CLIMATE VARIATION AND ITS EFFECTS ON OUR LAND AND WATER

Part B. Current Research by the Geological Survey

GEOLOGICAL SURVEY CIRCULAR 776-B

WORKSHOP ON EARTH SCIENTISTS' PERSPECTIVES OF CLIMATE CHANGE

Convened near Denver, Colorado, December 7-9, 1976

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Climate Variation and Its Effects on Our Land and Water

Part B. Current Research by the Geological Survey

By George I. Smith, Editor

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A product of the Workshop on Earth Scientists' Perspectives of Climate Change, convened near Denver, Colorado, December 7-9, 1976

1978

United States Department of the Interior

CECIL D. ANDRUS, *Secretary*

Geological Survey

W. A. Radlinski, *Acting Director*

Free on application to Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202

PREFACE

The enormous impact on society of climatic variation is being recognized increasingly by both the public and government. Numerous recent publications as diverse as the public press, governmental documents, scientific journals, and special volumes of learned societies have dealt with the subject. Despite this heightened awareness of human vulnerability to shifts of climate, solutions to the political and scientific problems involved continue to be elusive.

Climate changes constantly. The reasons for climatic variability are not well understood, however, despite the formulation of many attractive and reasonable hypotheses. Perhaps of even greater concern is the growing realization that we do not yet fully understand the numerous subtle ways in which changing climate affects us. These are problems that merit more concentrated scientific attention.

Climate is generally considered primarily of interest to atmospheric scientists. Yet all scientists who have dealt with the earth, and even with other planetary bodies, have had to consider climatic problems. That past changes of climate on Earth have exceeded those measured by meteorologists is well recorded in rocks and surface features studied by earth scientists. The detailed histories of parts of the Earth's crust developed in studies of resource and environmental problems document beyond doubt that many of the differences in rocks and fossils found in local stratigraphic sequences were caused by changes in climate and their geological consequences. The rates at which geologic processes modify the landscape and impact man's use of the land are affected by climatic changes. And water supplies are obviously affected by changing climatic patterns.

In the course of their studies of the Earth and its geologic history, scientists of the Geological Survey have thus also contributed to a better understanding of past climatic changes. They are also fully aware of their obligation to help apply that knowledge of climatic history to the recognition of present and future climatic trends and to their probable future impact on human activities.

For these reasons, a workshop was convened near Denver on December 7-9, 1976, by scientists of the Geological Survey to explore the role of earth science in addressing national needs regarding information on climate. This three-part report is an outgrowth of the discussions by members of the workshop. Part A explores the roles and methods of the earth sciences in climatic research. Part B summarizes the types of climate-oriented work now being carried out by earth scientists of the Geological Survey. Part C proposes a research strategy designed to increase our understanding of the earth-science aspects of climatic variation.

V. E. McKelvey

Director
U.S. Geological Survey

CONTENTS

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SUMMARY

The U.S. Geological Survey is one of the world's major institutions of earth-science research, with responsibilities for gathering information on the Nation's resources and physical environment. Geology and hydrology, two of the major disciplines in the Survey, are intimately tied to climatic processes. Many of the research investigations undertaken by the Geological Survey, therefore, have been producing information on past and present climates and their effects.

The Survey was established almost a century ago, in large part because of the need for better understanding of the West where the landscape presents a natural laboratory that displays the varied effects of geologic and climatic processes. About half of today's programs in the Survey are concerned with processes that occur at or near the Earth's surface, and information related to climate is either required or generated as a byproduct. Most water-resource investigations collect data having climatic significance, and about 15 percent of the geologic investigations make identifiable contributions. Although primarily concerned with other objectives, approximately 1,500 Survey scientists are presently involved in studies that relate to our present climate, past climates, and climate's effect on land and water resources.

Current research that is generating data of climatic significance in the Geological Survey has great breadth and depth. Processes related to present climate that are under study involve glaciers, runoff, ground water, plant and animal communities, erosion, evaporation, lakes, water chemistry, isotope ratios, permafrost, weathering and soil formation, sedimentation, estuaries and near shore environments, and more. Geological techniques and criteria that provide data on climates of the past include paleoecology, isotope geology and hydrology, tree-ring study, stratigraphy, glaciology, pedology, geochemistry, geomorphology, and study of near-surface thermal profiles. An extensive capability for dating and correlating the climatic events, variations, and environments indicated by these criteria rounds out the Geological Survey's ability to contribute to studies of past climate variations.

This Circular presents a summary of the <u>types</u> of work in progress in the Geological Survey and gives brief <u>examples</u> of the rationale and results of about 50 selected efforts. Many of these efforts are described in detail by one or more of the several hundred technical publications by Survey authors listed at the end of this report. The studies that are related to climate are divided into five categories: I. present climate-related processes and indices that provide baseline data for climatic interpretation; II. geologically short-term changes in climate; III. geologically longer term climate changes, IV. the areal distributions of past climates; and V. dating and correlation methods.

INTRODUCTION

The U.S. Geological Survey is one of the world's major institutions of earth-science research, with responsibilities for gathering information on the Nation's resources and physical environment. Geology and hydrology, two of the major disciplines in the Survey, are intimately tied to climatic processes, and many of the research investigations undertaken by the Geological Survey, therefore, have been producing information on past and present climates and their effects. These investigations, however, are mostly undertaken for specific mission objectives, and the climatic aspects of the work have previously lacked strong focus and visibility. As a first step in better identifying and coordinating the climatic work within the Survey, a USGS Workshop on "Earth Scientists' Perspectives of Climatic Change" was convened near Denver, Colorado, December 7-9, 1976.

This Circular is a product of that workshop. Because of its diverse subject matter, it is divided into three parts that are bound separately. Part A helps provide a focus and perspective by exploring the role of earth science in climatic research. Part B (this report) summarizes the types of climate-oriented research now being carried out by the Geological Survey. Part C recommends the establishment of a specific program of climatic research which would serve to expand the Survey's present efforts and also provide maximum coordination of the climate-related work undertaken for other reasons.

PAST TRADITIONS AND PRESENT RESPONSIBILITIES

The Geological Survey was established almost a century ago, in large part because of the need for better understanding of the West where the landscape presents a natural laboratory that displays the varied effects of geologic and climatic processes. Among the eminent members of the new agency was a nucleus of earth scientists dedicated to documenting and understanding the effects on the landscape of the present climate and the evidence of past changes. Examples of this early work illustrate the beginnings of a tradition in the Survey to understand climatic effects.

- John Wesley Powell and N. S. Shaler published reports that could have largely prevented the dust bowls of the 1930's had they been heeded. Powell understood and forcefully advocated as early as 1878 that water was of overriding importance in the development and management of the western lands, and that any "improvements" in rainfall are likely to be parts of cycles and thus temporary. Unfortunately, climatic change that was favorable to farming happened to follow plowing of the high plains, and his arguments were ignored as the wishful conviction spread that "rain follows the plow." Less than 15 years later, Shaler demonstrated that the formation of soil, so necessary to agriculture, requires geologic intervals of time. He advocated that inasmuch as its destruction occurs rapidly after tillage, both man and his government have a duty to succeeding generations to protect and conserve the soil—an obligation that was largely avoided until the early part of the present century.
- G. K. Gilbert recognized the value of monitoring subtle landscape changes by use of photographs in the 1880's and he set up camera stations that could be (and have been) reoccupied by later generations for that purpose.
- I. C. Russell and G. K. Gilbert published reports between 1885 and 1890 that described the Pleistocene histories of Lakes Lahontan, Mono, and Bonneville in the Great Basin and provided some of the first field evidence of the relation between lake expansion and the times of glaciation in adjacent mountains.

● T. C. Chamberlin and Frank Leverett were part of the group that first mapped and described the stratigraphy of the glacial succession in the midcontinental U.S. Before 1900 they had named and defined the Wisconsin, Illinoian, and Kansas Glaciations and the Sangamon, Yarmouth, and Aftonian Interglaciations.

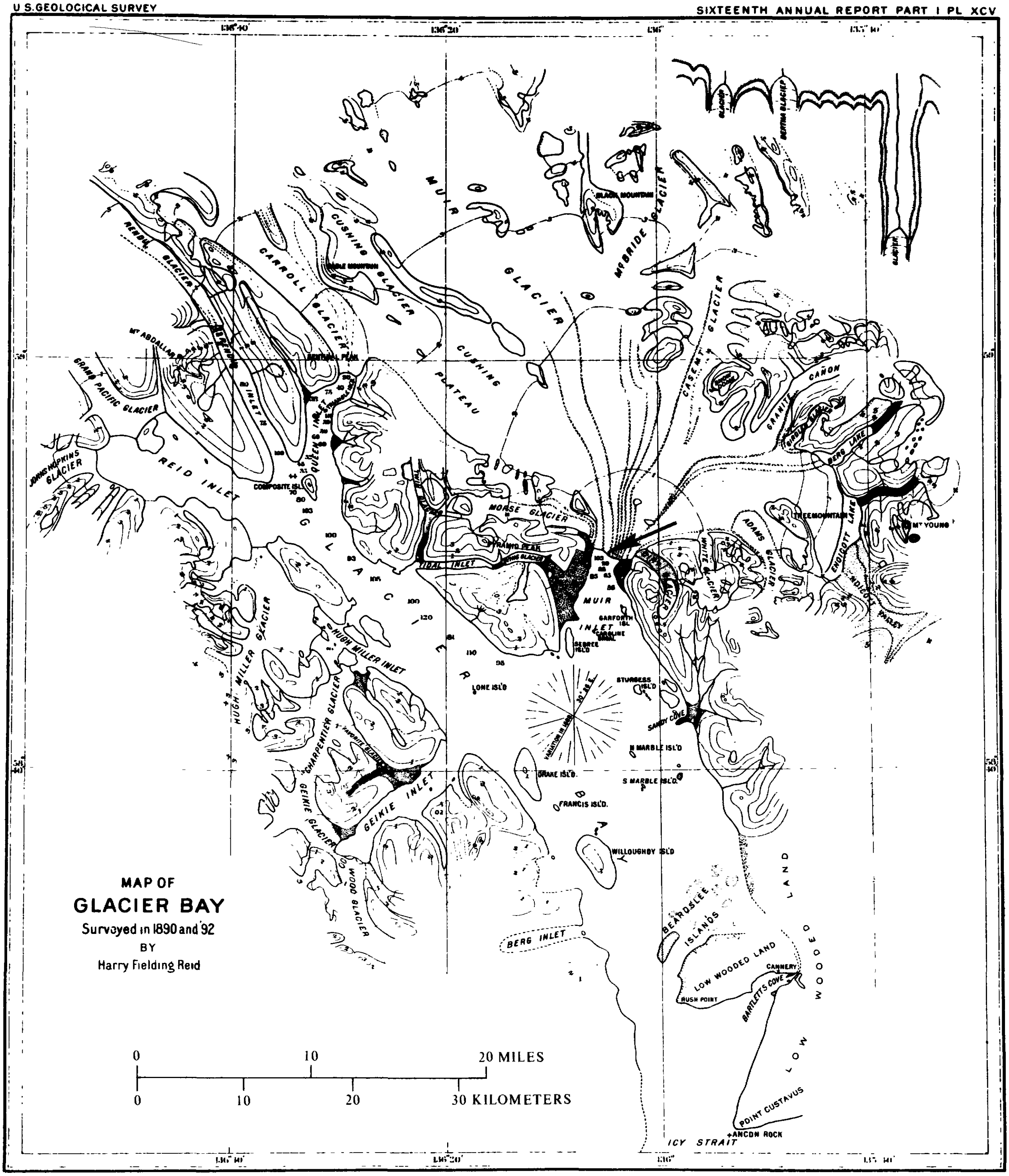
Since the inception of the Geological Survey, therefore, its scientists have been studying the impact of climate on geologic and hydrologic processes. The Survey's responsibilities for doing so began with the Organic Act of 1879, which broadly authorized the new agency to undertake the "...classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain." Subsequent acts and the separation of portions of the Survey that became new entities (the Forest Service, the Bureau of Reclamation, the Bureau of American Ethnology, the Grazing Service which is now incorporated in the Bureau of Land Management, the Bureau of Mines, and the Geophysical Laboratory of the Carnegie Institution) have led to present-day Survey responsibilities focusing on the Nation's energy, mineral, land, and water resources. Today the Survey's principal mission is to collect the factual information and develop the expertise that will provide a reliable basis for (1) the identification and evaluation of the Nation's land, water, mineral, and energy resources, and (2) policy- and decision-making on the part of the Administration, the Congress, State and local governments, and the general public. Clearly, an increased knowledge of the effects of climate change on the Nation's land and water resources serves both parts of this mission.

CURRENT RESEARCH

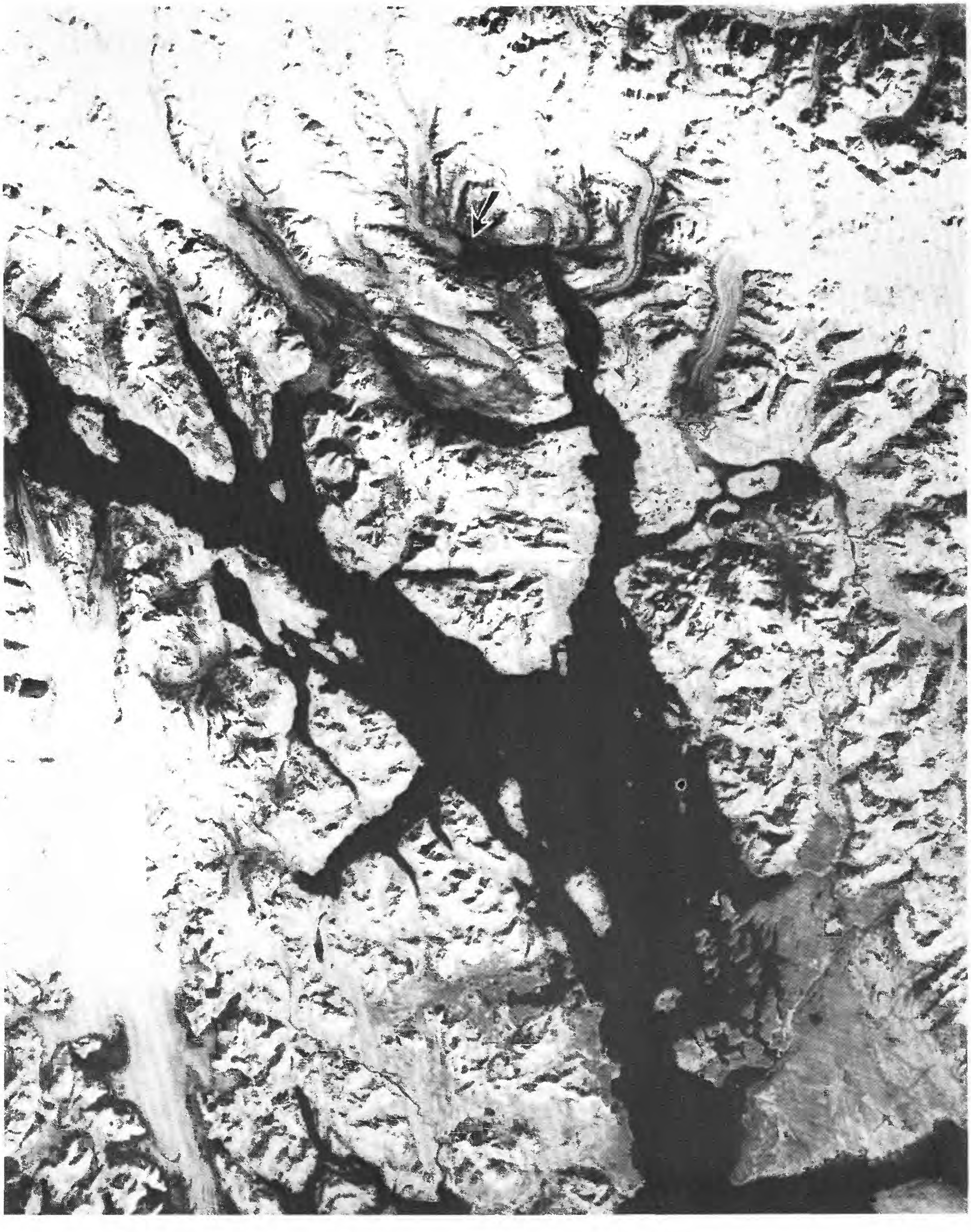
About half of the current programs in the Geological Survey contribute some information on present or past climates. Their concerns are with processes that occur at or near the earth's surface, and information related to climate is either required or generated as a byproduct. Most water-resource investigations involve collecting and interpreting data of climatic significance, and about 15 percent of the Survey's geologic investigations are making identifiable contributions to the subject. We estimate that about 1,500 professional hydrologists, geologists, mathematicians, chemists, paleontologists, biologists, limnologists, and representatives of other sciences in the Geological Survey are presently involved in studies that relate to our present climate, past climates, and climate's effect on land and water resources.

Much of the Geological Survey's ability to contribute to studies of long-term climate variation stems from its capability for dating and correlating geologic events of the last few million years. The Survey has radiometric dating facilities at each of its three major centers (Reston, Va., Denver, Colo., and Menlo Park, Calif.), and several of the techniques available, including carbon-14, potassium-argon, uranium series, and fission track, provide ages useful for Quaternary studies. Approximately 25 Survey scientists and technicians, excluding supporting staff, produce and interpret more than 2,000 age measurements each year using these four techniques alone.

In addition to radiometric dating, a number of other methods are being developed or used by about 100 scientists. Techniques based on tree rings, varves, annual snow layering of glaciers, archaeology, paleomagnetism, and fossils are relatively well established, although refinements in them continue. Other techniques using obsidian hydration, superhydration, thermoluminescence, amino-acid racemization, lichenometry, mineral alteration, soil development, rock weathering, and rind-thickness methods are in varying stages of development.



Survey geologist H. F. Reid began studies in the 1890's designed to monitor climatic cycles as expressed by changes in existing glaciers. Reid's map of Glacier Bay, Alaska, in 1890-91 (left), when compared with a 1973 Landsat photograph (right), shows that in eight decades the terminus of the Muir Glacier (arrows) has receded about 34 km.



Activities in the Geological Survey that require or produce information on climate

Reduction of natural hazards
- Landslides
- Glacier-related hazards
- Floods
- Ground subsidence
- Earthquakes and faults

Land resource utilization
- Classification of Federal lands
- Urban studies
- Land use information
- Fragile environments

Water supply and utilization
- Surface-water resources
- Ground-water resources
- Water quality and geochemistry
- Effects of water management strategies

Mineral and energy supply and utilization
- Geothermal resources
- Environmental effects of energy production
- Mineral resources
- Regulation of exploration, development, and production from onshore and offshore Federal lands

Special concerns
- Management of radioactive waste
- Siting constraints on nuclear power reactors
- Environmental impact analysis

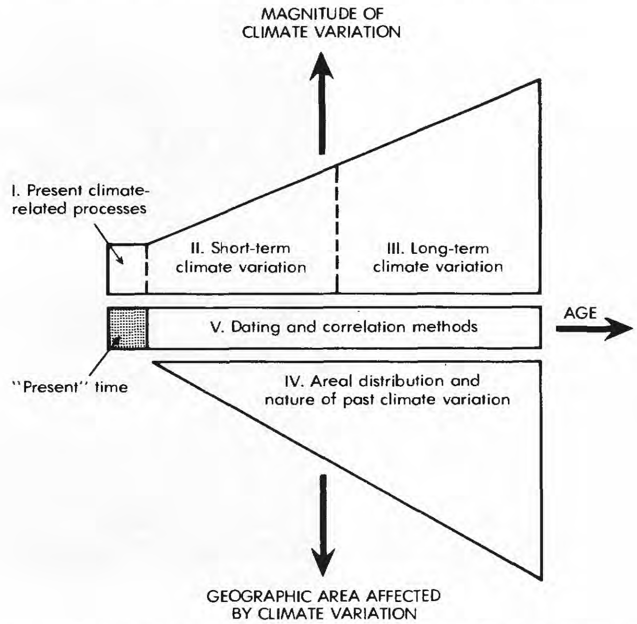
Advances in the methods of correlating deposits that are physically separate and lithologically different are continuing. Tephrochronology, the most precise and highly developed basis for correlation of widespread volcanic ash deposits, is the main concern of about 10 research scientists in the Survey. Stable-isotope evidence of climate or climatically related events is being produced in three laboratories and used by 10 or 20 research projects. Quantitative application of geomorphic evidence of correlation is used to varying extents by dozens of projects and programs.

The breadth and depth of current research makes it impractical to describe each program and project that is generating data of climatic significance. What follows is a summary of the types of work in progress and brief examples of the rationale and results of selected efforts. Many of these efforts are described in detail by one or more of the technical publications listed in the bibliography at the end of this report.

Studies now being carried out that are related to climate can be conveniently divided into five categories: I. present climate-related processes and indices that provide baseline data for climatic interpretation; II. geologically short term changes in climate; III. geologically longer term climate changes; IV. the areal distributions of past climates; and V. dating and correlation methods. The relation between these categories is illustrated by the diagram below.

I. PRESENT CLIMATE-RELATED PROCESSES AND INDICES

Our present climate is reflected in

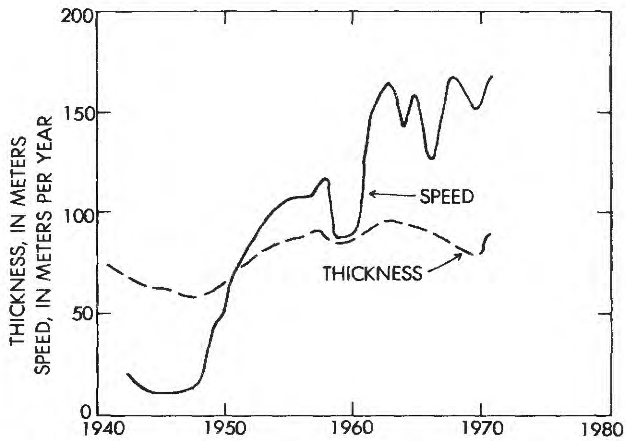


Categories of Geological Survey research related to climate.

a number of natural processes that are observable directly or indirectly. Some processes are almost instantly responsive to the climate of the moment—the weather—whereas others integrate and average the effects of weather and climate over longer periods. Response times range from minutes to several thousand years. The value of studying the more rapidly responding phenomena is twofold. They provide a statistical basis for estimating the likelihood that a given short-term variation in a climate or a climate-related event will happen in a given area, and thus help decisionmakers to avoid hazards and make the best use of our land and water resources. They also serve as the means by which the geologic consequences of climate and climate change can be observed and quantitatively related to the climatic elements that caused them, so the past climates can be interpreted quantitatively when evidence of them occurs in the geologic record.

Current projects that concentrate on climate-related processes and indices mostly fall into one or more of the following categories:

- Periodic or continuous measurement of streamflow at 1,100 gaging stations in 50 states.
- Systematic measurements of depths to ground water, and monitoring and recording their variations.
- Comparison of historic climate patterns with the ages and growth rings of trees, the age distributions of selected species of plants, and documented changes in the natural vegetation and the composition and amount of airborne pollen.
- Comparison of the amount of precipitation with the amount of runoff.
- Development of mathematical expressions that relate stream and river channel geometry to flow volumes.
- Measurement of erosion rates by determining volumes of sediment and dissolved materials that are removed, carried, and deposited by running water.



Climatic variations are expressed by fluctuations of glaciers, but it is necessary to understand the dynamic response mechanism of glaciers: how changes in thickness translate into changes in the rate of ice deformation and the speed of sliding on the bed. After many years of thinning, the Nisqually Glacier, Washington, began thickening in 1945-46. This was one of the first recorded observations of a response to the world-wide cooling trend that began in the mid-1940's. During the ensuing decade, as shown by this diagram, the speed of flow also increased. The wave of thickening travelled rapidly downglacier causing the terminus to advance 520 meters between 1953 and 1966.

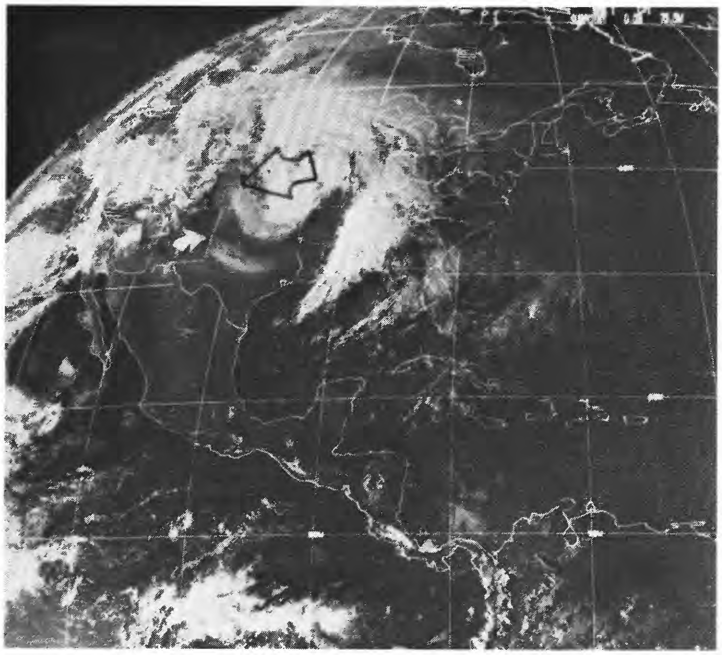
- Studying the initiation, growth, and stabilization of a variety of erosional landforms in relation to major climatic events.
- Identification for future comparative purposes of remote areas that have geological and biological characteristics comparable to less remote areas being affected by man.
- Measurement and calculation of evaporation from lakes and reservoirs as a function of water temperature, air humidity, wind, and solar radiation.
- Study of the relation of lake hydrology, limnology, and water chemistry to regional hydrology and climate.
- Measurement and mapping of changes in the terminus positions and dimensions of glaciers which respond to climate.

- Measurement of the hydrologic balance of existing glaciers, and relating those measurements and physical changes in glaciers to climate.
- Determination of the physical processes involved in glacier flow and volume changes so that measurements of them can be related to climate.
- Computer modeling the relations between water velocity and volume, sediment load, slope of flow, channel geometry, and sediment deposition.
- Measurement of the annual and regional variations in the stable-isotope composition of surface and ground water, ice, and vegetation in different climatic settings.
- Measurement of the variations in the stable-isotope composition of rain and snow during and between storms, between areas, and between years.
- Measurement of the variations in the stable-isotope composition of evaporating water in closed-basin lakes as functions of weather, evaporation, and crystallizing salts.
- Studying climate-related current movements, salinity variations, and sedimentation patterns in delta, estuary, bay, and near-shore marine environments.
- Determining the ecologic limits of marine faunas and floras, and the natural climatic events that cause recorded stress or wholesale mortalities.
- Monitoring thermal profiles in permafrost areas.
- Studying the rates, mechanisms, and types of weathering and soil formation caused by present climates.
- Measurement of variations in temperature, moisture, and other variables in the near-surface parts of deposits where climatically controlled soil-forming reactions occur.
- Monitoring throughout much of the world of seasonal and yearly changes in glaciers, vegetation, and albedo by study of Landsat pictures and other types of satellite imagery.

The total impact of the contributions made by above-listed types of projects can be better assessed by more detailed descriptions of a few.

- Data on the fluctuations of 114 U.S. glaciers over the five-year period 1970-75 show some are advancing, some are retreating, and some are stationary. The data illustrate the complexity of relating areal differences and short-term changes in climate to glacier activity.
- A series of "hydrologic benchmark" stations, established in areas relatively unaffected by and permanently protected from man's activities, allow for continuing observation of ground-water level, streamflow, water chemistry, sediment transport, and channel geometry in relation to long term climatic records. The benchmark stations are intended to aid recognition of the relative importance of climatic events and the activities of man on surficial processes.
- The "Vigil Network" consists of areas where systematic repeated observations of changes in the landscape are made through use of relatively simple instruments. Changes in landforms and vegetation can be related to meteorologic and hydrologic records and the activities of man.
- Aircraft and spacecraft photography and imagery are being used to compile

South Cascade Glacier, Washington, is the main site for glaciological research by the Geological Survey. The elevations of about 100 points on the surface of the South Cascade Glacier were determined in 1970 and again in 1976 by the simultaneous use of theodolite and laser measuring devices as shown here. Changes in the level of the horizontally located points give the change in the average thickness and volume of the glacier. Between 1970 and 1976 the glacier thickened, and the observed mass change was corroborated by measured differences between the snow that accumulated and the ice that melted.



Left: The dust storm of February 23, 1977 in the western great plains, as seen from the GOES-1 Weather Satellite about seven hours after the period of most intense surface erosion (3 p.m. local time). Two large plumes can be seen, which in these pictures are gray in contrast to the lighter clouds and much darker gray ground surface. The white arrow points to one source area of the southernmost plume in the Clovis-Portales region of eastern New Mexico. This plume extends almost across the entire central part of the state of Texas. The black arrow points to another large plume that originated in eastern Colorado, and that at the time of this picture had reached southern Oklahoma. Right: During a seven hour period on February 23, this barbed wire fence was almost completely buried by sand and silt that was eroded from a large field to the right. Similar drifts buried wheat fields downwind from severely eroded areas. The drifts are composed of the coarser sand and silt that was moved during the windstorm; the silt and clay was carried away in suspension and provided the material for the plume that rose to heights of thousands of feet only a few hours after the windstorm began. Note relatively undamaged rangeland in the background (arrow). The degree of erosion depended on soil type, vegetative cover, and soil moisture; in general, irrigated fields suffered less than areas where dry farming was being practiced.

land-use and land cover maps and related data of the entire United States. When processed to separate the different wavelengths of reflected light, they indicate what percentage of solar radiation that reaches the ground is returned to the atmosphere or to space. In populated areas, land uses influence the percentage and wavelengths of reflected energy and change the energy balance. With the quantitative definition of these characteristics, in conjunction with solar and atmospheric data, it is possible to determine the net radiation, radiation temperature, and albedo of both populated and unpopulated areas. These are essential data in evaluating the thermal interaction between the atmosphere and ground surfaces, and they allow estimates to be made of the impact on climate caused by man's alteration of the landscape.

- Study of the precipitation that fell at the stations on the slopes of the Sierra Nevada, California, and in areas to the east during the 1968-69 season shows that the stable-isotope composition of precipitation is chiefly controlled by the temperatures at condensation levels and by trajectories of air masses relative to the large mountain range. Large variations in the deuterium content of precipitation occurred during storms and between storms. However, correlations exist between the isotopic composition of the precipitation and the location and

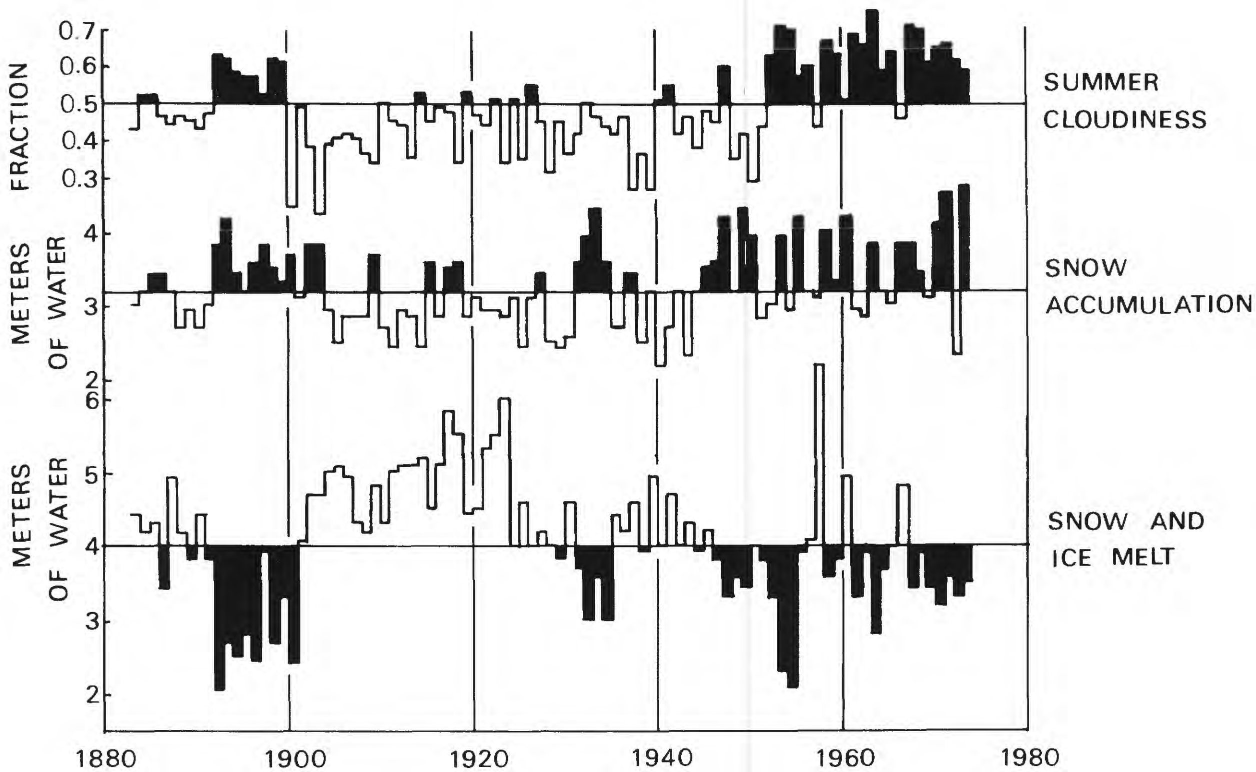
The content of oxygen-18 in calcite deposited as crusts beneath existing glaciers records the oxygen-isotope composition of the ice. Temperate glaciers, like the Blackfoot Glacier in Glacier National Park, Montana, dissolve carbonate minerals on the uphill side (dark areas of photograph) of irregularities in the carbonate bedrock and deposits calcite on the downhill side (light areas) where the pressure at the ice-rock interface lessens, the meltwater freezes, and the remaining solution concentrates to the point of resaturation. Isotopic analyses of carbon and oxygen in bedrock calcite and subglacially redeposited calcite show that the carbon-13 content of the subglacial calcite reflects that of the parent bedrock whereas the oxygen-18 content is that of the glacier ice. Subglacial calcite that originated beneath Pleistocene continental ice sheets is therefore also expected to reflect the oxygen-isotopic composition of the Pleistocene snow, a function of prevailing air temperatures and stormtracks. Photograph by Bernard Hallet, Stanford University, California.

elevation of the station, the amount of precipitation, the month in which the storm occurred, and the early-versus-late stages of the same storm. Significant variations also occurred in the precipitation of successive years, as shown by snow cores over a period of five years.

- Owens Lake, California, which is normally dry, was flooded in 1969 as a result of an uncommonly large amount of rain and snow the previous winter. During 1970 and 1971, as the lake dried up and salts crystallized, observations of the types of minerals, the chemical composition of the brine, and the isotopic composition of both provided a basis for interpreting the mineralogy and isotopic composition of salts that crystallized in Pleistocene lakes and the climates in which they formed.
- Arroyo cutting is caused by runoff from intense summer rains. Near Santa Fe, New Mexico, the development of arroyos has been measured by repeated surveys and photography, and the rainfall and resulting discharge that caused the arroyo growth have also been measured. Measured discharges accounted for up to 30 percent of the rain that fell in the drainage area, total flow times during erosional episodes could have been as brief as 30 minutes, and headward cutting rates approached 3 m/yr. In Arizona, headward cutting rates have been measured that exceed 30 m/yr.
- Study of time-sequential aerial photographs, in conjunction with weather and streamflow records going back to the 19th century, has helped evaluate the degree to which recent timber harvest and road construction have influenced the erosional impacts of infrequent high magnitude floods in the Redwood National Park of northwestern California. The results have been used in drafting forest practices legislation and in resolving controversies concerning physical protection of the park, and they provide baseline data on the relation between climate-related events—floods—and erosion in similar areas.
- Sclerochronology, the marine counterpart of dendrochronology, is the study of the density bands of stony corals. It shows promise of providing a means of detecting and dating past environmental variations in shallow warm coastal seas. For example, a patch reef off southeast Florida was almost entirely killed by an abnormal influx of cold water during the winter of 1969-70. Cores from the tops of large dead corals, as well as from those that survived the winter, show that stress caused by periods of cold decreases the thickness of the annual growth bands as detected by X-radiography. Atmospheric temperature data from a nearby weather station confirm that stress bands in the corals for the years 1970, 1964, 1958, and 1942 can be explained by abnormally cold winter air temperatures. Some coral heads may have lived as long as 400 to 500 years; the history of cold periods is expected to be recorded in them.

II. SHORT-TERM CHANGES IN CLIMATE

Short-term changes in geologically recent climate are here considered to be those occurring during the last several decades to a few thousand years. They provide data on the magnitude, rate, frequency, and duration of infrequent weather events and changes in climate that are representative of those that can occur within the framework of our present "interglacial" climate. These changes provide the records of climatic phenomena that occurred over longer periods of time than modern instrumental records provide and become the basis for estimating the probability and consequences of climate variations that could occur without prolonged shift in atmospheric circulation patterns. An added benefit stemming from some of these studies is that they help identify climate-related hazards that increased in recent times as a result of man's



Reconstruction by computer modeling of the annual accumulation, ablation, and mass balance of glaciers in the North Cascades of Washington shows that the period of pronounced glacier recession, which began before 1884, ended about 1945. A decrease in the summer air temperature of 0.5 degrees (C), or an increase in winter snow accumulation of 10 percent (0.35 mm), would have caused these glaciers to grow instead of losing mass during this period. Winter snow accumulation since 1945 has been greater and summer ablation less than the 1884-1975 average, meaning that the glaciers are now "healthy." The greater cloud cover shown during this period is probably responsible for more stable glacier balances during this period. The newly developed computer program that calculates cloud cover as well as the other variables shown above only requires data on low-altitude precipitation, temperature, and streamflow.

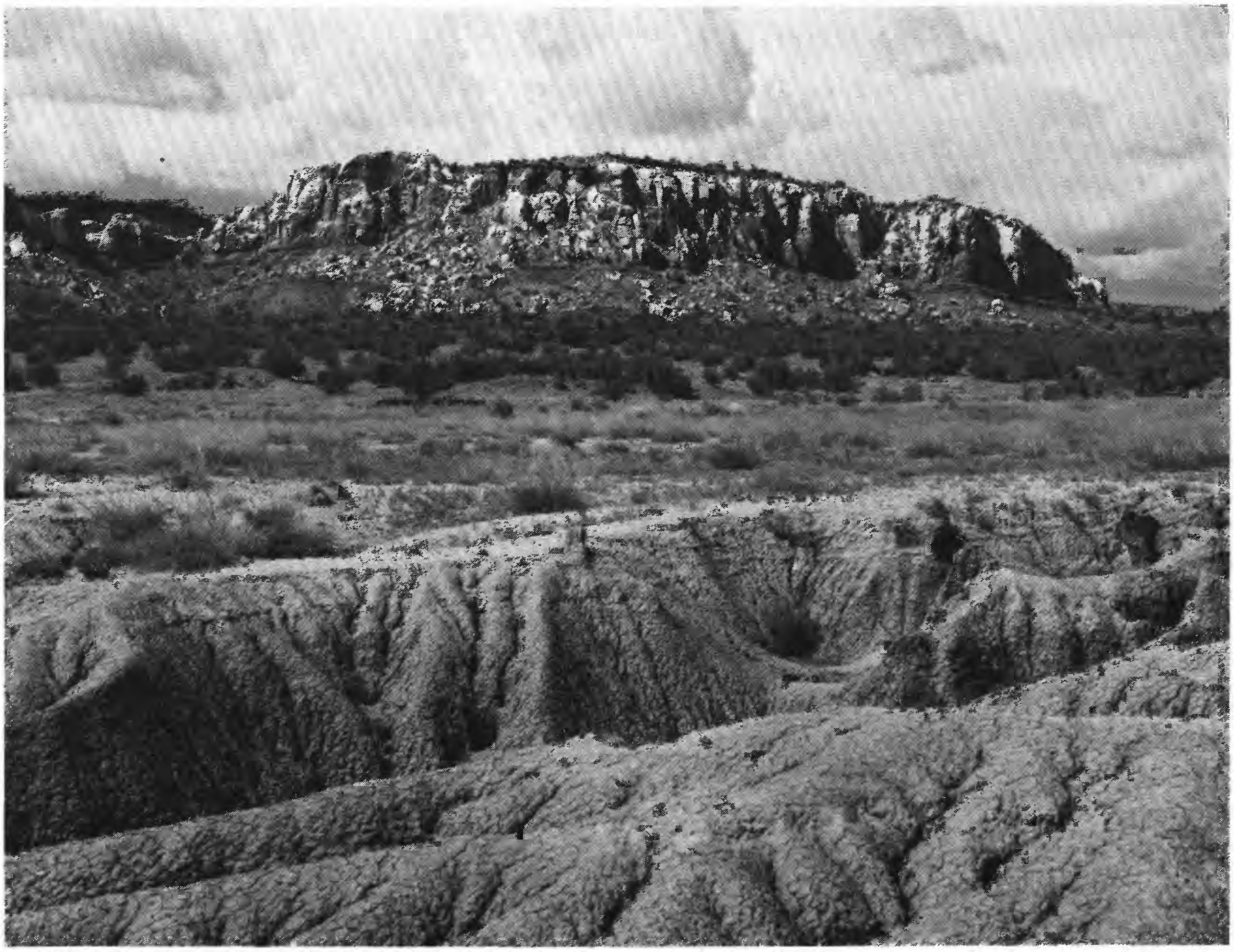
activities rather than from a change in the climate itself.

Current projects that focus on historic and geologically short-term variations in climate and supply data on them, mostly fall under one or more of the following program categories:

- Calculating, on the basis of stream-flow gaging data, the likelihood of past and future stream flows of all magnitudes, including those not actually represented by historic records.
- Documenting, by use of photographs made several decades apart, the climatically caused changes that have occurred in plant populations, in geomorphic features, in the extent of erosion, in the lengths of glaciers, and in the levels of rivers and lakes.
- Deriving, from tree growth rings, a history of past changes in precipitation, available ground water, or growth-season temperatures.
- Differentiating between the damage caused by high magnitude weather events that is a natural response versus an excessive response as a consequence of man's activities.
- Establishing, by means of fossiliferous stratigraphic sequences, the patterns of past changes in climate-sensitive biota—pollen, seeds, leaves, wood, the bones and shells of animals, and the remains of man.

Arroyos, which grow headward by progressive erosion, have been forming in the American Southwest since the 1880's, a circumstance seemingly initiated and perpetuated by the prevailing arid and semiarid climate. Under this climate, the dense ground cover needed to promote infiltration of rainfall and to impede erosion cannot develop. These two photographs document the rapidity of this destructive form of erosion. The left photograph was taken in 1915 by N. H. Darton; arroyo cutting was underway as shown by the bank of an arroyo in the middle distance (arrow), but the area invaded by arroyos was still comparatively small. The right photograph was taken in the same time of the year by H. E. Malde in 1970; arroyo cutting had expanded into the area where Darton had stood, and the grassland of the middle distance had become more barren.

- Compiling, in areas where sedimentary processes were responsive to climate, age-controlled stratigraphic records of climatic variations indicated by changes in the sediments and by discontinuities in their deposition.
- Systematically measuring, in geothermally stable areas and over a period of years, the changes in near-surface temperature profiles that reflect past variations in mean annual air temperatures.
- Reconstructing the periods of changing sediment load carried by rivers by study of stratigraphic variations in nearshore marine sediments.
- Determining past wind directions at low altitudes by study of stabilized sand dunes, and at high altitudes by the downwind path followed by volcanic ash plumes.
- Establishing geologically recent decreases in the distribution of permafrost by determining the areal



distribution of young geomorphic features that indicate its former existence.

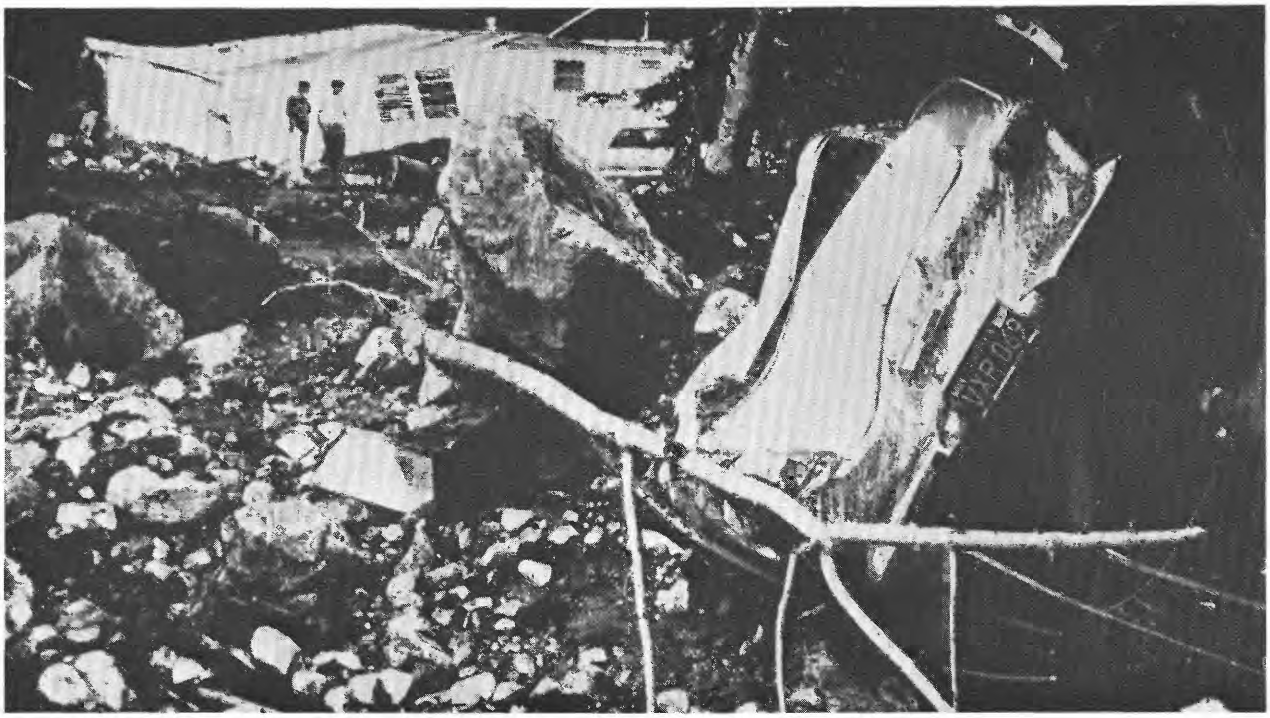
- Using geomorphological techniques of reconstructing past environments by study of the preserved landforms such as glacial moraines, lake shorelines, abandoned river channels, and inactive sand dunes.
- Collaborating with archaeological investigations.
- Determining chronological variations in the stable isotope composition of old glacier ice, lake deposits, or tree rings to reconstruct past changes in the climatically determined isotopic ratios of the precipitation.

Examples of such studies:

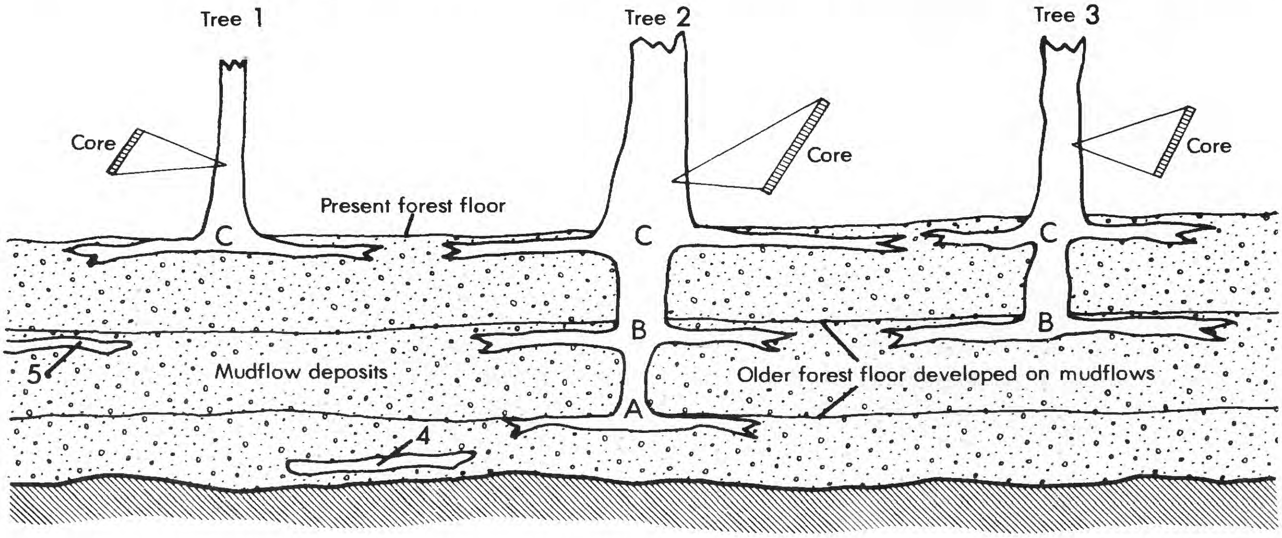
● The technique of repeat photography affords one of the best methods for recording historic changes in erosional features, in lake and stream configuration, and in vegetation. For example, approximately 200 photographs taken in Utah and Arizona between 1869 and 1937 have been studied and the sites re-photographed. Among the results are indications that the widespread dying of oaks now occurring in Arizona is a phenomenon that began only after 1935, and that some parts of Utah are undergoing an invasion by junipers while the more arid western mountains of the state are not. Other plant population changes that are documented involve burroweed, jumping cholla, velvet mesquite, saguaro, and several grasses. Rainfall change is strongly implicated as a force in producing vegetation changes at many sites. The recent photographs will also provide a future basis for judging alteration in the landscape—an especially important consideration where the rate of environmental modification is increasing in response to man-induced changes in weather or climate.

● Height-growth studies of certain desert plants may be used to extend rainfall and runoff records beyond the historic period for which these values are available. Among columnar desert plants, such as the saguaro, there is a close relationship between height

The South Cascade Glacier, in the North Cascades, Washington, is the main site for glaciological research by the Geological Survey. This glacier is about 3 km long and ranges from 1610 to 2100 m in altitude. Studies using carbon-14, tree rings, and lichens indicate that it grew from a small glacier to its present size about 5,000 years ago. Its largest extent was reached during the 16th century in response to an average increase of snow accumulation (or decrease of melting) of 0.9 m more than today. Continuing studies show, however, that this is small compared to recent year-to-year fluctuations. Photograph by Austin Post.



From mid-October 1972 through mid-February 1973, mudflows from the rugged Santa Lucia Range repeatedly invaded the community of Big Sur, Calif. The flows were generated by intense winter rains falling on steep slopes that had been denuded by fire in August 1972. Damage from mudflows and floodwater occurred in areas marginal to the lower courses of three creeks where California State Highway 1 was blocked by mud; structures and automobiles were heavily damaged, as shown in the photograph by R. W. Kopf, and one life was lost. The only other historic mudflows in these basins occurred during the winters of 1908-10 after a 1907 forest fire. However, during the prehistoric period 1370-1800, at least three periods of mudflow activity occurred on the average of once every 140 years. These are documented by the ages of successive root systems of redwood trees that developed higher on the tree after the previous root system was buried by mud. As illustrated by the diagram, cores were taken from trees 1, 2, and 3, and the rings counted to determine the minimum ages of the trees. For tree 1 (only one root horizon), this dated the top mudflow; for trees 2 and 3, ring counting dated the minimum ages of lowest (original) root systems. Division of the number of root horizons into this minimum age gave a minimum recurrence interval of mudflows. Carbon-14 dates of wood fragments 4 and 5 indicate the maximum ages of those flows.



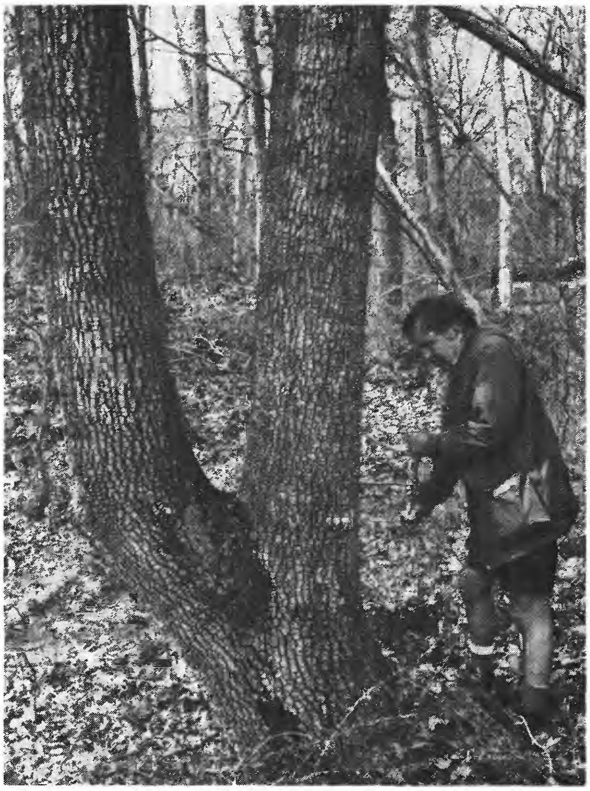
and age. The seedling establishment of these plants fluctuates in response to shifts in the climate in which they grow, and curves representing the age composition of plant populations can be used to identify those times when conditions favoring plant establishment existed. Our knowledge of climatic fluctuation in the desert has been extended back about 200 years by study of old plant communities. Other desert plants, not known in the United States but common in Baja California, are slower growing and longer lived, and future work with these plants as subjects may reconstruct the desert climate through the past four centuries.

● Pollen and macrofossil analyses of a swamp in the Sierra Nevada and a landslide pond on the San Francisco Peninsula, complemented by radiocarbon age determinations, suggest that conditions in central California were cooler and perhaps more moist between 350 B.C. and 0 A.D. and between 650 A.D. and 900 A.D. than at present. The Sierra Nevada swamp has also yielded a drowned tree stump that suggests that there was a century-long drought about a thousand years ago.

● Reconstruction of climatic events can be derived from studies of the ages of trees growing on land surfaces that were established during climate-related events. Trees of the same species as in the surrounding forests may start to grow within 2 to 5 years after a new deposit becomes physically stable. Young alluvial, terrace, glacial, and landslide deposits are therefore accurately dated by sampling a large number of trees growing on them, with the oldest trees indicating a close minimum age of that surface.

● Clues to the relative hydrologic regimes that prevailed in the southwestern states during each of the last 20 centuries come from tree rings, fossil pollen, stratigraphic relations, sediment character, soil development, and archaeological evidence. Studies of these types of evidence suggest that four regional hydrologic cycles of about the same duration affected this area. Long periods of drought are expressed by many discontinuities in alluvial chronologies, soils, sediment structures and sizes indicative of intermittent stream flow, high percentages of pollen from arid floras, and archaeological discontinuities in cultural styles. Moist cycles are indicated by fewer stratigraphic breaks in the alluvium, sediment structures and sizes that result from continuous stream flows, lower percentages of pollen from arid floras, and cultural continuity. Shorter term climatic cycles are indicated by variations in the numbers of minor stratigraphic breaks and in the widths of tree rings. The past record of continuing change makes it untenable to assume the indefinite persistence of this century's range of climatic and hydrologic fluctuations. Eventual climatic changes of the magnitudes recorded in the past must be considered in long-range planning for the future.

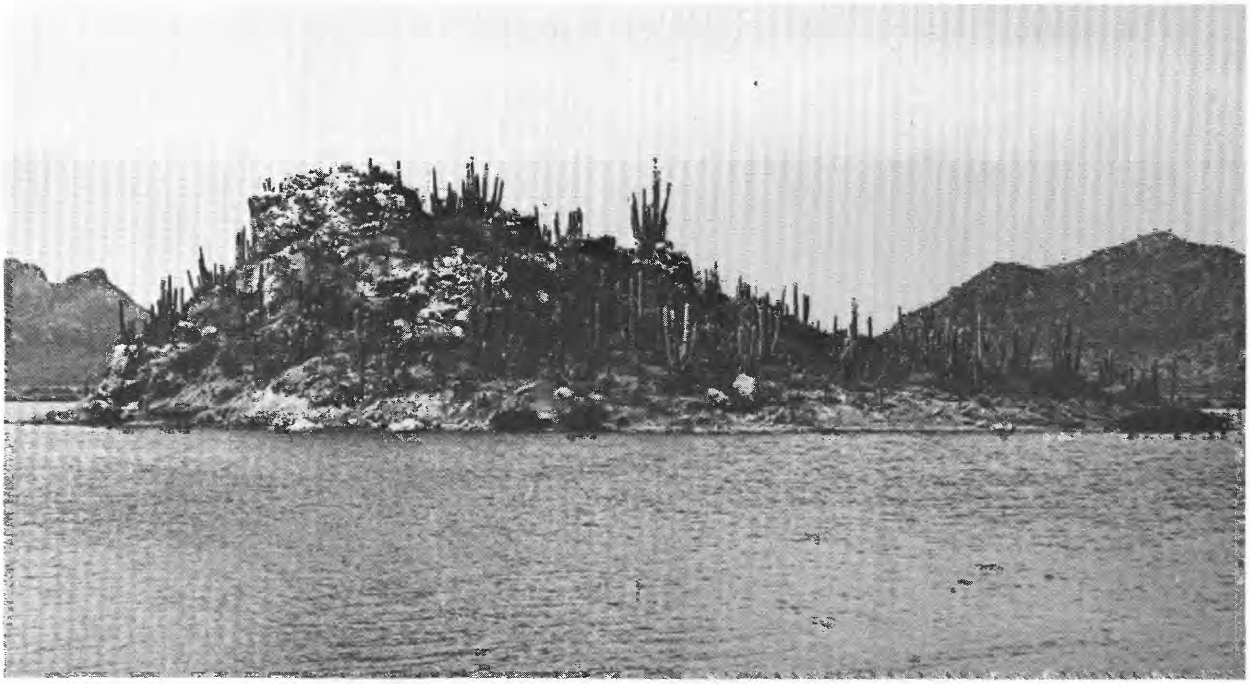
● Studies in the Black Mesa region, Arizona, show that juniper and pinyon forests buried by alluvium of various ages have ring patterns that are cross-datable with established dendrochronological records. These allow accurate dating of episodes of alluvial deposition and nondeposition, and the striking synchroneity of such events throughout the region probably means that climatically induced hydrologic changes were the primary controls. The overall record suggests a primary 500-600 year hydrologic cycle with periods of predominant alluvial deposition caused by relatively moist climates, alternating with periods of nondeposition, erosion, and soil formation caused by



Along many river in the eastern United States, mature trees survive on surfaces flooded more than once a year, but low flow must prevail for several years for seedlings to grow sufficiently to survive even minor floods. Clustered ages of mature trees thus date long periods of low flow, a condition commonly associated with drought. Floods are dated precisely by determining the ages of trees that have continued to grow since they were damaged by these floods. The bark on flood-plain trees often is damaged during floods by floating debris or ice; this leaves a scar within the upstream side of the trunk that preserves a record of the age, river level, and sometimes even the season of that event for the life of the tree. The inclined segment of the lower left trunk shown in this photograph is all that remains of the original tree which was felled (but not killed) by an extreme flood of the Potomac River in 1889. After the flood, the two vertical trunks started to grow. The age of the vertical trunk--and the flood--is determined by counting rings in a core taken with a borer as shown here.

one or two centuries of predominant drought that coincided with the most rapid changes in prehistoric cultures. If the modern arroyo cutting episode that began after the 1850's throughout the southwest represents a drought similar to those associated with the past 500-600 year hydrologic cycles, the present drought should terminate and reverse itself near the beginning of the 21st century. A more specific estimate, based on pattern matching of the higher frequency tree-ring record and the longer term geologic and hydrologic records, predicts that the current major drought interval in the Southwest will culminate around 1990 and that an initial return to wetter conditions will follow within 50 years!

- Examination of the annual growth rings in pinyon pine and juniper roots in the Piceance Creek area of Colorado indicate that erosion rates have varied over the last 800 years, presumably in response to climatic change. The minimum rates of erosion are indicated by the height of the once-buried roots of known ages above the present ground surface. Average calculated erosion rates are mostly near 0.5 mm/yr. Preliminary analysis suggests that 200-300 years ago, erosion rates were higher than at any other 100-year interval during the last 800 years.
- Alluvial deposits having structures indicative of fast-flowing streams are found along the east side of the Rocky Mountains in Colorado. Most are of the same age as the Pleistocene glaciations that occurred at higher elevations in the mountains, but some are younger. One extensive unit, whose structures are indicative of fast-flowing streams and thus a moist climate, was deposited between 4,500 and 1,500 years ago. In prairie areas to the east, the climate cooled and effective moisture increased during the same period; the evidence for this consists of stratigraphic sequences that show where bogs formed over sand dunes and fossil pollen sequences that show where forests replaced prairies.
- Sediments that have accumulated during the past several hundred years



Dramatic changes in the vegetation of southwestern North America during historic time may be related, at least partly, to changes in climate, although the effects of grazing cattle and the other activities of man are difficult to separate from purely climatic effects. These two photographs, taken in 1903 (upper photograph) and 1961, are of one of the ungrazed Melisas Islands in the bay at Guaymas, Sonora, Mexico. The giant cactus, Pachycereus pringlei, has greatly increased in number during the 58-year period, and this increase serves as a basis for comparing vegetation changes in nearby grazed areas. Photographs by D. T. MacDougal (1903) and J. R. Hastings (1961).

in the shallow marine waters south of Texas contain thin sand layers that probably were deposited during and after hurricanes. These sand layers are dated by use of lead- and uranium-isotope techniques, and their distribution is a probable indicator of hurricane frequencies in the past. Hurricane formation is directly related to sea surface temperatures which must approach or exceed about 30 degrees (C) for periods of weeks or months each year to permit strong cyclonic circulation to develop in tropical areas.

- Repeated measurements of temperature profiles in holes drilled in permafrost allow the reconstruction of changes in mean ground surface temperatures over the last century or more. Near Barrow, Alaska, for example, measurements of this type show that ground temperatures rose about 3 degrees (C) between the mid-1800's and mid-1900's. In general, historical weather records in such remote places are inadequate for the detection of such changes, and many areas suitable for measurements of this type are not represented by historical records of any sort.

III. LONG-TERM CHANGES IN CLIMATE

Studies of long-term changes in climate include the larger amplitude changes that produced the Pleistocene ice ages, as well as the climates that preceded and followed them. These studies document the magnitudes, frequencies, durations, and rates of climatic change. They also allow investigation of the possible synchroneity of globally documented climate changes, of similarities in the characteristics of past changes, and of rates of change. In addition, these studies document the limits of variation that have been allowed by the physical properties of the earth's atmosphere.

Projects now active in the Geological Survey that produce information on climates and changes in climate in the geologic past mostly use the following approaches:

- Collection and interpretation of dated stratigraphic evidence of past changes in sedimentation resulting from changes of climatically responsive continental surface processes; both exposed and buried stratigraphies are used. These studies are primarily concerned with deposits or erosion indicative of past glaciers, ground ice, lakes, running water, and wind.
- Collection and interpretation of sediment cores from continental shelf and deep-sea areas. These studies are concerned with both nearby continental climatic events, as expressed by variations in the sizes and compositions of locally derived clastic fragments, and global climatic events as indicated by criteria that record worldwide changes in the oceans.
- Study of stratigraphically controlled and age-controlled sequences of sediments that contain fossils that can be related to existing biota and the climates that support them.
- Measurement on steep mountains and at all latitudes of the differences between the present and past elevation and latitude limits of climate-sensitive geological processes and biological communities.
- Study of the present and past distributions of landforms that develop in climatically distinctive environments; examples are U-shaped valleys and cirques carved by glaciers, patterned ground and other structures produced by frost action, extinct lake shorelines, streamless valleys, stream and coastal terraces, sand dunes, and wind-eroded landforms.

- Identification of periods characterized by climates that resulted in erosion, nondeposition, or soil formation.
- Measurement of variations in the stable-isotope composition of dated samples of ice in glaciers and permafrost, organic remains, ground water, stalacites, and saline and other minerals that reflect the isotopic composition of the locally precipitated waters.
- Correlating major volcanic eruptions, as evidenced by globally widespread volcanic ash layers, with the other geologic records that indicate changes or aberrations in climate.

Examples:

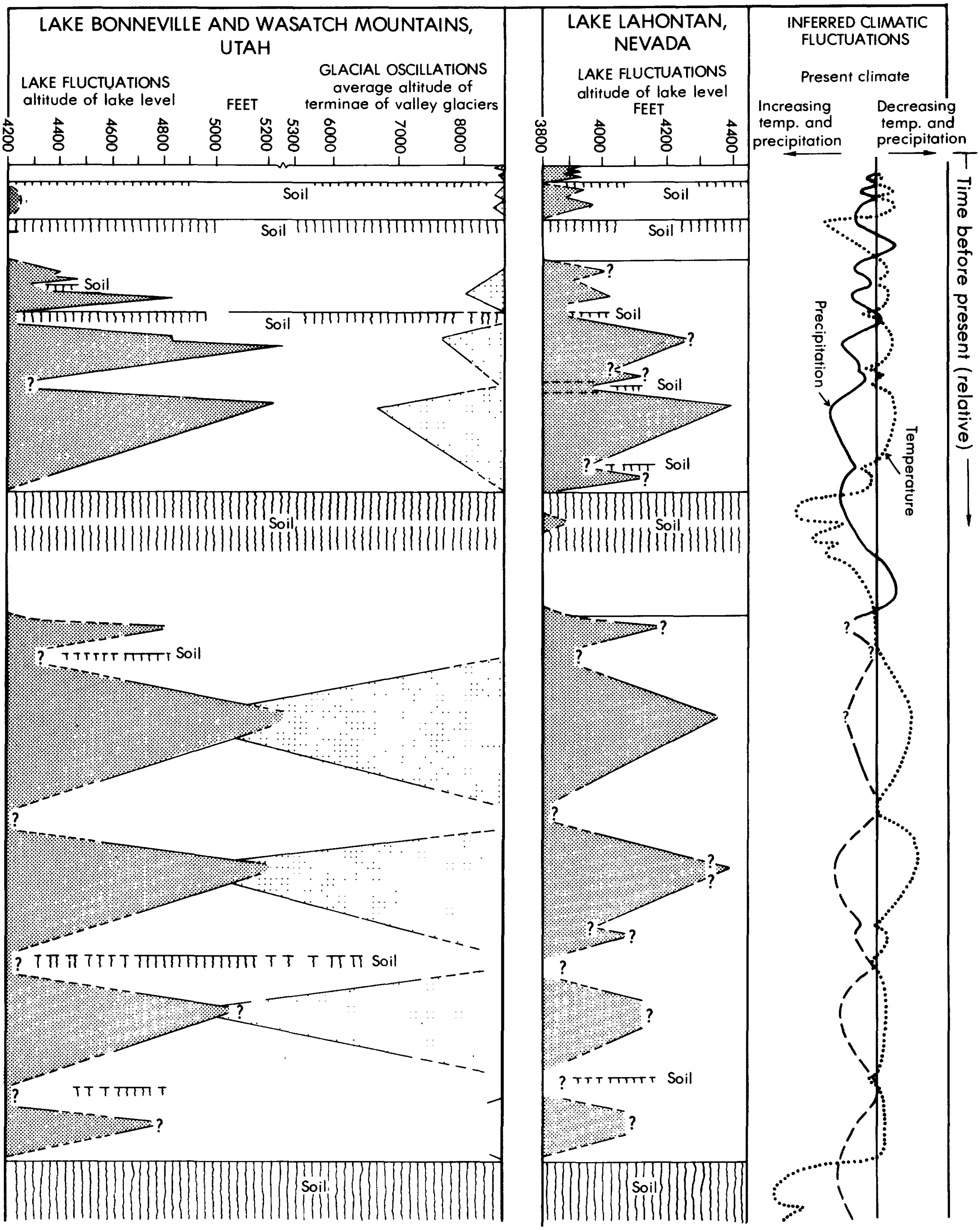
● A temperate climate prevailed in Alaska, northeastern Siberia, and the intervening continental shelves—collectively called Beringia—until shortly before the beginning of the Pleistocene Epoch, although earlier glaciation began in the mountains of Alaska and probably in the Siberian mountains of Kamchatka and the Koryak region 10 million years ago. The oldest recorded effects of severe frost action in lowland areas are in sedimentary rocks that are 2 million years old, and the earliest known evidence of permafrost in these areas is in deposits about 1 million years old. Forest vegetation probably covered most of Beringia throughout Pliocene time; tundra did not appear there until near the beginning of Pleistocene time although it seems to have emerged several million years earlier at latitude 80 degrees N in the Arctic Islands of Canada. The Arctic Ocean was ice-free and the water well mixed until shortly before the beginning of the Pleistocene Epoch. The present stratified and ice-covered regime of this area seems to have originated about 2.2 million years ago.

● Fossilized remains of sea otters in marine deposits of the Barrow area, Alaska, indicate a high sea-level stand, probably the one that occurred during the last interglacial period. Sea otters are strictly limited by the southern extent of winter sea ice, and the fossils indicate that winter ice did not cover all of the Arctic Ocean during the interglacial period. Warmer water mollusks associated with these vertebrate fossils corroborate the conclusion.

● Sequences of glacial deposits, outwash, and alluvium along the south flank of the Brooks Range and the coastal mountains of Alaska reveal a long history of glacier fluctuation dating back at least to middle Pleistocene time. These deposits commonly also contain abundant organic material which allows events of the last 40,000 years to be dated quite accurately by carbon-14 methods. Much of the organic material can be identified in terms of species, and this allows the climatically sensitive biological communities that coexisted in the area at that time, composed of such elements as plants, insects, mammals, and mollusks, to be reconstructed.

● Studies of altitudes of cirque floors in the Kigluaik Mountains, Alaska, indicate that the regional snowline was at least 75 m lower than the present snowline during a late prehistoric glacial advance, 150 m lower during an earlier Holocene glacial advance, and 300 m lower during the last glacial maximum. Similar studies in the Indian Mountains, Alaska, indicate that the snowline was at least 450 m lower at the time of the last maximum glaciation. These data suggest that relative to the present, mean annual temperatures lowered by no more than 2 degrees (C) in the Kigluaik Mountains and 3 degrees (C) in the Indian Mountains during the most extreme glacial times.

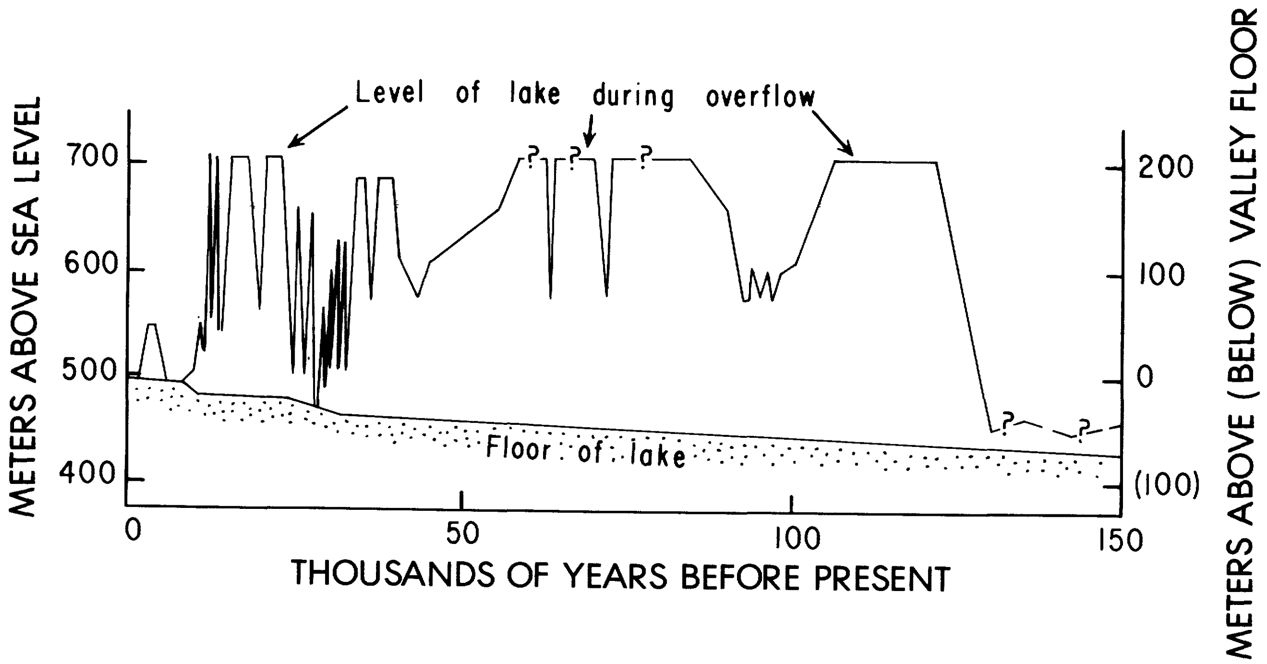
● Each of the five major river valleys in the Cascade Range that drain the slopes of Mount Rainier contains deposits formed during multiple glaciations. A glaciation that probably occurred more than 600,000 years ago produced an icecap that mantled much of the Cascade Range, and valley glaciers



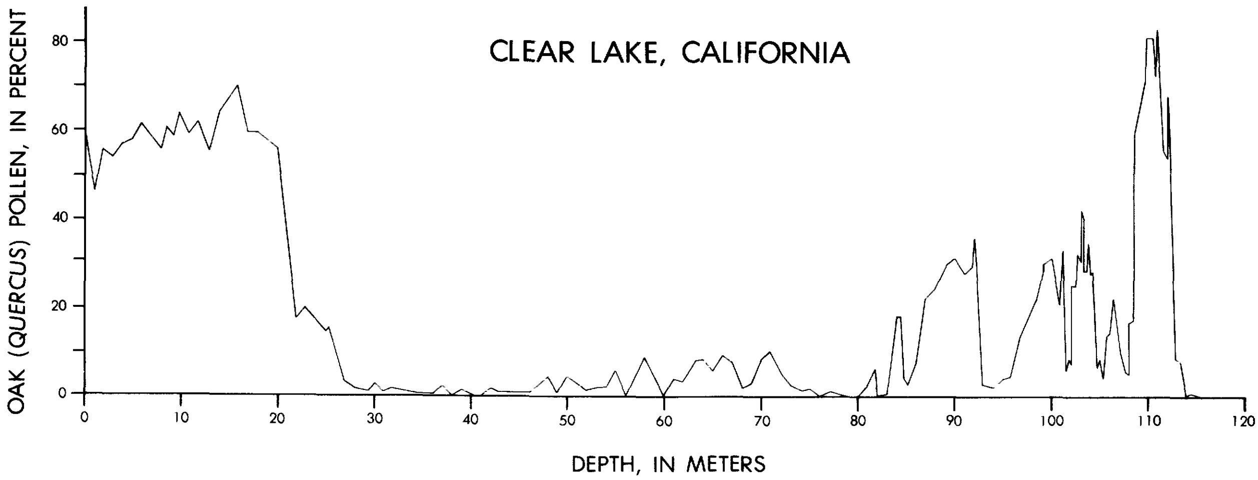
The levels of two large lakes in the Great Basin during the last part of the Pleistocene changed at the same times as did the lengths of mountain glaciers in the range east of one of them. Increases in the depth of the lakes and lengths of the glaciers indicate times having "pluvial" (wetter than at present) climates, and reversals indicate periods having climates more like the present. Soils mark times of stable land surfaces when weathering of exposed glacial and lake deposits--a slow process--could develop without the soils being buried by new deposits or eroded and destroyed.

reached lengths of as much as 120 km. Icecaps and valley glaciers as long as 105 km again formed in the region during two distinct later episodes. During the last major glaciation, the valley glaciers were only 25 to 65 km long, and as they were retreating upvalley during a late phase of this episode, rigorous climatic conditions caused them to expand again briefly before retreating and nearly disappearing. Glacier development occurred again between 4,500 and 2,500 years ago, and during most of the time between the early 17th and late 19th century, they were larger than at present.

- Lassen Volcanic National Park, California, was mostly covered by an icecap glacier during much of the last ice age and at least once before that time. Glacial deposits surround Lassen Peak, but Lassen Peak itself, a volcanic dome that formed about 11,000 years ago, has deposits only from the small glaciers that formed later. The altitudinal distribution of glaciers that existed before and after the creation of Lassen Peak suggests that the regional snowline during the earlier glaciation was near 2100 m and near 2500 m during the later one. These elevation differences indicate that mean annual temperatures during these two glacial episodes differed by about 2 degrees (C).
- Valley glaciers in the Front Range, Colorado, advanced to their maximum extents about 21,000 years ago, began to wane 14,500 to 13,000 years ago, and disappeared about 8,000 years ago. Carbon-14 dates on the organic materials first deposited in the lakes, bogs, and kettle ponds (depressions caused by the melting of large blocks of buried glacier ice) that formed at the edges of retreating glaciers, give minimum ages of deglaciation. The composition of the overlying sediments, and the plant remains in them, show that complete revegetation of the glaciated areas



The level of Searles Lake in California fluctuated during the last 150,000 years in response to climate changes. The wet (pluvial) interval between 130,000 and 32,000 years, when the lake stood mostly at high levels, is correlated with the glacial advances in northeastern North America known as early Wisconsin. The similar interval 24,000 to 10,500 years ago, correlated with the late Wisconsin glaciation, saw the lake expand and then contract at least five times. During the last 1,500 years of this period, six changes from one extreme to the other occurred, allowing 250 years or less for each climatic reversal.

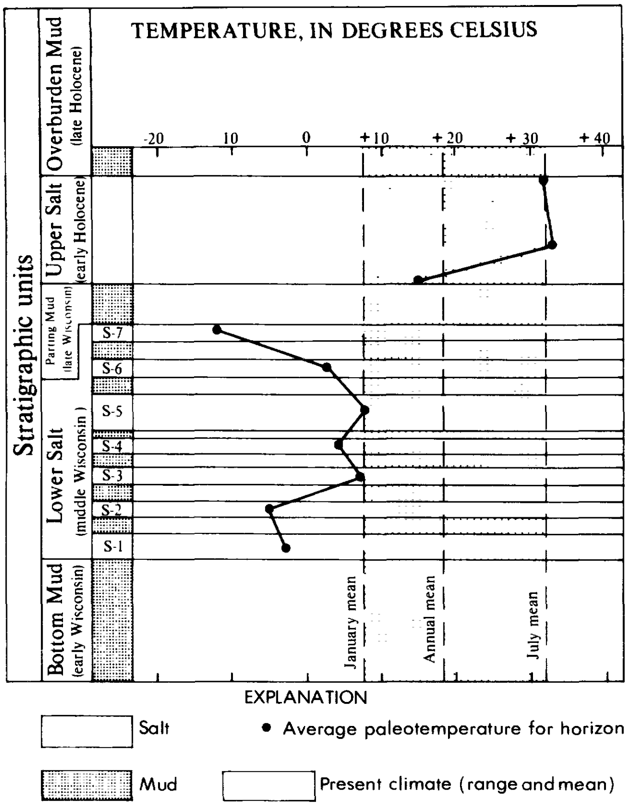


The varying percentages of fossil pollen in cores taken from the bottom of Clear Lake, Calif. indicate changes in the ratios of plant types along the shores and in the surrounding mountains as the lake mud was being deposited. This diagram shows the changes in the percentage of oak pollen in the upper 115 m of one core. Oak, which is now a common tree in the area, dominates the fossil pollen remains in the upper 20 m of core and in parts of the lower 35 m; pine pollen replaces oak in most of the intervening zone. These changes in forest type, caused by climate change, apparently occurred during transitions from glacial to interglacial periods. The change near 20 m probably took place about 10,000 years ago, the changes below 80 m probably reflect the last interglacial.

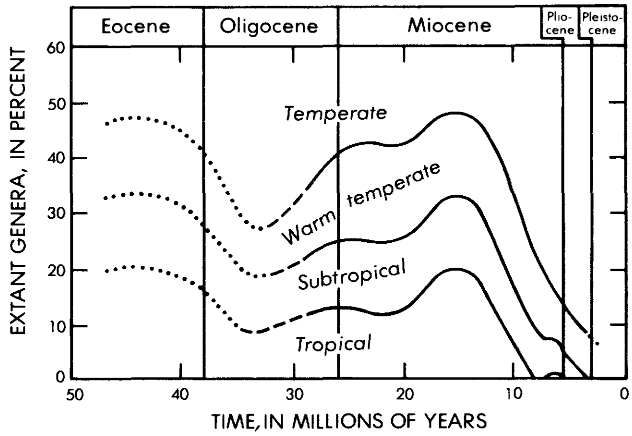
commonly occurred at least 3,000 to 4,000 years after the ice disappeared. (Land surfaces that have been glaciated are analogous in many ways to surfaces that have been bulldozed, and the time required for natural processes to develop soils and restore vegetation to its normal state in similar areas would presumably be comparable.)

- The past expansions of mountain glaciers commonly required increases in the amount of regional snowfall and annual meltwater runoff. For example, a Pleistocene glacier in northern Yellowstone National Park covered about 3,400 km^2, averaged 700 m in thickness, and had a maximum flow line 150 km long. Comparison of this reconstructed glacier with those of modern glaciers in analogous climatic environments leads to the conclusion that there was an annual flow of about 3 km^3 of ice from the glacier accumulation area to its ablation area where an equal amount melted. The present drainage from the land area that used to be covered by glacier ice is about 1.5 km^3/yr. During glacial times, therefore, the amount of meltwater flowing from the glacier was about twice the amount of water now draining from the same area.
- Pleistocene lake deposits exposed near Clear Lake, California contain fossil cones of the foxtail pine, a subalpine species now found growing in colder areas, and fossil pollen that show that the deposits represent a glacial period. The present distribution of vegetational types represented by these fossils suggest that mean annual temperatures in the Clear Lake area during that glacial stage were about 7 degrees (C) lower than now and that precipitation was slightly higher than now.
- Much of the suburban development on the peninsula south of San Francisco is built on stream deposits about 20,000 years old. When these deposits were formed, sea level was much lower than now, and San Francisco Bay was a large alluviating valley that drained through the Golden Gate to form a large delta to the west. In the southern bay area, fossil ground squirrels of a type now known to live only north of California and in the northernmost Sierra Nevada have been found in these ancient river

deposits, along with fossils of extinct mammoth, ground sloth, and camel. This squirrel is known to be limited to cooler climates and to areas of summer green grass, suggesting the absence of the present Mediterranean climate in the bay area during that part of Pleistocene time and the more common occurrence of summer rain. Associated wood, pollen, freshwater mollusks, and fish also



Crystallization temperatures have been estimated for salt layers beneath the surface of Searles Lake, Calif., using mineral assemblages and deuterium/hydrogen ratios. Seven salt layers that were deposited during short periods of aridity in the Middle Wisconsin interpluvial period (estimated to have extended from 32,500 to 24,000 carbon-14 years ago) are separated by six layers of mud that represent deeper lakes and less arid periods that lasted as long as 3,000 years. The reconstructed depositional temperatures indicate a distinct trend, with the arid periods near the middle of this interval being the warmest and those at the beginning and end of this time being the coldest. During Middle Wisconsin time, therefore, the local climate fluctuated every few thousand years between aridity and nonaridity, yet a trend of gradual warming followed by gradual cooling was superimposed on these shorter period fluctuations.



Changes in the percentage of marine fossils indicate coastal water temperatures during most of Tertiary time in the vicinity of the present San Joaquin Valley, Calif. Water temperatures both reflect and influence local atomospheric temperatures. During the Eocene, for example, about 20 percent of the mollusks were of types most closely related to forms now living in tropical waters, and smaller percentages were of types related to subtropical and warm temperate forms; by the end of Pliocene time, these percentages had shrunk to near zero and temperate forms had replaced them as shallow sea temperatures in this part of the world lowered in response to the growing ice sheets nearer the poles.

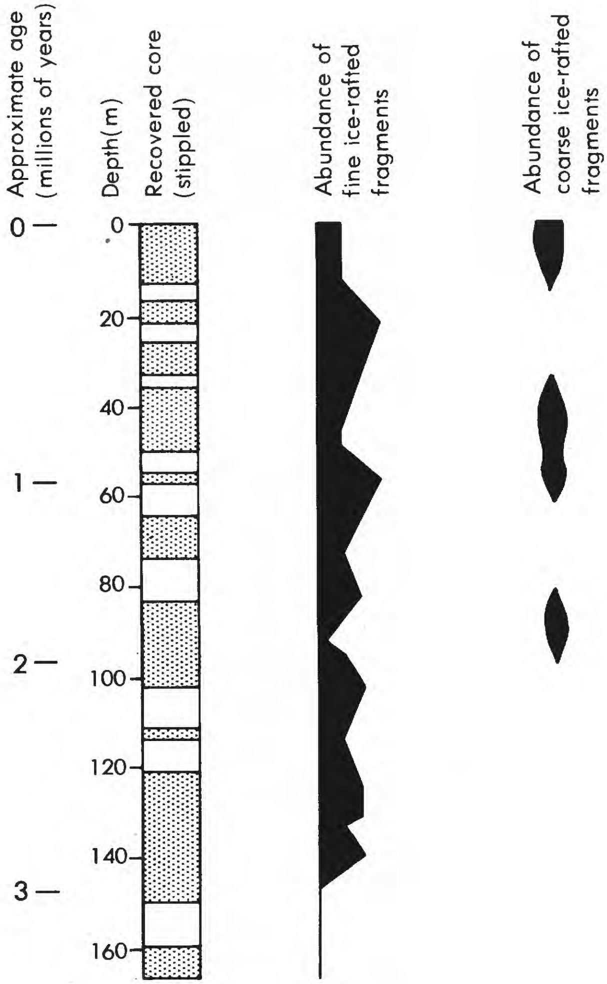
indicate much cooler and moister climates.

- The latest Tertiary and the Quaternary nonmarine alluvial and lake deposits of the eastern San Joaquin Valley of California record a long history of cyclical deposition, land stability with soil formation, and erosion. Fifteen episodes of terrace and alluvial fan aggradation have been identified, most of which can be related to climatic oscillations. The sequence of sediments can be correlated indirectly with glacial events in the adjacent Sierra Nevada. Radiometric ages from the San Joaquin Valley sequence show that lakes formed in the basin at the same time that fans were growing as a result of climates conducive to glacial expansion. At least eight major lacustrine units have been identified; four of them are younger than 600,000 years, and the youngest, dated by carbon-14 methods, was deposited between 27,000 and 9,000 years ago.

● Fluctuations in the oxygen-18 and carbon-13 content of ground waters in the southern Great Basin are recorded in a swarm of calcite veins in the Death Valley region. Veins ranging in age from 1.0 to 1.8 million years have been dated using uranium-234/uranium-238 techniques. Hydrogeologic field relations indicate that these veins are low-temperature ground-water deposits that were precipitated under closed-system conditions by ground waters of nearly constant chemical composition. The results provide a record of large-amplitude low-frequency fluctuations in oxygen-18 in these waters that can be related to long-period climatic oscillations of the southern Great Basin.

● During pluvial (wet) periods of the Pleistocene, the climates in south-central Asia and North America appear to have produced comparable increases in streamflow. Wind-eroded lake beds in the Seistan Basin of southwestern Afghanistan and adjacent parts of Iran and Pakistan, observed by a Survey scientist while on a technical aid mission, indicate an early or middle Pleistocene lake as large as 65,000 square kilometers. The inflow needed to offset Pleistocene evaporation from the lake is estimated at seven to nine times the flow of present rivers. These values are similar to the late Pleistocene streamflow calculated for the Owens River, California, where the latitude and the topographic and hydrographic settings are similar.

● The growth of continental ice sheets during Pleistocene time caused sea-level fluctuations that are recorded in the regional stratigraphic relations of shallow marine sediments. The continental shelf off south Texas is a slowly subsiding area with a high rate of sedimentation that favors the preservation of surf-planed terraces, river channels, and other indications of lowered sea levels. High-resolution seismic profiles from this area provide a record of sea-level changes caused by the waxing and waning of polar ice sheets. Four regional unconformities, dating back approximately 130,000 years, represent erosion when sea level



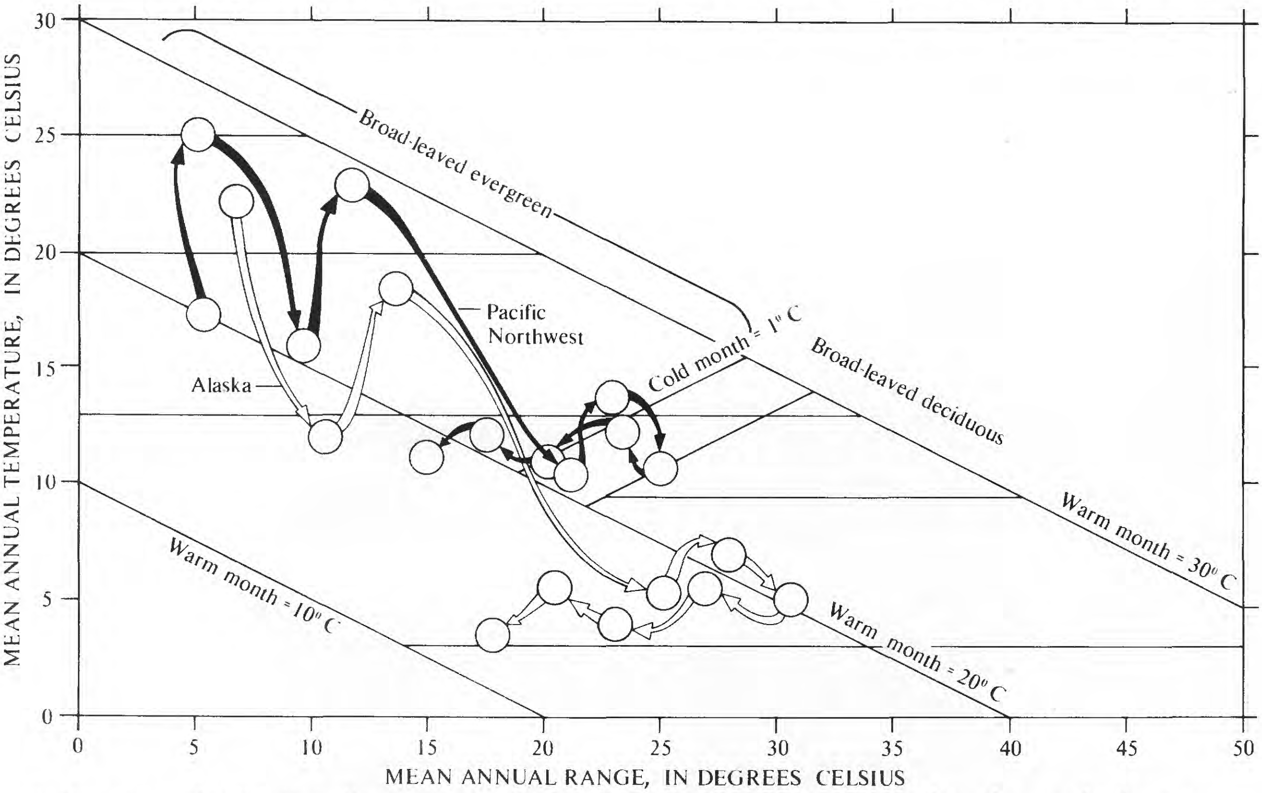
Cores taken from the sea floor by the Ship DSDP Glomar Challenger provide a nearly continuous record of sedimentation for long periods of time. The upper 150 m of this core from the North Atlantic (DSDP Site 410, lat 45 degrees N, long 30 degrees W), studied by Survey scientists, contains sand-size mineral grains (larger than 0.06 mm) that are interpreted as material that fell to the sea floor from icebergs as they melted. The abrupt beginning of this material at a level dated by fossils and paleomagnetic techniques as about 3 million years old is interpreted to mean that the polar ice sheets, which had been enlarging for several million years but chiefly at high elevations, finally expanded into areas that were at sea level. When they reached the coast, large blocks of them calved into the sea to produce icebergs. The larger glacier fragments in sediments younger than about 2 million years may mean more abundant bergs or more intense erosion by the glaciers before reaching the sea.

The striking landforms shown in this photograph are evidence of large lakes that existed in Searles Valley, Calif., during Pleistocene time. The towers, mostly 15 to 25 m high, are composed of calcium carbonate deposited by algae that lived in the upper few meters of the lake waters. The white salt flat visible several kilometers beyond the towers is the remnant of the last enlarged lake, a result of the more arid climate that now prevails.

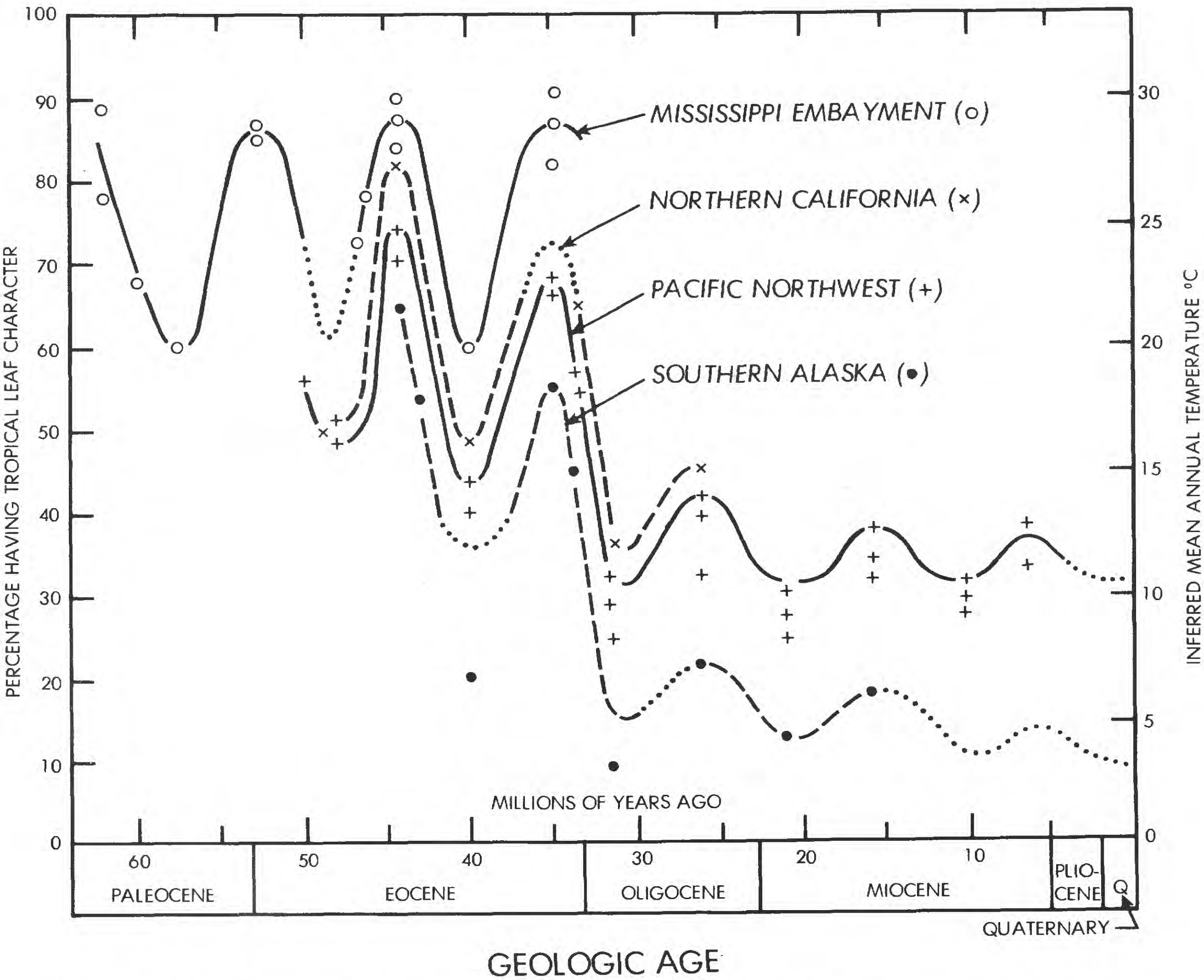
lowered. The sediments above the oldest unconformity represent the rising of sea level after the climax of the preceding glacial event, eventually reaching a sea level comparable to today. Deposits from the next transgression indicate a less complete glacial recession. The youngest sediments represent deposition since the last interglacial, about 30,000 years ago.

IV. AREAL DISTRIBUTIONS OF PAST CLIMATES

Studies of the distributions of



Evidence from fossil leaves allows reconstruction of the progression of climates that characterized areas during the Tertiary. For example, the mean temperature of the cold month determines the areas that support broad-leaved evergreen or broad-leaved deciduous trees. Other physical characteristics of the fossils allow subdivisions of these two forest types into categories that indicate the mean annual temperature, the annual range in monthly temperatures, and the approximate mean temperature of the warm month of the year. The arrows on this graph show how forest types, and therefore climates, of Alaska and the Pacific Northwest areas progressed from early Tertiary time to the present. The circles represent fossil leaf localities having known relative age relations but they are not separated by equal time intervals.

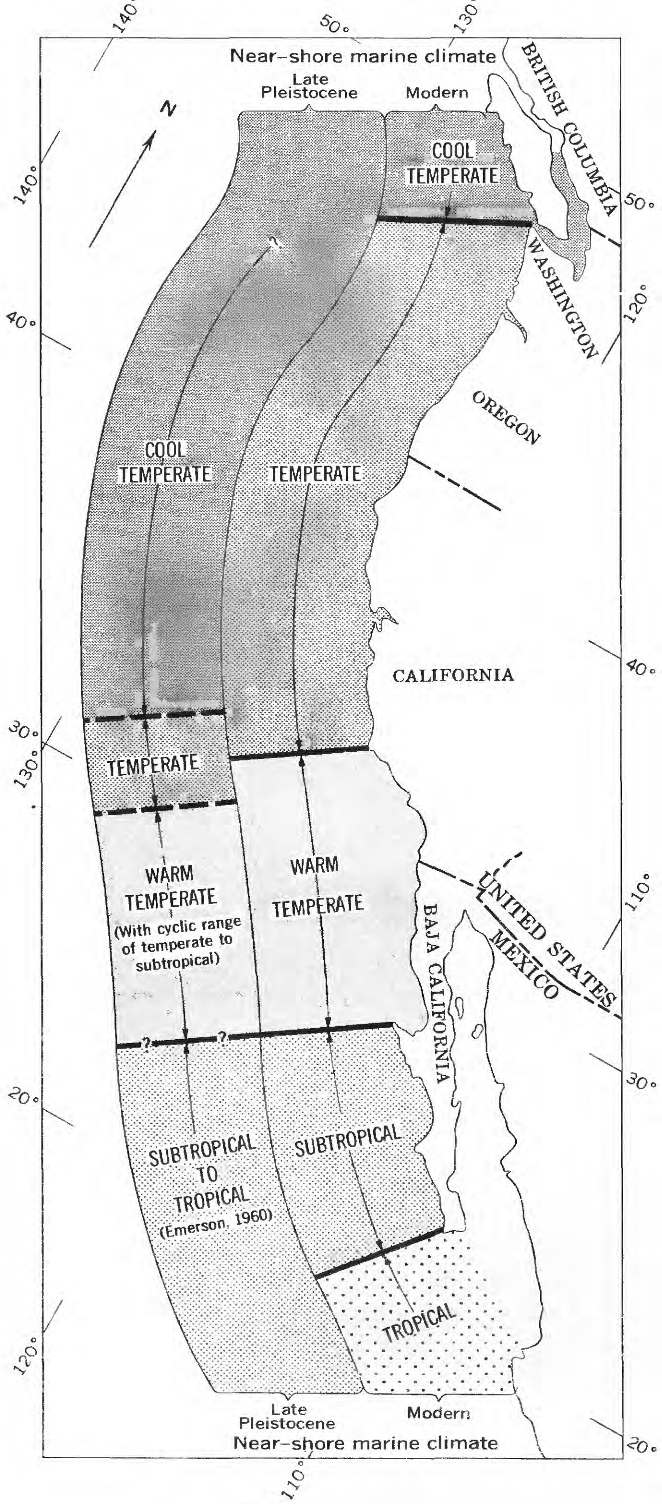


The shape of fossil leaves is a sensitive indicator of climate environment almost regardless of botanical classification. Changes in the percentages of fossil leaves having tropical characteristics show that climatic cycles about 10 million years long affected widely separated areas in early Tertiary time. Tropical climates existed in some middle-latitude areas during Paleocene and Eocene time, and a major cooling occurred during Oligocene time.

past climates not only allow comparisons of contemporaneous past climates in the two hemispheres, the several climatic belts, and the different continents, but also can show the degree of global synchroneity during climate change. This information contributes both to an understanding of how climate works and to ecologic reconstruction of regions that provide a perspective on possible future environments. In addition, this knowledge is essential to the correct reconstruction of areas favorable for prospecting for certain resources, such as evaporite minerals, coal, or oil shale whose deposition was made possible by favorable climates as well as geologic settings.

Examples of climatic synthesis made by Geological Survey personnel follow:

- Beringia—that is, Alaska, northeastern Siberia, and the intervening continental shelves—has played a strategic role in the evolution of northern climate and biota. Climatic fluctuations during the early part of the Wisconsin glaciation are poorly understood, but this cold cycle culminated in a period of extremely severe climate between 20,000 and 13,000 years ago that has been studied through a variety of geologic evidence. Glaciers covered the mountain ranges bordering the Pacific Ocean and southwestern Bering Sea, as well as large areas in the Brooks Range of Alaska and the mountains of Chukotka in Siberia. The climate of central and northern Beringia was strongly continental and very dry. Persistent barometric highs over the polar sea ice resulted in strong northeast winds in regions north of the Arctic Circle, and the ice fields of southern Alaska produced strong and persistent katabatic southwest winds in central Alaska. Tundra-steppe vegetation covered most of unglaciated Beringia. Forests persisted only in a few unglaciated enclaves in Kamchatka and possibly in an area on what is now the continental shelf near the modern Yukon River Delta.



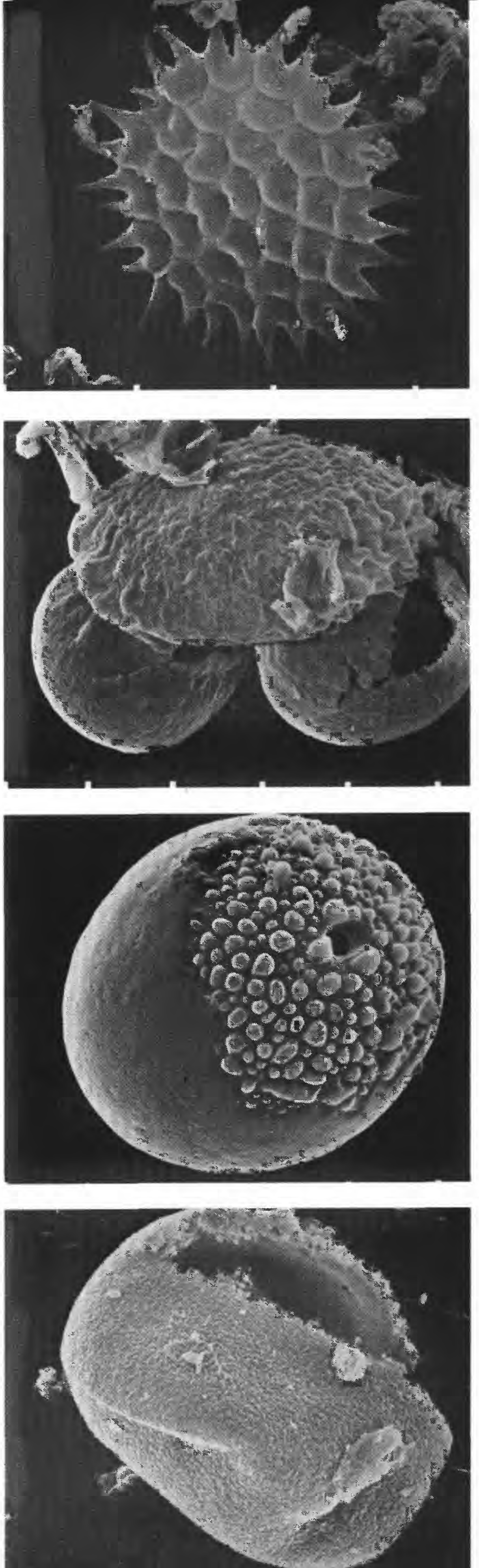
Comparisons of "marine climates"—near-shore water temperatures—during glacial periods of the late Pleistocene versus modern times are indicated by fossil and living mollusks along the northeastern Pacific Ocean. Not only did the boundaries of marine climate zones change but the widths of the zones changed. The greatest reduction in width was in the "temperate" zone during glacial periods. This may be because the upwelling waters along the presently "temperate" coastal areas come from the Gulf of Alaska, and they may have been substantially cooler during glacial periods because much larger glaciers existed along the south coast of Alaska at that time.

V. DATING AND CORRELATION METHODS

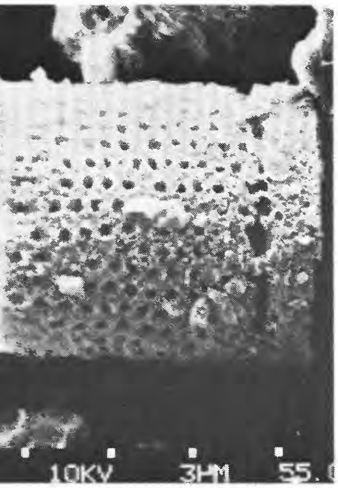
The value of the record indicating past changes in climate is greatest where the ages, rates, and durations of those changes are known. Some techniques provide absolute ages, others provide relative ages, and still others allow regional correlation of key strata. The main techniques available are listed in Part A of this Circular, though others can be applied where the geologic setting is favorable. The following are examples of some of the lesser known methods being studied or used by Survey personnel.

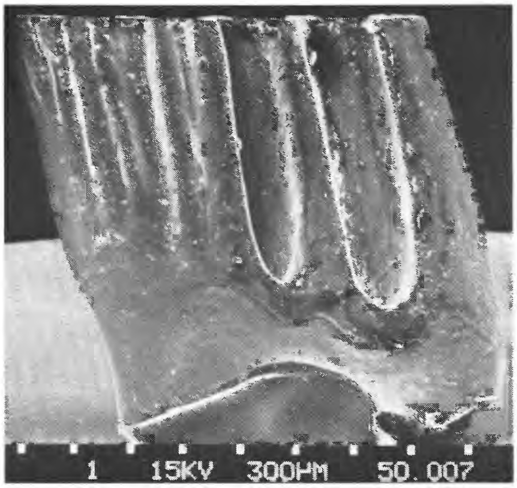
- Two experimental dating methods are being used in a study of faulted alluvial fan gravels north of the Idaho National Engineering Laboratory. One method is based on the amount of water that has diffused through the glass in volcanic ash fragments and collected in its cavities to date a volcanic ash that is interbedded with the gravels. The superhydration age of 250,000 years, is thought to be accurate within a factor of about two. The other method uses the stratified caliche rinds that coat the boulders in the soil that has developed on the fan surface. The technique depends on the growth of thorium-230 from uranium-234 to date the successive layers in caliche rinds. Uranium-series ages on the outer rind (the youngest), middle, and inner are 17,500+/-5,000, 67,000+/-10,000, and 133,000+/-30,000 years. Independent controls for evaluating the uranium-series dates come from the facts that the age of the youngest caliche layer is on the order of tens of thousands of years (because it is similar to rinds on nearby glacial outwash of this age), the fan material is probably a few hundred thousand years old (based on the age of the ash), and the caliche layers must increase in age inward.

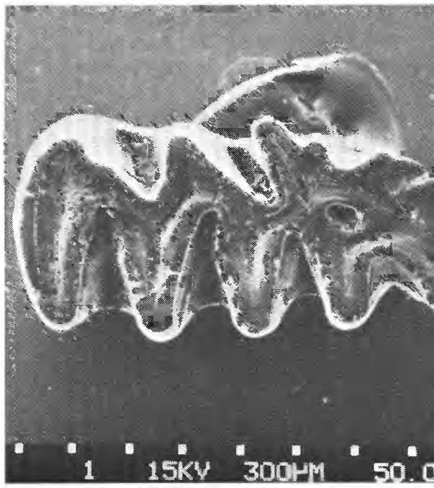
- Another experimental method of dating deposits consists of measuring the thickness of weathering rinds on rock fragments within the soil B-horizons. Climate and individual rock properties also affect weathering rind development, but the rind thicknesses indicate relative ages and very approximate estimates of absolute age. More than 6,300 measurements of the thickness of weathering rinds developed on andesitic and basaltic cobbles in Quaternary deposits at 70 sites in the western U.S. provide a means of



Fossil pollen found in a core from the mud at the bottom of Clear Lake, Calif. Photographs were made by scanning electron microscope, which enormously enlarges the image, thus allowing better identification and more detailed correlation between the deposits of this and other areas. Distances between white squares at base of pictures from top to bottom, are 0.03, 0.01, 0.003, and 0.01 mm. Top, an alga, Pediastrum; upper middle, a Pinus (pine) pollen grain; lower middle, a chrysomonad cyst; and bottom, a Brasenia (water lily) pollen grain. Upper three samples are about 3,000 to 4,000 years old, bottom is about 11,500 years old.







These scanning electron microscope photographs are of a fossil freshwater diatom and a fossil tooth from a mouse that were found together in a diatomite in northeastern California that underlies a basalt flow dated as 4.9+/-0.5 million years old. The picture on the left is of a diatom (Melosira sp. cf. M. islandica) that is a sensitive indicator of climate and is the most abundant species in the diatomite (the white squares at the base of the picture are 0.003 mm apart). Its modern counterparts are now most abundant in cool freshwater lakes such as the modern Great Lakes and Great Slave Lake of Canada. The presence of the ancestral form in rocks of this age documents a marked climatic cooling (and probably an increase in effective moisture) relative to conditions indicated by diatoms in somewhat older sediments in Northern California. Did this change in climate occur in other parts of the world? The two pictures on the right provide evidence that it did. They are side and top views of a tooth from a meadow mouse (white squares at base of these two pictures are 0.3 mm apart). This mouse (Mimomys (Cseria) sp.) is a member of a group known as the microtine rodents that was probably the most rapidly evolving, diversifying, and dispersing of the megascopic living organisms during most of the last 5 million years. Repeated waves of faunally distinct rodents left Asia and migrated rapidly to both North America and Europe, and their fossilized remains provide a means of correlating widely separated strata of continental sediments. The illustrated teeth are nearly identical to mice teeth found in Europe in deposits formed immediately after the end of the desiccation of the Mediterranean Sea, which also suggests a cooling or more humid climatic shift.

estimating the usefulness of this technique. The thickness of weathering rinds on fragments from the dated glacial sequence near West Yellowstone appears to be approximately a logarithmic function of age. Using the form of this function, calibrated using deposits known to be about 140,000 years old, the ages of glacial deposits in other nearby areas have been estimated. Their ages appear to fall into discrete intervals of time: 15,000 to 25,000 years, 30,000 to 45,000 years, 60,000 to 70,000 years, and near the calibration age of 140,000 years. These intervals correspond closely to those characterized by large global ice volumes according to the marine oxygen isotope record.

- Annual layers in lake sediments (varves), where they can be unambiguously identified, provide a powerful tool for precise time-series calibration and basin-wide correlation. Geochemical cycles that were probably climatically induced caused layering in many of the lake deposits of the Green River Formation of Eocene age, and investigations are underway aimed at developing a precise varve-calibrated time-series. It will provide terrestrial documentation of the magnitude and frequency of very short term climatic variation during the Eocene as well as allow exploration of the technique as an interbasin correlation method.
- Short-lived radioactive isotopes (lead-210 and radium-226) are being used experimentally to obtain ages of shallow marine sediments. Excess radioactive lead-210 is produced and accumulated in

the atmosphere and waters of the world because of a series of favorable nuclear and chemical properties of the elements in the uranium-238 radioactive family. The lead-210 isotope, with a half-life of 22.3 years, is formed from the decay of its radon-222 grandparent which diffuses into the atmosphere because of its properties as a noble gas. After lead is formed, it is precipitated into the hydrosphere and adsorbed on suspended sediment fragments that are eventually deposited. This scenario produces a constant flux of lead-210 in the accumulating sediments. By knowing the extent of disequilibrium at the time of sedimentation, the age of any horizon in the sediment column less than two hundred years old can be determined with a resolution of approximately one year in areas of rapid sedimentation (5 cm/yr). Radium-226 has a half-life of about 1,500 years and is useful for dating events up to 10,000 years old. It follows a geochemical cycle similar to that of lead-210; however, the element is more often associated with organisms, and sediments rich in organic remains are better suited for radium dating than is terrigenous material.

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This bibliography is by no means complete. The selections are limited to those published since 1964. Abstracts, open-file reports, theses, and articles in guidebooks published by local or informal organizations are not included. Most maps and reports that describe surficial deposits primarily for engineering or resource planning purposes are also omitted (even though they are of value in the reconstruction of past climates) as are most publications that consist primarily or systematically collected data on surface water flow and ground water levels (even though they provide the data base for many of the listed publications). Many papers that constitute significant contributions have undoubtedly been overlooked during compilation, and many studies in progress have to date been described only in the summaries of "Geological Survey Research" published annually by the Agency.

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CLIMATE VARIATION AND ITS EFFECTS ON OUR LAND AND WATER

Circular 776-A -- Earth Science in Climate Research

CONTENTS

Circular 776-C -- Geological Survey Climate Plan

CONTENTS

Names and bounding ages of geologic eras, periods, and epochs, and frequently used names of Quaternary stages.

Geologic time scale, complete

Era or Erathem	System or Period		Estimated ages of time boundaries, in millions of years ago
Cenozoic	Quaternary		2 - 3
Cenozoic	Tertiary		65
Mesozoic	Cretaceous		130
Mesozoic	Jurassic		180
Mesozoic	Triassic		225
Paleozoic	Permian		?280
Paleozoic	Carbon-iferous Systems	Pennsylvanian	310
Paleozoic	Carbon-iferous Systems	Mississippian	350
Paleozoic	Devonian		410
Paleozoic	Silurian		435
Paleozoic	Ordovician		480
Paleozoic	Cambrian		600
Proterozoic & Archeozoic	Precambrian		4500 ±

Cenozoic time scale

	Series or Epoch	Estimated ages of time boundaries, in millions of years ago
Quaternary	Holocene	0.01
Quaternary	Pleistocene	2 - 3
Tertiary	Pliocene	5.5
Tertiary	Miocene	26
Tertiary	Oligocene	38
Tertiary	Eocene	54
Tertiary	Paleocene	65

Quaternary stage names

Holo-cene	(interglacial)
Pleistocene	Wisconsin (glacial)
Pleistocene	Sangamon (interglacial)
Pleistocene	Illinoian (glacial)
Pleistocene	Yarmouth (interglacial)
Pleistocene	Kansan (glacial)
Pleistocene	Aftonian (interglacial)
Pleistocene	Nebraskan (glacial)