Division, AAAS, held at the University of Idaho, June 1979, a symposium, "Frontiers of Western Geological Exploration," was presented on the occasion of the USGS centenary. The present volume is based on this symposium, which provided a retrospective review of geology in Western North America during the previous hundred years. Also included are several papers from a related symposium, "Geological Exploration of the Trans-Mississippi West by National and State Agencies from 1860 to 1900," held at the same meeting.

Given the end of the territorial surveys as a benchmark, we can ask how much has been learned of western geology in a century. The answer in two words is "a lot." As the papers in this


124°
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24°
EXPLANATION
U.S. Geological Exploration of the Fortieth Parallel (King)
U.S. Geological and Geographical Survey of the Territories (Hayden)
U.S. Geographical and Geological Survey of the Rocky Mountain Region (Powell)
U.S. Geographical Surveys West of the One Hundredth Meridian (Wheeler)

volume clearly indicate, the combined efforts of governmental, academic, and industrial geologists have enormously increased our knowledge of western geology.

The basic organization of the book is by broad topic beginning with an introductory historical essay (Nolan and Rabbitt) followed by several biographical papers mostly related to geological activities prior to 1879. The succeeding papers follow an almost classic stratigraphic arrangement from the regional setting and basement rocks to Holocene deposits and current mining activity. Some of the authors take a broad historical and regional perspective (Monger and Davis); others emphasize developments in more restricted areas (Berry, Swanson, Waitt, Weissenborn and Killsgaard). Some indicate the present state of knowledge (Jones and Silberling), which by implication contrasts strongly with earlier ideas. Some stress personalities (Drake, Leviton and Aldrich, Nelson and Rabbitt, Roberts), or political factors (Park); others stick to the rocks (Reid and Reid). And, in keeping with the diversity of geology, our authors come from a variety of institutions.

During the past several hundred million years, Western North America—the Cordilleran Region—has been the mobile western edge of the continent, the site of thick shelf to deep-water sedimentation, and an area of intensive and pervasive tectonism. Western North America is unmatched in the scale, variety, visibility, and accessibility of major geologic features, and many aspects of western geology have become standards of reference, ranging from the establishment of biostratigraphic and time-stratigraphic reference sequences to the development of new models of plate tectonics and continental accretion. But as the revolution in thinking forced on us by plate tectonics has shown, we need to know much more, and each advance in field and laboratory reinforces this conclusion. One of the charms of earth science is the uncertainty that accompanies the breaking of a rock with a hammer; at least once in his career, each geologist has experienced the thrill of finding the unexpected. The eruption of Mount St. Helens, one year too late for the USGS centenary, dramatically reaffirms that geology is very much alive in Western North America.

Figure 1. Systematic mapping by the territorial surveys that immediately preceded the United States Geological Survey. The areas shown were mapped (1867-1879) by the four principal Federal surveys of the territories, using triangulation (trigonometric) techniques from measured or astronomically determined base lines. Areas mapped by meander or other less controlled methods, or those examined in route reconnaissances, have been omitted from this compilation. Hayden (1883) published a geologic map covering about 420,000 square miles in the Rocky Mountains and Great Plains that summarized both his reconnaissance mapping and "systematic surveys"—the latter 110,000 are shown here. In 1867, Hayden also examined but did not map selected parts of Nebraska; a map by Goetzmann (1966:544) shows most of the "areas explored and mapped with less than geodetic accuracy. . .by each of these surveys."

The Hayden survey (fieldwork, 1867-1878; publications, 1867-1890) and the Powell survey (fieldwork, 1871-1878; publications, 1872-1893) published atlases of parts of the Rocky Mountains and Colorado Plateau, mapped principally at a scale of 4 miles to the inch (1:253,440). In 1874, these two surveys embarked on an Interior Department program to map and evaluate the resources of the 140-plus quadrangles into which the Nation's lands had been divided west of longitude 99°30′W. After 1876, Hayden mapped north of latitude 42° N., and Powell worked south of that parallel and mapped in all 67,000 square miles. In 1875, a third Interior-sponsored survey (not shown on this map), led by Walter Jenney and Henry Newton, examined the geology and resources of about 9,000 square miles in the Black Hills of the Dakota Territory; its atlas (1879; 1:253,440) and final report (1880) were published by the Powell survey.

In 1867, the King survey introduced to the territories the methods of triangulation mapping used earlier by the Whitney survey of California. The other three major Federal surveys adopted King's methodology in 1872-1873. The civilian-staffed King survey (fieldwork, 1867-1872; publications, 1870-1880) conducted its operations under auspices of the Corps of Engineers. The King survey issued a folio atlas (1876) of geologic and topographic maps, compiled at 1:253,440, that covered an area of about 87,000 square miles between the Sierra Nevada and Great Plains. The Wheeler survey (fieldwork, 1871-1879; publications, 1872-1889), principally a military reconnaissance and also directed by the Corps of Engineers, examined about 360,000 square miles in the West, mostly south of the 40th parallel, and published its maps at scales of 1:253,440 (130,000 square miles) and 1:506,880.

Map and caption compiled by Clifford M. Nelson; map drawn by Shirley A. Brown, U. S. Geological Survey, Reston, Virginia, from the reports of progress and other publications of the territorial surveys and from Schmeckebier (1904).

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THE USGS AT 100 AND THE ADVANCEMENT OF GEOLOGY IN THE PUBLIC SERVICE

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On March 3, 1979, the U. S. Geological Survey celebrated one hundred years of existence as a Federal agency. Much has happened since President Hayes on March 3, 1879 signed the bill appropriating funds for sundry civil expenses of the Federal government, a bill that provided the princely sum of $6,000 for the salary of the Director of the Geological Survey, and then established the organization in the following clause. The Director was given the responsibility for "direction of the Geological Survey, and the classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain." This rather oblique method of creating a new organization perhaps put an appropriate conclusion to the struggle for support, especially financial support, by three of the four predecessor exploratory surveys which were, by this action, replaced by one. In taking this action, Congress accepted one of the recommendations, but not the principal recommendation, of a committee of the National Academy of Sciences set up in accordance with a Congressional request for advice in determining a plan for surveying and mapping the territories of the United States to secure the best possible results at the least possible cost.

Four predecessor surveys had been established in the years following the Civil War to aid in the development of the West by acquiring additional knowledge of its geography and resources. The objectives of these surveys were primarily practical: to explore the geographic frontier, in part to learn about new and better routes by which it might be traversed, and to discover and appraise the natural wealth of the territory–not only the mineral wealth, which was the principal objective of the Exploration of the Fortieth Parallel, but also the soils, water, forests, and even scenic features. To achieve success in this sort of exploration of a physical frontier required development of both new concepts and new techniques. Fortunately, members of the early surveys and the new Geological Survey had the capacity to do this–were able, in a sense, to use the results of their exploration of intellectual frontiers in attaining their practical objective of delimiting the geographic one.

The record of the U. S. Geological Survey in later years seems to us to illustrate a continuing ability to utilize the products of intellectual curiosity in the solution of practical problems that arise in our economy. The industrialization of the country and the development of the West, participation in two World Wars, the need to resolve difficult and perplexing problems in water and mineral supply and environmental preservation, all have been accompanied by reorientation in the research programs of the Survey with concomitant applications of research results to the solutions of the problems. This ability to recognize or anticipate national needs and to use research results in their fulfillment has been the most significant contribution by the Survey to the advancement of geology in the public service and undoubtedly a primary reason for the Survey's longevity.

Clarence King, the Survey's first Director, gave the Survey's work a mission orientation–aid of the mineral industry–but from the beginning both practical and theoretical investigations, applied science and basic research, were part of the Survey program. Although he served only two years, that was long enough to gather a staff of outstanding scientists, to begin several geologic studies, to set up a chemical laboratory, to begin experimental investigations in geophysics, and in cooperation with the Census of 1880, to collect statistics on mineral resources, data that included geology and chemistry as well as production figures.

John Wesley Powell, who had headed a predecessor survey, succeeded King as Director in 1881. Powell aimed at establishing the Survey as a great scientific bureau with emphasis on research in many fields. Shortly after he assumed the office, paleontological laboratories were established and an independent topographic mapping program was begun. In 1882, Congressional authorization to prepare a geological map of the United States was obtained and the Survey embarked on the preparation of a topographic map of the United States because, Powell pointed out, sound geologic research must be based on geography. By 1884, the vigorous prosecution of the work and the rapid expansion of the Survey brought about a potential conflict of interest with the Coast and Geodetic Survey. This was one of the reasons that Congress agreed to investigate four Federal bureaus in order to achieve greater efficiency and economy in their administration. In his appearances before the Joint Committee, Powell proposed as guiding principles for Federal scientific bureaus that they should (1) promote the welfare of the people by investigations in fields that most vitally affect the great industries in which the people engaged, (2) have the broadest possible territorial base, and (3) not undertake work in fields in which private enterprise might be relied on for good and exhaustive work. Powell believed, however, that scientific principles must be established before science can be applied. The lack of practical results led Congress to slash appropriations, and Powell resigned in 1894.

While Powell was Director, the Survey began to study problems in the conservation of two major resources, forests and water. Data on forests and on the water supply in the arid regions were gathered as part of the mapping programs, although not systematically. In 1888, Congress authorized the Survey to undertake a study of the arid regions where irrigation was necessary for agriculture, but discontinued it two years later. Survey data on forests were used to establish the first forest reserves after passage of the General Revision Act of 1891.

Charles D. Walcott, who succeeded Powell as Director in 1894, brought both these programs to fruition. When Congress authorized creation of the forest reserves in 1891, it failed to provide for their protection and management. In 1896, the Survey housed a Committee on Forest Policy of the National Academy of Sciences, created to advise the Secretary of the Interior. In 1897, Walcott convinced Congress to pass the Forest Reserve Management Act, which included funds for the Survey to begin a comprehensive study of the forest reserves. Eight years later, administration of the forest reserves was transferred from the General Land Office and examination and classification of the forests from the Survey to the Forest Service of the Department of Agriculture. The Survey continued the topographic mapping of the reserves. In 1894 and subsequent years, the Survey received appropriations for "gauging the streams and determining the water supply of the United States" and began the systematic collection of water data. Eight years later, when Congress passed the Reclamation Act, administration of the act was assigned to the Survey, and Walcott became Director of the Reclamation Service as well as the Geological Survey. The work of the Reclamation Service, the planning and construction of large engineering works, were not part of normal Survey work. Thus the Reclamation Service became more and more independent of the Survey and in 1907 was completely separated from it as an independent bureau. F. H. Newell, who had served in a dual capacity as head of the Survey's Hydrographic Branch and Chief Engineer of the Reclamation Service, left the Survey to become the second Director of the Reclamation Service.

There was another spin-off from the Geological Survey in 1907, and yet another in 1910 that demonstrated the breadth of the Geological Survey under Walcott's direction, although both could also be traced to an initial impetus by Clarence King. A physical laboratory had been established in 1881, set up in part with King's personal funds, to investigate the effects of temperature, pressure, and related phenomena on rocks; studies of metamorphism and the paragenesis of minerals were also begun. Most of this work was discontinued in 1892, when Congress cut Survey funds drastically, but was begun anew in 1900. The newly established Carnegie Institution of Washington helped support the work for a few years and then, because the Survey's physical facilities at the time were unsuitable for delicate experimental work, voted to establish the Geophysical Laboratory and provide it with a suitable building. Arthur L. Day left the Survey to become Director of the Geophysical Laboratory.

The new bureau established in 1910 was the Bureau of Mines. Mining geology and technology, which had been an important part of the Survey's work under King but a much lesser part under Powell, again flourished while Walcott was Director. The mining industry soon became interested in the establishment of a separate division, or bureau, or even department of mines to serve its needs. In 1904 the Survey began an experimental program to determine the fuel value of coal and lignite, which immediately produced such significant results that Congress was persuaded to continue the work, and also an investigation of the properties of structural materials begun by the American Portland Cement Manufacturers, as part of the Survey's regular program. In 1908, because of the high death toll in the Nation's coal mines, the Survey was authorized to investigate mine safety. Again, these investigations were somewhat apart from normal Survey endeavors, and in 1910 they were transferred to other agencies, the fuel testing and mine safety programs to the newly established Bureau of Mines, and the structural materials investigations to the National Bureau of Standards. Joseph A. Holmes, head of the Survey's Technological Branch, became the first Director of the Bureau of Mines, and most members of the Branch were transferred to become the nucleus of the new bureau.

The Survey's regular program also flourished under Walcott's direction and in celebrating its first 25 years of existence in 1904, the Survey could report that mapping and investigations were underway in Alaska, Hawaii, Puerto Rico, and Cuba as well as in the States. Nearly a third of the country was topographically mapped, and geologic folios and almost 400 reports had been published on a wide range of topics. The investigation of the Leadville mining district in Colorado had demonstrated the practical importance of geological studies in mining; studies in the Lake Superior district had aided the discovery and development of reserves in that area; and studies in the Appalachian coal fields were pointing the way toward a scientific base for the development of fuel resources.

The second quarter of the Survey's history is nearly coincident with the directorship of George Otis Smith, who filled the office from May 1, 1907, when Walcott became Secretary of the Smithsonian Institution to December 22, 1930. Smith believed that the role of a scientific bureau was to collect and arrange facts to provide a basis for development of national policy or to aid in the administration of law, in particular, for the Survey the administration of public-land law. He became Director at a time when the Roosevelt administration had become very concerned about the conservation of natural resources and was at the same time vigorously prosecuting those who had obtained public lands through fraudulent means. The Survey embarked on an extensive program of evaluating the mineral and water values of public lands, and large areas of the West were withdrawn from entry in the interest of conservation. When German interests retaliated for the withdrawal of phosphate lands by making it difficult for the United States to procure potash, the Survey was called on to search for domestic deposits. The increased emphasis on widening the Survey's usefulness in applying science inevitably meant that less effort could be put into basic research, and the Survey's support by the profession declined. At the same time, however, Smith recognized the Survey's responsibility to make its work intelligible to the public, so non-technical descriptions of physical features and their origin were printed on the backs of topographic maps and guidebooks covering points of scenic or unusual geologic interest in some of the national parks and along transcontinental railroad routes were prepared. As a result, the general public was in closer touch with the agency than it had been previously and made more use of Survey data and products.

When World War I began in Europe, the Survey published a special bulletin entitled "Our mineral reserves–how to make America industrially independent." The bulletin was very optimistic about American resources of all but a few minerals, unreasonably so in some cases it became apparent as the war continued and intensified. The Survey expanded its program to aid in the discovery and development of new oil reserves and began investigations of oil shales as potential sources of petroleum. Even before the United States entered the war, it became necessary to search for certain critical metals needed by industry, a search that was widened after war was declared in 1917. Mineral statistics that the Survey had been accumulating for more than 35 years were used as a basis for planning by many of the war boards and the development of the strategic mineral concept. A beginning was also made in military geology through the service of a Survey geologist on the staff of General Pershing and studies of the mineral and water resources of the world in connection with the Peace Conference.

The twenties were difficult years for all Federal scientific bureaus as the Federal government emphasized the promotion of business and economy in government and the Nation withdrew from international involvement into isolation. Petroleum shortages immediately after the end of World War I intensified in the development of other energy sources, especially water power, and the Survey's topographic and hydraulic engineers made many surveys of potential sources and dam sites, but the petroleum shortages were succeeded by a petroleum glut. Topographic mapping and water-resources investigations by the Survey received increasing amounts of financial assistance from States, became increasingly practical, but grew in size. Geologic investigations, on the other hand, almost exclusively dependent on reduced Federal funds, became more long range.

The third quarter of the Survey's history was one of rapid and great changes as the nation struggled with the problems of economic depression and war. George Otis Smith resigned as Director in December 1930 to become chairman of the newly reorganized Federal Power Commission. He was succeeded by Chief Geologist Walter C. Mendenhall, who had persistently preached the necessity of basic research all during the twenties, and for a brief period the Survey was given a large, for those days, appropriation for fundamental investigations in geologic sciences. The continuing depression soon forced reductions in appropriations that resulted in reductions in force and suspension of programs. Then allocations of funds from the Public Works Administration, established a few months after Franklin D. Roosevelt became President, and from other Federal agencies, including the newly established Tennessee Valley Authority, resuscitated Survey programs and brought about the resumption of basic research, particularly in the topographic mapping and water-resources investigations. Gradually, direct appropriations to the Survey were increased and more nearly normal operations were resumed. Then as the political situation in Europe worsened, Public Works funds were used to begin the search for strategic minerals. In June 1939 Congress passed the Strategic Materials Act, and on August 5, less than a month before Hitler's forces marched into Poland, appropriated funds for search for and procurement of strategic minerals.

Mendenhall served as Director until 1943, two years beyond normal retirement age, and was succeeded by W. E. Wrather, who served as Director for the remainder of the third quater of Survey history. During the war years, the Survey bent its entire energies to the war effort—the search for strategic minerals, strategic mapping, water supply, and military geology. Information was needed, and information was supplied, but in the course of procuring the data, new research methods and technology were devised.

Most of the postwar problems were not unlike those that followed the First World War. The war had taken its toll of the Nation's mineral supplies and had revealed an acute need for both topographic and geologic maps on scales suitable to meet modern needs; programs were initiated to remedy these deficiencies. The river investigations of the twenties were paralleled by investigations in support of programs of river-basin development. Technical assistance to Caribbean nations following World War I had its counterpart in technical assistance to developing nations in 1949 that found Survey scientists and engineers working in all parts of the World. The Nation, however, did not withdraw into isolation and the outbreak of the Korean War in 1950 and the stepping-up of the cold war brought on a state of partial mobilization. Again the Survey revised its programs to meet defense needs; the military geology program was expanded, as was the search for radioactive raw materials, and special studies were made of strategic minerals, including petroleum.

During all this time the Survey continued to develop new exploratory tools and improve its techniques of research. Geochemical prospecting methods were developed to aid in the discovery of mineral deposits. New rapid, sensitive, and inexpensive analytical methods suitable for use in the field were developed, and geobotanical and hydrogeochemical techniques were investigated. Geophysics took to the air, and magnetic and radioactivity surveys were made of many thousands of square miles. Geologic mapping was accelerated by the development of photogeology to obtain coverage more rapidly and at less cost.

These many demands on the Survey during the war and post-war years led to its steady growth. When the Survey began its second half century, it had 1,000 employees and its total funds were approximately $3.5 million a year. In the year before the United States entered World War II, the Survey had about 1,700 employees and spent about $5.5 million. By the early 1950s, the number of employees had increased to about 6,000 and the total funds had increased to $48 million.

The last quarter of the Survey's first century has been marked by the necessity of coping with ever more complex problems resulting from the unprecedented growth in population, urbanization, and higher standards of living, all of which made increased demands for raw materials of all kinds. Through improved methods of exploration, the ability to exploit lower-grade sources, and the substitution of common for less common materials, science and technology combined to keep up with these increasing demands but new problems were generated. In some areas, over-specialized exploitation of mineral resources caused economic problems; in other areas competition for resources, where development of one precluded use of others, created management problems; and the inherent conflict between development and conservation and protection of the environment was sharpened. At the same time, the increasing industrial development and urbanization caused health hazards through waste products and heightened vulnerability to damage by natural geologic processes. The Survey has been called on to investigate such widely divergent problems as the geologic conditions affecting the peaceful uses of atomic energy and the disposal of radioactive wastes, the bearing of differences in the natural distribution of chemical elements on public health, the causes of landslides, the resources of the ocean floor, the prediction of earthquakes, and land use in developing areas. At the same time it must continue its primary responsibility of assessing the mineral resources of the nation. The uncertain future of our energy supplies has been well publicized; less well known is the fact that supplies of many major minerals are also a matter of concern. Millions of acres of Federally owned land thought to be favorable for the occurrence of minerals, including energy sources, are also considered candidates for dedication to uses that would in many instances exclude them from mineral entry. The Survey is making a mineral assessment of these lands to determine their mineral potential before final decision is made as to their use.

Fundamental research is more than ever a necessity as the complexity of the problems increases. More than 20 years ago, Survey scientists began crossing a new geographic frontier, first by the photogeologic mapping of the Moon, then the training of astronauts in geologic and geophysical investigations of the Moon, and still more recently by investigations of other planets in the Solar System. All of these have profoundly influenced our thinking about the origin of our own planet and its early history. At the same time, they have provided us with vast amounts of data to aid in the solution of practical problems. For example, before we were long into this new Space Age, the Survey undertook a feasibility study of using space vehicles and high-altitude aircraft to observe and record the features of the earth from distances of 20 to 900 kilometers. In 1966, the EROS program was launched, and now data from satellites are being used by agricultural interests, in forest and range management, in urban planning, hydrologic reporting, mapmaking, and the search for minerals. At the other end of the spectrum, more and more laboratory investigations are underway, seeking data on the physical properties of rocks, on the nature of ore-forming fluids, on the physical, chemical, and biochemical changes that take place in weathering in order to develop an understanding of the processes by which mineral deposits are formed and thus guide the search for new sources.

This chronological recital alone records the very considerable contributions made by the organization to the "advancement of geology in the public service." They may be summarized in another way by pointing out four broad categories in which these activities have been especially productive.

One includes the development or refinement of new fields or new principles. We believe it is fair to say, for example, that mining geology as it is practiced today is very largely the product of Survey work. Such work began with Clarence King who, in addition to his own activities, initiated the work of George Becker in the Comstock and S. F. Emmons in Leadville, continued through the widespread activities and generalizations of Lindgren and the timely analysis of the newly developed porphyry copper deposits by Arthur Spencer and F. L. Ransome, the field development of airborne and geochemical exploration methods, and laboratory researches in geochemistry and petrology. An even stronger case might be made for the new field of ground-water hydrology, with the early work of Mendenhall in southern California, the long period of development under O. E. Meinzer, and more recent investigations by A. N. Sayre, C. V. Theis, and others.

Contributions to geologic thinking and to the development of principles are basically made by individuals rather than organizations, but organizations may provide an environment in which such contributions may flower. We believe that this has been true in the Geological Survey. Certainly, basic concepts in sedimentation and stream dynamics have been continuously influenced by the work of Gilbert, Rubey, and most recently, by Leopold. Similarly, glacial geology has been influenced by Survey men from T. C. Chamberlin through W. C. Alden and F. E. Matthes; structure, from Dutton to Gilluly; petrology from Arnold Hague through Whitman Cross, J. P. Iddings, and E. S. Larsen, Jr. The list could be greatly expanded.

Less glamorous, perhaps, but certainly of inestimable value to the profession have been the many new and improved tools or techniques that have resulted from the Survey's work. The Bibliography of North American Geology, the Lexicon of Geologic Names, and the Data of Geochemistry, for example, have been invaluable to the practicing geologist. A whole series of recommendations or developments, from the standardization of cartographic methods for geologic maps to the devising of the instruments and methods of photogeology have made it possible for geologists to do field work and write reports more accuately and effectively.

A third category involves the recognition and sponsoring of new and desirable areas of endeavor in fields related to geology and the earth sciences. The establishment of such Federal agencies such as the Bureau of Reclamation, the Bureau of Mines, and the Grazing Service (now a part of the Bureau of Land Management) and the non-Federal Geophysical Laboratory of the Carnegie Institution of Washington resulted directly from activities initiated in the Geological Survey. In view of the current crusade against the Federal bureaucracy, the creation of additional Federal agencies may be considered in some circles a dubious contribution, but we believe that most thoughtful observers will agree that the part played by the Survey in the creation of professional agencies in the resource-management field with the high standards that characterized the parent agency has been a significant contribution to the Nation's well being.

Finally, we believe that the Survey has played a large and beneficial role in education in this country, in addition to the contributions to geologic thinking mentioned earlier. In part, this has been the result of its personnel policies and, in part, of its extensive publications program. The bureau has from the beginning encouraged an interchange of personnel between its staff and that of university and college faculties as well as the summer employment, as field assistants, of advanced students in geology. This policy has led to the widespread use of the so-called "w.a.e" appointments, which are in effect when the individual is actually employed—commonly during the summer field seasons. Among the earliest of these appointments were those of T. C. Chamberlin, J. S. Newberry, and N. S. Shaler. Utilization of scientists such as these not only benefitted the Survey through the individual skills thus made available to it, but inevitably contributed to the universities and to geologic education by making available promptly the results of field and laboratory work as instructional material, not only their own work but the work of other members of the Survey with whom they were in contact. This interchange of personnel and the widespread utilization of w.a.e appontments has continued to be a major element in Survey policy to the present day. Possibly of even greater assistance to geologic education has been provided by the publications which record the results of the Survey's work. We suspect that directly, through the use of such classics as Gilbert's Lake Bonneville monograph, and indirectly, through the contributions of Survey material in textbooks and lectures, almost everyone in the geologic profession is indebted to the long series of reports on the Survey's field and laboratory work.

It is apparent that we believe that the Geological Survey has contributed significantly to the advancement of geology and to the public service. It is tempting to try to assign a dollar value to this contribution–either by adding up the value of the ore bodies discovered, or savings made in Federal development plans. We doubt, however, that such figures would have any lasting meaning even if we could adequately appraise the dollar value. To us, the real and lasting contribution made by the Survey, along with other Federal scientific agencies, is the part they have played in securing general recognition throughout the country that scientific and professional work of the highest quality is not only possible in the Federal government, but that it has been one of the essential contributors to the development of this nation to the international power that it is today.

THE ROLE OF CLARENCE KING IN THE ADVANCEMENT OF GEOLOGY IN THE PUBLIC SERVICE, 1867 - 1881

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From 1867 to 1872, the U. S. Geological Exploration of the Fortieth Parallel, led by Clarence King, examined the natural resources, geology, and topography of the lands flanking the transcontinental railroad between the Sierra Nevada and the eastern slope of the Rocky Mountains. King's talents as a field geologist, theoretician, and administrator, his staff's abilities, and the long-term service of his field geologists and topographers were all factors in his survey's contributions to applied and basic earth science. The King survey's organization, field methods, and scientific standards and products served as models for the Hayden, Powell, and Wheeler surveys of the western territories in the 1870s. Of these four reconnaissances, only the King survey from its beginning investigated a well-defined area for specific purposes.

In 1879, Congress terminated the three remaining territorial surveys and King turned his energies and skills to staffing, organizing, and orienting the new U. S. Geological Survey, as its first Director (1879-1881). King established a mission-oriented program of applied investigations for the Survey that yielded immediate practical results in support of economic geology vital to the Nation. He initiated pioneering studies in geophysics, geochemistry, and microscopic petrography that supported the applied work in mining geology, but also led to significant basic advances in the earth sciences. The standard of excellence and the spirit King installed in the USGS have been transmitted from one generation to another of its staff, so that even today many of the successful policies and philosophies he espoused are still evident.

Clarence King (1880:4) marked 1867 as the year when Federal geology "ceased to be dragged in the dust of rapid exploration and took a commanding position in the professional work of the country." From the time of Amos Eaton's survey of the Erie Canal route, geological knowledge had been sought to aid economic development of areas in the United States traversed by transportation routes and other internal improvements. Beginning in the 1830s, the Federal government responded with route and areal studies, principally those of topography and natural history. The Civil War interrupted these reconnaissances, but in March 1867 Congress authorized two areal surveys of the economic resources of the lands flanking the routes of the Central and Union Pacific Railroads, to continue the scientific examination of the mineral resources of the western lands. The two surveys were King's own U. S. Geological Exploration of the Fortieth Parallel (to 1878) and Ferdinand Vandeveer Hayden's small organization that became his U. S. Geological and Geographical Survey of the Territories (to 1879).

Of the four Federal surveys of the western territories, King's organization did the most to advance applied (King insisted on immediate results of practical value) and basic earth science in the public service. King's scientific and administrative talents, the abilities of his staff, and the limited turnover among his field geologists and topographers were the principal factors in his territorial survey's accomplishments. The organization, field methods, and scientific standards and products of the King survey also served as models for Hayden's, and later, Powell's and Wheeler's Federal surveys in the 1870s.

Clarence King represented a new professionalism in American geology. King had studied under

James Dwight Dana and George Brush in Yale's Sheffield Scientific School as a member of the first class to receive the degree of bachelor of science. He had heard Louis Agassiz's lectures about glaciers. He had read William Brewer's letters to Brush describing the achievements and romance of Josiah Dwight Whitney's California Geological Survey, which he later joined.

In 1866, after three years with the California Survey, King sought sponsorship by the Army Corps of Engineers for a survey of the economic resources of a wide strip across the Great Basin from the eastern base of the Sierra Nevada to the eastern front of the Rocky Mountains, an exploration he had dreamed of as early as 1863. On March 2, 1867, Congress authorized "a geological and topographical exploration" (Sanger 1868:457) along the 40th Parallel–if it could be done with existing appropriations–and the Secretary of War, Edwin Stanton, appointed the 25-year-old King "U. S. Geologist" at $250 per month.

On March 21, Brigadier General Andrew Humphreys, Chief of Engineers, directed King to

> examine and describe the geological structure, geographical condition and natural resources of a belt of country extending from the 120th meridian eastward to the 105th meridian, along the 40th parallel of latitude with sufficient expansion north and south to include the line of the Central and Union Pacific railroads and as much more as may be consistent with accuracy and proper progress which should not be less than 5 degrees of longitude yearly. . . (quoted in Rabbitt 1979:162).

The survey was also to examine all rock formations, mountain ranges, detrital plains, coal deposits, soils, minerals, ores, and saline and alkaline deposits; gather material for a topographic map; measure elevations and temperatures; and collect plants and animals to define their occurrence and distribution. King had written most of the orders himself (Wilkins 1958:96; Goetzmann 1966:437; Rabbitt 1979:162).

Humphreys told King that he could expect $100,000 for the three-year reconnaissance. In May 1867, the New York *Times* reported King's departure and his intent to establish first a topographic base on which to compile geologic information. The *Times* said that he had determined next to examine (metallic) mineral deposits and

> coal, the discovery of which may be of more practical value to the railroad than a gold mine; and for water, which in the desert track between the Sierra Nevada and the Rocky Mountains proper, is not always to be found when wanted. All the work of nature. . . is to be scanned (Horan 1966:152).

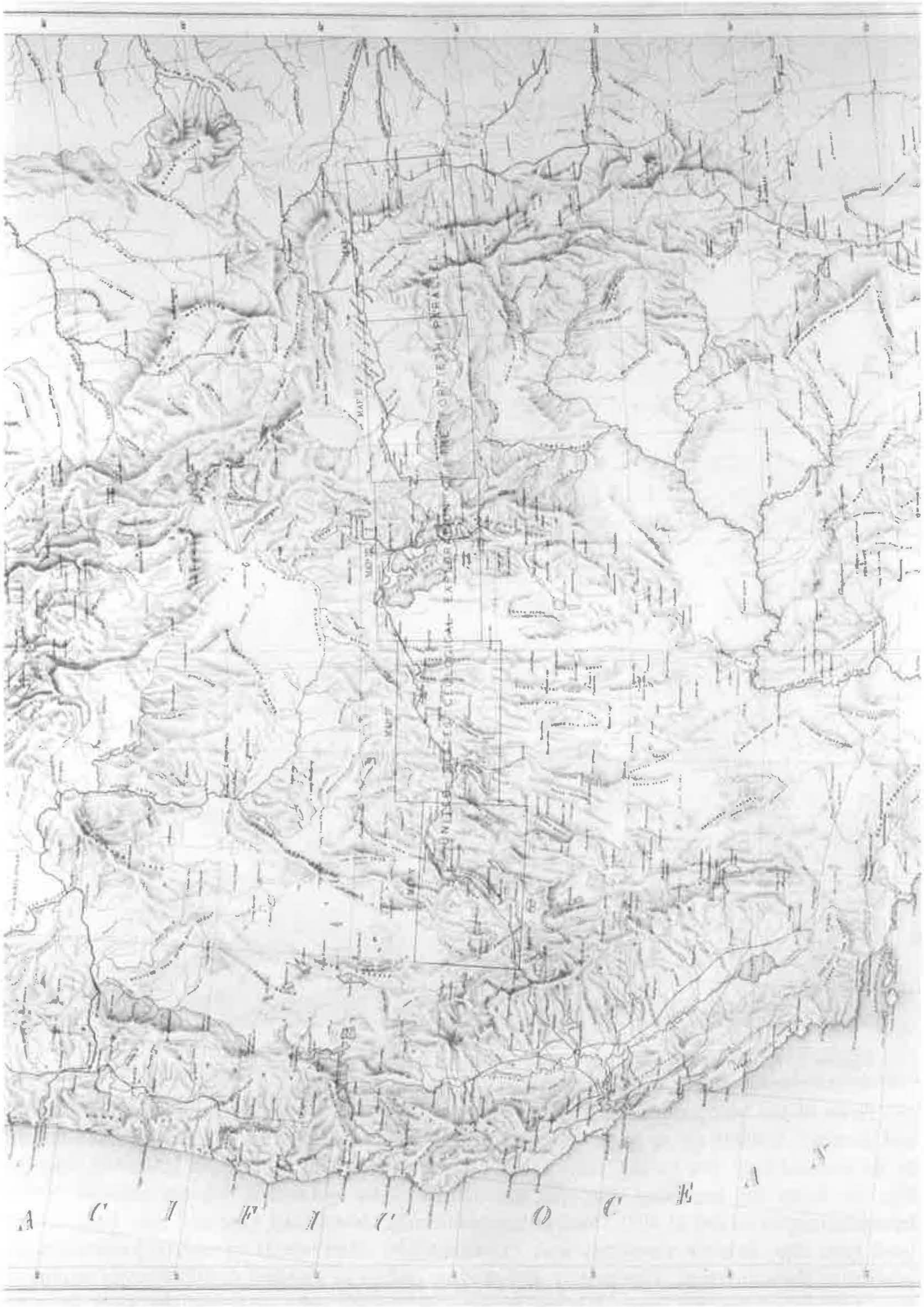
Topographic data from King's exploration would also aid military operations in 40th Parallel country, and the Engineers believed the work would help them reestablish their pre-war leadership in exploring and mapping the West. The *Times* reported that "perhaps three years more will be occupied in working up the result; but preliminary reports will be sent on from time to time, embodying all the discoveries of immediate practical interest" (Horan 1966:152), indicating that King intended to undertake both applied and basic studies.

King's skill in choosing his scientific staff of eight and in organizing the field studies equalled that shown in his conception of the work and in seeing it through Congress. The geologists were James Hague, Arnold Hague, and Samuel Franklin Emmons, all trained at Yale or Harvard and at major universities in Europe. James Terry Gardner ("Gardiner," after 1880), chief topographer, had served with Charles Hoffmann (and King) in the California Survey, and the other topographers were experienced. King was also sensitive to the scientific, esthetic, and publicity value of photographs, then printed from wet-plate glass negatives. He hired Timothy O'Sullivan, a combat photographer with the Army of the Potomac in the Civil War, to record geology, field operations, and landscapes–a practice later adopted by the other territorial surveys.

King made a comprehensive plan for the exploration before taking the field, a plan systematically followed in all essential features throughout the reconnaissance. It was important to determine the broad outlines of the geology and mineral resources as soon as possible, he believed, but it was obviously impossible to make a detailed survey under such conditions; hence, the work was entitled an "exploration."

Figure 1. Clarence Rivers King (1842-1901), at 25.

None of the topographic maps of the Fortieth Parallel country then available were of a scale and accuracy suitable for geologic compilation (Gardner *in* King 1878:763). King divided the area to be mapped into five blocks, each about 165 miles long and more than 100 miles wide (see Fig. 2). From the beginning, mapping was controlled by systems of primary through tertiary triangulation, extended at first from an astronomically determined base and later from a measured base line. Relative elevations were determined by observations of cistern barometers and gradienter measurements. Topography and geology had to be mapped simultaneously within the time established for the work. George Becker (1912:646), who observed the work from the University of California, pointed out that


UNITED STATES GEOLOGICAL EXPLORATION OF THE FORTIETH PARALLEL
ACIFIC OCEAN

> all the men had constantly to guard against two temptations, one being to follow out their problems by detailed studies at an undue expenditure of time, and the other to gain time by slighting important matters in which they might happen to feel relatively slight personal interest. There can be no doubt that they displayed great self-control; and in my opinion the result was an unrivaled model of a preliminary survey of an unknown region.

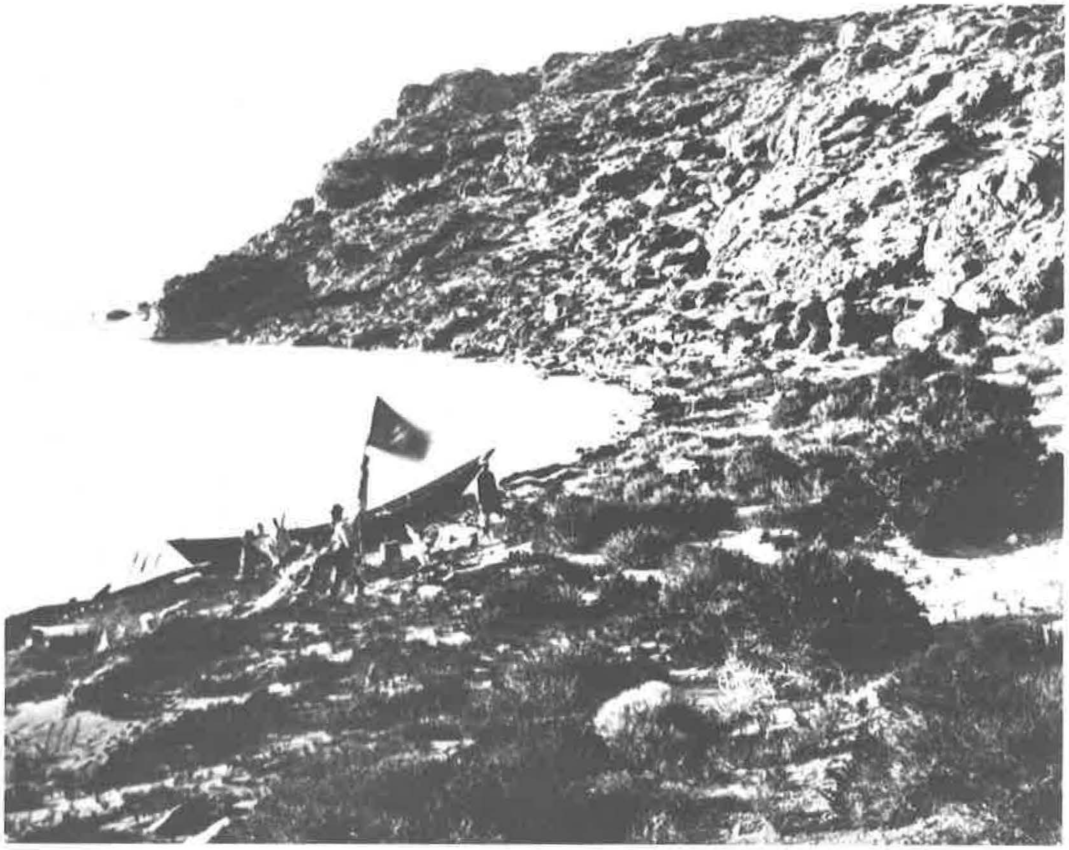


Figure 3. Camp of the party led by Robert Ridgway, King's zoologist, and Timothy O'Sullivan, during the survey's first examination of Pyramid Lake, western Nevada, August 1867. The King survey's flag—bearing a crossed pick and hammer, white on a dark blue field—flies from a makeshift staff in front of the boat. The flag is a lineal ancestor of the USGS' present standard. Photograph by O'Sullivan, courtesy of the National Archives and Records Service.

King arranged for *Mining Industry*, Volume III of the final reports, to be published first as the work "most directly applicable to the material development of the great extent of mountain territory opened by the Pacific Railroad" (King *in* Hague 1870:vii). The volume yielded information of immediate practical value to the mining industry and demonstrated the utility, quality, and scope of 40th Parallel science. In the volume, the Hagues and Emmons described the principal mining districts of the West. James Hague's analysis of the Comstock mines and treatment of their ores accompanied Arnold Hague's recommendation for improving the Washoe reduction process. King

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Figure 2. The five map quadrangles of the Fortieth Parallel Exploration, from the "Cordilleras" index map ("Scale: 60 Miles to 1 Inch") by Edward Freyhold that introduced the King survey's principal *Atlas* (King 1876; reproduced in Schwartz and Ehrenberg 1980: pl. 191). The survey mapped an area of 87,000 square miles, from the Sierra Nevada to the Great Plains.

Figure 4. Samuel Franklin Emmons (1841-1911), in the 1870s. Photograph courtesy of the Library of Congress.

described Comstock geology and ore genesis, the first such discussion widely available, and predicted silver at greater depths—a prediction confirmed in 1876. King also described the extent and geochemistry of the Green River coal fields (Cretaceous and Tertiary), then being mined for locomotive fuel. The Hagues and Emmons reported on the silver mining districts of Nevada and Colorado and the gold mines of the Central City area in Colorado. Paleontologist Fielding Bradford Meek of the Smithsonian, the survey's first collaborator, determined the relative ages of the silver-bearing Devonian limestones at White Pine, Nevada and the coal-bearing Cretaceous and Tertiary sandstones in southwestern Wyoming (Nelson and Yochelson 1980:609-610).

In *Mining Industry*, King related the mining districts to the geologic and tectonic history of the continent and created wide interest by suggesting that mineral deposits in the West were grouped in seven longitudinal zones from California to Colorado, emplaced principally during two major intervals of mountain building. King also presented a preliminary synthesis of the physiography and general geology of the 40th Parallel country. *The American Journal of Science* recommended that the volume "be studied by every one interested in the development of our western mining regions" (Anonymous 1871:219) as the "most valuable contribution yet made to the literature on the Mining Industry in the United States." Whitney (1875:297), author of the classic *Metallic Wealth of the United States,* called it "a superb piece of work, and far in advance of anything previously done in this country in the same line, and we know of nothing published in Europe superior to it."

The *Atlas* to *Mining Industry*, the first of the great chromolithographic works published by Julius Bien of New York for the territorial surveys, displayed geologic maps (with topographic

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Figure 5. S. F. Emmons' chromolithographic "Geologic Map of the Toyabe [Toiyabe] Range" (scale: 1 inch=3 miles; contour interval, 300 feet) in central Nevada, on Allen Wilson's topographic base, published as Plate 13 in the *Atlas* to *Mining Industry* (Hague 1870). "The most productive [silver] veins in the district occur on the south slope of Lander Hill, the granite spur, which extends to the westward from Mount Prometheus" (Emmons *in* Hague 1870:331)—just east of Austin in the upper left portion of the map.

GEOLOGICAL MAP OF THE TOYABE MOUNTAINS

GEOLOGY S. F. EMMONS TOPOGRAPHY A. D. WILSON

Plate 13.

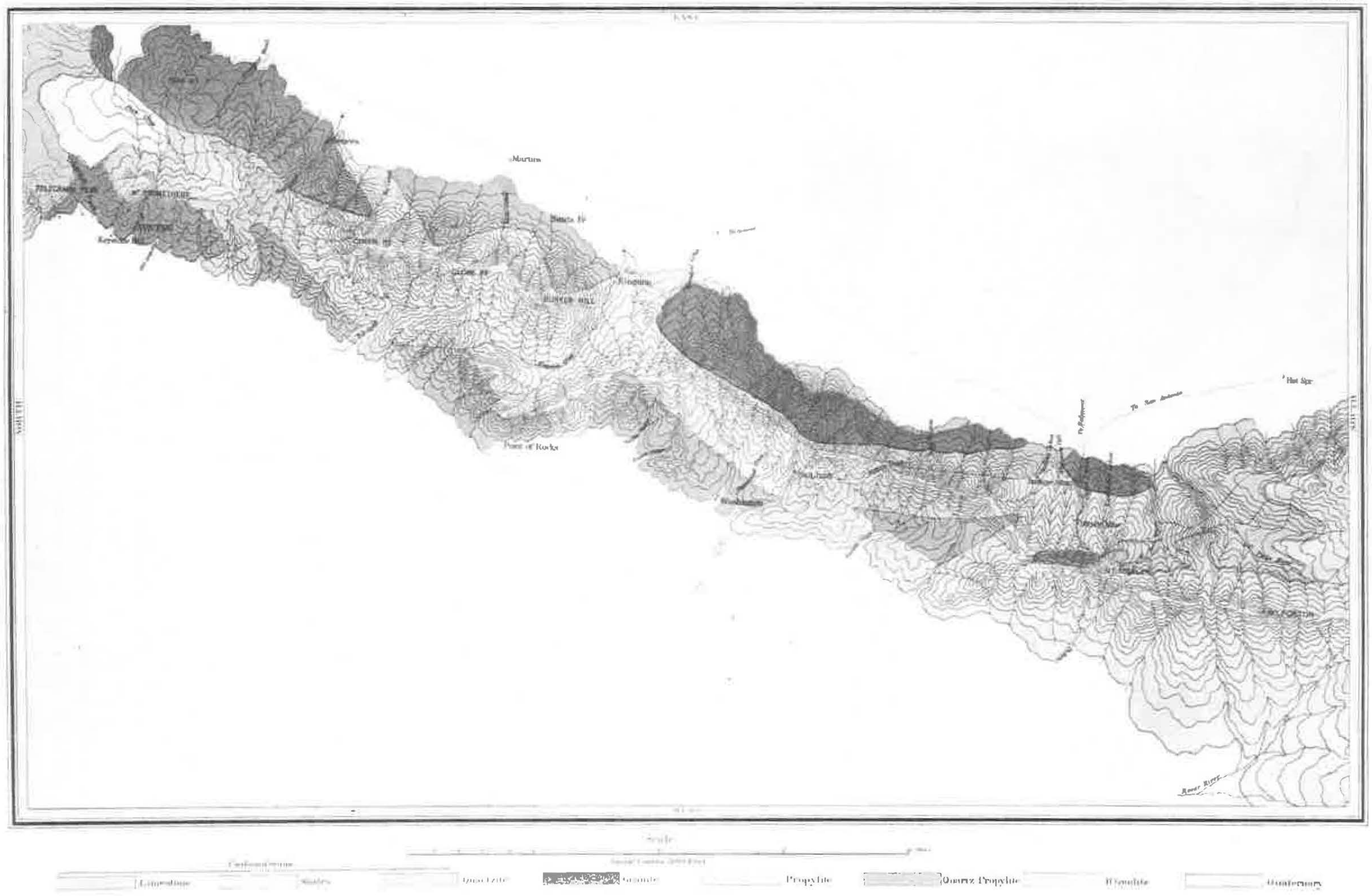


Figure 6. Topographer Allen Wilson at the King survey's "astronomical observatory" in the Ruby Valley, northeastern Nevada, August 1868. Wilson holds a chronometer and faces the zenith (at right) and meridian (at left) telescopes. The telegraph to Wilson's right connected to the "observatory," via the transcontinental line's relay at nearby Camp Ruby, with the Coast and Geodetic Survey's astronomical station at Salt Lake City. Photograph by O'Sullivan.

contour lines) and cross sections of the Comstock (by King and Gardner), Austin (by Emmons and topographer Allen Wilson), and White Pine (by Arnold Hague and topographer Fred Clark) mining districts in Nevada. Humphreys, pleased with the work, extended the detailed reconnaissance eastward to the 104th Meridian, requiring additional field work through 1872.

In 1872, as King's field work ended, Congress appropriated money for a topographic reconnaissance, by the Corps of Engineers, west of the 100th Meridian. Lt. George Montague Wheeler's plan called for 95 maps at a scale of eight miles to the inch, each covering about 150 by 200 miles. As Congress had continued to appropriate money for Powell's Exploration of the Colorado River of the West, in 1873 three Federal surveys were examining the natural resources beyond the 100th Meridian and competing for increased areal and topical opportunities and appropriations. Hayden's field parties encountered Wheeler's in Colorado in 1873, leading to a dispute about duplication, accuracy, and economy of effort. In 1874, Congressional investigation of the control of science in the West–military versus civilian–resolved none of the problems, but Congress did recommend consolidation of the surveys' functions into a single department, and the Powell survey was transferred from the Smithsonian back to the Department of the Interior (Rabbitt 1979:214-221). During the investigations, the King survey's methods were upheld as a model and both Powell and Humphreys highly praised the work.

Mining Industry and the King survey goals, organization, and field methods served as both model and standard for the other three Federal surveys of the western territories. Their impact is reflected in the operations and products of the other surveys through 1878. Ferdinand Hayden especially praised *Mining Industry* in 1870 and began his own studies of metallic resources. Hayden's annual report for 1869 had contained Persifor Frazer's review of Colorado mines and minerals. Hayden's increased concern with western mining reflected his boosterism and previous interest in coal, the influence of the King survey's work, and the demands of the flourishing mining industry. After three years of limited financial support from the Congress (a total of $20,000 through 1869), which allowed only a limited staff, Hayden received $25,000 in 1870 and Congressional approval of his plan for a survey of the western territories under the auspices of the Interior Department. In contrast to the established programs of the King and Hayden surveys, in 1870 John Wesley Powell was seeking Congressional support to add science to daring exploration in a second reconnaissance of the Colorado River by boat. Lt. Wheeler, following a successful route-reconnaissance south across Nevada in 1869, was formulating his plan to map topographically the lands west of the 100th Meridian—principally for military purposes.

King's work significantly influenced the Powell and Wheeler surveys, principally in the adoption by these geographically oriented reconnaissances of King's "quadrangle" approach to blocking out areas for mapping and his methods of triangulation surveying, but its effect can be seen most clearly in the first three years' work of Hayden's survey. Hayden's organization remained an all-purpose natural history reconnaissance; however, the quality of its scientific work and its studies of economic geology increased in subsequent years. Topographic mapping began in 1871 in Yellowstone, but data were gathered by traverse or meander-astronomic methods and displayed by hachures rather than contour lines. In 1873, Gardner and Wilson of the King survey joined Hayden's staff and his survey began mapping by triangulation from measured base lines. The Hayden survey spent the next four seasons in Colorado, and publication of the *Geological and Geographical Atlas of Colorado* (Hayden 1877) marked the apex of its work. Hayden's *Atlas* reflected the methods Gardner and Wilson had used in compiling King's *Geological and Topographical Atlas* (1876). King's geologic and topographic maps, two double-folio sheets for each of the five map rectangles, were printed by Bien at a scale of 4 miles to the inch (or about 1:250,000, equal to that of the USGS present series of 1 x 2-degree sheets).

King submitted brief reports to the Chief of Engineers, but, unlike Hayden, King refused to publish "geology of the routes" narrative reports or hurry work on the remaining final volumes after field work ended in 1872. "The day has passed in Geological Science," he wrote in February 1874 (quoted in Rabbitt 1979:210) to General Humphreys,

> When it is either decent or tolerable to rush into print with undigested field observations, ignoring the methods and appliances in use among advanced investigators. It is my intention to give this work a finish which will place it on an equal footing with the best European productions and those few which have redeemed the wavering reputations of American investigators.

Among the final reports published by the Engineers was Ferdinand Zirkel's study, using the newest techniques in microscopic petrography, of rocks sampled by the King survey.

In 1877, Arnold Hague and Emmons published *Descriptive Geology*; it and King's own *Systematic Geology*, published the next year, capped the exploration's contributions to a comprehensive review of the geology, tectonics, and geologic history along the 40th Parallel. Nearly 35 years later, Becker (1912:646) recalled how *Descriptive Geology* was "full of news, and Gerhard vom Rath, to whom geology (directly and indirectly) owes so much, told me in 1883 that it was the interest the Descriptive Geology aroused in him which led him to visit the United States." Reviewers of King's synthesis noted (Grove Karl Gilbert 1879; quoted in Wilkins 1958:215) that "Few American geologists have undertaken so wide a range of theoretic and economic studies and none have acquitted themselves with greater credit." *The American Journal of Science* commented (Anonymous 1879:67) that "Mr. King's graceful pen never showed itself to better advantage" and Rossiter Raymond (1879:22), editor of *The Engineering and Mining Journal*, remarked that

Figure 8. Clarence King examining crevasses in the Whitney Glacier, that "shattered chaos of blue blocks" on the western slopes of Mount Shasta, September 1870. On September 11, King, Emmons, and topographer Fred Clark climbed the satellite cone Shastina and gazed down on the river of ice, the first active glacier observed in the United States. The next day, the party discovered the three main glaciers on Shasta's northern slopes (King 1871:159). Photograph by Carleton E. Watkins.

> we will not prematurely commit the error of the lady who said of another, "Oh! She can't be good, because she is so pretty," by fancying that because Mr. King's volume is brilliant it cannot therefore be also sound. The gods do sometimes (most unfairly) grant both gifts at once.

Historians have criticized as erroneous King's analysis of the structure and evolution of the Basin and Range Province, for depending solely on the folded-mountains model then based on the Appalachians and the Alps (Manning 1967:32; Pyne 1980:52-53, 234). These critiques seem based solely on King's initial evaluation of the regional structure, in which he "alluded to the Basin Ranges as a series of folds" (King 1878:735) "in a brief sketch of the Green River Basin" in *Mining Industry*.

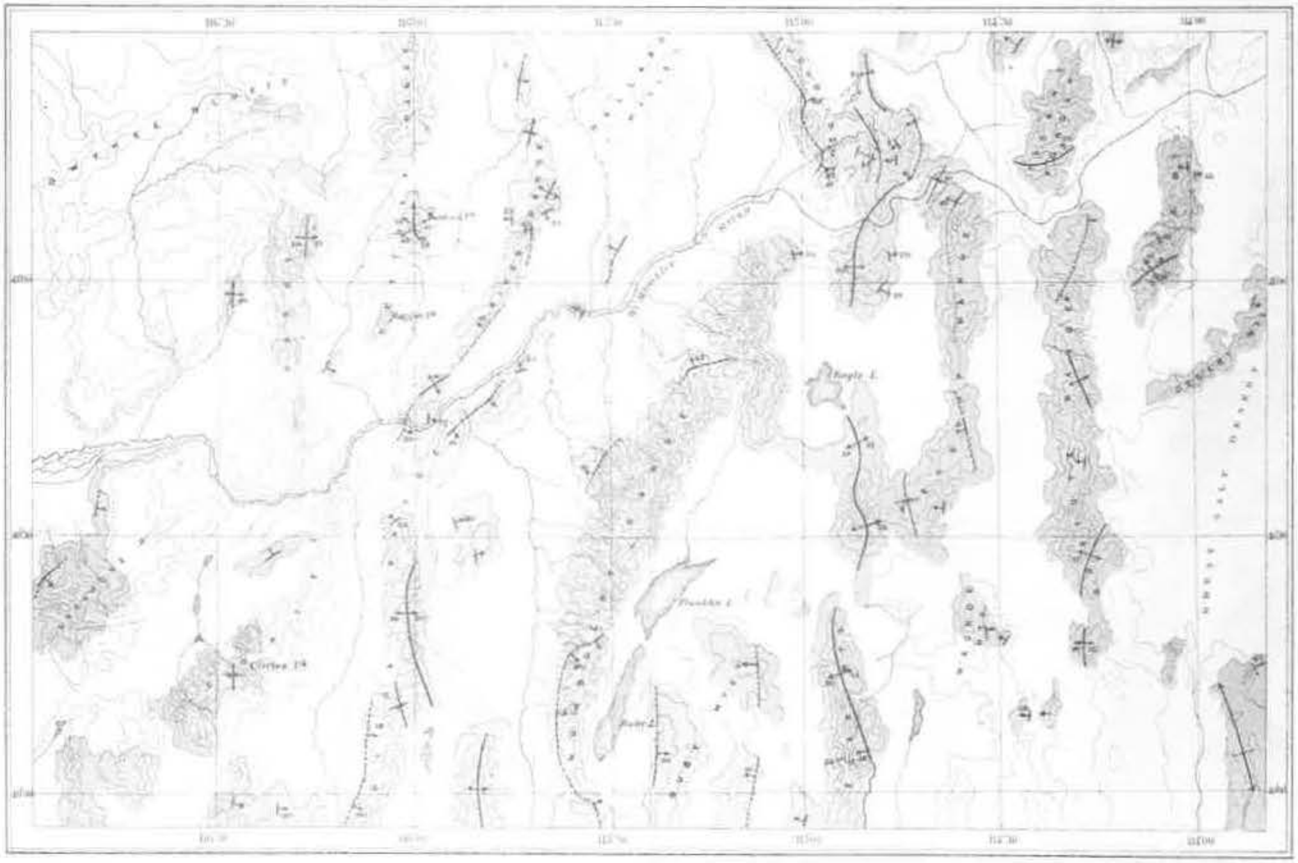
> Those low mountain chains which lie traced across the desert with a north and south trend, are ordinarily the tops of folds whose deep synclinal valleys are filled with Tertiary and Quaternary detritus (King *in* Hague 1870:451).

Figure 7. The U. S. Geological Exploration of the Fortieth Parallel, in camp near Salt Lake City, 1868. Clarence King (in front of the tent pole) manages to look dapper, even in field duds. Dick Cotter, with whom King shared adventures in the Sierras in 1864 (see King 1872, Chapters II, III, and IV) during the Whitney survey of California, rides the pole. Photograph by O'Sullivan.

ANALYTICAL GEOLOGICAL MAP. XI

EXPOSURES OF SUCCESSIVE OROGRAPHIC DISTURBANCES

CORRESPONDS TO ATLAS MAP IV.



▭ POST ARCHÆAN ▭ POST JURASSIC ▨ TERTIARY

Continuous heavy black lines indicate geological axes, dotted lines indicate strike, arrows dip, figures angle in degrees.

King had marked the great fault zones that define the west (Sierras) and east (Wasatch Range) margins of the Great Basin. He became well-aware of Gilbert's subsequent emphasis on high-angle, block-fault control of the Basin and Range structure, included it in his revised explanation, but continued to emphasize that the detailed and earlier structure reflected large-scale compression folding. In *Systematic Geology*, King pointed out that

> Powell and Gilbert have called attention to the abundant evidence of local vertical faults and the resultant dislocation into blocks. One of the most common features of the Basin Ranges is a mountain body composed of steeply or gently dipping monoclinal mass, edged on both sides by the horizontal desert formations, the back of the monoclinal mass consisting of inclined planes of strata, while the other face of the mountain body consists of an abrupt cliff, evidently the result of a vertical fault, which has been more or less modified by a comparatively recent erosion. The frequency of these monoclinal detached blocks gives abundant warrant for the assertions of Powell and Gilbert that the region is one prominently characterized by vertical action; yet when we come to examine with greater detail the structure of the individual mountain ranges, it is seen that this vertical dislocation took place after the whole area was compressed into a great region of anticlinals with intermediate synclinals. In other words, it was a region of enormous and complicated folds, riven in later time by a vast series of vertical displacements, which have partly cleft the anticlinals down through their geological axes, and partly cut the old folds diagonally or perpendicularly to their axes (King 1878:735; see also pp. 742-744, and Maps X, XI, and XII).

Gilbert, in his critical review of interpretations of the Basin-Range structure, dating from the King survey and his own initial work in the region for Wheeler in 1871, quoted (Gilbert 1928:2) all of the preceding passage by King. Gilbert (1928:2-3) also quoted a later passage from *Systematic Geology* in which King distinguished between the main tectonic intervals of "post-Jurassic" folding and "Tertiary and post-Tertiary" deformation by fracture. King observed that

> When we remember that the Eocene and Miocene Tertiary rocks which have been laid down within the hollows of these post-Jurassic folds have themselves been thrown into waves and inclined positions up to 40° and that these Tertiary beds are often violently faulted, it is evident that in extremely modern geological history there has been sufficient dynamic action to account for the system of faults (King 1878:743).

Gilbert's (1928:3) own evaluation of King's interpretation emphasized that the

> recognition of two principal epochs of disturbance helped greatly to clarify conceptions of range structure and constituted a valuable contribution to this subject.

King has recently been credited (Monger and Davis 1979:22) with firmly establishing "Cordilleran tectonic studies" when he recognized

> the long evolution of the Cordillera, analysed it by outlining internally conformable sequences separated by unconformities, described associated structures and magmatic rocks and identified different types of vertical movements.

The continuity of King's program and the limited turnover among his field geologists and topographers were also principal factors in the survey's scientific accomplishments. Staff continuity was greater in the King survey than in the other surveys, as is evident in the table (see next page). Only the King survey investigated a well-defined area for specific goals. By accomplishing

Figure 9. King's (1878) chromolithographic "Analytical Geologic Map-XI. Exposures of Successive Orographic Disturbances," that corresponds to *Atlas* Map IV (King 1876). The colors showed the areas of "Post-Archaean," "Post-Jurassic," and "Tertiary" orogeny in eastern Nevada. "Post-Carboniferous" events were grouped with the "Post-Jurassic" orogeny for the map areas west of Salt Lake City. The five maps of this series, precursors of present tectonic maps, display only fold axes.

these goals, the King survey completed its mission—field work, analysis, and reports on mineral resource evaluation and mapping—then went out of existence.

STAFF CONTINUITY IN THE FEDERAL SURVEYS OF THE TERRITORIES
1867-1879

		Field Geologists[a]		*Field Topographers*[b]	
Survey	*Seasons*	*Number*	*Seasons Each*	*Number*	*Seasons Each*
King[c]	6	4	5.3	5	3.8
Hayden[d]	12	16	3.0	23	2.4
Powell[d]	8	6	4.2	14	2.5
Wheeler[c]	9	13	1.6	32	2.5
Mean	8.8	9.8	3.5	18.5	2.8

[a] E. D. Cope, Gilbert, and C. A. White served with more than one survey.
[b] Clark, Gardner, and Wilson served with more than one survey.
[c] War Department, Corps of Engineers.
[d] Interior Department.

The Hayden, Powell, and Wheeler surveys continued to duplicate field work and publications. In March 1878, as King sent the manuscript of *Systematic Geology* to Humphreys and the 40th Parallel survey officially came to an end, Congress again called for an investigation of the western surveys. King suggested that the National Academy of Sciences should study the matter. Congressional legislation, introduced by his friend Representative Abram Hewitt of New York, generated a report by a special committee of the Academy on the best and cheapest way to map the territories. Congress did not approve several measures to reform the mapping as recommended by the committee, but it did pass an appropriations bill, signed into law by President Rutherford Hayes on March 3, 1879, that contained an item giving the Director of the Geological Survey responsibility for administering a new organization charged with

> the classification of the public lands and the examination of the geological structure, mineral resources, and products of the national domain (U. S. Congress 1879:394).

Congress established the Geological Survey to promote greater economy, efficiency, and utility in the conduct of geologic investigations by merging many of the *functions* of the three remaining Federal geological and geographical surveys of the Nation's territories in the West—organizations discontinued by the same legislation. More realistically, however, Representative Hewitt (1879:1206-1207), one of the chief proponents of a national geological survey had emphasized in the House debate on the bill that

> The need of a thorough survey for the wise organization and distribution of American industry is in the future as imperative as a constitution on which to found our laws.

The success of the new agency required that its first Director be the best scientist-administrator available, one who could both create and direct the organization. King and Hayden were the leading candidates, but King's scientific reputation and the efforts of a small group including Powell and John Strong Newberry led to his nomination by President Hayes on March 20, 1879 (Rabbitt 1979:287-288, 1980:17). On May 24, King took the oath of office.

As he had done in the 40th Parallel survey, King set goals for scientific excellence and utility in the Geological Survey. Several years before the passage of the Civil Service law, King and Interior Secretary Carl Schurz established educational and professional requirements for geologists that differ only in detail from those in effect today (Rabbitt 1980:25). His principal appointees, Carl Barus, George Becker, Whitman Cross, Clarence Dutton, S. F. Emmons, G. K. Gilbert, Arnold Hague, William Hillebrand, Joseph Iddings, Raphael Pumpelly, and Charles D. Walcott—all elected to the National Academy of Sciences—contributed excellent, innovative investigations in economic geology, geophysics, geochemistry, and geochronology.

King's program responded to the Nation's needs for information on its mineral resources. With his personal participation, the Geological Survey gathered statistics on nationwide mineral production and geological, geographical, and chemical data and analyses of mineral deposits in cooperation with the Tenth Census of 1880 (Rabbitt 1980:24-25). Some of the Survey's foremost geologists conducted geological and technical studies of silver mining districts, especially the Comstock and Eureka in Nevada and Leadville in Colorado, and of the iron and copper ores of Michigan. With this work, King established a long-term principle that guided the Survey's subsequent investigations in economic geology. Research in mining geology was directed toward the immediate solution of specific problems, but the ultimate goal was the advancement of basic science. The field relations of ore deposits were examined systematically in their geologic context by accurate detailed mapping assisted by paleontological investigations and chemical and microscopical studies in the laboratory. These studies yielded information on why these mining districts had been eminently successful so that the practical data could be applied in exploration and development elsewhere. By the end of the 1880s the Geological Survey's reports had taught the entire mining industry the value of geology in developing a district, and Survey geologists had proposed the structural control of ore deposits and contributed ideas on the origin and genetic classification of these resources (Rabbitt 1980:55, 137-139).

In establishing his mission-oriented program of applied investigations in support of economic geology for the Geological Survey, King strongly supported basic research. He intended the Survey's information on mineral resources to aid the formulation of a genetic classification of ores, based on the origin and relations of mineral deposits; to assist the mining industry; and to foster an increased understanding of the Earth and its history. Several pioneering studies in geophysics, geochemistry, and microscopic petrography, which were undertaken by the Survey to support its mining geology program, led to other significant advances in the earth sciences.

When King became Director, he intended to serve for only a short time. The Executive Branch's interpretation of the law that established the Geological Survey restricted the agency's operations to the public-land States. King's inability to extend *official* operations of the Geological Survey east of the Mississippi and to increase significantly the Survey's appropriations, beyond the 50% increase approved for fiscal year 1880-1881, strengthened that intent. As Secretary Schurz would not serve under President James Garfield, King expected to lose support from Interior (Rabbitt 1980:45). When he resigned on March 11, 1881 (Rabbitt 1980:54), King had served State and Federal geology for 18 years—all before he reached age 40.

As second Director of the Geological Survey, John Wesley Powell reversed King's policies and thus King's work was made to seem a failure in light of Survey programs in the 1880s that emphasized basic research in a wide variety of disciplines. Interpretations of King's later life, in stressing his search for wealth and his personal "eccentricities," have negated not only his contributions to the earth sciences in those years, but somehow eclipsed many of those before 1881. Historians have asserted that King failed after 1881 through ill-luck (Adams 1918:416), lack of character (Stegner 1954:21, 344-345), or poor judgment (Bartlett 1962:214; see also Bartlett 1956:147). If so, his was an odd sort of failure indeed, for King retained to the end of his life the respect of the mining industry and that of his colleagues in geology and the USGS. Moreover, when Congress—which expected continued practical investigations—became dissatisfied with the Survey's overemphasis on basic research under Powell, it slashed Survey funds drastically. When requests for Powell's resignation increased in 1892, King was asked if he would resume the directorship; King agreed to serve again if the change could be made without fuss (Rabbitt 1980:213). Powell, however, did not resign, and instead, in 1893, the Secretary of the Interior assigned many of Powell's responsibilities as Director to Charles Walcott by appointing him "Geologist-in-Charge of Geology and Paleontology." When Powell finally resigned in 1894, Walcott became the Survey's third Director.

Walcott revived and expanded in scope the economic and mission orientation of the Geological Survey's work, as planned by King, "To bring the Survey more in touch with some of the economic and educational interests of the country" (Walcott 1896:7). Under Walcott, the Survey's investigations aided not only the mineral industry but many other practical objectives that could be advanced by a greater knowledge of the Earth and its natural resources. Basic and applied geology, Walcott affirmed, could not be separated; the Survey would undertake basic research not so much for its own sake but to meet specific needs for knowledge to solve specific problems (Rabbitt 1980:13, 239, 241-242).

King's influence on the direction of Federal geology was brought out in resolutions adopted at a meeting, attended by all the scientists of the Survey, following King's death in 1901

> As organizer and, during 10 years, chief of the United States Geological Exploration of the Fortieth Parallel, he set higher standards for geological work in the United States and laid the foundation of a systematic survey of the country. He gave practical recognition to the fact that a good topographic map is the essential basis for accurate geological work.
>
> As first Director of the present Geological Survey he laid down the broad general lines upon which its work should be conducted and which, as followed by his able successors, have led to its present development. He established the principle that a Geological Survey of the United States should be distinguished among similar operations by the prominence given to the direct application of scientific results to the development of its mineral wealth.
>
> In that essential quality of an investigator–scientific imagination–no one surpassed King, and his colleagues have all profited by his suggestiveness. He was never content with the study of science as he found it, but always sought to raise the standards of geology, as well as to apply known principles to the survey of the country (Walcott et al. 1902:198-199).

Another contribution, not mentioned in the resolutions, was undoubtedly the spirit King instilled in both organizations he directed. King's own assessment of his achievement in the 40th Parallel Exploration was that he had made the corps uniformly "harmonious and patient . . . by a sort of natural spirit of command and personal sympathy with all hands and conditions, from geologists to mules" (quoted in Rabbitt 1980:56). Clarence Dutton (1880, quoted in Rabbitt 1980:42) observed that King was "enthusiastically loved by everyone" in the Geological Survey, and so everybody did their best. That spirit has been transmitted from one generation to another of the Survey's staff (Rabbitt 1980:55-56). Thus the seventh Director of the Survey could say that King had "impressed into the fabric of the Geological Survey a surprisingly large proportion of the policies and philosophies that still are in effect" (Nolan 1963).

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JOHN BOARDMAN TRASK: PHYSICIAN-GEOLOGIST IN CALIFORNIA, 1850-1879

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Among the seven men who gathered in the office of San Francisco notary and commissioner of deeds Lewis W. Sloat, Jr. the evening of April 4, 1853 to found the California Academy of Natural Sciences, was John Boardman Trask (Fig. 1), a San Francisco physician, with a penchant for spending more time in the field investigating California's geology than attending his patients in the city. Trask had only recently returned from the last of several geological and agricultural excursions into the Sierra foothills, excursions which he had begun shortly after his arrival in California in November 1849. His observations were incorporated in a report on the geology of the California Ranges [Sierra Nevada] and in time led to his recognition as California's first, if unofficial, State Geologist. Trask's varied career in San Francisco and California–geologist, botanical collector, museum curator, journal editor, physician–spanned nearly three decades, terminating with his death in his adopted city at the age of 55, in 1879.

Trask was born in Roxbury, Massachusetts in 1823 or 1824 (1)*. According to the 1830 Census (2), only one Trask family in Roxbury had a son in his age bracket, that of Samuel Trask (presumably John's father). In addition to Samuel, the household included a woman aged over 30 and under 40 (probably Samuel's wife), two boys aged under 5, one over 5 and under 10 (presumably John), and one girl aged 15 and under 20 (perhaps a housekeeper or relative). The 1840 Census (3) again listed Samuel Trask and family. At this time the household included among the male family members one boy aged between 10 and 15, one between 15 and 20 (again presumably John), and a man aged between 40 and 50. Among the female members of the family were two girls under 5, one between 5 and 10, and one aged over 30 and under 40. Although two other Trask families were recorded in the Roxbury 1830 Census, neither meets the requirements dictated by John Trask's presumed age.

We know virtually nothing of Trask's early years before he enrolled in Yale's Medical School for one year in 1846-1847. In those days, physicians-in-training commonly apprenticed to an experienced doctor and then attended some institution such as Yale for a short time. A letter (4) written in 1884 by John W. McLean, who served briefly with Trask as a physician during the early days of the Civil War (5), referred to Trask as "an old friend and *pupil* [italics ed.] of my father." Thus, it appears that Trask followed the tradition by associating himself with McLean's father, Dr. John Adams McLean (1798-1883) of Norwalk, Connecticut. The elder McLean had studied medicine at Yale in 1822 and, except for two years during which he resided in Maryland, he spent his entire professional career in Norwalk (Yale College 1891:151). During his year at Yale, John Trask learned a little about many subjects. As a student he had access to the medical and anatomical libraries, cabinet of minerals, and to lectures on anatomy, physiology, and obstetrics, as well as natural philosophy (Yale College 1846:43-44). He wrote his dissertation (Fig. 2), a requirement of all candidates for a licence to practice medicine, on scrofula, a tubercular infection of the lymph nodes of the neck, a common disease of children during the 18th and 19th centuries (Trask 1847).

Trask's earliest biographer, botanist Albert Kellogg, indicated that Trask also was a licentiate in mineralogy and geology, as well as medicine, from Yale College (Kellogg 1879:5); so far we have been able to confirm only the licence in medicine (Yale College 1910). Irrespective of the

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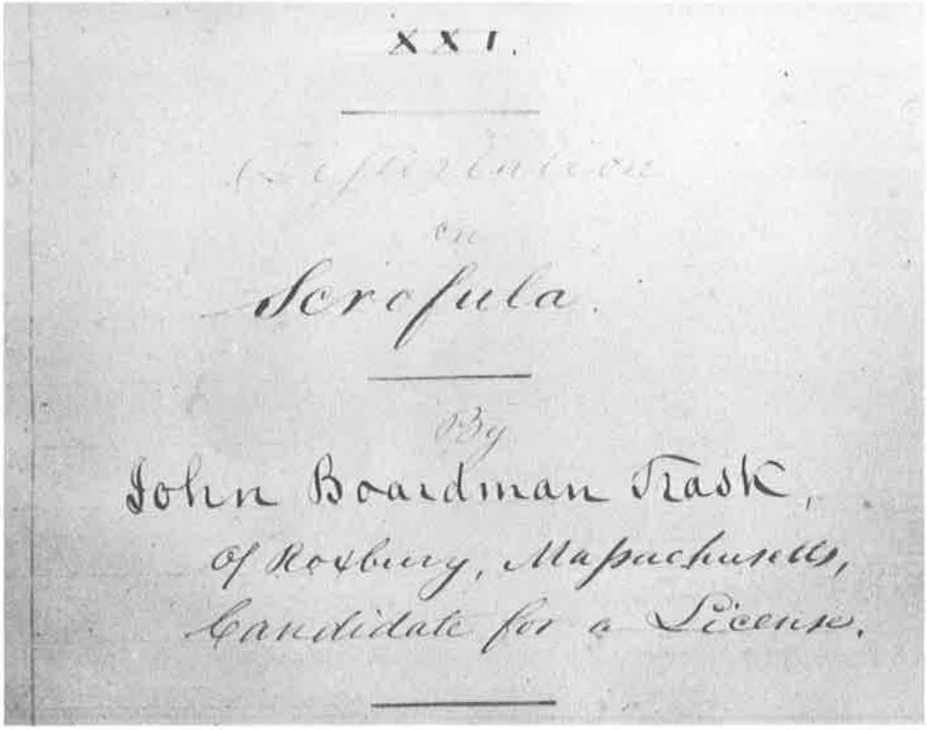
*** See Reference Notes, pp. 61-64.**

Figure 1. John Boardman Trask, in Civil War uniform, taken sometime in 1861 or 1862, at the approximate age of 35.



XXI.

Dissertation
on
Scrofula.

By
John Boardman Trask,
of Roxbury, Maſsachusetts,
Candidate for a License.

Figure 2. Title page of Trask's "Dissertation on Scrofula," submitted in partial fulfillment of the requirements for a Licentiate in Medicine, Yale College, 1847.

licentiate in geology, John Trask certainly had an abiding interest in the subject, an interest that may have been aroused during his year at Yale where he likely attended lectures given by Benjamin Silliman. He may also have become acquainted with James Dana, who at that time was writing up the results of the Wilkes Expedition, and whose geological writings Trask from time to time cited in his reports.

Trask arrived in southern California in November 1849 as part of the "California Company," (6) headed by John Woodhouse Audubon (Fig. 4), a son of the ornithologist, John J. Audubon. Organized during December 1848 and January 1849, this company of adventurers (7) departed New York on February 8, 1849, via steamer to Philadelphia and Baltimore, then overland to Cairo, and by riverboat to New Orleans (Van Nostrand 1942:289-291). Trask was among this hardy group, and he was among the 51 who completed the second phase of the trip, New Orleans to California, first via boat to Rio Grande City and Roma, both on the Rio Grande, and thence overland through Mexico via Monter[r]ey and the Gila River Valley to the latter's confluence with the Colorado, and on to San Diego. During the second phase of the trip disease, especially cholera, and desertions plagued the party. And, it was during this part of the trip that Trask's name began to crop up in Audubon's journal. According to Audubon, it was Trask who recognized the disease and who then saved the life of at least one of its victims, Navy Lt. Browning, with "indefatigable exertions" (Audubon 1906:85). During the march, Trask was also assigned "captain . . . [of] Mess No. 12," which Audubon described as "a queer lot . . . [some of whom were] both very original, and perhaps would not get on very well with the others but for Dr. Trask, a truly good man" (Audubon 1906:119). In addition to his other tasks, Trask took a keen interest in the minerals and rocks, and identified desert plants encountered enroute. Audubon viewed Trask as a "philosopher . . . but most eccentric in his ways" (Audubon 1915:80).

Figure 3. John Woodhouse Audubon.

On September 22, Audubon and his followers came upon the valley of the Gila River, which they followed for several days to its confluence with the Colorado. The latter was crossed on October 14th in the vicinity of the future site (1852) of Fort Yuma (Audubon 1906:162). There they met Lt. Cave J. Couts commanding a patrol of U. S. Dragoons assigned to Lt. Amiel Weeks Whipple, one of Major William Emory's Mexican Boundary surveyors (8). The Audubon party spent three or four days in camp, and it was at this time that Trask made the acquaintance of Andrew Randall (Fig. 4), on his way to California to become a customs inspector in San Francisco. Randall, like Trask, had a keen interest in geology and had earlier served as an assistant to David Dale Owen in the geological survey of the Territory of Minnesota and Wisconsin. He was travelling in the company of Col. James Collier, who had been assigned collector for the port of San Francisco (9). The Collier party, which consisted of more than 120 civilians and 30 soldiers (Audubon 1906: 164), arrived at the Yuma-crossing campsite on October 15th and, according to a report filed by Lt. Whipple, had taken the Audubon party under its protection (Audubon 1906:164-165). Randall and Trask were to meet again in San Francisco, and their second meeting had a lasting impact on the history of science in the West; it was the evening of the founding of the California Academy of Sciences.

The Audubon party, reduced in number, short of rations and money, many without even shoes, arrived in San Diego on November 3, 1849. From there 11 of the band, including Trask, went by boat to San Francisco, while Audubon and the rest traveled overland to San Francisco via Los Angeles. Reuniting in San Francisco in late December, Trask, Audubon, and 36 others departed the city on December 29th for a tour of the gold fields, via steamer to Stockton and then overland with pack-mules to the diggings at "Chinese Mines." They arrived at the diggings sometime between the 11th and 20th of January, 1850 (Audubon 1906:199-202). Although the party remained in the gold fields for several months during the winter and spring of 1850, Trask apparently did not begin his geological reconnaissance in the Sierra foothills until the autumn of that year (Trask 1853c:2).

It is not known if Trask had any contact with Andrew Randall in California before he began his geological excursions. Randall had moved from San Francisco to Monterey sometime in 1850 and in 1851 was elected to the State Assembly. During the Legislature's second session he intro-

Figure 4. Andrew Randall. (Courtesy California Academy of Sciences.)

duced a bill, accompanied by an impassioned plea, that the State authorize a geological survey for the promotion of its mineral and agricultural wealth (Randall 1851:1689-1702). The bill was introduced in response to several letters addressed to the Legislature, one of which by John LeConte (10), argued that such a survey "would be regarded with intense interest by scientific men throughout the world." LeConte opined that the value of "a geological survey in shewing [*sic*] the mineral and agricultural wealth of any region must be self-evident. In no science can the results obtained be so productive of immediate and practical advantage as in geology." LeConte recommended a full natural history survey in part to make known "animals injurious to agricultural labors" so that "means to diminish them" could be taken. As happened so often in other states on the occasion of the first introduction of a proposal for a state survey, the proposal failed, despite the pleas of LeConte and the favorable report of the State Assembly's "Select Committee," which Randall chaired (Calif. State Legis. 1851:1790)(11). Since the ayes and nays were not recorded, it was not possible to determine what factors, e.g. geographic, political, influenced the vote. Another intriguing but unanswerable question is, would Trask have been the immediate beneficiary of the bill had it passed at this time? Irrespective of legislative action, and in a manner reminiscent of Denison Olmsted in North Carolina in 1824, Trask began such a survey on his own, albeit more limited in scope than that proposed by Randall. In this unofficial survey, Trask covered "portions of the eastern valleys of the Sacramento and San Joaquin, and to the coast line within the 41st and 42nd degrees of north latitude" (Trask 1853c:Preface).

Figure 5. Philip T. Tyson. (Courtesy Smithsonian Institution Archives.)

Trask was well aware of the writings of his predecessor in the field, Philip T. Tyson (Fig. 5), quoting from Tyson's report "Upon the Geology of California," published as U. S. Senate Document No. 47 in 1850. He accepted Tyson's view that "in Geological structure the Sierra Nevada resembles the Andes," and in this context he looked at the economic potential of the region, principally that of coal production (Trask 1853c:10). He argued early in this first report for the separation of that portion of the "California Ranges" north of the 40th parallel, which, he noted, were more like the Cascades than the mountains to the south. However, his principal concern throughout his brief report was detailing the location of auriferous deposits and the manner of association with "the rocks with which they are found in connection," this in the "hope that less disappointment may be experienced by those who seek a profitable and laudable employment in those branches of industry [mining]. . ." (Trask 1853c:22).

Trask also showed concern for underground water supplies in the central valleys, as evidenced by the occurrence of mineral springs. He quoted several passages from Tyson and added his own thoughts that water for agricultural purposes would be available in sufficient quantities at comparatively low rates (Trask 1853c:28). And, he took an interest in the availability of "buhr-stone" [mill-stone] in the northern part of the state, which could be used in the grinding of the cereal grains he believed would be a major agricultural product (Trask 1853c:15). He noted that this would reduce the need for foreign imports of mill-stone, creating a more independent state economy, a concern of several eastern state survey geologists (Aldrich 1981:6). Finally, in this first of his four geological reports, he attempted one incursion into theory, arguing that the "lake and river theory" was not adequate to account for the formation of the "Valley of the Sacramento"; he posited instead that "gradual elevation by forces from beneath the surface raised the country some fifteen hundred feet . . . [and] a careful examination will convince us that these forces are still in activity . . ." (Trask 1853c:30).

Trask began a collection of rocks and minerals from districts of the state he visited. This collection he had with him when Sir Henry Vere Huntley, British naval captain and colonial governor, met him in January 1852, in Sacramento. Of the collection, Huntley observed, "It forms a very curious assemblage, and is valuable as a beginning" (Huntley 1856:47). In a note appended to his 1855 report, Trask stated that he would deposit collections made during 1854 and 1853 in the office of the Secretary of State "as soon as arranged" (Trask 1855a:[unnumbered 'p. 94']). Whether the transfer was accomplished is not known for part of the State collection, housed in a warehouse in San Francisco, was destroyed by fire in 1865 (Blake 1866:357). Further, according to Blake (Fig. 6), who during the mid-50s had worked as a geologist on the Pacific Railroad Survey, Trask's collection became part of a "public" collection housed at the California Academy of Natural Sciences (Blake *loc. cit.*). Trask gave some of his fossils to Blake who sent them to Timothy Conrad of Philadelphia for identification. At Blake's request Conrad described one of the new bivalves in Trask's honor, *Lutraria? traskei* Conrad (1855:14, pl. 3, fig. 30; see also Blake 1857:182, pl. 3, fig. 23). Trask also collected plants during his travels, and these were given to his friend, Albert Kellogg, for study and description. However, his interest in plants was not limited to making collections. Jepson (1934:117) observed that very early in his career in California Trask

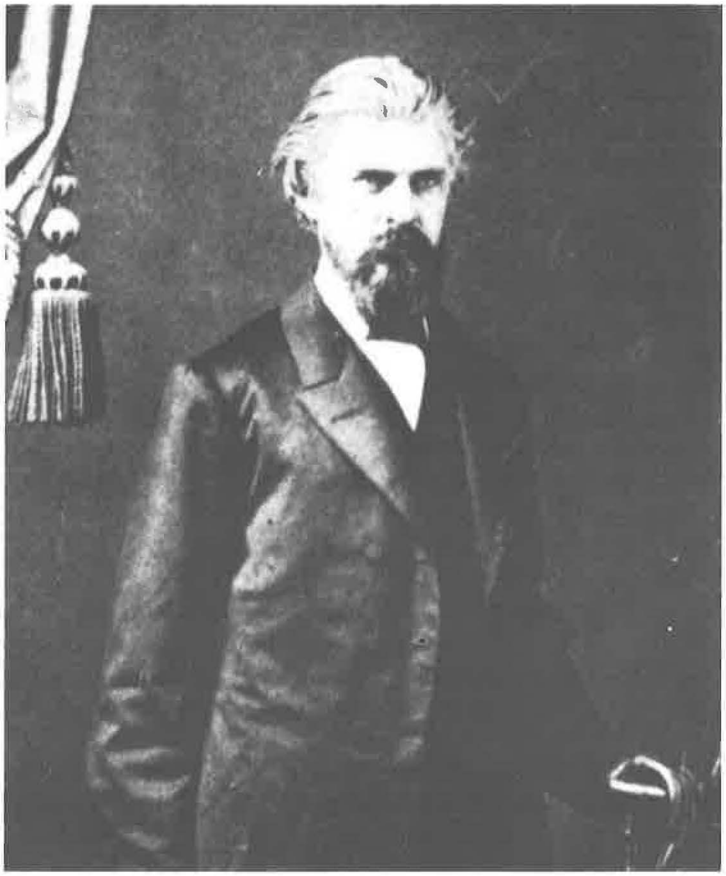


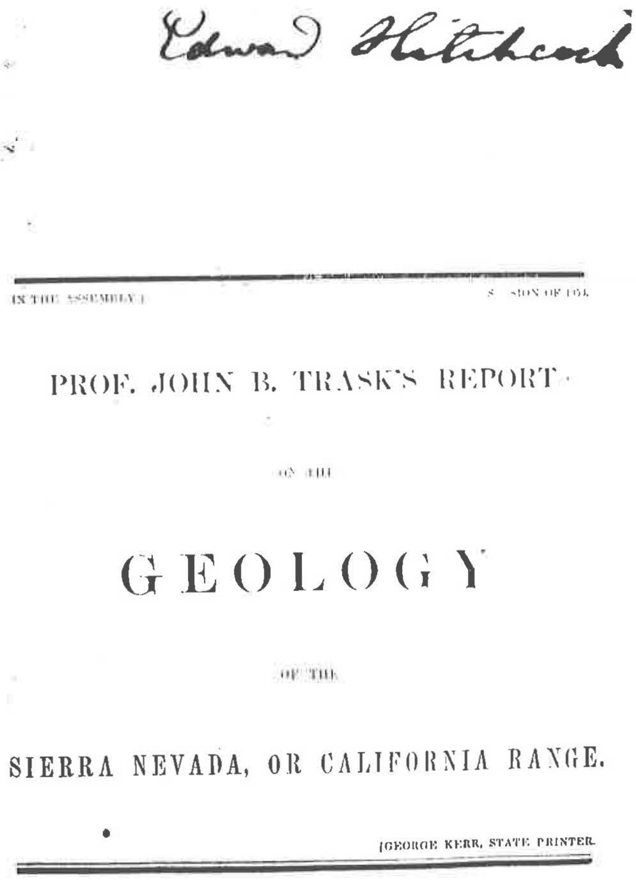
Figure 6. William Philip Blake. (Courtesy Smithsonian Institution Archives.)

studied native plants, taking note of "such species as Yerba santa (*Eriodictyon californicum*) for rheumatism, damiana (*Turnera aphrodiscaca* of Lower California) for nerve aberrations, *Grindelia robusta* for poison oak dermatitis . . . " and others which could be medicinally beneficial.

On March 26, 1853 State Senator Jacob R. Snyder introduced a resolution in the California Legislature:

> Whereas, any information connected with the geology of this State is of great importance, not only to the miner but to the agriculturist, and as an opportunity is now offered through Dr. Trask, (a gentleman who has made a thorough examination of the mineral districts), by which we may add to the very limited state of knowledge upon that subject, therefore,
>
> *Resolved*, That a select committee of five be appointed to obtain from Dr. Trask such information as he may possess relative to the subject; which, if deemed of sufficient importance, will be reported to the Senate on the 6th day of April next. (Calif. State Legis. 1853a: 267.)

Two weeks later, on April 7th, Mr. Snyder submitted Trask's report (12), which was published as Senate Document No. 59 (Trask 1853c)(Fig. 7)(13). At the same time the Legislature entertained a motion (Calif. State Legis. 1853a:393, 401, 430, 450, 465; 1853b:478, 479, 501) that Trask



Edward Hitchcock

IN THE ASSEMBLY.] SESSION OF 1853.

PROF. JOHN B. TRASK'S REPORT

ON THE

GEOLOGY

OF THE

SIERRA NEVADA, OR CALIFORNIA RANGE.

[GEORGE KERR, STATE PRINTER.

Figure 7. Title page of Trask's 1853 report. Although first printed as a Senate document, on April 26, 1853 the State Assembly ordered 2000 copies printed for its own use. The copy whose title page is shown here was owned by Edward Hitchcock, first state geologist of Massachusetts. (Courtesy Amherst College Library.)

continue with his geological investigations, for which a stipend of $5,000 would be paid (the Legislature also agreed to reimburse Trask $2,000 for personal expenses incurred in the preparation of his 1853 report [Calif. State Legis. 1853a:393, 407, 416, 417, 450, 482; 1853b:494, 503, 545, 562, 564, Appendix Doc. 56]). An examination of the aye and nay votes on the survey does not disclose any geographical pattern which would explain support or opposition on the issue. At no time did either house of the State Legislature establish the office of State Geologist, and it was not until Governor Bigler transmitted Trask's report for 1854 (Calif. State Legis. 1855:letter of transmittal accompanying Senate Doc. No. 14) that the phrase was used to describe Trask. As a matter of record, neither the position nor the office of State Geologist was established in law until 1860 (Calif. State Legis. 1860:243, 367), and Josiah Whitney was appointed to head the newly authorized State survey.

Despite California's apparent geographic isolation, Trask's 1853 report did not languish in the obscurity of the State's legislative documents. For instance, shortly after its publication by the State, a lengthy abstract appeared in *The Mining Magazine* (Trask 1853d) and again as an appendix to Marryat's *Mountains and Molehills; or, Recollection of a Burnt Journal* (1855). In part, in 1855 it was reprinted in the *Pharmaceutical Journal and Transactions*. Further, copies of the report itself went East. Joseph Henry, the director of the Smithsonian Institution, and Edward Hitchcock, president of Amherst College and the former state geologist of Massachusetts each received one. Both of these copies survive, the Henry copy, inscribed in Henry's hand, in the Henry Library at the Smithsonian Institution, the Hitchcock copy, inscribed by Hitchcock (Fig. 7), on the shelves of the Robert Frost Library of Amherst College. It is likely that Trask sent copies to other Eastern scientists, too. Thus, it cannot be said that it was not given wide circulation.

It is unfortunate that the two extraordinary maps that Trask had prepared at the time he wrote his first report were not ordered published by the Legislature. Rather, Trask had these maps, "Map of the State of California" (Fig. 8) and "Topographical Map of the Mineral Districts of California," (Fig. 9) published by Britton & Rey, in San Francisco in 1853. California's noted cartographic historian Carl I. Wheat (1942:112) described Trask's State map as "one of the best, as well as one of the rarest maps of the period." Wheat elaborated:

> Full of the place names of the gold diggings, it is an interesting map in that respect alone—the miners working up the rivers and their placers everywhere . . . But the emigrant routes are fascinating. No less than five are shown . . . . Trask was an interesting character . . . and the maps he drew are a valuable contribution to the development of the West. (Wheat 1959:159-160.)

Of Trask's mineral district map, Wheat (1942:113) observed, "Curiously, this map is constructed with east at the top, but despite the resultant difficulty in reading the legends it is a beautiful map, more complete than any previous representation of the mining districts." The mineral district map is particularly intriguing inasmuch as it located all of the mining towns of the period. It also showed the existence of two railroad lines, the Marysville-Benicia Railroad from Yuba City via Knights Landing to Benicia, and the San Joaquin Railroad from Benton to Stockton.

Profound differences exist between the two maps in the quality of the topographic mapping, differences that are most apparent in a comparison of the central California coastlines and San Francisco Bay and its environs. The State map more closely approximates the physical setting; north-south distortions in the mineral map are extreme, although the center portion, to which Trask paid greatest attention in locating the numerous mining towns, mining claims and other prominent localities, appears to be respectably accurate.

Trask based his 1854 report upon nearly ten-months field work, about six months in the Sierra foothills and four months in the Coast Ranges from San Francisco and Alameda counties in the north to San Luis Obispo and San Joaquin counties in the south. Although the report contained much descriptive geography and surface geology, Trask again emphasized mining activities in the Sierra foothills, while in the Coast Ranges, especially the Salinas, Livermore, and San

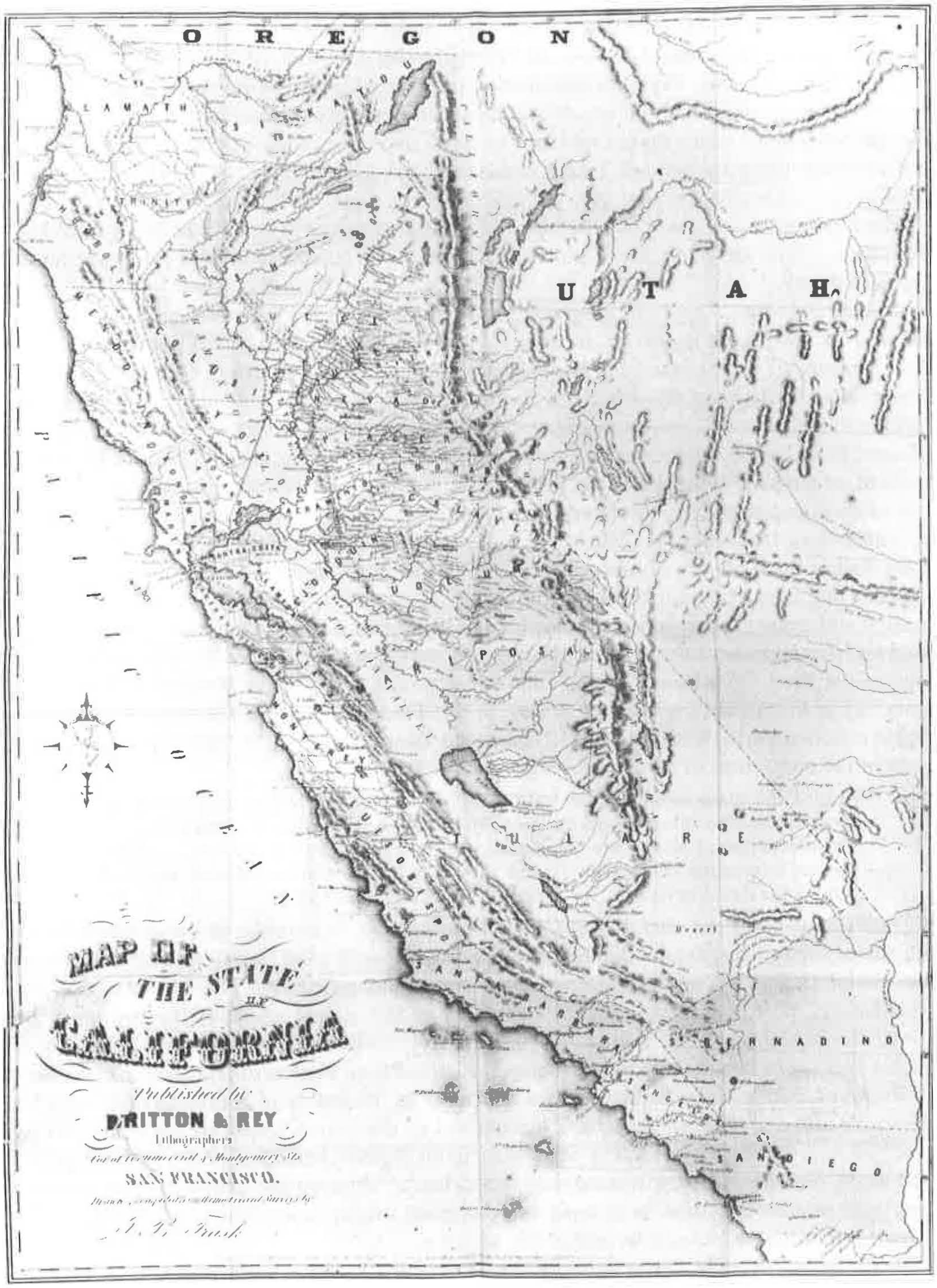


Figure 8. "Map of the State of California" by John Boardman Trask, 1853. (Courtesy Bancroft Library, University of California, Berkeley.)

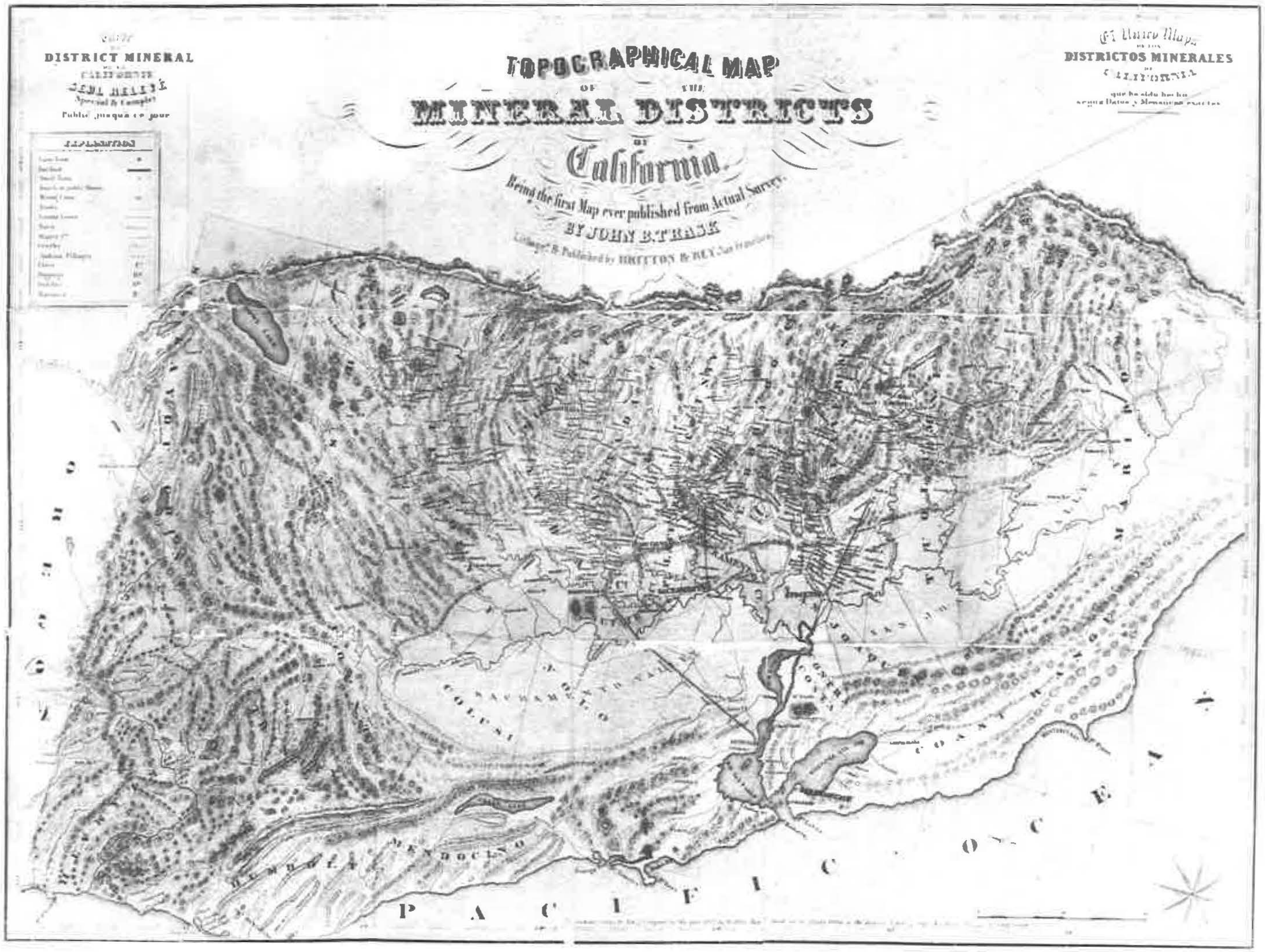


Figure 9. "Topographical Map of the Mineral Districts of California" by John Boardman Trask, 1853. (Courtesy Bancroft Library, University of California, Berkeley.)

Joaquin valleys, he stressed the agricultural potential and coal. In each instance Trask directed his work toward maximizing regional economic capacity, although at least at one point he did comment on an unusual geological phenomenon, the nearly vertical position of the slates (Calaveras Formation) of the Sierra, supposedly caused by the intrusion of dikes (Trask 1854a:71). Trask was clearly concerned with economic geology, and in the 1854 report he included in the appendix a statement addressed to the Legislature advocating changes in the laws as they applied to State lands to protect capital investment and labor (Trask 1854a:78). He argued that it would be in the best interests of the State to open those lands over which it had jurisdiction to development, increasing its revenue and "thereby reducing taxation of the great mass, [and] render less burdensome the support of the State government" (Trask 1854a:78-79).

Although Trask may have established his permanent residence in San Francisco before 1854, his name first appeared in that year in the San Francisco City Directory, as "State Geologist" with offices at 174 Clay Street (Fig. 10). Although the building must have been subdivided in 1857, inasmuch as Trask's quarters were renumbered 174½ Clay Street in later issues of the Directory (Langley 1858:271; 1859:269), Trask remained at this address until at least 1859. In that year Trask changed his listing in the city directory from "geologist" to "physician," and while his address changed from time to time thereafter, his occupational listing did not.

Although Trask's 1854 report was not well received by the editors of the *American Journal of Science*, who commented that it was "not a result of a careful survey" (Anonymous 1854:302), both houses of the California State Legislature seemed satisfied with the document he submitted to them. In May 1854, the Legislature authorized publication of the report as a legislative document (14) and then passed an act instructing Trask to continue his geological reconnaissance (Calif. State Legis. 1854a:619, 636, 640; 1854b:628, 640). Ten months later, on March 8, 1855, Governor Bigler transmitted Trask's third document titled "Report on the Geology of the Coast Mountains . . ." to the Legislature.

During the nearly seven months from June through December 1854, Trask toured the agricultural districts of the Sacramento Valley in the north and from Monterey to Los Angeles counties and portions of San Bernardino and San Diego counties in the south. The Coast Range interested him. Besides correcting errors in their geography, he asserted that the "correct understanding of the situation of these ridges, will explain many of the phenomena constantly occurring in these inland districts . . ." He noted that

> Their study . . . becomes a matter not only of scientific interest alone, but engages our attention in a practical, and enonomic [*sic*] point of view . . . [because] The altitude of these mountains is such that they have the effect to absorb much of the aqueous matter carried from the ocean through the various gaps that occur in the coast-line proper, and when the higher hills fail to accomplish this, the increase of temperature, consequent from the relative position which the mountains hold to the plain lands that may be situated along the immediate ridges, or beyond them to the east, is such that it has the effect to dissipate whatever aqueous matter that might have remained. (Trask 1855a:11)

The problem of the rain-shadow described by Trask retarded agricultural use of the western lands in the valley for nearly a century after he wrote.

Merrill (1924:305) suggested that Trask failed to appreciate the significance of fossils, and although Merrill referred specifically to Trask's first report, the inference is that this was true of all of Trask's work. In 1854 Trask did comment upon fossils briefly, and in one footnote suggested a correlation between California and Northeastern sequences based on fossil contents (1854a:61). Even more telling is a statement in his 1855 report:

> On the summits and sides of the hills [California's Coast Range] we find the fossiliferous rocks of this part of the country, maintaining the same relative positions which they occupy in other and distant parts of the State . . . Sufficient is now known respecting the distribution of the vertebrate and invertebrate animals

> inhabiting the country during these remote ages, that we are able to frame, at least, an approximate opinion of the relative periods at which the different classes of animals existed . . . (Trask 1855a:15)

And in a later paper, not related to the reports submitted to the State Legislature, Trask observed

> Since that time I have been fortunate enough to discover fossils of as much antiquity, at least, as those of Western Texas, and probably still lower in the series, the rocks containing them forming the coast of the Pacific Ocean in this State. There can be no doubt, therefore, at present, that the Cretaceous rocks extend from the Atlantic to the Pacific. (Trask 1856:86)

Returning to the 1855 report, not only did Trask use fossils in correlation, but he demonstrated a clear awareness of their implications:

> Between the Tulare plains and the American River, there are some fou [*sic*] or five other localities in which the tertiary deposits have been observed, and which contain imbedded fossils closely allied to those found in the localities specified; and the evidences thus furnished . . . are very conclusive . . . as pointing to that period when the Tertiary seas had their boundaries far to the east of their present limits. A recession of the waters of the Pacific Ocean has therefore taken place, to the distance of 140 miles, since the period at which those fossils lived. (Trask 1855a:65)

Trask was also aware that fossiliferous beds could be used to determine where one is in the section. He was particularly concerned with the location of auriferous gravels, and he drew attention to these relationships, noting that

> The position of these auriferous deposits . . . and the corresponding character of a large portion of the country lying north and south of the above section [at Beale's Bar and Alder Springs in Placer County] is adverted to at the present moment for the purposes of directing attention to those districts near the foot-hills which present similar features, and which are as yet untouched. These districts on either hand having the same altitude above the plains present equal certainties of the existence of the same deposits as those met with in the county of Placer. (Trask 1855a:66)

Trask was familiar with Lyell's method for assigning ages to Tertiary rocks. In at least one instance, however, he was led astray by this familiarity. At Chico Creek he found an ammonite among the assemblage of mollusks. On the basis of the percentage of supposed extant species in the sample, he felt compelled to assign a Miocene age to the rocks. He knew that ammonites had not been found so high up in the section and his comments indicate he was troubled by this apparent contradiction (Trask 1856c:85).

Crude though it may have been, Trask did use fossils in correlation. That he erred in dating the formations cannot be denied. But to say he failed to realize the value of fossils as indicators of particular geologic horizons is not true. Trask also paid attention to the influence of paleoenvironments on the local biota:

> The fossiliferous sandstones of the mountains [San Luis Obispo County] possess many of the lithological characteristics which are found among the rocks of the same age in the more northern parts of the State, and belonging to the same chain [Coast Range], and when differing from this rule, the cause will be found entirely local, and of limited extent. Any diversity in species that may be found imbedded in these rocks, will be more attributable to local climatal influences rather than to any differences in relative age . . . (Trask 1855a:16)

Trask was clearly impressed by the east-west trending San Bernardino Mountains, by their influence "on the productive capabilities of the adjoining lands," and by the differences in the fossils recovered from the "coarse-grained sandstones in the county of Santa Barbara" that flank the "primitive series [granites]. . .[which] form by far the most of all the higher ridges and more elevated peaks belonging to the chain" from those found further north (Trask 1855a:20-21). Trask's

Figure 10. Street map of San Francisco, 1852 (from Baker's City Directory for 1852). In 1854, Trask had his office at 174 Clay Street, between Mason and Powell. (Courtesy Library of Congress.)

descriptive geology markedly improved between his first report, published in 1853, and the 1855 document. He was more conversant with the subject, and his descriptions were clearer, as were his locality citations: "In the County of Santa Cruz these rocks are met with to the right of the road crossing the Sousal, and also on the north bank of the Pajaro River near the junction of the Pescadero" (Trask 1855a:28).

About one-third of the 1855 report was devoted to the Los Angeles area, to its agricultural potential, and to the occurrence of minerals. Trask was particularly interested in bitumen, distilled to yield illuminating gas, and "asphaltum" which, he noted, if delivered to San Francisco would yield not "less than sixteen dollars per ton [and] this amount alone would offer sufficient inducement" to begin extraction operations (Trask 1855a:41; White 1968:6-7). The remainder of the report dealt with the geology of the northern coast ranges and the east side of the Sacramento Valley. Based on fossils found in both Placer and Sacramento counties, Trask confidently stated that at one time the valley was covered by "Tertiary seas" and that "A recession of the waters of the Pacific Ocean has . . . taken place" (Trask 1855a:65). Trask cited borings from the valley which "with other collateral evidence [assists us] . . . in forming an opinion of the relative positions of the beds below and those above the surface, and which are equivalent, the one with the other" (Trask 1855a:58-59). He drew upon these data to determine the depths to which one must penetrate to locate artesian water. He also observed that the distribution of "lignites and dycotyledonous leaves found in every portion of this part of the State, as well as in many parts of the coast mountains . . . leads to the conclusion, that a great uniformity of climate, and other conditions, prevailed for a long period after the disturbance of the older . . . slates" (Trask 1855a:68). At one point in his report, Trask could not resist a glowing burst of State patriotism:

> Had we the same facilities of exhibiting the characters which our gold mines present, through the agency of mining journals and jobbing boards, like those in New-York, Boston, and the English Metropolis, we have no fear but that the mines of this State would take their position in the front rank of those operations. But unlike the mines abroad, they do not require at home the prestige which fancy paper throws around the many faltering institutions of our distant neighbors . . . . That our mines have thus withstood the violent assaults that have been made upon them by those who stand behind the scenes of a foreign press, and thus attempt to give a fatal thrust unseen, is one strong evidence that they inherit a vitality which it is beyond the powers of those in this State still thus employed to deprive them of. We have passed that day when either British *skill* or capital is required to foster these operations . . . (Trask 1855a:84)

The final pages of the report reviewed major mines of the State. It is this portion of the report that most intrigued European geologists, especially the French. For some years the French seemed fascinated by California's mines. As early as 1849, a paper was published in the *Annales des Mines* (4th Ser., 16:111 ff.) on an analysis of ores from California sent to the Ecole des Mines by the French Counsul in Monterey. One year later, a charming and graceful but geographically hilarious map of the San Francisco Bay area and the California gold fields (Fig. 11) was published in the same journal (*Ann. Mines* 1850. 4th Ser., 17:pl. 2). In the next volume of the journal, also published in 1850, there appeared an article by M. Butler King, "Rapport sur la Californie, sa population, son climat, son sol, ses diverses productions, etc. addressé au secretaire d'Etat des Etats Unis" (*Ann. Mines* 1850, 4th Ser., 18:475-534). Therefore, it is not surprising that the distinguished French mining geologist Achille-Ernest-Oscar-Joseph Delesse should prepare a verbatim translation of those sections of Trask's 1855 report (pages 69-90) which dealt so extensively with California's mines and their production. Delesse's translation was published under Trask's authorship in the *Annales* in 1856 (Trask 1856f:649-667).

Trask's final report (1856a) as State Geologist dealt largely with northern California geology, although he also devoted three pages to a brief description of the elevated plain between Los Angeles and San Bernardino, which he visited during October and November 1855. Field work in

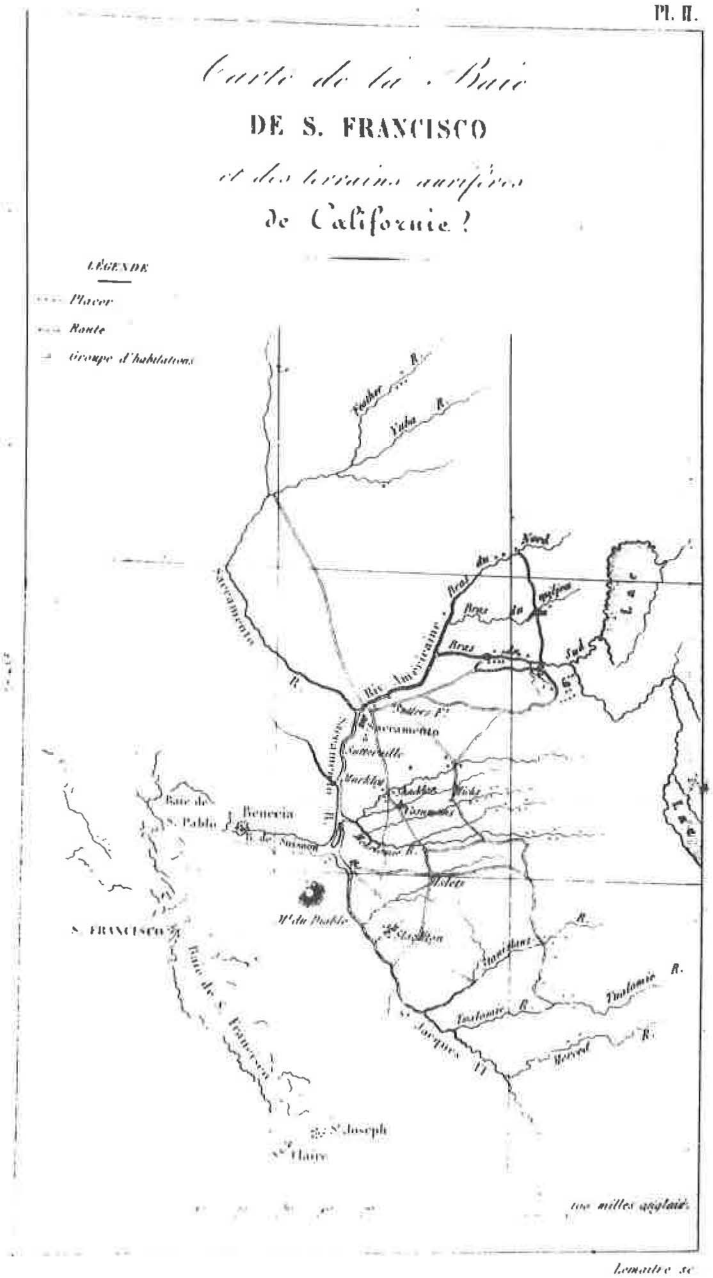


Figure 11. "Carte de la Baie de S. Francisco et des terrains auriferes de Californie." *Annales de Mines* 1850, 4th Ser., 17:pl. 2. In a footnote on page 788, the following explanation is given for this map: "Cette carte communiquée à M. Dufrenoy par M. Dumas, ministre de commerce, n'a pu être annexée à l'*étude des sables aurifères*, publiée par M. Dufrenoy dans le tome precédent (page 111); l'interêt qui s'attache à tous les documents qui concernent la Californie a paru justifier l'insertion isolée de celui-ci."

northern California during the preceding summer had been hampered by "Indian troubles" which "rendered traveling alone a dangerous undertaking" (Trask 1856a:1). On his return from the Los Angeles area at the end of November, he spent the remainder of his final field season in the mining districts compiling data on productivity, which formed the bulk of his 1856 report to the State Legislature.

The Legislature did not renew its mandate for Trask to continue with his geological survey, and four years passed before it was to act again, establishing the office of State Geologist on March 20, 1860 (Calif. State Legis. 1860:243, 367, 506), and naming Josiah Dwight Whitney (Fig. 12) to that post (April 21, 1860). John Boardman Trask did not disappear from the scene, however. He participated in the activities of the California Academy of Natural Sciences, which he had helped to found in 1853. He presented papers on fossils and pioneered in chronicling earthquake activity in the State beginning with 1800. It was at this time that he announced the discovery of Cretaceous rocks in California in the Los Angeles region (1856d:86) based on their fossil content. He also corresponded with Eastern colleagues. In a letter (15) to Joseph Henry (Fig. 13) of the Smithsonian Institution, dated February 16, 1856, Trask recalled that Henry had asked him for information on West Coast thunderstorms. Trask vividly described one he had observed in the vicinity of San Bernardino on October 16, 1855. He then described in minute detail the earthquake that had occurred in San Francisco the day before. Trask reported "Yesterday morning we had a smart shock

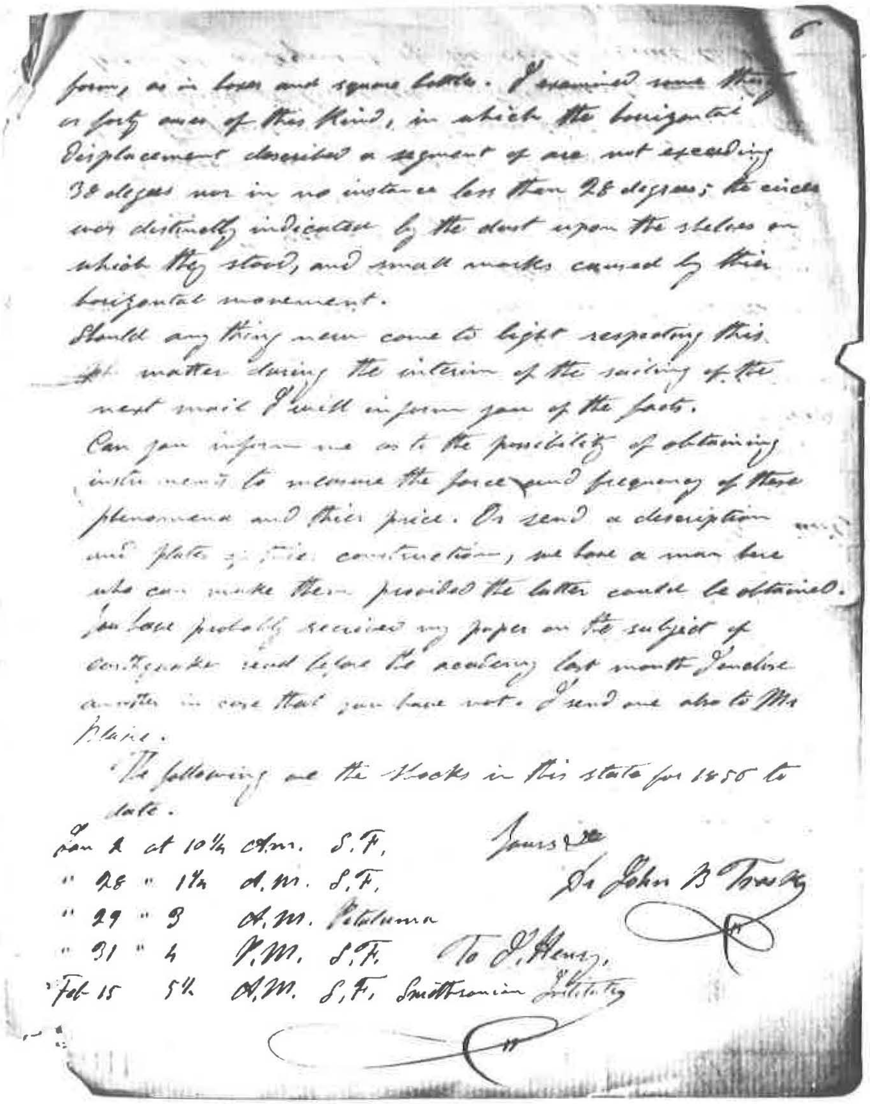
Figure 12. Josiah Dwight Whitney, after his return to Harvard University from California. (Courtesy Smithsonian Institution Archives.)

Figure 13. Joseph Henry. (Courtesy Smithsonian Institution Archives.)

of an earthquake in this city; some of our papers (16) as usual came out with a column of nonsense on the subject, and when you see those accounts you will wonder how the city stood through so powerful a convulsion." He described the motions of the shock and some of the damage he had seen, and then observed "Several persons much frightened, left thier [*sic*] beds, and some very ludicrous scenes occured [*sic*], particularly about the hotels where both sexes were assembled." To obtain accurate data on the extent of the quake, Trask informed Henry that the "State Telegraph gave me the use of the line through the day, and by it, those parts of the state thus connected with this city were heard from . . ." Finally, he asked Henry for information on "instruments to measure the force and frequency of these phenomena . . ." (see Fig. 14).

Trask's observations on this and other earthquakes were described in a series of papers published in the ***Proceedings*** of the Academy between 1856 and 1866. The task Trask set for himself was gathering data about recent and past earthquakes in California. He saw two purposes to his research: he wanted other scientists to use this evidence to test theories on the causes of earthquakes, and he wanted to disprove stories circulating outside the state about how dangerous the California quakes were.

In his first paper on this subject, published in 1856, Trask stated that errors had crept into accounts of quakes between 1812 and 1855, especially in regard to their severity (Trask 1856b). He interviewed older residents at earthquake sites to document magnitude, frequency, and direc-



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forms, as in boxes and square bottles. I examined some thirty or forty cases of this kind, in which the horizontal displacement described a segment of arc not exceeding 30 degrees nor in no instance less than 28 degrees; the circles were distinctly indicated by the dust upon the shelves on which they stood, and small marks caused by their horizontal movement.

Should any thing new come to light respecting this matter during the interim of the sailing of the next mail I will inform you of the facts.

Can you inform me as to the possibility of obtaining instruments to measure the force and frequency of these phenomena and their price. Or send a description and plates of their construction, we have a man here who can make them provided the latter could be obtained.

You have probably received my paper on the subject of earthquakes read before the academy last month. I enclose another in case that you have not. I send one also to Mr Blake.

The following are the shocks in this state for 1856 to date.

Jan 2 at 10¼ A.m. S.F.
" 28 " 1½ A.M. S.F.
" 29 " 3 A.M. Petaluma
" 31 " 4 P.M. S.F.
Feb 15 5½ A.M. S.F.

Yours &c
Dr John B Trask

To J. Henry
Smithsonian Institute

Figure 14. Last page of letter from John Boardman Trask to Joseph Henry, dated February 16, 1856. (Courtesy Henry Papers, Smithsonian Institution.)

tion of the tremors and the amount of damage sustained by buildings. He also checked with ships' captains to collect information on how the ocean behaved during quakes felt ashore. For each quake he drew a separate portrait—its speed, damage, start time and duration, direction of motions, number of aftershocks, distance that shocks were felt, accompanying noises, and the weather at the time. In this first study, he found no seasonal pattern in the occurrence of earthquakes and no cycles across the years. Trask knew of the theory that volcanos and earthquakes were associated, and he noted that there seemed to be some correlation between the locality of quakes and geologically recent volcanic activity. Like other scientists of his era, Trask did not associate earthquakes with geological faults.

In his subsequent, nearly annual publications on earthquakes, Trask gave details on those which occurred between 1856 and 1866. As early as 1856 he used observations by telegraph station operators to gauge the direction, speed, and origin of quakes, a practice he continued into the 1860s. He also repeated in these later papers his assurances that California quakes were no more severe or frequent than those felt on the East Coast. Trask's data were cited in subsequent compilations on earthquakes (e.g. Shaler 1870; Holden 1887) and thus gained an enduring place in the literature.

Between 1855 and 1857 Trask also published the results of zoological research in the Academy's *Proceedings*. He described thirty-two new species and one new genus of animals. His zoological papers showed that he was familiar with the major contemporary American workers in zoology, such as Augustus Gould, James DeKay, and Timothy Conrad. Trask collected some of the specimens himself and received others from fellow scientists and amateur collectors, whose donations he acknowledged in his works (especially when they were State Legislators). He reported on modern species as well as fossils in these works. In publishing the descriptions of new species in the journal of a scientific society rather than in his geological reports to the State, Trask followed the common practice of government scientists of that time. He also took an interest in the perennial problem faced by San Francisco and every other port city, how to control damage to piers caused by the shipworm, *Teredo*. Trask and Academy ichthyologist William Orville Ayres together studied the problem and concluded that there was no satisfactory preservative to prevent damage to the piers caused by these boring animals. In their report to the members of the Academy, read April 2, 1855, they observed further that "a great number of [San Francisco] buildings, in the lower part of the city, are supported upon piles which must sooner or later yield [to the borers]. The fall of a block of buildings on Sacramento St., a few days since, is merely a warning of much greater losses . . ." (Trask 1855f:39).

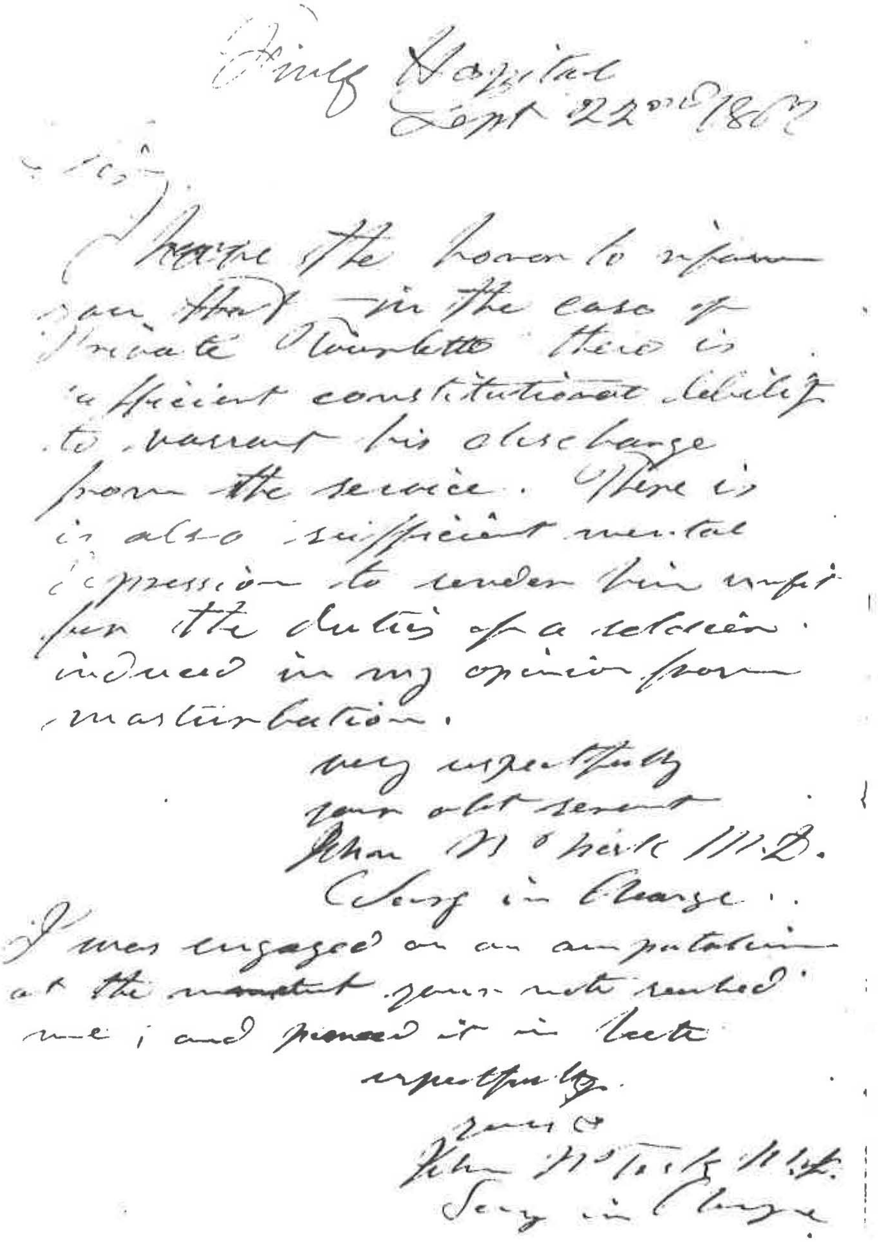
Trask's contributions during this period included one foray into biography. In 1856 Andrew Randall, one of the seven cofounders of the California Academy of Natural Sciences, was shot to death by Joseph Hetherington, supposedly in a dispute over money owed Hetherington by Randall. Hetherington was tried by San Francisco's "Vigilance Committee," found guilty and hung on July 29, 1856, five days after the shooting. A special meeting of the Academy was called on July 27 at which the Academy was requested to be in attendance at the funeral of Randall. A memorial for the occasion was read by Trask (17).

Trask's biographers have stated that at one time he served as geologist for the State [Territory] of Nevada (Kellogg 1879:7; Vodges 1907:28 [after Kellogg]), but we have not been able to confirm this (18). In 1858 he and Dr. David Wooster began publishing the *Pacific Medical and Surgical Journal*, the first California medical journal. In 1859, "on the recommendation of the Medical Society of Connecticut," Yale College conferred on Trask an honorary doctoral degree in medicine (Yale College 1970:478), a degree he had not attained earlier. This may have been accomplished through the intercession of his mentor, John Adam McLean, or more likely of his fellow San Francisco physician, naturalist, and Academy colleague William Ayres, himself the recipient of a doctoral degree in medicine from Yale and a member of the Connecticut Medical Society.

In 1861 and 1862, during the Civil War, Trask served as a "contract officer" with the rank of Acting Assistant Surgeon. He signed his first contract on June 4, 1861 (19) and worked mainly with Dr. Richard Coolidge at the Presidio and on Alcatraz Island. From August 27 to November 29, Trask served at Camp Downie (20) in Alameda County. His contract elapsed, but on June 24, 1862, he offered to work again as a surgeon, this time in Washington, D. C. Coolidge apparently thought enough of Trask's work in California to endorse his application (21), but Trask's service in Washington was not to be as smooth as it was in California.

Trask signed his contract in Washington on August 6, 1862 and reported to Finley Hospital the next day. In September, he met his friend of earlier years, John W. McLean, ill from diarrhea in the hospital; McLean was the son of the doctor under whom Trask had apprenticed in Connecticut. Trask, who had earlier demonstrated a penchant for introducing new medications in the treatment of his patients in San Francisco, experimented with bismuth subnitrate to treat the diarrhea of McLean (22) and other patients at Finley (Trask 1863).

About this same time, Trask clashed with Assistant Surgeon C. C. Byrne over the timing of discharges of wounded and ill soldiers from the hospital. Their dispute came to a head over the case of one Private Tourlette, whom Trask wanted discharged from the army not only for his physical disability but also because the Private's "mental depression" made him unfit for further battle action (23, 24)(Fig.15). Byrne, evidently exasperated by Trask's failure to "follow orders," told his superiors that ample evidence had accumulated on Trask's "incompetencies" (25) to warrant his firing (26), and on September 24 Trask was put under the command of an officer junior to him, which amounted to a demotion. Trask immediately asked for a release from his contract or an explanation of the charges against him (Fig. 16) (27). Without detailing the charges,



Finley Hospital
Sept 22nd 1862

Sir

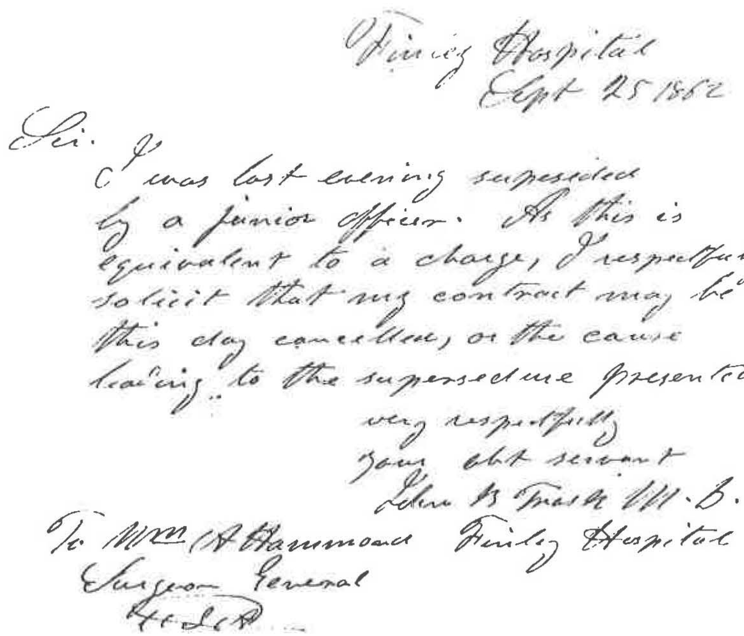
I have the honor to inform you that in the case of Private Tourlette there is sufficient constitutional debility to warrant his discharge from the service. There is also sufficient mental depression to render him unfit for the duties of a soldier induced in my opinion from masturbation.

Very respectfully
your obt servant
John [illegible] M.D.
Surg in Charge.

I was engaged on an amputation at the moment your note reached me; and penned it in haste

respectfully
yours &c
John [illegible] M.D.
Surg in Charge

Figure 15. Letter from John Boardman Trask to C. C. Byrne, dated "Sept. 22nd 1862" relating to the case of Private Tourlette. (Courtesy National Archives and Records Service.)



Finley Hospital
Sept 25 1862

Sir:
I was last evening superseded by a junior officer. As this is equivalent to a charge, I respectfully solicit that my contract may be this day cancelled, or the cause leading to the supersedure presented.

very respectfully
your obt servant
John B Trask M.D.

To Wm A Hammond Finley Hospital
Surgeon General
Hd Qrs

Figure 16. Letter from John Boardman Trask to William A. Hammond, dated "Sept 25 1862" requesting cancellation of his contract or an explanation for having been superceded by a junior officer. (Courtesy National Archives and Records Service.)

Surgeon General William A. Hammond annulled the contract (28) the next day, September 26, and Trask returned to San Francisco.

During his Civil War service, Trask, like most military physicians, had to deal with the mundane but serious medical problems caused by diarrhea among the troops. His California assignment had introduced him to the disease in its acute form, as an epidemic hit suddenly at Camp Downie, while his Washington work at Finley Hospital presented the disease in its chronic state. Trask experimented with bismuth compounds to control the disease in both settings and both manifestations. He noted that he was reviving an old remedy in doing so, not inventing a new treatment. Trask wanted to find the optimum dosages; he started with modest doses and increased the amounts until he stopped the symptoms. Since some doses got to be heroic in size, his experiments showed Trask to be no homeopath in medical philosophy. Trask berated camp hygiene among the troops in Virginia as a sideline to his analysis of the Finley Hospital problem, but his main concern was treatment, not prevention. He sent a report on his results to Richard Coolidge in the Surgeon General's office and shortly thereafter obtained permission to print the report, which appeared as a pamphlet in San Francisco (Trask 1863).

Apart from this pamphlet, from 1862 until his death on July 3, 1879, we know virtually nothing of Trask's activities save that he was a practicing physician in San Francisco. At least through 1868 he continued to be active in the life of the California Academy of Natural Sciences (29). During this period, his principal contributions in geology centered on the chronicling of earthquake activity in California from 1800 to 1866 (see Trask bibliography). There is no indication that he made any direct contribution to the Whitney survey, although Whitney did cite some of Trask's earlier geological observations (Whitney 1865:202-203). From 1857 to 1862 Trask served the Academy as its second curator of geology and mineralogy, then as curator of conchology from 1862 to 1865 and concurrently as vice-president, from 1863 through 1865. He was not elected to any office in 1866, and in 1867 the presidency of the Academy passed to Josiah Whitney rather than to its past vice-president. Trask published his final paper on earthquakes in the *Proceedings* of the Academy in February 1866. On January 7, 1867 he was elected a Life Member of the association, and in January 1868 President Whitney appointed him Curator of Radiata, the last event in his association with the organization he helped organize 15 years earlier.

One of Trask's biographers observed that Trask did not seek pecuniary advantage and that even his later years as a physician in San Francisco were neither always financially rewarding nor tranquil. In 1871 Trask filed suit against one Laura Fair, an inmate in the county jail, for unpaid medical fees which he estimated at $3,040 (Read & Mathes 1958:63). Physicians called to testify could not fault Trask's fee schedule, but Trask's case was unclear because he failed to keep records, a general failing his biographer, Albert Kellogg (Fig. 17), painfully observed (Kellogg 1879). Although the suit appeared to be settled in Trask's favor, inasmuch as he was awarded the sum of $312.50, he was then "ordered . . . to pay the jurors and the court reporter" (Read & Mathes *loc. cit.*).

It is difficult to put Trask's geological and other accomplishments into the perspective of his time in part because of the unusual circumstances in which he worked. With respect to his geological contributions, Merrill (1924:305) suggested that Trask held outmoded, or at least older concepts (which he did), that his understanding of metamorphism was crude (which it was), and that he failed to use fossils in correlation (which was wrong). In our view, Merrill was unjust in failing to recognize that Trask worked alone in a complex geological province, which generated questions certainly as difficult as those of the Taconic region, which bothered Eastern geologists for many decades. Only within the last few years has the problem of the "Franciscan-Knoxville" sequence and the history of California's Coast Range, to which Trask addressed himself so long ago, been partially resolved, and this because of the introduction of plate tectonics, a paradigm scarcely 20 years old. Do we deny recognition for not doing in the 1850s what we were unable to do a century later? Viewed in the context of the complex and heterogenous geology of the State and the fact that Trask attempted the description of a region which in Eastern geography would encompass the states of Virginia through Maine, one cannot help but be awed by the energy of this nearly forgotten nineteenth century physician-naturalist. Perhaps Trask's greatest contribution was in preparing the way for the first "scientific" geological survey of the State, beginning in 1860 with Whitney. Certainly Whitney and his cadre of luminaries eclipsed Trask, and there is little to indicate that those who followed in Trask's footsteps saw fit to give him much credit for the pioneer work he did save for William Blake, who not only exchanged specimens with Trask, but clearly acknowledged Trask's investigations in his railroad survey geological report (Blake 1857). However, the State Legislature had responded favorably to Trask's work, and as Oakeshott (1971:142) observed, Trask "laid the groundwork for an 1860 act of the legislature 'to create the office of the State Geologist and to define the duties thereof.'" Trask's reports and changes in the way gold was mined led to a public outcry for a State geological survey.

It has been noted that Audubon thought of Trask as a "philosopher . . . but most eccentric in his ways" (Audubon 1906:80). Some years later the distinguished California botanist Willis Jepson observed: "The gold rush brought many remarkable men to California but few in that early day more outstanding as a scientist than Trask" (Jepson 1934:117). Trask was imaginative and perceptive, both in his geology and in medicine, but he was not equipped to frame the questions which bothered him into forms suitable for investigation. Even so, his intellectual achievements are notable. In his geological studies, for instance, he recognized that the Sacramento Valley is structurally controlled and not an erosional phenomenon, that the Coast Ranges of southern and central California are distinct from the Siskiyous, that the southern and central Sierra Nevada are not continuous with the northern volcanics, and that the transverse ranges are a unique (even if at the time inexplicable) phenomenon. Especially intriguing were Trask's observations in paleoecology and his recognition that paleoclimates influenced the kinds of organisms found in the rocks. His clear, if somewhat labored description of the effects of topography on weather, including that of orographic uplift and adiabatic warming, suggest a penetrating mind. In his medical practice, his

Figure 17. Albert Kellogg.

willingness to try new medicinals, his observations on hygiene, and his perception of mental depression as a medical problem, are further testimonies to his stature as a scientist.

Of the man, Dr. John Boardman Trask, we must rely on the personal remarks of those who knew him and who looked upon him as a friend and colleague. Trask's contemporary Robert Stearns observed:

> Soon after my arrival in California in June, 1858, I became acquainted with most of these pioneers in science, and with some of the earlier recruits who joined the little squad of charter members [of the California Academy of Natural Sciences]. Of these latter and their associates it may be said, without injustice to any, that Dr. Trask, by virtue of his genial qualities, was the leader, closely followed by Dr. Albert Kellogg . . . (Stearns 1908:240)

When the maverick Hungarian naturalist John Xantus passed through San Francisco on his way to Baja California in February 1859, he met Trask and fellow Academy naturalist William Ayres. In a letter to Spencer Fullerton Baird, then Assistant Secretary of the Smithsonian Institution, Xantus wrote "Dr. Trask is particularly kind to me and so is Dr. Ayres, who both told me, to consider their houses as my own, and command there services no matter how" (30)(Madden 1949).

But of those who spoke warmly of Trask, none knew him as well as his old friend and fellow physician-naturalist, Albert Kellogg. In his memorial to Trask read before the members of the California Academy of Sciences, July 21, 1879, Kellogg said of Trask

> he was professional and skillful; remarkable for originality and independent thought; earnest and generous-hearted; free from the acquisitive instinct; and, like many others of this liberal profession, was ever ready and prompt to save those who needed his services, without money and without price. If he had been avaricious, he might have amassed wealth; for no one was more active, and none more widely known. Opportunities for pecuniary advancement were frequently within his reach; but he was as careless in such matters as in his dress. Direct and

> blunt of manner—perhaps some thought him rough and rude of speech—he was nevertheless sympathetic and co-operative, and, as we who knew him best actually can testify, was ever ready to lend a helping hand or do a kindly deed. (Kellogg 1879:3)

On July 5, 1879, the public was left with only a brief reminder of the deceased. Obituary notices appeared in at least two local newspapers. The *Daily Alta California* wrote: "He was a man with large scientific achievements and leaves many friends to mourn his loss."

ACKNOWLEDGMENTS

In our pursuit of information about this elusive 19th century physician-naturalist, we have been helped by many people and institutions. For assistance in locating source material we are indebted to William Deiss and Richard Szary, Smithsonian Institution Archives; Charles Shaunessy, National Archives and Records Service (NARS), Navy and Old Army Branch; Cynthia Gee, NARS Reference Room; Judith Schiff, Yale University Archives; Ferenc A. Gyorgyey, Yale University Medical Library; Jack Marquardt, Smithsonian Institution, Natural History Museum Library; Frank Carol, Library of Congress, Newspaper and Periodicals Division; Tony Bliss, University of California at Berkeley, Bancroft Library; and Ray Brian, California Academy of Sciences, Library. Nathan Reingold, Smithsonian Institution, Joseph Henry Papers, authorized our use of the letter written by Trask to Henry in February 1856, and C. P. Butler, California Academy of Sciences, Department of Geology, gave us free access to his manuscript and other notes on Andrew Randall. We are especially indebted to Peter U. Rodda, California Academy of Sciences, Department of Geology, and Ellis L. Yochelson, U. S. Geological Survey, for reading and criticizing the manuscript, and to Margaret Berson, Department of Herpetology, California Academy of Sciences who both read the manuscript and offered sound editorial advice.

REFERENCE NOTES

(1) We do not have a date of birth for Trask. His biographer, Albert Kellogg, stated that at the time of his death in July, 1879 Trask was 55. This suggests he must have been born during the second half of 1823 or in 1824. While Trask supposedly was born in Roxbury, Massachusetts, his name does not appear among the birth records for the City of Boston and of Annexed Towns for the period in question (Joanne A. Prevost, City Registrar, City of Boston; pers. commun. [Sep 10, 1981]). There are no Roxbury city directories for these early years. The *Vital Records* for Roxbury, assembled and published by the Essex Institute in 1925-26, also do not list John Trask in the extant non-governmental documents (e.g. church baptisms and the like). A check with the Department of Public Health for the City and County of San Francisco established that all death records and the associated indices for the period May 1, 1873 through March 31, 1882 were among the documents destroyed during the earthquake and fire that ravaged the city in April 1906. Finally, a search of the standard printed genealogical literature provided no information because these sources do not trace the Trask family to this era.

(2) NARS (National Archives and Records Service), Census records for 1830, Mass. Roll # 60 (NOR), pp. 215, 221.

(3) NARS, Census records for 1840, Mass. Roll #191 (NURF), p. 131.

(4) Letter from John W. McLean to O. P. G. Clark, Pension Office, Nov. 5, 1885 (NARS: Record Group 15 [Records of the Veterans Administration, Civil War Pension Records]; Box 43483, Application #393994, Certificate #282580 and #458527).

(5) According to a memo written by D. L. Huntington to the Commissioner of Pensions, Feb. 29, 1884, John W. McLean was on duty at Finley Hospital, Washington D. C., 22 Sept. to 22 Oct. 1862 [overlapping Trask's duty period at that hospital]. NARS: RG 112 (Surgeon General Office), Ser. 2, vol. 64B.

(6) Audubon's "California Company," also referred to as the "California Argonauts," were a band of fortune-seekers on their way to the California gold fields. This was not a "business" venture but rather individuals brought together by Audubon for the trip west.

(7) The number of persons in the company varied widely from time to time, with a maximum of 98. See Audubon (1906:241-243) and Van Nostrand (1942:304-310) for a partial list of the company. Among those who accompanied Audubon and Trask on the trek west was Lewis Warrington Sloat, son of Rear Admiral John D. Sloat. In 1853 Lewis Sloat was to join Trask and five others in founding the California Academy of Natural Sciences in San Francisco.

(8) In his biographical memorial on Trask, Kellogg said "We have been obliged to omit much [in this memorial]. . .e.g., his connection with the Mexican Boundary Survey. . ." (Kellogg 1879:7). Subsequent biographers have interpreted Kellogg's statement to mean that Trask was with the Survey, a biographical "fact" on Trask which we have been unable to confirm. We believe that Trask's only connection to the Survey was the few days when the Audubon party traveled with Cout's troops. Nothing is said of Trask in Bartlett's, Gray's, or Emory's published reports on the Survey (see Goetzmann 1959). A search of the Emory papers at Yale University uncovered some references to the Audubon party, but nothing indicating that Trask was on the Survey proper.

(9) A diary kept by Andrew Randall exists in the California State Library, Sacramento. Mr. C. P. Butler, California Academy of Sciences, prepared a typescript of this diary and included it in an unpublished manuscript, "Andrew Randall: Editor and Geologist, [and] Founder of the California Academy of Sciences." Copies of this manuscript are on file in the library of the Department of Geology (recently renamed Department of Invertebrate Biology and Paleontology) and in the Archives of the Academy.

(10) Letter by John LeConte to the California State Legislature, March 19, 1851. (Bancroft Library, University of California, Berkeley, Calif.)

(11) A second attempt to establish a State geological survey was made in 1852 when Governor McDougal, in his annual message to the Legislature, recommended that one be authorized (Calif. State Legis. 1852:20, para. 2). On March 24, 1852, the Legislature adopted a report on "Joint Resolutions to Congress for a Geological and Mineralogical Survey of the Mineral Lands of this State" (Calif. State Legis. 1852:213, 659-665); the Legislature did not address the question of a State-supported survey at this time. In April 1852 another bill was introduced to provide "for the collection of the Geological, Botanical, and Agricultural products of California, and the preservation thereof." This bill was referred to the State Senate's Committee on Agriculture, which reported back with a substitute to "authorize C. A. Shelton, to make a Botanical collection of the native trees, shrubs, plants, and flowers, of the State of California." This substitute was adopted (Calif. State Legis. 1852:325).

(12) The manuscript copy of Trask's 1853 report (without the maps) is preserved in the California State Archives at Sacramento (David Slater pers. commun.).

(13) The California State Assembly (1853b:479, 483) evidently wanted to distribute copies of Trask's report, too. On a motion introduced by Mr. Redding of Yuba, it was "*Resolved*, That 2000 copies of the Geological Report of Professor Trask be printed for the use of the Assembly."

(14) The California State Senate (Calif. State Legis. 1854a:542) ordered 3000 copies of Trask's 1854 report printed; the State Assembly concurred and on May 15, 1854 instructed that 200 copies of the report be given Trask for his own use (Calif. State Legis. 1854b:636).

(15) SI (Smithsonian Institution Archives), Record Unit 60 [Meteorological Project, 1849-1875], Box 2, Folder 1855-1856.

(16) For example *Daily Alta California* Feb. 16, 1856:1 (col. 1).

(17) A memorial, prepared by Trask and dated "the 28th July 1856," was supposedly read at a special meeting called that day. That memorial was not recorded in the minutes of the meeting of the Academy held on the 28th and, in fact, only routine business appeared to have been transacted (Calif. Acad. Sci., Minutes Book April 4th 1853 to Aug. 20th 1866:202). [N.B. The Minute Books of the meetings of the Academy survived the earthquake and fire that devastated the Academy in 1906.] A "Special Meeting" had been called on the 27th, but the minutes of that meeting are also silent on the matter of a memorial (CAS, Minutes Book *op. cit.*:201). Trask's memorial was not published. The original copy had been presented to the Randall family and kept among the family records until recently when it was presented to Mr. C. P. Butler of the Academy's Department of Geology by a relative of Andrew Randall in the belief it would be of interest to the Academy. The memorial is reproduced with the permission of Mr. Butler.

> At a Special meeting of the "California Academy of Natural Sciences" assembled at their rooms, at the Call of the President, on 28th July 1856, the following proceedings were had.
>
> Dr. John B. Trask arose and announced the death of the Hon. Andrew Randall M. D. late President of the association, and read the following brief notice, which on motion was approved and ordered to be spread upon the minutes.
>
> Dr. Randall, whose untimely death we are called upon to mourn, was a native of Providence, Rhode Island.
>
> He imigrated [*sic*] to this State in 1849: previous to which time, he was engaged in the arduous duties of the Survey of the North Western Territory in company with, and under the direction of D. D. Owen, Esq. U. S. Geologist. He had charge of a portion of the survey lying between Lake Superior and the Mississippi River.
>
> Dr. Randall was one of the founders of the Academy of Natural Sciences of California and the first President.
>
> In 1850 [*sic*] he was elected a member of the Legislature of this State, and during the Session, made an elaborate report in favor of a scientific survey of the State, setting forth in a clear and impressive manner, the necessities and advantages of such a work.
>
> He was well known throughout our own, as well as the Atlantic States, from his connection with scientific pursuits, both of a public and private nature.
>
> In his disposition, he was generous and kind, possessing a firm resolute and clear mind, and ardent in his attachments.
>
> Therefore, be it Resolved,
>
> That in the death of the Hon. Andrew Randall, M. D. we have lost a steadfast and devoted friend and member, whose manly virtues and kindnesses, we take this opportunity publickly [*sic*] to acknowledge, as a last tribute to his worth.
>
> Resolved: that we deeply sympathize with his family in our mutual loss, and that we shall ever entertain for his memory feelings of high respect, which his past associations with us have naturally engendered.
>
> Resolved, that the usual badge of mourning be worn by the members of the Academy for thirty days.
>
> Resolved, that a copy of these proceedings and resolutions be forwarded to the members of the bereaved family.
>
> [Signed] Leander Ransom
> President
>
> [Signed]
> M. G. Reade
> Rec. Sect.

(18) The records in the Nevada State Archives, the Nevada Historical Society, and in the Special Collections Department of the University of Nevada are silent on this matter (Guy Louis Rocha, Nevada State Archives, pers. commun. Nov. 18, 1981; Ellen Guerrocagoiti, Spec. Coll. Dep., Univ. Nevada Library, pers. commun. Nov. 23, 1981). Further, according to Merrill (1920: 291) "No systematic and independent geological survey of the State [Nevada] was ever carried through, although an abortive attempt was made in 1865. . ." when the State Legislature passed a bill to initiate a survey. In 1866, R. H. Stretch was appointed State mineralogist. We know that Trask was in Virginia City sometime in April 1860, but we do not know how long (Trask 1860: 160; Van Nostrand 1942:309).

(19) Trask contract dated June 4, 1861. NARS: RG 94 (Military Officers & Physicians of All Classes), Box 762.

(20) Trask contract dated August 28, 1861. NARS: RG 94, Box 762.

(21) J. B. Trask to R. H. Coleridge [*sic*]. NARS: RG 112 (Surgeon General Office), Letters Received T-1862.

(22) NARS: Civil War Pension Records. John W. McLean, claim #393,994. Memo (#5093/1884) dated June 20, 1884 on file.

(23) Letter from J. B. Trask to C. C. Byrne, Sept. 22, 1862. NARS: RG 112 (SGO), Letters Received T-1862. "Sir: I have the honor to inform you that in the case of Private Tourlette there

is sufficient constitutional debility to warrant his discharge from the service. There is is [*sic*] also sufficient mental depression to render him unfit for the duties of a soldier . . . . [Signed] John B Trask M. D. Surgeon in Charge."

(24) Letter from C. H. Alden to J. B. Trask, Sept. 23, 1862. "Sir: You will immediately make out and send to the proper office, the discharge papers of private Tourtelotte [*sic*], a patient in your Hospital. It is your duty to discharge such of your patients as are proper subjects for discharge, and not to keep them uselessly in Hospital. [Signed] C. H. Alden, Ass. Surg. USA." NARS: RG 112, vol. 33, ser. 2, p. 124.

(25) While differences in medical judgment may have been the deciding factor in the decision to replace Trask as head of Finley Hospital, paper work, for which Trask was not ideally suited, must have contributed significantly to his undoing. In response to repeated demands for hospital discharge papers to be expeditiously processed, Trask addressed a letter to C. C. Byrne on Sept. 23, 1862 in which he stated, ". . . in the matter of discharges I have now the papers of nearly fifty cases made out . . . . Farther, the papers made out are more than two weeks old and are not yet signed on account of press of other business at the department, and also in consequence of absence on duty of the surgeon in chief of Eckington and Finley Hospitals. *I am an acting surgeon only*, and therefore you are aware that my signature is of no value, at least such is the interpretation at office of Med Director." NARS: RG 112, Letters Received T-1862.

(26) Letter from C. C. Byrne to R. C. Abbott, Sept. 23, 1862. "Repeated evidences of the incompetency of Act'g Assistant Surgeon John B Trask having been afforded the Surgeon General directs that he be relieved from the charge of the Finley Hospital and placed in a subordinate position." NARS: RG 94, Box 762.

(27) Letter from J. B. Trask to W. A. Hammond, Sept. 25, 1862. "Sir: I was last evening superseded by a junior officer. As this is equivalent to a charge, I respectfully solicit that my contract may be this day cancelled, or the cause leading to the supersedure presented. [Signed] John B Trask M. D." NARS: RG 112, Letters Received T-1862.

(28) Letter from C. H. Alden to J. B. Trask, Sept. 26, 1862. "Sir: Your communication of the 25th inst has been received. In reply the Surgeon General directs me to inform you that, in compliance with your solicitation, your contract has been this day annulled. [Signed] C. H. Alden, Ass. Surg. USA." NARS: RG 112, vol. 33, ser. 2, p. 138.

(29) In 1868 the name of the association was shortened from California Academy of Natural Sciences to California Academy of Sciences.

(30) Letter from John Xantus to Spencer Fullerton Baird, February 11, 1859. SI: RU 7212, John Xantus papers 1857-1864.

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xviii pp. (Trask's work is mentioned on page 358. Trask's map of California is reproduced on page 359. Goetzmann stated, "He [Trask] produced a thrity-one page pioneer work entitled *On the Geology of the Sierra Nevada or California Range*, although he never really explored the Sierras himself." In the preface to his 1853 report, to which Goetzmann referred, Trask stated "Personal observations were made during the autumn and winter of '50 and '51, and also of '52, and the entire line of travel was conducted for the most part on foot, for the better purpose of more critical examination." Perhaps an argument can be made that the gold fields, lying at elevations mostly below 1500 meters, are in the foothill zone and that Trask did not in fact explore the "High" Sierra. If this were Goetzmann's intent, it was not made clear.)

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ADDENDUM

Davison, Charles. 1927. The founders of seismology. Cambridge Univ. Press, London. xiii+240 pp. (Page 143: "One of their [earthquakes] students was John B. Trask (*c.* 1823-79), a skilful and original physician, who attended to them from 1850 to 1858 and, during these nine years, recorded altogether 98 earthquakes*. If his lists are now known to be far from complete, and if, since his time, some of the gaps which he left have been partially filled in, he must none the less be regarded as a pioneer of Californian seismology.")

PIONEER GEOLOGIST THOMAS CONDON OF OREGON: SCIENTIST, TEACHER, PREACHER

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The current fashion among historians of science is to eschew the great-man theme in describing the development of a science. This attitude is based on the defensible position that the great scientist is, after all, a product of his social, economic, cultural and intellectual milieu; without the latter, greatness cannot be engendered. The milieu in which Thomas Condon (1822-1907), pioneer minister/geologist of Oregon found himself, however, consisted of the stereotypical mid-19th century "Wild West." Condon was not a "great" scientist in the sense that Newton or Einstein was great in the development of science, but Condon's achievements were remarkable and significant considering the conditions under which he worked, and in many senses Condon *was* a great man.

Figure 1. Thomas Condon as a young man of 30. (From McCornack 1928)

CONDON, SCIENTIST-EXPLORER

Discovery of the John Day Fossil Beds

Within the human environment of frontier settlers, saloon keepers, prospectors, gamblers, friendly and hostile Indians, and the United States cavalry, Condon discovered Oregon geology and became an investigator of stature respected by many Eastern establishment scientists. He discovered the now famous John Day Fossil Beds and thoroughly explored the region, collecting

Cretaceous and Tertiary fossils. In an early article (Condon 1871), he described the Tertiary strata, assigning accurate ages to the stratigraphic units. He recognized the old ocean bed of the Cretaceous period at the bottom of the sequence "with its teeming thousands of marine shells, as perfect today in their rocky bed as those of our recent sea shores, their cavities often filled with calcareous spar or chalcedony as if to compensate for the loss of their own proper marine hues." He went on to describe in his fluent style the earliest fresh-water Tertiary strata "so full of the leaf prints of the grand old forests which during that age of semi-tropical climate covered those lake shores." He realized, however, that the real significance of the Tertiary rocks of the John Day did not lie in the fossil remains of its forests but from its finely preserved fossil bones. He collected and identified abundant extinct specimens such as the *Oreodon* and the *Lophiodon*. He discovered the "richest chapters in the history of the horse" in the upper part of the John Day Valley.

Figure 2. The John Day River and Sheep Rock from the south. The fossil-bearing beds of the John Day Formation are on the flanks of Sheep Rock, which is capped by the Picture Gorge Basalt of the Columbia River Group. (From University of Oregon Natural History Museum Bull. 19, 1972)

Condon's descriptions of the rocks, the fossils and the sequence of events are never laborious; rather, he paints with words a panoramic view and brings the scenery alive for the reader. His purpose in writing was always to interest the average person in the wonders of natural history. Although he did not write just for other scientists, it is clear that he was quite capable of doing so. His letters to Eastern scientists show that he was very well versed in the state-of-the-art scientific knowledge and verbiage of his age.

The Development Theory

In studying the John Day fossils, Condon became fascinated with the paleontological evidence for the "Development Theory," as the theory of evolution was then called. In an age when Darwin's Theory of Evolution was disturbing the very foundation of religious faith and the creationists churchmen were seemingly united as one voice against any form of evolution, the unassuming minister/geologist in Oregon was asking his audience to consider "any given 100,000 vertebrates," and he asked, "did God so respect his own thoughts as to make them by 100,000 separate and distinct acts of his will?" Condon became one of the first clergymen to become so enlightened on this subject. In his article in *The Overland Monthly* in which he described the rocks of the John Day Valley, he wrote

> If anyone supposes that all the differences that beset these lines of inquiry and research rest only in the path of the theologian who claims a separate creation for each great type of animal life, he greatly misapprehends the present state of these investigations. . . Indeed one can hardly look over its historic archives of the Tertiary period, without a conviction that this Columbia basin is destined to be the great battle-ground of conflicting theories, upon the question of the Origin of Species. (Condon 1871).

For a minister in America to express these views so early was certainly rare. Even James McCosh, prominent theologian and president of Princeton, considered liberal on evolutionary views, was silent for at least a dozen years after the 1859 publication of the *Origin of Species*. When McCosh did speak out and took a position on the issue in the 1870s, he did so with caution and did not go beyond Condon's views (Clark 1975).

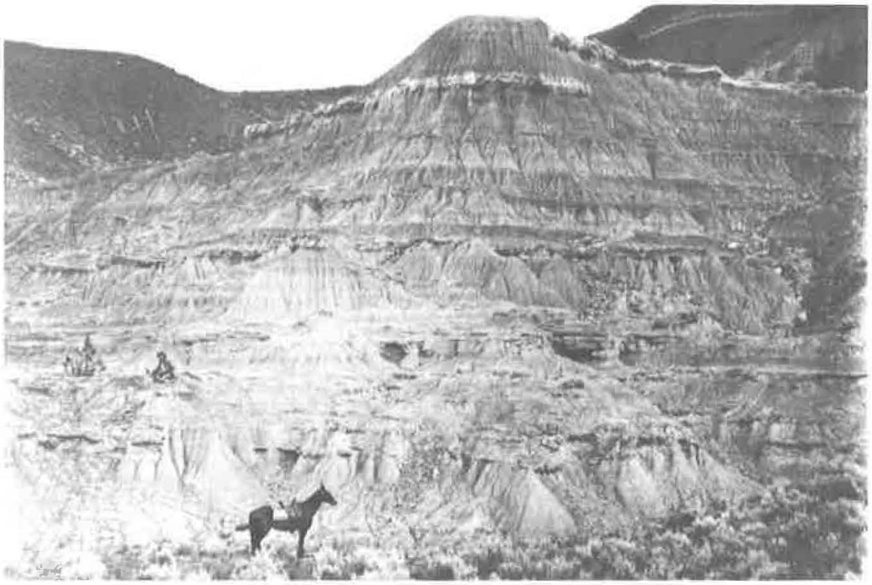

Figure 3. John Day Fossil Beds. (From University of Oregon Natural History Museum Bull. 19, 1972)

Condon's ideas on the "Development Theory" were summarized in a lecture that was reprinted in his book *Two Islands.* In this eloquent speech, Condon used his extensive scientific knowledge to illustrate the position of the theistic evolutionist. He stated that Christendom had survived the Copernican revolution and Galileo's heresy and the acceptance of the great antiquity of the earth—"six thousand years would not cover the scope of history geologists saw in the rocks," but he warned, "The church cannot put herself in a position of chronic antagonism to science without harm."

Contribution to Horse Genealogy

The defenders of the sociological historiographic approach might argue that even though Condon seemed to be isolated here in the Far West among the "wild and woolly," he was not in an intellectual vacuum; he was, after all, in correspondence with the scientific establishment in the East upon which he depended for his intellectual nurture. A study of Condon's life, however, shows clearly that the Eastern establishment seemed to need Condon more than vice versa. Without Condon, O. C. Marsh of Yale University probably could not have worked out the genealogy of the horse that was so important to his fame. Condon provided Marsh with specimens of three-toed horses that were invaluable evolutionary links in the development of the horse, enabling the Yale scientist to work out the evolutionary lineage of the horse. This work of Marsh (1874) and others he published on dinosaurs and the toothed birds were hailed by Charles Darwin as the "best support" for the theory of evolution that had appeared since his own great work, *The Origin of Species*, in 1859. Marsh gave scant credit to Condon for the latter's contributions, treating him as an amateur collector rather than as a fellow-scientist. The extent of Condon's help to Marsh has recently become evident. His not insignificant part in contributing to knowledge on horse evolution is documented by Drake (1978).

Bridge of the Gods

Thomas Condon was among the first to make geologic observations of the Columbia River gorge. The feature at Bonneville known as the collasped "Bridge of the Gods" had puzzled every explorer of the gorge since Lewis and Clark. Various prominent geologists through several decades to the 20th century had tried to explain the presence of large drowned pine trees above the Cascade Locks. Explanations ranged from the damming of the river being caused by the washing out of an underground channel to the wearing down of an anticlinal arch (Beverly Vogt, oral comm. 1980). The Indians had their own explanation: there once was a natural bridge that spanned the river at the Cascades but during a violent quarrel between Mount Hood and Mount St. Helens when these mountains threw fire, smoke, and rocks at each other, the bridge collapsed and dammed up the river's waters. In his characteristically analytical style that invites the reader to think, Condon (1869) wrote

> The gold hunter takes a pan of dirt and shakes it violently in water till he sees the gold it contains, if there be any. Let us treat this Indian legend to a like process. Is it supposable that any existing cause could have increased the obstructions in the river here at the Cascades so as to have brought about the change indicated in the legend? Or are there now any existing indications of any such changes having occurred?

He went on to explain that the basalt here overlies a softer rock and the erosion of the latter has caused the basalt to overhang the river bank. At the same time the presence of characteristic vertical fractures throughout the basalt contributes to a general tendency of the rock to crumble; this friability is not just at the surface but exists deep into the rock. He cited the railroad engineer's frequent readjustment of the railroad lines on both sides of the river as evidence that there was a

Figure 4. Celilo Falls, on the Columbia River, near The Dalles. (From McCornack 1928)

slow movement of both banks toward the river. It was not inconceivable to Condon, therefore, that a violent disturbance, such as an earthquake, could trigger a major slide of this material from both banks, thus obstructing the passage of the river. He concluded that when the trees were living, the Columbia River between the Upper Cascades and The Dalles must have been more than twenty feet lower than it was in Condon's day.

The debate about the cause of this phenomenon continued until Ira Williams (1916) proclaimed the cause to be unequivocally the slide (Vogt, oral comm. 1980). Condon's simple deductive reasoning had given him the correct answer in 1869.

Two Islands

Although Condon had published several short articles on the geology and paleontology of Oregon, his *Two Islands* (1902; 1910) is his only published book. In it he traced the geologic history of Oregon in a lively narrative style. Although his geological knowledge did not encompass the present concepts of sea floor spreading and plate tectonics, through his careful observations and keen instinct, he provided the reader with a remarkably modern interpretation. Without the plate tectonics paradigm as home base or such terms as "subduction" or "continental accretion" as conceptual tools, he wrote in *Two Islands*

> The geological history of the Pacific coast consists chiefly in the description of the slow elevation of successive belts of the bed of the ocean into dry land, and the progressive additions of these to the western border of North America.

Condon's "two islands" refer to the Blue Mountain region and the Siskiyou-Klamath mountains region both of which he recognized as representing the oldest rocks in Oregon, of Mesozoic age as evidenced by the occurrence of Mesozoic fossils. This book served as the only book on Oregon geology for six decades.

CONDON, TEACHER-PREACHER

In Thomas Condon it is difficult to separate the scientist from the teacher and the teacher from the preacher. Condon himself found that he had a hard time separating his teaching from his preaching. His first assignment in Oregon was to start a congregation in St. Helens in 1853. Later, in writing to a friend about his first Oregon experience, he said, "I had taught school in New York a good deal, and felt that I could make teaching. . .a ready means of acquaintance with the people. I told our town board. . .that I would teach their proposed school and preach too." (Condon letter courtesy of the Oregon Historical Society.)

After ten years of missionary work in western Oregon first at St. Helens, then at Forest Grove, then as pastor of the Congregational Church in Albany, Condon felt the urge to go to a more needy field and he moved to The Dalles where he founded a Congregational Church. His daughter, Ellen Condon McCornack, in 1928 wrote, "His heart went out with all the yearning of his loving nature to the wild reckless sinners around him. . . Saloon keepers, drunkards and gamblers loved him."

Condon and the Lay Public

Condon gave free public lectures all through his career. He spent many summers with his family at Nye Beach where an informal announcement would be made that "Professor Condon would lecture on the beach" and a crowd would gather to hear him. As John Eliot Allen, Professor Emeritus of Portland State University noted, Condon's "belief that a knowledge of the earth should be a part of every man's cultural heritage has been an inspiration to those who followed him, down to the present day" (Allen unpublished ms).

Condon always possessed a sense of humor. He enjoyed shocking some of his flock by creating "miracles." Once he showed a workman an ordinary looking rock and said, "What would you think if I should give this piece of rock a blow with my hammer and find a spray of leaves on the

Figure 5. Professor Condon lecturing on the beach. (From McCornak 1928)

inside?" And then he proceeded to do just that. He had collected extensively Miocene fossil leaves and knew the odds of finding some.

In a letter Condon wrote to J. S. Newberry in 1870 (McCornack 1928:55), he said

> One of my means of getting help and information, in the line of my geological inquiries in Oregon is to interest our young men. Many of these are teamsters, packers, or trappers who spend their summers in the wilderness, their winters at The Dalles. I have for a few years past tried to keep up weekly lectures through the winter months free to all—my thoughts being. . .to interest the young people. These lectures have drawn the young people around me, laid open to me a great deal of valuable information, and brought me many a fine specimen.

There was method, then, in his madness. Through his weekly lectures on geology and paleontology he had aroused the interest of so many people in his collections of rocks and fossils that the rough-and-ready types from all over the territory collected specimens for him. Captain John M. Drake, commander of a cavalry troop at the nearby fort and his men were among Condon's converts (if not to religion, at least to science). Drake wrote to Condon in 1864 that while he was absent from his camp on Beaver Creek in pursuit of a party of hostile Snake Indians, the soldiers who were left behind found some fossils. He said, "On my return to camp. . .I found our camp converted into a vast geological cabinet. . . You will receive a large contribution to your cabinet" (McCornack 1928:36-37).

The general lay public today seems to harbor more suspicion of the achievements of science than these soldiers. Could it be that modern scientists have failed to convey the sense of wonder and discovery in science that Condon seemed to be able to instill in the least likely student of science? Or have we been pre-empted by television, our would-be audience jaded by special effects? Perhaps we should possess a bit of the preacher in us while amassing the cold facts of science!

Condon had little formal education and practically none in science. He was the son of an Irish immigrant to New York City and had only one year of high school and three years at the Auburn Theological Seminary. His extensive knowledge in the sciences was gained entirely on his own. Lacking specimens for his comparative anatomy studies, he even trained an old donkey to follow him around so that should it drop dead, it would not be too far away and Condon could retrieve the old bones for his studies. Somehow the early Oregon educators and administrators recognized his talents and used them to the advantage of Oregonians in spite of Condon's lack of credentials, degrees, and qualifications which people today, talented or not, must have to teach.

State Geologist and University Professor

Condon began formal teaching in 1873 as professor of natural science at Pacific University in Forest Grove. By then he had also been appointed the first State Geologist of Oregon. In 1876, he was offered the Chair of Geology and Mineralogy and Natural Science at the newly established state university in Eugene. The University of Oregon was patterned after such institutions as Yale and Oxford with emphasis on the Classics so that at first the sciences played only a small part in the curriculum. Condon carried out his duties with creativity, leading his students on field trips and using his extensive personal collections for illustrative purposes. He introduced a new course entitled "Physical Features of the Earth." Without a textbook he lectured on scientific geography, the earth's motions, its winds and tides and other natural phenomena of the earth's surface. During the first years the teaching staff at the University was small and since the other professors were teaching the classical curriculum of Greek, Latin, and mathematics, Condon had to teach not only the physical features of the earth, but also geology, paleontology, mineralogy, botany, rhetoric, Guizot's history of civilization, mental philosophy, international law, Constitution of the United States, and ethnology. Condon's daughter noted (McCornack 1928), "But the breadth of his scholarly tastes was such that all of these studies had long been of deep interest to him and this made their teaching a pleasure."

CONCLUSION

In spite of his busy schedule, Condon never stopped exploring Oregon to discover its geological and paleontological secrets or giving free public lectures. Besides writing his several articles and book *Two Islands*, opening the John Day Fossil Beds and discovering important evolutionary links in horse genealogy, he made a number of other significant contributions. He discovered, described

Figure 6. Thomas Condon at age 80. (From McCornack 1928)

and named several important vertebrate fossils; *Desmatophoco oregonensis*, for example, is a fossil seal representing an intermediate form between sea lions and seals. Jacob L. Wortman, one of his famous students and a distinguished vertebrate paleontologist, attested to Condon's fine description of the fossil and accepted Condon's name for it.

Condon continued teaching at the University and serving as head of the Geology Department until his 83rd year, tending the specimens in his growing museum. When he died on February 11, 1907, tributes poured in from all parts of the country, from his former students, some of whom had become eminent scientists, and from his colleagues. The University of Oregon *Bulletin* devoted an entire issue in his memory. One of the University presidents, C. H. Chapman, writing for *The Oregonian* newspaper stated

> Professor Condon will be best and most worthily remembered as a teacher, like LeConte, for whom he cherished a warm and deep affection. He was less productive than LeConte as a writer and is not so well known in the wider world of science, but as an inspiring instructor of youth he stands in the first rank of college professors. His equal has never appeared in Oregon and seldom elsewhere. . . He taught with power and fruitfulness. Oregon is populated with his students who perpetuate in their lives the spirit of his deep earnestness and love of truth.

Oregon has perpetuated the name of Thomas Condon in several ways, the most appropriate of which is the establishment of the Condon Lecture Series, which brings distinguished scientists from many parts of the world to lecture at Oregon State University in Corvallis, University of Oregon at Eugene and Portland State University. The Condon Museum has also been revitalized as present-day scientists realize the extent of Condon's exploration and collection. Condon was a true frontiersman and one of America's pioneer scientists. He laid a sound foundation in Oregon for all scientists who came later—and he was also a humanist.

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I. C. RUSSELL: FRONTIERSMAN OF SCIENCE

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When the U. S. Geological Survey was established in 1879, geology was already changing from a science of exploration to one of systematization and specialization, and only a decade later Western settlement had so progressed that there was no longer a frontier. Israel Cook Russell, who joined the Survey in 1880, was one of the last of the great geologic explorers. Restless under the routine and obligations of civilization, he delighted in the challenge of the unknown and made the most of the remaining opportunities for exploration of the West and Alaska. His earliest years with the Survey were spent in investigating the desert basins of the arid West and the glaciers of the Cascade Mountains and the Sierra Nevada. After three years mapping in the southern Appalachians, an assignment he did not enjoy, Russell then spent three seasons in Alaska. His notes on the surface geology of Alaska, published in 1890, laid down the principal lines of investigations followed by others in later years. After his appointment as Professor of Geology at the University of Michigan in 1892, Russell spent many summers studying the geology of areas in the Pacific Northwest, giving special attention to water supply. Primarily a scientific observer rather than a theorist, Russell made exceptionally large contributions to the knowledge of the areas he studied because of his energy and industry. He was prompt to publish, and an attractive literary style, coupled with his skill as a photographer and in sketching, makes his reports enjoyable reading even today.

In the last decade of the 19th century, more especially in the last two decades that coincided with the early years of the U. S. Geological Survey, American geology and geography, which had been largely sciences of exploration, began to make demands on the systematist and specialist. The United States changed during this period from a rural, agrarian, isolated nation into an urban industrial world power, and the physical frontier which had shaped much American history ceased to exist. Geologists and geographers turned their attention from surveys of large geographically unknown areas to topical studies; instead of investigations chosen by individual scientists, research was organized to meet an objective; instead of seeking only to add to the sum of human knowledge, solutions to problems of economic import were sought.

Israel Cook Russell, born in New York State in 1852 and appointed to the U. S. Geological Survey in 1880, lived and worked in this transitional period but remained at heart and, longer than most, in work an explorer. He delighted in discovering the unknown, and hardships endured in so doing were unimportant. "We rejoiced," he wrote after his second trip to Alaska in 1890, "at the thought that we were nearing the place where the actual labors of the expedition would begin; we were approaching the unknown; visions of unexplored regions filled with new wonders occupied our fancies, and made us eager to press on." (Russell 1891:82). He took equal delight in sharing his experiences with others, and publishing reports promptly.

There was little in Russell's appearance or in his early life to suggest the explorer. He was small, below medium height, slender, and looked frail. Until he was 12, he lived in New York State, and then moved with his family to Plainfield, New Jersey. His boyhood "expeditions" were all in the already well-settled Northeast. He was graduated from Hasbrook Institute in Jersey City, and after being graduated from the University of New York at the age of 19, went on for a graduate course at the Columbia School of Mines.

Evidence of his true inclinations came to light when he sought a post with the U. S. Transit of Venus Expedition in 1874-75. Finding only one position open, that of photographer, he learned the then difficult art and received the appointment. During the expedition he also served as naturalist and became keenly interested in physical geography. In later years he was able to draw many apt comparisons between the phenomena observed during this period as he traveled around the world and those observed in the western United States and Alaska.

After his return from the Transit of Venus Expedition, he settled down to teach geology at the Columbia School of Mines in the department headed by John S. Newberry but resigned two years later to join the U. S. Geographical Surveys West of the 100th Meridian under Lt. George M. Wheeler. That survey was discontinued only a year later, when the U. S. Geological Survey was established, but the year's work in New Mexico, even more than the Transit of Venus Expedition, shaped his future. Many years later, Russell wrote "When investigators of surface geology and geography made their bold explorations into the vast arid region of the southwest, they discovered a land of wonders, where the mask of vegetation which conceals many countries is absent and the features of the naked land are fully revealed beneath a cloudless sky. It was in this arid region of strong relief that a revival of interest in the surface forms of the earth was engendered. The seeds of what is practically a new science--physiography--gathered in this land by J. S. Newberry, J. W. Powell, G. K. Gilbert, C. E. Dutton and others, when carried to other regions, bore abundant fruit." (Russell 1898b:Preface). Russell himself was one of the "others," listed by Bailey Willis (1908:586) along with Newberry, Hayden, Powell, and Richthofen as the pioneers "who have blazed out the way, both physically and intellectually, for the road-builders who follow."

In 1880, Russell was appointed an assistant geologist in the U. S. Geological Survey and assigned to the Division of the Great Basin as an assistant to G. K. Gilbert in his studies of Lake Bonneville. In 1881, Russell was given independent work and sent to study the Quaternary geology of the western part of the Great Basin. During the field season he traveled some 3,500 miles by horseback through northwestern Nevada and portions of California and Oregon, an area that he described as comparable only to the parched and desert areas of Arabia and the shores of the Dead Sea and the Caspian. This was pure reconnaissance–he worked the entire season without scientific assistants and deferred all instrumental work for another season–in the course of which he discovered several fossil lakes of Quaternary age in a land that is now extremely arid. He also observed in some detail Lake Lahontan, so named by Clarence King of the Fortieth Parallel survey, which occupied a position on the western rim of the Great Basin analogous to that of Lake Bonneville on the east. On the basis of the season's work, he prepared his first Survey report, a 46-page sketch of the geological history of Lake Lahontan (Russell 1883).

In 1882, Russell and topographer Willard D. Johnson made a reconnaissance from the head of Quinn River, Nevada, northward and westward into southern Oregon so as to cross the country within the rim of the Great Basin that was most likely to afford information on its Quaternary geology. Part of the reconnaissance was through open country, without a road or trail of any kind. Part of the country traversed was a rough and irregular basaltic tableland where stream beds were few and usually dry, and the sole source of water was the "water-pockets" in the surface of the basalt which, according to Russell, were sufficiently abundant to meet the traveler's need in spring and early summer. Other parts of the area were regions of very rugged topography with abrupt precipices enclosing valleys extremely difficult to explore. Russell reported his observations promptly in the Annual Report for 1882-1883 (Russell 1884).

During the summers of 1883 and 1884, Russell completed his work in the Great Basin. In 1883, he and Gilbert, along with Johnson, visited the glaciers of the Sierra Nevada. Their combined observations indicated that there were nine glaciers in the southern rim of the Mono Lake drainage basin, a somewhat larger number elsewhere. In addition to these personal observations, Russell combed the literature and prepared a report on existing glaciers of the United States for the Survey's Annual Report for 1883-1884 (Russell 1885a). After another season in the Mono

Valley region, he prepared a report on its Quaternary geology (Russell 1889a). Civilization was beginning to encroach on the area, making it less interesting to him. In 1881, his whole 3,500-mile journey had been made on horseback but in 1883, he traveled by railroad, stagecoach, and muleback (mules being more satisfactory than horses, he had found, where water and grass were scarce). By an ironic twist of fate, many years later the people of the Mono Valley region offered to pay for a reprint of his report to be used to attract tourists.

Russell's next assignment was also with Gilbert, in the Appalachian Mountains, but he did not enjoy it and after three years gratefully relinquished it to young C. W. Hayes. For three field seasons he faithfully mapped sections across the Appalachians in accordance with Gilbert's plan for studying structure, but there was evidently no sense of adventure or exploration. For his annual reports to the Director, he recorded in detail the manner of travel and the routes followed—all journeys were made either on horseback or on foot while carrying a camping outfit—but a scientific product was not forthcoming. The sole report, on the subaerial decay of rocks, was incidental to his principal work and in large part a continuation of an investigation begun with his work on the western Pleistocene.

In 1888, Russell was called on to prepare a correlation essay on the Triassic, an assignment that permitted him to travel in the West once more, but before it could be completed he was offered an assignment for which he was especially suited. In the spring of 1889, the U. S. Coast and Geodetic Survey prepared to establish the position of the boundary between Alaska and what is now the Yukon Territory of Canada. The Superintendent of the Coast and Geodetic Survey invited the Director of the Geological Survey to send someone along with the boundary survey parties to make geological observations. Russell sought the assignment, the first opportunity for a Survey geologist to work in Alaska, and sailed with the Coast Survey expedition in June 1889. The survey party to which he was attached traveled up the Yukon River in a stern-wheeled steamboat, which Russell found did not allow much opportunity for geological observations. He therefore made arrangements to travel with a party of miners who were on their way from Fortymile Creek to Juneau, by canoe or on foot.

On December 26, back in Washington, he presented a paper at the meeting of the Geological Society of America, "not with the hope of contributing largely to geological science, but because the observations relate to a little-known region and for that reason may have some interest." (Russell 1890:102). In this paper, Russell suggested the principal lines of investigation which guided those who later undertook the geological exploration of Alaska. He also called attention to enterprises that would aid in the development of the interior of Alaska—a survey of the Yukon delta to determine if there were a channel by which ocean-going vessels could enter the river and a survey of the passes between the headwaters of the Yukon and the coast to furnish data for making trails and wagon roads. In this, too, he anticipated later Survey involvement in Alaska.

Russell spent the next two seasons around Mount St. Elias and Yakutat Bay, where there was an unrivaled opportunity for study of glacial phenomena. The 1890 expedition was sponsored jointly by the National Geographic Society and the U. S. Geological Survey; the party consisted of Russell, Mark Kerr, Survey topographer, 7 camp hands, and 2 dogs. Russell thoroughly enjoyed the summer—it is evident in his 139-page report published in 1891—although to some it might have seemed difficult and dangerous. On his very first day's reconnaissance, accompanied only by the two dogs, he decided to slide down a snow slope and came close to two huge brown bears, one of which became curious and ambled across the snow to look him over. He departed in haste. Another time he became so intent on studying the formation of icebergs that he forgot the tide was running out and he had to cut his way through the ice fragments with an axe so he could get his canoe to water and return to camp. At one time his tent was flattened by an avalanche—he escaped just in time—and toward the end of the season he became separated from the rest of the party and lived for several days in a chamber excavated in the snow. On his return to Washington he reported that "not a man was seriously sick and not an accident happened. The work planned at the start was carried out almost to the letter, with the exception that snowstorms and the lateness of the season did not permit us to reach the summit of Mt. St. Elias." (Russell 1891:163). An attempt to reach the summit in 1891 also had to be abandoned because of snowstorms and avalanches. During the final attempt to reach the top of the peak in 1891, three of the party lived for several days in a single tent of light cotton cloth, 7 feet square at the bottom and 5 feet high, subsisting on corn griddle cakes, bacon or corn beef, and coffee cooked on a coal oil stove, and sharing two canvas blanket-covers, one double blanket, and one feather quilt as bedding. For the first time a mild note of complaint crept into his report: "To live under these conditions at an altitude of 8,000 feet during snow storms and dense fog, when during much of the time the snow was melting so as to wet our blankets through and through, was very trying to our endurance." (Russell 1893a:51).

In 1892 Russell was elected to succeed Alexander Winchell as Professor of Geology at the University of Michigan. His departure from the Survey coincided with a change in the orientation of Survey work after Congress slashed appropriations to express its dissatisfaction with the Survey's emphasis on general geology under Powell. It is likely, however, that the pass beyond youth–the attainment of age 40–and a growing family influenced his decision. Then, too, the 1890 Census had just reported that the population had spread so far that the frontier had ceased to exist.

Russell retained a part-time affiliation with the Survey for the remaining 14 years of his life and was several times employed on special investigations. In the Geological Survey under Director Charles D. Walcott, much of Survey research was directed into channels that would aid in solution of national problems. Many of Russell's Survey investigations during these years were concerned with water problems. All of them were in the states of Washington, Oregon, and Idaho, which were still largely virgin territory for Survey geologists, so he was able to add considerably to the knowledge of the geology and geography of the region as well as to provide the needed data on water resources.

Russell was primarily a scientific observer rather than a theorist. His mentor, Gilbert, said that his contribution to the body of scientific philosophy was not of the broadest scope, being largely restricted to the field of his own observations, but his contribution to the body of scientific fact was exceptionally large because he was keen, energetic, and industrious, and did not delay publication to search for broad generalizations. The freshness of his experience, and his enthusiasm, are clearly evident in nearly all reports. Russell also had an attractive literary style and has provided us with many colorful word pictures of Western and Alaskan scenes and phenomena. He possessed unusual skill as a photographer, which enabled him to take photographs that had both scientific and artistic value, and was adept at making field sketches as well. His reports have preserved for us, in text and art, a vision of some of the late 19th century American wilderness.

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ALFRED HULSE BROOKS AND THE GEOLOGICAL EXPLORATION OF ALASKA

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The year 1898 marked the beginning of the United States Geological Survey's concerted, large-scale exploration activities in the Territory of Alaska and the introduction of Alfred Hulse Brooks to the USGS-Alaska, where he would spend the rest of his life exploring and/or administrating the geological exploration of the region.

Brooks directed and participated in more than 30 expeditions into the wild, unexplored reaches of the frontier, overcoming major natural obstacles to gain a better understanding of the arctic and subarctic environments. He published more than 100 articles and books on the geology and topography of the area, many of which continue to be the definitive works to this day. Brooks exemplified the perfect proportions of geologist, naturalist, and administrator necessary to coordinate the exploration of such a vast, unknown region. Through his perseverance and leadership, the Tanana, Yukon, and Kuskokwim drainage basins were explored and mapped with an accuracy far ahead of the state of the art at that time. Brooks authored the initial report on the Nome gold region as well as the first in-depth paper on the Mount McKinley area. His untiring zeal to understand the geology of Alaska and his ability to organize the energies of others brought about a better understanding of the geology of North America as a whole and represent a major contribution to American science in the early 20th century.

In April, 1898, a young American geologist, Alfred Hulse Brooks, stepped ashore at Skagway, Alaska, to begin a career that would last 25 years. Through his untiring zeal to understand the unknown, as well as his innate ability to organize and administer the work of others, he would see vast tracts of the Alaskan interior mapped and analyzed, and the American public informed of the natural wealth lying hidden beneath Alaska's surface. Brooks' relaxed style of writing and his personable nature did much to break down the myth of "Seward's Folly," for his messages were of the reality of the North, not the romance of a mythical landscape.

Alfred Hulse Brooks began working for the United States Geological Survey in 1894 under the supervision of C. Willard Hayes. Hayes lighted Brooks' enthusiasm to work in the Alaskan wilderness by recounting to the young scientist his own experiences in exploring the interior during an expedition under Frederick Schwatka in 1891 (Sherwood 1965:173). So interested was Brooks in the new territory, that when an opening for a geologist came up in 1898, Hayes readily recommended him for the job (Sherwood 1965:173-174). Having traveled throughout Europe and the continental United States, Brooks viewed the chance to take part in the exploration of the interior of Alaska with open excitement. When Hayes' offer arrived, he hurriedly left Paris, where he had been studying, and booked passage home. In a whirlwind of preparedness, he hastily put together an itinerary for the journey and left for Seattle, where the party to which he was assigned was to meet.

On April 5, 1898, Brooks' group, under the direction of topographer William J. Peters, left Seattle in company with three other Alaska-bound exploratory parties. They arrived in Skagway six days later (Brooks 1900a:431). Brooks' group was assigned to survey the areas immediately adjacent to the White and Tanana rivers (Fig. 1).

Several days after their arrival in Skagway, the expedition made ready their provisions and began a five-month journey into the wilderness. Leaving by way of White Pass, they travelled to

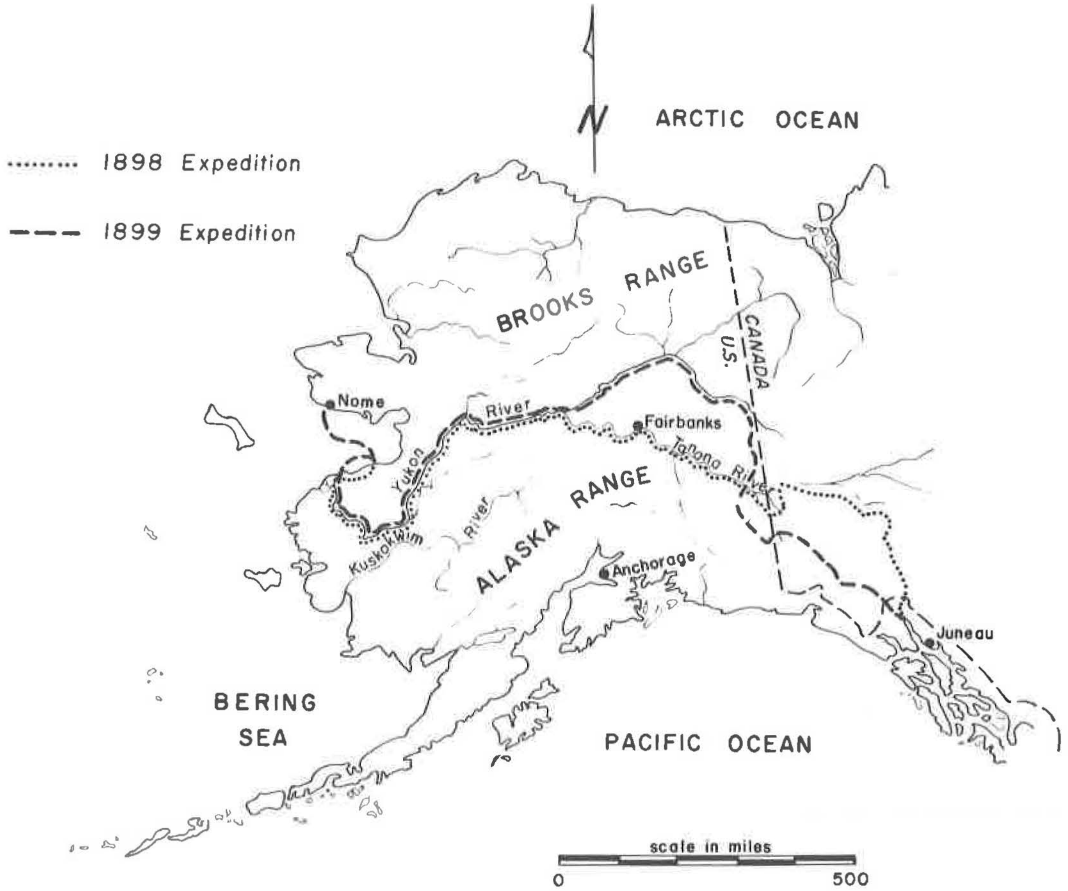

Figure 1. Route map of Brooks' Alaskan expeditions of 1898 and 1899.

the Canadian side of the border and halted at Bennett City where Brooks took several days leave to investigate outcrops in the vicinity of Chilkoot Pass. Finding the area under several feet of snow and ice, Brooks returned to Bennett City where he had left his companions (Brooks 1900a: 432).

The next day the party made its way to the upper end of Marsh Lake, which was just beginning to thaw. This necessitated a delay of nearly three weeks while they waited for the ice pack to break up. Once again, Brooks took leave of the party to survey the surrounding countryside, this time journeying some one hundred miles to investigate the geology of the Atlin Lake region. Since this area was also under snow, he had to confine his studies to occasional outcrops and the general topography of the area (Brooks 1900a:432). In the report later published on the expedition, Brooks indicated that the area offered prospects for future consideration as "a good route for railway" and general travel (Brooks 1900a:432). This was his first mention of potential rail routes; but during the next few years, Brooks became known for his interest in determining the best railroad routes. While most professionals in Alaska concentrated on their specialities, Brooks worked not only as a geologist but as a topographer, naturalist, and ethnographer as well.

Returning to the expedition's camp a few days later, Brooks spent the time inquiring about the local Indian customs and the fauna of the region. Finally, on May 27th, the party started out on the treacherous waters of Marsh Lake, navigating around the still present large ice floes, in canoes they had carried with them from Skagway. Two days later, May 29th, they reached the northern (lower) end of Marsh Lake and began a swift six-day journey to Fort Selkirk. From

Figure 2. Lake Bennett, from Bennett City, British Columbia, Canada. April 1898 [6:00 p.m.] (Courtesy U. S. Geological Survey.)

Marsh Lake and began a swift six-day journey to Fort Selkirk. From this point the expedition entered uncharted territory. Little of the information on the area was trustworthy, having come from local natives who, it turned out, had hardly traveled outside the immediate area. Assured that a journey to the west on the Yukon River would bring disaster, the expedition left Fort Selkirk by canoe and arrived at the confluence of the White and Yukon Rivers on June 5 (Brooks 1900a:433).

With only three months provisions remaining, the party began their intended reconnaissance. Under the harshest conditions imaginable, Peters attempted to survey the region by relying on sightings made at each stop. Brooks had to attempt the near impossible task of unraveling the stratigraphy with scattered samplings and only occasional observations (Brooks 1900a:424-494; Smith 1925:2). The two worked effectively with one another, assisting each other whenever necessary (Brooks 1900a:431-435).

Leaving the White River at its confluence with the Snag, the party ascended the Snag at a slow pace of about three miles a day. Portage through five miles of thick brush, through which they had to cut their way for most of the distance, brought them to the waters of Mirror Creek, from which point they made a swift journey to the Tanana River, which they reached on August 1. With only enough provisions to last about 30 days, they set out on the Tanana River on August 3 (Brooks 1900a:435). Averaging nearly 40 miles per day in the swift current of this large river, on September 1 they reached present-day Tanana (Weare), where they boarded a river steamer for a trip down the Yukon River and a return to Seattle via St. Michael (Brooks 1900a:435).

Although the journey had been brief, Brooks was able to make a general appraisal of the geology, incorporating his observations with what was already in the literature and information he had obtained from the natives and occasional prospectors he had met along the way. Within six months after his return he published a comprehensive report on the history, geography, and geology of the White and Tanana Rivers. He recognized that the northwesterly trend of the Canadian Rockies changed to the east-west trend of the Alaskan, Pacific, and Aleutian Ranges, and in the light of this, he was able to establish the general drainage pattern of Alaska. Although he modestly appealed to his readers to curtail their criticism because of the expedition's fragmentary observations (Brooks 1900a:431-494), later studies confirmed both his observations and conclusions.

Figure 3. Looking up the Lewes River from McCauley's Landing. View includes Survey party with loaded raft and boats on the river. Yukon Territory, Canada. May 11, 1898. (Courtesy U. S. Geological Survey.)

The following spring (1899), Brooks returned to Alaska to accompany Peters on a cross-country expedition from Pyramid Harbor to Eagle City to investigate mineral deposits and topography of the region for the benefit of prospectors. The six-man expedition departed Pyramid Harbor, which lies at the northwest extremity of Lynn Canal, on the 26th of May, with provisions enough to last just over three months, including food supplements for the 15 pack horses (Brooks 1900b). Since the expedition traveled on foot, initially it was able to manage only 10 miles per day, or less, which contrasted strikingly with the previous season's swift pace by canoe. Only three days out of Pyramid Harbor, the party was forced to halt at Pleasant Camp, a Canadian customhouse post, because of an unusually heavy snow pack. For the next 24 days, under the watchful eyes of the Northwest Mounted Police, they anxiously awaited the first thaw of spring. During this long wait, Brooks attempted to survey the surficial geology of the immediate area, but even this proved an exercise in futility since the outcrops were buried beneath the snow (Brooks 1900b: 338).

By the time the first thaw occurred, the party was eager for the journey before them. Leaving Pleasant Camp on June 21, they traveled the famous Dalton Trail of 1898, which followed hard by the Klehini River. They covered 15 miles the first day out, but then decided to make camp through the following day in order to rest the pack horses. During this one-day halt Brooks visited Rainey Hollow, a newly discovered copper claim three miles southeast of camp. Although it later proved to be a significant copper deposit, Brooks, at the time of his cursory visit, noted that the veins being exploited were of secondary importance, the main mineralization occurring within the contact between calcareous sediments and an igneous intrusive (Brooks 1900b:379). Although he made only a casual survey of the Rainey Hollow deposits, Brooks was able to write a report that proved very useful to prospective mining interests. Within a few years of its publication in 1900, the Rainey Hollow deposits were being successfully exploited, not only for copper, but also gold, zinc, and lead.

Figure 4. View of peaks near Chilkat Lake, Skagway District, southeastern Alaska. October 3, 1901. (Courtesy U. S. Geological Survey.)

The next day, June 23, the party returned to the trail, working their way to the divide separating the Lynn Canal and the Tatshenshini River drainages. They halted at Dalton House, the last supply post along their route, to replenish supplies and rest the pack horses. When they departed Dalton House, the expedition left the Dalton Trail, which turned northward, and continued to the west to the Kaskawulsh River, which they reached on July 15. The next two days were spent building a large raft to ferry across the turbulent river, an event that had to be repeated twice more during the next 14 days, once to cross the Kluane River, and again to cross the Donjek. In fording the Donjek, Peters' horse lost its footing and rider and animal were swept away in the swift current. Both regained the bank, but at some distance downstream (Brooks 1900b:338-339). This was the only serious mishap during the entire journey.

Crossing the Klutlan Glacier, the expedition made a swift reconnaissance of the Kletsan Creek copper deposit, a placer deposit that proved to be slight in comparison with Rainey Hollow. However, continued ease of travel dictated that the expedition keep moving. On August 14 they crossed the source glacier of the Tanana River and, after a series of portages and raftings, they finally turned north toward the Fortymile River area (Brooks 1900b:338-339). Brooks conducted a general survey of the Fortymile placer fields, which convinced him that most of the "easy" gold had been played out, but the region still held financial incentive to those with patience and financial reserves to undertake a detailed prospecting program (Brooks 1900b:376-377). On September 16, the expedition ended at Eagle City. The reconnaissance provided accurate maps of the geology and topography of the region.

On the return trip by steamboat to Seattle via St. Michael, Brooks and Peters encountered many prospectors bound for Nome. The two men, during the past several months of isolation, had not heard of the gold strike in the southern region of the Seward Peninsula. Brooks, with two other USGS employees he met in St. Michael, headed for Nome to investigate the strike. While surveying the area, he contracted typhoid fever and returned to the States. Upon his recovery, he quickly put together two papers, one on the expedition and one on Nome (Smith 1925:23-24).

The Nome paper, although brief, provided advice on securing the abundant riches of the

Figure 5. Alfred Hulse Brooks standing beside an exposure of massive rocks. Alaska, July 8, 1902. (Courtesy U. S. Geological Survey.)

placer deposits. Brooks suggested the location of ancient shoreline placer deposits, which proved even richer than he anticipated. His "Dutch-Uncle" advice on being prepared before entering the region fell on deaf ears, but because of his bout with typhoid fever, and his growing reputation as an expert on the Territory, the general population took up his ideas on sanitation, prospecting, and mineral development.

The following year, 1900, Brooks returned to the Nome region for a more detailed study (Brooks 1901). His report became the Bible for Nome miners, and his reputation grew. Turning his attention southward in 1901, he undertook a reconnaissance of the Ketchikan district, providing a framework for understanding the complex geology of the region. Carefully evaluating the igneous and sedimentary processes involved in the formation of the mineralized portions of the region, Brooks once again provided the layman geologist and prospector with the knowledge to exploit the abundant resources of the district (Brooks 1902).

Brooks had supplied the public with much information in his survey publications from 1898 to 1901. But his most rewarding work came in 1902, when he undertook to survey the Mount McKinley region. In a little over three months, his party surveyed 10,000 square miles of wilderness. Out of the expedition came a paper that covered literally every aspect of the region–geology, flora, fauna, history, and geography (Brooks 1911). The paper received wide circulation among the general public and led to his advancement in 1902 to the position of supervisor of all geologic work in Alaska, and in 1903, to his appointment as geologist in charge of the Division of Alaskan Mineral Resources. In spite of its restricted name, this was in effect a miniature geological survey for the Territory (Rabbitt 1980).

During the next 21 years (except 1918 and 1919, when Brooks served as the Chief Geologist of the American Expeditionary Forces in Europe), the Alaska Branch of the USGS grew in excellence under Brooks' leadership and administration. Although he never again had the time to take long journeys as in his first years in Alaska, he continued to coordinate the exploration of the Territory with the talent and experience of a man of superior vision (Smith 1925:28).

His great knowledge and understanding of the geology of Alaska led to his appointment to the Alaska Railroad Commission in 1906 and to the adoption of his pet views on the development of Alaska. Where the Commission failed to followed his recommendations, time has proved the wisdom of his ideas.

History will not forget Alfred Brooks. His achievements as geologist, explorer, administrator, and scientist will continue to influence the development of Alaska. Other men may attempt to understand the reality of our northernmost state, but few will fathom her as did Alfred Hulse Brooks.

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100 YEARS OF GEOLOGY BY THE UNITED STATES GEOLOGICAL SURVEY IN THE PACIFIC NORTHWEST

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The United States Geological Survey was created by an Act of Congress on March 3, 1879, from four previously existing and sometimes competing "Territorial Surveys." The Act was brief. It abolished the existing surveys and provided for a Director who "shall have the direction of the Geological Survey, and the classification of the public lands, and examination of the geologic structure, mineral resources and products of the national domain." This succinctly outlined the Survey's mission at its founding. Its objectives were intensely practical; to explore the then largely undeveloped West and to appraise the natural resources and products of the national domain. There have been changes over the years. "National domain," which was originally interpreted as the public lands of the West, has been broadened to include the entire country and its possessions. Additional responsibilities have been added, and some of the Survey's functions have been assigned to other agencies. Nevertheless, the Survey's mission today remains essentially the same as it was at the time of its founding. The Survey's approach from its beginning has been broad and has included all branches of geology and related sciences. It could not have fulfilled its practical responsibilities without engaging in research of a highly theoretical nature.

It seems appropriate at this meeting in Moscow at which we are commemorating the Survey's 100th birthday to review briefly how in one particular area, the Pacific Northwest, the Survey has carried out the responsibilities given to it so long ago. This discussion will be confined to the work of only one part of the Survey, its Geologic Division.

In this paper, the Pacific Northwest is considered as comprising the states of Washington, Oregon, Idaho, and that part of Montana west of the Great Plains, or approximately the 109th Meridian. The United States Geological Survey has long been active in the Pacific Northwest.

The first record we can find of published work in the Pacific Northwest by the Survey is a report by I. C. Russell on "A geological reconnaissance in southern Oregon" that appeared in the Survey's 4th *Annual Report*, 1882-1883.

By the 1890s, Survey work in the Pacific Northwest was in full swing. In Montana, Iddings and Weed completed USGS *Geologic Folio No.* 1 on the Livingston Quadrangle in 1889, and Peale followed this with the Three Forks *Folio* in 1896. W. H. Weed and L. V. Pirsson studied the region north of Yellowstone Park, and by 1893, Weed and Knowlton had published *Bulletin* 105 on the Laramie and Livingston formations. Weed followed this in 1897 by a study with S. F. Emmons and G. W. Tower of the Butte *Special Folio.* The Survey's 18th *Annual Report*, 1896-97, included a paper by Weed and Pirsson on the "Geology and mineral resources of the Judith Mountains." Weed also produced the Little Belt Mountains, Montana, *Folio* in 1899. *Monograph* 32, on the "Geology of Yellowstone Park" by Arnold Hague and a group of distinguished collaborators, was released in 1899. This early work of the Geological Survey had much to do with the revitalization of interest in Yellowstone, our first National Park.

The Annual Reports and other Survey publications prior to 1900 record extensive activity by the Survey in other parts of the Pacific Northwest, as well as its widely varied interests in all phases of geology. In 1887, Bailey Willis' report on "Changes in river courses in Washington due to glaciation" appeared as *Bulletin* 40. I. C. Russell's report on "A geological reconnaissance in Central Washington" was published in 1893. The 18th *Annual Report* (1896-97) contains another report by Bailey Willis on "Some coalfields of Puget Sound" as well as a description of the "Glaciers of Mount Rainier" by I. C. Russell. The latter paper is accompanied by a discussion of the rocks of Mount Rainier by George Otis Smith, later to become the Survey's fourth Director. I. C. Russell's "A preliminary paper on the geology of the Cascade Mountains in northern Washington" was published in the 20th *Annual Report* (1898-99). Bailey Willis and G. O. Smith produced the Tacoma *Folio* in 1899.

Early Survey reports on Idaho geology include "The Lafayette Formation" by W J McGee in the 12th *Annual Report* (1890-91); "A geological reconnaissance across Idaho" by G. H. Eldridge in the 16th *Annual Report* (1894-95); and "The mining districts of the Idaho Basin and the Boise Ridge" by Waldemar Lindgren in the 18th *Annual Report*. Other notable reports by Lindgren are the Boise *Folio*, 1898, as well as "The gold and silver veins of Silver City, DeLamar, and other mining districts in Idaho" in the 20th *Annual Report*.

Work in Oregon also was going on during this period. Quicksilver deposits in Oregon were discussed in G. F. Becker's *Monograph* 13, "Geology of the quicksilver deposits of the Pacific Slope," published in 1888. *Bulletin* 60, "Report of work done in the division of chemistry and physics during 1887-1888," contains an article by F. W. Clarke on nickel ores in Oregon, but it is interesting to note that it was not until the 1950s that laterite nickel deposits of Oregon were successfully mined. J. S. Diller began his long and distinguished career in Oregon with a report on "The Coos Bay coal fields, Oregon" in the 19th *Annual Report*. He followed this almost immediately with publication of the Roseburg *Folio* in 1898. One can only admire the amount and variety of work accomplished by these early geologists under extreme logistical difficulties.

The list of Survey geologists who worked in the Pacific Northwest after the turn of the century reads like a roll call of great names of American geology. The numerous publications that resulted are much too long to recite here. They include *Professional Papers* by J. S. Diller and H. B. Patton on "Crater Lake, Oregon"; by George Otis Smith on the "Geology and physiography of Central Washington"; Bailey Willis on the "Physiography and deformation of the Wenatchee-Chelan district, Cascade Range"; by F. L. Ransome and F. C. Calkins on "The geology and ore deposits of the Coeur d'Alene district"; by W. H. Weed on the Butte district; by W. H. Emmons and F. C. Calkins on the Philipsburg district; and a notable paper by Joseph Barrell on the "Geology of the Marysville mining district, Montana—a study of igneous intrusion and contact metamorphism." These papers set high standards and are regarded as classics in geologic literature.

Other work of special interest includes Lindgren's reconnaissance across the Bitterroot and Clearwater mountains, published in *Bulletin* 213-B (1903) and in *Professional Paper* 27 (1904). Lindgren, with N. F. Drake, also produced the Nampa and Silver City, Idaho, *Folios* at that time.

Also published during that period were the Ellensburg, the Mount Stuart, and the Snoqualmie *Folios*, all in Washington. *Bulletin* 199, "Geology and water resources of the Snake River Plains of Idaho," by I. C. Russell (1902) is a good example of a somewhat different type of report. Umpleby produced a whole series of reports on mining districts in south central Idaho, the most notable probably being *Professional Paper* 97, "Geology and ore deposits of the Mackay region, Idaho" (1917). *Bulletin* 527, "Ore deposits of the Helena mining region, Montana," by Adolph Knopf (1913) is another notable contribution. The Survey began its investigations of the Idaho phosphate deposits around 1910. These investigations continued for many years and resulted in numerous publications. The work was summed up by G. R. Mansfield in 1927 in the monumental *Professional Paper* 152, "Geography, geology, and mineral resources of part of southeastern Idaho." J. S. Diller, working in Oregon, published numerous reports, among them the Coos Bay and Port Orford *Folios*.

World War I brought a curtailment of the Survey's normal programs. It also brought an awareness that many of the so-called strategic and critical minerals were in short domestic supply. Domestic sources of mineral commodities were reassessed and information was gathered on the potential resources of other countries. The backlog of scientific data in the Survey gathered over many years of field investigations was invaluable in the search for new deposits. This was the start of the Survey's Strategic Minerals Program, which later was very active in World War II.

The Geological Survey's programs were resumed in the 1920s and continued at a slower rate during the depression of the 1930s. Gilluly and Wells were working in Oregon, and Mansfield, Schroeder, and others in Idaho. C. P. Ross, as assistant to Schroeder, was beginning his long and prolific career in Idaho. J. T. Pardee, Reeves, Alden, and others were active in Montana and Pardee and Kirk Bryan in Washington.

As it became more and more evident that the United States was likely to become involved in World War II, the Strategic Minerals Program was revived, largely through the efforts of D. Foster Hewitt. The Pacific Northwest became a beehive of activity with Survey geologists searching for strategic and critical minerals. In this program, the Survey participated with its sister organization, the U. S. Bureau of Mines, in the exploration and development of new mineral reserves by drilling and other means of physical exploration. To supervise this work, the Survey established a field office in Spokane. One of the outstanding results of the Strategic Minerals Program was the unexpected discovery of rich tungsten ore in a diamond drill core at the Yellow Pine Antimony-Gold Mine at Stibnite, Idaho. The discovery was of sufficient importance to ease appreciably the war-time shortage of this important metal. Geologic mapping begun in 1936 led to the publication in 1943 of *Professional Paper* 202, "Geology and ore deposits of the Metaline Quadrangle, Washington," by C. F. Park and R. S. Cannon. An extensive war-time drilling program by the Bureau of Mines and the Geological Survey helped establish the existence of a major ore body that could be mined by large-scale underground methods. Field investigations by the U. S. Geological Survey helped direct mining company interest to the Blackbird Mine at Cobalt, Idaho. The mine is not operating now but was in production for several years and remains a potentially important source of cobalt, a highly essential metal.

Following World War II, the Survey returned to a peace-time program, and a number of research projects were begun in the Pacific Northwest. A major effort was the Western Phosphate Project under the direction of V. E. McKelvey, later to become the Survey's 9th Director. It was essentially an extension of the earlier investigation of the western phosphate deposits. The announced purpose was to make an overall appraisal of our western phosphate resources. The project was largely financed by the Atomic Energy Commission because of the presence of trace amounts of uranium in the Phosphoria Formation–at the time a closely guarded secret. The project resulted in a large number of preliminary publications and culminated with the publication in 1959 of *Professional Paper* 313-A, "The Phosphoria, Park City, and Shedhorn formations in the western phosphate field," by V. E. McKelvey and others. This program was closely followed by industry and a significant expansion of the western phosphate industry ensued.

Another major effort was a restudy of the Coeur d'Alene district by S. W. Hobbs and his associates. In the many years since the publication of the Coeur d'Alene *Professional Paper* by Ransome and Calkins, much new information had become available. The restudy resulted in the publication of several *Bulletins* and two *Professional Papers*. It has been followed up by an extensive geochemical sampling of the district under the direction of Garland Gott.

A third major effort, a study of the Boulder Batholith in Montana, under the guidance of the late M. R. Klepper, was begun soon after the war. Publications on this work have thrown light on the mechanics of igneous intrusions and their relation to metalliferous ore deposits.

A somewhat different type of project was an investigation of landslides in Lake Roosevelt behind Grand Coulee Dam. The results are embodied in *Professional Paper* 367 by Fred O. Jones and associates (1961).

Other Survey work in the period immediately following World War II consisted of the compilation of geologic maps of the states of Idaho and Montana by C. P. Ross. Somewhat later (1963) Ross published another monumental work, *Professional Paper* 346, "The Belt Series in Montana." A thorough investigation of the Belt Basin, including stratabound copper deposits, has been underway for several years under the direction of Jack Harrison. Survey geologists also contributed unpublished data to a geologic map of Washington, prepared by the State Bureau of Mines and Geology.

The above is only a sampling and many other projects could be cited including a geologic map of Oregon, prepared in cooperation with the State under the supervision of George Walker, and an extensive reconnaissance for uranium deposits in the Pacific Northwest.

In 1951, the Survey's program took a different turn. During the long depression of the 1930s, exploration for new deposits by the mining companies came to a virtual standstill. During World War II, emphasis was on production and little exploration was done except that which gave promise of yielding immediate results. The onset of the Korean War found many mineral reserves in the United States seriously depleted. The Defense Minerals Exploration Administration was set up by the government to help remedy this situation. Under the DMEA program, the government participated with mining companies, particularly the smaller ones, in financing mineral exploration, receiving back its share of the exploration costs through royalities if the explorations were successful. Supervision in the field was delegated to the Geological Survey and the Bureau of Mines. Much of the effort of the Survey's Spokane office went into administration of this program. Among the successful projects in the Pacific Northwest in which the DMEA participated were the Brown's Lake Tungsten Mine, Montana, the Ima Tungsten Mine in Idaho, the Crescent Project in the Coeur d'Alene district, and the Northwest Uranium Mine (now the Sherwood Mine) in the Spokane Indian Reservation, Washington.

Passage of the Wilderness Act in 1964 placed a different type of pressure on the Geological Survey. The Wilderness Act charged the Survey and the Bureau of Mines with determining the mineral value in wilderness areas and in areas of the public domain that are being considered for inclusion into the Wilderness Preservation System. Of the initial 14.8 million acres of wilderness and primitive areas, about 6.6 million acres are in the Pacific Northwest. This vast acreage has been increased substantially since then through the addition of other study areas and more recently by Roadless Area Review and Evaluation (RARE II) areas, mineral surveys of which have been requested by the Forest Service. We have maintained a tight schedule of these Wilderness Act mineral studies and have published our findings in Geological Survey bulletins, or in some cases, released the information in *Open-File* reports. Our goal is to complete the mineral surveys by 1984. Although our studies have been of necessity surficial, they have produced a wealth of geological, geophysical, and geochemical information that increases our knowledge on the mineral-resource potential of our country.

This, then is an account of how the U. S. Geological Survey has in one particular area fulfilled the responsibilities given to it 100 years ago. It has not been an easy task because of the high standards set by our predecessors, and because we face ever changing problems that did not concern the earlier workers.

Although we use different and more sophisticated tools, our basic objectives remain essentially what they were 100 years ago: to provide basic, accurate, and unbiased information to government, industry, and individuals on the land, its geology, and natural resources. Sound information is essential if we are to meet our resource needs and use our land wisely.

METAMORPHIC ROCKS: 100 YEARS IN WESTERN NORTH AMERICA (ESPECIALLY THE NORTHWEST)

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This paper on metamorphic rocks is a part of the AAAS Symposium honoring the U.S. Geological Survey on its 100th Anniversary. We shall attempt to summarize 100 years of progress in metamorphic rock studies and look briefly to the future with regard to some few of the problems.

Limits are necessary. Within the available space, it is possible neither to cover everything implicit in the title nor to cover all the papers on each topic. Therefore, we shall confine our attention principally to northern California, Nevada, Utah, Colorado, Montana, Idaho, Oregon, Washington, British Columbia, and Alaska, with emphasis on the northwestern region. We shall look at each quarter century as a convenient index of progress, selecting representative papers from among the large numbers available, particularly for the later years.

THE FIRST QUARTER CENTURY (1879-1903)

This quarter century began with the completion of the Wheeler reconnaissance surveys west of the 100th Meridian (Wheeler 1872-1880) and the King reconnaissance along the 40th Parallel (King 1878). The general outlines of the metamorphic rocks in the conterminous U.S. were sketched in. The annual reports of the U.S. Geological Survey continued in part to fill in knowledge on the areal distribution of metamorphic rocks.

Becker (1886) initiated studies on the glaucophane schist terrane of California, suggesting that the rocks were formed through the direct (metasomatic) action of hydrothermal solutions on sandstones. Good descriptions of major metamorphic rock types in California are found in publications by Turner, 1894; Diller, 1894 and 1895; Lindgren, 1897 and 1900; and Lindgren and Turner, 1894 and 1895.

Dawson (1877-78, cited in Cairnes 1939) examined the Shuswap rocks in British Columbia and supposed that they were of Archean age.

Work got underway in Alaska (Spurr 1898) with study and naming of the Birch Creek Schist in central Alaska. Becker (1898) studied the gold fields of southern Alaska and briefly examined some metamorphic rocks, both eruptive schists and others of sedimentary origin.

Mineral deposits, then as now, triggered many of the studies. Lindgren (1901) studied the gold deposits in and about the area of the Burnt River schist in Oregon, noting E-W trends. Weed (1901) studied contact metamorphic rocks and associated ore deposits in the Helena region of Montana, taking an early position on the origin of schistosity: "In none of the altered rocks at Elkhorn is a true slaty cleavage developed by thermal metamorphism." Bedding schistosity had been discussed among European workers since the early 1880s.

Several major problems were sketched out during this quarter century (glaucophane schists, Birch Creek Schist, Shuswap terrane), which were still receiving attention and were partly still far from final solutions in 1979.

THE SECOND QUARTER CENTURY (1904-1928)

Reconnaissance studies continued in the second quarter century. Lindgren (1904) initiated work on the Idaho batholith and commented particularly on the Bitterroot front, a shallow-dipping zone of sheeted gneisses attributed by him to the operation of a shallow-dipping normal fault at the eastern margin of the batholith. Analysis of contact metamorphic aureoles and related ore deposits was done in several states (Barrel 1907; Emmons and Calkins 1913; Knopf 1918; Lindgren 1924). Pardee (1910) examined the metamorphic rocks north of the Idaho batholith, correlated them to the Algonkian formations of the Coeur d'Alene mining district, and described a partly thermal, partly dynamic metamorphism.

McConnel and Brock (G.S.C. Map 792, 1904, cited in Cairnes 1939), published the West Kootenay Sheet in continuing reconnaissance in British Columbia; it covers some 6,000 square miles and includes the Shuswap terrane. In his 49th Parallel Survey, Daly (1912), like Dawson, regarded the Shuswap as Archean. In that same work, Daly distinguished in the northwest Rocky Mountains, east of the Columbia River, an eastern geosynclinal belt characterized by moderate intensity of development, and a western geosynclinal belt characterized by close folding, strong regional metamorphism, and major batholithic intrusion. This may have been the first formal recognition of the Cordilleran geosyncline. In further study on the Shuswap terrane, Daly (1915) concentrated on the recumbent foliation developed throughout that terrane, held that field observations prove conclusively that dynamic metamorphism played no part, and that the profound influence of static metamorphism operating vertically caused mineral grains to form in a horizontal plane, in accord with Riecke's principle. Schofield (1913, cited in Cairnes 1939) found that Belt-equivalent (Algonkian) rocks pass under the Shuswap. Thus, the Shuswap was held to be of Algonkian or younger age. Woodford (1924) studied Franciscan rock mineralogy in California, and showed the extension of a belt of Franciscan rocks along the coast of California.

Moffit (1907) analyzed schists, limestones, and greenstones in a broad synclinal trough in the Nome area and noted the rich development of quartz veins or stringers in the schists, parallel to the cleavage, partly in lenses, and partly in crossing joints. Brooks (1911) carried out a particularly arduous packhorse reconnaissance in the Mt. McKinley region in rocks earlier named the Birch Creek Schist by Spur (1898). The party carried bottled lime juice to combat scurvy, and Brooks commented that it had the additional merit of making the swamp water more palatable.

Ball et al. (1908) studied economic geology in the Georgetown quadrangle, Colorado, proposing the name "Idaho Springs" for the extensive metamorphic rocks in which the ore deposits occurred. Bastin and Hill (1917) accepted Ball's term and extended the studies to several adjacent counties. These works show further the economic geologic motivation that underlay much of the early geologic mapping.

Thus, the second quarter century saw further reconnaissance geology tied to judicious selection of economic geology problems, filling in holes in the maps. The problem of the Bitterroot frontal gneisses was raised, bedding foliation was proposed for the Shuswap, and the concept of the Cordilleran geosyncline was articulated.

THE THIRD QUARTER CENTURY (1929-1953)

The third quarter century saw a marked increase in problem-oriented work in the western states. In California, Knopf (1929) analyzed the gold deposits of the Mother Lode System in steeply dipping slates, greenstones, and serpentines, and noted refraction of veins passing through rocks of different competencies. Durrell (1940) studied metamorphism in the southern Sierra Nevada. Later, a study of copper and zinc in the foothills belt of the Sierra Nevada by Bramel et al. (1948) featured detailed descriptions of structures in the low-grade metasedimentary and metavolcanic rocks. Work increased in the Franciscan rocks. Pabst (1942) analyzed their serpentinites; Rice (1953) examined the Franciscan north of Eureka, finding older rocks thrust over Franciscan rocks, with a large mass of intervening peridotite. Switzer (1945) studied eclogite in the glaucophane schists of the Franciscan and attributed its formation to conditions of moderate P, T, in hydrothermal contact metamorphism.

Contact effects of the Sierra Nevada batholith and associated ore deposits were analyzed by several workers, e.g. a scheedlite deposit in hornfels and calc-silicate rocks at Round Valley (Chapman 1937), and greenstones at the Mokelumne River (Fitch 1932). According to Fitch, rocks of the batholith preserved in roof pendants comprise metasedimentary rocks of Calaveras(?) age or older, which were folded and metamorphosed by the time of the invasion of the granitic units. This work showed that the batholith emplacement in itself was not responsible for the metamorphism of the country rocks. Further, in a somewhat related study, Mayo (1937) suggested that the N-S trending Sierra Nevada batholith, which cuts across the grain of the metasedimentary rocks, was controlled in its emplacement primarily by N-S forces.

Granitization, an idea that had been under consideration in Europe for nearly 100 years, was applied by Anderson (1937) to explain the origin of the Pellisier granite overlying the Boundary Peak granite in the Inyo Range area.

In an early study on metamorphic effects related to faults, Alf (1948) described a 2,000-ft. mylonite zone parallel to the Cucamonga fault in the southeastern San Gabriel Mountains, developed at the expense of quartz diorite gneiss when the gneiss was only partly crystallized.

Scattered work in Nevada and Utah concerned itself with contact metamorphism and related ore deposits (Vitaliano 1944; Gilluly 1932; Stringham and Erickson 1948). Eardley (1940) described metasedimentary and meta-igneous rocks in north-central Utah.

In Colorado, Singewald (1942) analyzed contact metamorphic and metasomatic features in Pennsylvanian-Permian rocks. Other work involved Precambrian rocks, such as contact metamorphism of a roof pendant of the Idaho Springs Formation in the Precambrian Silver Plume granite (Dings 1941), and their structures (MacQuown 1945) in NW-trending schist and greenstone correlated to the Idaho Springs Formation. Boos and Boos (1948) wrote further on structure; in the Mt. Olympus quadrangle, they found the area to be underlain by the Precambrian Big Thompson metasedimentary series and the Longs Peak granite (Silver Plume type). Rock structures were strongly influenced by the emplacement in the metamorphic rocks of a multitude of large and small intricately related bodies of granite and pegmatite from the batholith. Lovering and Goddard (1950) summarized Front Range geology in Colorado. The crystalline core of the Front Range is essentially Precambrian granite schists and gneiss. Oldest are schists and gneisses of the Idaho Springs Formation, estimated to be 20,000 ft. thick. Foliation nearly parallels the original bedding, and regional trends are mostly to the northwest. Several ages of granitic intrusion occurred, from older synkinematic to younger postkinematic bodies.

Contact metamorphism and metasomatism were the subject of several projects in Montana: Little Belt Mountains (Taylor 1935), Highwood Mountains (Larsen and Buie 1941), and Philipsburg (Holser 1950). Mafic sills of Purcell type (Algonkian) in the Libby quadrangle were attributed to a hydrothermal metamorphism due to Mesozoic intrusion (Gibson and Jenks 1938).

Archean metamorphic rocks were studied in several areas. In the Beartooths, James (1946) ascribed an igneous origin to extensive high-grade gneisses. Tansley et al. (1933) made a detailed reconnaissance of the Tobacco Root Mountains of southwestern Montana, contributing to knowledge of the metamorphism and structures of the Prebeltian Pony and Cherry Creek units.

The problem of the origin of the gneisses in the Bitterroot frontal zone was considered further. Langton (1935) suggested that it is due to underthrusting produced by laterally moving, mushrooming, batholithic material. Ross (1952), on the other hand, regarded the frontal zone gneisses as due to feldspathization of Beltian rocks by the Idaho batholith, another granitization proposal.

Analysis of ore deposits provided the impetus for some studies in Idaho, notably in the Pend Oreille district (Gillson 1929) and in the Casto quadrangle (Ross 1934). Ross described low-grade meta-argillites and meta-quartzites believed by him to be broadly equivalent to Beltian rocks of northern Idaho. Johnson (1947), in the Orofino region of the Idaho panhandle, in rocks west of the Idaho batholith, proposed that mafic (tonalitic) gneisses originated from siliceous sediments, changed by emanations from the Idaho batholith, which added biotite, andesine, diopside, hornblende, scapolite, epidote, zoisite, and clinozoisite to the siliceous sediments.

Anderson (1934) suggested that the Cassia batholith of southern Idaho had feldspathized its roof and wall rocks to such an extent that the batholith was three times larger than it would have been without the operation of replacement processes. This constituted yet another example of proposed granitization.

Granitization concepts received major impetus in Oregon, where Goodspeed (1937a,b, 1939) proposed an origin for the Cornucopia quartzofeldspathic pluton involving partial replacement of pre-existing country rock in metasomatic processes. Buddington and Callaghan (1936) analyzed contact metamorphic effects around dioritic intrusive rocks in the Cascades. In the Baker quadrangle of eastern Oregon, Guilluly (1937) studied highly deformed metasedimentary and metavolcanic rocks (Burnt River Schist) containing a distinctive E-W pencil-linear schistosity with prominent A-C joints perpendicular to the lineation. Thayer (1948) examined Upper Triassic thrusting in the Aldrich Mountains of northeastern Oregon and found considerable tectonic interlaminations of Paleozoic(?) rocks, the whole cut by lenses of highly sheared serpentinite. The serpentinites were regarded as tectonic units, involved in the thrusting, rather than igneous intrusions.

Work in the State of Washington raised further interesting problems. The Swakane gneiss in the Entiat Mountains (Waters 1932) was shown to be a complex with late-stage cataclasis associated with more or less horizontal thrusting throughout. The gneiss, which contains up to 40% andesine and abundant lit-par-lit pegmatites parallel to the recumbent foliation, is of uncertain origin, as is the foliation within it. In the view of the writers, the similarity of these rocks to those in the Shuswap terrane is striking. Waters and Krauskopf (1941) studied gneisses of the Colville batholith and suggested an origin by protoclasis.

A problem comparable to that in the Swakane gneiss was elucidated by Campbell (1940) at the eastern border of the Colville batholith in northeastern Washington. A shallow-dipping mylonitic border phase of the batholith with pronounced lineation trending due east grades westward into the uncrushed granitic rocks. Again, there are similarities to the Shuswap; indeed, these rocks form a southern prolongation of the Shuswap terrane. There are also fascinating similarities to the rocks of the Bitterroot frontal gneiss zone in Montana.

Misch (1949) proposed that geosynclinal Paleozoic rocks in the Okanogan region of north-central Washington were deformed, variously metamorphosed, and partly granitized in the Jurassic(?).

Work in British Columbia concentrated in the Coast Range area and the Shuswap region. Phemister (1945) showed that basaltic and allied rocks along with tuffs and intermediate and acidic lavas underwent an early regional metamorphism and porphyry dike injection, prior to intrusion of the Coast Range batholith. H. H. Reid, in presenting this paper before the Geological Society of London for Phemister who could not attend, commented humorously that it was unfortunate that Phemister, in presenting the Coast Range batholith as an intrusive body, had suppressed so much evidence that would support an origin by granitization.

The Shuswap problems were examined further. Gilluly (1934) studied mineral orientations in the Shuswap rocks and found them analogous to those common in the great Alpine overthrust sheets. Therefore, they were held to be incompatible with derivation of a bedding schistosity under static conditions, as proposed by Daly (1915). Brock (1934) arrived at comparable and somewhat more detailed conclusions. He found that the structure of the gneiss reveals a common quaquaversal habit due to the updoming of granite stocks into the flat-lying, deeply buried sediments. "The effects of the upward thrust of the magma results in the compression of strata normal to the bedding and a complementary elongation of the strata in their long direction necessary to cause an orientation of the minerals, by the process of rock flowage." This passage might well have been written in 1979. Cairnes (1939) saw the matter in still a different way: "The recumbent foliation is inherited from original bedding. Batholithic invasion has progressed under stable conditions by the process of gradual soaking of superincumbent rocks with tenuous mobile products from the magma reservoir in a granitization process." Yet once again: granitization.

The study of contact metamorphism and related deposits continued in British Columbia, as exemplified by the work of Dolmage and Brown (1945) at Nickel Plate Mountain near Hedley.

During this third quarter century, the U.S. Geological Survey had a vigorous program in Alaska, principally relating to mineral deposits, which also happened to involve metamorphic rocks. Buddington and Chapin (1929) described a metamorphic belt of Paleozoic schist, marble, and injection gneiss in the Glacier Bay region, adjacent to the Coast Range batholith. Metamorphosed ultrabasic rocks and associated mineral deposits in southeastern Alaska were analyzed by Kennedy and Walton (1946). Kennedy (1953) also described contact metasomatic ore deposits associated with a granodiorite stock in a schist-calc-schist-greenstone sequence on Prince of Wales Island.

A Mesozoic greenstone-slate sequence intruded by granitic rocks on Kodiak Island was studied by Capps (1937). Similar rocks in the Kenai Peninsula–Anchorage area were examined by Barnes (1943). Complex structures emerge in a series of NE-striking units with near-vertical beds and cleavage in which fold axes plunge at angles up to 75° in the cleavage. Vertical A-C joints in the rocks are quartz-filled. Right-lateral strike-slip faults lie sub-parallel to the cleavage.

Work also progressed in the Alaska Range. In the Copper River region, Moffit (1938) noted siliceous and micaeous schists derived from sedimentary and siliceous igneous rocks that are probably correlative to the Precambrian to early Paleozoic metamorphic rocks of the Yukon-Tanana region. The rocks are intensely deformed in NW-trending, near recumbent isoclinal folds. Further work by Moffit (1942) in the Gerstle River area on the north side of the Alaska Range disclosed schist and gneiss derived from sedimentary beds of prevailing quartzitic character and from igneous rocks, tentatively correlated to the Birch Creek Schist. Moffit (1943) also studied metamorphic rocks at the eastern end of the Alaska Range in the Nabesna River area. Devonian or older schists and phyllites are much intruded by granite gneiss. Contact metamorphism and related metasomatic mineral deposits were analyzed in the central Kuskokwim region of southwestern Alaska (Wallace et al. 1949).

The third quarter century saw considerable innovative work. The Franciscan rocks were examined more closely. Contact metamorphism and allied metasomatic ore bodies were studied all over the West. Granitization became popular and its concepts were applied to rocks in California, Montana, Idaho, Oregon, Washington, and British Columbia. The shield rocks of the Rocky Mountain states were examined in some detail. The Bitterroot frontal zone gneisses were restudied and new ideas came forth. Recumbent gneisses with E-W lineations were analyzed in Washington, Idaho, and Montana, but their similarity to Shuswap, at least physically if not genetically, seems to have escaped notice–an international boundary line fault. Shuswap problems were studied further and new suggestions for their origin generated. Alaskan metamorphic rocks and related orebodies were subjects for considerable mapping and study.

THE FOURTH QUARTER CENTURY (1954-1979)

This quarter century was destined to see a major increase in the amount of geologic research done in the West, as elsewhere. Within the strategy employed for papers selected for reference in this compilation, the first 75 years yielded 81 references and the last 25 years yielded 220.

The Franciscan terrane of California underwent much vigorous, detailed examination. Bailey et al. (1964) and Ernst (1965) characterized the terrane as part of an eugeosynclinal assemblage metamorphosed at pressures in excess of 5 kb and at temperatures less than 300° C. Detailed studies on mineralogy and petrology of these rocks were done by Lee et al. (1963), Ghent (1965), Essene et al. (1965), Lee et al. (1966), and Bloxam (1966). Holdaway (1965) examined Paleozoic rocks in the Klamath Mountains of northern California metamorphosed earlier under kyanite-sillimanite conditions, and suggested the possibility that the glaucophane schist mineralogy developed in regions of localized tectonic pressures, partly involving fluid pressures.

The Franciscan rocks of the Santa Lucia Range were compared by Hsu (1965) to the *Argille Scagliose* of the Italian Apennines. The many similarities led him to suggest a tectonic history for the Franciscan rocks involving gravity slide masses displaced many kilometers. The conceptualization of blueschists as rocks metamorphosed at high pressure and therefore at great depths was challenged by others also. Blake et al. (1967) described a regional thrust in California and Oregon below which low-grade rocks of the blueschist facies become more strongly developed upward to the sole of the thrust. In a variation of the ideas on tectonic overpressure, they supposed that the blueschists formed in a zone of cataclasis and anomalously high water pressure under the thrust fault, at possibly shallow crustal levels.

Glaucophane schist pebbles in the Franciscan had been interpreted as evidence of erosion intervals in the Franciscan sequence. Fyfe and Zardini (1967) showed that metaconglomerates in the Pacheco Pass area of California have the same mineral assemblage both in the matrix and in the pebbles; moreover, individual metamorphic prisms may cross sharp pebble boundaries. Therefore, the pebbles and the matrix were metamorphosed at the same time (see also Platt et al. 1976).

Suppe (1969) demonstrated two periods of high-pressure–low-temperature metamorphism in the Franciscan of the northern Coast Ranges, one at 150 my, and another at 127-104 my. Coleman and Lanphere (1971) showed that blocks of high-grade blueschists and related amphibolite-facies rocks crystallized about 150 my ago and were subsequently mixed tectonically with younger Franciscan rocks during plate interaction.

Gresens (1970), among others, applied the plate tectonic concept to the blueschists and their associated serpentinites, suggesting further that the metastable formation of blueschists at relatively shallow depths was compatible with observations on amphibolite, detrital serpentine and glaucophane, and alpine ultramafics. Island-arc ophiolites are involved in the blueschist complexes (Snoke 1977).

The eclogites of the Franciscan rocks came in for considerable study; a useful summary of that and related work is given by Coleman et al. (1965). They found eclogites divisible into three major groups, formed under such widely varied conditions as to call into question the utility of the eclogite facies.

Allied alpine ultramafic rocks involved in thrusting and metamorphism were analyzed by Davis (1969). Coleman (1967) described metasomatic effects of serpentine bodies with enrichment of Ca and Mg in the wall rocks combined with loss of wall-rock silica to the serpentine.

A complex metamorphic history was noted by Davis (1965) in the eugeosynclinal rocks of the Klamath Mountains, involving two orogenic phases, the earlier in amphibolite facies with recumbent folds, and the later one a retrograde green-schist facies event. Complexities involving metamorphism of blueschist rocks under different conditions, followed by tectonic juxtaposition in the late Mesozoic, were described by Cowan (1974). Hotz et al. (1977) and Lanphere et al. (1978) dated blueschist of Triassic and Cretaceous ages, suggesting repeated subduction activity along the western margin of the North American Plate.

Contact metamorphic rocks of the Sierra Nevada batholith came in for considerable study (Compton 1960; Loomis 1966; Rerrick 1970). Pre-batholith regional metamorphism along the Sierra belt was also examined (Sherlock and Hamilton 1958; Ehrreich 1964; Clark 1964). Steeply dipping rocks strike to the northwest and contain steeply plunging lineation ascribed to an origin by horizontal movement. In a somewhat alternative view, regional and contact metamorphism and origin of magmas in the northwestern Sierra Nevada were studied by Hietanen (1973a,b, 1976, 1977). The contact zones of the plutons have higher grade mineral assemblages and steep lineation reflecting dynamothermal overprint by rising magmas (Cretaceous) on metasedimentary and metavolcanic rocks, deposited in late Paleozoic and early Mesozoic and deformed and metamorphosed regionally in Jurassic time. Westward stepping of the Benioff zone is indicated by the ages of igneous rocks. An angular unconformity due to the Sonoman Orogeny was suggested by Brook et al. (1974) in the eastern Sierra Nevada: Paleozoic metasedimentary rocks are overlain unconformably by Mesozoic metavolcanic rocks. In the western Sierra Nevada, Springer (1980) described two phases of emplacement of alpine-type ultramafic rocks, the first in near-horizontal thrusting and metamorphism.

Granitization received a blow in California. Emerson (1966) re-examined the Pellisier granite, previously considered a granitization product by Anderson (1937), and showed it to be of igneous origin.

Metamorphic and tectonic work in Nevada took a major step forward with the study by Misch and Hazzard (1962), showing that in the miogeosyncline, the late Precambrian through lower Paleozoic rocks have been metamorphosed in shallow-dipping recumbent folds in a Mesozoic orogeny. Further work in this province was done by Woodward (1963) and Howard and Armstrong (1979). Thorman (1966) found mid-Tertiary K-Ar ages for some of the metamorphics and proposed a mechanism of argon loss by post-metamorphic heating in the mid-Tertiary. Howard et al. (1979) and Lee et al. (1970) showed by K-Ar dating of mylonite and other rocks that flat thrusting in the province occurred about 21 my ago, variously resetting older K-Ar ages. Nelson (1969) and Snoke (1975) suggested a tectonic scheme involving paracrystalline thrusts and folds at depth which ended with Tertiary decollement across the crystalline mass created earlier, following a time of rapid uplift prior to the mid-Tertiary. Best et al. (1974) described high Sr^{87}/Sr^{86} ratios in granite intrusions in Nevada suggestive of remobilized sialic basement diapirically emplaced in the shallower crustal levels. Taylor and O'Neil (1977) described garnet-pyroxene skarns in the Osgood Mountains, formed in a multistage event 90 my ago in a declining temperature situation from 550° C to below 480° C.

In Utah, Everett (1966) studied contact metamorphism of the Carmel Formation in the Iron Springs district, and showed that the distribution of the entire range of contact facies there is more a function of variable water content than of distance from the intrusion. Damon et al. (1966), using Pb-alpha methods, dated the Farmington Canyon Complex at 2,430 my old. Bryant (1979) mapped lineated sillimanite-bearing gneiss in the Farmington Canyon Complex.

A major contribution to understanding the low-angle tectonics and metamorphism of the Nevada-Utah region was made by Compton et al. (1977), in northwestern Utah. Precambrian, Paleozoic, and Triassic sedimentary rocks in the area of the Grouse Creek and Raft River Mountains were folded, metamorphosed, and transported westward and northwestward by two events dated at 38 and 25 my ago. Deformation is attributed to gravity acting on a broadly heated dome. Following metamorphism, transport up to 30 km to the east occurred by low-angle thrusting.

Studies in Colorado flourished in the fourth quarter century, concentrating on the Precambrian gneisses and schists of the Central Rocky Mountains. Many workers described similar basic elements of metamorphic geology throughout western Colorado; e.g. Larsen and Cross (1956), Dings and Robinson (1957), Tweto (1966), Wobus (1968), Gable (1968), and Braddock (1970).

The oldest rocks are a complex of ancient, highly metamorphosed schists and gneisses partly of undetermined origin. These rocks are in places overlain unconformably by younger rocks such as greenstones, conglomerates, and schists, metamorphosed with the growth of andalusite and other metamorphic minerals. The older rocks are injected by granite gneisses of Boulder Creek batholith type. Wahlstrom and Kim (1959) found an unconformity of regional extent in the Front Range to pre-date metamorphism. Massive igneous intrusions are largely post-kinematic in Precambrian time. Some workers (e.g. Wells et al. 1961) find evidence for three periods of deformation including young cataclasis in the Precambrian, whereas others find evidence elsewhere for only two, including cataclasis (e.g. Moench et al. 1962). Cordierite and andalusite in certain of the metamorphic rocks may be due to the effects of post-kinematic granites of the Pikes Peak type or late-kinematic granites of the Silver Plume type (Salotti 1962; Gable et al. 1970). Braddock (1969) proposed that the foliation in the gneisses, which parallels lithologic contacts, is a bedding foliation formed parallel to original bedding. The senior author of this paper has a specimen of Front Range gneiss that displays a minor isoclinal fold with distinct axial-plane foliation, which casts considerable doubt on the validity of bedding foliation in the Colorado gneisses. Sims and Gable (1967) prepared a detailed structural analysis in the Central City region of Colorado showing primarily NE-trending folds with mineral lineations and small fold axes both parallel to and perpendicular to major fold axes. Van Alstine (1971) showed that certain amphibolites are of igneous origin.

Lowman (1965) tested the theory of anatectic generation of migmatites in the central Front Range and found it not viable. The characters of the Idaho Springs Formation suggest an origin of the migmatites through the lit-par-lit injection of magmas from pegmatite dikes. Hedge (1972), on the other hand, found evidence for solid-state segregation of the leucosomes. Nesse (1977) studied conditions of metamorphism in the Front Range rocks and arrived at a pressure of about 4.5 kb and a temperature of about 680° C. Several possible origins have been suggested for the gneisses in the Colorado region: metavolcanic(?) by Tweto (1966); both metasedimentary and injection character by Dings and Robinson (1957); and metasomatic or granitization by Steven (1957). Boardman (1976) showed that gneisses in the Salida area are derived principally from welded tuffs of dacitic to rhyodacitic composition. A very interesting paper by Helmstaedt and Doig (1975) showed the existence of Franciscan-derived eclogites in kimberlite pipes on the Colorado Plateau. Many implications for subduction and plate-movement mechanics are to be found in this work.

A portion of the Colorado Precambrian is characterized by vertically plunging folds with mineral lineations parallel to the fold axes (Steven 1957; Kirst 1968; Braddock and Cole 1979; Sims et al. 1958). This suggests a somewhat unusual tectonic regime that merits further study. Murray (1973) suggested that the Ilse fault of the Wet Mountains might be related to a subduction zone of Precambrian age.

The older metamorphic rocks of Colorado are dated at about 1,700-1,800 my. Intrusion and metamorphism occurred at about 1,650 my ago, and later metamorphism followed by intrusion occurred at about 1,460-1,330 my ago (Bickford et al. 1969; Peterman et al. 1968; Silver and Barker 1967; Hansen and Peterman 1968; Barker et al. 1969; Barker et al. 1976).

Work in Montana, like that in Colorado, concentrated on the basement metamorphic rocks. The Beartooth Mountains received considerable attention. Eckelmann and Poldervaart (1957) analyzed gneisses in the eastern part and came to a hypothesis of granitization. Others of Poldervaart's students, as well as some other workers, came to comparable conclusions and other details of the geology involving structural history and mafic rock intrusion were worked out (Butler 1965; Bentley 1968; Butler 1970; Skinner and Rowan 1969).

Butler (1970) reviewed hypotheses for the origin of the Beartooth gneisses and preferred a metasomatic model, while recognizing that a combination of synkinematic magmatism and metasomatism is also possible. Reid et al. (1975) studied gneisses in the western Beartooths, showed that they originated by synkinematic intrusion in several pulses, beginning at least 3.1 by ago, and noted similarites to the eastern Beartooth gneisses suggesting that those rocks too might be synkinematic intrusions. In a major revision of earlier work, bringing views on the eastern and western Beartooth gneisses into reasonable accord, Casella (1979) proposed that the eastern Beartooth gneisses originated as a large synkinematic, composite granitic batholith. Another area of granitized rocks was thereby eliminated.

In age-dating work on the Beartooth rocks, Brookins (1968) found that the metasediments may be as old as 3.3 by, intruded by igneous rocks at about 2.68 by, and metamorphosed again in a late thermal event at about 1.7 by ago (see also Fraser et al. 1969). Hayden and Wehrenberg (1960) found ages of metamorphism at about 1.6-1.7 by ago widespread in southwestern Montana. Montana rocks are generally older than the Colorado rocks, belonging to a southwesternly extension of the Superior province of the central Canadian Shield.

Other studies in southwestern Montana elucidated details of amphibolite and granulite facies metamorphism in polydeformed schists and gneisses of Precambrian age (Foster 1962;

Reid 1963 [in an article rewritten from his Ph.D. thesis with Peter Misch at the University of Washington]; Burger 1969; Garihan 1979; Garihan and Swapp 1977; Desmarais 1978). Gillmeister (1976) described small ultramafic rock bodies metamorphosed under granulite facies polydeformed in the lower crust. Zen et al. (1975) analyzed intrusive and related contact-metamorphic rocks of the Pioneer Mountains, formed about 70 my ago.

The Bitterroot frontal gneiss zone was reinterpreted by the University of Montana group (see, e.g. Hyndman et al. 1975; Chase 1977; Chase and Hyndman 1977). The hypothesis advanced is generally that the Sapphire Mountains block, now lying east of the Idaho batholith, slid off the roof of the batholith during batholithic emplacement in the Late Cretaceous. Shearing and recrystallization associated with the zone of detachment and gliding converted the upper part of the batholith to mylonitic gneiss. In part, this concept returns to Lindgren's idea (1904) of low-angle normal faulting, in that it provides a mechanism for the low-angle shearing he envisioned.

Work in Idaho concentrated on the Panhandle metamorphic rocks, partly of Beltian and Prebeltian age, lying in or near the axial zone of the Cordilleran geosyncline and providing some of the most deeply exposed rocks along the Cordillera. Hietanen (1956, 1961a,b,c, 1962, 1963a,b,c, 1968) made major contributions to the knowledge of these rocks. She proposed that two fold sets developed concurrently in the Nevadan orogeny, and that metamorphic grade in the rocks increased toward the Idaho batholith. Wall rocks near the batholith were altered metasomatically to such an extent as to resemble plutonic quartz diorites and tonalities. Pressure-temperature conditions in the metamorphism were near the aluminum-silicate triple point, and kyanite, andalusite, and sillimanite co-exist in some of the rocks. Anorthosite in the Belt rocks appears to be generated primarily through metamorphic and metasomatic alteration of metasedimentary rocks, rather than by intrusion.

Reid (1959) described evidence for sequential fold events in metamorphic rocks north of the Salmon River. Leonard (1962; Leonard and Stein 1965) analyzed metavolcanic rocks in the Yellowjacket-Hoodoo sequence and showed that folding and metamorphism on northwest trends occurred in the Precambrian (minimum age 680 my).

Mantled gneiss domes examined by Armstrong (1968) are cored by basement gneiss about 2.5 by old, and have participated in Mesozoic or later metamorphism and low-angle tectonics like those of the Nevada miogeosynclinal rocks. The Cassia batholith, which according to Anderson (1934) was largely granitized, was described as a simple Tertiary intrusion.

Reid and Greenwood (1968) and Reid et al. (1973) found evidence in the metamorphic rocks north of the Idaho batholith for Precambrian metamorphism overprinted by Mesozoic metamorphism. Reid et al. (1970) dated a synkinematically intruded augen gneiss of the Salmon River by its zircon (Pb-U) at a minimum age of 1,500 my, and suggested that it represented the age of earliest metamorphism of the Beltian(?) rocks in that area. Cater et al. (1973) delineated older Precambrian rocks in the Salmon River region which may represent a basement upon which the possibly Belt-equivalent Yellowjacket and Hoodoo Formations were deposited. Greenwood and Morrison (1973) described metasedimentary rocks north of the Salmon River, metamorphosed in the amphibolite facies, containing four non-parallel fold sets. These rocks were correlated provisionally to the Belt Supergroup.

Armstrong (1975) dated augen gneiss along the Salmon River at 1,500 my old and suggested that it forms a part of a Prebeltian basement complex. Bennet (1977) found that the supposedly Belt-equivalent Yellowjacket Formation is cut by the 1,500-my-old augen gneiss and suggested the possibility of a younger age of intrusion in which whole-rock Rb/Sr ages were not reset. Norwick (1977) described evidence for early burial metamorphism in the Beltian rocks of northern Idaho.

In Oregon, Taubeneck (1964) studied the Cornucopia pluton, which Goodspeed had held to be formed by granitization, and gave evidence to show that the pluton is a product of igneous intrusion. Irwin (1966, 1972) has done major work in the Klamath Mountains. Dickinson and

Vigrass (1965) have studied metamorphic rocks in central Oregon. Kays (1968, 1970) analyzed Mesozoic metamorphism of eugeosynclinal rocks in the Klamath Mountains of southwestern Oregon. Metamorphic intensity increases toward an axis of igneous intrusion, suggesting that the igneous bodies may have provided the heat for metamorphism. Ashley (1968) showed that the Burnt River Schist of eastern Oregon consists of two units separated by a high-angle fault trending E-W. The southern unit is at least in part of Permian(?) age, based on a bryozoan. Both units are doubly folded, but the folds differ in style and orientation.

Swanson (1969) mapped lawsonite blueschists in two windows of pre-Albian rocks in north-central Oregon, associated with serpentine, chert, quartzite, marble, and mafic metavolcanic rocks. This occurrence supports the view that the Klamath trend extends northeastward across Oregon, following the late Paleozoic or Mesozoic continental margin. Coleman (1972) and Ghent and Coleman (1973) described the Colebrook Formation as late Jurassic deep-ocean sediments and minor basaltic rocks metamorphosed in the blueschist facies, and thrust over younger Mesozoic sedimentary rocks of the continental margin. Eclogite, high-grade blueschists, and amphibolite blocks were tectonically emplaced during the thrusting.

In the State of Washington, Misch and his students and co-workers in the Northern Cascades contributed most to progress in the study of metamorphic rocks. The framework of the partly granitized metamorphic rocks is outlined by Misch (1952), established by an extraordinarily large amount of work. Vance (1954) and Misch (1959) discussed blueschists occurring in the western part of the region, presumably a continuation of such rocks from the California-Oregon region and also in Alaska along the Mesozoic continental margin. Crowder (1959) studied granitization and migmatization in the northern Entiat Mountains involving biotite gneisses like those of the Swakane gneiss described by Waters (1932). Tabor (1960) found diaphthoritic gneisses in a thrust fault zone. Hibbart (1964) showed how protoclastic shearing can lead to the development of foliation in an initially massive alpine-type gabbro intrusion. Libby (1965) examined an orthogneiss developed at the expense of igneous quartz diorite. Adams (1964), on the other hand, described a quartz diorite generated through partial fusion of Skagit gneiss on the west, to complete fusion on the east. Other important work in the northern Cascades was done by Crowder and others (1966), Cater and Crowder (1967), Cater and Wright (1967), Yeats (1964, 1967), and Yeats and Engles (1971). Snook (1965) reworked a part of the "Colville batholith" gneiss east of the Okanogan River and found it not to be a protoclastic border zone of a batholith, as Waters and Krauskopf (1941) had earlier suggested, but rather a body of high-grade gneiss, amphibolite, and calc-silicate rocks, formed during regional metamorphism and later mylonitization in shear along shallow-dipping surfaces. Van Diver (1967) noted contemporaneous faulting and metamorphism in the Wenatchee Ridge area of the Northern Cascades. Hawkins (1968) described regional metamorphism involving partial fusion of plutonic rocks in the northwestern Okanogan Range.

Hawkins (1967) analyzed a field of prehnite-pumpellyite facies metamorphism in graywackes of the Olympic Peninsula. Zeolite-facies metamorphism in the Olympic Peninsula was described by Tabor (1972), and by Stewart (1974), and in rocks of the Chiwaukum graben by Cashman and Whetten (1976). Vance (1968) discussed prehnite-pumpellyite facies metamorphism in the San Juan Islands and suggested that aragonite in the rocks might be metastable rather than an indicator of high pressure. Later, Glassley et al. (1976) discovered fibrous lawsonite in the San Juan rocks and held that aragonite is probably a stable high-pressure phase.

Misch (1968) presented evidence to show that the Skagit Gneiss of the Northern Cascades is primarily a product of metasomatic processes involving the introduction of Na_2O and SiO_2 and removal of FeO and MgO, a variety of granitization. Babcock and Misch (1969) described late synkinematic dikes in the Skagit Gneiss, presumably of anatectic origin. In more general work, Misch (1969, 1971) discussed evidence for synkinematic growth of metamorphic minerals as well as problems concerned with the interpretation of bowing-out of schistosity around porophyroblasts: the latter phenomenon may occur either by tectonic flow of matrix around porophyroblasts or by the pushing aside of the matrix during porophyroblast growth.

Fox et al. (1976) analyzed the age of emplacement of the Okanogan gneiss dome, a part of the Shuswap terrane, and found that it was emplaced in the Late Cretaceous (87-65 my ago). Mattinson (1972) showed that the Yellow Aster Complex of the Northern Cascades is 1,452-2,000 my old, and that the Swakane Gneiss and the Skagit Gneiss may have been deposited more than 1,650 my ago. The ages of metamorphic minerals suggest major metamorphism at about 415 my ago and at 69-90 my ago. Lawrence (1978) described left-lateral simple shear during early Late Cretaceous cataclastic shear in movement along the Chewack-Pasayten fault of north-central Washington, a result of oblique subduction movement.

Work in Canada concentrated in two principal regions: metamorphic rocks in the vicinity of (a) the Coast Range batholith, and (b) the Shuswap terrane.

Sharp and Rigsby (1956) found high-rank gneisses, schists, amphibolites, and marbles in the central St. Elias Mountains of the Yukon Territory. Mathews (1958) in southwestern British Columbia described metavolcanic and metasedimentary rocks of unknown age and structure invaded by early quartz diorites of the Coast Range batholith. Read (1960) studied the Fraser River valley near Hope in southwestern British Columbia, finding evidence for a Jurassic(?) and a post-Lower Cretaceous folding and accompanying metamorphism. An older granite gneiss was mobilized and moved upward into lower-grade rocks.

In part of a major project in the Coast Range batholith, Roddick (1965) proposed that the dioritic-to-granitic rocks were created from pre-existing metamorphic rocks through the process of granitization, following which they moved to higher crustal levels through a process of "plastic diapirism." Most of the plutonic rocks are reportedly of porphyroblastic textures. Therefore, the entire Coast Range batholith may be a product of granitization. An alternative to this view was put forward by Hollister (1975) and Hollister et al. (1975). In the central Coast Range batholith area, granulite facies metamorphism occurred at pressures and temperatures high enough to begin partial melting of the stratified rocks of the lower crust. This partial melting was followed by mobilization to produce tonalitic plutons. Lappin and Hollister (1980) showed that partial melting of hornblende-bearing gneiss goes forward as represented in the following equation: $\mathrm{Hbl_1 + Plag\ AN_{35\text{-}40} + Q = Hbl_2 + Plag\ An_{32}\ (melt) + Bi\ (melt) + Q\ (melt)}$. Local melts occur as small isolated spherical domains in the gneiss with normally zoned euhedral plagioclase.

Baer (1968), also in the Coast Range batholith, found evidence for two orogenic cycles, with synkinematic intrusion of granitic plutons in at least the second cycle (see also Woodworth 1973). Hutchinson (1969), in the northern Coast Mountains, worked in a belt of metamorphic rocks which increase in grade from greenschist facies on the west to amphibolite facies on the east. A central migmatite zone displays evidence for metamorphism in the sillimanite-K-feldspar and sillimanite-cordierite-K-feldspar facies intervals. East of the batholith, Pigage (1976) described metamorphism in the Barrovian facies series.

Surdam (1970) described low-grade metamorphism in the Karmutsen Group of central Vancouver Island, involving zeolites in the upper part of the section and prehnite in the lower half; a continuation of the low-grade belt of the Olympic Peninsula and the San Juan Islands. These rocks were further studied by Muller et al. (1974), who showed that the gneisses of Vancouver Island yield a zircon age of 264 ± 7 my, supporting the concept that they are derived from late Paleozoic volcanic rocks migmatized during the major Jurassic plutonic event of the Vancouver Island region.

Jones (1959) inaugurated the fourth-quarter century studies in the Shuswap terrane with a major paper on the west-central part. Kyanite and sillimanite gneiss is widespread, as is augen gneiss; gneiss predominates over other rock types. Foliation dips at shallow angle throughout with common lenticular pegmatites lying parallel to the foliation. Cataclastic features are ubiquitous in the gneisses. Gneissic layering does not everywhere represent bedding, but the "underlying cause of the deformation is obscure."

Reesor (1965) analyzed the structural evolution of the Valhalla gneissic complex in one of several mantled gneiss domes in the eastern Shuswap. Domal axes lie E-W, as do minor fold axes and mineral lineation. Veined gneisses were emplaced in horizontal sheets. Hyndman (1968) presented evidence in the Nakusp area of the southeastern Shuswap that Triassic and older rocks pass laterally with increasing metamorphism into the Shuswap gneisses. The high-grade rocks show a strong shallow-plunging E-W mineral lineation in a shallow-dipping schistosity, and the metamorphism post-dates lower Jurassic rocks but does not affect granitic plutons of lower to upper Cretaceous age. Preto (1970a) studied extensively developed amphibolites in the southern Shuswap terrane and found them to be derived from basaltic sills.

Chemical petrology of pelitic gneisses and migmatites from Thor-Odin dome of the eastern Shuswap was analyzed by Froese (1970). A core of migmatites and granitoid gneiss, surrounded by a mantle of unmigmatized gneisses were metamorphosed in the sillimanite-orthoclase-almandine subfacies of the amphibolite facies at a pressure of 2-3 kb and a temperature of 600°-650° C. Preto (1970b) studied structure and petrology of the Grand Forks Group in the southern Shuswap. Some 22,000 feet of strata are correlated to the latest Precambrian rocks of southern British Columbia. The rocks were metamorphosed at low pressure and high temperature, an environment not found farther north in the Shuswap. The mineral assemblages belong to an Abukukma type of metamorphism and include sillimanite-orthoclase-cordierite-hypersthene-wollastonite. Pressure of 3-4 kb is suggested.

A summary of the Shuswap data was presented by Reesor (1970). The Shuswap is a narrow belt of high-grade metamorphic rocks in southern British Columbia, dominated in its eastern part by a series of gneiss domes at about 40- to 50-mile intervals along its length. Domes are positioned in the earliest stages of deformation recognized in the gneiss complex. Rocks in the complex are considered to be equivalents of Windermere (late Precambrian) and Paleozoic to Triassic rocks.

Structural analysis by Fyson (1970) in the western Shuswap disclosed four deformation phases, of which the first two generated recumbent folds. Reesor and Moore (1971) studied the structure and petrology of the Thor-Odin gneiss dome in the eastern Shuswap. A complex history of folding and gneiss development emerged from this work. Metamorphism reached the sillimanite-almandine-orthoclase subfacies in D_1, followed by cordierite-andalusite growth in post-movement time. Structural and petrographic analysis of western Shuswap rocks by Bolm (1975) showed a single penetrative deformation during which migmatization, intrafolial folding, and cataclasis were accomplished. Sub-horizontal *s*-surfaces indicate deformation under sub-vertical compression, and shear was away from the central long axis of the pluton consistent with a gravity tectonic model. The association of migmatization with deformation suggests that buoyantly rising plutons may have resulted in deformation and metamorphism. Nielson (1978) studied structural and metamorphic constraints for tectonic models of the Shuswap terrane. Four major fold episodes were postulated, with peak metamorphic grade reached at pressures of 4-5 kb and temperatures of 500-600° C. Late-stage folds are invaded by plutons with K-Ar ages of 128-140 my.

Okulitch (1973) studied the Kobau Group, highly deformed, low-grade metamorphic rocks west of the Shuswap terrane with structural affinities to the Shuswap. Parrish (1976) described rocks of the northern Wolverine Complex, northwest of and on strike with the Shuswap Complex, which display two phases of earlier recumbent folding with phases of synkinematic igneous intrusion, followed by upright folding.

Through the application of age-dating techniques, Campbell and Reesor (1977) made a major breakthrough in understanding Shuswap geology, in showing that the Shuswap includes Hudsonian crystalline rocks, probably 1,900 my old, and that the existence of post-metamorphic plutons about 160 my old places an upper limit on the age of metamorphism. Now it was possible, as they suggested and as Bolm (1975) implied, to think about diapirism. Work by Simony et al.

(1977) in the northeastern Shuswap was also consistent with diapirism. They demonstrated upward movement of Precambrian gneisses and outward thrusting onto the Rockies measured in terms of kilometers (see also Chamberlain et al. 1978). Duncan (1978) carried the matter still farther. Rb/Sr data established the existence of an extensive Precambrian basement in the Shuswap. The core gneisses of the Thor-Odin dome previously correlated with the Late Proterozoic are now shown to be about 3 by old and to retain evidence of two subsequent Precambrian events (shades of Dawson 1877; the wheel turned full circle in this 100 years). Granitic intrusion occurred at about 2 by ago, and high-grade metamorphism and partial anatexis occurred at about 935 my ago. This contrasts with previous suggestions of Proterozoic sedimentation and Jurassic metamorphism. The Shuswap terrane generally has lower average Rb/Sr and Sr^{87}/Sr^{86} than the Purcell-Belt rocks.

Duncan's work clearly makes it now necessary to consider a diapiric origin for much, if not all, of the Shuswap rocks. The timing of the diapiric emplacement relative to Mesozoic metamorphism and thrusting seems to remain a major problem. In the northeastern Shuswap rocks in the Wells-Gray Provincial Park, Pigage (1978) demonstrated the existence of kyanite to sillimanite zones of metamorphism in the Barrovian facies series, for instance (P-7.6 kb, T-700° C). Now one must wonder if that reflects Mesozoic metamorphism or basement metamorphic effects preserved through the diapiric process. Finally, what triggered the diapirism?

Most of the remaining work in British Columbia was done in the rocks of the Kootenay arc. Greenwood (1967) studied the stability of wollastonite in a contact metamorphic aureole. Dodds (1968) showed that garnet in amphibolite in the Kootenay arc is principally almandite. Hunt (1972) demonstrated a K-Ar age of 1,665 my for amphibole in the aureole of a diabase sill, suggesting that the Aldridge county rock is older than the broadly equivalent Prichard in the United States, generally thought to be younger than 1,500 my. In the eastern Selkirks, Read (1973) found evidence for three fold generations and two regional metamorphic events, with the younger forming andalusite and staurolite.

Thus, the metamorphic rocks east of the Shuswap terrane in the Kootenay arc and vicinity display a complex array of metamorphic features including polyphase structures and several pulses of metamorphic activity (see also Ghent et al. 1975; Ghent et al. 1977; Hoy 1977; Craw 1978; Cruickshank and Ghent 1978; Leatherbarrow and Brown 1978). These rocks were apparently metamorphosed in the same general series of events as those involved in the diapiric rise of the Shuswap Complex.

Paterson and Harakal (1974) described blueschists of the Pinchi Lake area in central British Columbia, formed during the Triassic (215 my old) subduction activity farther north along the California-Oregon belt mentioned earlier, presumably marking the North American plate margin in the Triassic.

Campbell (1970) analyzed structural changes from infrastructure to suprastructure in the Cariboo Mountains. A deep zone of arched, recumbent isoclinal folds passes upward into a zone of large similar folds in which axial-plane schistosity is perpendicular to that below. This is the sort of thing that might happen to an upright-folded sequence as a diapir moved up through it, flattening the superjacent rocks low in the folded section.

During this fourth quarter century, work went forward at widely separated places in Alaska. Cady et al. (1955) commented on contact metamorphic effects in the Kuskokwim graywackes adjacent to bodies of albite rhyolite and quartz monzonite. Rossman (1959) described major metamorphism and deformation occurring concomitantly with dioritic intrusion in a sequence of Paleozoic rocks in Chicagoff Island, believed to occur during the orogeny in which the Coast Range batholith was emplaced. Forbes (1959) noted 20,000 ft. of crystalline schists near Juneau, isoclinally and progressively metamorphosed from west to east with the entry of migmatitic gneisses at the kyanite zone. The migmatites were ascribed an origin by the synkinematic entry of alkalites metasomatically into the schists—a version of granitization. MacKevett and Blake (1963) studied pyrometasomatic ore in a roof pendant of gneiss schist, and marble in the Coast Range batholith in southeastern Alaska. MacKevett (1974) also described sedimentary and volcanic rocks in southeastern Alaska metamorphosed in the greenschist facies.

Ragan and Hawkins (1966) found a polymetamorphic complex in the eastern Alaska Range involving Precambrian rocks related to the Birch Creek Schist. Four metamorphic events occurred, ranging from a Precambrian granulite facies event through two retrograde events to Mesozoic thermal reconstitution in contact aureoles about quartz diorite stocks.

Wahrhaftig (1968) described E-W folds and parallel lineation in Birch Creek and younger schists in the central Alaska Range. Forbes et al. (1968) confirmed the occurrence of eclogite in the crystalline schists of the Fairbanks district in discontinuous lenses and layers (see also Swainbank and Forbes 1975). Sainsbury et al. (1970) found blueschist rocks in the Nome Group of the Seward Peninsula. Older igneous and metamorphic rocks were retrograded in this event. Fritts (1970) outlined two metamorphic episodes in rocks of the Ambler River area: the first was thermal in Cretaceous aureoles synchronous with regional low-grade metamorphism, and the second was an episode of dynamothermal metamorphism in the lower greenschist facies.

Foster et al. (1970) described a greenschist to amphibolite facies metamorphic complex in the Yukon-Tanana upland metamorphosed in the Precambrian, Ordovician, and Jura-Cretaceous, noting also that interregional correlation of metamorphic terranes in Alaska must await further structural and petrologic work. Foster and Keith (1974) also described ultramafic rocks of this region. Forbes et al. (1971) analyzed blueschists in southwestern Alaska possibly analogous to blueschists in Japan, Kamchatka Peninsula, and Siberia (see also Forbes et al. 1976; Hill 1979; Connelly 1978). Smith and Lanphere (1971) dated a regional Barrovian-type metamorphic event in central Alaskan Triassic-Jurassic sedimentary rocks and showed it to be contemporaneous with Late Cretaceous plutonism. Forbes and Weber (1975) described progressive metamorphism and of schists in a deep drill hole near Fairbanks and showed that greenschist to amphibolite facies metamorphism occurred at depths of 17-19 kilometers under a thermal gradient comparable to that of the present day.

Looking back over the fourth quarter century, we see that good progress was made on many of the outstanding problems. Californian and other blueschists were shown to be formed in plate-marginal processes, although some uncertainty seemed to remain as to the extent to which tectonic overpressure may have led to their metastable formation at relatively shallow crustal levels.

Supposedly granitized rocks were shown to be of igneous origin in California, Montana, Idaho, Oregon, and parts of British Columbia. Granitized rocks in Washington continued to stand up well (e.g. the Skagit Gneiss studied by Misch). The concept of a granitized Coast Range batholith was not universally agreed upon. The basement gneisses in Colorado were variously considered to be produced by isochemical recrystallization of sedimentary rocks, or of igneous rocks, by granitization, or by anatectic processes. No doubt all these types exist, and much work remains to be done on the related difficult problems. The question of bedding foliation vs. axial plane-foliation is also unresolved in many of the Colorado rocks.

The Bitterroot frontal gneiss zone in Montana was reinterpreted as due to sliding off of a roof block from the Idaho batholith.

Multiple folding, including Precambrian deformation, in the metamorphic rocks of the Idaho panhandle was recognized and studied by several workers. Nevada and southern Idaho metamorphic rocks were shown to be involved in a complex, little-understood belt of recumbent folding and flat thrusting also involving the generation of gneiss domes.

Important progress was made on understanding the Shuswap Complex in British Columbia, in that the discovery of basement gneisses within the Shuswap led to its recognition as a major diapir.

Alaska remains as a major frontier for geologic research, a situation also true for the whole western United States, if in lesser degree.

In closing this paper, we shall mention two more general papers that have applicability to certain problems that have been prominent throughout, and suggest ideas that may be tested in future work.

Gastil (1979) commented that contemporary geologic thought accords possibly undue importance to plate-marginal processes in the formation of metamorphic rocks and structures, and too little to structural features allied to diapirically rising batholiths. Such bodies may produce many structures conventionally attributed to plate-marginal tectonic processes.

Work briefly reported by Reid et al. (1979) reinforces Gastil's comments; so apparently does detailed work done in two areas (Hamilton 1963; Hietanen 1963c, 1967, 1968, 1969). Structures on the maps in the referred publications and descriptions of the contact zones are important. Particularly significant are data on isograds and isobars accompanying the multiple intrusions of the Idaho batholith (Hietanen 1969). The diapiric Idaho batholith has strongly modified older structures in an envelope of rocks at least several kilometers thick during its emplacement. Vertical flow structures were formed during emplacement and wall rocks flowed downward to compensate for the volume vacated by the rising pluton. The fabric of the rocks within the batholith envelope was completely made over in metamorphic recrystallization, and no mineral or textural evidence of earlier events survived. Therefore, a considerable amount of work is needed to discern what part of the metamorphic rock contains structures and textures due to batholith emplacement and what part (farther away from the batholith) contains textures and structures reflecting the several metamorphic/structural events that pre-date batholith emplacement. In short, it would appear that both plate-marginal and diapiric batholithic processes are important, and that the problem is to find out the balance between them.

A paper by Davis and Coney (1979) proposes an origin for metamorphic core complexes along the western Cordillera through basement stretching and necking in a manner styled "megaboudinage." Several of the mantled gneiss domes of the Shuswap, northeastern Washington, northern Idaho, and southern Idaho are considered as a part of this scheme. Tensional features necessary to the megaboudinage idea are not found in the vicinity of the referenced core complexes in the northwest; indeed, overthrusting of rocks marginal to these gneiss domes is not uncommon (see, e.g. Simony et al. 1977).

The data for the gneisses of the northwest seem more compatible with diapirism generally than with megaboudinage, involving the lateral spreading by thrust movements of such bodies in the upper crustal levels. The Shuswap rocks and comparable elements in northern Washington (eastern Colville batholith, Okanogan gneiss, Swakane gneiss), northern Idaho (Selkirk gneisses), and southwestern Montana (Bitterroot frontal gneiss zone) are all characterized by N-S trends and E-W flow lineations, cutting across the northwest-trending structural grain of the region. The N-S trends may be explainable in the way first suggested by Mayo (1937) for the Sierra Nevada batholith. N-S stresses related to inter-plate slip have created extension fractures of crustal dimensions which have initiated and guided the rise of diapirs along N-S trends. As these diapirs rose into high crustal levels, they have tended to spread laterally in an E-W direction, generating primary E-W trending flow lineations. This concept, applied to the Bitterroot frontal gneiss zone, would see E-W lineations as normal stretching lineations near the roof of the batholith in a zone of marginal primary flow foliation (cf. Balk 1937). The Sapphire slide may not have happened.

Yet the gneiss diapirs may have important interrelations with the Tertiary low-angle thrusting so well described by Davis and Coney (1979). Much remains to be learned about that process and the metamorphic rocks generated therein.

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WESTERN NORTH AMERICAN PALEOZOIC ROCKS
Retrospect and Prospect

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Western American Paleozoic rocks commanded attention from geologists in the latter part of the 19th century for their economic importance: they are hosts for gold, silver, lead, and zinc in certain areas. Phosphates have been mined from Paleozoic rocks in southeast Idaho and adjacent states. Since the early 1880s, the noted mining district of Eureka, Nevada has attracted geologists, and it has become a geological training ground. During the Paleozoic, a continental shelf margin lay in the present central Nevada, central Idaho, and eastern Washington. Shelf seas were primarily sites of carbonate accumulation. The Antler Orogeny (latest Devonian-Early Mississippian) resulted in a highland at the former shelf edge, thrusting of basinal sequences over those of the shelf, and perhaps invasion of ore-rich solutions into Lower Paleozoic carbonate hosts. Paleozoic faunas occur in rocks in melange terranes in the Sierra Nevada, the Klamath Mountains, parts of Oregon and in western Washington. Faunal affinities indicate that the rocks originated in areas distant from Paleozoic North America, and future study of Paleozoic rocks may identify sites of origin of these rocks. Future paleobiologic research will reveal the Paleozoic continental shelf topography and will document paleocommunities. Paleocommunity studies may lead to increased understanding of an apparent close relationship between environmental and community stability.

Paleozoic rocks have drawn geologic attention since well before the melding of the four great western surveys into the U. S. Geological Survey in 1879. The economic stimulus of mining, primarily for lead, silver, zinc, and gold has been at the heart of interest in the western American Paleozoic rock record. A high percentage of Paleozoic rocks in the American West are carbonates that have been demonstrated to be hosts for economically important ores.

Ore-bearing Paleozoic rocks were exploited for scores of millions of dollars in ores, most of which were gleaned before the end of the 19th century. Some roisterous mining camps of western American legend grew up around that mining activity. Origins of the ores served as a magnet that drew geologists, including those from the U. S. Geological Survey in the years following the birth of that organization. Economically valuable ores have been mined from Paleozoic rocks in Utah, Nevada, Idaho, California, and Washington. Uranium-bearing phosphate deposits of Late Paleozoic age in Idaho and adjacent parts of Wyoming and Montana as well as oil shales of Permian age in Montana have attracted attention as well.

For the most part, Paleozoic rocks in the western United States may be divided into those deposited in continental shelf environments on a North American Paleozoic platform or plate, and those deposited oceanward from that plate. Many rocks in the second set were formed from sediment deposited around islands, many of which were atolls in a tropical Paleozoic ocean that lay west (in terms of present-day directions) from the North American Paleozoic plate. Other rocks in the second set were deposited in environments that were remote from a Paleozoic North America. Late Paleozoic and/or Mesozoic plate motion has brought these rocks to their present place in North America. The boundary of the North American Paleozoic continental shelf was in what is today central Nevada, and it trended generally northward (in terms of modern directions) into central Idaho and eastern Washington.

Paleozoic rocks that formed on a North American plate appear to have been deposited in a broad spectrum of marine continental shelf as well as deep oceanic environments. Continental rise and abyssal oceanic environments lay west (in terms of today's directions) from the shelf seas. Two distinct facies characterize these Paleozoic rocks. Carbonate rocks with interspersed quartzites comprise one of the two facies, and they dominate much of the western North American Paleozoic stratigraphic record. It is these rocks, primarily those of Early Paleozoic age, that acted as hosts for ore deposits of economic importance exploited during the late 19th and early 20th centuries. It is these rocks, too, that have been the focus for a number of paleoenvironmental and paleobiological analyses.

The carbonates contrast with the argillites, cherts, mudstones, shales, and volcanic rocks that comprise the second prominent facies. These rocks accumulated in oceanic environments west (in modern directions) from the western North American Paleozoic continental shelf.

A marked diversity of Paleozoic rocks, many of which bear unique faunas or faunas dissimilar from those commonly found in North American Paleozoic plate rocks, are found today west of the North American Paleozoic plate rocks. Some of these rocks were deposited in shallow shelf seas, while others formed in bathyal and abyssal oceanic environments. Volcanic rocks and even ophiolites occur in Paleozoic rock suites found west of North American Paleozoic plate rocks. These rocks commonly occur in structurally complex terranes, and many of them appear to have been formed in an island arc system.

NORTH AMERICAN PALEOZOIC PLATE

The primary focus herein will be on the North American Paleozoic plate rocks because they have proven to be both significant in economic recovery of ores and important in stratigraphic and paleontologic inquiry in western North America. Historically, description of these rocks proceeded rather slowly, taking about a century before regional syntheses began to take shape. However, during the past two decades there has been rapid progress in synthesis.

Study of North American Paleozoic plate rocks commenced in earnest almost as soon as they were recognized as ore-bearers. The names of and deeds done in certain noted gold, silver, lead, and zinc producing districts, such as Belmont, Cortez, Eureka, and Pioche in Nevada, Bayhorse and Hailey in Idaho, and Metaline in Washington, form a part of the fables that are the heritage of the American West. These and other western American mining towns with legendary pasts were centers of mining activity for a score or more years in the latter 19th century. Mining continued in some districts well into the 20th century, and gold mining at Carlin, Nevada since the late 1960s has rekindled interest in mining in the western United States.

Developments in the Study of Paleozoic Rocks: Some Vignettes

Ore-rich districts in Utah, Nevada, and Idaho came to be both centers for the recognition of stratigraphic sequences of Paleozoic rocks and the training grounds for generations of geologists. It was in the mining districts about Belmont, Cortez, Eureka, Manhattan, and Pioche, Nevada, Bayhorse and Hailey, Idaho, and Gold Hill and Stockton, Utah that H. G. Ferguson, James Gilluly, Adolph Knopf, George Rogers Mansfield, Thomas Nolan, Clyde P. Ross, and other renowned American geologists so amply demonstrated the value of careful geologic mapping followed by precise stratigraphic and structural geologic interpretations. They and their associates soundly laid down the basic steps in geological inquiry so necessary to the regional syntheses that could follow after their meticulous geology.

Eureka, Nevada. Of all the mining centers in the western United States from which ores were obtained from Paleozoic host rocks, perhaps none has held more enduring charm for geologists than that near Eureka, Nevada. Generations of geologists have been enchanted by the geologic record revealed as though pages in a book on the hillsides about Eureka and its environs. It was there that an embryonic U. S. Geological Survey sent Arnold Hague to examine the stratigraphic record and to sort out some disputed bits of geologic structure related to the mining activity. There, too, went George Becker and Joseph Story Curtis in 1879-1880 to study the mines. Concerted investigations by the U. S. Geological Survey into invertebrate fossils commenced when the paleontologist Charles D. Walcott accompanied Hague to make some sense from the multitude of fossils collected from the stratigraphic record about Eureka.

Almost half a century after Hague and Walcott's Eureka excursions, Thomas B. Nolan, then Director of the U. S. Geological Survey, was to make Eureka a sort of hub of western American geological mapping and detailed stratigraphic and structural geologic studies by establishing his residence there and commencing, with several associates, a long-standing geologic interest in the area. His interest in and description of the geologic wonders in and about Eureka attracted scores of geologists. The long-term result of his interest, and that of those who have followed him, has been that budding geologists have and continue to go to Eureka from all parts of the country to learn first-hand those stratigraphic and structural geologic developments that drew generations of geologists before them. In many respects, Paleozoic rocks in the environs of Eureka have become a geological text.

Ores of economic significance were discovered near Eureka in 1864, and two smelters were erected in the town in 1869. The Eureka Consolidated Mining Company, funded by San Francisco's financial district, erected a smelter at the north end of town, and the Richmond Mining Company, developed with British investor's funds, built another at the town's south edge. Profits from the mining activity stimulated growth of what was thought, at least by Eureka's citizenry, to be, for a decade or two, the second largest town in Nevada. Progress of work in the mines was recorded weekly on the pages of the town's newspapers, tucked neatly beside recountings of local shootings, mostly over the gain or loss of feminine affections, the progress of typhoid fever in Europe, notably amongst royalty, and concern for the decline in the value of the dollar.

For twenty years after the smelters opened, Eureka flourished. A railroad connected the town to Palisades and proudly acclaimed a "fast train" every morning. The trip to Palisades by this special "fast service" took about five hours. Three newspapers, all dailys, the *Eureka Evening Leader,* the *Eureka Daily Republican,* and the *Eureka Daily Sentinal*, were published. A brass band was assembled, militia companies formed, five fire companies were organized, and a town baseball team could be brought together. The Opera House was built to accommodate audiences for travelling shows such as "Mabel Sentley's Burlesque Company" and such auspicious gatherings of the local populace as that at the Miner's Union Grand Ball. In addition, the town apparently supported a large number of attorneys and physicians, including one Dr. Men Lee, the "Celebrated Chinese Physician" who claimed to work wonders with herbal potions, all served warm.

For a time, living was so rich and varied and the mines so productive that a local editor rhapsodized that Eureka's mountains were so heavily mineralized that riches awaited only the hands and minds of men to bring forth nature's bounty to usefulness and profit. Indeed, more than 40 million dollars worth of ores were produced from the mines, and the town survived devastating fires, floods, and even an outbreak of smallpox that nearly decimated the citizenry.

Sadly, however, the ores were depleted, ore prices dropped, and the smelters closed. The Richmond Company banked its fires for the last time in 1889. The Eureka Consolidated Company kept its smelter going a scant two years longer. An attempt to reopen the mines and rekindle mining activity was made in 1909, but an unusually hard cloudburst hit the area shortly after rail connections were rebuilt and timbers emplaced and, rather literally, mining interest was "washed away." But, although Eureka's economic fortunes have waned since the disastrous flood, geologic interest in its environs has grown over the years. The Paleozoic rock and fossil record found in the vicinity of Eureka has served as a starting point for lithofacies analysis and paleobiologic interpretations.

Despite several stratigraphic and paleontologic studies in the Eureka area, and despite the model of paleontologic description set forth in Walcott's (1884) monographic treatment of the fossils from the Eureka district, paleontologic inquiry into western American Paleozoic faunas remains in its infancy, a subject for future development. As Hague (1884) commented in his introductory remarks to Walcott's monograph, fossil collections assembled to that time had been "in most instances small, incomplete, and hastily gathered from more or less widely separated localities." In the view of at least some paleontologists, Hague's remarks written close to a century ago could be said equally well today of most fossils collected from western North American Paleozoic rocks. Although some Paleozoic fossil faunas have been obtained from carefully measured stratigraphic sections, many collections with which paleontologists have worked are, as Hague described, small and incomplete representations of what is actually present. Indeed, many collections turned over to paleontologists have been dubbed "lunch bag" as they commonly bear the adornments of some not too-distant lunch. Despite certain limitations, paleontologic study has provided a number of carefully stratigraphically-located Paleozoic faunas that have been used in establishing a time-stratigraphic framework for correlation of the many stratigraphic sections from area to area.

Central Idaho. Central Idaho had, as did Eureka, Nevada and certain other Nevada mining districts, a proud record of important silver, lead, and zinc production from older Paleozoic host rocks. Mines in Custer County were prolific enough to result in erection of smelters at Bayhorse and Clayton in the 1870s. Notable among the Paleozoic host rocks in the Bayhorse area was the Late Ordovician Saturday Mountain Dolomite. Silver, lead, and zinc ores came from it for more than 20 years, from 1877 to 1898. Smelting at Bayhorse continued from 1880 to 1897, and the Clayton smelter continued in operation until 1902 (Ross 1937).

The area about the Sawtooth Mountains, slightly south of Bayhorse, shares Idaho's mining heritage. Rich silver, lead, and zinc ores were found near Hailey in 1878-1879. The smelter built at Ketchum to handle most of those ores operated for only about 10 years, when lowered prices for ore and declining production forced its closure.

Northeastern Washington. Northeastern Washington's Paleozoic rocks have played a significant role in supplying the nation's needs for silver, lead, and zinc. Silver mines were developed in Stevens County in 1885, and a smelter built at Colville operated until 1892, primarily taking silver from silver-rich lead ores (Moen 1976).

Lead and zinc were produced from mines in Paleozoic host rocks in Pend Oreille County for many years, starting early in the 1900s. From 1902 to 1969, Pend Oreille County mines produced approximately 146 million dollars worth of lead and zinc (Mills 1977; Moen 1976).

Late Paleozoic Phosphates. Certain western American Late Paleozoic rocks have been as economically significant as have their Early Paleozoic counterparts. Phosphate deposits in Late Paleozoic rocks in southeastern Idaho and adjacent parts of Wyoming and Montana were a major source of the raw material for commercial fertilizers. Phosphates from Idaho were shipped in large quantities in the first quarter of the 20th century to southern California to nourish an expanding citrus fruit industry. Since that time, these phosphate-bearing rocks have attracted the attention of a number of U. S. Geological Survey geologists. Comprehensive reports on these deposits by McKelvey and others (1959), Sheldon (1959, 1963), and Swanson (1970) probed the phosphates and related rock units for their distributions, origins, and economic potential. These studies drew attention to the uranium possibilities in the phosphate-bearing rocks as well as to oil sealed in the Park City Limestone, the lateral equivalent of the phosphate-bearing strata, that lies beneath the shales of the Triassic Dinwoody Formation. Late Paleozoic oil shales in Montana that are coeval with the phosphate-bearing rocks in Idaho have a petroleum potential as well (Swanson 1970).

Late Paleozoic environments of deposition in southeast Idaho and adjacent states appear to have been most propitious for production and accumulation of organic matter (Sheldon 1963). A basin that was at least partly surrounded by a lip or shelf edge was present in the area. The lip or shelf edge baffled water currents, causing local upwelling of nutrient-rich waters to fertilize oceanic floating plants. The lush plant growth in turn nourished small plant-feeding animals in vast abundance. The remains of these tiny organisms apparently were entombed in what are today the phosphate and organic-rich mudstones, shales, and limestones of Late Paleozoic age.

Developments in the Study of Paleozoic Rocks: The Steps Toward Synthesis

As the fortunes of mining ores from Paleozoic host rocks waned during the first half of the 20th century, synthesis of the western United States' Paleozoic stratigraphic and paleontologic record lay as a rich but somewhat tattered and still unfinished fabric. Stratigraphic sequences of Paleozoic rocks had been described, some in greater detail than others, in studies of the several mining districts. A carefully collected fossil record necessary to establish correlations among the stratigraphic sections was incomplete. No attempt at synthesis could be made because the tools needed to accomplish it were not available. For a number of years, quadrangle mapping and geologic investigations about mining districts progressed slowly. Ferguson, Gilluly, Nolan, and others documented more and more of the Paleozoic rock record. Investigations such as that of Nolan (1935) at Gold Hill, an old mining district that lay astride the stagecoach route between San Francisco and Salt Lake City, and those of Ferguson (1924) and Gilluly (1932) in then essentially abandoned mining districts characterize the post-active mining era development of knowledge of Paleozoic rocks in the western United States.

The Second World War, and the need for minerals it created, provided an incentive for the reexamination of the old mining areas. The Idaho phosphate deposits were restudied, mining activity was rekindled in eastern Washington, and some of the old mining districts in Idaho and Nevada drew attention anew.

These studies, and an agreement between the Nevada Bureau of Mines and the U. S. Geological Survey to generate geologic maps of Nevada's counties, provided the stimulus that led to a regional synthesis of Paleozoic history. Careful areal mapping together with fossil collections from measured stratigraphic sections provided the basic data needed for stratigraphic correlations. In addition, close scrutiny of stratigraphic sequences from area to area resulted in recognition of regionally distinctive lithofacies. Slowly, a regional synthesis grew from knowledge and comparison of the local stratigraphic sections, and enough fossil assemblages were collected in stratigraphic order to establish zonal successions to use in precise correlations.

A significant factor in the development of a regional stratigraphic synthesis was the restudy of the Paleozoic section in the Eureka district of Nevada by Nolan and his associates (Nolan et al. 1956). Nolan was joined in his endeavors about Eureka by the stratigrapher and paleontologist Charles Merriam. Merriam, son of a distinguished vertebrate paleontologist and himself an expert not only on Cenozoic snails but also on Devonian corals and brachiopods, joined in the mapping as well as fossil collecting.

The task that lay at hand as the several mapping programs went forward in the separate areas was a regional synthesis of Paleozoic history woven from correlations of the stratigraphic sections. However, only the most major features of Paleozoic history were known by the mid-20th century.

The division of the Paleozoic rocks in the western United States into two distinct facies or rock suites had been recognized by the King Survey, and since that time numbers of geologists had commented upon the markedly different graptolitic and carbonate-rich facies of essentially coeval Paleozoic rocks in the Great Basin. It lay to Merriam and Charles Anderson (Merriam and Anderson 1942) to discuss fully the differences in lithologic aspects between the two facies and to point out that the argillites, cherts, shales, and volcanic rocks comprising the "Western Assemblage" or western facies had overridden the carbonates and quartzites that comprise the "Eastern Assemblage" or eastern facies. Merriam and Anderson (1942) suggested that the western facies rocks had been thrust eastward over the eastern facies rocks along a line of thrusts known today as the Roberts Mountains Thrust (Fig. 1). Merriam and Anderson (1942) indicated that the western

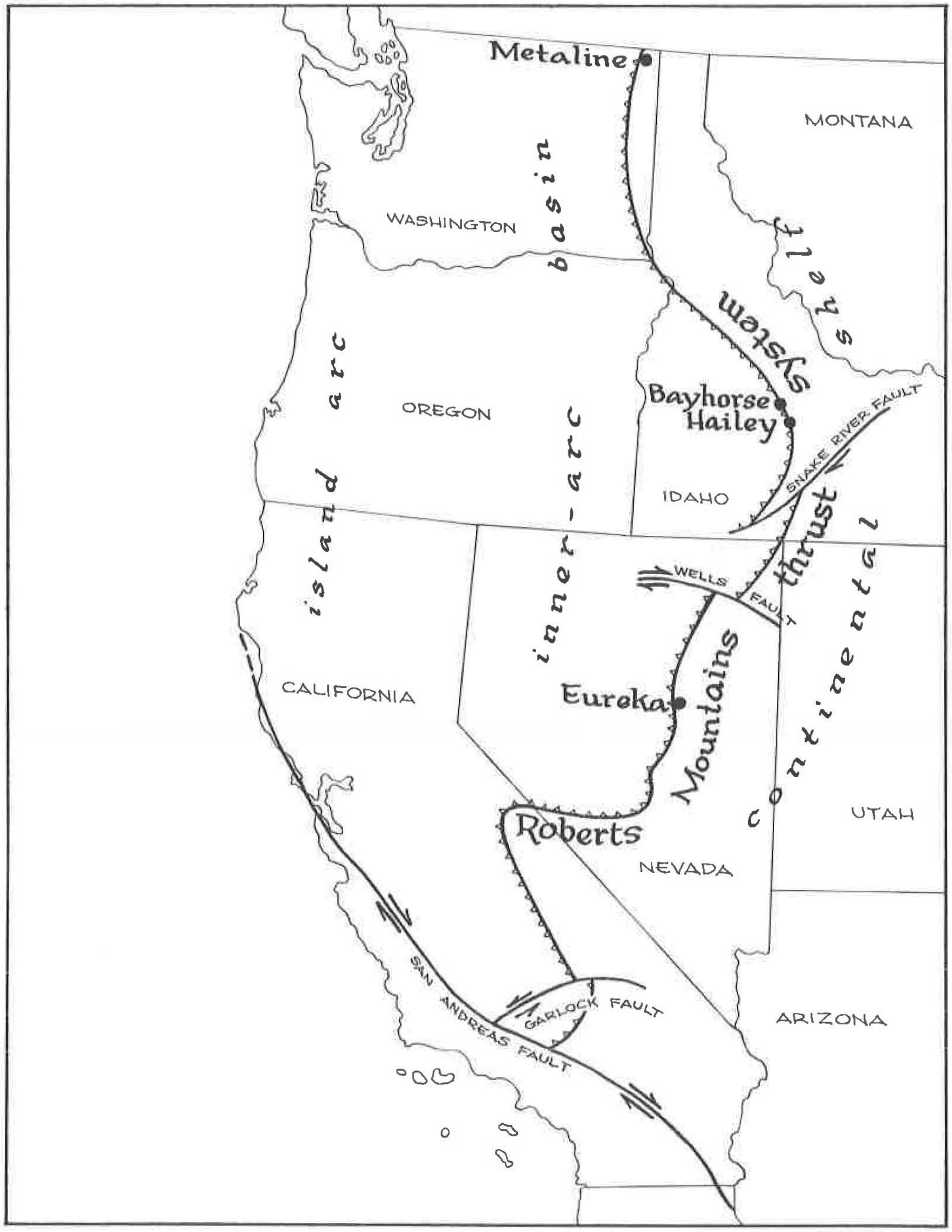


Figure 1. Index map showing major Paleozoic paleotectonic settings, certain post-Devonian faults, and locations of selected mining districts in the western United States.

facies rocks occur not only in Nevada but also in central Idaho and in British Columbia. Eastern facies carbonates occur in central Idaho as well as in northeastern Washington.

After the major facies relationships were described fully, stratigraphic sequences in each of the two major facies belts were then grouped to regional lithofacies patterns leading to a comprehensive Paleozoic geologic history of western United States. The masterful summary of Paleozoic structural and stratigraphic relationships in north-central Nevada by Ralph Roberts, Preston Hotz, James Gilluly, and H. G. Ferguson (Roberts et al. 1958), all of whom had mapped extensively in the Great Basin, was a great stride toward regional synthesis. Roberts and associates (Roberts et al. 1958) unravelled complicated geologic structures to reveal that the eastern facies rocks apparently passed laterally to western facies rocks through a transitional facies. That facies relationship developed during the Cambrian and was maintained until the latest Devonian when a major tectonic event, the Antler Orogeny, created a tectonic highland in the transitional facies terrane and resulted in thrusting of western over eastern facies rocks. The Antler highland apparently lay in about what is today east-central Nevada. Coarse-grained clastic materials were shed from it to both east and west. Those materials shed to the east were deposited in a relatively deep and rapidly subsiding basin or linear trough. A broad continental shelf, upon which carbonate sediments accumulated under a spectrum of relatively shallow marine environments, lay east of the deep trough. The trough apparently nearly filled by Pennsylvanian time in some locations. Shallow marine conditions spread west and covered part of the Antler highland by the end of the Pennsylvanian (Roberts et al. 1958). Locally, the Antler highland was a source of detrital materials during parts of the Pennsylvanian and Permian.

The summary of the Paleozoic history for a part of the Great Basin produced by Roberts and associates was followed by publication of the results of mapping programs in many areas in Nevada, Idaho, and eastern Washington. The results of those programs and the summary provided by Roberts et al. (1958) yielded the information that could be forged into lithofacies patterns and reconstructions of ancient environments. Berry and Boucot (1970) recorded the major Silurian lithofacies suites throughout western North America. Silurian-age strata in the several mapped areas were grouped into three main lithofacies, which are from east to west: the dolomite suite, the limestone suite, and the western facies rocks (Berry and Boucot 1970). These suites were traced from Nevada and adjacent portions of California northward through Idaho and eastern Washington into adjacent Canada (Berry and Boucot 1970). Berry (1972, 1974) noted that similar lithofacies suites could be recognized in Late Cambrian and Ordovician-age strata in western North America.

Stewart and Poole (1974) and Poole (1974) discussed more fully Early and Middle Paleozoic history of the western United States. These authors, and Churkin (1974), interpreted Paleozoic history of the western United States in terms of plate tectonic models. Their suggestions concerning the Paleozoic history of not only the Great Basin but also of the entire western part of North America were expanded upon in a series of papers that comprise the symposium "Paleozoic Paleogeography of the Western United States," organized by the Pacific Section of the Society of Economic Paleontologists and Mineralogists. That symposium, developed by John Stewart of the U. S. Geological Survey and Calvin Stevens of San Jose State University, was presented in Bakersfield, California, in April 1977. The symposium volume (Stewart, Stevens, and Fritsche 1977) contains a remarkable summary of interpretations of western American Paleozoic history. It is an impressive system by system summary of what was known to that time of western American Paleozoic stratigraphy, biostratigraphy, and geologic history. Since its publication, a symposium concerned with the Devonian System (Murphy, Berry, and Sandberg 1977) resulted in more detailed summaries of Devonian stratigraphy and paleontology in the western United States and adjacent Canada.

Developments in the Study of Paleozoic Rocks: A Current Synthesis

The stratigraphic record of Paleozoic rocks suggests that the western side of the North

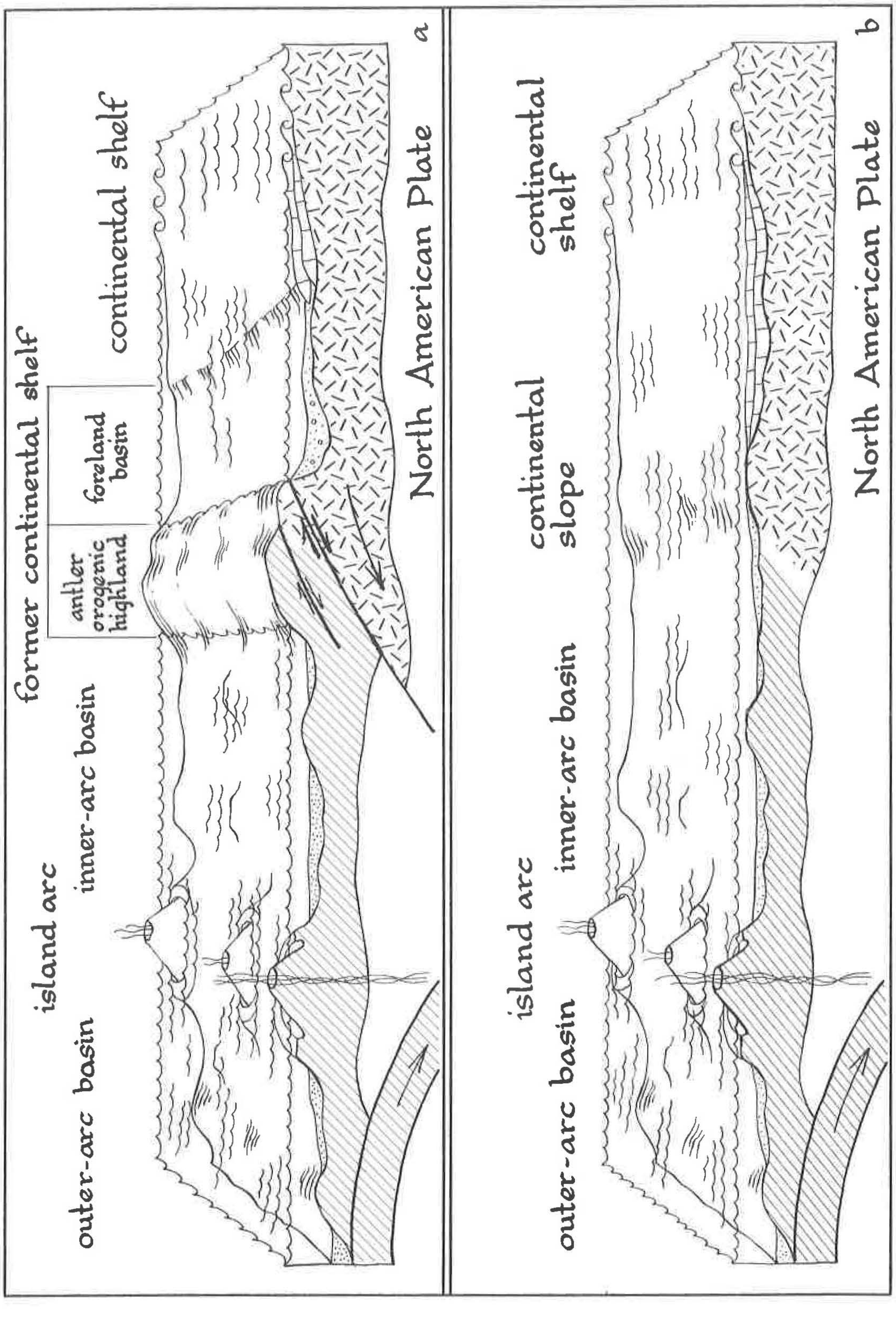
American plate during the Paleozoic was, for much of the time, a broad continental shelf. It lay under shallow seas in the tropics of that time. The shelf margin appears to have lain in about central Nevada, central Idaho, and eastern Washington. The trace of the Roberts Mountains Thrust seems to be approximately at the position of the edge of the North American shelf during the pre-Antler Orogeny interval of the Paleozoic.

West from the shelf margin (in modern geographic directions) lay a broad ocean basin in which mudstones, terrigenous detrital sandstones, cherts, some carbonates, and some volcanic rocks accumulated. As the sources for most of the volcanic and detrital terrigenous materials may well have been islands, some of which were volcanic atolls, Poole et al. (1977) suggested that an island arc system was present in about the position of the northern part of the present-day Sierra Nevada and Klamath Mountains. They depicted an island arc basin between that island arc system and the North American Paleozoic plate. That relationship was broken in the latest Devonian-Early Mississippian by the Antler Orogeny. Orogenic activity at that time resulted in creation of the Antler Orogenic Highland (Poole 1974; Poole and Sandberg 1977) from terrane that had been continental rise, continental slope, and perhaps the adjacent part of the inner arc basin prior to the orogenic activity. The Antler Orogenic Highland was a source for detrital terrigenous as well as carbonate clastic materials that were shed into a relatively deep trough formed as a result of the Antler Orogeny east (present-day direction) of the Antler Orogenic Highland (Fig. 2). The trough apparently subsided relatively rapidly and received a considerable thickness of coarse to medium grained sedimentary materials. The trough formed at the position of the outer part of the continental shelf prior to the Antler Orogeny. A marked relief inversion took place between former continental shelf and continental slope and rise as a consequence of the orogeny.

Poole (1974), Poole and Sandberg (1977), and Nilsen (1977) indicated that the Antler Orogenic Highland and its related trough extended from Nevada through central Idaho into eastern Washington. Poole and Sandberg also suggested that a relatively slowly subsiding "starved basin" was present during the Mississippian between the rapidly subsiding trough and a continental shelf upon which carbonates accumulated in an array of shallow marine environments. At least some of the Antler Orogenic Highland apparently was eroded to sea level or even partly subsided below sea level, and the trough next to it essentially filled by the Pennsylvanian. Parts of the former orogenic highland became sites of shallow marine depositional environments in which carbonates accumulated from time to time during the Pennsylvanian and Permian. Other segments of the Antler Orogenic Highland remained relatively high topographically during the Pennsylvanian as sources of sediment or barely awash under shallow seas.

Whereas carbonate sediments were deposited upon a continental shelf that had only a small amount of topographic relief during the Mississippian, basins formed in several places on the shelf during the Pennsylvanian and Permian (Bissell 1974). The Pennsylvanian-Permian continental shelf appears to have had considerable topographic relief with relative highs separating basins of different sizes (Bissell 1974; Rich 1977; Stevens 1977). Certain basins, notably the Oquirrh, underwent rapid subsidence and had high rates of sediment accumulation. By Permian time, rates of subsidence in the basins were, from time to time, more rapid than sediment accumulation, whereas at other times, sediments accumulated more rapidly than the basin subsided. As a consequence, evaporites formed locally in some basins, whereas other basins were sites of anoxic waters and slow rates of sediment accumulation.

Figure 2. Generalized, diagrammatic sketches showing possible relationships between a North American plate and an island arc system during the Paleozoic in what is today the western United States. (a) Sketch showing relationships at the time of the Antler Orogeny (latest Devonian-Mississippian) between a North American plate, the Antler Orogenic Highland, and an island arc system. (Figure adopted from Poole and Sandberg 1977). (b) Sketch showing relationships between a North American plate and an island arc system during most of the Early Paleozoic (Late Cambrian to Late Devonian). (Figure adapted from Poole et al. 1977).


a
former continental shelf
outer-arc basin
island arc
inner-arc basin
antler orogenic highland
foreland basin
continental shelf
North American Plate
b
outer-arc basin
island arc
inner-arc basin
continental slope
continental shelf
North American Plate

Coordination of Paleozoic Stratigraphy and Paleobiology: Past, Present, Future

The general features of Paleozoic stratigraphic synthesis have been developed in the decade of the 1970s. More detailed integration of environmental interpretations of the rocks and the faunal associations they bear lies ahead. Today, as was true even in Walcott's day, more thorough documentation of the fossil record is needed. The tradition Walcott (1884) sought to establish remains to be carried forward more fully than it has been in the past. When details of the sedimentologic features of the Paleozoic rocks have been sought and careful analysis of the faunas in the rocks carried out, environmental and ecologic relationships during the Paleozoic may be more fully documented. Geologic history may become a more finely spun tale.

Some paleobiologic investigations have been coordinated with stratigraphic ones. For example, Ziegler (*in* Berry and Boucot 1970) suggested that Silurian marine benthic associations could be interpreted to establish relative depths of the Silurian sea floor. Boucot (1975) pointed out that paleocommunity studies could be used to document certain environmental conditions such as water turbulence at the time of deposition.

Berry (1977), Matti and McKee (1977), and Stevens (1977) examined Siluro-Devonian and Permian rocks and their contained faunas and demonstrated that not only water depth relationships but also environmental conditions at the place and time of deposition could be depicted relatively clearly for short duration time increments. Examination of the central Nevada Silurian-Early Devonian rocks and faunas indicates that a linear trough or basin lay between two submarine topographic highs on the outer part of the continental shelf of the time. Indeed, the western (in present-day directions) high was a sort of lip at the shelf edge. The trough that lay east of it received calcium carbonate sediment that was generated by activity of organisms growing on the highs and margins of the basin. The basin itself was anoxic, supporting no bottom life. The only faunas found in its sedimentary record are graptolites, remains of planktic organisms. Basinal sediments are thinly laminated with interbedded sheets and channels of debris from the nearby highs. The basinal sediments have drawn considerable attention both for their biostratigraphic and their economic importance. Gold is being mined at Carlin, Nevada from rocks (the Roberts Mountains Formation) formed from basinal sediments. The ore occurs in carbonate rocks located close to the Roberts Mountains Thrust.

The biostratigraphic importance of the basinal sediments was recognized by members of the international group of stratigraphers and paleontologists who comprised the Silurian-Devonian Boundary Committee. Their task was to identify one stratigraphic section in some part of the world that was richly fossiliferous in a number of different organismal groups across the Silurian-Devonian boundary. Inasmuch as the members of that committee decided to use an evolutionary event in a graptolite lineage as the specific event in time upon which to denote the boundary, a stratigraphic section in which the specific graptolite lineage was represented was a primary consideration. Of nearly equal importance was the presence of many other different types of fossils interlayered or co-occurring with the graptolites. The basinal sediments in central Nevada were attractive because they are dominantly graptolite-bearing, but they contain numbers of corals, conodonts, brachiopods, and some trilobites as well. The non-graptolite faunas occur in debris flows that washed into the graptolite-bearing basinal sediments. Although the stratigraphic occurrences of these fossils were still being documented in 1970, at the time that the committee visited stratigraphic sections in the Roberts Mountains and the Simpson Park Range, both north of Eureka, Nevada, and at Lone Mountain, about 30 km west of Eureka, the abundance and diversity of fossils in stratigraphic sections of easy access were considered among the finest in the world. A section in the Roberts Mountains might have been selected as the bearer of the internationally recognized Silurian-Devonian System boundary were it not for the paucity of the published record of fossil occurrences in stratigraphic sections there.

Precise paleobiologic analyses of Silurian-Early Devonian faunas, coupled with those of the sedimentologic data embodied in the rocks bearing them, reveals that at times organic activity was so great and calcium carbonate production so high that calcium carbonate sediment accumulation greatly exceeded rates of subsidence and portions of the continental shelf were built up above sea level to become sites of erosion until subsidence created new marine environments for deposition (Matti and McKee 1977). Available fossil and sedimentologic data suggest that rapid rates of subsidence of the sea floor appear to have been relatively short-lived and were followed by long intervals of time during which subsidence was relatively slow. Further, subsidence was not uniform across the entire shelf at any one time.

Paleobiologic analyses of fossil communities of marine organisms is in its infancy. Available data from western United States Paleozoic rocks indicate that communities of marine benthic organisms changed little as long as environmental conditions remained essentially the same (Boucot 1978; Berry et al. 1979). When environmental conditions changed significantly, organismal associations changed markedly as well. Areas of similar environmental conditions seemed to have had organismal associations of about the same taxonomic diversity. Indeed, if a particular suite of environmental conditions that existed in an area were destroyed but then returned to the area, the communities that lived in that area under similar suites of environmental conditions had about the same taxonomic diversity, even though the actual organisms present were entirely different. Environmental conditions appear, therefore, to have had a major influence on species diversity. These and other paleobiologic interpretations await further testing. Study of Paleozoic rocks and faunas will contribute significantly to an understanding of evolutionary processes through time as well as the influence that environmental factors have had on community stability and diversity.

WESTERN NORTH AMERICAN PALEOZOIC ROCKS OUTSIDE THE NORTH AMERICAN PALEOZOIC PLATE

Paleozoic rocks from the non-volcanic and volcanic island arc and other terranes west of the North American Paleozoic plate have drawn attention both for their fossil content, which may shed some light on origins of certain of these rocks, and for their significance in structural and tectonic history. Stevens (1977) pointed out that western United States Permian faunas appear to be representative of three faunal provinces. The three are, from east to west: the North American, the eastern Klamath, and the Tethyian provinces. Each province is characterized by unique coral and fusulinid faunas. Stevens also noted that the North American and Klamath faunas are similar enough to suggest that they were not totally isolated from each other. Tethyan faunas are, however, so distinct that they suggest that they lived in areas distant from the Klamath Mountains or North American shelf seas during the Permian. Stevens stated that limestones bearing Tethyan faunas has been recovered from "limestone pods in mélange terranes in the northeastern Klamath Mountains, central Sierra Nevada west of the Melones Fault, and southern Sierra Nevada foothills." And, he went on to point out that "chaotic terranes in central Oregon are similar to some of those in the western Klamath Mountains and the western Sierra Nevada in that they contain certain exotic limestone blocks bearing Tethyan fusulinids" (Stevens 1977:125). Finally, Stevens drew attention to fusulinid faunas of Permian age in Washington, commenting that Permian fusulinids from eastern Washington are similar to coeval fusulinids in the Klamath Mountains.

Permian fusulinids from western Washington are Tethyan, and they appear to occur in terranes similar to those in which Tethyan fusulinids occur in Oregon and California. Tethyan fusulinid faunas occur in the western United States in rocks, primarily limestones, that are associated with Mesozoic radiolarian cherts. Their presence in the western United States appears to be related to Mesozoic tectonic history. The rocks bearing the Tethyan fusulinids may have been deposited in environments far distant from North America during the Paleozoic and moved, by drift, to their present locations. Future investigations of western American Paleozoic rocks and faunas, particularly those in structurally complex terrane, may aid in discriminating past histories of these rocks and their movements through space and time.

IN RETROSPECT

Paleozoic rocks and their faunas are today of more interest to paleogeographers and paleobiologists whereas a century ago, their attraction was for miners. A belt of mines that yielded and, in the case of the mines at Carlin, continue to yield ores from older (Cambrian-Early Devonian) Paleozoic carbonate hosts seems to lie along or close to the Roberts Mountains Thrust. Mines in the Belmont, Carlin, Cortez, Eureka, and Pioche districts in Nevada, the Bayhorse and Hailey districts in Idaho, and those in northeastern Washington are in or near the Roberts Mountains Thrust system (see Fig. 1). Aspects of the Antler Orogeny (latest Devonian-Early Mississippian) may have been influential in development and intrusion of ore-bearing solutions that formed the ores mined from these host rocks.

The early study of western American Paleozoic rocks had the economic imperative of metal mining. Today, investigations into Paleozoic rocks focuses on plate motions, although the two may actually be closely allied when origins of the ores are considered. Modern theory may provide an explanation for what in the late 1800s was an issue of considerable economic significance to the mining industry. Inasmuch as the Eureka district, Nevada has charmed geologists of several generations and its ores were found in Paleozoic carbonates near the Roberts Mountains Thrust, perhaps a fitting conclusion to this retrospective review of the study of western American Paleozoic rocks may be the following quotation from a letter written by George F. Becker, June 1, 1883, to J. W. Powell, Director of the U. S. Geological Survey, transmitting "An abstract of a report on the mining geology of the Eureka District, Nevada" by J. S. Curtis. That "abstract" was included as one of the "accompanying papers" in the report on the operations of the Geological Survey for the 1882-1883 fiscal year. Becker wrote: "The information to be gained in Eureka is not, however, of merely local importance, for although these deposits, like those of every mining region, present features peculiar to themselves, they belong to a class of very wide distribution throughout the world and which is abundant in the Western United States. This class is characterized by the occurrence of irregular bodies of argentiferous lead ores in limestone, generally accompanied by somewhat obscure evidence of connection."

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MESOZOIC STRATIGRAPHY–THE KEY TO TECTONIC ANALYSIS OF SOUTHERN AND CENTRAL ALASKA

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Southern and central Alaska comprises an enormous tectonic mosaic composed of separate structural blocks and fragments that accreted to North America during Mesozoic and early Cenozoic time. Some of these blocks are far-traveled, as shown by paleomagnetic studies. More than 25 discrete tectonostratigraphic terranes now are known, each of which exhibits a characteristic internal stratigraphic sequence that differs markedly from that of neighboring terranes.

Lower Mesozoic rocks are widely distributed in these terranes, and they provide the most complete information for analyzing regional depositional and structural patterns. Sedimentary and volcanic facies of these ages include: nonmarine red beds with intercalated basalt flows; shallow marine sandstone, conglomerate, and siltstone; deep-water limestone, chert, and argillite; pillow basalt with associated deep-water volcaniclastic sedimentary rocks; inner to outer platform carbonate rocks; andesitic flows, tuffs, and volcanic sedimentary rocks with marine fossils; subaerial basalt flows; and deep-water cherty crystal tuff. No systematic depositional patterns are perceived that would permit these contrasting facies to have been deposited in their present structural positions. Instead, large-scale tectonic juxtaposition is required.

The dominant structural style produced during accretion is thrust faulting, modified by concurrent and/or subsequent strike-slip faulting. Some terranes may form enormous nappes, but much more detailed stratigraphic and structural studies are needed, with emphasis on the age and stratigraphy of deep-water siliceous and carbonate rocks, before the complex history of deposition and subsequent accretion can be adequately elucidated.

Stratigraphic studies are so essential to tectonic syntheses of large areas that it is impossible to clearly separate the two. This report emphasizes the contribution that Mesozoic stratigraphic research has made to concepts regarding the tectonic evolution of western North America–particularly of southern and central Alaska. The point to be stressed is that an understanding of regional deposition and tectonic patterns can only be gained within a well-defined, precise, and readily available biostratigraphic framework. The key to geologic history is geochronology, and for Mesozoic and older rocks, this really means biogeochronology, because only rarely do nonplutonic rocks of pre-Cenozoic age yield accurate radiometric ages. The need for precise biostratigraphic dating is especially critical in the tectonically mixed terranes that are so abundant along the Pacific margin.

In this brief summary, it is possible to review only some examples that illustrate how studies of Mesozoic rocks have played a key role in formulating important tectonic concepts. These examples are drawn from the diverse Mesozoic strata of southern and central Alaska that occur in a number of discrete tectonostratigraphic terranes that constitute parts of a gigantic tectonic mosaic produced by accretion of allochthonous blocks.

TECTONOSTRATIGRAPHIC TERRANES OF ALASKA

Recent geologic and geophysical studies have shown that much of Alaska constitutes an enormous tectonic mosaic composed of separate structural entities termed "tectonostratigraphic terranes" (Jones, Silberling, and Hillhouse 1977, 1978; Berg, Jones, and Coney 1978; Churkin and

Carter 1979; Dutro and Jones, in press). Each terrane is characterized by one or more distinctive internally coherent stratigraphic sequences composed of rock units that can be linked through time by depositional relationships and by recycled clasts derived from underlying units. Within terranes normal facies changes are expectable and can be studied through application of well-known stratigraphic procedures. Between adjacent terranes, however, normal facies changes cannot be demonstrated and totally unlike packages of rocks showing radically differing geologic histories are commonly closely juxtaposed. Thus, elucidation of the tectonic history of Alaska relies entirely on detailed stratigraphic studies that pinpoint discontinuities in facies trends or depositional histories that require tectonic explanation.

A simplified tectonostratigraphic terrane map of Alaska (exclusive of the Seward Peninsula and southeastern Alaska) is shown on Fig. 1. Some terranes are too small to be portrayed at the scale of this map and have been omitted or combined with others. A map at a much larger scale (1:2,500,000) for all of Alaska is now in preparation. Twenty-nine terranes are discriminated on the small-scale map. At least 50 terranes, blocks, and fragments have been recognized to date, but future work will undoubtedly require both splitting of some terranes and amalgamation of others, so that the total number of separate structural entities cannot be accurately predicted at this time.

No attempt is made herein to describe each terrane or to summarize the incredibly complex tectonic and depositional histories recorded by the formation and accretion of each terrane. Rather, the emphasis will be on the methodology and kinds of information that were required in order to percieve and discriminate the various terranes. To do this, we will concentrate on lower Mesozoic rocks in the southern and central parts of the state where the stratigraphic sequences and age relations of most terranes are reasonably well understood.

Stratigraphic sequences characteristic of 10 tectonostratigraphic terranes extending from southern Alaska near the Canadian border to central Alaska are shown in Fig. 2. The generalized location for each column is indicated on Fig. 1. Brief descriptions of each sequence are given in the following section, starting in the southeast corner of the state and proceeding in a generally northwesterly direction.

STRATIGRAPHIC SEQUENCES OF TECTONOSTRATIGRAPHIC TERRANES IN SOUTHERN AND CENTRAL ALASKA

Wrangellia

Four formations of Triassic age are known from the Wrangell Mountains of east-central Alaska (loc. 1, Fig. 1), where they have been studied in detail by MacKevett and coworkers (see MacKevett 1976). The lowest unit of Middle Triassic (Ladinian) age has a limited distribution and comprises a thin sequence (100 m) of grayish-black thin-bedded chert, siltstone, and fissile shale in which the bivalves *Daonella degeeri* and *D. frami* are locally abundant. This unit overlies Lower Permian argillite and limestone of the Hasen Creek Formation and is overlain by the Nikolai Greenstone of Middle and/or Late Triassic age.

The Nikolai Greenstone constitutes a vast, largely subaerial, but locally pillowed basaltic lava field that occurs throughout the Wrangell Mountains and the adjoining eastern Alaska Range. It extends eastward into Canada, where it is an important element of the Mush Lake Group of Muller (1967). MacKevett and Richter (1974) report that the Nikolai consists of intermixed aa and pahoehoe flows between 0.3 and 15 m thick and reaches a cumulate thickness exceeding 3,500 m. Chemical analyses reported by MacKevett and Richter (1974) indicate that the basalts generally are slightly quartz-normative tholeiites but also include some that are olivine normative. Amygdules are abundant and are mainly filled with chlorite and calcite and less commonly quartz, epidote, prehnite, or zeolites, and native copper or copper-bearing ore minerals.

The Nikolai is disconformably overlain by a sequence of Triassic sedimentary rocks up to 1,400 m thick, commencing with limestone and dolomite that locally contain stromatolites, algal-mat chips, relicts of evaporites, and other indicators of deposition under sabkha conditions

(Armstrong and MacKevett, in press). These inner-platform carbonate rocks of the Chitistone Limestone grade upward into more open platform limestones and then into the open platform or basinal limestones of the Nizina Limestone (Armstrong et al. 1969).

Some beds at the transition between the Chitistone and Nizina limestones contain a remarkably diverse silicified fauna of lower Norian invertebrate shells and skeletal fragments representing gastropods, bivalves, brachiopods, corals, spongiomorphs, cephalopods, and echinoderms. About 30 specifically distinct taxa of gastropods alone are represented.

Conformably above the Nizina are basinal deposits of calcareous shale, impure limestone, impure chert, and spiculite of the McCarthy Formation of Late Triassic and Early Jurassic age (MacKevett 1976). Larger invertebrate fossils from the Triassic part of this formation are restricted to pelagic forms such as *Monotis, Heterastridium,* and ammonoids. Ammonites of Hettangian to late Sinemurian age occur in the upper part of the formation.

The Lubbe Creek Formation of Pliensbachian to late Toarcian age conformably overlies the McCarthy Formation. This unit consists of 100 m of impure spiculite with lenses and beds of coquinoid limestone and minor chert. Disconformably above the Lubbe Creek is a sandstone unit up to 400 m thick named by MacKevett (1969) the Nizina Mountain Formation. This consists of well-bedded, feldspathic, reddish-brown-weathering graywacke with minor shaly beds and fossiliferous limy lenses and concretions containing fossils of Bajocian and Bathonian ages.

The uppermost Jurassic unit, the Root Glacier Formation, includes 1,200 m of mudstone, siltstone, graywacke, and conglomerate. Fossils range in age from early Oxfordian to late Kimmeridgian.

Deposition of Cretaceous rocks in the eastern Wrangell Mountains commenced in early Albian time, following a period of folding and faulting that affected older rocks as young as Late Jurassic (Jones and MacKevett 1969). Nearly continuous deposition of clastic rocks and minor chert continued through the Cretaceous until late Campanian or early Maestrichtian time.

In the western Wrangell Mountains, basal Cretaceous strata are as old as Hauterivian and Barremian (?). These are overlain unconformably by lower Albian beds similar to those of the eastern Wrangells. Aptian strata are absent.

Peninsula Terrane in the Talkeetna Mountains

Mesozoic volcanic, plutonic, and sedimentary rocks exposed in the Talkeetna Mountains of southern Alaska constitute the northeastern end of a long, nearly continuous belt that to the southeast forms the backbone of the Alaska Peninsula. Geologic mapping by Arthur Grantz (1960a, b, c; 1961a, b) and numerous paleontologic studies by R. W. Imlay (1953, 1961, 1962, 1964), D. L. Jones (1963, 1967), and Jones et al. (1965) have elucidated the basic stratigraphic framework of Mesozoic rocks in the Talkeetna Mountains.

The oldest exposed rocks are lavas, tuffs, and volcanogenic sandstones and siltstones of the Talkeetna Formation. This unit is more than 2,000 m thick and ranges in age from at least early Sinemurian to late Toarcian (Imlay and Detterman 1973:11). It is overlain unconformably by the Tuxedni Group, comprising 250 to 400 m of fossiliferous sandstone and siltstone of Middle Jurassic (Bajocian) age. Younger Middle and Upper Jurassic rocks of Bathonian, Callovian, and Oxfordian to Kimmeridgian ages are over 1,000 m thick and are subdivided into three unconformity bounded formations–an unnamed tongue, a middle Chinitna Formation, and the upper Naknek Formation. Succeeding Cretaceous rocks range in age from Early Cretaceous (late Valanginian) to Late Cretaceous (latest Campanian or early Maestrichtian) and are entirely clastic. A distinctive calcarenite composed dominately of comminuted *Inoceramus* shells (Jones 1973) occurs locally at or near the base.

Susitna Terrane

The Susitna terrane consists of two mappable units: a Cretaceous flysch unit and an Upper

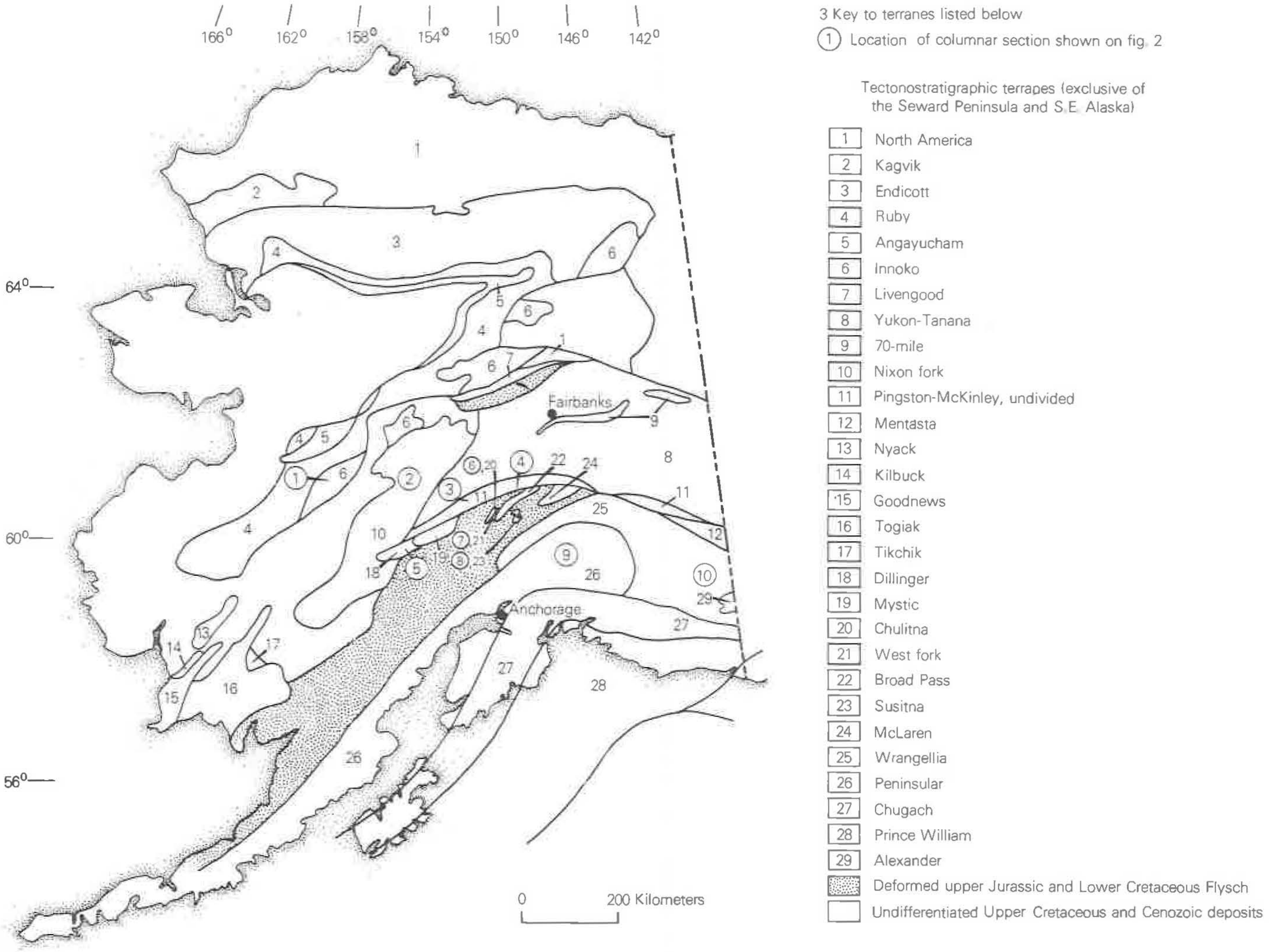

Figure 1. Simplified map showing tectonostratigraphic terranes in Alaska (exclusive of the Seward Peninsula and southeastern Alaska).

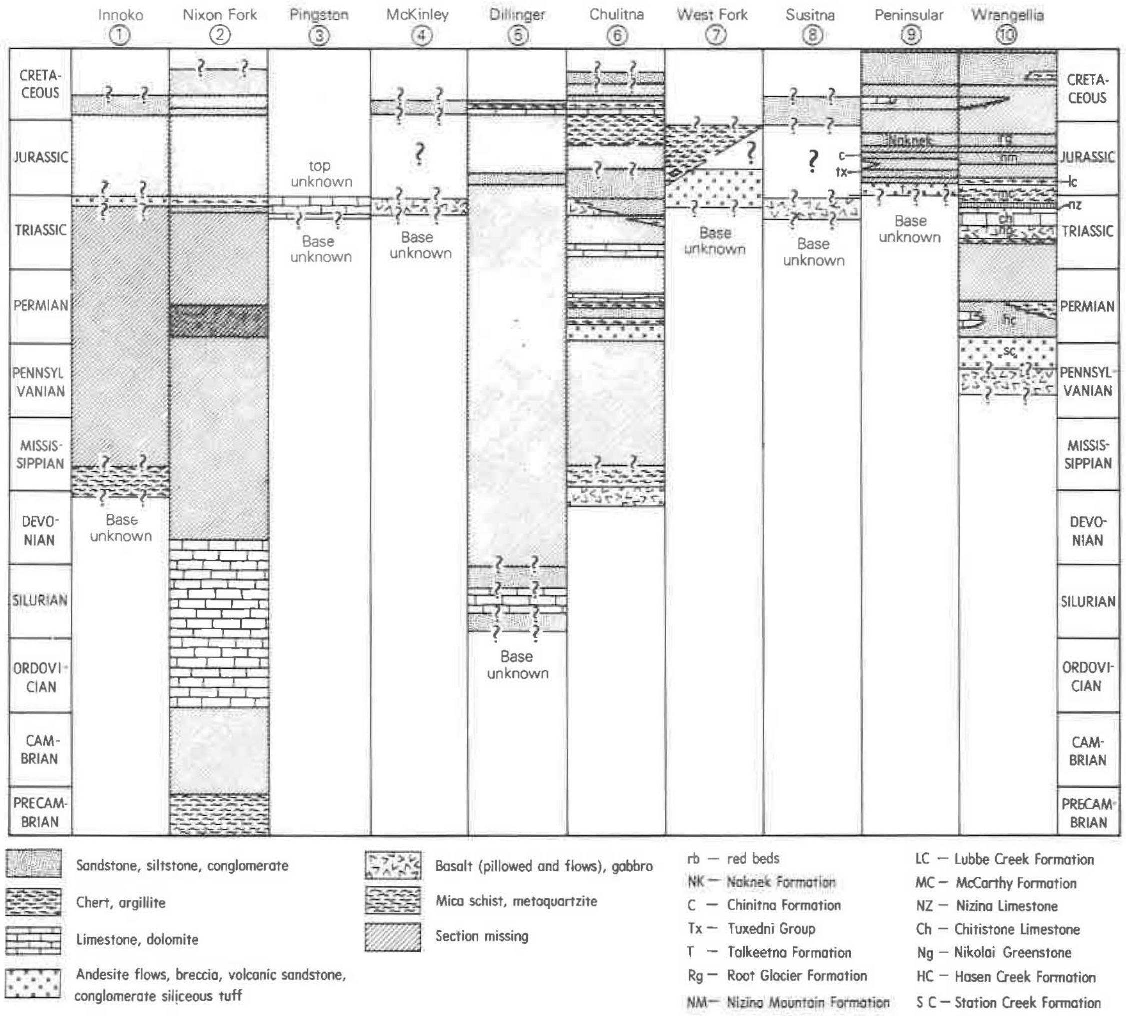

Figure 2. Columnar sections from selected tectonostratigraphic terranes of southern and central Alaska. See Fig. 1. for location of columns.

Triassic pillow basalt and clastic sedimentary rock unit. The flysch-like rocks of the Susitna terrane are not known in detail. They are dominantly fine grained with local interbeds of fine- to medium-grained graywacke. Bedding and slaty cleavage dip dominantly to the southeast, and many of the strata are overturned to the northwest.

Fossils are extremely rare within the flysch of the Susitna terrane and are known from only two localities. Only one poor specimen of *Inoceramus* of probable Cretaceous age and a bed of *Buchia*-bearing limestone of Valanginian age have been found.

Two large sheets of basalt (some pillowed) with intercalated tuffaceous sedimentary rocks are structurally interleaved with the upper Mesozoic flysch. The sedimentary intercalations contain the Late Triassic (late Norian) fossils *Monotis subcircularis* and *Heterastridium*. The Triassic rocks are overturned to the northwest and comprise two parts—a stratigraphically lower part of pillow basalt several hundred or more meters thick, and an upper part of intercalated massive basalt flows, tuff, sandstone, and siltstone 300 to 400 m thick. The fossils were obtained from the upper part of this unit. In the past, these rocks have been loosely correlated with the Middle and/or Upper Triassic Nikolai Greenstone of the Wrangell Mountains (for example Jones et al. 1977) but the presence of the late Norian fossils demonstrates that these two basaltic units are dissimilar in age.

Upper Mesozoic flysch occurs both above and below this inverted slab of Triassic basalt. Original depositional superposition of the flysch upon the Triassic basalt is possible, but the original nature of their contact is not known. The mapped distribution of the Triassic rocks suggests that they form a large thrust sheet or nappe that is isoclinally folded and overturned to the northwest.

West Fork Terrane

The West Fork terrane consists of three fault-bounded mappable units that are described below in descending structural order. It must be stressed that stratigraphic relations have not been established nor are the ages of some of the rocks in this terrane adequately determined.

Multiply deformed isoclinally folded beds of argillite, chert, and sandstone form the structurally highest part of the West Fork terrane throughout most of its length. Gray to black chert locally predominates, but argillite and thin-bedded sandstone are the most common rock types; locally, massive graded siltstone and sandstone with interbedded argillite form the bulk of exposures. Several samples of chert have yielded well-preserved radiolarians of Late Jurassic age (Jones et al. 1980).

Fault-bounded blocks and lenses of thick-bedded (up to 1 m) fossiliferous phosphatic limestone, siltstone, sandy limestone, and limy conglomerate occur within the argillite, chert, and siltstone unit. These bodies range in size from about 50 m to over a kilometer in length. Early Jurassic ammonites and bivalves were found at five localities and all are indicative of an early Sinemurian (Early Jurassic) age. Hence rocks of Early and Late Jurassic age are juxtaposed without any apparent stratigraphic order.

A very thick unit of massive, cliff-forming dark-grayish-green crystal tuff and argillite with minor fossiliferous sandstone and conglomerate lies in fault contact immediately southeast of the argillite, chert, and sandstone unit. Original thickness of this massive unit cannot be determined because of internal deformation and lack of marker beds. Original relations between these two units are obscure, but several lines of evidence suggest that the massive tuff and argillite unit now structurally underlies the argillite, chert, and sandstone unit and may, in part, be the older of the two. Fragments and pebbles of crystal tuff occurring in the argillite, chert, and sandstone unit suggets derivation from the massive tuff.

Relatively coarse-grained patches and layers of the tuff consist mostly of calcitized plagioclase crystals up to 0.5 mm in size, along with mafic volcanic and indeterminate lithic grains, set in a cryptocrystalline impure siliceous matrix. Finer grained layers are mostly cherty matrix with sporadic crystals up to about 0.1 mm in size.

Fossils of Early Jurassic (late Sinemurian) age were found at one place within the massive tuff unit in 2- to 3-m-thick beds of conglomeratic sandstone that contain phosphatic pellets. These coarse clastic rocks are overlain by 30 m or more of dark-gray siltstone with minor beds of conglomerate, which are in turn overlain by fine-grained crystal tuff similar to that forming the bulk of the unit. These appear to be among the youngest exposed beds of the massive tuff unit which may be several thousand meters thick.

The base of the massive tuff unit is unknown, as is the internal structure and the age of the bulk of the formation. Because of its great thickness, we assume that some of the rocks may be of Triassic age, but no fossils are available to prove this.

Chulitna Terrane

The upper Chulitna mining district is characterized by a distinctive sequence of Paleozoic and lower Mesozoic rocks found nowhere else in Alaska (Hawley and Clark 1974; Clark et al. 1972; Silberling et al. 1978; Jones et al. 1980). This sequence, termed the Chulitna terrane, is complexly folded and faulted, and structurally overlies Mesozoic strata of unlike character (including the West Fork terrane).

The oldest rocks of the sequence include serpentinite, gabbro, diabase, pillow basalt, basalt breccia, and red radiolarian chert. This assemblage is believed to constitute a dismembered ophiolite of Late Devonian age (Silberling et al. 1978), based on fossils obtained from the chert (Brian Holdsworth, written commun. 1976).

Rocks younger than the ophiolites include: Mississippian chert, Permian volcanic conglomerate and breccia, flysch, chert, and limestone; Lower Triassic limestone; Upper Triassic breccia composed of blocks of limestone in an argillite matrix; Upper Triassic red beds with interbedded basaltic and silicic volcanic rocks; Jurassic siltstone, sandstone, and chert; and Cretaceous argillite, chert, sandstone, and thin beds of coquinoid (*Buchia*) limestone.

The Triassic part of this assemblage is of particular importance as it contains a more complete record of Early Mesozoic history than any other place in Alaska south of the Brooks Range. As such, the Chulitna terrane constitutes a key reference section against which other nearby terranes can be compared and contrasted.

Exposed Lower Triassic rocks consist of about ten meters of limestone with beds of secondary chert. The uppermost limestone bed contains abundant specimens of ammonites of Smithian age that show southern faunal affinities (Nichols and Silberling 1980). This bed is locally capped by 10 cm of cherty, phosphatic argillite containing abundant fragments of fish bones and conodonts of lowest Spathian age, as determined by B. R. Wardlaw (written commun. 1978). These rocks are unconformably overlain by a few meters of sandy limestone, the base of which is conglomerate, and then, above a covered interval, by several meters of greenish-gray argillite containing boulder-size blocks of limestone. Fossils from these blocks are *Halobia*, brachiopods, and conodonts of Karnian age (B. R. Wardlaw, written commun. 1978). The age of the matrix is unknown. Red mudstone with limestone blocks overlies the greenish-gray argillite, and, in turn, is overlain by red conglomeratic sandstone with intercalated basalt flows.

Elsewhere within the terrane these red beds are hundreds of meters thick and contain a few thin limestone units which have yielded ammonites and other fossils of Late Triassic (Norian) age. The character of the clastic detritus in the red beds indicates two discrete sources. Basalt, gabbro, serpentinite, and chert clasts were derived from the underlying oceanic Devonian ophiolite, as evidenced by identical radiolarian faunas in the *in situ* chert and in clasts. Polycrystalline quartz, mica, metaquartzite, and schist clasts were derived from a metamorphic terrane of continental affinity. Clasts of similar composition are unknown in older conglomerates within the Chulitna terrane; instead, they are entirely of volcanic and sedimentary origin. The source for the silicic detritus has not been identified, but its sudden appearance, mixed with ophiolite debris, indicates a major tectonic event occurred during Late Triassic time along a continental margin.

The Triassic red beds grade upward into marine sandstone and siltstone of latest Triassic and

The Triassic red beds grade upward into marine sandstone and siltstone of latest Triassic and Early Jurassic age. The passage beds show numerous cycles of marine and nonmarine deposition before fully marine conditions were established. Shallow-water fossils, such as large heads of scleractinian colonial corals, *Heterastridium*, and diverse bivalves, are abundant.

Younger Mesozoic rocks consist of chert, argillite, sandstone, and minor limestone of Late Jurassic and Early Cretaceous age. As these strata are complexly faulted and isoclinally folded, a detailed stratigraphy for this part of the section has not been established and comparison with other terranes is difficult.

McKinley Terrane

Rocks in the southern part of McKinley Park, north of the Denali fault, comprise a poorly understood, structurally complex terrane composed of interleaved clastic rocks (flysch and conglomerate), minor chert, and large masses of pillow basalt, breccia, tuff, diabase, and gabbro. No stratigraphic sequences have been established and ages of only a few of the rocks are known.

Hickman and Craddock (1975) determined an age of "Permian and(or) Pennsylvanian" for the bulk of these rocks but suggested that older and younger rocks also may be present. Their age determination was based on two K/Ar analyses from gabbro, which gave ages of 307 m.y. and 139 m.y., and on several fossil localities that produced Paleozoic fossils. We revisited two of their fossil localities; at loc. UW1574/11 we recovered from limestone clasts in a massive conglomerate fossils of Devonian and Permian ages (J. T. Dutro, written commun. 1978). Black chert pebbles yielded probable Mississippian radiolarians. The age of the conglomerate is post-Permian, probably Late Jurassic or Cretaceous. From loc. UW1574/4 we found poorly preserved scraps of *Buchia*(?) in siltstone and Mesozoic radiolarians in chert. An Early Cretaceous (Valanginian) age for both seems likely.

Fossils from the volcanic rocks of the McKinley terrane are exceedingly scarce—only one small specimen is known. This consists of an incomplete example of *Halobia*, probably *H. superba* or *H. cordillerana*, which was found by Wyatt Gilbert west of Polychrome Pass (University of Alaska loc. A-370). A late Karnian to mid-Norian age is indicated. The relation of these rocks to the gabbros dated by Hickman and Craddock (1975) is unknown.

Dillinger Terrane

A thick sequence of deformed Paleozoic sedimentary rocks in the central Alaska Range have been referred to as "sedimentary rocks of the Dillinger River" (Armstrong et al. 1977; Reed and Nelson 1977). These rocks consist of three units: interbedded lime mudstone and shale of unknown thickness; deep-water lime mudstone more than 900 m thick; and interbedded lithic arenite, shale, and limestone at least 700 m thick. Because of structural complexities, the relative ages and stratigraphic relations of these rocks are unknown, but both graptolites and conodonts of Silurian age are known from the limestone unit (Armstrong et al. 1977:B62).

These lower Paleozoic rocks are overlain unconformably by a thin unit a few tens of meters thick of fossiliferous limy and phosphatic siltstone and sandstone of Early Jurassic (Sinemurian) age (R. W. Imlay, written commun. 1977). This unit is overlain by several meters of chert, siltstone, and limestone with abundant Buchias of Early Cretaceous (Valanginian) age. Triassic strata are absent.

Both the Mesozoic rocks and the underlying Paleozoic rocks are here referred to as the Dillinger terrane.

Pingston Terrane

A thick, isoclinally folded sequence of interbedded siliceous, laminated limestone, sooty black shale, and calcareous siltstone crops out discontinuously north of the Denali fault in the northern foothills of the central Alaska Range. These rocks are referred to as the Pingston terrane.

Southwestern exposures were mapped by Reed and Nelson (1977), who suggested a correlation with lower Paleozoic strata. Upper Triassic conodonts were reported from two localities by Hickman and Craddock (1975) in equivalent strata to the east in McKinley Park, and additional Upper Triassic conodonts have since been found in numerous localities in and east of the Park (D. L. Jones, N. J. Silberling, and B. R. Wardlaw, unpub. data; Paul Umhoefer, written commun. 1978). Lithologically similar, but more highly metamorphosed strata occur north of the Denali fault to the southeast near the Canadian border (Richter 1976), but no fossils have been found there to substantiate the lithologic correlation.

Throughout its known and inferred extent, the Pingston stratified rocks are intruded by large masses of gabbro and diabase, but no volcanic rocks are known within the terrane. The age of the basic intrusives has not been established, but it probably is Mesozoic.

Neither the depositional top nor the base of the Triassic rocks of the Pingston terrane have been observed. They are in fault contact with late Mesozoic clastic rocks and Triassic basalt of the McKinley terrane on the south, and regionally metamorphosed Paleozoic rocks of the Yukon-Tanana terrane to the north, across the Hines Creek fault.

Nixon Fork Terrane

A thick sequence of Precambrian(?), Paleozoic, and Mesozoic rocks in west-central Alaska is called the Nixon Fork terrane by Patton (1978). The basal unit consists of mica schist and quartzite of probable Precambrian age. This is overlain along a sheared contact (Patton et al. 1977:B39) by a thick sequence of platform limestones and dolomites of Ordovician to Devonian ages. Similar rocks occur to the southwest in the Lime Hills region.

Unconformably overlying the carbonate sequence is 60 meters of sandy limestone, grit, limy sandstone and mudstone containing abundant Permian brachiopods (Patton et al. 1977). Clasts of mica schist from the lowest unit locally occur in the basal part of this sequence.

Mesozoic rocks unconformably overlie the Permian and consists of 50 meters of limy sandstone, conglomerate, sandy limestone, and siltstone with species of *Eomonotis* and relatives of *Monotis ochotica* of middle and late Norian age. These clastic rocks grade abruptly into a thick (100 m) unit of dark-gray bedded chert composed dominantly of sponge spicules with rare radiolarians. This, in turn, is unconformably overlain by sandy limestone, grit, coquinoidal limestone, sandstone, and siltstone of Cretaceous (Valanginian and younger) age.

The occurrence in this succession of these particular species of the bivalve *Monotis* is of paleotectonic significance because they are characteristic of Triassic exposures in the Arctic and western Pacific. They are not found in any of the terranes that lie closer to the Pacific basin in southern Alaska where the genus *Monotis* is represented by different, but partly coeval, species.

Innoko Terrane

A thick, poorly exposed, and structurally complex assemblage of chert, volcanic and volcaniclastic rocks, minor limestone, and graywacke crops out in the Medfra and Ruby quadrangles of west-central Alaska. This assemblage, named the Innoko terrane by Patton (1978), continues on to the northeast and may include rocks of the Ramparts Group. It also is known to extend to the southwest, into the Ophir quadrangle (unpub. data of R. Chapman, D. L. Jones, and Brian Holdsworth).

The oldest rocks of the Innoko terrane consist of variegated cherts and argillite of latest Devonian and Carboniferous (Mississippian) age. Mesozoic rocks include a thick sequence of tuff, volcanic conglomerate, breccia, and basalt, with intercalated radiolarian chert of Late Triassic (Norian) age. Much of the volcanic detritus appears to be intermediate in composition, and probably represents andesitic arc volcanism.

Unconformably(?) overlying the Triassic volcanic assemblage is a thick unit of volcanic sandstone, conglomerate, and tuff of probable Early Cretaceous age.

STRATIGRAPHIC ANALYSIS

The basic stratigraphic data for 10 key terranes in southern and central Alaska have been briefly reviewed in the preceding section and are summarized in Fig. 2. Triassic rocks provide the most meaningful information inasmuch as important deposits of that age occur in 9 of the 10 terranes, and these show marked differences in lithology, fossil content, thickness, and history from one terrane to another. In contrast, Jurassic strata are well developed only south of the Denali fault, and only Lower Jurassic rocks display markedly different character in adjoining terranes. Cretaceous rocks are generally similar in all terranes in which they occur, although they do manifest significant differences in depositional history, thickness, and severity of deformation from place to place. Because of the relative abundance of Triassic and Lower Jurassic rocks, the following analysis will concentrate on the character and distribution of these strata.

As shown in Fig. 2, a wide variety of volcanic and sedimentary rocks characterize the early Mesozoic deposits of southern and central Alaska. Each terrane has an internally coherent stratigraphic sequence that records historical events unique to that terrane alone.

For example, the Wrangellian sequence is characterized by an enormous outpouring of subaerial basaltic lava that abruptly ceased in late Karnian time, to be succeeded by inner platform pure carbonate deposits. Later deposition records gradual sinking of this volcanic-carbonate edifice until deep-water basinal conditions were established that persisted until the end of Early Jurassic time. Coarse clastic detritus is unrepresented in the Alaskan exposures of this terrane, so its site of deposition must have been far distant from either volcanic or continental land masses.

In contrast, the Chulitna sequence totally lacks basaltic volcanics of Karnian age, but does contain basalt of Norian age intercalated with coarse clastic nonmarine and shallow marine deposits. Both locally derived and exotic (polycrystalline quartz and mica schist) detritus occur in the red beds, so proximity to a continental source is required. One possible source for the exotic material is the poly-metamorphosed Yukon-Tanana terrane that occurs extensively in east-central Alaska and the adjoining Yukon Territory. The difficulty with this source is that the coeval Upper Triassic, but nonvolcanic, Pingston terrane, which borders the Yukon-Tanana terrane through most of its extent in Alaska, is of deep-water facies and contains no recognizable coarse detritus that could have been derived from its metamorphosed neighbor to the north. Similarly, quartzose detritus is absent from the nearby Susitna terrane, which is characterized by pillow basalt and deep-water volcanogenic sedimentary rocks. Thus, with these terranes in their present positions, no area can be identified as the source of the Chulitna detritus, nor can a single depositional model relate these terranes to one another.

The Pingston terrane itself is in an anomalous position, as its southern terminus is sandwiched between the Dillinger terrane to the southwest, which lacks Triassic rocks altogether, the Nixon Fork terrane to the northwest, which contains a thin sequence of nonvolcanic Norian sandstone, conglomerate, and chert, and the McKinley terrane to the south, which includes very thick units of Upper Triassic (Norian?) pillow basalt mixed with Mesozoic flysch-like rocks. No obvious connections between any of these terranes are apparent. Deep-water volcanogenic (andesitic) deposits with intercalated chert, also of Norian age, lie farther to the north in the Innoko terrane, but the relation of these rocks to those farther south is unknown.

The Lower Triassic limestone unit that underlies the Chulitna red beds likewise presents an anomaly, as this is the only occurrence of rocks of this age in southern Alaska. Elsewhere, as in Wrangellia, Middle Triassic rocks lie directly on Permian strata with no discernible angular discordance.

As Nichols and Silberling (1980) point out, the ammonites from the Lower Triassic strata of Chulitna are entirely species described previously from localities in the western conterminous United States that were situated at paleolatitudes of about 10° north. Faunas from higher paleolatitudes are quite different in species content. The implication of this point is that the Chulitna rocks have been transported northward from their point of origin in tropical paleolatitudes.

Marked contrasts are seen in Lower Jurassic strata between the eastern end of the Peninsular terrane in the Talkeetna Mountains and coeval strata of Wrangellia. The former are entirely volcanic and volcanogenic, while the latter lack any evidence of volcanic activity. Likewise, as pointed out by Jones et al. (1977), Upper Triassic rocks that underlie the Jurassic volcanic rocks on the Alaska Peninsula lack Wrangellian affinities. Because of these differences, it cannot be demonstrated that the Peninsular terrane and Wrangellia shared a common early Mesozoic history. Later Jurassic and Cretaceous deposits of the two terranes are similar, implying a common history from at least Late Jurassic time to the present.

Other anomalous relations are apparent in the character and distribution of Lower Jurassic strata. For example, the deep-water, cherty crystal tuffs of the West Fork terrane have no known counterpart, and they contrast markedly with the shallow-water, fine-grained, limy clastic rocks of the nearby, structurally overlying Chulitna sequence. On the other hand, the large blocks of ammonite-bearing phosphatic, calcareous siltstone and conglomeratic sandstone that occur in the West Fork terrane mixed with deformed Upper Jurassic chert and argillite are faunally and lithologically similar to Lower Jurassic strata of the Dillinger terrane that lies to the southwest. Older rocks of these two terranes are totally dissimilar. The similarity in Lower Jurassic strata of the two terranes may signify their proximity during Early Jurassic time.

TECTONIC ANALYSIS

The preceding brief review of Mesozoic stratigraphic relations reveals marked, abrupt discontinuities in stratigraphic sequence in adjoining terranes that cannot be explained by simple facies changes. These marked discontinuities, coupled with paleomagnetic studies that indicate some Mesozoic rocks formed at low paleolatitudes (Packer and Stone 1974; Hillhouse 1977; Stone and Packer, in press), reinforce earlier interpretations that allochthonous fragments make up the bulk of Alaska and the adjoining Cordillera of Canada (Richter and Jones 1971, 1973; Berg et al. 1972; Monger and Ross 1971; Jones et al. 1972; Monger et al. 1972; Monger 1975, 1977; Csejtey 1976; Jones et al. 1976, 1977, 1978; Berg et al. 1978; Davis et al. 1978; Jones et al. 1980; Monger and Price 1979; Stone and Packer 1979).

The only part of Alaska that we interpret as clearly autochthonous and that has remained part of North America since Precambrian time is a small area in the northeastern corner of the state, bounded by the Yukon and Porcupine rivers. Everything else, including the Brooks Range, has moved to some extent, although little agreement exists as to the nature, timing, and magnitude of most of these movements.

Adequate paleomagnetic data exist only in the southern and southeastern parts of Alaska, so it is only for these regions that we have quantitative measurements for the amount of movement involved in the accretionary process. Wrangellia is clearly far travelled, as paleomagnetic data indicate extrusion of Triassic lava flows at low paleolatitudes (Hillhouse 1977). The Peninsular terrane likewise has moved northward, based on paleomagnetic data obtained from Jurassic rocks of the Alaska Peninsula (Packer and Stone 1974). These data are not adequate to determine whether Wrangellia and the Peninsula terrane moved together or separately, but geologic evidence supports their separation until post-Early Jurassic time.

The loci of origin of the other terranes in southern and central Alaska discussed in this report are not known, although a southern origin for most seems required. This is particularly true for the Chulitna terrane, as both the Upper Triassic red beds and the Lower Triassic ammonite faunas show clear southern affinities.

The large quantities of basalt, both pillowed and in flows, that characterize Wrangellia as well as the McKinley, Chulitna, and Susitna terranes may be related to rifting events. If so, the age of the basalt is a critical indicator for the time of initiating of rifting. Wrangellia, which is probably the most far-travelled block, contains the oldest basalt (Ladinian to late Karnian). All the other terranes contain basalt of Norian age, but by this time Wrangellia was quiescent with respect to basaltic volcanism. The Pingston terrane, which lacks extrusive volcanic rocks, is cut by enormous masses of gabbro and diabase of undetermined, but possibly post-Norian age. If these mafic intrusions are also related to rifting, they may record the youngest such event in southern Alaska. Triassic basalt is not present in the Dillinger and Nixon Fork terranes–does this signify that these terranes were not subjected to massive rifting and thus have undergone only little movement during their history?

The mechanical process of accretion of these disparate geologic elements is not understood. Certainly, thrust faulting has played an important and perhaps dominant role. Structural superposition of adjacent terranes along major thrust faults has been documented in a few places (e.g. Silberling et al. 1978; Csejtey et al. 1978; Berg et al. 1978), and the Border Ranges thrust fault in southern Alaska separates Wrangellia and the Peninsular terrane from late Mesozoic accretionary deposits of the Chugach terrane (MacKevett and Plafker 1974; Plafker et al. 1977). If nearly flat faults (now locally folded) do indeed bound the bases of the major terranes, the scale of thrusting is unprecedented in North America. For example, the Yukon-Tanana terrane (Fig. 1) and related rocks form an allochthon of at least 400,000 km^2–an area equal to that of the state of California. A southwest-dipping thrust bounds its northeastern edge in the Yukon (Tempelman-Kluit 1979, oral commun. 1979). A northeast-dipping thrust bounds rocks of the Tracy Arm terrane in southeastern Alaska (Berg et al. 1978), and this terrane may constitute a subdivision of the Yukon-Tanana allochthon. If so, and if these faults connect at depth, which is possible, the entire allochthon would then constitute an enormous, nearly flat, rootless slab. Geophysical data are required to test this hypothesis.

Whatever the role of major thrust faults may be, they certainly have been modified to some extent by extensive strike-slip faults, such as the Denali fault system. Minor offsets of Quaternary deposits are well documented in southern Alaska (Richter and Matson 1971; Plafker et al. 1978; Grantz 1966) but only a few major offsets of pre-Cenozoic rocks have been substantiated. Again, the key to analysis of any such lateral movements clearly lies within the nature and distribution of the separate tectonostratigraphic terranes described in this report. In a few cases, disruption of a terrane by strike-slip faulting is apparent, but the amounts of these offsets are minimal (a few hundred kilometers at most). No examples of terranes completely severed and separated by great distances have yet been discovered in Alaska. On the other hand, the very process of large-scale northward displacement must have involved transform boundaries that separated the moving terranes from the stable continental block. Discrimination of older transform boundaries from younger faults related to neotectonic activities is not yet possible–in part, at least, due to the fact that many young faults may simply be reactivations of older structures.

Despite these uncertainties in structural style and mechanics of emplacement, it is now apparent that the bulk of tectonic activity that produced the Cordilleran accretionary mosaic is confined to the Mesozoic. No evidence of accretion to North America during the Paleozoic is apparent from Alaskan data, although one instance of amalgamation of subterranes during the Permian is known from southeast Alaska (Berg et al. 1978). The final accreting events appear to have occurred in mid- to Late Cretaceous time, as Lower Cretaceous rocks are locally severely deformed and overridden by nappes (such as the Chulitna terrane). Elucidation of the long and complex history of accretion that followed Triassic rifting will require extremely detailed stratigraphic studies and structural analyses throughout the Cordillera, with emphasis on precise dating of sedimentary and volcanic sequences and correlations in space and time of major geologic events. Biostratigraphic control, particularly of deep-water carbonate and siliceous rocks, will be mandatory, as these rocks record depositional and tectonic events not necessarily apparent in shallow-water, megafossil-bearing strata.

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CENOZOIC STRATIGRAPHY WEST OF THE 100TH MERIDIAN

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Great interest in acquiring an understanding of the geology of the United States west of the 100th Meridian was the result of the discovery of gold in California. The 19th century railroad surveys, undertaken largely due to the gold bonanza, were at least indirectly responsible for the establishment of the California Geological Survey and the United States Geological Survey.

Early investigations on the Pacific Coast resulted in the gradual recognition of Epoch-Series relationships of marine strata. When the United States Geological Survey was established in 1879, a systematic study of other areas gradually established Epoch-Series relationships of the continental interior.

One of the major developments in understanding of Tertiary and Quaternary stratigraphy took place under the directorship of the Survey of C. D. Walcott (1894-1907) when geologic Folio-Atlases were first published for the Western United States. Subsequent work by Survey geologists has resulted in geologic maps of areas of the Western United States at increasingly detailed scales.

Biostratigraphic classification of marine Cenozoic strata has been attempted on the Pacific Coast since Dickerson's (1914) pioneering endeavors. Clark (1921, 1926), Clark and Vokes (1936), and others, including studies by Addicott (1973, 1976a, 1976b) have resulted in the recognition of molluscan provincial ages for both Paleogene and Neogene strata. Addicott (1976a) has pointed out the necessity of recognizing provincial stages on the West Coast in the Neogene due to the influence of cooling climates and increasing endemism of faunas.

Foraminiferal biostratigraphic classifications by Schenck and Kleinpell (1936), Kleinpell (1938), Laiming (1939, 1940, 1941), Mallory (1959), and Natland (1952, 1953) have resulted in the recognition of 16 Cenozoic stages, each with surface stratotypes, and understanding of diverse facies within each. Weldon Rau (1958, 1980, 1981) has contributed a provincial zonation for the Northwest that solves problems of Neogene foraminiferal endemism.

Nannofossil studies by Bramlette (1961), Sullivan (1964, 1965) and Warren (1976, and *in* Kleinpell 1980) have established zones for the Paleogene and Neogene of the West Coast and suggested correlation with other Cenozoic stages.

Other biostratigraphic schemes for Tertiary terrestrial deposits have been proposed for mammals by Wood et al. (1941). Savage and Barnes (1972) have modified and critically summarized the mammalian provincial ages.

Increased use of radiometric dating; tephro-chronology in the Quaternary, and potassium-argon ages in the Tertiary; better map scales; high altitude photography; and utilization of computers mark the most recent additions to tools for aiding our knowledge of Cenozoic stratigraphy.

HISTORICAL PERSPECTIVES

Geologic work on the West Coast of North America was spurred on by the discovery of gold in California. Ramifications of the gold rush were many. Not only did it stimulate the first great railroad surveys that led to the first transcontinental railroad system, but also to the eventual formation of both the California State Geological Survey and the United States Geological Survey.

Recognition of Series-Epoch Relationships

A quarter of a century or more would elapse before Lyell's (1833) Tertiary subdivisions found their way into Western North America. A member of one of the early railroad surveys, W. P.

Blake (1855) picked up fossil mollusks from a float boulder near Fort Tejon in California and sent them for identification to Timothy Conrad on the East Coast. Conrad identified the fossils as having come from strata of Eocene age. William Gabb (1866-1869) was responsible for the mistaken idea that ammonites persisted in California into the Tertiary and also for the first recognition of Pliocene strata in beds exposed along Merced Beach south of San Francisco. Gabb's mistaken identification of ammonites involved their supposed association with giant venericards. The resolution of the controversy was the work of Angelo Heilprin of the Philidelphia Academy of Natural Sciences. As a result of the latter's work, the giant venericards were recognized as the worldwide "fingerpost of the Eocene" (Kleinpell 1980:4). J. P. Smith would later observe to his Stanford University students that the last of the supposed West Coast Tertiary ammonites turned out to be sea urchins, poorly preserved and misidentified (Kleinpell 1980:5).

The distinctive siliceous shales occurring along the Monterey Coast and elsewhere, which W. P. Blake (1856) had termed "Monterey," came to be recognized as Miocene on the basis of superpositional relationships and a few fossils, including some arc-shells. J. P. Smith's work (1912, 1919) further clarified usage of Miocene in California, although the relationships of such other stratigraphic entities as the Vaqueros, Santa Margarita, Temblor, and Monterey would continue to create controversy among stratigraphers well into the first half of the 20th century.

Another troublesome Series-Epoch boundary proved to be that between Pliocene and Pleistocene. There were not thought to be many distinctions between Pliocene and Pleistocene fossil mollusks on the one hand and Pleistocene and Quaternary on the other. Ralph Arnold (1903), while studying the stratigraphy of the San Pedro beds of southern California, established that float from the upper beds of the cliff in the past had been identified along with faunas from the lower San Pedro. These float fossils were shown to be Pleistocene. Arnold's (1906) monograph on pectens of the Pacific Coast provided additional data for the discrimination of both the Miocene and Pliocene series, and the Pliocene-Pleistocene boundary.

Recognition of the Oligocene series on the West Coast was initially the result of some miscorrelations and some others which proved accurate. W. H. Dall (1909) correlated the Astoria Formation of Oregon with some strata in the Caribbean thought to be Oligocene. Arnold (1906) designated the fossils occurring high in the San Lorenzo Formation of California as Oligocene and thought on the basis of biogenetic affinities with Astoria fossils to be their correlative. The Caribbean strata turned out to be Miocene, as was the Astoria, but the San Lorenzo was Oligocene, and the fossils only ancestrally related to the Astoria fossils (Kleinpell 1980:6).

Recognition of Paleocene strata along the West Coast was probably first accomplished by C. E. Weaver (1905), and subsequently by Clark and Woodford (1927). The correlation paper by Weaver et al. (1944) summarized the distribution of Cenozoic series, including the Paleocene.

Contributions of the U. S. Geological Survey

Four separate federal surveys were in existence prior to 1879. Much rivalry existed among these various groups for both territory and funding. Frequent overlap of areas and administrative problems led to attempts to bring about a single, unified government geological survey. Orchestrating a bill through Congress, John Wesley Powell finally succeeded in bringing the competing surveys under a single directorship; in 1879 Clarence King, an able administrator, was appointed as the first director of the consolidated geological survey. It was a most fortunate choice in terms of the progress and future of the Survey and in another way as well, for he "knew America, especially west of the hundredth meridian better than anyone. . ." (Adams 1938:311).

In 1879 King's analysis of the new Survey's most immediate priorities indicated the need for practical studies having to do with minerals and the burgeoning mining industry. Thus, the mining districts in Colorado and Nevada received a major part of the attention. Stratigraphy, paleontology, topographic mapping as well as other facets of geology were subservient to the search for raw materials and the development of a strong mineral industry to supply products for industrial

America. King was nonetheless innovative in establishing one of the early laboratories applying physical, mathematical, and chemical methods to geologic studies (Fenton and Fenton 1942:234). Among the basic Cenozoic studies begun during his administration were Arnold Hague's intensive investigation of volcanoes in California, Oregon, and Washington.

G. K. Gilbert had been a member of both the Wheeler (1871-1874) and Powell surveys (1875-1878). His experience included examination of a large portion of the Basin-Range, Colorado Plateau, High Plains, Sierra Nevada, and later Alaska. In fact, he had first-hand experience in much of the country west of the 100th Meridian. His observations and hypotheses were a major stimulus to the development of modern stratigraphic and geologic thought. Gilbert first demonstrated the relationships of the majority of basalt flows in Utah, Nevada, New Mexico, and California to Tertiary events, a basic key to many later stratigraphic interpretations.

One of the unfortunate, albeit important, episodes in the history of Cenozoic terrestrial investigations was the clash of two monumental personalities, Othniel Charles Marsh of Yale University, New Haven, and Edward Drinker Cope of Philadelphia. Each worked for a different territorial survey, but only Marsh (1885) published for the U. S. Geological Survey. Both of these wealthy paleontologists assembled enormous collections of vertebrate fossils from the West, and although both contributed substantially to our knowledge of the relationships and evolution of vertebrates, they "became so involved in lamentable personal conflict to excel each other that their methods and behavior detracted greatly from their stature as capable paleontologists" (Stirton 1959:106). The competition to collect both Mesozoic and Cenozoic fossil vertebrates, and to be first to publish, became absurd. Often, to ensure priority in publication, manuscripts were sent to publishers by telegraph from the field stations. Many fossil lots were never unpacked during their collectors' lifetime. Their work was of great benefit to subsequent generations of workers in Cenozoic terrestrial biostratigraphy for both the new taxa described and the age designations for many terrestrial deposits. One wonders, nonetheless, if the ill-will and errors in stratigraphic placement of some fossils resulting from the often hasty work did not greatly reduce the importance of their contributions.

Powell assumed the directorate of the Survey in 1881 and a number of papers which had been in progress at the time were published, such as Dutton's (1882) Tertiary history of the Grand Canyon, Marsh's (1885) monograph on Cenozoic mammals, and Gilbert's (1890) study of Lake Bonneville. Hilgard (1887) published the earliest attempt at correlation of marine strata in the Western United States with terrestrial beds.

Following the discovery of gold in Alaska in the 1890s, there was increased emphasis on geological mapping of that area, not only for gold, but for all potential mineral resources. C. D. Walcott assumed the directorship of the Survey in 1894, and his policies enlarged the scope of this work for he believed that "any practical objective could be advanced by knowledge of the surface and interior of the earth" (Rabbitt 1974:12). Thus, geologic mapping in California, Oregon, Alaska, and elsewhere continued at a rapid pace. The increased pace was helped by the fact that the number of employees of the Survey had grown to more than 400 persons (Rabbitt 1974:13).

For the future of stratigraphic studies in Western North America, the publication of the *United States Folio and Atlas Series* was particularly significant. J. S. Diller had begun studies in northern California that resulted in a preliminary report on the geology of the Lassen Peak district (1889), to be followed (1895) with the Lassen Peak Folio-Atlas. Diller carried his investigations into southwestern Oregon (1896) and completed two more atlases, the Roseburg Folio-Atlas (1898) and the Coos Bay Folio-Atlas (1901). He then returned to northern California for work on the Redding Folio-Atlas (1906).

Elsewhere in the West, Survey parties were also active. Hague (1896) published the Yellowstone Folio-Atlas, which was followed (1899) by his classic study of Yellowstone National Park. Bailey Willis (1896) was sent to northwestern Washington to investigate coal-bearing beds in Pierce County; this was expanded later into the Tacoma Folio-Atlas (1897). Ralph Arnold (1905) was sent into Clallam County to look at potential coal-bearing strata. G. O. Smith and Frank Calkins (1904) made an intensive study of the geology and stratigraphy of the 49th parallel and followed this with the Snoqualmie Folio-Atlas (1906).

An important contribution to the biostratigraphy of terrestrial deposits was made with the publication of Newberry's (1898) study of the fossil floras of North America.

Walcott left the Survey in 1907 to become Secretary of the Smithsonian Institution and George Otis Smith, at a youthful 36, became its head. His acceptance of the directorate coincided with increasing interest in safeguarding development of oil and public lands. This was the beginning of the withdrawal of such lands to form military oil reserves: Elk Hills in California, in 1908, and the Wyoming Naval Petroleum Reserves, in 1912. Protection of existing energy resources and exploration for new sources were the result of fears produced by the spectre of World War I. The interval preceding and following the war saw a significant increase in contributions to knowledge of Cenozoic stratigraphy in the Western United States. These included those contributions of a general nature as well as detailed stratigraphic and paleontologic studies. Before the first decade of the 20th century ended, Henry Fairfield Osborn (1909) of the American Museum of Natural History in New York had described the Cenozoic mammal horizons of Western North American Tertiary deposits. Dall (1909) had published papers on correlation and Tertiary fossils at Astoria and Coos Bay, Oregon, referred to previously. The paleontology of the middle Tertiary Florissant beds was described by Knowlton (1916), and Pardee (1913) published an important study of coal in Tertiary lake beds in southwestern Montana.

In California, Ralph Arnold and others continued investigations on oil producing areas. During the years 1907 to 1915 appeared Arnold's geologic study of the Santa Maria area (1907), with H. R. Johnson, a report on the McKittrick-Sunset oil field (1910), and with Robert Anderson, the geology and oil resources of the Coalinga area (1910). Branner et al. (1909) published the Santa Cruz Folio-Atlas, an important addition to Coast Range stratigraphy. Anderson and Pack (1915) finished the wide-ranging study of geology and oil resources of the west border of the San Joaquin Valley.

Following the end of World War I, other important contributions to the knowledge of stratigraphy of the West appeared. Two such contributions were Walter English's (1921, 1926) studies of geology in California: the geology and petroleum reserves of northwestern Kern County and geologic studies of the Puente Hills region. Also, energy sources were still much in the minds of politicians and scientists and "Exhaustion of domestic supplies of petroleum within a decade was forecast. . ." (Rabbitt 1974:18). This stimulated the Survey to start intensive studies of possible oil-bearing formations in Naval Petroleum Reserve No. 4 on the Arctic coast of Alaska (Rabbitt 1974:19), and a number of important contributions to stratigraphy resulted.

In 1943 William Wrather, the sixth Survey director, discovered that less than 10% of the country had been mapped on scales suitable for an appraisal of natural resources. With the return of more adequate funding in the economic expansion that followed World War II, he initiated a major program of geologic mapping as well as intensive regional studies in the search for petroleum and other mineral deposits. As a result of this expansion, a number of detailed geologic maps became available. In California, Woodring and Popenoe (1945) investigated the Paleocene and Eocene stratigraphy of the northwestern Santa Ana Mountains. Woodring, Bramlette, and Kew (1946) studied the geology and paleontology of the Palos Verdes Hills, and in 1950, Woodring and Bramlette published on the geology of the Santa Maria district. Ralph Stewart (1946, 1949) completed a study of the geology of the Reef Ridge-Coalinga area and a lower Tertiary stratigraphic study of Mt. Diablo, Marysville Buttes, and the west border of the lower Central Valley. Indeed, important contributions could be cited in each of the western states for this period. And, it should not be forgotten, it was during this time that Joseph Cushman and Frances Parker (1947) published their important *Professional Paper* on *Bulimina* and related foraminiferal genera, a basic reference for foraminiferal Cenozoic biostratigraphy.

During the past quarter-century, four Survey directors, Nolan, Pecora, McKelvey, and Menard have been responsible for a number of important advances: improved exploration; investigation of nuclear power and radioactive waste disposal; energy studies on coal and oil; and the increasing utilization of radiometric dating in stratigraphic studies. Utilization of radiometric study techniques is exemplified by Fiske, Hopson, and Waters' (1963) geologic study of Mount Rainier, Lamphere's (1966) potassium-argon ages of Tertiary plutons in the Prince William Sound area of Alaska, and by Wahrhaftig, Wolfe, Leopold, and Lamphere's (1969) bulletin on the coal-bearing group in the Nanana Coal Field, Alaska. So many important detailied studies have been made that it is impossible to list them all. Addicott (1965, 1966) has contributed a number of important biostratigraphic, stratigraphic, and paleontologic studies in California, Oregon, Washington, and with Plafker (1971), Alaska. Two particularly interesting papers by Addicott (1967, 1970) were those on the San Andreas fault and on Tertiary paleoclimatic trends in the San Joaquin Basin. Yerkes et al. (1965) published a detailed study of the much studied geology and paleontology of the Santa Maria District, California. Roberts (1958), Weldon Rau (1958), and Snavely et al. (1958) have contributed greatly to the understanding of Cenozoic stratigraphy in Washington and Oregon. Peck et al. (1964), and others have made intensive studies of Cenozoic rocks in Oregon.

Elsewhere in the Western United States, Survey geologists in studies of Colorado, New Mexico and Wyoming have contributed much to our knowledge of Cenozoic strata. Among these, Bradley's (1964) comprehensive study of the Green River Formation and associated Eocene rocks, Donnell's (1961) Tertiary geology and oil-shale resources of the Piceance Creek Basin, Gill, Mereweather, and Cobban's (1970) stratigraphy and nomenclature of some upper Cretaceous and lower Tertiary rocks, and Fassett and Hind's (1971) geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin are of particular significance.

MOLLUSCAN BIOSTRATIGRAPHIC CLASSIFICATIONS

Dickerson (1914), in an early attempt at biostratigraphic classification of the California lower Tertiary marine strata, proposed four molluscan zones. Bruce Clark (1921:142, 161) later demonstrated that Dickerson's zones had little validity since the presumed youngest proved to be the shallow water facies equivalent to the oldest. Continuing his biostratigraphic studies, in 1926, Clark proposed some four major divisions within the lower Tertiary. Each was named for a lithologic entity. Presumably each of the formations for which each of the four divisions was named contained a distinctive fauna. In reality, however, some formations contained faunas of slightly differing ages, and none of the divisions was given an objective type section. There was little control of either biofacies or fossil range, so that much confusion existed.

An understanding of the correct utilization of molluscan faunas in biostratigraphic classification of the West Coast Cenozoic would not have been possible without some discoveries made by J. P. Smith. Smith (1919) utilized mollusks to interpret climatic changes throughout the Cenozoic. He discovered that although mollusks were distributed within a single broad province extending from southern California to Washington and southern Alaska during the Eocene, subsequently there were many changes as climates cooled. A high degree of endemism began shortly before Neogene times and continued throughout the remainder of the Cenozoic. Smith demonstrated the gradual cooling of marine climates and a consequent southward shifting of the cool isotherms. A work by Durham (1950) supplements Smith's data considerably by adding data for many taxa other than mollusks to the interpretation of Cenozoic marine climates.

Clark and Vokes (1936) summarized the lower Tertiary West Coast succession, proposing some six stages and nine zones. Although much valuable detail was added, the zones lacked adequate superpositional control, the zonal designations remained those originally proposed for cartographic entities, and there were no objective types established (Mallory 1959:11, 12).

In western Washington, Durham (1944) made detailed studies of marine Oligocene strata. He recognized six zones and two stages, all with type sections, and with much improved control for range of species and their geographic and facies distribution.

Weaver et al. (1944) summarized the existing molluscan Cenozoic biostratigraphic classifications on the West Coast and attempted to show relationships with classifications based on foraminifers. They recognized three additional Neogene stages and five zones. In their summary, they subdivide the Paleogene into eight formal stages and fifteen zones. Durham (1954), Corey (1954), and Addicott (1972) made substantive refinements and modifications of the California Neogene stages; the eight stages described by Weaver et al. (1944) were reduced from eight to six.

The most significant recent additions to the formal molluscan biostratigraphic classification have been made by Addicott (1973, 1976a, 1976b). In the Paleogene of California, Addicott (1976b) recognized an unnamed Oligocene provincial stage and six stages through the remainder of the Neogene. Increasing endemism during the Neogene, initially recognized by Smith (1919), resulted in intensification of the latitudinal thermal gradient. Thus, Addicott (1976b:156) maintained, separate chronologies are needed for each of the provinces. Addicott (1976b) formally named and defined a series of seven provincial stages for the Neogene of the Pacific Northwest. Armentrout (1975) proposed late Eocene and Oligocene stages and zones which complement those recognized by Addicott.

FORAMINIFERAL BIOSTRATIGRAPHIC CLASSIFICATIONS

Just as the studies of Smith (1919) were of great significance to a molluscan biostratigraphic classification, so too were the pioneering studies on the West Coast of foraminiferal ecologic distribution by Manley Natland (1933). In a study of the modern foraminiferal distribution off Long Beach, California, there were five different depth-temperature related subdivisions recognizable from intertidal to 8300 ft, each marked by a characteristic species of foraminifer. In the same paper, Natland was able to recognize each of these subdivisions in the Pliocene-age strata exposed in the vicinity, thereby proving the effectiveness of utilizing Foraminifera for interpreting bathymetry. Of Natland's work, Kleinpell (1980:8) observed, "through Natland's work the significance of chronology and facies in biostratigraphic chronology based on foraminifers were [*sic*] clearly and demonstrably documented." Subsequently, based on an analysis of the foraminiferal content, Natland (1957) demonstrated the existence of deepwater (bathyal to abyssal) sediments in both the Los Angeles and Ventura basins.

The earliest micropaleontologic classification of the marine Tertiary succession of the West Coast was by Schenck and Kleinpell (1936). Following a principle established by Albert Oppel (1856-1858:813), they designated the Refugian Stage and several zones, each with appropriate stratotypes. In their work, and in Kleinpell's (1938) subsequent contribution in which he established six additional stages with sixteen zones of the Miocene, foraminiferal evolution was analyzed to establish ranges, and as many diverse facies as possible were determined within the province. These stages and zones have proven to be widely recognizable, with a few subsequent modifications (Kleinpell 1980).

Manley Natland (1952, 1953) proposed three younger Tertiary stages and corresponding zones for the Pliocene West Coast Series, and a fourth stage for the Quaternary. These were based, as were those of Schenck and Kleinpell (1936) and Kleinpell (1938), on Oppelian principles.

The first micropaleontologic classification of the Paleogene was accomplished by Boris Laiming (1939, 1940, 1941). He proposed a five-fold classification, based largely on subsurface data, which carried Greek letter designations to emphasize their tentative nature. Mallory (1959) modified Laiming's conclusions, selected surface stratotypes, and formalized five Paleogene stages with ten zones.

Welden Rau (1958, 1980, 1981) has subjected the Paleogene and Neogene marine strata of Oregon and Washington to intensive study. In addition to recognizing most of the California stages from middle Eocene through upper Pliocene in the Northwest, he proposed a local zonation which effectively solves correlation difficulties due to the increasing endemism caused by changes in marine climates in the Northwest during the Neogene.

Turner (1970) suggested radiometric ages for Pacific Coast foraminiferal stages based on potassium-argon determinations. Ryan et al. (1974) inferred paleomagnetic assignments for Neogene stage boundaries.

Bramlette (1961) and Sullivan (1964, 1965) established a series of nannoplanktonic coccolith zones in the lower Tertiary and correlated them with the foraminiferal stages and zones. Lipps (1967) examined the distribution of planktonic foraminifers, age, and intercontinental correlation of mid-Cenozoic microfaunal stages. Warren (1976) made an intensive study of the plankton biostratigraphy of the Refugian and adjoining Tertiary stages, and later (*in* Kleinpell 1980) he summarized the calcareous nannoplankton biostratigraphy of Cenozoic marine stages in California. He inferred relationships with the U. S. Atlantic, Gulf Coastal Province, Europe, and New Zealand based on interpretation of the nannoplankton and planktonic Foraminifera.

VERTEBRATE FOSSIL BIOSTRATIGRAPHIC CLASSIFICATIONS

Wood et al. (1941) proposed a nomenclature for the North American continental Tertiary units. These provincial land mammal ages had stratotypes, primarily west of the 100th Meridian. The work also includes a discussion of formational nomenclature and correlation. Subsequent attempts at correlation of the continental vertebrates with marine mollusks in southern California have been made by Repenning (1961). Savage and Barnes (1972) summarized the Pacific Coast Miocene vertebrate geochronology and added much valuable detail to improve both its accuracy and its utility.

THE FUTURE

Increased utilization of tephrochronology for latest Cenozoic deposits, and improved potassium-argon dates for other terrestrial and marine deposits, will enlarge our understanding of age relationships. Improvements in topographic mapping, the result of using satellite photography, and use of map-scales at 1:24,000 or less, will advance stratigraphy. Quantitative studies will play an increasingly important role in analyses of strata and their biologic components. Particularly to be desired are paleoecologic studies, and comparative studies of evolutionary rates of various marine invertebrate, terrestrial vertebrate, and plant communities throughout the Cenozoic. Biogeographic analyses of whole faunas to determine provincial and subprovincial distribution, as well as the range of taxa in time is a goal to be achieved.

While utilization of presently available techniques, and some yet to be invented, will no doubt help us solve a number of current pressing problems, new and exciting challenges certainly await us in the future.

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QUATERNARY RESEARCH IN THE NORTHWEST 1805-1979 BY EARLY GOVERNMENT SURVEYS AND THE U. S. GEOLOGICAL SURVEY, AND PROSPECTS FOR THE FUTURE

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Maps summarizing observations 1805-1882 and the distribution and quality of works published by the U. S. Geological Survey (USGS) 1879 to 1979 chart the progress of U. S. Government surveys of Quaternary deposits in the Northwest. Observations prior to 1867 by early explorers and the Pacific Railroad surveys were casual though often perceptive. While most of the great geologic reconnaissance surveys 1867-1879 were peripheral to the Northwest, G. K. Gilbert's Henry Mountains report was highly influential.

During the period 1879-1913 the USGS surveyed in reconnaissance Quaternary history and surficial processes broadly over the Northwest. Stratigraphy and relative-age discrimination from quadrangle mapping showed multiple ice-sheet glaciation of the Puget Lowland and multiple alpine glaciation in the Bighorn Mountains. Detailed reports elaborated cyclic fluctuations of Pleistocene lakes Bonneville, Lahontan, and Mono, and of Pleistocene alpine glaciers in the Sierra Nevada, Uinta, and Wasatch ranges.

The period 1914-1946 was skimpy of USGS Quaternary research, which was mostly accessory to investigations on exploitable resources. The influential studies were G. K. Gilbert's on transport of coarse debris by streams, F. E. Matthes's on multiple glaciation of Yosemite Valley, W. H. Bradley's on Cenozoic tectonism and erosional landscape evolution of the Uinta Range, and W. C. Alden's on glacial and terrace deposits in Montana.

The period 1947-1979 saw development of many new dating techniques and increased quantity of USGS surficial mapping in the Northwest, including reconnaissance maps of Quaternary deposits of a third of the region. Detailed stratigraphy and surficial geologic maps were done of the southeastern Puget Lowland, the Portland area, the Snake River Plain, and the Yellowstone area. Especially detailed sequences of glaciation and eruption history were deciphered at Mount Rainier and Mount St. Helens.

Many large areas and attendant topical studies that have escaped scrutiny during the past half century suggest important projects for the future. The need to predict climate and to forecast natural hazards to engineering structures and to ever-growing human populations probably will sustain a vigorous USGS program of Quaternary research in the Northwest during the coming decades.

This essay charts a century of Quaternary research in the Northwest revealed by publications of the United States Geological Survey (USGS). The USGS work is summarized on three maps (Maps 2-4), each of a one-third-century interval bounded by episodes of economic and political change. Summarized on a fourth map (Map 1) is a review of pre-1880s discoveries and geologic reconnaissance in the Northwest, upon which in 1879 the USGS began to build. Quaternary reports prior to 1947 having been sparse within strictly the "Northwest," while influential work flourished on the periphery, review of the pre-1947 periods embraces areas as far south as latitude 38° and as far east as longitude 107°. Because of the very large number of reports since 1955, the period 1947-1979 is reviewed systematically only north of latitude 42° and west of longitude 111°, plus Yellowstone National Park. Non-USGS publications even by USGS authors are ignored.

This essay is thus not a comprehensive review of Quaternary science in the Northwest, but of the contribution to it by USGS publications.

Full citation of some 500 works consulted for this review is impractical. The USGS publication series and volume number identifies reports outlined on Maps 2 through 4, while the text speaks of authors and dates. Referring to the appropriate map, the reader with a sense for Northwestern geography will find but few ambiguities, among which he can distinguish with *Publications of the Geological Survey* or other bibliographic sources. A few classic non-USGS reports referred or alluded to are well enough known to North American geologists as not to require full citation; complete references can be found in textbooks or historical reviews, for example Merrill (1924), Flint (1965, 1971), Thornbury (1969), White (1973), or Higgins (1973). Full citations for the pre-USGS period occur in the earliest comprehensive USGS work in a particular region—for example Gilbert's 1890 monograph on the Lake Bonneville basin. Merrill (1924), Goetzmann (1959), and Meinig (1968) give progressively more popular summaries of the early explorations and of the political and economic climates in which they flourished.

Reports mostly related to geophysics, tectonics, water, minerals, and engineering were less systematically searched than reports mainly on Quaternary stratigraphy, history, and surficial processes. Of the USGS Open-File series, only reports dated 1974-1979 were systematically reviewed, most others of importance having been superseded by more formal publication. The relative quality of the reports as distinguished on Maps 2-4 was subjectively judged on their contribution to surficial geology. The primary criteria were the degree to which geologic maps distinguish units by relative age, and within age groups by lithology and genesis. Other criteria include scale and contour interval of geologic maps, thoroughness of description and analysis of map units, originality of interpretations, and for the older works, their durability.

EARLY EXPLORATIONS: 1805-1882

(Map 1)

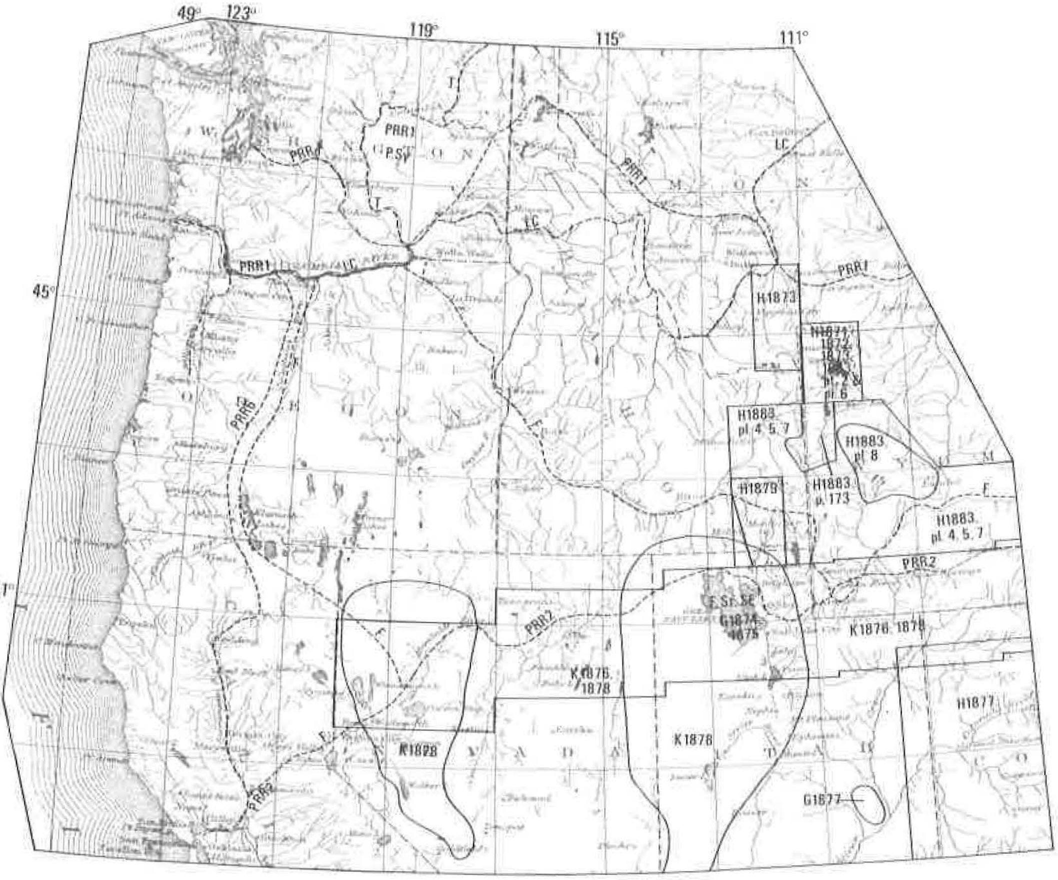
Pioneering Discoveries: Physical Geography

The history of geologic exploration of the West is to a significant degree the history of exploration by the U. S. Geological Survey (USGS), a century old at this writing. The early reports of the USGS, however, refer to the great reconnaissance surveys of the 1860s and 1870s and to the Pacific Railroad Reports of the 1850s, which in turn cite the records of Stansbury, Frémont, Lewis and Clark, and other early explorers. The prelude to the early history of the USGS is the early explorations.

Lewis and Clark's exploration of the upper Missouri and Columbia rivers in 1805-06 initiated scientific discovery in the Northwest, including observations later relevant to Quaternary science. The explorers' account of their run through the Dalles, where the Columbia constricts to a precipitous gorge, incidentally described a peculiar channel form that later figured in the great scabland debate. Lewis correctly thought that the Cascades Rapids and a submerged forest above them had formed because mass-wastage debris had obstructed the river. In the Spring the explorers iterate of blowing sand, the process later held responsible for the "Palouse soil," the substrate of the wheat economy of eastern Washington. Clark's 1814 map shows the volcanoes Mount St. Helens and Mount Jefferson and a northwest-trending eminence later labeled as the Olympic-Wallowa lineament.

There followed many explorers in the Northwest who gradually deciphered regional geography: Colter, Stuart, Thompson, Bridger, Ogden, Smith, Parker, Whitman, De Smet, and Bonneville are the principals, Thompson, Smith, De Smet and Bonneville having constructed primitive maps. The Rev. Samuel Parker in 1835-36 recognized the Grand Coulee as the abandoned former channel of the Columbia River, and described and analyzed in some detail the Dalles and the channeled scabland.

The Great Salt Lake had appeared speculatively on the Baron La Hontan's 1710 map at



KEY TO MAP 1

Explorer (chief) or Report	Symbol
Lewis and Clark*	LC
David Thompson*	T
Frémont*	F
Samuel Parker*	P
Howard Stansbury*	St
Simpson and Engelman*	SE
Pacific Railroad Reports*	PRR (nos.=volume)
Hayden surveys	H (dates=Ann. Repts. publ.)
King surveys	K (dates=published)
G. K. Gilbert (Wheeler and Powell surveys)	G (publication dates)
Symons	Sy

*Routes, as distinguished from areas surveyed, are in broken lines

Map 1. Reports of explorations prior to the U. S. Geological Survey.

partly correct coordinates and with its largest influent river (Bear River) correctly shown on the northeast. Rediscovered by Bridger and Ogden in 1825, the lake first appeared within a basin of interior drainage on Bonneville's map. The lake became a focus for trappers, inland settlement, emigrant routes, transcontinental railroads, and geologic reconnaissance.

U. S. Army Topographical Engineers and Pacific Railroad Reports

Great Basin. The U. S. Army Corps of Topographical Engineers (1838-63) made most of the early truly scientific observations. John C. Frémont in 1843-44 ascertained the dimensions of a 'Great Basin' having wholly interior drainage and rimmed by high mountains. Within the basin Howard Stansbury in 1849-50 surveyed the Great Salt Lake and briefly reported ancient shorelines indicating a formerly much more extensive lake. During the Pacific Railroad survey of 1853, Lt. E. G. Beckwith discussed ancient shorelines as high as 800 ft above the modern lake. Exploring for wagon routes in 1859 (published 1878), Capt. J. H. Simpson and his geologist Henry Engelmann noted lacustrine silt, tufa, and fresh-water shells—sedimentologic evidence of a formerly expansive lake.

Far Northwest. Recognition that ancient volcanic processes have influenced the far Northwest began with discovery of great volcanoes during the 1792 voyages of George Vancouver and Robert Gray. Lewis and Clark reported that Mount St. Helens had erupted in 1802. George Gibbs, geologist for the Northern Pacific Railroad Survey, reported (1855) that Mount St. Helens and Mount Baker each erupted "smoke" in 1853-54 and that both volcanoes had erupted in 1843, when ash from St. Helens reached the Columbia River. East of the Cascades, Gibbs noted alluvium and terraces in the Columbia valley and tributaries, counting in the Methow valley as many as 18 terraces, incorrectly attributed to former lakes.

J. S. Newberry, geologist for the Pacific Railroad Survey along the West Coast, reported (1857) recently uplifted shell beds near San Francisco Bay, the great alluvial plain and older terraces of the Sacramento Valley, and volcanic phenomena between Lassen Peak and the Columbia River. He correctly inferred from striae that a Quaternary ice cap had covered the Oregon Cascades, though he incorrectly attributed the subsequent climatic warming to reduced altitude caused by tectonic subsidence.

A result of the Pacific Railroad surveys, an 1859 geographic map of the Northwest by the Topographic Engineers, vastly improved their 1838 map. The revised map included geography by the expeditions of Charles Wilkes in 1841 and Frémont in 1843-44, and by a wagon-road survey across the Washington Cascades in 1853. Mount Adams volcano is correctly shown east of the Cascade crest distinguished from Mount St. Helens to the west. Not even the 1859 map, though, shows the course of the Columbia River through Washington so well as David Thompson's remarkably accurate 1814 map, which had languished obscurely at the Northwest Company's post on Lake Superior (Meinig 1968:39-40).

The last geologic reconnaissance in the Northwest by the military was Lt. T. W. Symon's (1882) accurate mapping of the upper Columbia River, made to suggest engineering improvements for navigation of the many falls and rapids. His geomorphic details of Kettle Falls and Rock Island Rapids (now drowned behind dams) suggest superposition of the river through alluvium into buried bedrock spurs. Symons recognized evidence in southern Washington of a Pleistocene lake, which he named after the explorer Lewis and mapped as exceeding 5000 mi^2 in area.

The Great Reconnaissance

In 1867 a more systematic geologic reconnaissance opened with F. V. Hayden's U. S. Geological Survey of the Territories. Reports published 1871 through 1883 discuss glacial phenomena in western Wyoming and adjacent Idaho and northeastern Utah. Some reports lengthily describe hot springs, geysers, and affiliated deposits of Yellowstone, the 1871 report having been a factor in the creation of Yellowstone National Park in 1872. The contoured geologic atlas published in 1883 differentiates four volcanic and four surficial Quaternary units in Yellowstone, and delineates terraces and moraines in the southwestern Wind River Mountains and near Jackson Hole. Hayden and his associates correlated old shorelines in the Cache Valley northeast of Salt Lake with lacustrine deposits and inferred that terraces along marginal streams had aggraded into (and because of) the former lake.

Headed by Clarence King, the U. S. Geological Exploration of the Fortieth Parallel (1867-73) published in 1876 contoured maps of a belt across the Great Basin from the eastern scarp of the Sierra Nevada to northern Colorado. The maps only sparsely show Quaternary alluvium, but on the northern flank of the Uinta Range valley-floor alluvium is distinguished from much older divide-capping conglomerate. A separate exploration documented active glaciers on Mounts Shasta, Hood, and Rainier volcanoes. The comprehensive *Systematic Geology* (1878) shows extensive inferred former glaciers in the Uinta, Wasatch, and Medicine Bow ranges and in four basin ranges and shows the inferred extent of Pleistocene lakes Bonneville and Lahontan. Lake Lahontan sediment was found to overlie subaerial gravel, proving that a drier climate had preceded the more humid lake epoch; salt stratigraphy showed that Lake Lahontan had twice formed and dried.

Clarence King (U. S. Geological Survey Photo Library, Denver)

The West of the One-Hundredth Meridian Survey (1869-1884), headed by G. M. Wheeler, produced hachured topographic maps of large tracts of the Great Basin and Sierra Nevada. Attached to the party 1871-73, G. K. Gilbert argued (1874, 1875) that basin-range structure and physiography, and the Great Salt Lake anomalously situated against the Wasatch front, had resulted from faulting and tilting—contrary to Clarence King's opinion that the ranges originated as anticlines, the basins as synclines.* Gilbert discussed glacial, eolian, and stream processes, and the growth and drying of pluvial lakes, the largest named for the explorer Bonneville. He predicted that the prominent Bonneville and Provo shorelines would be found to have been stabilized by a spillway threshold. Deducing that both glaciers and pluvial lakes resulted from cooler climate and consequently reduced evaporation, he believed Lake Bonneville to have been coeval with alpine glaciers in adjacent mountain ranges and with the Pleistocene ice sheets farther north.

The United States Geographical and Geological Survey of the Rocky Mountain Region, headed by John Wesley Powell, was mostly east or south of the region of this review. The monumental 1877 Henry Mountains report by G. K. Gilbert, however, who in 1875 had gravitated from the Wheeler to the Powell survey, included an imaginative and detailed analytical discussion of stream processes, terrace development, drainage changes, and landscape evolution. Gilbert was the first to appreciate the significance of smoothly planed-off rock surfaces, more than a half century ahead of lengthy discussions in the 1930s of planation and pedimentation. Gilbert inferred that terraces generally form during progressive degradation, rather than during successive episodes of aggredation as Edward Hitchcock had argued in New England. Except perhaps when W. M. Davis's peneplain theory held its greatest sway, Gilbert's concepts of grade, stream planation, and degradational surfaces have dominated analyses of alluvial deposits in the West down to the present day. Gilbert found opportunity in 1875-78 to continue his investigations of Lake Bonneville.

U. S. GEOLOGICAL SURVEY: 1879-1913

(Map 2)

In 1879 the four great reconnaissance surveys, which despite overlapping areas had been independently funded variously by the War and Interior Departments, combined into the U. S. Geological Survey (USGS) under Clarence King's directorship. The new organization began field work almost immediately, and as early as the *First Annual Report* appeared a paper significant to Quaternary geology of the Northwest. Some early USGS reports by I. C. Russell, G. K. Gilbert, and Arnold Hague were continuations of their work under the Wheeler, Powell, and Hayden surveys.

Broad Regional Reconnaissance

Comprehensive but swift reconnaissance covered large tracts of the Northwest during the first quarter-century of the USGS. Few of these reports distinguish surficial deposits by relative age, and geologic maps are either lacking or are at so small a scale as to show but one or two genetic or lithologic units. Most important of these reconnaissance reports are of the Lake Bonneville area (G. K. Gilbert 1880, 1882); the Lake Lahontan area (I. C. Russell 1883); of Pleistocene drift limits from the Atlantic coast to the Pacific (T. C. Chamberlin 1888); central Washington (Bailey Willis 1887; Russell 1893, 1900; G. O. Smith and Frank Calkins 1904; Calkins 1905); northern California and southwestern Oregon (J. S. Diller 1889, 1894); northwestern Oregon (Diller 1896); west-central Idaho (Russell 1901); the Snake River Plain (Russell 1902, 1903); and southeastern Oregon (Russell 1905).

Topographic Mapping and Geologic Atlas of the United States

Topographic mapping of landforms in remote mountainous areas grew apace, epitomized by F. E. Matthes's masterly contouring of the Cloud Peak quadrangle (1898-99), the Chief Mountain quadrangle (1900-01), Yosemite Valley (1905-06), and Mount Rainier (1910-11). These and other skillfully drawn maps clearly showed the extent to which the western mountains had been sculptured by alpine glaciers.

By 1894 when the first of the *Geologic Atlas* folios was published, modestly detailed mapping was underway in several parts of the Northwest. While most Quaternary study was ancillary to

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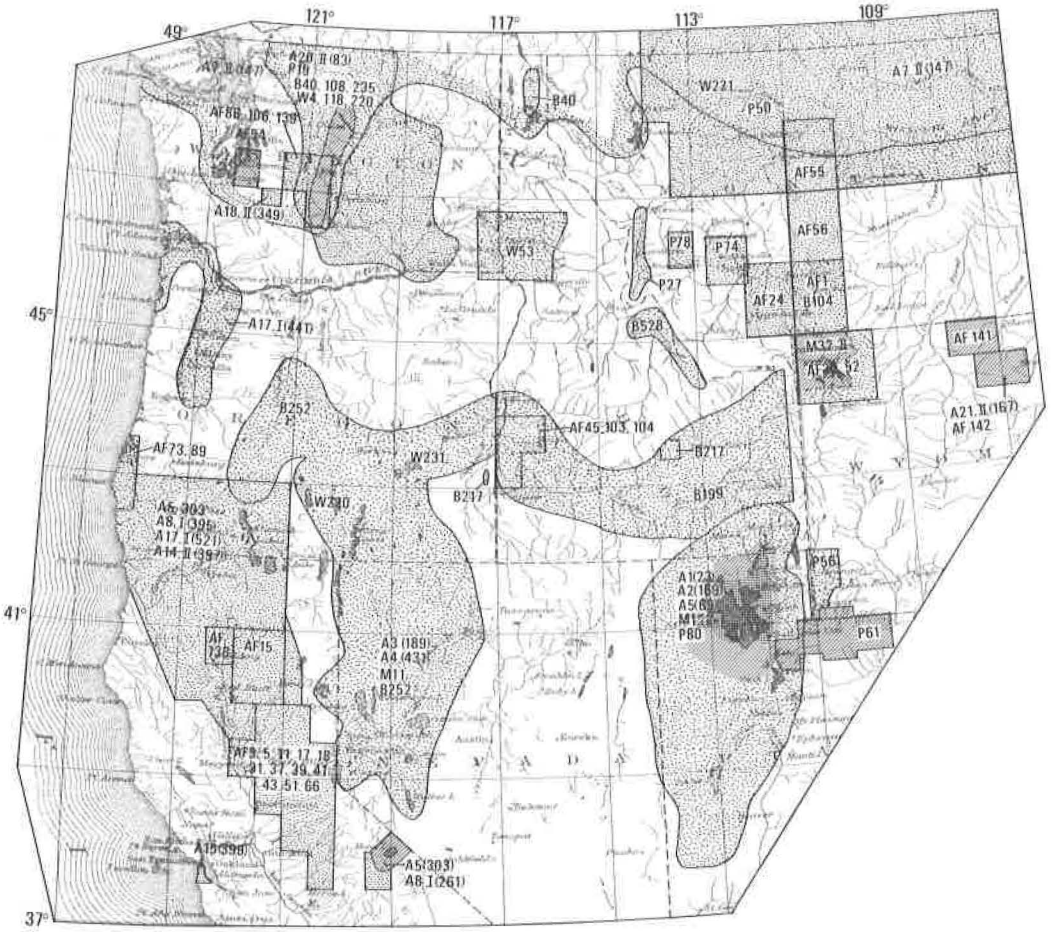
* See comments on pages 29 and 31 (this volume) by Nelson and Rabbitt. [Ed.]



KEY TO SOURCES, MAPS 2, 3, 4

USGS series	Symbol
Annual Report	A
Geologic Atlas folio	AF
Bulletin	B
Circular	C
Misc. Field Studies Map	F
Misc. Geologic Investigations Map	I
Journal of Research	J
Monograph	M
Open-File Report	OF
Professional Paper	P
Geologic Quadrangle Map	Q
Water-Supply Paper	W

Examples: (1) U.S. Geological Survey 20th Annual Report, Part II p. 83ff= A20, II(83)
(2) U.S. Geological Survey Professional Papers 729-B, 729-D, and 729E=P729BDE
(3) U.S. Geological Survey Professional Paper 600-D, p. D79ff=P600D (79)

Relative quality of contribution to Quaternary geology

░ ▒ Reconnaissance
▨ ▨ Detailed reconnaissance to Detailed
▦ Detailed to Thorough

Map 2. Reports by the U. S. Geological Survey 1879-1913.

bedrock mapping in mineralized areas, division of Quaternary deposits into two or more units on contoured bases improved prior mapping. Five 1° x 1° maps at 1:250,000 scale published 1894-1899 variously by J. P. Iddings, A. C. Peale, W. H. Weed, and Arnold Hague in western Montana and the Yellowstone-Absaroka area each show three or more Quaternary units distinguished on lithology and genesis. J. S. Diller's 1895 Lassen Folio shows five such Quaternary units, three of them volcanic.

At the 1:125,000 scale (30′ x 30′), the most ambitious project was 12 folio maps in the gold-mining region of the northern Sierra Nevada and Great Valley, published 1894-1900 variously by Waldemar Lindgren, H. W. Turner, and F. L. Ransome. The Quaternary, though plotted on contoured maps, in the Great Valley is divided only into older and younger alluvium—the division noted 40 years earlier by Newberry—and in the mountains is differentiated lithologenetically into alluvium, moraines, lake beds, and basalt. At the northern end of the Sacramento Valley and in coastal Oregon, Diller's (1901-1906) maps are similarly sparse. Lindgren's three maps (1898-1904) in the western Snake River Plain, however, differentiate three gravel units by relative age distinguished by relative height of terraces above streams.

The most thorough Quaternary map at 1:125,000 scale was the 1899 Tacoma Folio by Bailey Willis and G. O. Smith, who distinguished in the Puget Lowland ten Quaternary units that revealed two major ice-sheet glaciations and three interglaciations. The nearby 1903-1906 folio maps by Smith and by Smith and Calkins east of the Cascade crest, while excellent bedrock maps, lumped surficial deposits into only three or fewer units, albeit including a few alpine moraines significant to later studies.

The most thorough alpine-glacial mapping on the folio series nearest the Northwest are four 1:125,000 sheets (1906) in the Bighorn Mountains region, where on Matthes's sensitive topographic maps detailed surficial mapping by R. D. Salisbury (assisted by Eliot Blackwelder) was combined with exceptional bedrock geology by N. H. Darton. Salisbury mapped two stages of alpine-glacial deposits distinguished by relative position of moraines that showed distinct differences in weathering and erosional modification. The younger drift was subdivided into as many as seven geomorphic-lithologic (hereafter, morpholithologic) units.

Explicitly Quaternary Studies

Some relatively detailed Quaternary mapping, stratigraphy, and geomorphic studies are noteworthy. Russell (1885) compiled an inventory of known existing glaciers in the Sierra Nevada, Cascade, Wind River, and Teton ranges—an elaboration of the inventory by King's Fortieth Parallel Survey. Russell (1885), again elaborating the King survey, discussed shoreline features and stratigraphic evidence of two successive stages of pluvial lakes in the Lahontan basin.

Delayed many years in publication, Gilbert's (1890) Lake Bonneville monograph is the most objective and imaginative, eloquent and durable Quaternary report of the 19th century. He mapped the extent of the Pleistocene lake at 1:800,000; elaborated lengthily on shoreline processes and landforms—especially on the forms of shorewise bars, many shown on large-scale maps with 10-ft contours; deciphered two episodes of filling and drying of the lake; inferred general synchrony of the lake with Pleistocene glaciers; inferred that the abrupt drop from Bonneville to Provo shore was effected by a flood engendered by catastrophic incision of alluvium at the Red Rock Pass spillway; related theory to field observations on differential isostatic uplift in the basin by as much as 170 ft; and discussed evidence of Quaternary faulting of these shorelines and of contemporaneous moraines along the front of the Wasatch Range. The report is a gracefully didactic treatise on processes of erosion, transportation, and deposition of debris by waves, littoral currents, and influent streams. The concept of sequential landscape development from adolescence through maturity to senility anticipates the general laws of shoreline development later popularized by W. M. Davis and D. W. Johnson. As in his Henry Mountain report, the principal concepts in Gilbert's

I. C. Russell (U. S. Geological Survey Photo Library, Denver)

Lake Bonneville monograph, having been more elaborated than revised by later workers, are among the most durable in the Quaternary literature.

A 1903 study by Bailey Willis transplanted into the Northwest W. M. Davis's (1889, 1899) cyclic-erosion paradigm of landscape evolution. In the eastern Washington Cascades, Willis described upland surfaces by which he inferred two stages of tectonic stability and reduction of erosional relief, each followed by an episode of uplift and tilting and consequently by general stream incision.

Russell's 1889 account of the Mono Basin and adjacent Sierra Nevada demonstrated a Quaternary icecap on the Sierra Nevada (generalized on Chamberlin's 1888 reconnaissance map), from which glaciers advanced down valleys into the Mono Lake basin during two distinctly different periods (now "Mono Basin" distinguished from now "Tahoe-Tenaya-Tioga"). The outer moraines of the younger set (now "Tahoe") had been notched by shorelines, proving that the maximum stand of the lake followed the maximum stand of the glaciers.* He discussed Holocene faulting of moraines and lake deposits along the base of the Sierra Nevada and west-tilted shorelines indicating tectonic tilting of the downthrown Mono block—which also accounted for the lake positioned

* Russell compared a pre-last-glacial (Tahoe) moraine to a probably last-glacial (Tioga) lake stand. Gilbert (1890), on the other hand, thought that the Lake Bonneville maximum had predated the alpine maximum in the Wasatch Range, a notion that more recent studies suggest is incorrect.

W. W. Atwood (U. S. Geological Survey Photo Library, Denver)

anomalously at the very base of the escarpment. Russell also discussed Quaternary volcanism in the nearby Mono Craters.

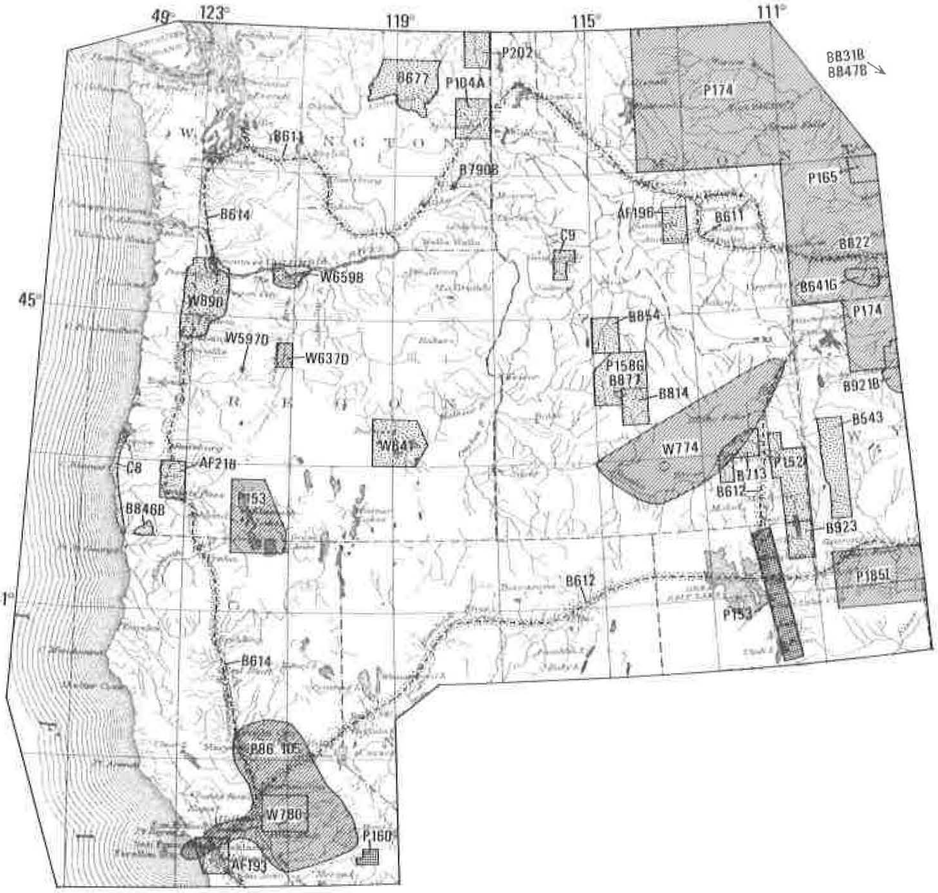
A 1906 paper by F. H. H. Calhoun, a member of Chamberlin's team tracing terminal moraines and the Wisconsin drift limit across the continent, delineated the Wisconsin drift limit and terminal moraine in Montana, ice-dammed lake deposits outside the moraine, and a few recessional moraines inside. He sketched former courses of the ice-deranged Missouri drainage. Where Laurentide drift overlapped local alpine drift along the Rocky Mountain front, Calhoun's stratigraphy showed that the alpine maximum preceded the Laurentide maximum.

W. W. Atwood's 1909 report on alpine glaciation in the Uinta and Wasatch Ranges delineated drift from two glaciations, which he distinguished by two sets of moraines that had marked differences in weathering of surface stones and in erosional modification. Atwood's 1:125,000 Uinta map distinguished within each of the two drifts crested moraines, ground moraine, scattered drift, and outwash. Prior to Eliot Blackwelder's (1915) classic paper that named regional stages of alpine drifts in Wyoming, USGS maps in several mountain ranges peripheral to the Northwest had deciphered two discrete glaciations separated by a lengthy non-glacial interval.

U. S. GEOLOGICAL SURVEY: 1914-1946

(Map 3)

1914 to 1946 was a slack period for Quaternary geology by the USGS in the Northwest. War,



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Journal of Research	J
Monograph	M
Open-File Report	OF
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Geologic Quadrangle Map	Q
Water-Supply Paper	W

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Relative quality of contribution to Quaternary geology

░ ░	Reconnaissance
▨ ▨	Detailed reconnaissance to Detailed
▦	Detailed to Thorough

Map 3. Reports of the U. S. Geological Survey 1914-1946.

G. K. Gilbert (U. S. Geological Survey Photo Library, Denver)

depression, and drought focused activity on minerals, coal, and water, while funding for less obviously applicable science was scarce. The fewness of reports on the Quaternary, however, is compensated by the exceptional quality of some of them.

Gilbert's Last Works

Three *Professional Papers* by G. K. Gilbert dominate the USGS Quaternary literature of the first half of the period, though most of his research had been completed before 1914. Drawing on his lifelong interest in fluvial processes, particularly shown by his 1877 Henry Mountains report, Gilbert in 1903 undertook for the USGS an impartial study of the effects of hydraulic mining in the western Sierra Nevada. Some detrimental effects of mining debris on the Sacramento Valley and San Francisco harbor had been contested and litigated for decades. The first phase of Gilbert's investigation, a flume study eventually published in 1914, was the first comprehensive report to quantify relations between streamflow and transportation of tractive bedload. Among the relations scrutinized were the directly proportional relations of capacity to coarseness of transported debris, capacity to stream gradient, capacity to stream discharge, and the inversely proportional relation of capacity to bed roughness.

Newly armed with these empirical data, Gilbert in his 1917 paper on hydraulic-mining debris showed that an abrupt increase in bedload supplied to a stream by the hydraulic miners had caused aggradation and increased stream gradient; showed that erosion and decreased grade are the consequence of an abrupt decrease in load downstream from small dams that had been thrown up to impede the fugitive debris; and showed the limited utility of such dams, which inevitably fill and overflow with the debris they are supposed to impound. This report remains the most articulate study of its type.

The wave of aggradation had buried farmland in the Sacramento Valley and had partly infilled the San Francisco Bay, such that the tidally maintained bay-mouth bar had migrated landward. Gilbert thus showed how disruption of a natural equilibrium between erosion and transportation in distant headwaters had manifested itself potentially even to impede shipping in the San Francisco harbor. Although affected landowners had known some adverse consequences of the hydraulic mining long before Gilbert, his was a dispassionate report to which all sides of a divided public could turn for reliable data and analysis. Anticipating by half-a-century the environmental consciousness of the 1960s, here is one of the most thorough, objective, and instructive environmental-geologic reports of the 20th century.

Gilbert's posthumously published 1928 paper on basin-range structure described and analyzed the geomorphology of late Cenozoic fault scarps—elaborately along the Wasatch front, briefly at Klamath Lakes and elsewhere. Gilbert eloquently refuted J. E. Spurr and others who had advocated folding as the cause of basin-range topography and clarified that most scarps indeed are dip-slip fault scarps—as he the youthful geologist of the Wheeler survey had opined in 1871. It was a graceful finish for the man who surely is the foremost Quaternary scientist in the history of the USGS.

Erosional Geomorphology, Glacial Geology

François Matthes's 1930 paper and 1:24,000 geologic map on Yosemite Valley, an area he had earlier mapped as a topographer, developed John Muir's thesis of glacial erosion of the valley. Matthes inferred from tributary-valley profiles that the glaciers had widened and straightened more than deepened the valley. Having distinguished preglacial from glacial landscape, he inferred from the preglacial three intervals of uplift and westward tilting of the Sierra Nevada block, the oldest late Miocene in age. From the relative position of moraines and unequal degrees of post-depositional weathering and erosion, he inferred the downvalley and upper limits of three Pleistocene stages of drift. The younger two drifts were further divided as crested moraines, ground moraine, outwash, and marginal lake deposits. Although Eliot Blackwelder's 1931 paper detailing four glaciations was destined to become the more quoted standard for the Sierra Nevada, Matthes's report is the most detailed and thoughtful qualitative analysis of glacial processes in a single alpine valley in the West.

W. C. Alden's 1932 report of surficial glacial deposits in the Montana High Plains and along the Rocky Mountain front significantly augmented Calhoun's reconnaissance three decades previously. Alden divided drift into three stages within which he distinguished alpine-glacier deposits from Laurentide ice-sheet deposits, which he in turn divided morpholithologically. By their relative heights above streams, gravel terraces were divided into four broad relative-age groups, the younger two inferred to be interglacial deposits, the older two preglacial. The abandoned preglacial courses of the ice-deranged Missouri River and tributaries were delineated in some detail. Though the scale of the geologic map was small (1:500,000), it was a masterful correlation over 110,000 square miles.

Wilmot Bradley (1936) on the north flank of the Uinta Range added an older glacial stage to Atwood's (1909) two and correlated the three stages with Blackwelder's (1915) three in Wyoming. From four principal erosion surfaces Bradley read the late Cenozoic dissection of the range and adjacent Green River Basin. In less analytical reports elsewhere, such upland surfaces had been identified with Davisian peneplains, implying cyclic oscillation between tectonic stability and substantial uplift. Bradley traced two Tertiary erosion surfaces beveled across crystalline rocks in the high Uintas basinward into surfaces planed across weak sedimentary rocks and thickly mantled by

F. E. Matthes (Geological Society of America)

stream conglomerate. He inferred that the surfaces therefore were not peneplains formed by downwasting of interfluves and later tilted and greatly uplifted. Rather the surfaces had *formed* steeply, as a consequence of lateral planation by steep-gradient mountain streams. The smoothly concave-up profiles were thus explained by ordinary graded streams transporting coarse rock waste. The surfaces were ancient pediments formed by tributaries graded to an incising Colorado River system. Bradley inferred that a normal process of stream shifting during erosional degradation was abstraction of steep-gradient mountain streams by low-gradient basinal streams. The resemblance of Bradley's concepts to the contemporaneous but independent analyses of J. Hoover Mackin (1936-37) in the Bighorn basin and of Charles B. Hunt, who was reinvestigating the Henry Mountains (see page 185), illustrates the conceptional swing in the mid-1930s from Davis's peneplanation and uplift theory that had dominated the early 20th century, back toward the planation and degradation theory postulated by Gilbert.

Quaternary Mapping Ancillary to Studies of Economic Resources

Besides particularly Quaternary studies, other USGS reports that evaluated water, coal, or minerals contributed to regional Quaternary history.

Water-resources reports chiefly authored by Harold Stearns in the Deschutes River basin of Oregon (1934) and in the eastern Snake River Plain of Idaho (1938) delineated fairly detailed

W. C. Alden (U. S. Geological Survey Photo Library, Denver)

Pliocene to Holocene volcanic and interbedded sedimentary sequences, mapped at 1:62,000 or larger. The recognition of intracanyon flows in both areas revealed an intermittent competition between streams that excavated valleys and invading lava that subsequently filled them. In the Snake River Plain, augmentation to the early reconnaissance of Russell was substantial, Stearns having differentiated more than 20 late Pliocene to Holocene units and having contributed detailed geologic maps of Craters of the Moon and of parts of the Snake River Valley.

Authored chiefly by H. S. Gale and A. M. Piper, a 1939 *Water-Supply Paper* and map at 1:62,000 distinguished in the California Great Valley six Pliocene and younger alluvial units, a much more detailed division than on the earlier folio maps. Descriptive *Water-Supply Papers* chiefly by Piper distinguished five alluvial and volcanic units in the Harney Basin of eastern Oregon (1939) and three Quaternary alluvial units in the Willamette Valley (1942), adding details to previous USGS reconnaissance.

Large tracts of central Montana and adjacent Wyoming underlain by near-surface coal were mapped at 1:62,500. While treatment of surficial deposits in most of these *Bulletins* is meager, in areas just east of 107° N. W. Bass (1932) mapped six different levels (relative-age groups) of terrace gravel along Missouri River tributaries; W. G. Pierce (1936) showed 12 such units, the highest and oldest 800 ft above the Yellowstone River. Augmenting Mackin's elaborate erosional history of the central Bighorn Basin, Pierce and Andrews (1941) distinguished five major age-groups of terrace gravel in the western tributaries of the basin.

W. H. Bradley (U. S. Geological Survey Photo Library, Denver)

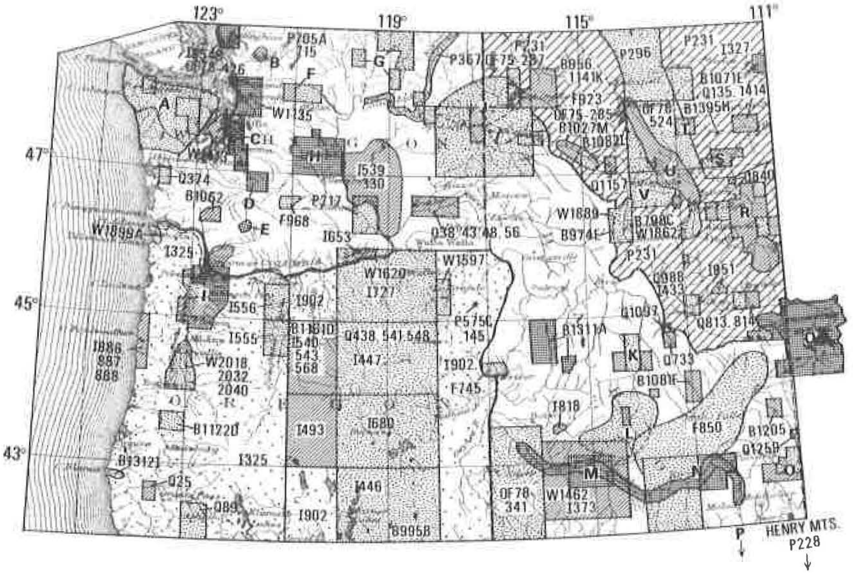
U. S. GEOLOGICAL SURVEY: 1947-1979

(Map 4)

New Methods

Since the mid-1950s Quaternary research in the Northwest has substantially increased. Because most geologic maps are at scales 1:62,500 or larger, they show distribution and division of some Quaternary deposits, though the vast majority are bedrock maps having but brief descriptions of surficial units and little analysis of their age or genesis. The postwar reports showing Quaternary deposits, however, are so many that most areas peripheral to strictly the "Northwest" are omitted from this review. Some reports from the Lake Bonneville basin and Henry Mountains are included because of their importance as crucibles of ideas—which in turn owes partly to Gilbert's previously imaginative studies.

Methods of research evolved considerably since World War II, permitting a detail and breadth of research not possible earlier. The abundance of fresh exposures along new roads has increased exponentially, as has ease of travel to them. Increased understanding of modern processes provides the more recent investigator a very large experience from which to draw interpretation. The rapidity of technologic advance and application to Quaternary geology has altered the whole complexion of research. In the 1950s aerial photographs became available for much of the Northwest, and now it is rare to map without them. Concurrently the 1:24,000 USGS topographic map series have appeared with contour intervals of 40 ft or less, encouraging a detail of surficial mapping impossible on the older 1:125,000 maps. After radiocarbon dating was developed about 1950, organic samples were avidly sought for age calibration of stratigraphic sections. Many older techniques for dating, correlation, and analysis of surficial deposits have transformed the general field of Quaternary research into an interdisciplinary amalgam of interdependent specialists. Among the new techniques are K-Ar dating, fission-track dating, U-series dating, hydration-rind dating, dendro-



ADDITIONAL SOURCES FOR MAP 4

Area	Sources
A	Q129, 958, 969,970 I994 P501D(135)
B	P1022C F774
C	P388A, 422A, 672 B1194-0 Q125, 158, 159, 405-407, 707 I354
D	P387AB, 422A, 444, 600D(79),677, 847 B1221A, 1238, 1288, 1292, 1326 I836 F774
E	B1383 F774
F	P604 Q473, 646, 647 F774
G	B1161F, 1169, 1216, 1402 Q636 OF78-732
H	F908 OF77-531, 77-753
I	Q104 B1119 W1600, 1697, 1793, 1833, 1847, 1997
J	P428, 510, 525C(128) B1027P, 1122A, 1131 W1779I Q375, 538, 734, 953 I464, 768, 1336
K	Q464 OF75-76, 78-1059, 78-1060
L	B1252A W1478, 1479 OF76-75, 78-546, 78-1058
M	P596, 644F B1131D F809
N	P596 B1121G, 1399, 1400 OF78-533
O	B1042A, 1153 Q109, 194 I557 OF78-1018
P	P221A, 257ABC, 424CDE, 477
Q	P729BDE, 435 B1144, 1427 Q1189-1193, 1209, 1243, 1244, 1247, 1459 I635-652, 710, 781A, 943 J3(67)
R	P292, 370, 428, 510, 665 B972, 1121J, 1141G, 1151, 1042N W1482 I452, 486 OF75-211
S	Q974-977, 1240, 1241, 1411 I409, 468, 564
T	Q453, 454, 499, 597, 610, 991
U	J6(425) OF77-196 to 203, 465, 466, 539, 540, 860, 861, 78-135, 136, 173, 174, 437 to 447
V	B1111F OF77-529, 78-371, 418

Map 4. Reports by the U. S. Geological Survey 1947-1979.

chronology, climatic palynology, lichenometry, magnetostratigraphy, archeologic dating, improved vertebrate chronologies, analysis of meteorologic and climatic data, and remote imagery. In the Northwest with its many Quaternary volcanoes, tephrostratigraphy and tephrochronology have become an especially fruitful means of correlation. The remainder of this section shows not only a steady upswing in volume and detail of work but some effects of the technologic advances.

General Reconnaissance

Comparing Map 4 to Maps 1-3 shows that more area has been covered in greater detail since World War II than in all the previous periods together. Some Quaternary deposits are shown on USGS maps of more than a third of the Northwest—or more than a half if the entire areas of Alden's map of western Montana and Peck's and Walker's maps of Oregon are counted. Only salients of the more thorough works and in the larger areas of contiguous maps are discussed below.

Several maps variously by Malde, Elkren, Armstrong, Smith, and others show in reconnaissance Quaternary deposits in most of southern Idaho. Maps at scales 1:125,000 to 48,000 show 2 to 18 lithologic units, many of them basalt; except for basalt, most units have meager description and relative-age distinction.

In eastern Oregon six 1:250,000 maps variously by Walker, Brown, Thayer, Swanson, Greene, and others divide the Quaternary into as many as nine lithologic units, some of them volcanic. Description and relative-age distinction are meager except on Swanson's map of the Bend sheet. Ten other maps of scales 1:125,000 to 1:62,500 show six or fewer sparsely described Quaternary lithologic units. With Walker's (1977) 1:500,000 map, however, surficial deposits of all of eastern Oregon are shown at least at reconnaissance level.

About 20 widely scattered geologic maps at 1:62,500 to 1:48,000 show as many as six lithologic units in western Oregon and Washington. Maps by Roberts (1958) in southeastern Washington and by Wells and Walker (1953) in southwestern Oregon show as many as five relative-age groups distinguished either by lithostratigraphy or 'morphostratigraphy.' Peck's (1961) 1:500,000 map of western Oregon shows 27 briefly described Quaternary units. In the Olympic Mountains, Tabor and Cady's (1978) 1:125,000 map and four variously authored 1:62,500 quadrangle maps show three to eight sparsely described lithologic units almost without relative-age distinction. A brief summary of the lowlands on the southwestern Olympic Peninsula by Crandell (1964) distinguishes some Wisconsin-age stratigraphic units.

In northeastern Washington and adjacent Idaho, Grigg's 1:250,000 maps distinguish eight briefly described Quaternary lithologic units. Eighteen nearby and variously authored maps at 1:125,000 to 1:24,000 show one to eight such units. A brief analysis by Weis and Richmond revises the "late Pleistocene" ice limit in the region, which had been previously drawn farther south.

In western Montana, 1:125,000 to 1:500,000 reconnaissance maps of Glacier National Park by Ross (1959), of a large area to the south by Mudge and Earhart (1978), and of a large part of the Missouri drainage to the east by Colton et al. (1961) show three to five Quaternary lithologic units having little relative-age distinction. Larger scale maps incompletely cover west-central Montana.

Reports Specifically on the Quaternary

Explicitly surficial geological research in the Northwest steadily increased when the fiscal austerity of war ended, when a new generation of geologists populated the USGS during its postwar expansion, and when the Russian launch of *Sputnik* encouraged broader national support of science. The fluid economy and national environmental awakening of the 1960s focused the USGS more strongly on Quaternary geology than since the days of Chamberlin, Gilbert, Russell, and Willis. The discussion below proceeds geographically, sinuously clockwise from northern Utah to the Pacific and back to northwestern Wyoming.

C. B. Hunt (U. S. Geological Survey Photo Library, Denver)

While the Henry Mountains are peripheral to the "Northwest," C. B. Hunt's late-1930s restudy (published 1953) of Gilbert's classic area had import to western fluvial landscapes in general. Hunt reaffirmed and developed Gilbert's nascent theory of landscape evolution by fluvial planation and backwasting of slopes (contrasted with W. M. Davis's theory of peneplanation by interfluvial downwasting). Hunt elucidated that during regional degradation a low-gradient pediment formed by local streams commonly abstracts an adjacent high-gradient mountain stream, which thickly veneers the pediment with coarse gravel. This process explained the conglomerate that Bradley had mapped overlying the basinward extension of ancient pediments in the Uinta Range.

In another deferred publication, Schmidt and Mackin (1970) in west-central Idaho distinguished almost 30 surficial units grouped into four broad relative ages, including two glacial stages (Pinedale and Bull Lake). The 1:62,500 map and brief text is the most detailed account of alpine-glacial history in central Idaho.

Beginning in 1946, the USGS reexamined parts of Pleistocene Lake Bonneville along the Wasatch front, elaborating Gilbert's great monograph and deciphering a glacial-pluvial sequence important to the Columbia drainage. *Professional Papers* by Hunt, Varnes, Morrison, and Richmond in 1953-1965 delineate a detailed stratigraphy within each of four major Pleistocene lake stages. The deposits of each lake stage were thought to be distinguished in stratigraphic sections by paleosols traceable into Gilbert's geomorphic surfaces. Contiguous alpine-glacial deposits were referred to stades of the Bull Lake and Pinedale glaciations. Geomorphic and stratigraphic relations between the glacial and lake deposits at first suggested that the three earlier lake stages correlated with the Bull Lake Glaciation; later dating indicated that the Bonneville and Provo deposits correlate with the Pinedale Glaciation. Crittenden's restudy of isostacy did not substantially change Gilbert's analysis, though the new data on the Bonneville shoreline revealed a more lobate pattern of isostatic rebound and that the maximum rebound exceeded by 40 ft Gilbert's esitmate of 170 ft.

The Quaternary history of the Snake River Plain was significantly augmented in the 1960s by Malde along the river west of 113°, and by Trimble and Carr to the east. Malde (1968) detailed the effects of the Bonneville flood, caused by Lake Bonneville filling deeply enough to overtop an alluvial fan at Red Rock Pass. The swift excavation of the fan catastrophically drew down the lake—some 375 ft from the Bonneville to Provo shoreline according to Gilbert, or from a super-Bonneville level to the Bonneville shoreline according to Malde. The catastrophic discharge having been, Malde showed, too great for the sinuous Snake canyon, floodwater poured across the highly jointed basalt, quarrying bizarre scabland, huge cataract alcoves, and depositing great gravel bars armored with huge boulders. The suite of landforms and deposits compare to the almost outrageous features in Washington's Channeled Scabland that had been described and imaginatively analyzed by J H. Bretz in the 1920s. The giant alcoves of the Snake Plain, which Stearns had attributed to gradual sapping by springs, Malde inferred to have formed almost overnight beneath the great flood. Quadrangle maps at scales 1:62,500 to 1:48,000 of the central Snake Plain variously by Carr and by Trimble (1963, 1976) show 11 to 19 Quaternary units, some of them volcanic, all of them fairly described, one of them a huge fan of gravel deposited by Bonneville floodwater distending into the Snake River valley. In the central and western Snake Plain, several reports and maps at 1:125,000 to 1:24,000, chiefly by Malde (1963-1972) and Covington (1976) depict a detailed stratigraphy of more than 20 units that include Pliocene vertebrate-bearing lacustrine beds, and Pleistocene basalt sheets, intracanyon basalt flows, and Bonneville flood gravel.

On the lower Snake River in Washington, four 1:62,500 geologic maps variously by Trimble, Waldron, and Gard (1954-1955) distinguish six or fewer Quaternary lithologic units including flood gravel, only sparsely described and revealing little stratigraphy. A prominently portrayed, sinuous intracanyon basalt flow now known to be 12 m.y. old, shows that the lower Snake River has been locked approximately in its present course since the late Miocene.

Farther west on the Columbia, 1:62,500 maps by Grolier and Bingham (1971) show nine units including catastrophic Missoula-flood gravel; descriptions and analyses, however, pale before the earlier publications of Bretz. Reports on downstream areas, chiefly by Newcomb (1971, 1972), include maps at 1:31,680 to 1:62,500 of modestly described Pliocene to Holocene units. Eschewing the hypothesis of catastrophic flooding, however, the analyses of Pleistocene units are archaic. Collectively these reports describe and show the extent of the Pliocene Ringold formation, which like contemporaneous strata on the Snake River Plain implies a significant tectonic ponding if not derangement of major rivers.

Maps at 1:62,500 and geologic reports by Trimble (1957, 1963) of the Portland area discuss as many as 15 well-described Quaternary units; variously authored *Water-Supply Papers* and maps (1964-1967) at 1:48,000 in the northern Willamette Valley show three to seven briefly described units. Some of these reports, especially Trimble's, infer that gravel and sand of the "Portland delta" and the erratic-bearing Willamette silt are deposits of Bretz's catastrophic Missoula floods that flushed down the Columbia almost 400 ft deep, backflooding the Willamette.

In the central Puget Lowland, *Water-Supply Papers* and maps at 1:62,500 to 1:48,000 by Newcomb (1952) and Sceva (1957) describe as many as 11 Quaternary units grouped into six lithostratigraphic units. In the southeastern Puget Lowland several reports and geologic maps mostly at 1:24,000 variously by Crandell, Mullineaux, and Waldron (1959-1972), show as many as 13 age-groups of mainly lithostratigraphic units, including four drifts interbedded with nonglacial alluvium—a substantial augmentation of earlier work. Deposits of the last glaciation, which Mullineaux and others subdivided lithostratigraphically, were ^{14}C dated in Seattle between 15,000 and 13,500 years old. A surficial till-like mass along the Cascade mountain front, which Willis had

D. R. Crandell (U. S. Geological Survey Photo Library, Denver)

thought to record a substantial readvance of alpine glaciers after retreat of the ice sheet, Crandell reinterpreted as a catastrophic mudflow that had originated on Mount Rainier and flowed some 70 km to the Lowland. The USGS has done little in the northern Puget Lowland, but it did publish a 1:62,500 map by Easterbrook (1976) showing a detailed last-glacial stratigraphy including a late-glacial glaciomarine drift that has been isostatically uplifted as much as 600 ft.

In comprehensive surficial mapping of the eastern Cascades, partly in areas of early reconnaissance by Russell, Willis, and Smith, Waitt (1977) mapped at 1:100,000 to 1:24,000 about 40 Quaternary units grouped into six broad relative-age classes. The units record Pliocene aggradation, mass wasting and topographic inversion, and sequential Pleistocene alluviation and glaciation. The effects of four glaciations dominate the alpine areas and valleys of the eastern Cascades, while the effects of catastrophic Missoula floods as deep as 1000 ft dominate the Columbia River valley. Along the Columbia River farther east, Jones et al. (1961) delineated a stratigraphy of glaciolacustrine and glaciofluvial deposits from which they specifically evaluated the causes and effects of landsliding along recently created hydroelectric reservoirs.

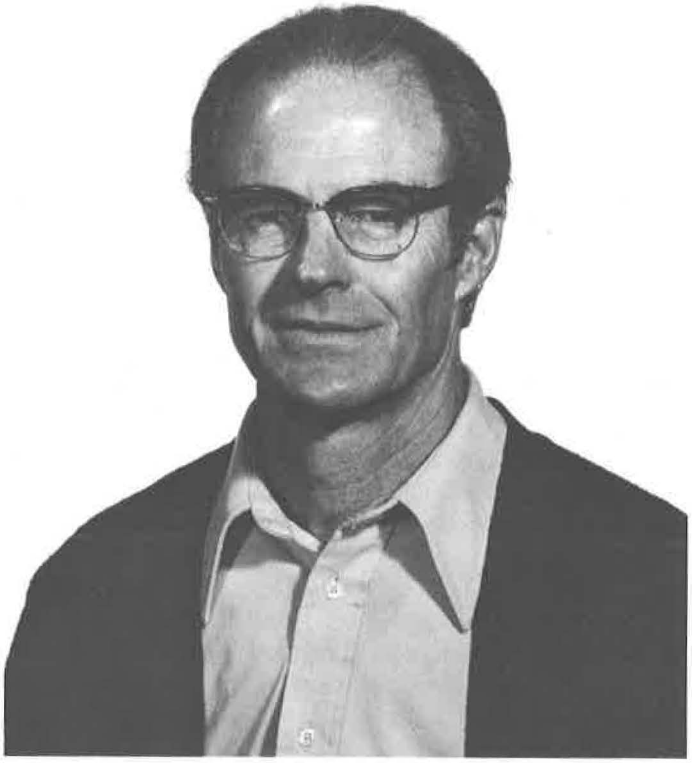
Alden's *Professional Paper* and 1:500,000 map (1953), covering a broad area in western Montana and northernmost Idaho west of his 1932 paper, distinguishes more than 15 Quaternary units including three glacial stages. It distinguishes alpine from ice-sheet deposits, distinguishes morphologic units like moraines, shows the deposits of glacial lakes Missoula, Kootenay, and others, and delineates the deranged preglacial Missoula drainage.

Western Montana has been discontinuously covered over the years by geologic maps at 1:63,360 to 1:24,000—the Quaternary having been variously ignored, acknowledged, or embraced. Until recently maps and reports focused on bedrock, water, or minerals, to which surficial geology was incidental. Some of the more recent maps are somewhat more ostensibly based in the Quaternary. Only a few such areas can be mentioned here. Smith et al. (1959) in the Marias drainage mapped two ice-sheet drifts each divided morpholithologically, and they distinguished four river-terrace-gravel units. Maugham (1961) and Lemke (1977) near Great Falls mapped as many as 10 units grouped into four major relative-age classes, delineated ice-dammed lakes, and suggested that stream gradient had increased through time. Schmidt, Soward, and others in 1964 to 1975 mapped along the Missouri and tributaries below Helena as many as eight Quaternary alluvial units grouped into five relative-age classes, but with the briefest description and analysis. Variously authored maps published 1951 to 1971 of the Missouri drainage above Helena show as many as 11 Quaternary morpholithologic alluvial units grouped into five relative-age classes. Along the Columbia headwaters of Swan River and Blackfoot Creek, Witkind and Weber (1977 to 1979) in 25 preliminary maps mostly at 1:24,000 show as many as 17 briefly described Quaternary alluvial and glacial lithologic units.

The large area most thoroughly mapped and analyzed by the USGS in or near the Northwest is Yellowstone National Park and its periphery. Most of 30 maps at 1:62,500 covering this area are either bedrock maps showing as many as 14 Quaternary volcanic units, published 1974-1975 variously by Christiansen, Blank, and others, or are surficial maps published 1971-1977 variously by Richmond, Pierce, and Waldrop. The surficial maps show ice-flow directions, ice limits, and terrace scarps, and show almost 30 glacial and alluvial morpholithologic units grouped into about five age classes, including three major glaciations that are further subdivided. The quadrangle maps and a general surficial map (1972) of the Park at 1:125,000 are elaborated by several separate reports on dating, stratigraphy, and climatic interpretation. Maps and reports by Love, Witkind, and others expand somewhat less detailed analyses to peripheral areas. The Yellowstone region in 1979 thus retains its relative status of 1879: compared to other regions in the Northwest, the Quaternary of the Yellowstone region is very well studied.

G. M. Richmond (U. S. Geological Survey Photo Library, Denver)

The areas most competing with Yellowstone for density, detail, and continuity of USGS Quaternary publications are the Cascade volcanoes, especially Mount Rainier. The volcanoes harbor accessible active glaciers, some having 100 years of historic observations; they were extensively glaciated during the Pleistocene; they are potentially hazardous to nearby property and inhabitants; and they have been sources of tephra useful for Quaternary correlation broadly in and beyond the Northwest. Between 1961 and 1976, the USGS published 14 maps and reports on Quaternary deposits and history of the Mount Rainier area. Papers variously by Fiske et al., Crandell, Crandell and Miller, Millineaux, Sigafoos and Hendricks, Richardson, Fahnestock, and others collectively delineated the eruptive history; a surficial-deposit sequence of seven age groups including four glacial stages; a complex stratigraphy of lahars from the volcano and air-fall tephra from several Casacde volcanoes; a history of catastrophic rockfalls, mudflows, glacier-outburst floods, and other hazards; and from botanical and tephrochronologic evidence, a history of Holocene glacier fluctuations. Works by Mullineaux, Hyde, and Crandell published 1973-1978 have delineated an exceptionally detailed and well-dated eruptive history of Mount St. Helens, especially of lahars and air-fall tephra, the latter constituting time-stratigraphic marker beds hundreds of kilometers downwind. Less thorough studies deciphered an eruptive and glacial history of Mount Baker.



D. R. Mullineaux (U. S. Geological Survey Photo Library, Denver)

In a political climate conditioned partly by such earthquake damage as at Hebgen Lake in 1959 and Anchorage in 1964, the search for Quaternary faults has increased. Maps of Idaho and western Montana by Witkind (1975, 1977) and of the Puget Lowland by Gower (1978) summarize existing data on young faults.

Population having rendered water supplies more critical, mass-balance analyses of water-contributing glaciers in the headwaters have increased. Inventories of glaciers in the North Cascades and mass-balance studies of South Cascade Glacier, published 1971 and 1977 in *Professional*

Papers variously by Post, Meier, Tangborn, and others, provide not only meteorologic and hydrologic data, but also data useful for reconstructing past climate from past glacier fluctuations.

FORECAST FOR THE FUTURE: 1980-2001

Quaternary research in the Northwest by the USGS is historically high and increasing. Ongoing or only recently completed work includes a 1:250,000 to 1:62,500 mapping of the eastern Snake River Plain and adjacent uplands (Scott, Richmond); mapping and stratigraphy of loess along the Snake River and tributaries in and upriver of the Snake Plain (Pierce); renewed studies on stratigraphy of the eastern Lake Bonneville Basin (Scott, Shorba); 1:24,000 surficial mapping in west-central Montana (Witkind); studies on Neoglaciation and mass wastage in Glacier National Park (Carrara); on Mount St. Helens detailed stratigraphy and dating of air-fall tephra (Mullineaux) and of lahars and pyroclastic flows (Crandell, Hoblitt); Holocene stratigraphy and geologic hazards of Mount Shasta (Miller, Christiansen), of Mount Hood (Crandell), Glacier Peak (Beget), Newberry Crater (MacLeod), and Crater Lake (Bacon); mapping, stratigraphy, and geomorphology of alpine-glacial and alluvial deposits in the Washington Cascades and of ice-sheet drift and catastrophic-flood deposits in the Columbia drainage (Waitt); and continued studies on modern glaciers (Meier, Post, and others). A comprehensive project on applied geology is underway in the Puget Sound area (Pessl, Minard, Yount, Foxworthy, and others) similar to those recently concluded in the San Francisco Bay area and in the Colorado urban corridor. A recently completed study documents the isostatic effects of ice loading of the Puget Sound (Thorson). Super-regional projects are underway on relative and numerical dating (Pierce), especially from Quaternary soils (Marchand*, Harden), from weathering rinds (Colman), from regional tephra sheets (Mullineaux, Izett, Sarna-Wojcicki, Pierce, Waitt), and from coastal deposits (Lajoie). The Northwest is a part of a nationwide compilation of Quaternary geology at 1:1,000,000 (Richmond) and of Quaternary faults (Gower, Witkind).

Some of the substantial blank areas on Map 4 suggest regions and topical studies important to a comprehensive regional Quaternary-geologic program in the Northwest:

1) Quaternary tectonism in (a) the Yakima foldbelt of eastern Washington, (b) the basin-range region of southeastern Oregon, and (c) coastal Oregon and Washington, where Quaternary sea-level and alpine-glacier fluctuations also are poorly known;

2) Stratigraphy and chronology of surficial deposits in the northernmost U. S. tier of 1° x 2° sheets, between north-central Washington and northwestern Montana—a region affected by at least two major Cordilleran ice-sheet glaciations, by contemporaneous ice-dammed lakes and regionally significant catastrophic floods, by glacioisostatic rebound, and in Montana perhaps by range-front faulting;

3) Detailed stratigraphy of loess in eastern Washington, which may contain a more detailed history of fluctuating climate than the fragmentary glacial and alluvial records in peripheral areas;

4) Detailed stratigraphy and volcanic-hazards evaluation of several Holocene volcanic centers in Oregon that are known only in reconnaissance;

5) Stratigraphy and chronology of interbedded Quaternary volcanic, glacial, and stream deposits in many areas scattered in and adjacent to the southern Cascade Range between Mount Rainier and southern Oregon;

6) Stratigraphy and chronology of Holocene glacier deposits, which contain fragmentary records of regional climatic fluctuations across the Cascades, northern Rockies, and intervening ranges;

7) Stratigraphy, sedimentology, palynology, tephrochronology, and radiometric dating of continuous cores from bogs and lakes in Oregon and Washington. In glacial terrane are oppor-

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* Deceased.

tunities for late Wisconsin or Holocene records, while sites beyond glacial limits could yield much older continuous records;

8) Glacial stratigraphy in the ranges, and alluvial stratigraphy and chronology along range fronts, in the Basin-Range Province of southeastern Oregon, a region known only in reconnaissance.

A government agency, the USGS answers to the U. S. public and is duly influenced by national politics and economics. Some of our pressing national needs as for metals, coal, and oil may have only tangential bearing on Quaternary research. But other needs no less important in the long-term—prediction of climatic or geologic hazards to the physical and biologic environment, to agriculture, to life and property, to dams, power plants, and radioactive waste repositories, to water quality—inextricably rely on comprehension of Quaternary processes and history. As population expands, more geologically hazardous sites are utilized for housing, agriculture, and engineering works, and more of the population becomes vulnerable to inevitable natural changes. Understood modern processes and deciphered Quaternary records are the surest guides for predicting natural changes in the future. Barring some extraordinary political or economic upheaval, the basic human concerns about long-term availability of food, clean water, and natural resources, and about safety from natural or induced disaster, should sustain a vigorous USGS program of interdisciplinary Quaternary research in the Northwest into the 21st century.

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ADDENDUM—DECEMBER 1981

"Safety from natural disaster" and "vigorous USGS program of interdisciplinary research" proved to be not mere abstractions when in March 1980 Mount St. Helens suddenly resumed activity after a century and a quarter of quiescence. Crandell and Mullineaux had recently (1978) written that the volcano was a threat to people and property and that it would again erupt violently as it had in the recent geologic past (USGS *Bulletin* 1383-C). With the first precursory eruption on 27 March 1980, the Geological Survey established an extensive program to monitor all phases of the eruptions and to predict hazards therefrom. In 1981, drawing from experience at the Hawaiian Volcano Observatory, the USGS opened the Cascade Volcano Observatory in Vancouver, Washington with a staff of about 60. Relevant to surficial geology are monitoring and analysis of ongoing processes in a rapidly changing landscape: analysis of catastrophic processes of the cataclysmic eruption of 18 May 1980; stratigraphy and sedimentology of deposits that can be unambiguously related to observed eruptive and flow events; erosional and depositional effects of ongoing "normal" stream runoff and mudflows; behavior of glaciers beheaded by the catastrophic collapse of the summit cone on 18 May 1980. Studies of 1980 ashflows, instrumental monitoring of ongoing deformation and episodic additions to the new dome, and other related activities commonly classed as "volcanology" are also investigations in surficial processes and geomorphology. The establishment in Vancouver of a new USGS base of operations specifically to monitor Mount St. Helens will doubtless also facilitate USGS investigations of surficial deposits and processes elsewhere in the Pacific Northwest—particularly at other Cascade volcanoes, but also broadly in Washington and Oregon.

VOLCANIC STUDIES IN THE PACIFIC NORTHWEST, 1879-1979

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Geologic study of volcanic rocks in the Pacific Northwest since 1879 passed through an early period of exploration (1879-1910), during which broad outlines of the volcanic history were established. Between about 1910 and 1960, a period of qualitative topical study produced many papers on specific problems, such as the history of a single volcano or the origin of a particular rock body. The modern period, since about 1960, has stressed more quantitative research enabled by technologic advances in petrologic, radiometric, and paleomagnetic fields. Most important petrologic problems that have interested volcanic petrologists for many years are still with us, but modern techniques promise major rewards in the future. Much forthcoming effort will be expended in trying to understand volcanic-tectonic relations and patterns, particularly in terms of plate tectonics. This effort will entail cooperation of researchers in many branches of the earth sciences and will require considerably improved geophysical knowledge of the crust and mantle. We are still in a poor position to forecast future volcanic activity in the region; improvement of this capability is mandatory.

> The entire absence of easily recognized volcanic craters in the eastern part of the United States has tended to create the impression that in volcanos this country is below average; but to dispel this notion it is necessary only to make a trip through our Northwest. (J. S. Diller 1891:9)

No geologist would argue with Diller's evaluation; indeed those who made the trip find that volcanos and their products, volcanic rocks, dominate the landscape of the Pacific Northwest. Many of these geologists have not only made the trip but, figuratively at least, have stayed to engage themselves in studies of volcanism, especially that which took place during the Cenozoic. There are almost certainly more papers on Pacific Northwest geology that deal at least partly with volcanic rocks than with any other single topic. Yet we recognize more unsolved problems today than at any time in the past; the more we know, the more we know how little we know.

This paper presents a brief review of the historic development of volcanic studies in the Pacific Northwest since 1879. Rather than summarizing knowledge of the subject at one or more specific times, I have simply listed some important papers published during three broad periods of time, with little comment on them. The papers and their titles speak for themselves by showing rather clearly how volcanic research in the Northwest progressed from a period of geologic exploration through a period of qualitative topical studies into the current period of diverse and more comprehensive projects. The approach to a problem, as reflected by published papers dealing with it, tells much about the contemporary state of knowledge as well as what kinds of topics were considered important and approachable. I have deliberately stayed away from attempting to summarize our present state of knowledge regarding volcanism in the Northwest. The topic is so complex and in such a state of flux that any such attempt would be overly subjective, unduly long, and surely inadequate.

The emphasis here is on field-based rather than petrochemical studies for three reasons: (1) most past work has been field oriented; (2) petrogenetic studies of Pacific Northwest rocks are part of a more general problem, whereas field studies are much more specific to the Northwest; and (3) my interests are mostly field oriented. The two approaches are really inseparable, of course, and many of the cited papers deal with both field relations and petrogenetic implications derived from petrochemical work.

In addition to the historic summary, a few comments at the end of the paper address problems of possible future interest, including renewed volcanism.

To the native of the area, the Pacific Northwest has its southern boundary at the Oregon-California state line and its eastern boundary in western Idaho. In this paper I have forsaken my heritage by appending the Cascade Range and Modoc Plateau of northern California to the Northwest. Geologic continuity wins out over ethnocentrism. Volcanic areas of southeast Idaho, such as Yellowstone, are excluded, however. I consider only studies of Cenozoic volcanism while realizing that important research has also been completed on older, particularly Mesozoic, volcanic rocks.

PERIOD OF GEOLOGIC EXPLORATION (1879-1910)

Most pioneering geologic work in the Pacific Northwest was of a general reconnaissance nature by both choice and necessity. These investigations were designed to provide a broad background of information concerning the geology, hydrology, and in some instances topography, botany, and even geography of large, poorly known regions. Widely spaced traverses were followed, generally on horseback, and high points providing panoramic views of untraversed areas were sought out. Some surveys covered irregularly shaped areas; others were confined to 30′ quadrangles. All labored under the difficulties of inadequate maps, poor road systems, and limited time. Volcanic rocks were found to underlie much of the Northwest, and consequently reports based on these early geologic expeditions devoted considerable space to volcanic rocks and landforms.

These early surveys were of high, often superb, quality. Observations were careful, descriptions complete and lucid, and interpretations generally sound within the conceptual guidelines of their time. These studies directly provided the foundation for later work, including some in progress today. Recognition of important stratigraphic units, their relative ages, and general geometric relations have proven to be the most useful legacy of this period. I can testify firsthand to the high quality of maps portraying volcanic rocks in central Washington prepared by George Otis Smith (1901; 1903). Contact and age relations that these maps show are either correct or have required much additional effort to be proven wrong. Many interpretations, particularly of a genetic nature, have naturally fallen by the wayside as modern petrology has developed. How many of our present interpretations will hold in 2060?

Some of the most important papers dealing with Pacific Northwest volcanic rocks during the period of geologic exploration include:

Hague and Iddings (1883)–Summarized observations of Cascade volcanos, particularly Lassen Peak and Mounts Shasta, Hood, and Rainier, made by the Fortieth Parallel Survey in 1870.

Russell (1884)–Recognized that, in southeastern Oregon, "the rocks are almost entirely igneous, and occur on the southern border of an immense volcanic region that stretches indefinitely northward."

Diller (1891)–Detailed description of Cinder Cone near Lassen Peak. An exception to the generally reconnaissance nature of work during this period.

Russell (1893, 1897)–Documented the wide extent of Columbia River basalt in eastern Washington (most of his Columbia lava) by mapping.

Diller (1895a)–General description of Mount Shasta. Served as foundation upon which Williams (1932b, 1934) did later work.

Diller (1895b)–First map of large area including Lassen Peak, showing broad extent of Neogene volcanic rocks.

Russell (1900)–First recognition of Teanaway Basalt (his "earlier sheet of the Columbia lava") in central Washington. Described Glacier Peak.

Smith (1901)–First good description of Ellensburg Formation (central Washington). Clear recognition that what we call today the Columbia River Basalt Group is restricted to the Miocene.

Merriam (1901)–Lithologic and paleontologic summary of Clarno and John Day Formations, central Oregon. First description of what is today called the Picture Gorge Basalt.

Calkins (1902)–First good petrographic description of rocks in Clarno and John Day Formations and Columbia River basalt in north-central Oregon. Still quoted.

Diller and Patton (1902)–First major study of the Crater Lake region. Excellent petrographic descriptions utilized by Williams (1942) in his now classic account of Mount Mazama.

Russell (1902)–Thorough description of basalt on the Snake River Plain. His conclusions that "the Snake River lava is in general much younger than . . . [the Columbia River basalt] . . . although its basal members seem to be of about the same age" has been challenged many times but still seems valid.

Russell (1903)–Outstanding descriptions of young basaltic cones and flows in southeast Oregon and southwest Idaho.

Smith (1903, 1904); Smith and Calkins (1906)–Pioneering attempts at mapping volcanic rocks in the central Cascade Mountains of Washington. Definition of several units. Subsequent work has elaborated upon but not replaced these outstanding contributions.

This list is far from inclusive but provides a flavor of the times. Most of the papers represent work done by geologists of the U. S. Geological Survey, because the Survey then was really the only organization set up to conduct regional studies. The rapidity with which results of field work appeared in text and map form is astonishing by present standards. For example, the last field work for the Lassen Peak *Folio* was completed in 1893, and the *Folio* was published in 1895 (Diller 1895b). A 192-page report on the Snake River Plain based on field work in 1901 appeared the next year (Russell 1902). This speed reflects in part the high priority of such regional studies as viewed by the government.

By about 1910, a broad stratigraphic framework for volcanic rocks in the Pacific Northwest had been established. The north and south ends of the Cascade chain had been investigated and found to have a long volcanic history, although the central part of the chain was still little known. Geologists knew that Miocene flood basalt dominated the Columbia Plateau and unconformably rested on lower Tertiary andesitic and rhyolitic rocks in the John Day country. They realized that large areas of southeastern Oregon, northern Nevada, and the Snake River Plain were blanketed by young volcanic rocks, chiefly basalt, although age relations were insecure in many places and the volume and distribution of different rock types largely unknown.

PERIOD OF QUALITATIVE TOPICAL STUDIES (1910-1960)

During this period, most volcanic studies in the Pacific Northwest concentrated on specific problems, generally field related, such as the history of a single volcano or the origin of a particular rock unit. The pace seems to have been slower than during the great reconnaissance surveys, and the nature of investigations changed to one of rather detailed mapping and interpretative projects. Geologists were able to devote more effort to the "how" and "why," not just to the "what" and "where."

Comparatively few volcanic studies were conducted during this 50-year period, considering the surge of effort that preceeded it, the larger number of geologists being trained, and the prevalence of volcanic rocks in the Northwest. I suspect that this results from the difficult problems that volcanic rocks pose. They are dominatly fine grained, non-fossiliferous, and occur in complicated sequences that sometimes challenge the law of superposition and stratigraphic concepts regarding lateral continuity. It is no wonder that so many geologists of the period bypassed volcanic rocks in favor of rocks with internal structures that followed predictable patterns. The common practice of lumping diverse assemblages of lava flows and tuffs into one unit, volcanic cover, probably derives partly from this syndrome.

But many of the volcanic studies that were undertaken produced classic results. Howel Williams' papers on southern Cascade volcanos were then and are today read around the world and led to his definitive treatise on calderas. Richard Fuller and his field assistant, Aaron Waters, using remarkable observational and conceptual abilities, recognized Miocene lava deltas on the Columbia Plateau 40 years before such deltas were observed to form (Moore et al. 1973). Waters' long-term studies on the Columbia Plateau and surrounding areas culminated in his major paper in 1961 on the Columbia River basalt.

Some of the important papers of this period of qualitative topical studies include:

Fuller (1925)–In a notable Masters thesis, Fuller recognized evidence that Cascade volcanos may be produced by "explosive deroofing" of a pluton, a concept popular in one form or another today.

Fuller (1931a)–Recognized lava deltas and described their formation in Miocene basalt on the Columbia Plateau. A classic example of inductive reasoning proven correct by modern observations of moving lava flows.

Fuller (1931b)–Still the best description of the Steens Basalt and older units in extreme southeast Oregon.

Peacock (1931) and Powers (1932)–Companion papers giving much information about the geology and petrography of the Modoc Plateau. Part of this work was the basis for Anderson's (1941) classic study of the Medicine Lake Highlands.

Williams' studies of Cascade volcanoes–1932a (Lassen Peak and surroundings); 1932b and 1934 (Mount Shasta); 1933 (Mount Thielsen); 1935 (Newberry Volcano); 1941 (treatise on calderas based partly on his work in the Cascades); 1942 (Crater Lake area); 1944 (Three Sisters area). Each of these remarkable investigations was a model in its time of how volcanic problems should be attacked in the field.

Callaghan (1933)–Subdivided "The Cascade Range south of Mount Hood in two parts, the Western Cascades and the High Cascades, on the basis of a pronounced unconformity . . ." Showed that the Western Cascades are older. This subdivision is still used today by many workers.

Anderson (1933)–Fine description and discussion of the origin of volcanic breccias, particularly those formed by mudflows, in the Tuscan Formation.

Buddington and Callaghan (1936)–Fine petrographic study of shallow-seated dioritic bodies probably related to Western Cascades volcanism.

Coombs (1936)–First monograph on Mount Rainier.

Thayer (1937)–Good field and petrographic study of High Cascade flows, Columbia River basalt ("Stayton lavas"), and Western Cascade rocks west of Mount Jefferson.

Verhoogen (1937)–First descriptive summary of Mount St. Helens. Paved the way for recent work by C. A. Hopson and others.

Coombs (1939)–Still the only available summary of Mount Baker.

Anderson (1941)–A fine monograph of the complex Medicine Lake shield volcano. The basis for present work there.

Park (1944)–Good discussion of Eocene basalt in the Olympic Mountains, its alteration, and its associated manganese deposits.

Snavely and Baldwin (1948)–Definition of Siletz River volcanic series and discussion showing widespread nature of Eocene basaltic rocks in Coast Range of Oregon and Washington.

Waters (1955)–Summarized Cenozoic volcanic activity in most of Oregon and Washington and proposed model for genesis of andesite by mixing of tholeiitic basalt magma with constituents "distilled from the metamorphosing geosynclinal sediments." Particularly valuable for regional summary of Eocene basaltic volcanism in western Washington and Oregon.

Thayer (1957)–Showed a variation in style of volcanism related to deformation along the diffuse southern edge of the Columbia Plateau and the northern edge of the Basin and Range Province.

This list of publications, incomplete though it is, shows several different characteristics from that of the pre-1910 period. (1) The emerging importance of university-based personnel is evident; most of the cited references are to university professors, and comparatively few are USGS workers. The Pacific Northwest had become a laboratory for academic study rather than just a frontier for exploration. (2) The emphasis was now on the Cascade Range. Most of the large Quaternary volcanoes had been studied, and major attempts at unraveling the Tertiary history had been made. Large parts of eastern Oregon and Washington received little new investigation, but the volcanic rocks of the Coast Range were beginning to attract interest. (3) Most papers contained chemical analyses and made attempts at petrologic interpretations, although the work was still primarily field oriented.

Field studies throughout the century before about 1960 had utilized similar tools and methods. There had been no real "breakthroughs" that markedly improved one's abilities to recognize and correlate rocks in the field. To be sure, progress had been made in relating deposits found in the geologic record to specific types of eruptions as defined by historic volcanic activity, particularly breccias related to explosive eruptions. Several workers had recognized that some of the extensive "rhyolite flows" were produced by pyroclastic flows (glowing avalanches or nuées ardents) (Williams 1942, 1957; Wilkinson 1950), although the significance of ash-flow tuffs as stratigraphic markers throughout the Cenozoic section was not recognized until a few years later. The volcanic rocks difficult to work with in 1900, however, remained so in 1960. The following years brought a drastic change.

THE MODERN PERIOD (1960-1979)

Four publications of particular importance to volcanic studies in the Pacific Northwest appeared in 1961. Aaron Waters and J. Hoover Mackin showed that the dominant volcanic unit in the region, the Columbia River Basalt Group, could be subdivided, and Waters found that chemistry was one of the best ways to do this. These papers collectively formed the key to Pandora's box; they spawned a host of derivitive papers over the next 18 years that could not have been written without them as guides.

The other two particularly significant publications in 1961 were geologic maps of Washington (Huntting and others) and western Oregon, including the Cascade Range (Wells and Peck). These maps both summarized known spatial and temporal relations and provided a regional framework in which studies of smaller areas could be analyzed. They, moreover, have served as a kind of "ground truth" for many subsequent plate tectonic speculations.

At about the same time, studies of intermediate and silicic volcanic rocks in the Pacific Northwest, and indeed throughout the world, were literally revitalized by the publications of R. L. Smith and C. S. Ross describing ash-flow tuffs and their origin (Smith 1960a, 1960b; Ross and Smith 1961). Over the next ten years, ash-flow tuffs were found in abundance throughout the Cenozoic record in the Northwest, particularly in Oregon (Walker 1970). Many of these tuffs are so extensive that they serve as remarkable aids in regional correlation and paleogeographic reconstructions (Walker 1970), and they have notable petrogenetic significance as inverted solidified replicas of parental magma reservoirs.

New technical advances came so rapidly during the 1960s and 1970s that it is difficult to present them in an orderly fashion. Potassium-argon and more recently fission-track dating became common, opening up possibilities for regional correlations and rate calculations and lessening the need to depend on fossil control for age assignments. Paleomagnetic studies demonstrated numerous polarity reversals, and the geomagnetic polarity time scale was developed. Rapidly obtainable and accurate chemical analyses (see section on petrogenetic studies) became available, and field workers jumped on their use for correlation as well as petrogenetic purposes.

These technical advances have greatly altered the nature of field work. Geologists working in volcanic terraines now have independent means to check correlations, to consider rate-related problems, and to evaluate alteration effects. There is much less guesswork involved, and problems can now be addressed using a variety of approaches. Many field workers now carry a fluxgate magnetometer on their belt with their Brunton and hammers. Many work together with chemists and geochronologists, and results frequently become available before the next field season or even sooner in some cases. For example, chemical analyses of Columbia River basalt were returned within 2-3 weeks following submittal of samples during 1978, enabling field workers to check flow correlations while still in the area (analyses were done at Washington State University under contract to the U. S. Department of Energy through Rockwell Hanford Operations). This example may now be a special case but shows what can and hence will be done more and more in the future.

Current volcanic studies in the Northwest are numerous, and I find it difficult to select a list of the most significant publications since 1960. I do have favorites, however, such as the remarkable series of reconnaissance maps prepared by George Walker and associates in the volcanic region of southeast Oregon. These maps (Walker 1963; Walker and Repenning 1965, 1966; Walker et al. 1967; Greene et al. 1972) cover a huge, heretofore virtually unknown area, and utilize K-Ar dating and chemistry as well as vertebrate fossils to show regional relations only dimly suspected before. These maps, combined with others, were used for compilation of the geologic map of eastern Oregon (Walker 1977), which will be referred to for many years to come. The recently published geologic map of Idaho (Bond 1978), combined with that of eastern Oregon, provides an up-to-date summary of space-time relations for a large part of the Pacific Northwest.

A few other standouts since 1960, in addition to those mentioned in later sections of the paper, are:

Waters (1962)—Often referenced summary paper relating basalt types to tectonic setting in the Northwest.

Fiske et al. (1963)—Modern study of Mount Rainier. Defined a lower Tertiary stratigraphy now widely used in Cascades.

Hay (1963)—Outstanding study of diagenesis of silicic volcaniclastic rocks in the John Day Formation with regard to stratigraphic context.

Peck (1964)—Established stratigraphy in the John Day Formation that holds throughout a wide area.

Macdonald and Katsura (1965)—One of the first well documented examples of physically mixed magmas. Ushered in the current period in which mixed magmas are in vogue.

Macdonald (1966)—Modern overview of volcanic geology in northeast California, including the Cascade Range and Modoc Plateau. Best available summary of this area.

Schmincke (1967a, b, c)—Showed how stratigraphy and paleogeography of the Columbia River Basalt Group can be unravelled by detailed field and petrographic observations.

Snavely et al. (1968) and Snavely and MacLeod (1974)—Excellent description and genetic interpretation of Eocene basalt in the Oregon Coast Range.

Tabor and Crowder (1969)—Modern study of Glacier Peak volcano and underlying rocks.

Wise (1969)—Petrologic study of Mount Hood and surroundings.

Wright et al. (1973)—Showed a close relation between chemistry and stratigraphy of the Columbia River Basalt Group. Established broad stratigraphic subdivisions of the basalt.

McBirney et al. (1974)—Stimulated suggestion of episodic volcanism in and east of the Cascades.

Pearson and Obradovich (1977)—Good summary of stratigraphy and radiometric ages of Eocene volcanic rocks in northeast Washington.

Hammond (1979)—Summary of Cenozoic stratigraphy in the Cascade Range, emphasizing regional correlations and suggesting a tectonic model explaining the volcanism.

Such modern studies as these reflect the wide range of current interests, from single lava flows to entire provinces. Even reconnaissance work utilizes methods undreamed of a few years ago. A new conceptual framework, plate tectonics, within which volcanism and most other aspects of earth science can be profitably interpreted, has been established. Rapid progress is now being made on all fronts and is transforming many past ideas. It is important to remember, however, that this progress would not be possible without the background of past work. Inverting a well known dictum, the past is a key to the present (and future)! Modern workers owe much more than is often realized to their forerunners. Put in a charming metaphoric way, "Pygmies are pygmies still, though percht on Alps" (Edward Young "Night, VI," 1742-1745).

PETROGENETIC STUDIES

For many years, petrogenetic studies of volcanic rocks labored under a paucity of chemical and mineralogic data. By necessity, most such studies had a strong conceptual flavor, applying a few chemical analyses or petrographic observations to broad, in retrospect often highly subjective, schemes. Many important and innovative concepts developed during this time, such as those of petrologic provinces and rock suites, magma types and series, and the development of various ways to portray these features (norms, variation diagrams, etc.). Bowen's "The evolution of the igneous rocks," published in 1928, is probably the single most influential petrologic study yet made. However, I think it fair to say that comparatively few genetic problems were resolved by early studies, and most interpretations before about 1960 are outdated by present standards. As a result, volcanic petrologists today are engaged with many of the same fundamental problems that occupied their predecessors: the origin(s) of andesite, the nature of the source rocks in the mantle and crust, the relative scarcity of volcanic rocks of intermediate SiO_2 content, the nature of modification of magmas between source region and site of final emplacement, and many more.

The present direction of volcanic petrology has been strongly affected by technologic changes during the last 20 years. Rock analyses, including trace elements, are now obtained at an astounding rate, as such procedures as X-ray fluorescence, atomic absorption, instrumental neutron activation analysis, and others have won general usage. The tables of Washington (1917) list 8,602 igneous rock analyses published throughout the world in the 30 years between 1883 and 1914; in contrast, between 2,000 and 2,500 analyses were obtained in one laboratory (Washington State University) for one volcanic province (Columbia River basalt) in 1978 alone (P. R. Hooper, pers. commun. 1979). Ph.D. students in the early 1960s were fortunate to obtain a handful of rock analyses; now many theses contain scores of analyses, commonly relegated to an appendix because the tables are too bulky for inclusion in the text proper. Development of the electron microprobe has enabled detailed studies of mineral zoning and glass inclusions, mass spectrometers routinely measure isotopic ratios to fourth and fifth place accuracy, and sophisticated computer techniques have been devised to test models based on huge bodies of data. Vastly improved means of dating rocks, both by radiometric and fission-track methods, facilitate time correlations between separate areas and permit determination of rates of volcanic activity. Experimental petrology has developed techniques for studying natural rock compositions, melt behavior at high pressures, magma rheology, effects of volatiles (notably CO_2 and the halogens), and many other facets of magmatic systems. Isotopic finger-printing provides a totally independent way of examining some petrogenetic problems, particularly those involving proposed mixing or fractionation of magmas.

The data explosion is, in my view, a double-edged sword, with both edges cutting equally well. One edge uses the data to provide a test of conceptual models developed to explain general patterns. The other edge enables the development of new models based on the data themselves. Concepts can now be rapidly tested and confirmed, modified, or abandoned, almost before the ink is dry. For this reason the present and foreseeable future seems likely to see a surge in our understanding of volcanic petrology. All the ingredients are available for major advances; stimulation, excitement, and abundant data naturally add together to attract top talent. Prospects for successful petrogenetic work seem much brighter than ever before, and Pacific Northwest volcanic studies in particular will benefit from such work because so much is known about spatial and temporal relations of its volcanic rocks.

VOLCANIC-TECTONIC PROBLEMS

Many of the outstanding problems related to Pacific Northwest volcanic rocks are of a fundamental nature common to all volcanic provinces: source material, reasons for melting, mechanics of rise of magmas, petrogenetic evolution. The remarkable array of rock types in the Northwest—from basanites to high-SiO_2 rhyolites, flood basalts to ash-flow tuffs—provides a fertile ground for all types of petrologic investigations. Few other areas of comparable size offer such a variety of fresh, young volcanic rocks.

Why is there such a diversity? That, I believe, is one of the most challenging questions facing future volcanic studies specific to the Pacific Northwest. The diversity must be tied directly to the tectonic history of the region. If the past 100 years have taught us nothing else, it is that tectonism and volcanism are intimately connected, and that both reflect important processes within the mantle.

Many volcano-tectonic problems face workers in the Northwest. Some of my favorites are:

(1) The symmetric relation between the progression of silicic volcanism across southeast Oregon and southern Idaho. Silicic volcanism was prevalent near the Oregon-Idaho border 14-16 m.y.; starting about 11-12 m.y. it migrated west-northwest and east-northeast from there at about the same rate (MacLeod et al. 1976; Armstrong et al. 1975). Dikes of basalt in northern Nevada (Zoback and Thompson 1978) and on the Columbia Plateau (Waters 1961; Taubeneck 1970) of 14-16 m.y. age project along an approximate "plane," actually a rather wide zone, of symmetry separating the two areas of silicic volcanism. The age progression across Idaho has been interpreted as due to the passage of the North American plate over the hypothetical "Yellowstone plume or hotspot." Such an idea is unsatisfactory in light of the symmetric age progression in the other direction across Oregon. Eaton et al. (1979) and Christiansen and McKee (1979) offer different, provocative models to explain these relations, but neither adequately deals with some important observations. Improved understanding of these large scale volcano-tectonic interactions, extending across much of the Pacific Northwest, will be a notable step forward.

(2) Persistence of calc-alkaline volcanism in the Cascades throughout most of the Cenozoic despite large-scale clockwise tectonic rotations recently proposed by paleomagnetists. Calc-alkaline magmas have been produced along the nearly linear Cascade axis since at least early Oligocene (McBirney 1978). Since then, parts of western Oregon, possibly including the Cascades, have rotated as much as 45 degrees, according to paleomagnetic data (Simpson and Cox 1977; Plumley and Beck 1977). What is the nature of the zone of melting that allows calc-alkaline magmas to be generated while crustal blocks are rotating? Can younger episodes of Cascade volcanism (McBirney et al. 1974) be related to younger episodes of small rotation? How does all this tie in with coeval subduction? How does the Challis arc, if indeed such an ancient arc did exist, relate to rotation and later Cascade volcanism? These questions point out how rapidly research emphasis can change as a result of entirely unexpected discoveries. Who a decade ago could have even considered that such questions would ever be asked?

(3) Occurrence of vents for Columbia River basalt both east and west of the Cascade Range. Most feeder dikes occur in the eastern half of the Columbia Plateau, but Snavely et al. (1973) have documented the presence of intrusive and extrusive rocks of virtually identical composition in the Coast Range of Oregon and Washington. Correlation of the coastal rocks with those on the plateau is almost certain, as age, chemical, isotopic, and paleomagnetic data match perfectly (Hill 1975; Bowman et al. 1973; Choiniere and Swanson 1977). Stratigraphic relations prove that the Cascades were active during the period of basalt extrusion. Thus the problem is how could tholeiitic basalt of precisely the same composition and age be erupted hundreds of kilometers apart on both sides of an active calc-alkaline province? Snavely et al. (1973) suggested several models but considered none as satisfactory. We must provide a satisfactory explanation to this almost unbelieveable relation before we can claim to know much about the nature of melting events along a convergent plate margin.

These are only three of a wide array of volcano-tectonic problems confronting present and future workers in the Northwest. There are many others, for example (1) explanation of regional differences in composition among basalt of Miocene age east of the Cascades (tholeiitic in the north, high alumina in southeast Oregon, mildly alkalic in northern Nevada); (2) considerable refinement in knowledge of Eocene volcanism and its relation to plate margins; (3) reevaluation of the widely held distinction between the Western and High Cascades (arguments can now be made for and against distinguishing the two provinces by criteria other than age); (4) continued testing of recent ideas about volcanic episodicity related to plate motions (so far the data are suggestive but skimpy for the late Cenozoic); (5) the nature of the event giving rise to the Columbia River flood basalt, unique in the Phanerozoic history of North America. One could go on and on.

All of these kinds of problems require the help of many subdisciplines for their solution. Information concerning the subsurface structure throughout the Northwest is particularly needed. Present geophysical knowledge is decidedly inadequate, and prospects for better data in the near future are not favorable except perhaps in some selected areas. For instance, we have only a poor knowledge of crustal thickness over most of the region because of the lack of deep seismic refraction data. Moreover, available geophysical tools and techniques are able only to give the broadest of pictures concerning the physical makeup of the lower crust and mantle. I suspect that no real "breakthroughs" will be made along these lines until better geophysical equipment is developed. Thus I believe that many of the volcano-tectonic questions of today will confront future workers for decades to come. This is, I suppose, as it should be, for such questions are of truly fundamental nature, involving basic concepts and interrelations ultimately tied to the heat engine that drives both volcanism and tectonism.

FUTURE VOLCANIC ACTIVITY

The next eruption in the Pacific Northwest will probably take place from one of the existing volcanos in the Cascade Range. Small eruptions were quite common during the first part of the 19th century (Table 1). Since then Cascade volcanos have been quiet except for the major explosive outbursts at Lassen Peak in 1914-1917. Periods of repose lasting a few centuries or less apparently typify these volcanoes, if detailed studies of Crandell et al. (1975) at Mount St. Helens can be generalized. The current period of dormancy should not mislead us; clearly we should expect future eruptions from most of the existing volcanos, and perhaps the growth of new volcanos, in the Cascades.

TABLE 1. HISTORIC ERUPTIONS IN THE CASCADE RANGE

Volcano	*Dates of eruptions*	*Reference*
Mount Baker	1840s and 1850s; 1880?	Malone & Frank (1975); Majors (1978)
Mount Rainier	Between 1820 and 1854?	Crandell (1969)
Mount St. Helens	Several eruptions between 1806 and 1857.	Crandell et al. (1975); Crandell & Mullineaux (1978); Hoblitt et al. (1980)
Mount Hood	1859-1865	Harris (1976); Crandell (1980)
Lassen Peak	1914-1917	Day & Allen (1925)
Cinder Cone	1850-1851?	Harris (1976)

Awareness of volcanic hazards in and bordering the Cascades followed rather than preceded population growth. As a result, many valley bottoms susceptible to innundation by lahars and pyroclastic flows became heavily populated before risks could be properly assessed. Notable studies by D. R. Crandell and his associates have recently provided evaluations of volcanic hazards for several of the major volcanos, for example Mounts Rainier (Crandell and Mullineaux 1977), St. Helens (Crandell and Mullineaux 1978), and Baker (Hyde and Crandell 1978). These evaluations will greatly help local governments plan for disaster preparedness and future land use. Such types of studies may be the single most important way in which volcanologists can as a group directly influence society.

Knowledge of what to expect leads naturally to the question of when to expect it. Eruptions can not now be predicted with any semblance of reliability. Contrary claims found in the literature are in every case based on only one eruption; one may guess right once, but reliable prediction demands repeatibility. To my knowledge, no two successive eruptions from any volcano have ever been forecast correctly, that is, within a socially useful period of time of several days. The Cascades present a particularly difficult problem to predictors, as no eruption has taken place in modern times to provide us with hints as to what precursory phenomena should be monitored. Surveillance techniques currently used in attempts to predict eruptions throughout the world monitor seismicity, ground tilt and other surface deformation, fumarolic gas geochemistry, thermal infrared (IR) output, gravity changes, and various geoelectric and geomagnetic phenomena. Most of these techniques are of unproven reliability, and none is adequate by itself. All deserve increased attention. Of utmost importance in the Cascades is the establishment of baseline data for each menacing volcano during periods of repose; this involves installation and initial occupation of various survey networks, determination of normal background seismicity, definition of the ambient thermal IR level, and so forth. Such background information is necessary to evaluate possible changes in behavior that may permit early warning of an eruption. A case in point is Mount Baker. Seismic, tilt, gravity, and other monitors were established soon after a major increase in thermal activity in 1975, but the lack of such data from the past precluded evaluation of how much the volcano had changed before the onset of the event (Frank et al. 1977).

The emphasis in this discussion has been on the Cascades because of their high eruption potential. In all probability, however, the widespread late Cenozoic volcanism elsewhere in the Pacific Northwest is not yet over. Future eruptions can be expected on the Snake River Plain, in southeastern Oregon and northeast California, and, by analogy with other flood basalt provinces, even on the Columbia Plateau. Large volume ash-flow eruptions are likely from vents in the Cascades and southeast Oregon, and their occurrence could be devastating. Considerably improved geophysical information throughout this large area is necessary before there is any chance of forecasting in even the vaguest way an eruption in one of these general areas.

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ADDENDUM

The preceding text was written in the spring of 1979. Since then, Mount St. Helens has dramatically shown us that the Cascades are not dead. A series of eruptions, with a seismic prelude of about a week, began on March 27, 1980 and continues to the time of writing (late November 1981). Relatively mild phreatic activity took place sporadically until May 18, 1980, when the now almost legendary landslide, lateral "blast," and towering plinian column changed the landscape forever. Since then, St. Helens has erupted 11 times, the last six of which have been nonexplosive dome-building events.

Books could be and indeed are being written about this series of eruptions, particularly that of May 18. I want to emphasize only two of the many obvious lessons learned. The first lesson is that the rapid unloading of a volcano by a large landslide can cause such sudden release of pressure on a magma reservoir, a hydrothermal system, or both, that catastrophic results are possible. This realization has led to reinterpretation of many past eruptions in this country, Japan, Kamchatka, and elsewhere.

A second lesson is that monitoring programs are of paramount importance for saving lives and providing insights into magmatic processes. This lesson, really taught long ago in Hawaii, has been hard to apply to the Cascades because of budget constraints, "more immediate priorities," and the relative infrequency of Cascade eruptions. Seismic and geodetic monitoring of the growth of the famous bulge before May 18 led to land-use decisions that potentially saved several thousand lives. It is tragic that more than 60 people were killed, but consider how much greater the tragedy could have been without the monitoring efforts. Expanded monitoring since May 18 has led to successful prediction of each eruption from a few hours to, for the dome-building eruptions of 1981, several days to two weeks before the event. This heretofore unprecedented predictive capability demonstrates that we now have some of the tools and expertise for building strong monitoring programs at other volcanos should conditions warrant.

The past 2½ years have seen a possible resolution of the volcano-tectonic problem caused by the occurrence of vents for the Columbia River basalt along the Oregon coast. This "solution," suggested by Beeson et al. (1979), following ideas that I expressed to Beeson several years earlier, assumes that the vents are not vents at all but instead are areas in which plateau-driven basalt flows plunged into and mixed with unconsolidated sediment, forming peperites and invasive flows (Byerly and Swanson 1978). This concept raises problems of its own, however, and in fact no currently available evidence can distinguish between the two interpretations. Discovery of diagnostic evidence will be critical toward either emphasizing or eliminating the volcano-tectonic problem posed in the preceding text.

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MINERAL DEPOSITS OF THE WESTERN UNITED STATES

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From its formation in 1879 through the Second World War, the United States Geological Survey mapped and described most of the larger mining districts as well as many smaller deposits in the western states and in Alaska. This type of district mapping now has been largely abandoned in favor of geochemical and genetic studies.

Unexplored outcrops of mineralized rock are scarce in the United States and in the future hidden orebodies must be sought. This will require close cooperation among specialists in many fields and the United States Geological Survey is admirably equipped to conduct such exploration. More attention should be paid to grades of ore and to other economic factors.

THE PAST

Many expeditions took place through the western mountains during the early and middle parts of the 19th Century. Most were designed to explore, to map, and to "open up" the country. Two that were truly extraordinary feats of endurance, courage, and tact, were the trips of Lewis and Clark through the Northwest and of David Thompson through southern Canada and northern Washington. Some of these expeditions recorded the presence of minerals but the regions explored were far too remote and too sparsely settled to permit mining other than the washing of gravels for placer gold. It was not until after development of the Mother Lode in California in 1849 that serious prospecting was extended throughout the West. From California the miners scattered in all directions, and many deposits were discovered. Gold and silver were sought primarily because their unit value was high and they could be recovered and transported cheaply. Development of copper, lead, and zinc deposits had to await further settlement and better access. Many deposits thus remained undeveloped until after the Civil War, though a few, notably the Comstock Lode, were mined and helped to finance the war.

Following the Civil War people began to realize the tremendous potential of the West and national attention was turned to exploration. Expeditions led by King, Powell, Hayden, and Wheeler, explored and mapped large areas of the West and recorded the locations of many mineral specimens. In 1879 these independent surveys were brought together to form the United States Geological Survey. Through the remainder of the century and until the First World War, the Federal Survey published large numbers of reports on most of the larger mining districts; some of these reports are now among the classics of geology. When the difficulties of travel are taken into consideration, the accomplishments of these early geologists are truly remarkable both for volume and quality of publications. For example, between 1882 and 1900, Whitman Cross published or coauthored 56 articles, including 2 bulletins, 2 monographs, and 4 folios. Another tower of strength in the early Survey was S. F. Emmons who between 1879 and 1900 published 30 articles, many of them dealing with previously undescribed western mining districts.

Early in this century exceptional work was done by many excellent field geologists. Two of the best known are Waldemar Lindgren and F. L. Ransome. Between 1904 and 1911, a period of only 8 years, Lindgren published a total of 83 articles and books, including 5 *Professional Papers* and 22 *Bulletins*. Among the *Professional Papers* were the classical studies of contact metamorphism at Clifton-Morenci, Arizona, Gravels of the Sierra Nevada, and the very comprehensive Ore

Deposits of New Mexico. During the same period, Lindgren formulated many of his ideas concerning ore genesis that were expressed so convincingly in his book "Mineral Deposits," first published in 1913. Between 1903 and 1911, Ransome published 54 articles and books. These included 6 lucid and very well written *Professional Papers*, among which were the studies of Globe and Bisbee, Arizona, Coeur d'Alene, Idaho, and Goldfield, Nevada. During the same 9-year period, Ransome published 12 *Bulletins*.

Discussion of mining geology and exploration in the West and Northwest would be incomplete without mention of Alaska, where A. H. Brooks and a small group of dedicated associates did yeoman work. Brooks published his first paper on Alaska in 1896 and throughout the rest of his life (he died in 1924) he continued to explore and to map in the Far North. Much of what is known of Alaska stems from these early explorations.

Geologic mapping in the Northwest lagged a few years behind that in other sections of the nation. In 1908 Ransome and Calkins published the results of their studies in the Coeur d'Alene district of Idaho. Several short articles describing the copper deposits of Butte, Montana, were published during the 1890s, but it was not until 1912 that W. H. Weed published the Butte *Professional Paper*. This was followed in 1913 by the *Professional Paper* dealing with the Philipsburg district, Montana, by W. H. Emmons and F. C. Calkins. Shorter papers and bulletins treating with many smaller districts were also published. Among these the work of J. B. Umpleby in Idaho deserves special mention.

State geological surveys early added their efforts toward unraveling the geology of mineralized areas. Some states, Colorado for one, elected to help finance the studies of the Federal Survey and they coordinated their efforts with this bureau. Others, such as Washington, conducted their investigations independently. Some of the state surveys were closely associated with state universities, and teaching faculties spent their summers examining mining districts and doing regional mapping. Prior to the First World War, many mining companies relied on mining engineers for their geology. Those companies that did have geologic staffs, with a few exceptions such as the Anaconda Company at Butte, Montana, seemed to consider them as luxuries, gave them little or no authority, and paid scant attention to their recommendations.

By the time of the depression of the 1930s, the Geological Survey had mapped most of the larger mining districts in the country and many other mineralized areas had been briefly described. Geology was slowly earning recognition; even the most conservative companies were finding it useful. The time had arrived for the semi-reconnaissance studies of the early days to give way to more detailed examinations.

During and after the depression of the 1930s, the United States Geological Survey added many persons to its professional staff and geologic mapping of all types was greatly accelerated. State agencies also increased their activities, though privately financed exploration nearly ceased during the early days of the depression. From the hundred or so professionals of pre-depression days, the United States Geological Survey has grown continuously to its present size of several thousand professional employees. Prior to and during the Second World War, the Federal Survey emphasized the study of resources needed for the war effort, particularly those considered to be strategic or critical. The contributions of the Geological Survey did a great deal to help the country to obtain quickly the resources so badly needed. Sampling was done and unusual efforts were made to evaluate the economic aspects of many properties, both at home and in friendly nations.

At the conclusion of the war, emphasis in the Survey slowly swung away from mineral exploration. Offshore studies and oceanography, the nature of the Mohorovicic disconformity, exploration of outer space and aspects of aerial photography, details of geochemical processes, and aspects of laboratory science such as geochronology and the development and use of many new devices—the electron microprobe, computers, and many others have gradually come to the forefront. In recent years the Federal Survey has relegated the detailed studies of mineralized areas to a very low priority and has become preoccupied with the study of genetic processes, some of which will of course eventually help in exploration. However, much more exploration is now being done by industry than by government. Many large mining districts discovered since the Second World War need the detailed regional studies of the type that the Survey has done so well in the past.

THE PRESENT

Mining in the western states has been depressed during the past few years but conditions are now slowly improving. Temporary surpluses of metals have existed in many places so that world prices of the common materials, copper, zinc, and iron, in general have been near or below the cost of production. Only uranium, gold, silver, and a few other commodities such as molybdenum, have been energetically sought. Major districts, especially copper districts such as Butte, Montana, and the deposits south of Tucson, Arizona, have curtailed production and are simply maintaining their staffs and skeleton crews underground. Prices are slowly improving as surpluses are depleted.

Owing to extensive expropriation of raw materials properties in Third World countries, to political difficulties in southern Africa, and to unfavorable laws and high taxes in many places, exploration and development abroad are unattractive to private venture capital. As a result, many companies have curtailed foreign exploration and devote more time and money to efforts in the United States or a few places where they consider governments to be stable and to welcome foreign investments in raw materials extraction.

Grassroots exploration also has been partly curtailed by many mining companies because of the depressed markets and resulting shortages of capital, though several large oil companies are expanding their programs, especially in the search for uranium. A new factor in this search is the entry of public utilities and power companies. A few utilities hire geologists and conduct their own exploration efforts, but most advance money to companies better qualified to do such search. The utilities expect to be repaid with "yellow cake" if the search is successful. Makers of reactor equipment—General Electric and Westinghouse—are also active in the search for uranium.

Another interesting factor in exploration in the United States is the injection of foreign capital. Canadian companies such as Noranda, Placer Development, and Cominco, discouraged by socialistic trends, high costs and taxes at home, are increasingly active here. Japanese and European companies, especially West German, also are helping to finance exploration activities in the United States.

One of the principal factors damaging to the minerals industry is the unbelievable plethora of government regulations. One of the most difficult bureaus to be satisfied is the Environmental Protection Agency or EPA, though other agencies, particularly the Forest Service, the Bureau of Land Management, and several bureaus concerned with personnel safety and training, at times cause real confusion and expense. The cost of efforts to comply with regulations of the EPA is estimated to have increased the price of copper between 9 and 15 cents per pound. Production of copper in the underdeveloped nations such as Chile and Zambia, is subjected to no such restrictions, hence these producers have decided cost and marketing advantages. Preparation of "Environmental Impact Statements" is particularly onerous and expensive and involves not only direct costs but also at times long delays.

In the western parts of the United States and in Alaska, the removal of public lands from mineral entry and the setting aside of large regions as wilderness and primitive areas, have removed much of the most favorable mineralized lands of the country from exploration and development. Many examples can be given. Plummer's Ridge copper deposit near Glacier Peak, Washington, and the White Cloud molybdenum deposits of Idaho are two areas in the Northwest where viable deposits are known but have not been developed because of pressures from environmental groups. A recent and incomprehensible example is the continuing effort to prevent mining of zeolites in the desert of the Vale region of southeastern Oregon.

Alaska, a state owned almost entirely by Federal and State governments and by Indian Tribal Councils, is fighting a battle for survival of its mineral industry. Figure 1 is reproduced from a

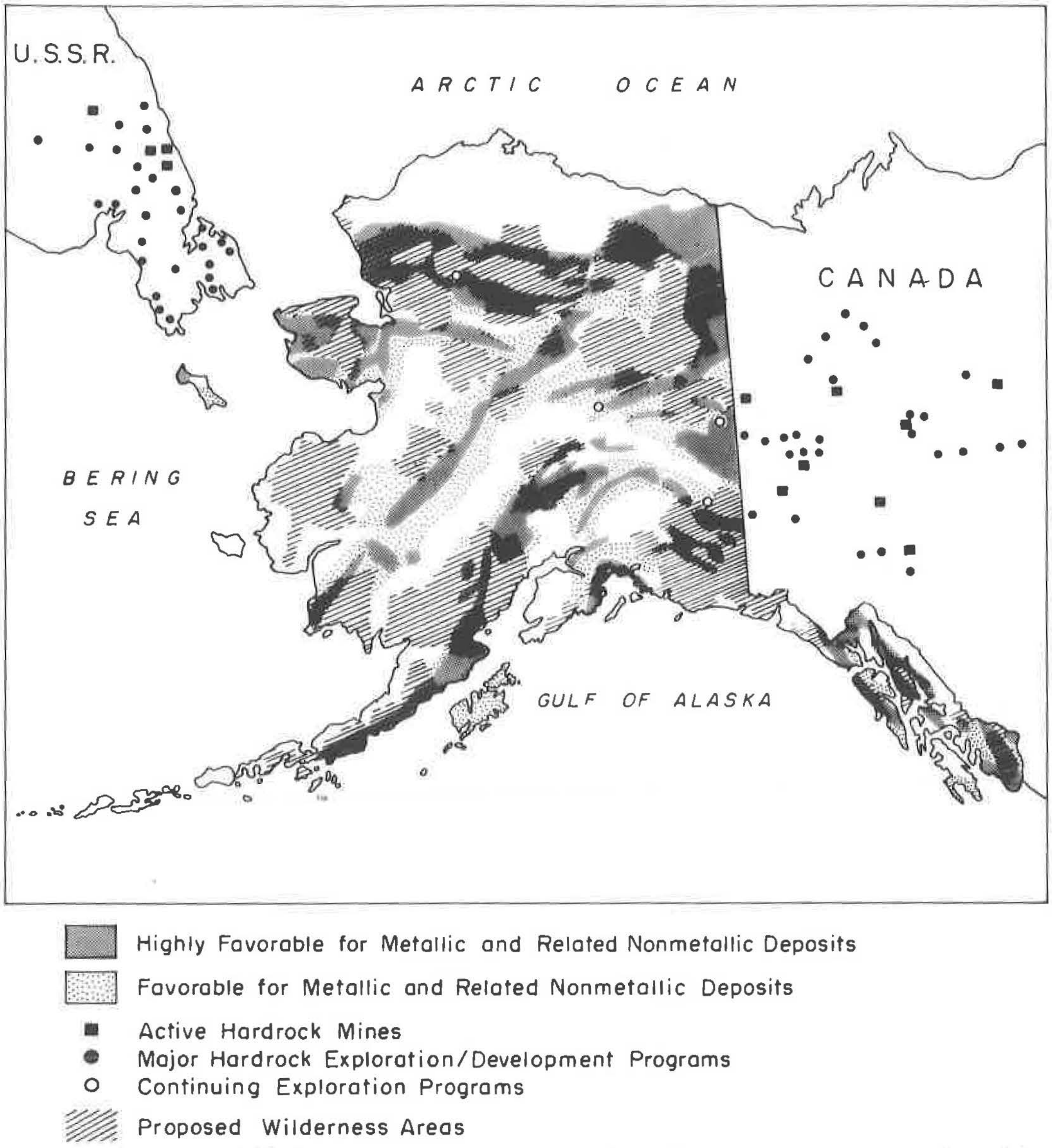

Figure 1. Map of Alaska and adjacent parts of Canada and Russia. Notice the extensive mining in Canada and Russia in contrast to Alaska where there is not a significant hardrock mine in the State. (After American Mining Congress.)

publication of the American Mining Congress and shows the absence of developed mineral deposits in Alaska relative to the numerous mines in adjacent areas of Siberia and Canada. No reason is known why similar viable deposits should not be present in Alaska; in fact everything points to their being present. Prospecting in much of the state is forbidden. The 1978 session of Congress was unable to agree on the amount of land in Alaska that should be set aside. However, Secretary of the Interior Andrus set aside 117 million acres, an area nearly the same size as that of Washington and half of Oregon combined, for a minimum of three years with the stated purpose of studying how this could best be preserved in its primitive condition. About the same time President Carter invoked an old, nearly forgotten antiquities law and added 56 million acres to the National Park system, thus doubling the size of the entire system.

If exploration is now prohibited in much of Alaska, and this seems likely, the government will be closing the last large favorable area for prospecting in the nation; nowhere in the United States are such activities welcomed on public lands. This is patently ridiculous and cannot help but adversely affect the economic health of the country. It will fuel inflation and tend to curtail jobs.

A great deal of money and professional time are being wasted by the Federal government in the rapid examination of proposed wilderness terrane to determine whether or not it is favorable for mineral development. Who would be so good that he or she can walk through a mountainous region and say that mineral deposits will or will not be found there in the future? Who would be so naive as to believe any statement to that effect? Of course it is possible to say that an area may be favorable for mineralization, but as a general rule are not most of these areas in the "lower" 48 states already known?

Several states have added their share of difficulties to the mining industry. Exxon recently found a large, high-grade, massive sulfide deposit near Crandon, Wisconsin. Exploration and development of the deposit have been stopped because of near-confiscatory taxes proposed by the State legislature.

One of the few bright spots at the present time is the exploration for gold in northern Nevada where Jerritt Canyon is being intensively studied by geologists of Freeport Minerals Company. The gold here is similar to that of the better known Carlin deposits and is so fine grained that it cannot be seen nor recovered in a pan. Freeport has claimed 48 square miles, much of which is known to have high gold anomalies, and has announced positive development of 5 million tons of surface ore averaging 0.3 ounce of gold per ton. Drilling is continuing and almost surely additional tonnage will be found. These deposits appear to have been unknown to early-day prospectors as the only evidence of previous search is a couple of small prospect pits. Several other promising deposits of this general type are being sampled and evaluated in Nevada.

THE FUTURE

Fortunately most successful mining geologists are optimists. Obviously with world population continuing to grow and standards of living slowly improving, the needs for all types of raw materials are going to expand and geological information will be in ever greater demand. The growth in needs for raw materials will take place in spite of conservation, recycling, and any other steps that can be taken to prevent it. We are indeed going to have to increase production as well as to practice conservation and to avoid waste wherever possible.

What part does an explorationist play in this developing panorama? Present difficulties are clearly discouraging but it is doubtful if they will remain so indefinitely. One of the responsibilities of the organization for which a geologist works is to keep up-to-date inventories of resources, to know where and how much material can be obtained and utilized, and how much it will cost. These should be prime functions of the Geological Survey and the Bureau of Mines. It is the explorationists' direct responsibility to determine where supplies of scarce and critical minerals can be obtained; in other words to find the materials needed at reasonable costs. This is a challenging opportunity for the future.

Exploration in the future will be different from that in the past. The days of finding rich outcrops of ore, always with a few exceptions, are a thing of the past. Future discoveries will be of hidden ore bodies and to find them will require extensive knowledge, ingenuity, and patience. The sum of knowledge available is far too great for one person to absorb, hence the need for cooperation and mutual respect among the various specialities. Successful exploration will require access to public and mineralized lands and also close cooperation among scientists using all aspects of earth sciences–structure, sedimentation, and stratigraphy, petrology and mineralogy, geochemistry and geophysics. No one is better equipped than the United States Geological Survey to conduct this type of exploration.

For years emphasis in mineral exploration was placed on structure and stratigraphy. These subjects are still of unquestioned value but sedimentary processes are assuming more significance than previously thought and they will receive greater attention in the future. Features such as offshore reefs, submarine landslides, and apparently minor physical and chemical factors are thought to have influenced ore localization. Many ore bodies, formerly thought to have been of hydrothermal replacement origin are now considered to be original sediments and reasons for their concentration are not always obvious.

The future must be tolerant of new ideas and new theories. Concepts relating to ocean mining, to the origin of Kuroko or massive sulfide deposits and to the relationships of different types of ore to the elements outlined in the descriptions of plate tectonics have already furnished new ideas concerning genesis and where to look for specific kinds of ore deposits. This has given a boost to creative thinking and has added zest to exploration. Mineral exploration has not been subjected to as intensive application of geophysical methods as has petroleum exploration though several methods are widely used and new ones will surely be developed. More geophysical research on hidden ore bodies is needed and new methods of discovery must be developed.

Our form of government responds to the will of the majority of its citizens. Excessive wilderness and primitive areas are being set aside in response to the demands of the people, urged by a vocal and well financed minority. In some manner, hopefully not through another deep depression, the majority, and through them the government, must be made to understand that mineral resources are where nature put them and that their location cannot be changed by legislation. Resources are essential and are not always available for purchase from other nations. Purchase of large amounts of foreign materials also serves to increase the deficit in the balance of payments and hence fuels inflation.

Mining is a capital intensive industry, a fact that many governments, including our own, frequently forget or ignore. A viable mine may cost as much as several hundred million dollars to put into production, and costs of a billion dollars or more are being estimated for development of each of several large scale open pit properties. A time lag of 5 to 10 years is required between discovery and operation of a mine. Thus the exclusion of public lands from exploration means that minerals which should now be under development will remain unavailable for some years, even though lands are reopened. The only action that will furnish a long-term solution to shortages of raw materials is to permit and to encourage domestic developments and production, together with required conservation. Congress is already reacting to over-regulation and to non-productive paper work. Hopefully this is a first step toward a change in attitude concerning exploration and development of mineral resources.

Third World nations that a few years ago forbade foreign exploration and were expropriating raw materials properties are slowly realizing that mining requires both skill and capital as many of their properties remain idle or at best are marginally profitable. Recent comments and actions by several developing countries indicate that more nations in the future will again seek foreign technology, venture capital, and mine development.

In spite of the current adverse political activities both at home and abroad, the future of the minerals industry is brighter now than it was just a few short years ago.

EVOLVING CONCEPTS OF THE TECTONICS OF THE NORTH AMERICAN CORDILLERA

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Cordilleran tectonic studies were firmly established by Clarence King, who in 1878 recognized the long evolution of the Cordillera, analysed it by defining internally conformable sequences separated by unconformities, described associated structures and magmatic rocks and identified different types of vertical movements. Cordilleran geology was outlined in the next thirty years. In 1912 Daly divided the Cordillera into a sedimentary Eastern Geosynclinal Belt, with open folds and large thrusts, and a volcanosedimentary Western Geosynclinal Belt, with intrusions, metamorphism and tight folds. Although refined and modified by Stille (1936) and Kay (1951), this scheme governed regional tectonic thinking until the 1960s and was a basis of major subdivisions on P. B. King's tectonic map of 1969. Emergence of the plate tectonic hypothesis had an immediate influence. Hamilton, in 1969, emphasized the great mobility implicit in the hypothesis, described depositional sequences in terms of present-day analogues rather than geosynclines, and emphasized the influence of Pacific plates on Cordilleran tectonics. Current views elaborate these concepts, suggest that much of the western Cordillera is a mosaic of far-travelled fragments accreted to the ancient continental margin by a variety of processes, and attempt to relate major structural features to plate motions.

In this review an attempt is made to summarize the nature and changes of concepts of Cordilleran tectonics over the last 100 years. We make no claims to present a balanced picture drawing on all significant references, for the literature on the topic is enormous and our selections are surely strongly prejudiced by our backgrounds. We explore the topic as regional geologists familiar with different segments of the Cordillera who, over the last decade, have attempted to account for the differences between those segments and to reconcile the vast amount of geological and geophysical information with the new, general tectonic hypotheses.

Tectonics derives its concepts from many sources, all of which must be taken into account in a region the size of the Cordillera. Three approaches that have contributed to our understanding of Cordilleran tectonics from the earliest days are: first, the nature and setting of depositional sequences commonly separated by unconformities; second, the geometry and ages of major structural features; and third, the relationship of both of these to magmatic activity. Traditionally, these have been investigated by regional geological mapping, which delineates rock units and establishes their natures, ages and relationships with one another. In recent years, geophysics has played a major role in determining the character of present-day tectonism, largely because of its ability to explore regions inaccessible by conventional means. The interaction of geology, with its capacity for unravelling the past, and the modern tectonic picture obtained from geophysics, gives tremendous insight into Cordilleran tectonics.

Tectonics has always had a large interpretive component, perhaps because the origins of many tectonic processes are obscure. Climates of opinion develop and at times have great influence, positive in catalysing and guiding new research and forcing reassessments of older studies, negative in imposing dogmas. The earliest works in Cordilleran tectonics were strongly influenced by opinions derived from mid-nineteenth century studies in the Appalachians. In the 1920s, the negative attitudes towards continental drift expressed by several great American geologists were sufficient to delay exploration of mobilistic concepts of Cordilleran geology for forty years. As regional geologists working during the period of introduction of the "new global tectonics," the writers participated in the enthusiastic swing to mobilistic hypotheses. Our reading and personal experience indicate these changes of opinion have less of a lasting impact than is suggested by first impressions. There is an empirical core to Cordilleran tectonic concepts that has gradually evolved by adding new data to the vast quantity of accumulated information. Our task herein is to isolate and identify this core and to show how it acquired its present state. Below, an overview of general syntheses of Cordilleran tectonics is followed by discussions of some specific aspects that have contributed to the picture we hold today.

HISTORICAL OVERVIEW: THE FIRST NINETY YEARS

Foundation Stones: The Work of King and Daly

An appropriate date to start this discussion is 1878, one year before the foundation of the United States Geological Survey, when Clarence King's "Geological Exploration of the Fortieth Parallel" was published by the Engineer Department, U. S. Army. This work, together with the "Geology of the North American Cordillera at the Forty-ninth Parallel" by R. A. Daly, which appeared in 1912, provided firm foundations for broad concepts of Cordilleran tectonics. Both studies involved vast amounts of field work in latitudinal strips that covered much of the width of the Cordillera. King mapped a belt about 160 km wide of geologically unknown territory from the Great Plains on the east to the eastern boundary of the Sierra Nevada on the west, between longitudes 104°W and 120°W. He was able to link-up his work with earlier studies in California to provide an overview of the Cordillera at its widest part. Daly mapped a strip up to 16 km wide between 114°W and 122°W, from the prairies to the Fraser River delta, in a terrane known in a general way from International Boundary Commission studies made 50 years before Daly's work. Fortunately and fortuitously each report provided information on segments of the Cordillera that had very different characteristics. Most of King's traverse was in strata that later would be said to originate in continental platform and miogeosynclinal settings, whereas much of Daly's traverse was in eugeosynclinal rocks. Because each segment maintains its character for a considerable distance along trend, a reasonable picture of the geology and tectonics of much of the North American Cordillera was obtained at an early stage in its geological exploration.

King recognized the major events in Cordilleran history. He established in the Cordillera the method of analysing tectonic evolution by recognizing broad, internally conformable depositional sequences separated by unconformities, a method particularly applicable to the Cordillera with its long, complex history. He described the timing and nature of structures associated with these packages. He laid the groundwork for future concepts of borderlands and geanticlines. Lacking were descriptions of what later would be called eugeosynclinal rocks.

Largely from stratigraphic relationships, King deduced the long, still-active orogenic history of the Cordillera, providing evidence for thirteen "periods of orographical activity" ranging from within the Precambrian to historical times. Major episodes were those separating Archean (Precambrian) from Paleozoic, Paleozoic from Mesozoic, Jurassic from Cretaceous and Cretaceous from Tertiary. Each major episode had its own characteristics. King felt the greatest episode of all was between the metamorphic "Archean" and the Paleozoic divisions and, perhaps influenced by then current theories, suggested that the resulting Archean mountains strongly influenced later mountain-building; where there was flat Archean country, subsequently there were broad (epirogenic) uplifts; where there were ancient mountains, so later terranes were highly deformed. The later orogenic episodes can best be understood in terms of the relationships between subsiding basins and elevated landmasses. Paleozoic strata were believed to be essentially conformable with one another and accumulated on and eventually buried the Archean mountains. According to

King, they formed a westward-thickening prism ranging from 300 m in the Rockies to about 13,000 m at its western limit near longitude 117°30′. West of this a landmass of Archean rocks was the western boundary of the depositional basin and the main source of detrital material. Carboniferous strata known to lie west of this landmass, in California and Oregon, were thought to have accumulated in bays and gulfs penetrating the landmass. Following deposition of Paleozoic strata, the western side of the sequence was elevated to become a source terrane, whereas the thinner, eastern part of the Paleozoic succession remained submerged to floor a basin that received Triassic and Jurassic sediments. The western Archean landmass sank to great depth and on it was deposited a great thickness of Triassic and Jurassic strata. King was impressed with the contrast between the gradual, slow subsidence of the Paleozoic basin, believing, with Hall in the Appalachians, that this was due to sedimentary loading, and the catastrophic reversal at the end of the Paleozoic, in which the region lightened by erosion went down dramatically. He drew an analogy between the latter event and faulting in earthquake regions. At the end of the Jurassic, the western ocean with its "Archean" basement and Triassic-Jurassic cover was uplifted and folded, with deformation strongest on the western flanks of the present Sierra Nevada and gentlest near the old west shore of the Paleozoic sea. Eastwards, although no break occurred in the sedimentary succession, the clastic rocks became much coarser, with abundant conglomerates. Coarsest and thickest deposits, located near the Wasatch Mountains (longitude 111°30′), thinned eastwards towards the Rockies. Although coal beds occurred early in the Cretaceous sequence in the west, beds in the east remained entirely marine until the uppermost part of the Cretaceous. King established that some of the most important movements in the history of the Cordillera took place at the end of the Cretaceous, producing broad undulations and sharp folds between the Wasatch Mountains and the eastern front of the Rockies; the movements elevated the interior of the continent, so that all subsequent strata were non-marine. Several orogenic episodes were documented in the Tertiary, with the last prominent events at the close of the Pliocene. In the following years King's discoveries were investigated, elaborated and, in some cases, refuted, but the picture of Cordilleran tectonism he presented is readily recognizable today.

The thirty years after the date of King's publication produced tremendous advances in Cordilleran geology. Prior to King, there were scattered reports from exploratory surveys and mining districts, and any maps of wide coverage showed generalizations so broad as to be of little use. By the early years of the twentieth century, many aspects of Cordilleran geology were outlined. Several general syntheses were published but did not change most of King's conclusions. The Nevadan and Laramide orogenies were named and younger orogenies recognized along the Pacific Coast. Perhaps the best illustration of what was known, or reasonably could be inferred, in the first decade of the twentieth century is the 1906 map of North America with geology compiled by Bailey Willis, and Willis' monumental "Index to the Stratigraphy of North America," published in 1912. There were few blank areas on the 1906 map, and although the simpler patterns in Canada and Alaska reflected the lack of detail there in comparison with the conterminous United States, all main geological elements were readily recognizable. The map shows the marked difference between the Cordillera north of 47°, with its rectilinear belts and relatively wide western region of metamorphics and intrusive rocks and the broader Cordillera to the south with its complex structural trends. Daly's work must be seen against this background.

Daly's main contributions to our understanding of Cordilleran tectonics lie in his statement of the major tectonic divisions in the Cordillera and his correlation of units along the Cordillera from Alaska to California. As somewhat more than one-third of his traverse along the forty-ninth parallel was in "miogeosynclinal" strata and the remainder in the complex "eugeosynclinal" terrane to the west, he was well equipped to compare and contrast the two tectonic regimes. He divided the Cordillera into two great belts, which overlapped at latitude 49° near the Columbia River (longitude 117°30′) (Fig. 1a). His Eastern Geosynclinal Belt comprised Proterozoic to Tertiary sedimentary strata and was characterized by "open folds, fault blocks and overthrusts, with but

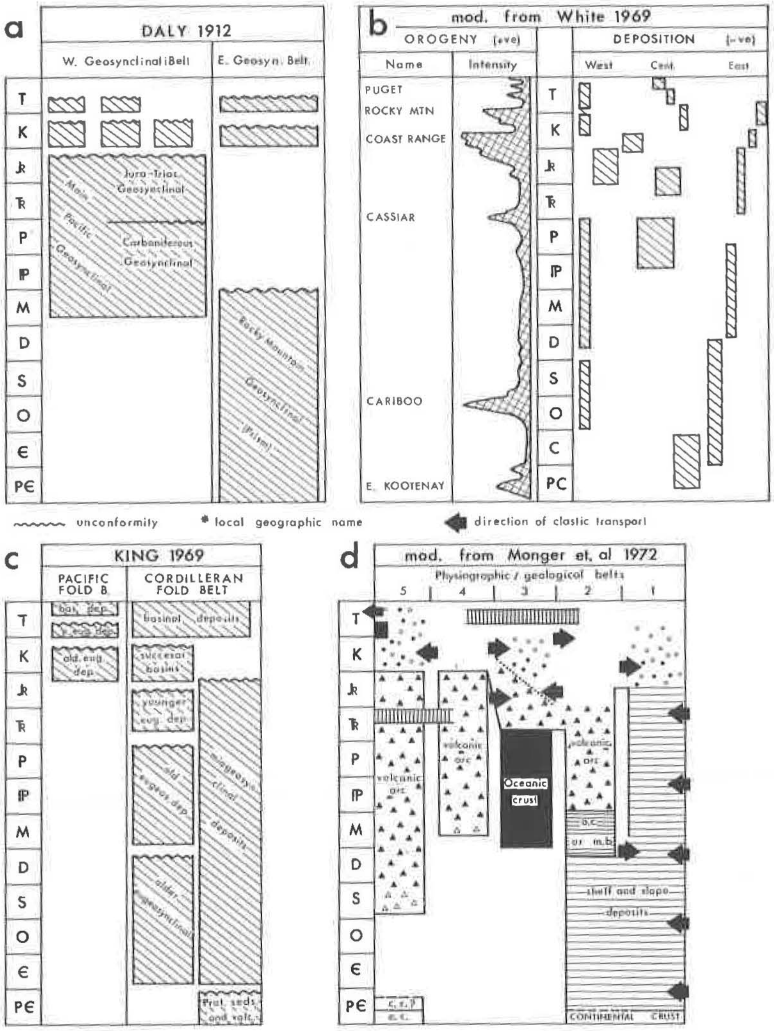

Figure 1. Changing concepts of depositional sequences in the Cordillera. Wavy lines at the top of sequences in *a* and *c* indicate unconformities. Patterns in *d* correspond with those in Fig. 4 and are sequences interpreted in terms of present-day tectonic settings. Gaps between columns in *d* indicate that relationships between rocks in adjacent columns are unknown; linkages between columns are shown by clastic detritus shed from one to the other (arrows) or by stratigraphic units joining columns.

moderate regional metamorphism and quite subordinate igneous action." The Western Geosynclinal Belt of sedimentary and volcanic rocks of Carboniferous to Tertiary ages featured "close folding, mashing, strong regional metamorphism, and by both batholithic intrusions and volcanic actions on a grand scale." This division was recognized as a fundamental one by Stille (1936), was formalized in the miogeosyncline and eugeosyncline of Kay (1947) and was a major one on the Tectonic Map of North America of King (1969). The stratified successions in each belt, internally generally conformable but separated by unconformities of varying magnitude, were called by Daly geosynclinal prisms or geosynclinals (Fig. 1a). The main geosynclinals were an eastern Proterozoic to Mississippian 'Rocky Mountain Geosynclinal,' extending from Alaska, through the Great Basin, to Arizona, and a western Carboniferous to Jurassic 'Main Pacific Geosynclinal,' from Alaska to

Southern California. Above these Daly recognized thick Cretaceous geosynclinals and overlying Tertiary ones, each given a local geographic name.

With Clarence King, Daly believed that the Eastern and Western Belts bore a reciprocal relationship to one another, appeared to assume that the rocks were always more-or-less in their present positions relative to one another, and equated lack of deposits with uplift. In the Rocky Mountain Geosyncline, Daly recognized a break within the Precambrian, then a more or less continuous sequence until the Mississippian. The source of detrital sediments was thought to be a western landmass with a shoreline near the longitude of the Columbia River. Local volcanic activity was associated with the downwarping of the geosynclinal. At the close of the Mississippian, the Eastern Belt was thought to have upwarped with little deformation, and the western source subsided to become the site of extensive Pennsylvanian volcanism and sedimentation. The extensive Late Jurassic "revolution," immediately followed by intrusion of many large batholiths, affected the Eastern Belt hardly at all. It was followed by rapid erosion, and local thick geosynclinals formed in both Eastern and Western Belts. The succeeding post-Cretaceous–pre-Eocene Laramide Revolution produced great lateral translations in the Eastern Belt. Local deformation took place throughout the Tertiary.

Daly speculated about causes of mountain-building, and allowed that his forty-ninth parallel studies led to new illustrations of "recognized orogenic principles" rather than new hypotheses. His view of the importance of the association of magmatism with orogenic activity, an association that he felt was downplayed by others, was perhaps derived from the abundant volcanic and intrusive rocks along his traverse. The general tectonic hypothesis presented by Daly was related to crustal contraction caused by the cooling earth, which for many years was thought to be the ultimate cause of deformation in orogenic belts. Because of contraction, a shell of compression formed above a shell of tension and magmatic rocks were injected along dislocations in the latter, which were localized by poorly defined "cosmical" forces. The surface above this injection line was downwarped, with consequent sedimentation, and the shell of compression, softened by rising isotherms, eventually collapsed, with the formation of mountains.

Although Daly (1912:573) recognized that "orogenic pressure" had been applied with greater intensity to the Pacific side of the Cordillera, and Dawson (1901) and others earlier had suggested that mountain-building was controlled by thrusts from the Pacific, no attempt was made by Daly to link this to his mountain-building hypothesis.

At about the same time as Daly, Schuchert (1910) was developing his concepts of borderlands--in part equivalent to the landmasses of Clarence King–in and west of the mobile belts flanking North America. He noted (Schuchert 1910:465) that Dana in 1846 had suggested that subsidence of the ocean basins had resulted in lateral pressure which gave rise to the folds in mountain belts bordering them. Later Schuchert (1923:159) elaborated on this relationship in the context of borderlands in the mobile belts flanking North America. He suggested that ocean basins subside, continental areas remain stable, and that magmas differentiate from the compensating subcrustal flow between the two and rise tangentially upwards and elevate the borderlands. These then became the main source of sediments in the geosynclinal trough.

1914-1947: Tectonic Doldrums

In contrast with the explosion of geological knowledge in the three decades before Daly's publication, progress was modest in the following three decades. Speculations on Cordilleran tectonics by most Cordilleran geologists remained conservative and provincial, for even at the time Daly's work was published, Taylor and Wegener were proposing continental drift. These ideas were discussed in a symposium published in 1928 (Van der Gracht et al.) and largely rejected by such famous geologists as Chamberlin, Schuchert and Willis. In so doing, they built a dam which held for forty years; when it burst, acceptance of mobilistic ideas was perhaps as uncritical as the early rejections had been critical! It should be noted that Daly (1926) supported continental drift, proposed that gravity was responsible, and suggested that the mountain chains bordering the western Americas were caused by sliding of the continental masses towards the ancestral Pacific, with the Atlantic Ocean opening behind.

A notable advance during this interval was clarification of the nature of the 'borderlands' that lay within the Cordillera. Crickmay (1931) perhaps first recognized the volcanic nature of many source terranes for clastic rocks—the borderlands. From an analysis of the Jurassic system of North America using paleogeographic maps drawn for thirteen time intervals, he suggested that there was no firm evidence for landmasses other than volcanic islands *west* of the Cordilleran geosyncline in the Jurassic, and probably other periods as well, although *within* the geosyncline he showed tectonic mountains which were the Triassic and Jurassic lands of Clarence King.

Stille (1936) made a significant addition to the concepts of Daly and King by stressing the eastward and westward vergence of structures in the Cordillera, in addition to the age and nature of deformation, the character of depositional sequences, and the importance of magmatic activity. His view of the Cordillera was stabilistic, with the Cordillera framed by a high-standing shield to the east and a low-standing ocean basin to the west. He divided the Cordillera into two parts. A western Nevadan realm was characterized by dominant pre-Cretaceous folds, by structures vergent towards the Pacific, by a late Paleozoic to Jurassic "orthogeosyncline" with extensive basic and intermediate volcanism and by extensive synorogenic plutonism. An eastern, Rocky Mountain realm featured dominant, post-Cretaceous, early Tertiary deformation, structures vergent towards the shield, a different geosynclinal history and weak volcanism and little plutonism. He contrasted the Alpinotype, folded Canadian and Montana Rocky Mountains, with the Germanotype, block-faulted character of the Rockies farther south in the conterminous United States.

Late Forties to Late Sixties: Geosynclines and Indications of Great Mobility

Prevailing views of Cordilleran tectonics in the 1940s are given in the publications of Kay (1947, 1951) and Eardley (1947, 1962). From Stille's work, Kay (1947) introduced the now-familiar terms miogeosyncline and eugeosyncline, naming the eastern, miogeosyncline in the Cordillera the Millard Belt and the western, eugeosyncline, the Fraser Belt; these differ little from Daly's Eastern and Western Geosynclinal Belts. Both Kay and Eardley emphasize volcanic archipelagos as source terranes for clastic rocks in the western Cordillera, although both carefully document non-volcanic sources and refer to 'tectonic welts' (Kay), or to offshore archipelagos with a long orogenic history like Japan (Eardley). Cretaceous strata in the complex late Mesozoic and early Tertiary sequences along the Pacific margin of the conterminous United States were regarded by Kay (1951:48) as being deposited in a new, post-Nevadan eugeosyncline. Both authors seemingly regarded terranes in the Cordillera as more-or-less fixed in relationship with one another. Eardley's tectonic maps (1951, 1962) are drawn on present-day bases. In the earlier edition the ocean is shown as entirely west of the continental margin and west of a long-lived orogenic-volcanic belt along the present margin. In the later edition the ocean is shown as overlapping the continental margin in western Washington and Oregon on the Jurassic and Cretaceous maps, which is perhaps a small reflection of the increase in knowledge of the nature of ocean floors achieved in the 1940s and 1950s, and the recognition that oceanic rocks may be exposed on land.

In the twenty years or so following the war, geological evidence accumulated that there was considerable lateral, in addition to vertical, mobility in the Cordillera. Shortening normal to the regional trend had long been recognized.[1] For example, Dawson (1901:60) estimated that the Canadian segment of the Cordillera had been reduced by at least one third of its width since the

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[1] The great amount of shortening observed in mountain belts was perhaps the strongest argument against the old, long-lived theory of mountain-building by cooling of the earth and contraction of its crust; the amount of contraction needed is tremendous.

early Paleozoic, and many authors had measured appreciable amounts of shortening in the eastern fold and thrust belt. New developments were proposals that hundreds of kilometers of right-lateral transcurrent displacements had taken place on many of the great faults in the Cordillera, such as 560 km on the San Andreas Fault in California (Hill and Dibblee 1953:449), 240 km on the Denali Fault in Alaska (St. Amand 1957:1366) and up to 400 km on the Tintina Fault in the Yukon (Roddick 1967:29). In addition, there were suggestions that considerable crustal expansion, perhaps related to transcurrent movements, had taken place in the Basin and Range province of the western United States (Carey 1958; Wise 1963). Hamilton and Myers (1966:529) proposed that this amounted to between 50 and 100 km in the late Cenozoic and perhaps up to 300 km if the whole Cenozoic is taken into account.

In the Canadian segment of the Cordillera, earth science studies proceeded at a pace which exceeded that of the early exploratory years. By the 1960s many rock units in the Canadian Cordillera were known regionally as well as those to the south, and the great differences between the Canadian and conterminous United States segments could be documented in detail rather than in the generalities shown on the 1906 geological map of North America. It became clear that the segment of the Cordillera north of latitude 48° was very different from that to the south. A belt of pre-Upper Triassic alpine-type ultramafics lies in the central part of the Cordillera in Canada rather than in the westernmost part as in the conterminous United States Cordillera, and there are two distinct belts of granitic and high-grade metamorphic rocks of Mesozoic age, rather than the one obvious one to the south. In 1959 White discussed Cordilleran tectonics in British Columbia. He demonstrated the great relative width and complexity of the western, volcanosedimentary terranes in Canada, delineating depositional sequences separated by intervals of orogeny in the classical way, and he attempted to estimate the intensities of the orogenies (Fig. 1b). This was followed in 1966 by a symposium on the tectonic history of the western Canadian Cordillera, southeastern Alaska and northern Washington, Idaho, and Montana (Gunning 1966) in which King (1966) discussed the different characteristics of the several segments of the Cordillera.

By the mid-1950s many elements later incorporated in the plate tectonic hypotheses were under serious discussion in North America, although several had been proposed much earlier (Davis et al. 1974). The Meinesz hypothesis, developed in the 1930s, of crustal downbuckling at trenches and its relationship to mountain building was becoming modified. Seismic evidence led Benioff (1949, 1954) to suggest that oceanic deeps were related to complex reverse faults whose hanging walls carried volcanic arcs. Stille (1955), in discussing the circum-Pacific orogenic belts, proposed that the stable Pacific Ocean floor was being overthrust by the surrounding continental blocks. A comparable conclusion, using different reasoning, was reached by Gilluly (1955), who was concerned with the relationship between erosion, uplift and isostasy. He suggested that material deposited in the ocean basins must be carried back into the continental mass by subcrustal currents. Lester King (1958:99), long an advocate of continental drift, was concerned with the absence of island arcs off the western coast of North America, in spite of the abundant evidence of volcanism in older (eugeosynclinal) sediments. He suggested that the continent moved westwards in the Mesozoic, swept up the island arcs, and incorporated them in the Cordilleran geosyncline. Some of these conclusions were to be strengthened by work in the Pacific, west of the Cordillera.

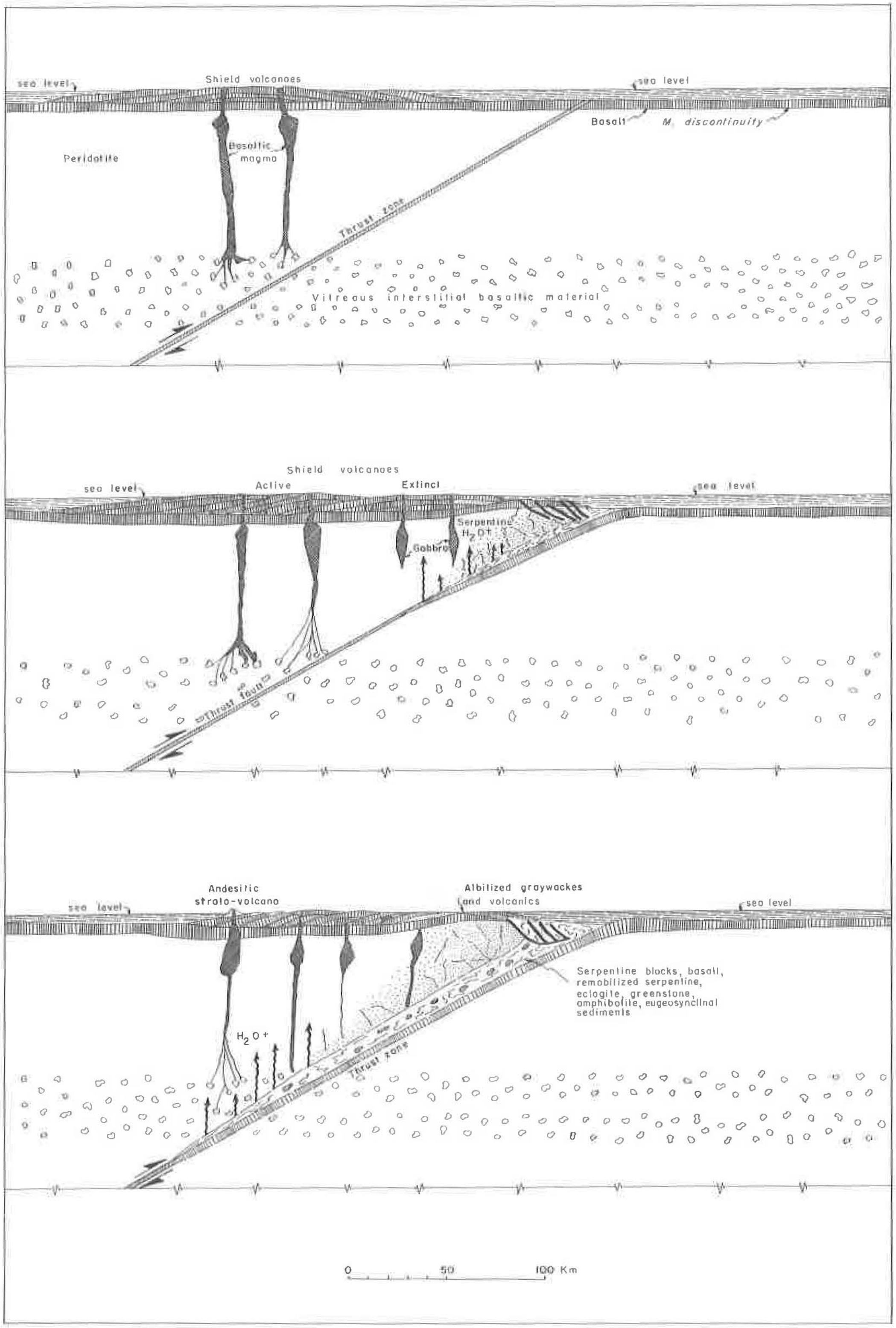
In 1955 Menard mapped four east-west trending fracture zones up to 5000 km long in the northeastern Pacific; it was suggested that these resulted from shears complimentary to the San Andreas fault system and were caused by northeast-southwest compression. In 1961 Vacquier et al. proposed, on the basis of magnetic anomalies offset across the northern two of Menard's fracture zones, that there was a total left-lateral offset of 1420 km. As it was not possible to show offsets of this magnitude or sense along the projection of the fracture zones into the continent, Vacquier et al. felt that either the fracture zones were old and pre-dated the San Andreas fault system or the faults were young and oceanic crust had slipped under the continental mass. Gilluly (1963) seized on the latter alternative to suggest that the continent and ocean crust were completely uncoupled and that the continent/ocean interface was a zone of great differential movement.

The Aleutian arc provided one of the first examples anywhere of an attempt to relate magmatic activity to tectonism in anything but the most general terms. It is an active volcanic arc that extends from continental crust at its eastern end on to oceanic crust, and it is flanked on the south by a trench. Early studies of seismicity indicated that a fault intersected the surface at the trench and dipped northward beneath the arc to a depth of at least 175 km (Benioff 1954). Coats (1962) combined this seismic study with his data on arc magmatism to produce an interpretation for the origin of the magmatism that has been evoked in modified form in many later plate tectonic models. He suggested that a southward-directed "megathrust" developed on the ocean floor; in the upper plate tear and tension faults developed and trapped magmas forming near the thrust plane at a depth of 100 km. Initially the magmatism was basaltic, but it became andesitic (or granitic) later as sediments trapped in the trench were dragged down the thrust plane and melted (Fig. 2).

Gilluly (1965) made a detailed analysis of the relationship between volcanism, tectonism and plutonism in the Cordillera of the conterminous United States. No simple picture emerged; there appeared to be no close association of plutonism with major tectonism, and orogenic activity in every system was demanded by the stratigraphic record. This paper well illustrated the complexity and longevity of Cordilleran tectonism. In admittedly tentative speculations, Gilluly suggested that many sialic plutons in eugeosynclinal terranes were produced by syntexis and palingenesis as the eugeosyncline was crowded against and carried under the continental margin by convection currents. Both White (1959:61) and Gilluly (1965:29) discussed the necessity for great crustal telescoping to account for the lack of source terranes—the old borderlands. It was becoming very apparent that old stabilistic concepts of mountain building were not sufficient to account for Cordilleran tectonics.

In the 1960s came general awareness that the orogen was tectonically two-sided, that is, the western "eugeosynclinal" terrane was characterized by west-vergent thrust faults and folds that crudely mirrored the east-vergent structures long known in the eastern miogeosynclinal belt. Stille (1936) had recognized this long before, although evidence for west-vergent structures was not widespread at that time, and Stille's views were not widely known. Hershey had concluded in 1906 that the Klamath Mountains of northwestern California were subdivided by at least four major east-dipping thrust faults ("comparable with the first magnitude faults the world over" [1906:59]), and C. H. Crickmay (1930) had mapped and interpreted the "Harrison Lake Overthrust" east of Vancouver, B. C., as the product of major westward thrust faulting. The documentation of a continuous or integrated system of west-vergent thrust plates in the western Cordillera (Burchfiel and Davis 1968) had to await the results of field studies in the late 1950s and early 1960s in northwestern Washington, west-central Idaho, western California, and southern Alaska. Reasons for the delay in recognizing an entire Cordilleran thrust belt are many and not difficult to discern. Many western Cordilleran areas had not been mapped in any detail until the mid-century, in part because of their isolation, rugged topography, and, commonly, forest cover. Rock units in those areas were not always conducive to establishing older over younger thrust-faulted relationships. Volcanic and metamorphic units are widespread, as are plutons that disrupt or obliterate the structure of the country rock and many sedimentary units lack well-defined stratal continuity and are poorly fossiliferous.

Figure 2. (Figure 9 of Coats 1962; with permission.) Time sequential diagrammatic cross sections through crust and upper mantle of a generalized island arc, showing suggested mechanism for the development of andesitic rocks through addition of water and hyperfusible materials from eugeosynclinal deposits to eruptible basaltic material in the mantle; steeply dipping tear faults in the upper plate, though probably numerous and important in localizing volcanic centers, have been omitted.


sea level
Shield volcanoes
sea level
Basalt
M. discontinuity
Peridotite
Basaltic magma
Thrust zone
Vitreous interstitial basaltic material
Shield volcanoes
sea level
Active
Extinct
sea level
Serpentine
H_2O+
Gabbro
Thrust fault
Andesitic strato-volcano
Albitized graywackes and volcanics
sea level
sea level
Serpentine blocks, basalt, remobilized serpentine, eclogite, greenstone, amphibolite, eugeosynclinal sediments
H_2O+
Thrust zone
0
50
100 Km

The 1960s closed with the publication in 1969 of P. B. King's monumental effort—the Tectonic Map of North America. For the first time Cordilleran geologists could view the entire Cordilleran system as an aggregate of unconformity and fault-bounded rock sequences (Fig. 1c). The map, by stressing contrasting depositional assemblages, focused attention on depositional environments and, therefore, paleogeography. That focus was needed to better understand Cordilleran evolution in the developing framework of the plate tectonics theory, although it is to King's credit that the format of the map was the consequence of his own insights into tectonic processes, not a response to the then youthful plate tectonics hypothesis. King's map can be seen as a direct descendant of the work of Clarence King, subsequently modified by Daly, Stille, and Kay.

Emergence and Impact of the Plate Tectonic Hypothesis

Even though many concepts incorporated in the plate tectonic hypothesis, such as continental drift, rigid plates separated by mobile zones, spreading oceans, and the relationship of volcanic arcs to seismicity, were in existence long before the hypothesis emerged (Davis et al. 1974), our reading suggests that none of them were seriously considered by Cordilleran geologists, with the exception of Daly (1926), to explain Cordilleran tectonics until the mid-1950s. By then evidence was accumulating that there was great mobility in the Cordillera and that the old "stabilistic" legacy raised more problems than it solved. The link needed to bind the scattered observations and inferences into a cohesive whole came from magnetic studies of the ocean floors in the late 1950s and early 1960s. The magnetic striping observed in many parts of the ocean was interpreted in the mid-1960s as the sequential imprinting of magnetic reversals on basalt extruded in spreading oceanic ridges. With this, continental drift became legitimized and was immediately put to work in unravelling the records of ancient plate motions preserved in mountain chains.

Hamilton, who earlier suggested some of the most mobilistic Cordilleran tectonic models, was perhaps the Cordilleran geologist who most influenced others to question old stabilistic concepts. In his 1969 paper, "Mesozoic California and the underflow of the Pacific mantle," he proposed, on the basis of magnetic data from the ocean, that more than 2000 km of the eastern Pacific plate disappeared below western North America, and he drew an analogy between Cretaceous California and the modern Andes. Although many of the concepts presented in the paper were not original, such as the underflow of Pacific mantle (e.g. Gilluly 1963), eugeosynclinal terranes as composites of oceanic crust and overlying sediments, continent-derived sediments and deposits of volcanic arcs (e.g. Dietz 1963), allochthonous fragments (e.g. King 1958; Wilson 1968), or the significance of the Franciscan complex (below), they were linked for the first time in a single synthesis of Cordilleran tectonics. Hamilton's map of tectonic elements in California (Fig. 3) was the precursor of many such maps (e.g. Burchfiel and Davis 1972; Monger et al. 1972), which showed the distribution of geosynclinal sequences interpreted in terms of modern depositional and tectonic analogues.

A second paper by Atwater (1970) complements Hamilton's in that it uses motions of the Pacific floor, determined largely from analysis of magnetic anomaly patterns, to interpret and predict Cenozoic tectonic and magnetic patterns in the Cordillera. The relative motions of plates of the northeast Pacific floor and the North American plate suggested that a mid-Tertiary trench lay off western North America and that, contrary to Hill and Dibblee (1953), the San Andreas Fault is no older than Oligocene.

Finally, and following Daly (1926) and some early proponents of continental drift, Wheeler (1970:162) and Coney (1971) correlated late Mesozoic and Cenozoic Cordilleran tectonic events with the opening of the Atlantic Ocean. Coney was able to show there was a close time correlation between Cordilleran tectonic events and magnetism, on the one hand, and migration of the North American plate away from the African plate as deduced from Atlantic magnetic anomalies, on the other. Atwater's and Coney's papers taken together give some indications of the complexities that are possible once the plate tectonic hypothesis is evoked.

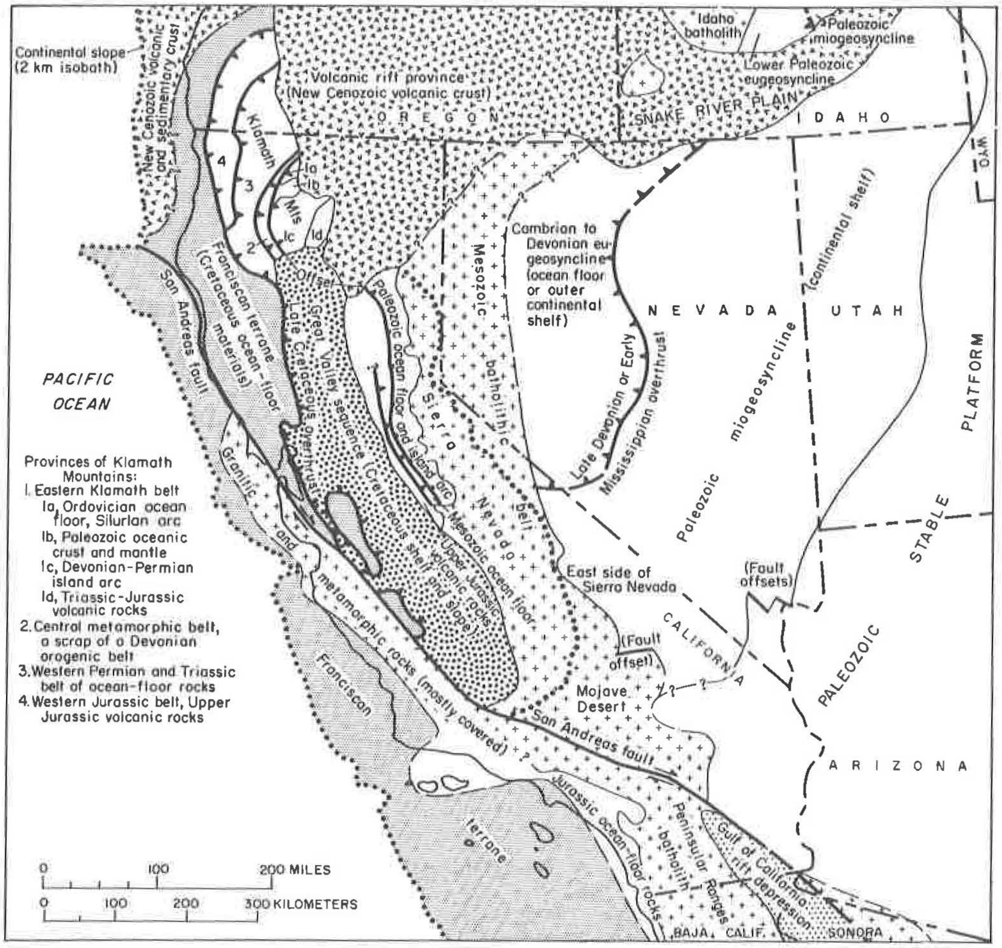


Figure 3. (Figure 1 of Hamilton 1969; with permission.) Tectonic elements of California, Nevada, and neighboring regions.

Within the Cordillera, the hypothesis appears to have had the following influences: (1) It introduced, as a permissible concept, the idea of great tectonic mobility. It is now necessary to prove that coeval but different terranes, now juxtaposed, always were in that relationship, whereas formerly they were assumed to be so unless there was extremely strong evidence to the contrary. (2) It provided the method of analyzing complex eugeosynclinal terranes by drawing analogies with modern depositional sequences laid down in specific tectonic settings. This has pointed up fundamental differences between northern and southern segments of the Cordillera that are obscured if the strata are all called eugeosynclinal. (3) Because of the rapidity and seemingly nonsystematic way in which changes occur in present-day tectonic settings, it becomes necessary to analyze the tectonic evolution as a complex series of events within each of which the dynamic setting may be very different, rather than as a continuum with pre-orogenic, orogenic, and post-orogenic phases. Inherited features may influence later tectonics, and there is "continentalization" of formerly marine terranes, but this is not a necessary aspect of the hypothesis. (4) As eloquently emphasized by Helwig (1974), plate tectonic interactions have great potential for disordering lithologic terranes and tectonic features so that it may be very difficult to understand older events. This aspect of plate tectonics poses particular problems for the Cordillera, which has evolved over a longer period than any of the other great Phanerozoic fold belts. In spite of this,

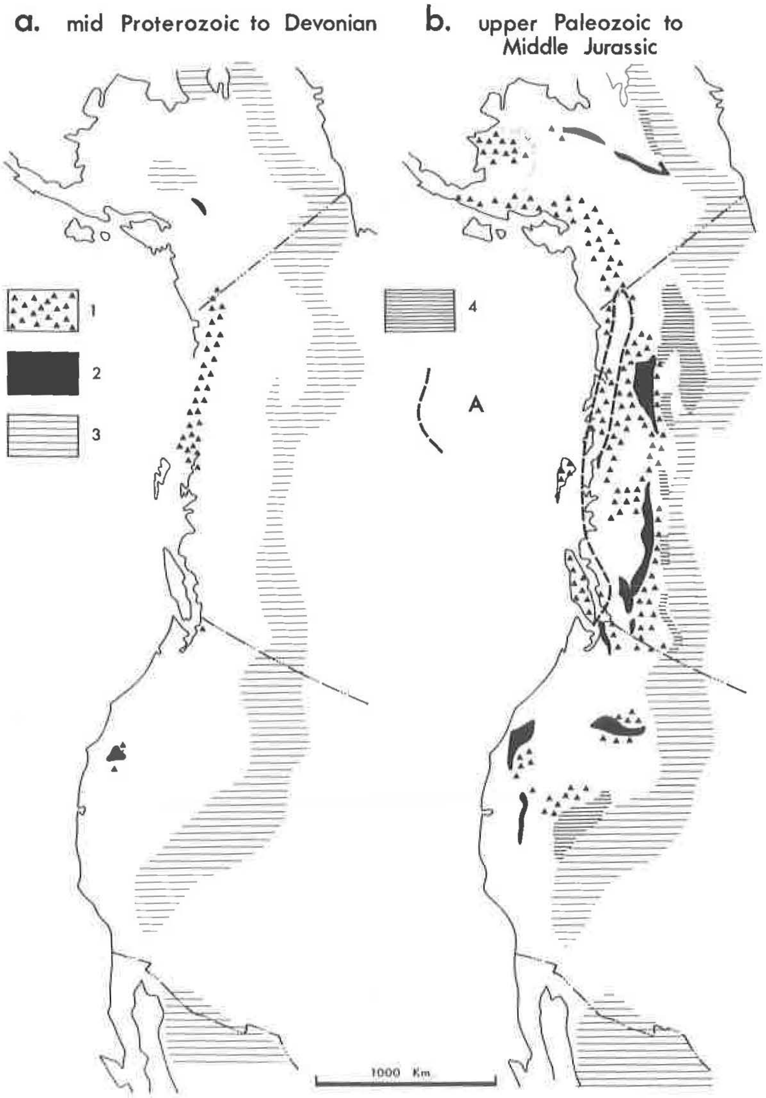
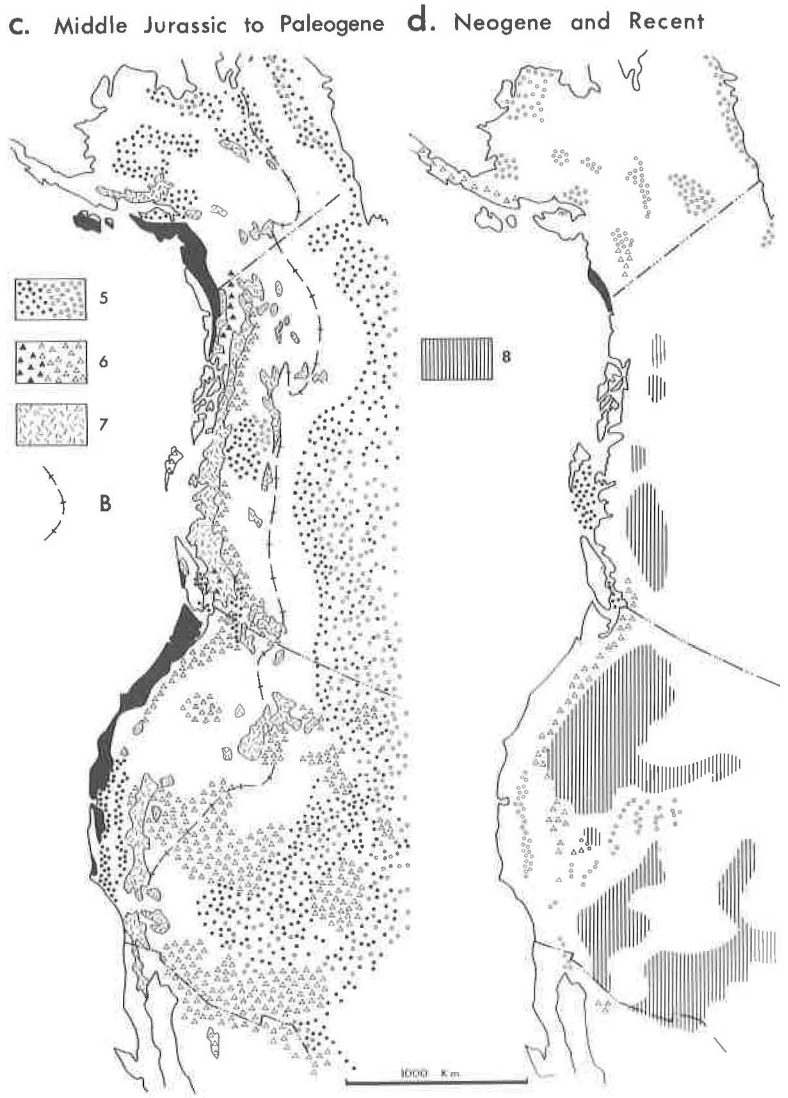


Figure 4. Distribution of depositional sequences, interpreted in terms of their tectonic settings during deposition. Key: (1) Marine volcanic arc; (2) Oceanic crust; (3) Continental shelf, slope; (4) Marginal basin; (5) Clastic rocks derived from within the orogen deposited in foreland, successor basins [marine: solid dots; non-marine: open dots]; (6) Volcanic arc [marine: solid triangles;

the generalized diagram of Fig. 4, interpreting depositional sequences in terms of settings of inferred modern analogues, is instantly recognizable as the pre-orogenic, geosynclinal (Figs. 4a, b), orogenic (Fig. 4c), and post-orogenic (Fig. 4d) phases of older works.

DEPOSITIONAL SEQUENCES

Figure 4 summarizes in four diagrams the distribution of mainly stratified rocks defined in terms of their interpreted tectonic settings during deposition. Older eugeosynclinal terranes on King's tectonic map are subdivided as shown into collages of deposits of volcanic island arcs, and oceanic and marginal basins (Figs. 4a, b). Internally, many of these subdivisions display similar gross stratigraphy (e.g. Jones et al. 1977; Monger 1977), which differs from the stratig-



non-marine: open triangles]; (7) Granitic rocks, largely related [?] to 1 and 6; (8) Terrestrial flood basalts [and rhyolites] equivalent to 4. (A) Boundary between different arc terranes; (B) Boundary between Paleozoic and lower Mesozoic sedimentary sequences to east, volcanic and sedimentary sequences to west.

raphies of adjacent but coeval subdivisions and, as shown later, many have distinctive faunal assemblages and paleomagnetic records. These diagrams emphasize one of the most fundamental differences between the conterminous United States and the Canadian-Alaskan segments of the Cordillera. The westernmost upper Paleozoic-lower Mesozoic strata in the south, thought to be oceanic basement and overlying deposits, are correlative, lithologically and faunally, with strata in the central part of the Canadian Cordillera that lie *east* of extensive coeval and older terranes. Permian faunas in this oceanic terrane are clearly exotic to North America and closest to faunas in lands bordering the western Pacific, and the belt is reasonably interpreted as ancestral Pacific crust and overlying deposits that were accreted to North America in the Mesozoic. The distribution of this belt implies, and is supported by paleontological arguments and paleomagnetic evidence (below), that extensive lower Mesozoic and older arc terranes to the west of it have been accreted to the continental margin in the north (Monger et al. 1972). In the south there is no evidence for this; on the contrary, terranes appear to have been removed in places during truncation of the continental margin in Permo-Triassic time (Hamilton 1969; Burchfiel and Davis 1972). This interpretation accounts for the great extent of older eugeosynclinal terranes in the north in comparison with those to the south. It is doubtful if it could have been arrived at within the context of the old geosynclinal theory.

The distinction made by King (1969) between eugeosynclinal deposits and younger terrestrial volcanics is not emphasized in Figs. 4c-d. The latter are interpreted as terrestrial volcanic equivalents of marine arc and (possibly) marginal basin volcanics. However, the distinction between submarine and subaerial is important as it points up the general emergence of the Cordillera terrane above sea level—its "continentalization"—towards the end of the Mesozoic.

In spite of these differences with geosynclinal interpretations, we see Fig. 4 as a descendant of the tectonic map of King (1969). In this sense, the plate tectonic hypothesis as applied to Cordilleran tectonics is an evolution and not the scientific revolution proclaimed by many.

We do not discuss herein the relationship between magmatism and Cordilleran tectonism in any detail except to point up the contribution made by studies of the Aleutian arc (above) and Mesozoic California (below) where active and fossil subduction of oceanic material in trenches can be related, spatially and temporally, to magmatism. Similar models involving crustal shortening (or plate convergence) can be applied to many of the calcalkaline volcanic and plutonic complexes in the Cordillera, although in many cases later tectonic disruption has obscured the picture. Whether this model can be used to explain the 1500 km-wide zone of Cenozoic magmatism (Fig. 4c) in the United States is a matter for conjecture. Ingenious schemes exist to do this (e.g. Lipman et al. 1971; Coney and Reynolds 1977) but, as pointed out by Gilluly (1971:2391), resolution of this problem is far from certain.

CRUSTAL SHORTENING

Evidence for crustal shortening in the Cordillera comes from the folded and thrust terranes. Figure 5 shows the distribution of major thrust faults and thrust-fault systems with their probable ages and the extensive, related (?) late Mesozoic-early Tertiary plutons and metamorphic complexes. The figure emphasizes the two-sided tectonic character of the Cordillera pointed out by Stille (1936) and Burchfiel and Davis (1968). There is a general decrease in age of thrusting outwards from the axis of the orogen. The easternmost belt of thrusts directed towards the continent involves no oceanic crust, although west of this probable oceanic crust is thrust (or obducted) over continental crust. Oceanward thrusts nearly all involve probable oceanic crust; many appear to be traces of subduction zones in which oceanic crust and overlying deposits have been driven below continental or transitional crust.

Structures Directed Towards the Continent

Eastern fold and thrust belt. The eastern or foreland fold and thrust belt features subhorizontal folded thrusts directed towards the interior of the continent. The belt has long been recognized as the largest structural entity in the Cordillera. It forms the easternmost structural element of the northern Cordillera as far south as Montana, then branches southwards across Wyoming and Nevada into southeastern California, diverging from the southeast-trending Colorado Rockies with their different structural style. From Canada into Nevada, the thrusts bring thick, miogeosynclinal strata over thinner strata of the stable platform (Keith 1928:346). The time of thrusting, originally thought to be Laramide (early Tertiary), is now known to be significantly older in places. In Idaho and Wyoming, Armstrong and Oriel (1965) demonstrated Eocene, Paleocene, latest Cretaceous, Early Cretaceous, and possibly latest Jurassic movements. Farther south, in Utah and Nevada,

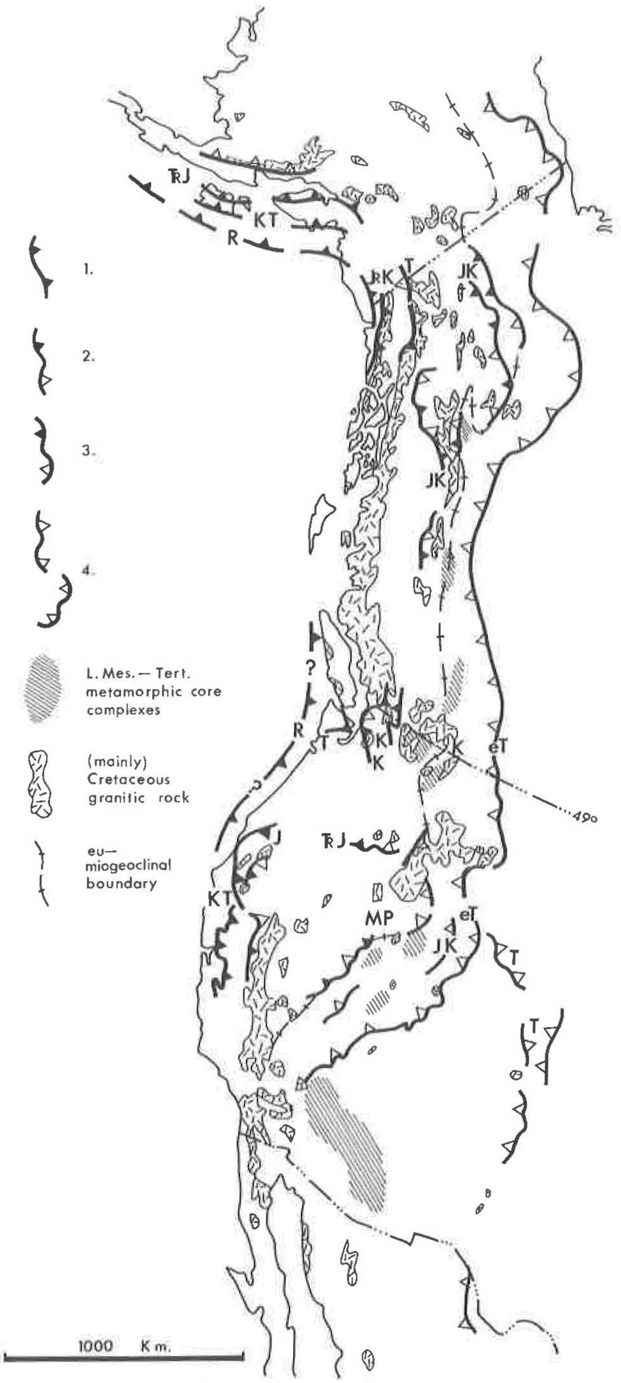


Figure 5. Distribution of major thrust fault systems in the Cordillera and their probable ages. (1) East-dipping, active and probable fossil, Benioff zones; (2) Maybe in part equivalent to 1; (3) West-dipping, possible obduction zones; (4) Thrust systems with no 'oceanic' rocks involved.

Armstrong (1968) states that major thrusting started at the beginning of the Cretaceous and continued into Late Cretaceous time. He proposed a new term, "Sevier orogeny," to add to the long-established Nevadan and Laramide orogenies. Some thrust plates in the foreland belt of southeastern California were emplaced prior to plutonic intrusion approximately 200 million years ago.

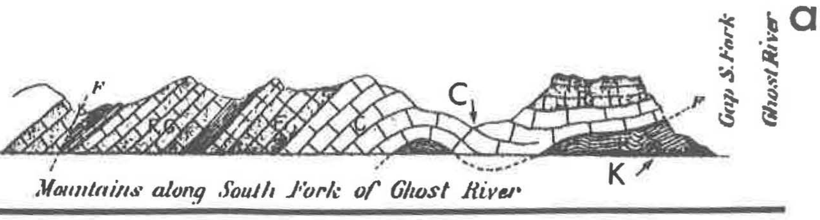
The fold and thrust system was first recognized by McConnell in 1887 in the southern Canadian Rockies where Paleozoic strata, mainly carbonates, are thrust from west to east over Cretaceous shales on several major faults (Fig. 6a). McConnell estimated 50% shortening across a present width of 40 km and described most of the characteristic features of this belt, such as folds changing into faults along strike, folded fault planes, and the structural contrast between little disturbed, incompetent shales in footwalls and broken, recemented and sheared rocks in the hanging walls of thrusts. He commented on the similarity between these structures and those reported earlier from the Appalachians of Tennessee. Bailey Willis (1902) worked just south of the International Boundary where Proterozoic strata are thrust over the Cretaceous. He studied the Lewis thrust in detail and theorized on the mechanism of thrusting, noting either that it had evolved in a single episode, closely following latest Cretaceous deposition or, because of the coincidence of the thrust plane with the highest peneplain developed in Cretaceous rocks in front of the thrust belt, that is developed in two stages, with initial warping, peneplanation, then thrusting across the peneplain perhaps as late as mid-Tertiary time. After Willis, the thrust belt was traced to the southwest, through the Basin and Range province in Nevada, where extensive normal faults obscure earlier thrusts (Keith 1928).

In following years detailed studies were made in this belt, particularly in southwestern Alberta, because of the petroleum potential of this region, with the result that the overall structure and mechanics of folding and thrusting became extremely well known. Surface and subsurface studies in this segment of the thrust belt have greatly influenced geologists working in thrust belts elsewhere. Douglas (1950), drawing on the work of Rich in the Appalachians, outlined a pattern of deformation interpreted from the detailed geometry of structures in the Rocky Mountain foothills. He pointed out that initial thrust faulting is mainly parallel with bedding and steps up section from west to east to relieve frictional resistance; this in turn results in the development of folds and back-limb thrusts (Fig. 6b). Bally et al. (1966) used seismic techniques to trace foothills thrust structures westward in the subsurface (Fig. 6c). Their paper was a landmark contribution in helping to resolve thick- versus thin-skinned ideas about the geometry of the thrust faults at depth in that it indicated that detachment of allochthonous sedimentary units in eastern portions of the belt has occurred along stratigraphic horizons without the involvement in faulting of crystalline basement rocks. The later seismic studies of Royse et al. (1975) in the thrust belt of western Wyoming, eastern Idaho, and northeastern Utah supported the general conclusions of Bally et al. regarding a characteristic decrease in dip of thrust faults with depth, and a regional westward deepening and, by inference, rooting of such thrusts into the crust.

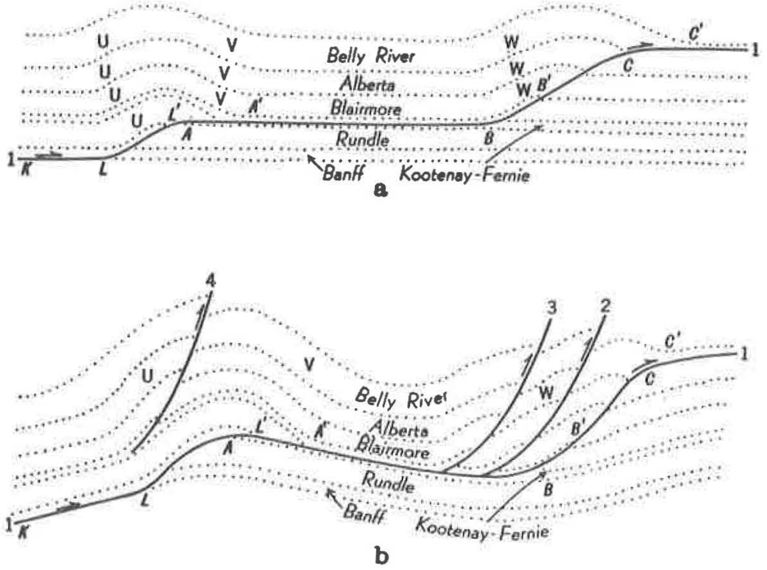
The problem of relating observed shortening in the stratigraphic cover to basement structure is one that has concerned geologists working in thrust belts the world over, the Cordillera included. Bally et al. (1966) interpreted their seismic sections as indicating major crustal shortening, on the order of 160 km, in the metamorphic core of the southern Canadian segment of the orogen.

Figure 6. Structures related to the eastern, foreland fold and thrust belt. (6a) Folded thrust in the southern Canadian Rockies: Cambrian [C] over Cretaceous [K] (from McConnell 1887). (6b) [Figure 26 of Douglas 1950, with permission.] Diagrams illustrate stages [a, b] in the formation of back-limb thrust faults [2, 3, 4] above initial thrust. [U, W, back-limb region; V, front-limb region]: (a) shows initial thrust [1-1] with small displacement; (b) shows relationship of back-limb thrust faults [2, 3, 4] to initial thrust [1-1] after additional displacement. (6c) [Plate 5, section CC of Bally et al. 1966, with permission.] Complex thrust systems in the southern Canadian Rockies; sections outlined seismically, proven by drill holes. (6d) [Figure 4 of Campbell 1973, with permission.] Interpretation of structural relationships between the eastern fold and thrust belt and high-grade metamorphic terranes to the west. Note the great amount of strain in the Rocky Mountain foothills [documented in 6c] and the lesser amount in strata above the metamorphic complex to the west.

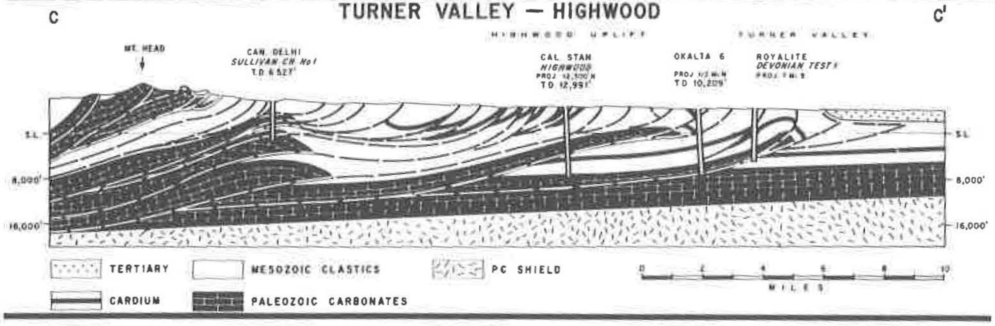
a.


F
C
C
F
K
Gap S. Fork
Ghost River
Mountains along South Fork of Ghost River

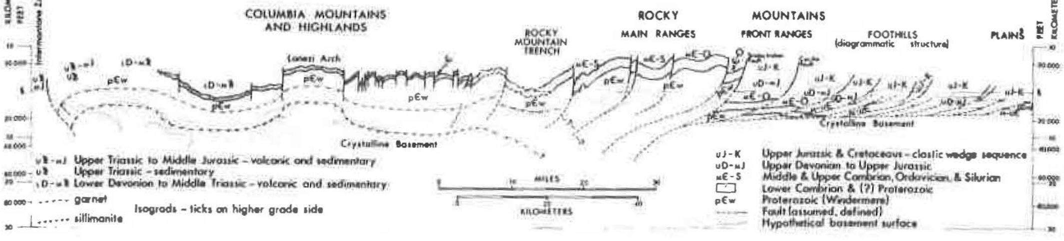
b.


U
V
W
C'
1
Belly River
Alberta
Blairmore
Rundle
Banff
Kootenay-Fernie
L'
A'
A
L
K
B'
B
C
a
4
3
2
b

c.


C
TURNER VALLEY — HIGHWOOD
C'
HIGHWOOD UPLIFT
TURNER VALLEY
MT. HEAD
CAN. DELHI
SULLIVAN CR No 1
T.D. 6,527'
CAL. STAN
HIGHWOOD
T.D. 12,991'
OKALTA 6
T.D. 10,209'
ROYALITE
DEVONIAN TEST 1
S.L.
8,000'
16,000'
TERTIARY
MESOZOIC CLASTICS
PC SHIELD
CARDIUM
PALEOZOIC CARBONATES
0
2
4
6
8
10
MILES

d.


KILOMETERS
FEET
Intermontane Zone
COLUMBIA MOUNTAINS AND HIGHLANDS
Lanezi Arch
ROCKY MOUNTAIN TRENCH
ROCKY MOUNTAINS
MAIN RANGES
FRONT RANGES
FOOTHILLS (diagrammatic structure)
PLAINS
pЄw
Crystalline Basement
uTr-mJ Upper Triassic to Middle Jurassic – volcanic and sedimentary
uTr Upper Triassic – sedimentary
lD-mTr Lower Devonian to Middle Triassic – volcanic and sedimentary
garnet
sillimanite
Isograds – ticks on higher grade side
MILES
KILOMETERS
uJ-K Upper Jurassic & Cretaceous – clastic wedge sequence
uD-mJ Upper Devonian to Upper Jurassic
mЄ-S Middle & Upper Cambrian, Ordovician, & Silurian
Lower Cambrian & (?) Proterozoic
pЄw Proterozoic (Windermere)
Fault (assumed, defined)
Hypothetical basement surface

Conversely, Price and Mountjoy (1970) attempted to relate structures in the fold and thrust belt to what they believed was the synchronous mobile upwelling of crustal rocks in the metamorphic core. This, they believed, caused lateral flow of the elevated orogenic core under gravity, in a manner analogous to the lateral flow of a continental glacier, thus driving miogeoclinal strata eastward and up the slope of the Precambrian basement-cover interface. Campbell (1973) documented the contrast between major amounts of shortening in the Canadian fold and thrust belt and minor amounts in correlative rocks to the west that form the cover of the metamorphic terrane. His cross-section (Fig. 6d) shows thrusts in the Rockies rooting near the eastern margin of the metamorphic belt. He speculated that the thrust structures arose from the westward-moving craton as it was driven downward into the high-temperature zone, a concept anticipated by Sales (1968) and Burchfiel and Davis (1968) who independently proposed that large-scale crustal shortening across the orogen was necessitated by the geometry of its flanking thrust belts. The role of a ductility contrast between thermally weakened core areas and the colder, more rigid craton to the east in localizing the eastern thrust belt, was the topic of several important papers at this time, among them Coney (1972), Armstrong (1974), Armstrong and Dick (1974), and Burchfiel and Davis (1975). Bally (1975) classified the foreland belt as an Alpine-type or A-subduction zone, envisaging sialic crust disposed of at intermediate depths below and behind the thrust belt.

Other Continentward-directed Structures. Studies in Nevada have shown that many eastward-directed thrusts, originally thought to have been of Laramide age, are of late Paleozoic-earliest Mesozoic age. Kay (1952) apparently was the first to suggest that the thrusts were old, pointing out that folding and thrusting pre-dated Pennsylvanian deposition, with further folding before Early Permian time. Later, Roberts et al. (1958) showed that pre-Early Mississippian eugeosynclinal strata, chert and clastic rocks with intercalated volcanics, were thrust over coeval carbonates and shales to the east. The thrust was dated by an overlying Mississippian conglomerate and the deformational event called the Antler orogeny (Fig. 5). Silberling and Roberts (1962) proposed a later Sonoma orogeny in the same region, in post-Early Permian, pre-Triassic time. Various models for these orogenies, proposed in the era following the introduction of plate tectonics concepts, evoked either the collapse and superposition on the ancient continental margin of marginal basins developed behind arcs still further to the west (Burchfiel and Davis 1972), or accretion of exotic arcs, formed by westward-dipping subduction, to the margin of the continent (Moores 1970).

Similar lithological juxtapositions developed along the eu-miogeosynclinal boundary in Canada where basic volcanic rocks, alpine-type ultramafics, and clastic successions, which lie on Middle Devonian and older miogeoclinal strata, caused Monger et al. (1972:586) to draw analogies with the Antler orogeny to the south. Recent work in Yukon Territory by Tempelman-Kluit (1979) has shown that the possible time of thrusting of some of the basic volcanic/ultramafic assemblages is as late as Early Cretaceous, and that this juxtaposition may be due to Mesozoic, west-dipping subduction, in the manner proposed by Moores (1970).

Structures Directed Towards the Ocean

As mentioned above, documentation of a thoroughgoing system of west-vergent thrusts in the western Cordillera did not come about until the 1960s. The 1962 Tectonic Map of the United States showed only isolated examples of such structures, largely in the Pacific Northwest where Misch and his students (summarized in 1966) and Hamilton (1963) had mapped west-directed thrust faults in the Northern Cascades and west-central Idaho respectively. In 1964 several descriptions of such structures were published. In papers or abstracts, thrust faults were reported in the Klamath Mountains of southwestern Oregon (Baldwin) and northwestern California (Irwin; Davis; both independent rediscoveries of structures first described by Hershey in 1906), and in the California Coast Ranges (Brown; Dickinson; Bailey et al.). From these first isolated discoveries of west-directed thrust faulting has come our present awareness of the consequences of convergence between the North American and various Pacific oceanic plates since early Mesozoic time. Although considered by some as direct expressions of plate convergence along subduction zones, the possibility exists that some of these east-dipping thrust faults developed within the North American plate as a response to plate convergence along the western margin of that plate.

Southern Alaska. Early work by Coats (1962) in the Aleutian arc linked seismic activity with a downgoing slab of oceanic crust above which magmatic activity occurred. Similar features, namely magmatic arcs bounded on the south by subduction complexes representing ancient trench deposits, occurred in this region in Late Triassic to Middle Jurassic time, in Early to mid-Cretaceous time, and in Lake Cretaceous to Paleogene time according to Moore and Connelly (1977; Fig. 5). The geometry of these ancient arcs appears to be generally similar to the present one, but their relationship to the ancient continental margin may be very different because of later translation on strike-slip faults.

Franciscan Complex. Probably no other rock assemblage in the Cordillera has become as widely known as the Franciscan complex of the California Coast Ranges, in large part because of its bearing on evolving plate tectonic concepts since the late 1960s. The origin of this graywacke, shale, chert, mafic volcanic, limestone and ultramafic assemblage, with its unusual metamorphism and local intense deformation, has long been debated. Although some workers (e.g. Taliaferro 1942) professed to see this assemblage as a unit with a stratigraphic base and top, most workers were unable to recognize either a consistent stratigraphy or a depositional base. The complex was later shown (Irwin 1957) to be largely coeval with the structurally higher Great Valley sequence of sedimentary rocks.

The major study by Bailey et al. (1964) suggested that Franciscan units lay on a basalt/peridotite basement, and that the upper contact of the complex was a west-directed "low angle dislocation of great magnitude" along a sheet of serpentinite at the base of the overlying Great Valley sequence (Fig. 7). The existence of a thrust fault between Franciscan and Great Valley rocks in two separate areas was documented that year in two separate areas by Brown (1964) and Dickinson (1964). It was not until 1969 that Bezore identified the serpentinite and associated mafic igneous rocks below the Great Valley sequence as an ophiolitic (oceanic) substratum on which distal sediments of the Great Valley sequence had been deposited, a relationship soon reported for widespread localities within the Coast Ranges (Bailey et al. 1970). Ophiolites have been a part of Cordilleran vocabulary since that time.

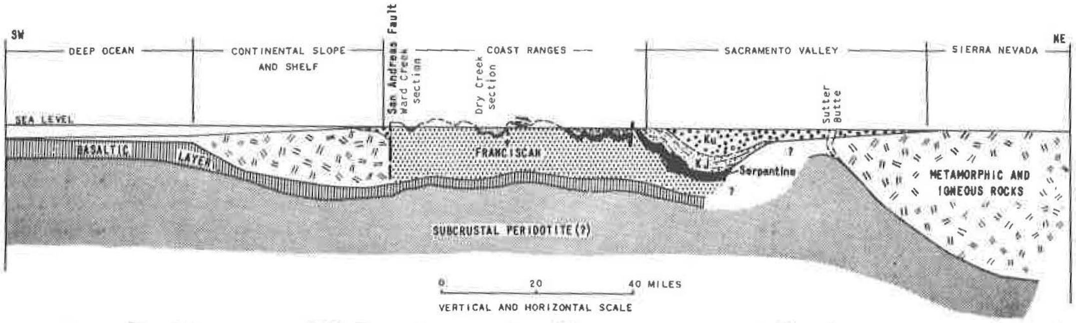


Figure 7. (Figure 35 of Bailey et al. 1964, with permission.) Idealized cross-section through western California and offshore area. Diagram shows Upper Jurassic to Upper Cretaceous Great Valley sequences thrust over Franciscan on a west-dipping thrust, with serpentine along thrust zone.

Hsü (1968) focused attention on the pervasive admixing of various Franciscan lithologies, which prior to his studies had often been attributed to the disruptive effects of Cenozoic strike-slip faulting and landsliding. His consideration of the Franciscan assemblage of rocks as a Mesozoic tectonic mélange rather than a rock-stratigraphic unit led to a major reorientation of thinking on the part of geologists regarding depositional settings for Franciscan sediments and the means by which they had been admixed with mafic volcanic and ultramafic rocks. Mélange soon became another common word in the Cordilleran vocabulary, although the origin of the diverse rock units to which the term has since been applied continues to be controversial.

Ernst (1965) studied the metamorphosed Franciscan rocks and suggested, from experimental evidence, that they formed at low temperatures (200-300°C) and at pressures equivalent to up to 30 km of burial. To achieve this unusual combination of P/T conditions, he suggested that the Franciscan rocks were metamorphosed in the roots of a downbuckled, rapidly subsiding oceanic trench. Later (1970), he speculated that the tectonic contact between the Franciscan and the Great Valley sequence was the surface expression of a late Mesozoic Benioff zone.

Ojakangas (1968) studied the petrology of Upper Jurassic and Cretaceous clastic rocks of the Great Valley sequence and concluded Great Valley sediments recorded volcanism, unroofing of plutonic rocks and plutonism in the ancestral Klamaths and Sierra Nevada.

Finally, Hamilton (1969) and Dickinson (1970) tied all of these observations together into what has become a major foundation stone of the geological (as opposed to geophysical) plate tectonic edifice. Hamilton (1969:2424) suggested that Pacific Ocean crust turned down along a Benioff zone along the Cretaceous continental margin, which at that time was bounded by a deep trench. Magmas generated in the Benioff zone gave rise to the plutons and volcanic rocks in the Sierra Nevada in a manner analogous to the modern Andes.

Dickinson (1970:846) further analyzed the tectonic, magmatic and sedimentological relationships of a Sierran-Klamath magmatic arc, a Great Valley sedimentary trough that lay west of the arc and the Franciscan trench and its deposits, pointing out that there were probably many unrecognized analogies in the circum-Pacific region. Although ideas regarding the tectonic and sedimentological interrelationships between Franciscan and Great Valley rocks continue to evolve, the concepts summarized briefly above have influenced geologists worldwide.

Nahlin-King Salmon-Vital Fault System. The oceanward-vergent structures and features discussed above lie near the present continental margin, and all have been related to processes of subduction. In the Canadian Cordillera an extensive system of thrust faults with the same sense of vergence and of Late Jurassic or Early Cretaceous age, is located 500 km east of the present continental margin (Fig. 5; Monger et al. 1978). These thrusts lie along the line of an early Mesozoic suture, delineated by a strip of oceanic crust and overlying deposits whose minimum age is Upper Triassic (Fig. 4b), and which contains Upper Triassic blue schists. This separates the ancient continental margin of North America to the east from Paleozoic and Mesozoic arc terranes to the west. The thrusts appear to be much younger than any upper Triassic subduction. Davis et al. (1978:28) suggest this thrust system is an intraplate one, located by the anisotropy within the North American plate made by the older structure. It may be that some of the thrust faults on the west of the Cascades, Klamaths, and even Franciscan system have a similar origin. Whether the line of Early Cretaceous quartz monzonitic plutons that lies east of this thrust system (Gabrielse and Reesor 1974) is related to these thrusts in the way that magmas are generated above a subduction complex, or whether to the westward-rooting thrusts of the foreland fold and thrust belt remains a matter for speculation.

LATERAL SLIP

Movements parallel with the regional trend play a major role in present-day Cordilleran tectonics and appear to have been important in the past. This is particularly true in the Alaska-Canada segment of the Cordillera, where juxtaposition of unlike terranes across major fault zones has long been recognized and where the linearity of Cordilleran tectonic elements is partly a reflection of such fault zones (Fig. 8). As pointed out by Helwig (1974), the presence of major strike-slip faults in an orogen makes it extremely difficult to construct the kinds of orderly, predictive, tectonic models such as those given in many early plate-tectonic scenarios. Unlike compressional motions, which are recorded not only by structures but commonly by such tectonic and depositional

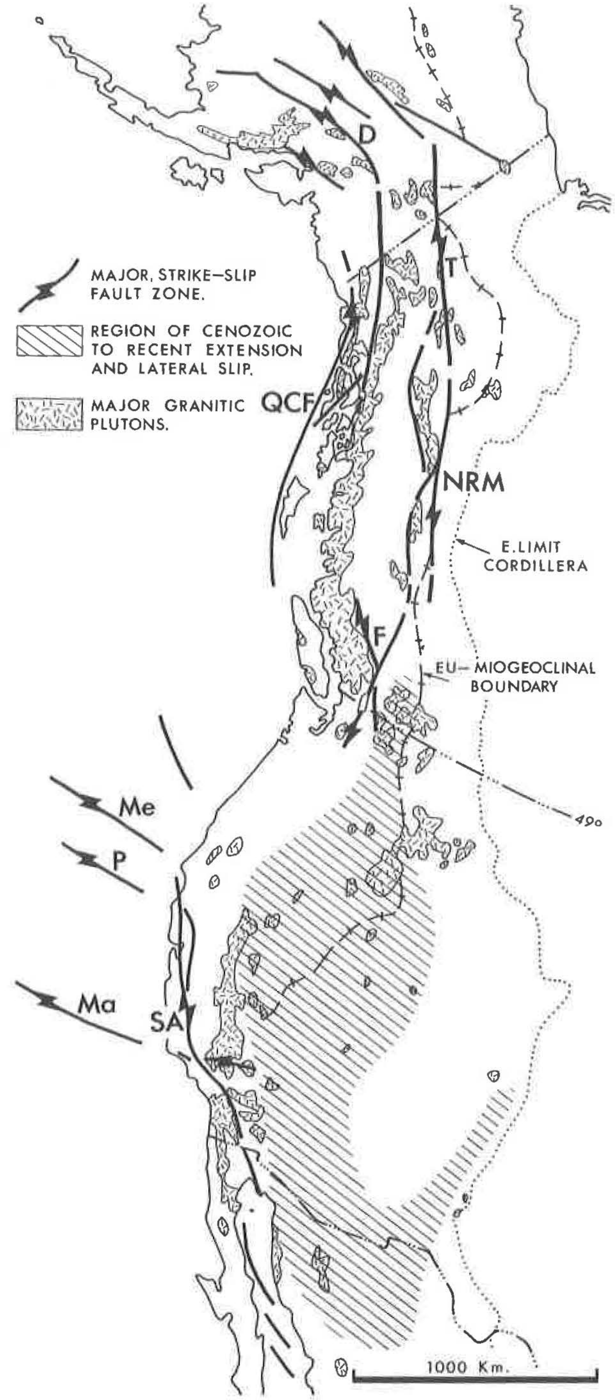


Figure 8. Major lateral slip systems. D-Denali fault system; F-Fraser fault system; Ma-Murray fracture zone; Me-Mendocino fracture zone; NRM-Northern Rocky Mountain trench system; P-Pioneer fracture zone; QCF-Queen Charlotte-Fairweather fault system; SA-San Andreas fault system; T-Tintina fault system.

features as floods of clastic detritus, subduction complexes and related calcalkaline magmatism, major strike-slip features may be marked by little more than broad or narrow zones of sheared rock. Ancient transcurrent faults, obscured by later events, may be extremely difficult to distinguish from other types of faults, and their nature may be revealed only by such evidence as dissimilar, juxtaposed biogeographic provinces or paleomagnetic records. As detailed below, the recognition of major strike-slip faults in the Cordillera has come slowly, but an accelerating awareness of the role of transcurrent displacements in the evolution of the orogen now threatens the abandonment or serious modification of those earlier tectonic syntheses that emphasized only deformations acting at right angles to the mountain belt.

Active Transcurrent Faults

Much of the North American continent is bounded on the west by active strike-slip faults. Principals among these are the 1000 km-long San Andreas fault in California and the 1400 km-long Queen Charlotte-Fairweather fault, located mainly along the continental slope of British Columbia and southeastern Alaska.

The San Andreas fault, because of its potential as an earthquake hazard, is perhaps the best known of any comparable structure in the world (e.g. Dickinson and Grantz 1968; Novach and Nur 1973), yet its very nature was in debate prior to the 1950s. As discussed by Hill and Dibblee (1953), there was general agreement that the fault was active and that latest movements were right-lateral strike-slip, but some early workers believed it was a fault with predominantly vertical motions and horizontal movements of perhaps as little as one mile. Hill and Dibblee's conclusions (1953) that right-slip along the fault had exceeded several hundred miles and that displacements of older units were greater than that of younger ones were truly revolutionary. Their controversial paper broke with the stabilist traditions of Cordilleran tectonic thought and made it easier for geologists after them to postulate large strike-slip displacements along major linear Cordilleran fault zones. Basic skepticism regarding large displacement along the San Andreas fault was eased by the field studies of Crowell in southern California (e.g. 1962). He documented the Miocene and younger cumulative offset of approximately 300 km of a distinctive Precambrian to Cenozoic rock assemblage along the San Andreas and San Gabriel faults. Nevertheless, his estimate of displacement was only about half that postulated by Hill and Dibblee (1953) from geologic relations in central and northern California. To the present day, this apparent difference in displacement is known as the "San Andreas problem," and it has yet to be fully resolved. Some workers have tried to resolve the "problem" by postulating large Late Cretaceous or early Tertiary displacements in central and northern California along an ancestral San Andreas fault, one essentially coincident with the late Cenozoic fault in those areas. Other workers, perhaps now in the majority, believe that a dispersed system of Miocene and younger faults with right slip in southern California merge northwards somehow into the San Andreas fault proper, thus increasing displacement along the northern segment of the fault. Crowell's recent studies along the southern San Andreas fault continue to be instructive. Recently (1974) he discussed the variety of features such as pull-apart basins and transverse folds and thrusts that have formed along it, and above all, he has emphasized the stratigraphic and structural complexities possible in a broad strike-slip tectonic environment (Fig. 9).

The San Andreas fault and its northern counterpart, the Queen Charlotte-Fairweather fault, have contributed to evolving ideas of plate tectonics. Carey (1958) and Wise (1963; Fig. 11) considered the fault to be the western structural boundary of a broad system of Cenozoic right-lateral shear affecting the entire western margin of the continent. Wilson (1965) hypothesized that the Queen Charlotte-Fairweather and San Andreas faults, linked by a system of spreading oceanic ridges off the Pacific Northwest coast, were a new class of faults—transform rather than transcurrent—a concept that became one of the main props of plate tectonics. His ideas were placed in a

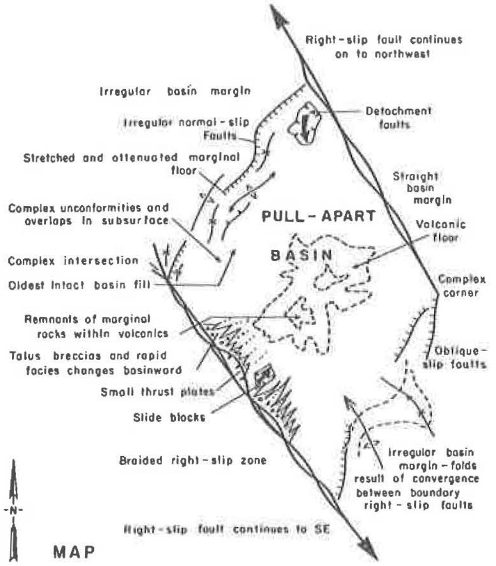


Figure 9. (Figure 10 of Crowell 1974, with permission.) Features associated with regions of strike-slip movements; an idealized diagram showing features in late Cenozoic basins of California.

direct plate tectonics context by McKenzie and Parker (1967) who first analyzed the geometric and kinematic relationships between the Pacific, Juan de Fuca, and North American plates. Atwater (1970) refined and expanded their perceptive work as to how and when the San Andreas fault had developed, following the direct juxtaposition of the Pacific and North American plates.

Early Cenozoic and Late Mesozoic Transcurrent Faults

Major transcurrent structures older than the San Andreas and Queen Charlotte faults are known inland in the northern Cordillera. The Denali system of southern Alaska (Fig. 8) was originally thought to be a right-lateral strike-slip fault with 240 km of movement (St. Amand 1957), but later work indicates that about 350 km of right-lateral movement took place on it between 55 and 38 million years ago and only about 40 km since (Lanphere 1978). To the east, 350 to 400 km of right-lateral movement were recognized on the Tintina fault system by Roddick (1967), but recent estimates have tended to be as high as 500 km (Gabrielse and Dodds 1977). The Tintina system extends to the south, in part along the Northern Rocky Mountain trench, but mainly farther west where it may join the major Fraser-Straight Creek system of southern British Columbia and northern Washington (Misch 1966; Davis et al. 1978). From geological evidence, the time of faulting was between 100 m.y. and Oligocene. Recently Vance (1977) suggested that the radiometrically determined absence of igneous activity in the Cascade region between 70 and 55 million years was related to the temporary coupling of plates in the Pacific to parts of the western Cordillera, thus perhaps narrowing the time of these transcurrent fault displacements to latest Cretaceous-early Tertiary.

The concept that transcurrent displacements have profoundly affected Cordilleran geography by the rearrangement of Cordilleran terranes or by the addition to the Cordillera of terranes derived from other continents did not make its appearance into the literature until relatively recently. Hamilton and Myers (1966) suggested that the southwestern United States had experienced a truncational tectonic event, but they did not suggest a mechanism for the truncation. Tozer (1970:635) and, independently, Monger and Ross (1971) noted puzzling distributions of, respectively, Triassic faunas and Permian fusulinids in the western Canadian Cordillera, and offered as one explanation the northward translation of the western terranes on transcurrent faults. Similarly, lower Paleozoic rocks in southeastern Alaska were thought by Jones et al. (1972) to be out-of-place, and they too postulated major right-lateral displacement of these rocks from a southern region, perhaps California.

Biological Evidence of Great Displacements

In the Cordillera, biological evidence of great displacements comes mainly from Permian faunas which are differentiated into well-defined biogeographic provinces. In cratonic western North America and the eastern, miogeoclinal part of the Cordillera, faunas show a transition from south to north, from tropical faunas with high taxonomic diversity in Texas and northern Mexico (which on paleomagnetic evidence lay on or near the Permian equator), through faunas with intermediate diversity in much of the conterminous United States and southern Alberta, to cool water, boreal faunas with low diversity in the north (Fig. 10, Yancey 1975). To the west, in the volcano-sedimentary terranes of the western Cordillera, are three well differentiated faunas that bear no relationship to latitude but are clearly tied to different tectonostratigraphic assemblages (Monger and Ross 1971). Most distinctive is a Permian Tethyan fauna, tropical in its taxonomic diversity but quite dissimilar from the Texas fauna and resembling in its fusulinids, faunas of Japan, south China, and Indonesia. This fauna occurs in a well-defined belt of limestone, radiolarian chert, basic volcanic and ultramafic mélanges (Fig. 4b), which is reasonably interpreted as disrupted ancestral western(?) Pacific Ocean crust and sediments accreted in the Mesozoic (Monger 1977). East *and* west of this fauna in Canada, but only east of it in the United States, are fusulinids, mainly in Permian volcanic arc terranes, that have some affinities with Russian forms but which readily can be correlated with faunas farther east. Finally, in the Saint Elias and Alaska ranges, Permian faunas featuring abundant brachiopods and bryozoa are more akin to boreal faunas. Taking all other evidence into account, the most reasonable way of interpreting this pattern seems to be that fragments of originally widely separated faunal provinces have been tectonically shuffled and juxtaposed along the continental margin.

Similar disjunct faunas are known in the Mesozoic. Tozer (1970:635) pointed out that Triassic faunas in the western Canadian Cordillera were deposited in warmer water than those in the eastern Cordillera.

Paleomagnetic Evidence for Major Displacements

Because of the roughly north-south orientation of the western margin of the continent in the Mesozoic, determinations of paleolatitudes emphasize transcurrent movements rather than crustal shortening. Major longitudinal shifts can only be recognized by belts of rocks which perhaps represent closed oceanic terranes, such as the Franciscan or rocks in the central part of the Canadian Cordillera. Paleomagnetic results from stratified sequences agree well with the northward shifts of the western Cordillera relative to cratonic North America suggested by the faunas. Paleolatitudes, derived from magnetic inclinations, of Middle to Upper Triassic basalt on Vancouver Island and in a coeval homotaxial succession in southern Alaska indicate a minimum northward displacement of 25° (Irving and Yole 1972; Hillhouse 1977). Upper Jurassic paleolatitudes of strata in southern Alaska are similar to those expected for Upper Jurassic rocks with the latitude of Oregon (Packer and Stone 1974). Irving et al. (1980) determined that paleolatitudes for Upper Triassic, Lower Jurassic, and Lower Cretaceous rocks, now at latitude 56° in north-central British Columbia, are those which would be expected for the California-Oregon boundary in those times. Alvarez et al. (1979) presented paleomagnetic evidence that Cretaceous limestone in the Franciscan complex, now north of San Francisco, was deposited in the southern hemisphere. Other evidence, stressing magnetic declination rather than inclination, points out of crustal blocks (e.g. Simpson and Cox 1977). Clearly, paleomagnetic studies, particularly when combined with stratigraphic studies that outline the continuity of tectonic blocks and the structural style produced by interaction of the

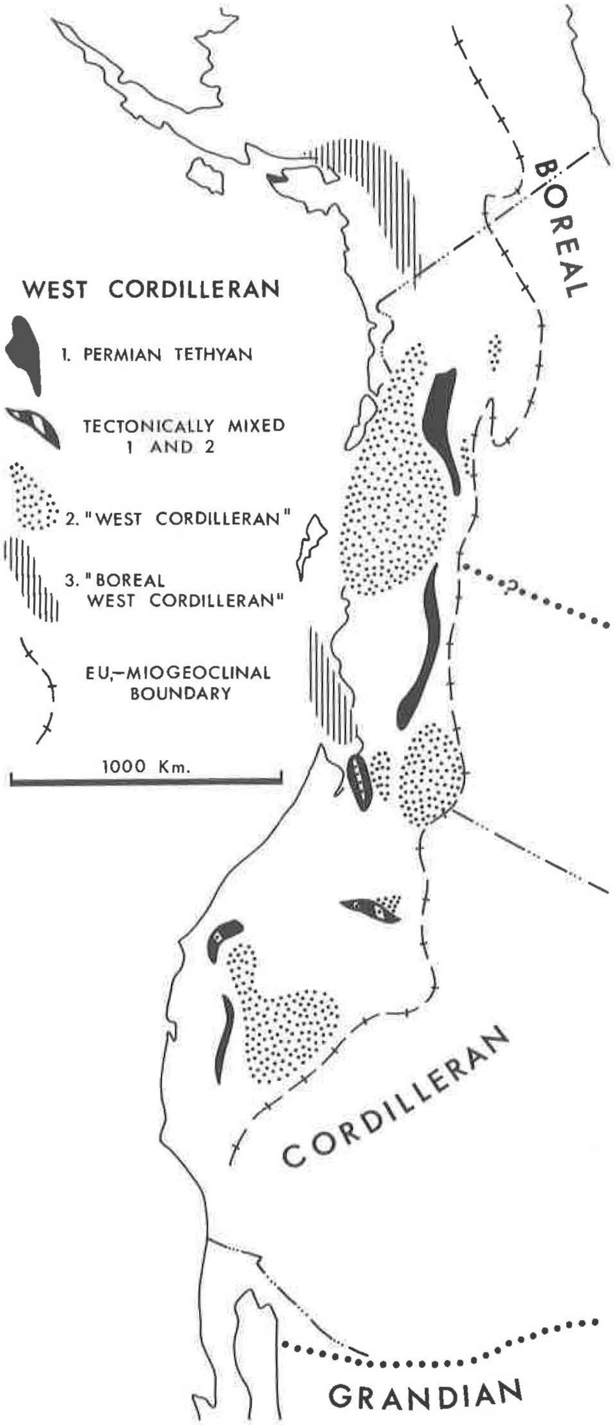


Figure 10. Distribution of the latitudinally controlled Permian faunas on the craton and the miogeosyncline (as shown by Yancey 1975), compared with faunas in the eugeoclinal, western Cordillera.

blocks with one another, provides a powerful tool for unravelling the complex geology of the western Cordillera, which is only now starting to be exploited.

CRUSTAL EXTENSION

The Great Basin of the western United States was studied by geologists of King's Fortieth Parallel Survey (1867-1873), who puzzled at its distinctive topography of alternating mountain blocks and intervening basins. Although it is now universally accepted that the Great Basin proper, and the more extensive Basin and Range province of which it is part, are the consequence of extensional tectonics, that was not clear to early workers in the Cordillera. Clarence King (1878) believed that the "Basin Ranges" and the valleys between them represented a series of "enormous" anticlinals and synclinals respectively, modified by later vertical faulting along their flanks and by the effects of erosion. G. K. Gilbert, a geologist with the Wheeler Survey of the southwestern U. S. west of the 100th Meridian (1871-1873), reached different conclusions. He (1875) attributed the ranges not to "great horizontal compression," but to nearly vertical uplift along boundary faults, usually present on only one side of the range. The basins of the region were regarded by him as merely "intervals between lines of maximum uplift." Although admitting that differential erosion of rocks of unequal resistance had modified the shapes of the ranges, he considered it "impossible" that the ranges themselves were the "residues of denudation."

Gilbert's conclusions were not apparently compelling to other geologists, even after 25 years of additional study of the Great Basin. The first decade of the 20th century was marked by a lively battle in the literature between geologists who favored an erosional origin for the basins and ranges and those who believed that the ranges were fault blocks bounded by normal faults. Subsequent field studies resolved the argument in favor of the latter interpretation and generally indicated a late Cenozoic age for most of the basin-range faulting. With the exception of Nolan's important summary of the Basin and Range province (1943), this region, like so many others in the Cordillera, lay essentially fallow, unseeded with significant new geologic ideas, for half a century.

Carey, in his monumental treatise on global tectonics (1958), suggested that the Basin and Range province could be explained as the product of east-west crustal extension with a broad, centralized zone of right-lateral strain—a zone bordered on the south and west by the San Andreas fault, and on the north and east by the Rocky Mountain trench. This basic concept, although modified greatly from paper to paper, was further developed by Wise (1963; Fig. 11) and by Hamilton and Myers (1966). It culminated in the early plate tectonics contribution of Atwater (1970), who considered block faulting in the province as the consequence of northwest-southeast crustal stretching within a broad transform zone related to the Pacific-North American plate boundary.

An alternative explanation for the origin of the Basin and Range province was suggested in the same general time period by Menard (1960) and Cook (1965). Both proposed that the province lay atop the East Pacific Rise where it had been overridden by the North American continent. They attributed the arching of the crust across the Great Basin, the horizontal east-west extension within it, and its high heat flow, to the continued effects of mantle upwelling and subcrustal spreading along the axis of the overridden rise. As plate tectonic theory developed and most workers concluded that an overridden (subducted) spreading center would cease to spread, the Menard and Cook hypothesis was replaced by others (most notably Scholz et al. 1971) that continued to postulate mantle upwelling beneath the province *but* in a back-arc setting, in a manner analogous to the secondary spreading centers documented beneath some western Pacific marginal basins.

Most present workers accept some variation of a back-arc spreading model for early Miocene initiation (or acceleration) of normal faulting in the Great Basin, primarily because this extension and synchronous basaltic magmatism in the Columbia Plateau of eastern Oregon and southeastern Washington occurred east of (behind) an active volcanic arc. At the present time, distributed right-lateral strain related to transcurrent motion along the Pacific-North American plate boundary *is* occurring within the western Great Basin, opposite the lengthening San Andreas transform plate

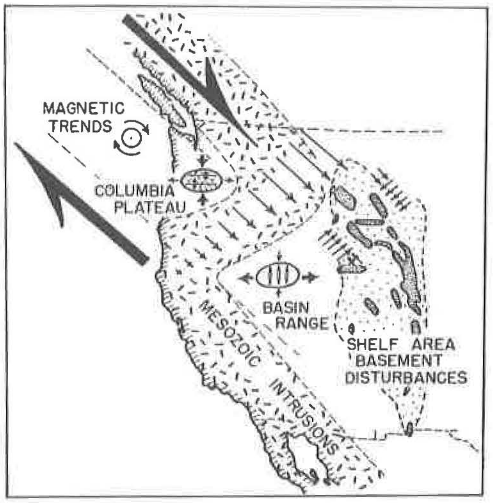


Figure 11. (Figure 3 of Wise, 1963, with permission.) Showing the hypothetical stress distribution in the Cordilleran region. California and Mexico batholith zone on the south, Canadian batholith zone on the north. Strain-ellipsoid orientation for Basin and Range province and for Pacific Northwest indicated. Rotational sense of marine magnetic pattern indicated at northwest. Small arrows in Wyoming indicate combined compression and shear to produce a parallelogram pattern.

boundary. However, this strain field appears to have been superposed on an earlier field characterized by east-northeast/west-southwest extension.

Apart from problems dealing with the origin of the Basin and Range province, there are many more specific aspects of basin-range structure that remain unresolved. Among these are the age of inception of normal faulting, the amount of extension across the province, the geometry of normal faults at depth, and the means by which brittle distension in the uppermost part of the lithosphere is accommodated at deeper structural levels. A full discussion of these problems is beyond the scope of this review and has been treated elsewhere (Davis, in press), but attention should be directed toward the problem which is of fundamental significance–i.e. the amount of crustal extension that has occurred across the Great Basin area of Nevada, Utah, and adjacent states. Estimates of extension have varied widely and are highly influenced by the assumptions that are made regarding the dip of range-front faults.

At latitude 40°N the Great Basin is now 750 km wide. Stewart (1971) assumed average dips for the range-front faults at this latitude of 60° and calculated 2.5 km of average extension across each major graben in the Great Basin, also at this latitude, for a total E-W extension in the province of 75 km (approximately 11%). Extrapolating from a single basin in northern Nevada (Dixie Valley), Thompson and Burke (1974) postulate 100 km of total Great Basin extension. Alternatively, Proffett (1977) estimates 160 to 180 km of overall extension (by his calculation, approximately 30 to 35%) based on an assumed downward flattening of normal faults in some portions of the Great Basin and on the observed patterns of crustal thinning beneath the region. Hamilton's most recent estimate of total extension across the Great Basin is from 50 to 100% depending on the extent to which the tectonically thinned crust has been thickened by Cenozoic magmatism (1973; pers. commun. 1978).

There are certainly localized areas of extreme extension within the Great Basin. Wright and Troxel (1973) calculated that 30 to 50% extension has occurred along downward-flattening normal faults between Death Valley and the Nopah Range, California. Davis and Burchfiel (1973) concluded from a geometric analysis of a larger area, that includes that studied by Wright and Troxel, that E-W crustal extension north of the Garlock fault between the Nopah Range and the

Spangler Hills has been approximately 100%. Finally, Proffett (1977) estimated more than 100% extension in the Yerington district near Reno as a consequence of multiple, superposed generations of curviplanar normal faults. Although these examples are not thought by the writers to be characteristic of the entire Great Basin, they are instructive in indicating that local or regional estimates of limited extension (10% or less), based on unproven assumptions of steep faults and constant dips, may be highly erroneous and much too conservative.

Beginning with the discoveries of Misch (1960) and his students, geologists working in the Basin and Range province have become increasingly interested in regionally extensive, low-angle faults that characteristically juxtapose younger, unmetamorphosed or weakly metamorphosed units over stratigraphically older rocks. The latter are typically of higher metamorphic grade than the rocks above them and in some areas exhibit an overprinting mylonitic fabric that indicates deformation accompanying semi-ductile flow. Misch's Snake River decollement of northeastern Nevada and northwestern Utah is the most famous of these flat faults, but others have since been recognized in the Death Valley area of California and, more widely, in southeastern California and Arizona. Evidence is accummulating, in some areas conclusively, that these faults are Tertiary in age, they have formed in an extensional regime, and they result from the thinning of supracrustal rocks by normal faulting above a basal detachment surface. Important papers in the development of these ideas are the works of Anderson (1971) and Armstrong (1972). Among the most exciting problems in Cordilleran tectonic research today are the spatial and genetic relationships between Tertiary detachment faults and lower plate metamorphic and/or mylonitic gneiss complexes of Mesozoic and Tertiary age (cf. Armstrong and Hansen 1966; Compton et al. 1977; Davis and Coney 1979).

CONCLUSIONS

We see an evolution of concepts on tectonics of the Cordillera, starting from principles first applied to this mountain system by Clarence King, continuing through Daly to P. B. King, to recent applications of plate tectonics. The transition from old, stabilistic, geosynclinal models to models that attempt to make analogies with modern plate tectonics revealed, perhaps for the first time, the complexity of the tectonic record preserved in the Cordillera. Conventional field studies show that deformation is due not only to crustal shortening, long recognized as characteristic of orogenic belts, but to lateral slip and extension. Each mode of deformation provides its own pattern; ultimately, all will have to be accommodated in a general model of Cordilleran tectonics.

The present state of concepts of Cordilleran geology is well beyond the first, simplistic, plate tectonic models, and has entered an empirical stage in which new techniques are being applied to old problems. The combination of paleomagnetic techniques with knowledge of the geometry and age of structures bounding terranes with internal stratigraphic continuity is a powerful tool for analyzing the apparently jumbled terranes of the western Cordillera. Deep-crustal seismic studies, such as those applied recently to uplifts in Wyoming (Smithson et al. 1978) may not only resolve relationships between the "Germanotype" central and southern Rockies and the remainder of the Cordillera, but they may force us to revise our concepts of tectonic processes in the lower crust. Such techniques will supplement, but never supplant, the continual need for more and better geological field mapping, the original method of understanding tectonic problems.

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