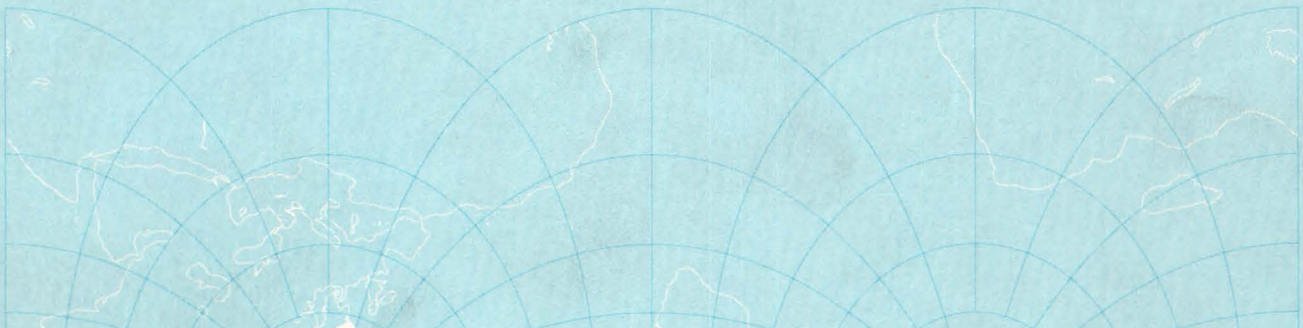
U.S. Geological Survey Polar Research Symposium—Abstracts with Program

GEOLOGICAL SURVEY CIRCULAR 911



In celebration of the 100th anniversary of the First International Polar Year, the 50th anniversary of the Second International Polar Year, and the 25th anniversary of the International Geophysical Year

The U.S. Geological Survey Polar Research Symposium celebrates the 100th and 50th anniversaries of the First and Second International Polar Years, respectively, and the 25th anniversary of the International Geophysical Year. The symposium is part of a series of worldwide activities that include lectures, symposia, and exhibits organized at the request of the International Council of Scientific Unions. The International Polar Years and especially the International Geophysical Year profoundly influenced the evolution of geophysics and served as models for international multidisciplinary cooperation in science.

U.S. Geological Survey Polar Research Symposium—Abstracts with Program

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In celebration of the 100th anniversary of the First International Polar Year, the 50th anniversary of the Second International Polar Year, and the 25th anniversary of the International Geophysical Year

October 12–14, 1983

United States Department of the Interior
JAMES G. WATT, *Secretary*

Geological Survey
Dallas L. Peck, *Director*

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U.S. GEOLOGICAL SURVEY POLAR RESEARCH SYMPOSIUM—ABSTRACTS WITH PROGRAM

INTRODUCTION

THE GEOLOGICAL SURVEY IN POLAR PERSPECTIVE

BY JOHN C. REED, SR.[1]

In 1958, legislation was passed that authorized the Survey to make studies in Antarctica. Before that time, so far as I know, only three men, two geologists and one topographic engineer, did Survey work in the Antarctic with authorization and funding from other agencies. Even now Survey work in the Antarctic is supported largely by the National Science Foundation.

Most of the Survey's Arctic work has been in Alaska. Administratively such studies were not separated from projects in non-Arctic parts of Alaska. Because of time restrictions this discussion is limited largely to the geologic work of the Survey's old Alaskan Branch. Survey field investigations began in Alaska in 1889. The first appropriation item for Alaska was in 1895, for $5,000. From then on came a long line of outstanding Survey Alaskan geologists. Starting in the 1930's, with more money, more men, better field methods, better communications, better transportation, and the like, the Survey's investigations increased greatly in number, size, and scope. The Survey's deep involvement is sketched in the Survey's programs of oil exploration in Naval Petroleum Reserve No. 4, known as Pet 7, from 1944 to 1953.

[1]U.S. Geological Survey, retired.

ANTARCTIC PROGRAM

CONVENER: J. S. BEHRENDT

UNITED STATES RESEARCH IN ANTARCTICA

BY E. P. TODD[1]

[No abstract]

[1]National Science Foundation, Division of Polar Programs.

NEW USGS RESEARCH INITIATIVES IN ANTARCTICA

BY ROBERT M. HAMILTON

[No abstract]

ANTARCTIC MAPPING AND INTERNATIONAL COORDINATION

BY RUPERT B. SOUTHARD AND WILLIAM J. KOSCO

International cooperation in Antarctica began long ago as expeditions from various countries frequently supported each others efforts. This was so, even though strong nationalistic movements established territorial claims to Antarctica very early.

It was during the third International Polar Year of 1957–58, that the spirit of cooperation in Antarctica was most highly developed. During 1957–58, 55 observatory stations were established to cooperate in IGY programs in Antarctica. Argentina, Chile, and the United Kingdom had already established stations prior to this time.

Following the International Geophysical Year, the Scientific Committee on Antarctic Research (SCAR) was formed within the International Council of Scientific Unions. It was determined that a scientific organization such as SCAR was required in order to provide the means for communication amongst the various countries active in Antarctica. It is through SCAR that the true spirit of international cooperation prevails by providing the coordinating mechanism which allows the involved countries to survey and map the continent and to exchange the products of these mapping efforts.

Mapping Antarctica poses both technical and political problems that are beyond comparison. The most difficult technical problems are the logistics required for transporting personnel and equipment in that hostile environment. Geodetic traverses are conducted by ground and air in order to establish ground control for mapping. People and equipment are moved in a leap-frog manner over a wide area, disregarding real or implied political boundaries. To carry out the spirit of cooperation, logistic efforts are shared. Several USGS geodetic traverses have been conducted jointly with the United Kingdom, New Zealand, and Australia.

The basic data input for map compilation comes from ground control and aerial photographs. In the early days of mapping in Antarctica the U.S. Navy VXE-6 squadron acquired trimetrogon aerial photographs over major map features. Ground control was established by surveyors from the U.S. Geological Survey. Trimetrogon photogrammetry was used to compile maps first in the Sentinel Mountains, Thurston Peninsula, Horlich Mountains, Executive Committee Range, and McMurdo Sound. In recent years, standard overlap aerial photography and image mapping have played an important role in the mapping process. Ninety 1:250,000-scale topographic maps have been compiled by USGS over the Transantarctic Mountains and Western Antarctica.

Working through the SCAR nations involved in mapping, the Antarctic standard symbols and specifications have been developed for preparing these maps. The Working Group on Geodesy and Cartography, a standing Committee within SCAR, published these symbols in 1961 and again in 1980. An international agreement was reached in the early 60's on the basic horizontal and vertical datums to be used for mapping. Recently, agreement was reached (1981) to include the contribution to geodesy in this age of satellites, by changing the basic geodetic reference datum in Antarctica from the International Spheroid to the World Geodetic System.

CONFIGURATION OF EASTERN GONDWANALAND

BY WARREN HAMILTON

Reconstructions of Gondwanaland by du Toit, by Smith and Hallam, and by many other recent authors vary in some details but agree on placing the east side of India against Antarctica, and the west side of Australia against some other continental mass now in, or under, Asia. These fits, despite their wide acceptance, juxtapose unlike Indian and Antarctic Precambrian terrains, and leave the marine Paleozoic and Mesozoic Tethyan north margin of India dead-ended against Antarctica or southwest Australia. The conventional fits produce untenable juxtapositions and separations of Paleozoic and lower Mesozoic paleoclimatic and paleobiogeographic indicators.

A reconstruction modified from those proposed by Carey, Krishnan, Shields, and a few others, placing the east side of India against the west side of Australia (see figure 1), satisfies constraints of ocean-floor ages and magnetic anomalies, accounts for known paleomagnetic pole positions, and matches continental geology and rifting histories. This fit, unlike the conventional one, leaves space for certain (Seychelles Plateau; Precambrian exposed), probable (Naturaliste Plateau and Broken Ridge), and possible (Kerguelen Plateau) continental fragments now in the Indian Ocean. Broken Ridge and the Kerguelen and Naturaliste Plateaus appear continental in foundering histories and some geophysical features. Naturaliste Plateau has yielded Cretaceous clastic sediments of continental provenance and continental basaltic and rhyolitic rocks; Kerguelen volcanic rocks are of types that could be either continental or oceanic, but they contain radiogenic strontium. Fossils in

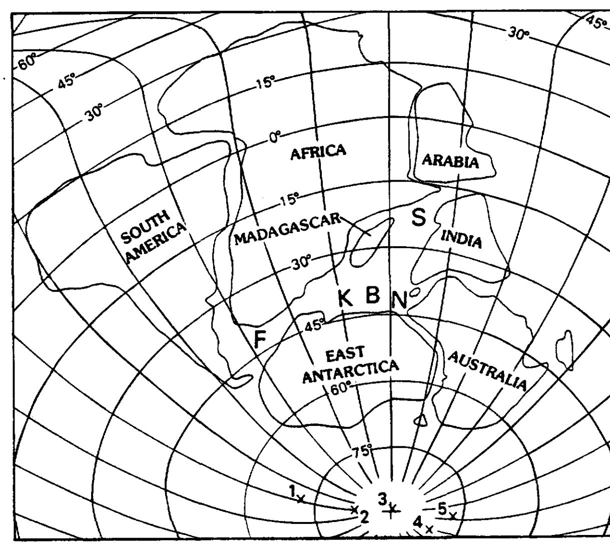

FIGURE 1.—Reconstruction of Gondwanaland in Late Triassic and Early Jurassic time. The longitude lines, 15° apart, illustrate the projection. Continental fragments: B, Broken Ridge; F, Falkland Plateau; K, Kerguelen Plateau; N, Naturaliste Plateau; S, Seychelles Plateau. Late Triassic-Jurassic paleomagnetic poles: 1, Africa and South America; 2, Madagascar; 3, Australia (used for pole of map projection); 4, India; 5, East Antarctica. Continents fitted to 1,000-m isobaths.

Kerguelen Tertiary lignites include wet-temperate austral araucarian and podocarpaceous conifers, and beech (Nothofagus), all of which are incapable of crossing large water gaps and hence require Late Cretaceous or Tertiary dry-land continuity with Antarctica or Australia, and continuous subsequent stand above sea level. Nepal (the northeast part of Indian plate) and Timor (the imbricated northwest edge of the Australian plate) have strikingly similar temperate to subtropical Permian marine faunas; the two terrains are juxtaposed by the reconstruction supported here, whereas they are far apart, and Nepal is at a continental-interior position and an impossibly high Permian paleolatitude, in the conventional assembly.

MINERAL RESOURCES OF ANTARCTICA

BY PETER D. ROWLEY, P. L. WILLIAMS, AND D. E. PRIDE[1]

Metallic and nonmetallic mineral occurrences are abundant in Antarctica. The most significant known deposits are of iron, copper, and coal. In the Precambrian shield of East Antarctica, for example, iron is present as banded iron-formation and as magnetite in veins, pods, and schist. The largest deposits of iron are in the Prince Charles Mountains, where bodies of banded iron-formation at least as thick as 400 m extend, mostly under the ice, for at least 120 km. Widely scattered morainal boulders and outcrops of iron-rich rock suggest that undiscovered iron deposits are also distributed over many other parts of East Antarctica. Magmatic iron is present in Pleistocene lava flows on Brabant Island, Antarctic Peninsula. The Jurassic stratiform gabbroic Dufek intrusion in the Transantarctic Mountains contains locally abundant magnetite and minor copper sulfides, and it may contain significant volumes of chromium, nickle, vanadium, iron, and platinum-group minerals. However, the base of the intrusion—where economically important metals are most likely to be concentrated—is not exposed. Low-grade copper and related metals are abundant in the Andean belt (mostly of Early Jurassic through Cenozoic age) of the Antarctic Peninsula. Here possible porphyry copper-molybdenum deposits and associated hydrothermal vein deposits occur on King George Island, Livingston Island, Anvers Island, the Melchior Islands, Brabant Island, Lassiter Coast, and eastern Ellsworth Land. Phlogopite and rock crystal occur in Queen Maud Land and Enderby Land, and graphite and beryl are locally abundant in other parts of East Antarctica. Sizeable coal deposits are present in the Transantarctic and Prince Charles Mountains, and smaller occurrences are in many other parts of East Antarctica.

Gondwana reconstructions suggest that many more mineral deposits occur in Antarctica. However, ice covers nearly 98 percent of the continent, and few of the bedrock areas have even been prospected or geologically, geophysically, or geochemically mapped in detail. No known mineral deposits now can be developed economically. Probably some presently known deposits in Antarctica would be drilled or perhaps even mined if they were located in a continent more favorable for development. However, Antarctica's severe climatic and logistic constraints and the fact that there are no international agreements concerning mineral rights or mining make it unlikely that exploitation will occur for many years.

[1]Department of Geology and Mineralogy, The Ohio State University, Columbus, OH 43210.

SPECULATIONS ON THE PETROLEUM RESOURCES OF ANTARCTICA

BY JOHN C. BEHRENDT AND CHARLES D. MASTERS

There are no known petroleum resources in Antarctica, and the petroleum industry is not particularly interested at present. Economic and political considerations may change this in the next few years, and exploration and exploitation are possible within one or two decades. A number of countries are actively carrying out multichannel seismic reflection surveys of the Antarctic continental margin, which are obviously focused on petroleum resource studies. Technology development will probably occur at a more rapid rate than research, exploration, and legal developments. By contrast, hard mineral exploitation in Antarctica is probably much further in the future. The only types of potentially exploitable petroleum resources in Antarctica from economic considerations would be giant or supergiant fields of which probably only four to ten supergiants remain to be discovered in the world. The points made based on my study of the available information on potential petroleum resources in Antarctica can be summarized as follows:

1. West Antarctica is probably the most prospective area of Antarctica because it likely contains large areas of unmetamorphosed sedimentary rock of post-rift age. It is comprised of a number of microplates that have moved significantly since the break-up of Gondwanaland. East Antarctica probably contains a number of subglacial sedimentary basins particularly adjacent to high mountain ranges and within the probable failed rift in the Amery Ice Shelf area.
2. Because of the moving grounded ice sheet several kilometers thick which covers most of Antarctica, the only practical areas for possible exploitation, were petroleum to exist, are the continental margins (possibly including the parts covered by ice shelves) with the most likely areas those bordering the Ross, Amundsen, Bellingshausen, and Weddell seas, in West Antarctica, and the Amery Ice Shelf in East Antarctica.
3. The sparse geophysical data suggest that there is a >8 kilometer thick section of sedimentary rock beneath the Ross and 14–15 km section beneath the Weddell Sea continental shelves. The Bellingshausen Basin probably contains >3 km of sedimentary rock. There is no available information on sedimentary rock thickness beneath the continental shelves bordering the Amundsen Sea and Amery Ice Shelf area but recent geophysical cruises can be expected to provide more information soon.
4. DSDP holes on the Ross Sea continental shelf indicate the presence of rocks from Oligocene to Pleistocene in age. Sedimentary rocks of Cretaceous or possibly Jurassic age might be present in the deepest parts of the section indicated by seismic reflection data and depths estimated from aeromagnetic data. Jurassic and Cretaceous and Tertiary sedimentary rocks are probably present beneath the continental shelf and adjacent glacierized areas of East Antarctica based on a number of samples by several investigators.
5. There is presently no direct information on the petroleum geology beneath Antarctic continental shelves relative to source and reservoir rocks, with the exception of the shows of gas reported in core holes beneath the Ross Sea continental shelf.
6. If future geophysical and geological (deep drilling) research were to indicate certain areas as worth exploration, programs of environmental research would be necessary to study possible meteorological, glaciological, oceanographic, and geologic hazards that might be encountered that would adversely affect future exploration or exploitation. Concomitant biological research programs into the fragile ecosystems that might be affected by possible blowouts or oil spills would also be required.

PLANNED MARINE GEOPHYSICAL GEOLOGICAL SURVEYS OF THE WILKES LAND AND ROSS SEA MARGINS

BY STEPHEN L. EITTREIM

In January and February of 1984, the ice-strengthened S.P. LEE will carry out 24-channel seismic surveys to better define the basins and seismic stratigraphy of parts of the Antarctic margin south of Australia and New Zealand. Gravity and gradiometer-magnetic data also will be collected underway, as well as sonobuoy refraction and 3.5 and 12 kHz echo sounding. Seafloor sampling will be done for age determination, for physical and geochemical properties of sediments, and for contained gases. A deep-towable side-scan system will be available for investigation of morphologic features.

Australia and New Zealand rifted away from Antarctica in the middle of the Cretaceous producing rift basins, some of which are hydrocarbon-rich, such as the Gippsland basin north of Tasmania. DSDP drilling in the region shows that the early phases of opening were a time of deposition of euxinic clays and silts, reflecting restricted basin circulation and probable local anoxic bottom-water conditions. Prior to the Eocene, a subtropical climate prevailed. On the Ross Sea Shelf, German and French seismic data and DSDP cores show sediment many kilometers thick in three north-trending basins, with interstitial gases suggesting a thermogenic source. The Wilkes Land to Victoria Land margin has been less explored, due partly to more difficult ice conditions, but thick sediments exist in places, and one major basin, the Wilkes basin, may be a structural counterpart of the Otway basin of southern Australia. In sum, the meager data existing at present give reason to consider this part of the Antarctic margin as a possible petroleum resource area.

Besides the resource questions, several significant marine-geologic questions can be addressed on this ice-fringed passive continental margin. Because of its relative youth and the probability that it has been sediment starved in the latter part of the Tertiary, the Antarctic margin here is a good place to study post-rift subsidence and structures related to the Gondwana breakup. The fracture zones tracing the motion of Australia-New Zealand from Antarctica intersect the Antarctic margin obliquely; the short ridge segments are offset by large distances, and the mid-ocean ridge axis is abnormally close to the margin, similar to the equatorial Atlantic configuration. How these fracture zones and the ridge proximity have influenced basin development are interesting questions for study. Two major climatic events, the drastic cooling of the Terminal Eocene Event and the ice sheet growth in the Miocene probably left prominent signatures in the seismic stratigraphy of this margin.

The hypotheses which exist to explain the anomalously great depth of the shelf break of Antarctica (500 m) need to be tested. The deep shore-parallel troughs that exist on the inner shelf present an interesting topic of study as well as the general questions of ice influence on sedimentation and morphology and how this influence might contrast to Arctic processes. In two months of time on the LEE (minus two weeks of transit time) we can only hope to establish a beginning toward addressing these and perhaps other more interesting questions for future years' work.

SATELLITE IMAGE ATLAS OF GLACIERS: THE POLAR AREAS

BY RICHARD S. WILLIAMS, JR., AND JANE G. FERRIGNO

In June 1977, the U.S. Geological Survey (USGS) began a long-term project to prepare a USGS Professional Paper, "Satellite Image Atlas of Glaciers." Now nearing completion, with publication expected in 1985, the Atlas involves 55 glaciologists representing 30 United States, foreign, and international organizations in an effort to produce a benchmark study of the glacierized areas of Earth. Landsat images provide the common data base for locating, describing, and mapping: (1) the areal extent of the Antarctic and Greenland ice sheets and ice caps in Iceland, Svalbard, the Russian Arctic islands, and northern Canada; (2) the termini of most large valley glaciers; and (3) the termini of tidal outlet glaciers.

The polar areas, especially the Antarctic, represent some of the most poorly mapped regions of our planet. Antarctica is estimated to contain 90 percent of the glacier ice on Earth, yet only 20 percent of the continent has been mapped at a scale of 1:250,000 or larger. Kvitoya, a small, ice-capped island east of Nordaustlandet in Svalbard, was, until the availability of Landsat, mapped as being thin and cigar-shaped (see the Central Intelligence Agency's Polar Regions Atlas, May 1978). Landsat images showed the island to be oval, and new Norwegian maps of the area now show this radical change in shape. A comparison of Landsat images with published maps of the Arctic and Antarctic reveals many discrepancies, including incorrect positions of glacier margins, inaccuracies in geographic locations of glaciers, coastlines, and offshore islands.

In addition to serving as the basis for the preparation of the "Satellite Image Atlas of Glaciers" to support future and retrospective studies of fluctuation in glacier termini and global climatological studies, Landsat images are being increasingly used as base maps (controlled or uncontrolled) to plot regional glaciological, geological, and geophysical data up to scales of 1:250,000 for Landsat multispectral scanner (MSS) images and up to 1:100,000 for Landsat 3 return beam vidicon (RBV) and Landsat 4 thematic mapper (TM) images. Landsat images have been used, in a time-lapse fashion, to monitor advance or recession of glaciers, to measure the velocity of outlet glaciers, and to monitor fluctuations in proglacial lakes.

Because of the brief field season and logistical costs and mobility difficulties in polar areas, satellite data will be increasingly used to monitor dynamic phenomena in these areas. The "Satellite Image Atlas of Glaciers," which, in the polar areas, involves a mutually beneficial exchange of scientific information among United States, Canadian, British, Norwegian, Swedish, Soviet, Danish, Icelandic, and New Zealand scientists, is representative of the type of multinational cooperative research endeavors that are possible with such data and which will jointly lead to better scientific knowledge about the polar areas.

WIND, WAVES, AND SWELL IN THE ANTARCTIC MARGINAL ICE ZONE BY SEASAT RADAR ALTIMETER

BY WILLIAM J. CAMPBELL AND NELLY M. MOGNARD[1]

During the Austral winter of 1978, the Seasat satellite acquired repetitive radar altimeter observations of the oceans surrounding Antarctica. By averaging these observations for three-day periods, quasi-synoptic fields of ocean surface wind speed, significant wave height, and significant swell height have been computed for the entire three months the satellite operated. The generation, migration, and attenuation of swell in the southern oceans have been measured for the first time.

Extensive areas of pronounced significant wave height and swell height were found to occur somewhere near the Antarctic marginal ice zone every few days during the winter 1978. During the period 7–9 October 1978, storms between Antarctica and Australia and in the eastern South Pacific with surface wind speeds as high as 20 m/s generated large areas with significant wave heights as large as 16 m and significant swell heights as large as 12 m. Extensive wave trains with significant wave height as large as 10–12 m and swell as large as 8–10 m were observed to impact large areas of the Antarctic marginal ice zone. Return signals from the ocean surface and the sea ice cover were analyzed, and it is shown that phenomena within the ice can be observed with the radar altimeter such as the opening of the Weddell Sea polynya in September 1978. See figures 2, 3, and 4.

[1]Groupe de Recherche de Geodesie Spatiale-CNES Toulouse, France.

SURVEYING IN ANTARCTICA DURING THE INTERNATIONAL GEOPHYSICAL YEAR

BY WILLIAM H. CHAPMAN

The Antarctic International Geophysical Year (IGY) program starting in 1956 initially emphasized the gathering of geophysical measurements throughout the western part of the continent. At the bases, the major scientific programs involved meteorology, seismology, geomagnetism, and measurements of the ionosphere. The traverse parties' efforts were directed toward glaciology, geology, and geophysics. As IGY scientists made flights and ground traverses into the interior of the continent, they discovered that the existing maps contained many errors, particularly where the original exploration was by aircraft. The plotted flight paths of Byrd, Ronne, and the other earlier explorers contained position errors as large as 60 miles, and the aircraft crews had a tendency to exaggerate their discoveries. As a result, it was very difficult to correlate the actual topography with that shown on the map; nonexistent mountains were shown, and existing mountains were plotted with large positional errors. There was one case where a 20,000-foot mountain that was shown on a map could not be found. It was obvious that the scientists needed maps for navigation, topographic data, and traverse planning that were more accurate than those available.

In an attempt to utilize new technology for producing the needed maps, Major Lassiter led an Air Force expedition of two DC-3 aircraft to the Ellsworth Station on the Weddell Sea. During November and December of 1957, a test network of 10 control points was established 200 miles south of the Ellsworth Station on the Filchner Ice Shelf in the vicinity of the Pensacola Mountains.

The positions of these points were determined by solar altitude measurements made every hour for 24 hours. The test site elevations were measured with barometric altimeters. The equipment that was to shorten the mapping cycle, a radio ranging system, was tested in January and proved to be unsatisfactory. Because of a strong ionospheric reflection, the range was limited to 75, instead of the expected 300, miles.

The following season, U.S. Geological Survey topographic engineers were assigned to IGY ship expeditions and geophysical traverses. In addition to navigating the traverses, the engineers were to survey any mountain ranges encountered. This was done by establishing positions by solar altitude measurement and elevations by barometric altimetry. The surveyor was generally at traverse camps, which were located on the flat snow surface within view of the mountains. The coordinates were then projected to the mountain peaks by intersection from a taped baseline. Elevations were transferred by vertical angle observations. This technique for obtaining control for mapping continued for several years and was then replaced by helicopter-supported survey traverses using electronic distance measuring instruments.

The Navy's VXE-6 squadron was taking aerial photographs over major mountain ranges using

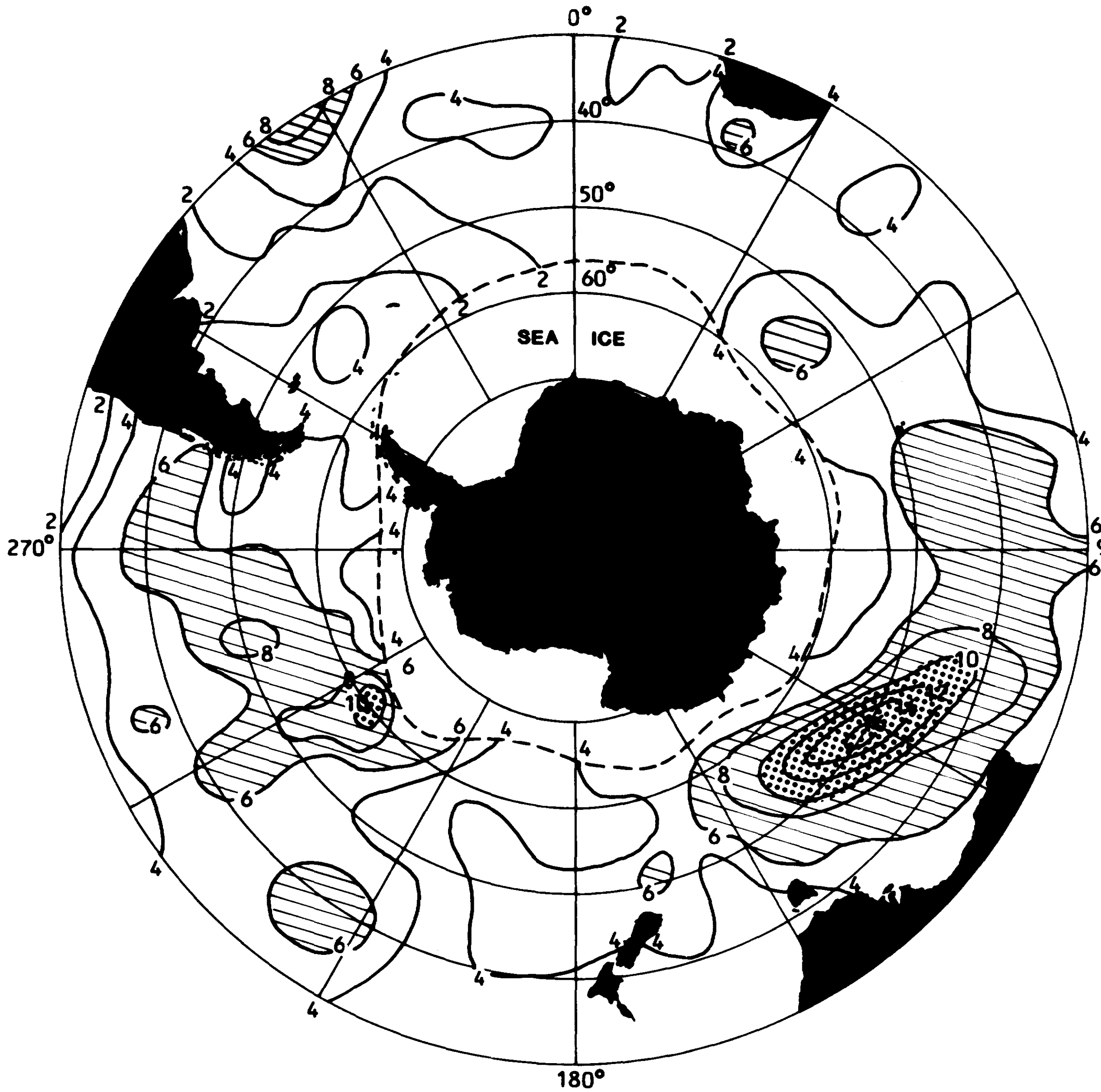

FIGURE 2.—Southern ocean field of significant wave height (m) derived from the Seasat radar altimeter measurements for October 7 to 9, 1978.

P-2V aircraft equipped with trimetrogon cameras. The aerial photography was combined with the control established by the surveyors at the U.S. Geological Survey, Branch of Special Maps, to produce 1:250,000-scale topographic maps. The first maps produced covered the Thurston Peninsula, Sentinel Mountains, Horlick Mountains, Executive Committee Range, and McMurdo Sound.

THE DUFEK INTRUSION OF ANTARCTICA AND A SURVEY OF ITS MINOR METALS RELATED TO POSSIBLE RESOURCES

BY ARTHUR B. FORD

The Dufek intrusion is an unusually large differentiated layered mafic igneous complex of Jurassic age in the northern Pensacola Mountains (lat 82°

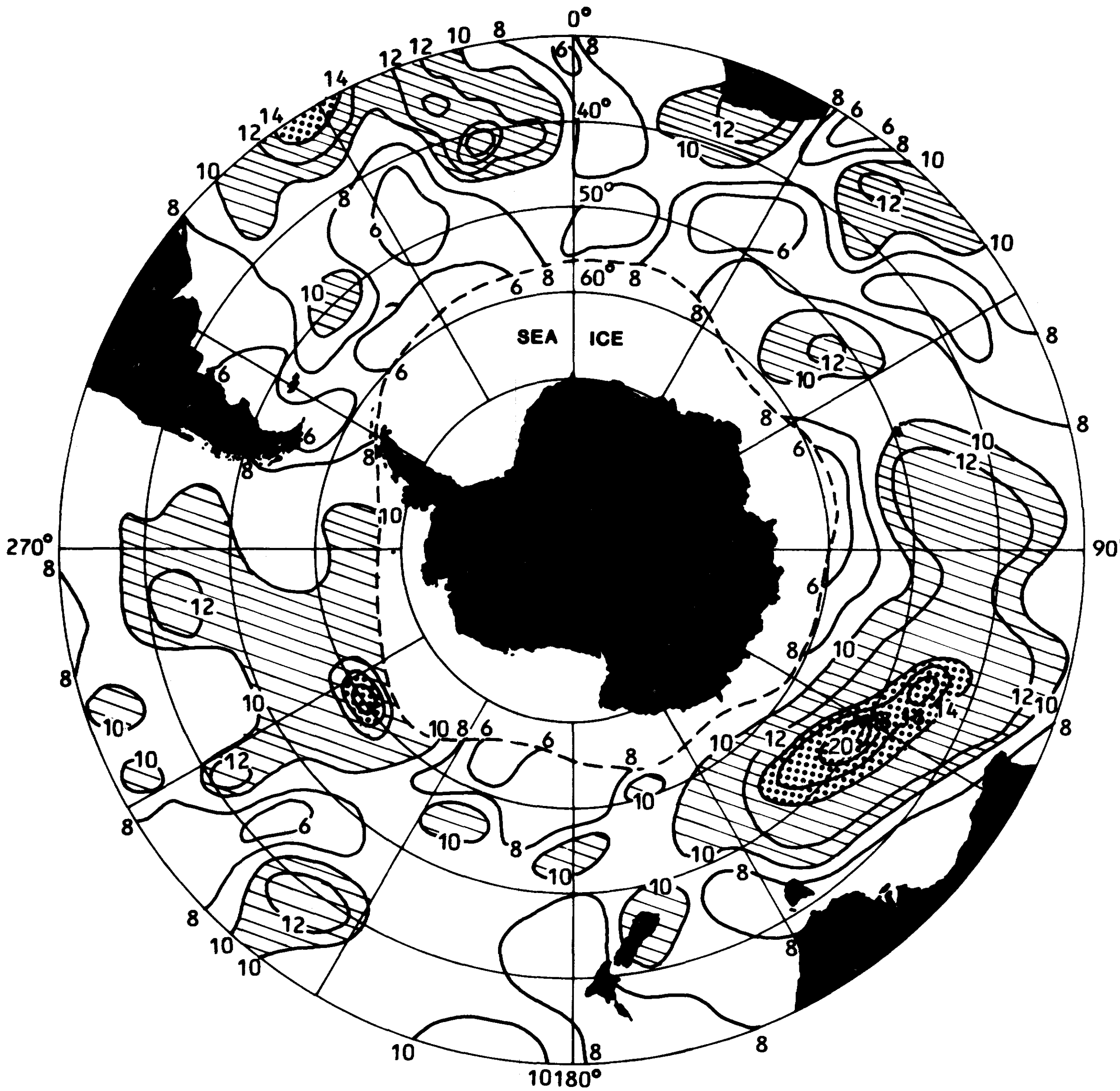

FIGURE 3.—Southern ocean field of surface altimeter measurements (m) for October 7 to 9, 1978.

30′ S., long 50° W.). Although it is mostly covered by ice, geophysical surveys indicate that it has an area (50,000+ km²) comparable to that of South Africa's Bushveld Complex. Geologic studies by U.S. Geological Survey parties in 1965–66, 1976–77, and 1978–79 determined that, of its total 8–9 km estimated thickness, nearly 2 km of a lower (not lowest) part of the body is exposed in the Dufek Massif and about 1.7 km of the Fe-enriched highest part is exposed in the Forrestal Range. Major concealed stratigraphic parts are a 1.8- to 3.5-km-thick basal section beneath the Dufek Massif rocks and a 2- to 3-km-thick intermediate interval, underlying Sallee Snowfield, between the two exposed sections. Except for late silicic differentiates of the Lexington Granophyre at the top, the rocks are generally well-layered cumulates of predominantly gabbroic composition. These gabbroic cumulates chiefly contain cumulus plagioclase and two pyroxenes (augite-ferroaugite and inverted pigeonite); additionally, cumulus magnetite and ilmenite are abundant in

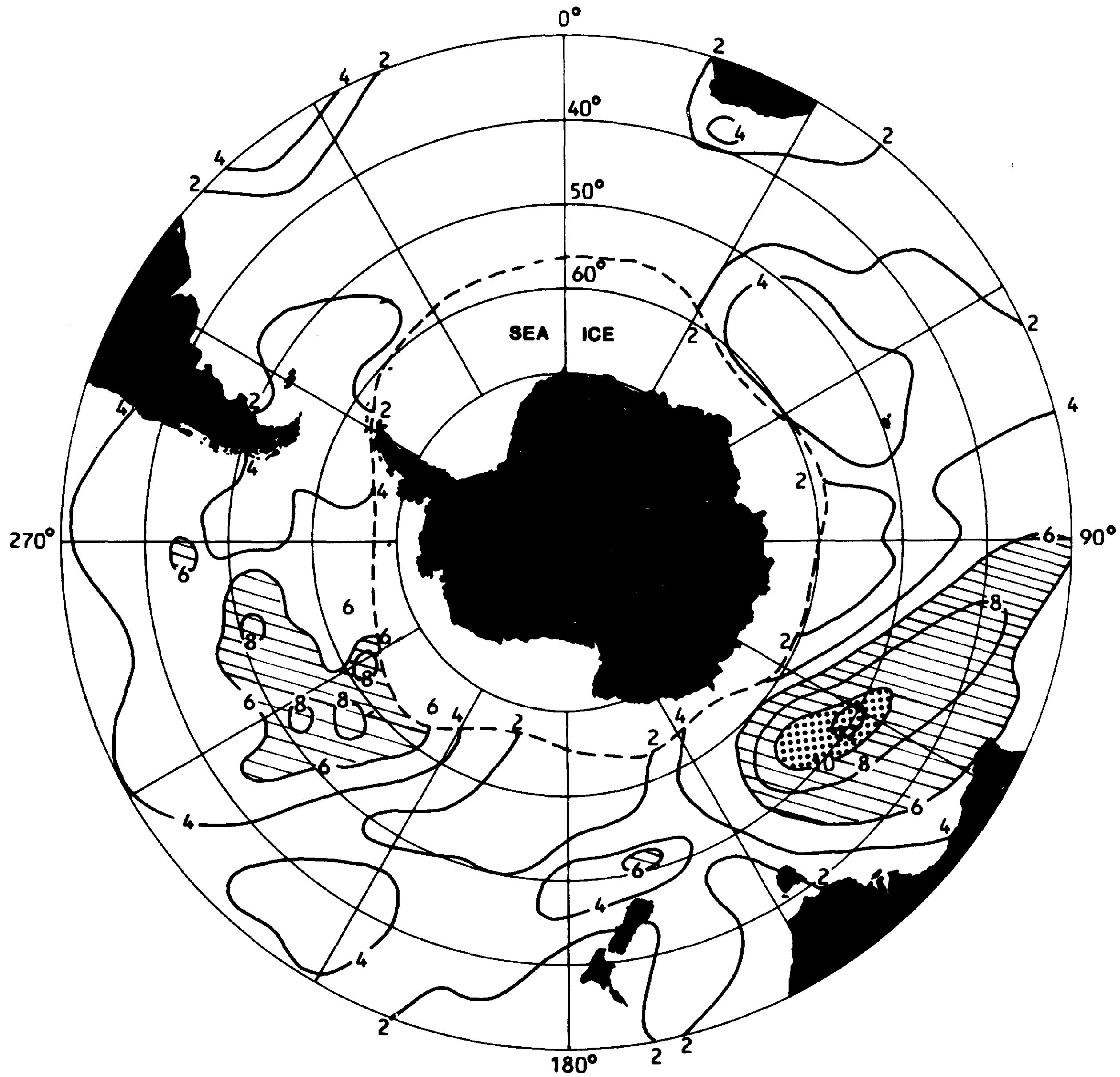

FIGURE 4.—Southern ocean field of minimum swell height (m) deduced from the significant wave height and surface wind speed measurements by Seasat altimeter and using Pierson and Moskowitz wave model for October 7 to 9, 1978.

the Forrestal Range section. In many areas, the gabbroic cumulates are interlayered with conspicuous but volumetrically minor layers, a few centimeters to tens of meters thick, of plagioclase cumulate (anorthosite and leucogabbro), pyroxene cumulate (pyroxenite), and Fe-Ti oxide cumulate (magnetitite) that typically show modal gradation upward from sharp basal to gradational top contacts with the gabbroic cumulates. Most layers of this kind have great lateral continuity with little variation in thickness: one, the Frost Pyroxenite, is traceable for 35 km before disappearing under ice cover. The general association of such layers with cut-and-fill channel structures (troughs) suggests a depositional origin related to magma-current activity. Layer-parallel alinements of xenolith trains in many places also indicate current activity.

The intrusion was emplaced in a multiply deformed mobile belt at the margin of the Antarctic craton, in which strong compressive deformations are of late Precambrian and Cambrian(?), Late Cambrian to Silurian, and probable Triassic age. K-Ar-age determinations of 172+4 m.y. indicate contemporaneity of the intrusion with sills, dikes, and flood lavas of the Middle Jurassic tholeiitic Ferrar igneous province throughout the Transantarctic Mountains. Representatives of the Ferrar in the Pensacola Mountains have high SiO_2 contents (53–55 weight percent), anomalously high $^{87}Sr/^{86}Sr$ initial ratios (0.7104–0.7126), and other chemical and petrographic features that characterize the province elsewhere. If the original magma of the Dufek intrusion had similar characteristics, this body provides a record of strong fractionation of a mafic magma different from those inferred for other major layered intrusions, which contain less SiO^2 and more MgO. The Ferrar province, including the Dufek intrusion, may have formed in a failed-rift arm of a radial-rift system centered near the South America-Africa-Antarctica join and associated with the breakup of this part of Gondwanaland.

Other major intrusions of this type contain economically significant magmatic deposits of one or more metals, generally concentrated in lower parts of the bodies and associated with early mafic and ultramafic cumulates. In view of the small percentage of rock exposure and the present reconnaissance scale of investigation, nearly all such deposits are considered to be "speculative resources" of the Dufek intrusion. Disseminated sulfides have been found locally in trace amounts to several percent, the greatest amounts in Fe-Ti oxide-rich layers in the Forrestal Range. A reconnaissance geochemical survey of average-appearing rocks shows marked enrichment in Cu, V, Ti, Pt, Pd, and S in the upper (Forrestal Range) section in comparison with the lower (Dufek Massif) section, and corresponding depletion in Cr and Ni. The variations relate to differentiation by fractional crystallization. Pt, Pd, and Rh have been found only in concentrations near or below their limits of determination (Pt, 10 ppb; Pd, 4 ppb; Rh, 5 ppb) in the lower section, but in greater concentrations (max 35 ppb Pt, 44 ppb Pd, and 12 ppb Rh) in the upper section. Platinum-group minerals have not been found.

Petrologic comparisons with other complexes, including use of cumulus arrival of pigeonite as a correlation marker, suggest that the major pyroxenitic members of the Dufek Massif section lie at a position analogous to a level about 2 km or more above the chief platinum-group-metal horizons of the pyroxenitic Merensky Reef of the Bushveld Complex. The Merensky-equivalent level in the Dufek intrusion is probably in the middle to upper part of the concealed basal section. Considering Antarctic operating costs, platinum-group metals would be of chief resource interest, but the absence of placers and soils will make exploration difficult. Correlation studies suggest that V may be a useful pathfinder element in a geochemical exploration for the metals within exposed units; however, drilling would be needed to explore basal layers, where metals are most likely to occur.

CRYSTALLIZATION OF THE DUFEK INTRUSION, ANTARCTICA

BY GLEN R. HIMMELBERG AND A. B. FORD

The Dufek intrusion is an unusually large differentiated layered gabbro of Jurassic age in the northern Pensacola Mountains (lat 82°30′ S., long 50° W.). The intrusion is mostly covered by ice, but geophysical surveys indicate it has an area of 50,000+ km², comparable to that of the Bushveld Complex. The gabbros are exposed in two partial, nonoverlapping sections. The lowermost 1.8 km of exposed rocks make up the Dufek Massif section, and the uppermost 1.7 km of rock make up the Forrestal Range section. The concealed intermediate section between the two ranges is estimated to be 2–3 km thick, and geophysical evidence suggests that the concealed basal section is 1.8–3.5 km thick. Thus the total thickness of layered rocks may be as much as 8–9 km.

The layered rocks are dominantly gabbro with lesser amounts of anorthosite and minor pyroxenite. A 300-m-thick granophyre layer caps the intrusion. The anorthosites are plagioclase and plagioclase-augite cumulates; the gabbros are dominantly plagioclase-augite-inverted pigeonite cumulates except near the base of the Dufek Massif section where the Ca-poor pyroxene is orthopyroxene, and in the upper Forrestal Range section where the magma differentiated beyond the two-pyroxene stability field and ferroaugite is the only cumulus pyroxene. Titaniferous magnetite and ferrian ilmenite are cumulus phases in most of the layered rocks from the uppermost Dufek Massif section through the Forrestal Range section.

In the upper part of the Dufek Massif section and in the Forrestal Range section the anorthosites have sharp basal contacts and grade upward into gabbros, a sequence that is repeated in a cyclic manner. The succession of appearance of cumulus phases in these sequences indicate the crystallization sequence plagioclase, plagioclase + augite, and plagioclase + augite + pigeonite. In the lower part of the Dufek Massif section the anorthosites have sharp basal and upper contacts with gabbro and there are no sequences of 1-phase cumulates progressing through 2- and 3-phase cumulates to indicate a crystallization sequence. Very slight changes in bulk composition or phase boundaries can affect crystallization sequence, and marked changes in crystallization sequence have been documented for other large layered intrusions. Thus there is no reason to infer that the crystallization sequence of the concealed basal section and of most of the Dufek Massif section was the same as the sequence for the upper part of the intrusion.

Cumulus pyroxenes show a general iron enrichment with stratigraphic height. Superimposed on the trend are (1) a 1-km-thick section in the lower part of the exposed intrusion that shows slight to no iron-enrichment and (2) a marked reversal in the Fe/(Fe+Mg) ratio at about 1 km below the top of the body. Cumulus plagioclase in the gabbros shows a general decrease in anorthite content with stratigraphic height and also shows a marked reversal in composition near the top of the body. The section with little pyroxene fractionation is not reflected in the plagioclase trend, and there are other reversals in the plagioclase composition trend that are not paralleled by reversals in the pyroxene trend. These differences in detail may reflect, in part, different degrees of interaction of cumulus minerals with upward migrating intercumulus liquid. The chemistry of cumulus iron-titanium oxides are dominated by subsolidus re-equilibration, although the contents of V_2O_3 and Al_2O_3 in ilmeno-magnetite parallels the pyroxene compositional trend.

The layering, textures, and mineral chemistry variation with stratigraphic height make it clear that the dominant process in the formation of the intrusion was fractional crystallization with accumulation, or crystallization, from the base upward. The cyclic sequence of plagioclase cumulates grading upward to plagioclase-pyroxene cumulates suggests either periodic convective overturn of magma or influx of more primative magma to the crystallization site. The major reversal in mineral fractionation trends near the top of the intrusion, which coincides with an angular discordance in layering dip, strongly indicates an influx of new magma at the site of crystallization. Reversal magnitudes suggest incursion of either less fractionated magma from some other part of the chamber or mixing of primative magma with Fe-rich residual magma.

GEOPHYSICAL INVESTIGATIONS OF THE DUFEK INTRUSION AND THE SURROUNDING REGION

BY JOHN C. BEHRENDT

Aeromagnetic, gravity, and seismic reflection measurements made in 1957, 1963–64, 1965–66, and 1978 over the Dufek layered mafic intrusion of 172±4 m.y. age in the Pensacola Mountains area of Antarctica have allowed extension of the known geology beneath areas covered by thick ice.

A combined aeromagnetic and radio echo ice-sounding survey (4,200 km of traverse) made in 1978 over the Dufek intrusion suggests a minimum area of about 50,000 km^2, making it comparable in size with the Bushveld Complex of Africa. Comparisons of the magnetic and subglacial topographic profiles illustrate the usefulness of this combination of methods in studying bedrock geology beneath ice-covered areas. Rocks are exposed in only 3% of the inferred area of the intrusion. It is about 400 km long along a NNE trend from about 80°45′ S. across the front of the Transantarctic Mountains. Interpretation of the magnetic data indicates that the northern part of the intrusion is downdropped about 4 km across the mountain front and underlies the 1,700-m-deep Crary trough.

West Antarctica has been interpreted to comprise several crustal blocks (microplates) that moved and rotated into their present configuration. In a recent paper Dalziel and Elliott (1982) suggested that the Ellsworth Mountain block was formerly placed against the present Transantarctic Mountains. Thus, if the Ellsworth Mountain block earlier occupied the area presently underlain by the northern part of the Dufek intrusion, the block must have been displaced either prior to or synchronous with rifting in Early Jurassic time that led to emplacement of that intrusion and the coeval Ferrar intrusive group.

Magnetic anomalies measured a few hundred meters above outcrops of the intrusion range in peak-to-trough amplitude from about ~50 nT over the lowermost exposed portion of the section in the Dufek Massif to about ~3,600 nT over the uppermost part of the section in the Forrestal Range. Theoretical magnetic anomalies, computed from models based on the subice topography fitted to the highest-amplitide observed magnetic anomalies, required normal and reversed magnetizations ranging from 10^{-4} to 10^{-2} emu/cm^3 having directions and magnetizations consistent with measurements previously made on oriented samples. This result is interpreted as indicating that the Dufek intrusion cooled through the Curie isotherm during one or more reversals of the Earth's magnetic field.

A broad regional Bouguer anomaly has gradients parallel to the northwest edge of the Pensacola Mountains block. Bouguer anomaly values decrease from 82 to −90 mgal across this transition from West Antarctica to East Antarctica. Theoretical profiles fitted to the gravity data indicate either an abnormally thin crust on the West Antarctica side or a normal crust on the West Antarctica side and a steep steplike transition from West Antarctica to East Antarctica that suggests a fault extending from the crust-mantle boundary to near the surface. Gravity, magnetic, and seismic data suggest a thick section of low-velocity, low-density, nonmagnetic, presumably sedimentary rock beneath the ice northwest of the Pensacola Mountains. A least-squares regression of the Bouguer anomalies compared with elevation in the Pensacola Mountains area suggests that the amplitude of the gravity anomaly associated with the Dufek intrusion is about 85 mgal, corresponding to about 8.8- to 6.2-km thickness for the intrusion, assuming reasonable density contrasts.

GEOLOGY OF THE NEPTUNE RANGE, ANTARCTICA

BY WILLIS H. NELSON AND PAUL L. WILLIAMS

Two superposed unconformities separate the rocks of the Neptune Range into three sequences. The oldest sequence, the Patuxent Formation of late Precambrian age, consists of several thousand meters of argillaceous metasandstone (metasubgraywacke), slate, and minor amounts of conglomerate. Igneous rocks, mostly mafic extrusive rocks, locally compose important members of the Patuxent Formation. These rocks were all tightly folded during the Beardmore orogeny.

The Nelson Limestone, and shale, siltstone, and fine-grained sandstone of the late Cambrian Wiens Formation, unconformably overlie the Patuxent Formation. Silicic volcanic rocks, mostly volcaniclastic, derived from centers within the Neptune Range compose the Gambacorta Formation, including the Hawkes Rhyodacite Member. Locally, the upper part of the Gambacorta interfingers with the lower part of the Wiens Formation.

The Cambrian and older rocks were moderately to strongly deformed during the early Paleozoic Ross orogeny, later beveled by erosion, and are now overlain unconformably by weakly to locally strongly folded clastic rocks of Ordovician(?) to Devonian ages. Still later, massive diamictite—the Gale Mudstone, probably tillite, of Permian(?) age—was deposited.

The general trends of structures in the Neptune Range and in the Transantarctic Mountains, of which the Neptunes are a part, all generally parallel the Pacific-Atlantic edge of the Antarctic craton, which lies mostly in eastern longitudes.

Although published descriptions of rocks of the Ellsworth Mountains about 500 km from the Neptune Range suggest possible correlations with rocks of the Neptune Range, structural trends in the Ellsworth Mountains at nearly right angles to the trend of the Transantarctic Mountains, suggest different tectonic histories for these two areas.

PROTEROZOIC TO MESOZOIC MOBILE-BELT GEOLOGY, PENSACOLA MOUNTAINS, ANTARCTICA

BY DWIGHT L. SCHMIDT

The Pensacola Mountains consist of four unconformable sequences of (1) graywacke (oldest), (2) platform, (3) molasse, and (4) continental (youngest) deposits that were deformed during three successive pre-Jurassic compressional tectonic events and a superposed Jurassic extensional rift event. The first sequence of Middle Proterozoic graywacke deposits (Patuxent Formation), at least several kilometers thick, consists of turbidite quartz-bearing sandstone and slate and volcanic rocks. The distribution of intercalated basalt flows, some pillow-structured, and sparse dacitic to rhyolitic flows, ignimbrites, and tuffs suggests a nearby island-arc source on the West Antarctic side of the

Pensacola Mountains. These subduction-related rocks were isoclinally folded and thrust most likely toward the East Antarctic shield during the Late Proterozoic Beardmore orogeny.

A major angular unconformity underlies the second sequence consisting of extensive platform deposits of Lower Cambrian archaeocyathid-bearing limestone and Middle Cambrian trilobite-bearing limestone (Nelson Limestone) that are overlain by shale (Wiens Formation), and silicic volcanic rocks (Gambacorta Formation) including rhyolitic ignimbrite (510±35 Ma) of caldera origin. The second sequence was intruded by calc-alkalic granite plutons of Late Cambrian age and deformed during the Cambrian-Ordovician Ross orogeny, which is interpreted as a cratonization event that was distally associated with subduction-related collisional tectonics in West Antarctica.

The third sequence is the pre-Devonian Neptune Group that is above an angular unconformity and consists of basal orogenic conglomerate and more than 1,500 m of quartz-sandstone molasse that resulted from the erosion of the early Paleozoic mountains of the Ross orogeny. The fourth sequence of continental deposits of the Beacon Supergroup disconformably overlies the Neptune Group. The Beacon Supergroup consists of Devonian quartz sandstone (Dover Sandstone), Permian glacial tillite (Gale Mudstone), and Permian siltstone and shale (Pecora Formation) containing glossopterid-bearing coal beds.

The rocks of the Pensacola Mountains again were deformed into tight to open folds during the Weddell orogeny of Triassic age. This latest compressional event was caused by intracratonic orogeny distally associated with latest Paleozoic to early Mesozoic subduction of the Pacific Ocean beneath the northern margin of West Antarctica (including the ancestral Antarctic Peninsula). The transverse structure of the Ellsworth Mountains probably was a direct, in-situ product of Weddell orogeny and does not require rotation as interpreted in a 1969 study by J.M. Schopf. The Weddell orogeny resulted in the final consolidation of this part of Gondwanaland.

During Early and Middle Jurassic time, a Transantarctic continental rift extensionally split the East Antarctic craton from West Antarctica as Gondwanaland began to break up. Continental tholeiitic flood basalt (Kirkpatrick Basalt) was deposited on, and tholeiitic diabasic sills (Ferrar Dolerite) were intruded into, the rift margin in the Transantarctic Mountains; the huge stratiform gabbroic pluton of the Dufek intrusion was intruded into the Pensacola Mountains. The continental rifting was shortly followed, during Late Jurassic time, by more vigorous extension resulting from major transform faulting, and perhaps by minor oblique formation of oceanic crust as East Antarctica was right laterally displaced 500 to 1,000 km relative to West Antarctica and as Africa separated from East Antarctica during the initial opening of the Indian Ocean. During this time, West Antarctica remained attached to South America. According to this reconstruction, the northern Marie Byrd Land part of West Antarctica, prior to transform faulting, was positioned in the present-day Ross Sea opposite north Victoria Land.

SEDIMENTOLOGY OF THE HORLICK FORMATION (LOWER DEVONIAN), OHIO RANGE, TRANSANTARCTIC MOUNTAINS

BY LUCY McCARTAN,
MARGARET A. BRADSHAW[1], AND
GRAEME AYERS[2]

Investigation of the sedimentology and paleoecology of the Horlick Formation was the main goal of a 1979–1980 New Zealand expedition to the Ohio Range. The study followed the reconnaissance work of previous expeditions, mainly from Ohio State University, and was supported by grants from the National Science Foundation, the New Zealand Antarctic Division, the Canterbury Museum.

The Horlick Formation of Early Devonian age consists of 10–50 m of subhorizontal interbedded subarkosic sandstone and chloritic shale and mudstone. It is exposed only in the Ohio Range of the Transantarctic Mountains between the Ross Ice Shelf and Ronne Ice Shelf, at about lat. 85° S. and long. 110°–117° W.

The Horlick Formation nonconformably overlies granitic basement rocks and is overlain by glacial and periglacial rocks of Permian age. It contains marine fossils, bone fragments and phosphatic clasts in several thin beds especially near the base, and calcareous concretions and beds of limestone.

Quartz and lesser amounts of muscovite and feldspar are the dominant minerals in the sandstones; biotite is subordinate. Magnetite, epidote, sphene, and tourmaline are trace minerals. Secondary calcite is locally abundant in sandstones, and authigenic chlorite is ubiquitous in shales and mudstones.

Some beds are laterally persistent for tens of meters whereas others contain different facies within a few meters. Channels filled with shale or sandstone with festoon crossbedding are common. Some sandstones are planar bedded or contain interference ripples. Bioturbation has destroyed primary structures in many beds. Trace fossils on bedding surfaces and burrows suggestive of shallow-water deposition are found in several beds.

Current directions are indicated by crossbedding, channel axes, current lineations, ripple marks, direction of sediment accumulation, and low-angle crossbeds probably deposited in the swash zone of a beach. These indicate that the offshore direction was dominantly southward and longshore drift was westward. Northward-dipping crossbeds were probably formed on the landward side of submerged bars.

All evidence indicates that the Horlick Formation is an eastward-trending, long, linear body that accumulated primarily in a shallow, marginal-marine environment. The source, as indicated by the mineralogy, was southward-sloping granitic terrane, similar to the underlying basement rocks.

No marine correlative of the Horlick Formation is known from Antarctica, but nonmarine beds that may be Lower Devonian are present in Victoria Land. Bradshaw correlates the Horlick Formation with a fossiliferous formation in southwestern New Zealand. The lack of tilting in most of the Ohio Range reflects a non-orogenic tectonic environment.

[1]Canterbury Museum, Christchurch, New Zealand.
[2]Mount Cook National Park, New Zealand.

SMALL-SCALE MAGNETIC FEATURES OF THE POLAR REGIONS

BY JOSEPH C. CAIN AND DAVE RAY SCHMITZ

A 29th degree and order spherical harmonic model was created from the vector and scalar Magsat data taken over the period November 1979–June 1980 (Cain and others, 1983). The field from the first 13 orders was subtracted from that computed by the total set of coefficients to simulate the trend removal commonly used by geophysicists in studying magnetic anomalies. The resulting differences were then contoured at the Earth's surface to produce maps of magnetic "anomalies" in the polar regions. Since the field representation is potential, it is thus possible to produce maps in any of the commonly used geomagnetic components. At this degree and order, features down to about 1,400 km in size may be displayed. The intensity at the center of the cells depicted for these regions is stronger than those at lower latitudes by about the factor of two that one would expect from crustal material magnetized in the Earth's predominantly dipole field.

The strongest anomaly noted in this representation is that near the Alpha and Mendeleyev Ridges. The vertical (and total) intensity peak is near 95 nT at about 150° W. and 85° N. Except for this positive cell, the remainder of the Arctic Ocean area extending into the northern Canadian Islands shows weaker negative cells. Greenland is covered by two positive cells, each about half the intensity of the north polar high, with one in the north and the other in the south.

The strongest anomaly over Antarctica has a +65 nT maximum in total intensity (but negative in the vertical contours since the vector is reckoned positive downward), and centered over Wilkes Land. This feature is surrounded on the ocean side by a general negative pattern which also intrudes into the Ross Ice Shelf. There are strong negative cells over both East and West Antarctica separated by a weak positive near the geographic pole. A positive feature of comparable intensity is seen over Enderby Land.

There is surprisingly good agreement with the patterns published by Behrendt and Bentley (1968) from an analysis of surface data, though their intensity variations are an order of magnitude greater.

If the high order and degree components of this expansion arise from the crust, the positive areas would represent regions where the total magnetization was highest. Possible geologic correlations have been investigated by Taylor (1982) for the north pole high, by Coles and others (1982) for northern Canadian area, and by Ritzwoller and Bentley (1982) for the Antarctic. These other workers have constructed residual maps derived from selections of Magsat data averaged after reduction by a 13th degree and order field model. They obtain very good agreement with most of the features in our representations for the vertical or total field, and larger differences in the horizontal components.

There are some questions as to whether these features are completely representative of the crustal field. It is not likely that the truncation of a spherical harmonic expansion gives a clean separation of crustal from core components. Judging from the results of Meyer and others (1983) the field model to n=13 must also contain a crustal contribution. If the source of the high order features were in the core, it would imply that they were not simple extensions of the lower order terms, but of greatly enhanced power.

There is also the possibility that some of the features arise from average external field effects. Most of the external currents are field aligned and being nonpotential, appear to have little effect on the potential expansion. Those other workers who have made residual maps from 13th degree potential expansions have carefully selected the data for passes containing little obvious current signatures. Their results generally agree with our own, especially for the vertical component of field. Either the horizontal component of the mostly vertical field-alined currents, or the E-layer ionospheric currents below the spacecraft orbit, could contribute to the residual maps. Due to the careful selection of the data that entered our model and the residual maps of the other workers, these currents are thought to produce only second order affects. However, until the currents can be numerically modeled and their magnetic components evaluated, their possible contamination cannot be evaluated.

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PALEOMAGNETIC STUDIES IN ANTARCTICA

BY RICHARD L. REYNOLDS AND
KARL S. KELLOGG

The use of paleomagnetism to determine rotations and translations of crustal blocks has contributed to our understanding of the tectonic evolution of Antarctica. The units most thoroughly studied paleomagnetically in East Antarctica are the Lower Jurassic Ferrar sills and Dufek intrusion of the Transantarctic Mountains. Virtual geomagnetic poles calculated from these intrusives cluster closely and yield a paleomagnetic pole at latitude 54° S., longitude 153° W. The corresponding paleolatitude requires about 35° of southward drift for cratonic East Antarctica since its separation from Africa in Middle to Late Jurassic time.

Geologic relationships point to a more complex late Mesozoic and Cenozoic tectonic history of West Antarctica than of East Antarctica, and they lead to speculation that West Antarctica consists of at least three distinct crustal segments or provinces having separate patterns of consolidation with the present continent. Paleomagnetic data have been obtained from each of the three provinces—the Antarctic Peninsula, the Ellsworth Mountains, and Marie Byrd Land.

Paleomagnetic studies of the Antarctic Peninsula have focused on the nature—oroclinal or primary?—and age of the pronounced structural curvature along the peninsula. Mean paleomagnetic declinations and associated uncertainty limits, determined for widespread Andean-type Late Cretaceous to Middle Tertiary plutons and dikes north of latitude 68° S., do not require large-scale structural rotations, suggesting that any oroclinal bending occurred prior to Late Cretaceous time. In contrast, paleomagnetic data from rocks of similar type and age from the Orville Coast (latitudes 74°–76° S.) are interpreted to indicate a clockwise rotation of the terrane by about 50°, thus accounting for the curvature of the southern Antarctic Peninsula by oroclinal folding. For the intervening area of the Lassiter Coast (latitudes 72°–74° S.), steep paleomagnetic inclinations combined with large uncertainty limits preclude assessment of oroclinal bending. Paleomagnetic inclinations from these Andean-type intrusives are consistently steep and indicate a lack of significant displacement of the Antarctic

Peninsula relative to the south pole in the past 100 m.y.

A number of investigators have postulated that a small continental fragment containing the Ellsworth Mountains occupied an original position along the Transantarctic Mountains-Cape Fold Belt margin of the Gondwana craton. Only preliminary paleomagnetic results from Cambrian argillites in the Ellsworth Mountains are available to test this postulate, but the data are consistent with such a reconstruction.

Data from Marie Byrd Land are also sparse. A paleomagnetic pole (latitude 36° S., longitude 116° E.) derived from Early Cretaceous intrusive rocks are highly divergent from the Jurassic pole of East Antarctica and from the Cretaceous-Tertiary poles of the Antarctic Peninsula.

The available paleomagnetic data thus support a picture of different tectonic histories for different parts of West Antarctica, but are still too few to test complex models. Continued paleomagnetic research offers potential for clarifying the tectonic evolution of this enigmatic sector of Gondwanaland.

MEDICAL PROBLEMS OF POLAR REGIONS IN THE EARLY 20TH CENTURY

BY STEVE BOYER, M.D.

Many diseases occur in specific temporal and regional settings. Some occur only until their pathophysiology is understood; with the advancement of medical knowledge they are easily prevented and become historical curiosities. These diseases may require infectious agents or dietary or other habits specific to certain regions. Polar explorers of the early 20th century occasionally experienced severe prolonged dietary restriction which, with the state of medical understanding of vitamin metabolism at the time or with their own ignorance of disease processes, created the setting for some interesting medical problems.

During the period 1910–1914 at least three polar expeditions occurred in which one member of the party died from an unknown cause. Detailed descriptions of the slow deaths in the journals of the dying or of their companions have enabled physicians to diagnose retrospectively the problems with varying degrees of certainty.

During the Australian Antarctic Expedition (1911–1914), Douglas Mawson, Xavier Mertz, and Belgrave Ninnis made a sled journey of several hundred miles with dogs into King George V Land. The setting for dietary restriction was created when Ninnis fell into a crevasse with the food sled. Mawson and Mertz then began their return to the coast, working the remaining dogs to exhaustion and starvation before eating their remains, including the livers. Descriptions in their journals of loss of epithelial tissues (hair, skin, bowel lining) and our current understanding of the concentration of vitamin A in predators' livers and its metabolism in humans have led to a relatively certain diagnosis of hypervitaminosis A as the cause of death of Mertz and the near demise of Mawson.

On the second British South Pole Expedition (1910–1913), R. F. Scott and his four companions reached the pole January 17, 1912. The dietary restriction inherent in a man-hauling polar sled journey was exacerbated by Scott's last-minute decision to include Bower in the polar party, requiring that five men live on rations intended for four. In addition to the caloric deficiency, the diet was devoid of vitamin C. On the return, Evans died at the base of the Beardmore several days after a fall into a crevasse. Again, detailed journal descriptions of his medical course enable us to create a differential diagnosis, among the likeliest causes of death being a subdural hematoma from minor trauma, a complication of scurvy (vitamin C deficiency).

While these Antarctic expeditions were taking place, Bernhard Hantzsch, a German zoologist, was leading a party of explorers into the Foxe Basin coast of Baffin Island in the Canadian Arctic. Dietary restriction this time was created by the sinking of their ship in Cumberland Sound, despite which they set off in the spring of 1910 to explore the coast to the north. Returning a year later they were forced to live on polar bear meat which Hantzsch preferred to eat frozen, raw. He did not realize the symptoms he accurately described in his own journals were those of trichinosis from which, there is little doubt, he died.

With a clear understanding of the pathophysiology of each of these illnesses, they have been eliminated as problems of modern expeditions, but so too has the remoteness of the polar regions been eliminated. These case histories are of great medical and historical interest.

MARS-ANALOG STUDIES IN WRIGHT AND VICTORIA VALLEYS, ANTARCTICA

BY E. C. MORRIS AND H. E. HOLT

During the 1971–72 field season, 1,300 photographs were taken of various geologic features in Victoria and Wright Valleys for comparative analysis with the pictures expected to be returned from the Viking Mars Mission in 1976. The cold dry weathering environments of the ice-free valleys of Antarctica provide one of the best terrestrial analogs of surface conditions on the planet Mars. The features photographed in Wright and Victoria Valleys, such as frozen dunes, patterned ground, various rock weathering phenomena, ventifacts, felsenmeers, tors, and desert pavements, have proved to be valuable in understanding features seen in the Viking photographs.

The scene at the Viking landing sites is reminiscent of the rock-littered landscape of Wright and Victoria Valleys. The Viking Lander 1 pictures show a surface strewn with rocks in the centimeter to meter size range. Between the rocks, the surface is blanketed by very fine grained (<100 mm) material that has been sculptured by martian winds into "tails" behind the rocks. Light and dark drifts of this material are distributed across the surface; these drifts probably are remnants of a thick blanket of very fine grained material that once covered the area and was subsequently eroded by wind.

The Viking 2 landing site is a flat boulder-strewn landscape that is part of the vast plains which occupy much of the northern hemisphere of Mars. Large blocks are more numerous here than at the Viking 1 site and are almost monotonous in their similarity to one another. Most of these blocks are subangular, equidimensional, and have numerous pits or holes a few millimeters to a few centimeters across that impart a sponge-like appearance to their surfaces. The interblock areas are composed of fine-grained material and patches of pebbly fragments; in places, this fine-grained material is banked into small drifts between blocks. The surface has a windswept or scoured appearance, and some boulders appear to stand on pedestals of fine-grained material. In many of the interblock areas the fine-grained material forms a discontinuous crust that breaks into platy fragments. A series of interconnecting troughs, typically 1 m wide and 10 to 15 cm deep, are visible at the Lander 2 site. These troughs form a polygonal network that probably developed from contraction either by cooling of lava or from thermal expansion and contraction of frozen ground.

The features seen in the Viking pictures that are analogous to those photographed in Antarctica include: armored pavements, wind tails (erosional and depositional features that record wind direction), ventifacts, frost shattering, and patterned ground.

AN ISOTOPIC AND CHEMICAL STUDY OF LAKE VANDA AND DON JUAN POND, ANTARCTICA

BY IRVING FRIEDMAN, ATHOL RAFTER[1], AND GEORGE SMITH

Temperature measurements made in Lake Vanda and in the lake subbottom sediments show that the high temperatures in the lake are not due to geothermal heat flow, but are probably trapped solar energy as suggested by Wilson.

On the basis of $Sr^{87/86}$ ratios the salts in Lake Vanda can be derived by a mixture of 58% weathered rock plus 42% from sea water or precipitation. Loss of efflorescences high in sodium, potassium and magnesium by high winds can yield the salt compositions present in both Lake Vanda and Don Juan Pond.

From isotopic data on deuterium, O^{18}, C^{13}, $Sr^{87/86}$, S^{34} as well as from chemical data on Lake Vanda waters, interstitial brines contained in the subsurface sediment and C^{14} dates we propose the following lake history:

(1) Fiord.
(2) Uplift caused isolation of Wright Valley from the Ross Sea.
(3) Some of the sea water flushed out by glacial meltwater.
(4) Glacial melt water flowed into the basin. Soluble salts, formed by weathering of local bedrock and salt contributed by original sea water and by precipitation slowly accumulated in the Lake. The climate cooled and inflow was less than evaporation. The lake desiccated. The final desiccation yielded a $CaCl_2$-NaCl brine. Sodium, potassium, and magnesium chloride sulfate and carbonate minerals formed an efflorescence that was

blown away, leaving a brine enriched in calcium chloride.

(5) Crystals of $CaCl_2 \cdot 6H_2O$ formed, enriched in 0^{18} but depleted in deuterium relative to the precursor brine.

(6) A brief climatic warming occurred 2,600±100 years ago resulting in the filling of the basin to the high stand now preserved as high beach levels.

(7) This episode was short lived, and a climate cooler than the present caused the lake to shrink to a low level, or to desiccate completely.

(8) Another climatic warming occurred about 1,200 years ago filling the basin to its present level. The initial warming was warmer than the present, since the inflow shows evidence of possible polar plateau glacier inflow or increased melt water from valley glaciers.

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CLIMATIC SIGNIFICANCE OF LACUSTRINE DEPOSITS AROUND LAKE VANDA AND DON JUAN POND, ANTARCTICA

BY GEORGE I. SMITH AND IRVING FRIEDMAN

Geologic reconnaissance in the valleys surrounding Lake Vanda and Don Juan Pond in Wright Valley, Antarctica, was carried out over a period of several days during November 1973. It was a byproduct of the drilling program at Lake Vanda (DVDP 4) carried out during the Dry Valley Drilling Project, sponsored in part by the U.S. National Science Foundation. The reconnaissance included observations and sampling of lacustrine sediments exposed around both lakes. Erosional shorelines around Lake Vanda have been reported by several workers; lake sediments, also described previously, lie well above the present lake level and consist of thick layers of sand and fine gravel that rest on older coarse gravels. The lacustrine deposits around Don Juan Pond are silts that had not been described prior to our earlier note (Smith and Friedman, 1974).

Large volumes of solid H_2O—ice—exist on the flanks and ends of most closed basins in the Dry Valley area, and a small amount of this ice melts annually to supply the lakes. The sizes of most closed-basin lakes in these areas are limited, therefore, by the amount of liquid H_2O available from their drainage or ground-water supply rather than by the total amount of H_2O. Thus, it is the intensity and length of the warm period during the summer months, acting on the ice areas at lower elevations, that control the amount of melting and the sizes of lakes in the Dry Valley area.

Expansion of Lake Vanda as a result of warmer temperatures was suggested by Nichols (1962), but he related the lake rise to the warming that caused the retreat of Trilogy-age glaciers which had been dated as more than 7,000 yr B.P. The C^{14} dates on algae from around the edges of Lake Vanda suggest that its expansion occurred 2,000 to 3,000 yr B.P. It seems more likely that the expansions of Lake Vanda and Don Juan Pond were the result of a more recent episode of warming, but it may not be documented by the exposed evidence of glacial retreats. The sizes of the present glaciers are presumably in equilibrium with the present climate, and we suspect the enlarged lakes are correlative with major glacial retreats that deposited moraines in areas now re-covered by ice.

The expanded lakes, therefore, seem to indicate a period, possibly only a few centuries long, 2,000 to 3,000 years ago, characterized by slightly-warmer-than-present summers; they raised the snowline, increased the volumes of ice that melted annually from the lower parts of the glaciers and ice-cored debris flows, and caused the glaciers to retreat and the lakes to expand. When the summers cooled and the snowline again lowered, little or no ice remained at the levels where summer melting could occur, and at first the lakes received almost no runoff and nearly desiccated, as inferred from other evidence by Wilson (1964). Eventually, however, the surplus ice accumulating above the new snowline would have been transported by glaciers far enough down into the valleys for summer melting to again produce sufficient runoff to nourish lakes of the sizes and levels we now find.

PROGRAM FOR MAPPING ANTARCTICA

BY PETER F. BERMEL AND CHARLES E. MORRISON

Mapping has been such an integral part of most nations' programs in Antarctica over the past quarter century that it may come as a surprise to learn that a program for Antarctic mapping was not among the activities recommended for the International Geophysical Year (IGY) in 1957-58. When the decision was made to pursue a post-IGY long-range Antarctic research program, the lessons of the IGY left no doubt that mapping must be included.

In the case of the United States, the Antarctic cartographic effort has been located at the U.S. Geological Survey (USGS), funded by the National Science Foundation as part of the U.S. Antarctic Research Program (USARP). The USGS has focused its mapping on West Antarctica and the Transantarctic Mountains to support the requirements of USARP. It has sent field parties to Antarctica every year since 1957 to establish geodetic control and has worked closely with U.S. Navy Squadron VXE-6 to acquire mapping-quality aerial photographs.

The program has been very productive, resulting in over 90 1:250,000-scale topographic reconnaissance maps of West Antarctica and the Transantarctic Mountains. Other products include 1:50,000-scale topographic maps, 1:500,000-scale sketch maps, 1:1,000,000-scale topographic maps and shaded-relief reconnaissance maps, as well as satellite image maps at several mapping scales. Future needs can be met by:

1. A primary series at 1:250,000 scale covering all mapworthy features in the area of West Antarctica and between longitudes 150° E and 180° E.
2. IMW sheets at 1:1,000,000 scale prepared from published 1:250,000-scale maps.
3. Satellite image maps at scales of 1:250,000 and smaller.
4. Larger scale (1:100,000 and larger) maps of areas of special interest where greater detail is warranted.

The USGS effort in support of NSF's USARP is a remarkable story unequaled in Antarctica. Over 100 National Mapping Division personnel have worked there in the field, and the challenge of "the ice" continues to be a lure to the candidates applying to work on the mapping projects.

THE USE OF SATELLITE TECHNOLOGY IN THE SEARCH FOR METEORITES IN ANTARCTICA

BY TONY K. MEUNIER

Until 1969 only four meteorites had been recovered from Antarctica, each during an overland traverse. During the 1969-70 field season, however, Japanese scientists discovered nine stony meteorites in a blue-ice area of the Queen Fabiola (Yamato) Mountains and suggested that Antarctica might prove to be an excellent source of meteorites. In 1973, Prof. William A. Cassidy, a meteoriticist at the University of Pittsburgh, reached the same conclusion and proposed a U.S. program to search for meteorites in blue-ice areas accessible by helicopter from McMurdo Station. Approximately 5,400 meteorite fragments have now been recovered from Antarctica, mostly from blue-ice areas, especially where the normal flow of glacier ice is impeded or stopped; hence blue ice is of special significance in the search for more meteorites.

Delineation of surficial blue-ice patches in Antarctica north of about 81° S. latitude became possible after the launch of the first Landsat spacecraft in July 1972 by providing higher resolution satellite images of various parts of Antarctica. Beyond 81° S. latitude advanced very high resolution radiometer (AVHRR) images from the NOAA series of weather satellites can be used to identify areas of blue ice, although the 1-km pixel size of the image provides 10 times less detail than that available from Landsat MSS. This resolution proved to be adequate in detecting the relatively large blue-ice areas, however. Landsat 1, 2, and 3 MSS have a pixel (picture element) size of about 80 m. The images are usually acquired in four spectral bands: MSS band 4, 0.5 to 0.6 cm; MSS band 5, 0.6 to 0.7 cm; MSS band 6, 0.7 to 0.8 cm; and MSS band 7, 0.8 to 1.1 cm. In the identification of blue-ice areas, MSS bands 6 and 7 are similar, with band 7 somewhat better than MSS band 6. MSS band 5, however, is best in areas of bedrock exposure, because blue ice and rock outcrops usually have a similar spectral response.

Various types of satellite data were used during the 1982-83 austral summer field season on Prof. Cassidy's United States Meteorite-Search Project in Antarctica, in the isolated, unmapped polar plateau region called the "Far Western Ice Fields." In the past, a dead-reckoning type of traverse would normally have to be employed for daily trips to meteorite-collecting areas. The field party used a 1:250,000-scale Landsat 1 image (1200-20293; 8 February 1973) of the meteorite-search area for the planning and execution of oversnow traverses. Although the polar plateau on a continental scale is a relatively flat, featureless area, from a regional perspective, as in the 60 km^2 "Far Western Ice Field," there is significant topographic relief that resembles an undulating ridge- and valley-type terrain. This made local traverses very difficult to negotiate by line-of-sight techniques. Landsat images permitted the field party to intermittently check their positions by locating and following features visible on the images, such as firn patches. Hence, the use of Landsat images was instrumental in successfully completing a number of difficult traverses in both the "Far Western" and "Far Northwestern Ice Fields."

Satellite tracking data were also used, for the first time, to accurately map meteorite finds by using a portable Magnavox 1502 Satellite Tracking Positioning System. This state-of-the-art geoceiver, on loan from the Bureau of Land Management, proved to be very effective in these remote expanses of snow and ice. With the Magnavox 1502, a base line consisting of five geodetic positions over a 30 km × 2 km collecting area was established. At the site of each meteorite find, the meteorite identification number was written on a flag implanted in the ice. After an area was systematically searched, and all the meteorites had been collected, the angles and odometer distances between the base station and the numbered flags were recorded. Final mineralogical identification of each specimen by NASA's Johnson Space Center along with the acquired control will result in a thematic map of the "Far Western Blue Ice Field" collecting area. These are the first controlled survey points ever established in this remote area. In addition, these positions can be reoccupied in the future to measure the change in the x, y, and z parameters. Determining the rate of ice movement in this area will be an important contribution to the understanding of the mechanisms which lead to the concentration of meteorites at blue-ice locations.

Aerial photographs were also used to help select areas for potential collecting sites. All the five blue-ice areas, selected from satellite images and aerial photographs for field investigation, were found to contain concentrations of meteorites. This was totally unexpected and highly significant. The use of satellite technology proved to be effective, and its continued use will be an important tool in the systematic search for and recovery of meteorites in Antarctica.

GLACIOLOGICAL AND GEOLOGICAL STUDIES OF ANTARCTICA WITH SATELLITE REMOTE SENSING TECHNOLOGY

BY JANE G. FERRIGNO, RICHARD S. WILLIAMS, JR., C. SCOTT SOUTHWORTH, AND TONY K. MEUNIER

The Satellite Glaciology Project of the U.S. Geological Survey has been using remotely sensed data to support a variety of glaciological and geological investigations in Antarctica. A significant attribute of the Landsat image is that it contains the precise time of acquisition, providing a method for making "time-lapse" measurements of the dynamics of the coast of Antarctica. Two Landsat images, 1185–13530 and 2022–13582, acquired on 24 January 1973 and 13 February 1975, respectively, were used to determine the velocity of the terminus of the Pine Island Glacier, a tidal outlet glacier on the Walgreen Coast, West Antarctica. During the 750-day interval, the terminus of Pine Island Glacier moved about 4.5 km at an assumed average velocity of 6 m per day.

Landsat images of the Amery Ice Shelf and terminus of the Lambert Glacier were combined as a 1:500,000-scale uncontrolled image mosaic to serve as a base for compilation of 1- and 5-m contours of the shelf derived from 45 Seasat radar altimeter traverses. The successful experiment reemphasized the fact that satellite image mosaics and maps can be effectively used as the compilation base for various types of geological, glaciological, and geophysical data.

Preliminary research with Charles W. M. Swithinbank has established that Landsat images of Antarctica can be used to prepare 1:1,000,000-scale planimetric maps of coastal areas, bedrock exposures, and blue-ice areas of Antarctica. A more accurate delineation of: (1) the coast of Antarctica, including the type of coast (bedrock, floating ice, grounded ice, outlet glacier terminus); (2) areas of bedrock; (3) areas of blue ice; and (4) plotting of other glaciological features (medial moraines, crevasse areas) will result from completion of this effort. The accurate location of blue-ice areas is important to the international program to recover meteorites from Antarctica.

Preliminary research was carried out to determine whether digital processing of Landsat multispectral scanner (MSS) images of rock outcrops in Antarctica could lead to a method of mapping rock units from nunatak to nunatak on the basis of their spectral reflectance characteristics. The Borgmassivet/Ahlmannryggen region of western Queen Maud Land, East Antarctica, located within the Iron Metallogenic Province, was targeted for analysis because of the availability of 1:250,000-scale reconnaissance geological maps (printed on a Landsat image mosaic base) published by the South African Scientific Committee for Antarctic Research.

USGS PROGRAM AT THE SOUTH POLE

BY THOMAS EDMONDSON AND KATHY COVERT

The United States Geological Survey, National Mapping Division, has sent 11 consecutive winter-over teams to the South Pole. This continuing effort has been in support of two ongoing projects. The first project, USGS Doppler Satellite Tracking, was initiated in 1972. Data are collected from overflights of Navy navigation satellites, transmitted to the United States for further data reduction, and then shared with other investigators for detailed analysis. The second project is the USGS Antarctic Seismic Project. In 1974 new seismometers were installed at the South Pole. The seismic station is now part of the Worldwide Standardized Seismograph Network because of its unique location in the Southern Hemisphere and an important source of seismic data. The USGS is responsible for relocating and remonumenting the true geographic South Pole.

This presentation will be a summary of the objectives and accomplishments of the ongoing USGS projects at Amundsen-Scott South Pole Station, Antarctica.

MODELING THE MOVEMENT AT THE POLAR ICE CAP AT THE SOUTH POLE

BY THOMAS HENDERSON

The United States has continuously occupied the South Pole since the International Geophysical Year in 1957–58. The original base was approximately 1 km from the Geographic South Pole and was used until the 1974–75 season. Snow drift accumulation over the old facility forced the construction of a new station about 400 m from the Pole. Manned since 1975, it features a large geodesic dome that shelters the main buildings.

A number of astronomic observations were made by various Pole parties between 1956 and 1970 to establish the position of the old base with respect to the Pole. These were also used to estimate the rate and direction of movement of the polar ice cap. In 1970, Bill Chapman and Bill Jones of the U.S. Geological Survey, National Mapping Division, published mathematical models describing the movement. The latitude-longitude positions calculated from the astronomic observations were first converted to an X-Y rectangular coordinate system, the Y-axis of which was coincident with the average longitude of the observation positions (24°40′ W.). The equations of straight lines were then fit by least squares to the plots of X versus time and Y versus time. The models indicated a movement of 19 m per year parallel to the 37° W. meridian.

The U.S. Geological Survey began sending winter-over teams to South Pole in 1972, primarily to man geodetic satellite tracking receivers. This continual tracking results in precise position measurements for the tracking antenna site.

A substantial amount of position information has been collected for the current site since it was established in 1975. The coordinates computed from satellite data represent a significant improvement in both accuracy and precision over astronomic positions. By analyzing the Doppler frequency shift curves received from passing satellites, ground points are resolved to within 1 m of their true coordinates. This information, then, provides a more accurate data base for modeling the ice movement.

During the winter of 1982, the author set about to generate new models based on the satellite-derived positions from 1975–81. Coordinates are provided in a geocentric X-Y-Z reference system, so the data are immediately usable in rectangular plots. Compensation is made for the slight wobble in the Earth's polar axis when reducing to the geocentric system to eliminate this source of comparison difference. Again, linear least squares fits were made to the plots of X versus time and Y versus time. The resulting three models fit the data with a standard deviation of 0.9 m in both X and Y. They indicate a movement of 10 m per year parallel to the 41°11′ W. meridian.

The models enable the prediction of the Pole position for a future date. Since the new antenna site is tied into a local survey network, the physical marking of the Pole for that date is reduced to a simple surveying operation.

ARCTIC PROGRAM

CONVENER: G. GRYC

HISTORY OF U.S. GEOLOGICAL SURVEY GEOLOGIC EXPLORATION AND MINERAL-RESOURCE EVALUATION, ARCTIC ALASKA

BY GEORGE GRYC AND ROBERT M. CHAPMAN

The history of geologic exploration, mineral resource evaluation, and topographic mapping in Alaska's Arctic region is well chronicled and documented in U.S. Geological Survey (USGS) publications and activities. Although several recorded expeditions traversed parts of the region before 1900, the USGS party in 1901, headed by W. J. Peters and F. C. Schrader, was the first to map in some detail the geologic structure and stratigraphy and topography along a transect from the Brooks Range to the Arctic coast. Their report, published in 1904 as USGS Professional Paper 20, named and described the Lisburne Formation, of Mississippian and Pennsylvanian age and described the sequence and structure of the Cretaceous rocks, both destined to become major petroleum exploration targets in Arctic Alaska. In USGS Professional Paper 109, published in 1919, E. de K. Leffingwell reported on the oil seepages at Cape Simpson, described and named the Sadlerochit Group and Shublik Formation of Prudhoe Bay fame, and described and mapped the geology of the Canning River region, now included in the Arctic National Wildlife Refuge. Leffingwell's description of the ice wedges and other frozen-ground phenomena along the Arctic coast and his proposed explanation for their formation remains a classic reference for students of permafrost. A knowledge of permafrost and its applications to engineering and exploration projects is essential to successful operations in the Arctic.

On the basis of these early reports, President Harding set aside the Naval Petroleum Reserve No. 4 (NPR-4) in 1923, and the U.S. Navy requested that the USGS map and report on the geology and potential resources of the region. From 1923 through 1926, eight USGS parties crossed the Brooks Range and the NPR-4 along many of the major rivers. Their findings were published in 1930 in USGS Bulletin 815, in which P. S. Smith and J. B. Mertie, Jr., concluded that the essential geologic conditions for petroleum accumulation were present, but cautioned would-be prospectors against the adverse geographic factors and the consequent high development costs. They recommended that the next step should be drilling in the Cape Simpson area, followed by geologic studies and more drilling in other areas that appeared favorable.

However, very little additional exploration was conducted on the North Slope until 1944, when a wartime effort (1944–53) was initiated by the U.S. Navy to further evaluate the petroleum resources of what was then popularly referred to as Pet–4. Again the USGS was asked to undertake the geologic aspects of the work. The Pet–4 program established the surface and subsurface framework geology of the North Slope and proved the feasibility of operating a modern-oil exploration program in the Arctic. All the technical results were published in USGS Professional Papers 301 through 306.

Stimulated by a major oil discovery in Cook Inlet in 1957 and building on the knowledge base and know-how provided by the Pet–4 program, the oil industry took up the search for oil in the Arctic and 10 years later discovered the largest field in North America at Prudhoe Bay, east of Pet–4.

The USGS, partly in cooperation with the U.S. Navy, continued its work in northern Alaska during this period, particularly in the Arctic foothills and Brooks Range provinces. While examining and sampling oil shales in northern Alaska in 1968, I. L. Tailleur collected stream sediment samples in the Red Dog area of the DeLong Mountains. Chemical analyses indicated 10 weight percent Pb and thus provided the first hint of sulfide mineralization in the western Brooks Range. Follow-up by other agencies and industry has now defined a "world class" belt of stratabound sulfide deposits that could provide the Nation with a 10-year supply of zinc and a 5-year supply of lead at present consumption rates. On the basis of limited Pet–4 data, F. F. Barnes in 1967 estimated the coal resources of northern Alaska at about 130 billion tons. More recent work by J. E. Callahan and others suggests a hypothetical resource of as much as 3 trillion tons of low-sulfur subbituminous coal. New concepts and syntheses of the geology of Arctic Alaska and the adjacent continental shelves continue to be formulated and published by USGS geologists.

USGS studies in the Brooks Range and on the North Slope have been stimulated and funded in response to a steady stream of national programs and needs, such as the trans-Alaska oil and gas pipelines, the Alaska Mineral Resource Assessment Program (AMRAP), the offshore leasing program, and the recently concluded program mandated by the Naval Petroleum Production Act of 1976. This act transferred the responsibility for Pet-4 to the Secretary of the Interior and renamed it the "National Petroleum Reserve in Alaska" (NPRA). The USGS was directed to (1) continue the exploration program begun by the U.S. Navy in 1974; (2) continue to operate and maintain the Barrow gas fields, which are virtually the sole energy source for the growing community of Barrow; (3) complete a cleanup and rehabilitation program begun by the U.S. Navy; and (4) participate in various resource surveys (the so-called 105(c) studies) and the petroleum resource assessment, (the 105(b) studies). All of the resulting technical data are being released by the Survey, utilizing the National Oceanic and Atmospheric Administration Data Center in Boulder, Colo., and through regular USGS map and book publications.

The USGS's experience in Arctic Alaska in gathering geologic and geophysical data, providing new concepts and syntheses of these data, and assessing resources is an excellent example of the scientific accomplishments that are possible and enhanced by working closely with other agencies and industry. It also illustrates the long leadtime needed to build a knowledge base leading to discovery and development. This knowledge base must be communicated on a timely basis and be in the public domain so that all concerned have access on an equal basis. Old data must be integrated with new findings and periodically reviewed to see what new concepts and interpretations may result. Although some programs may have narrowly defined objectives, spinoffs in other areas and scientific disciplines and serendipitous discoveries are virtually certain, especially in such a frontier region as the Arctic.

TECTONICS OF ARCTIC ALASKA

BY I. L. TAILLEUR, I. F. ELLERSIECK, AND C. F. MAYFIELD

[No abstract]

TECTONIC EVOLUTION OF THE ARCTIC CONTINENTAL MARGIN IN THE BEAUFORT AND CHUKCHI SEAS—EVIDENCE FROM SEISMIC REFLECTIONS

BY ARTHUR GRANTZ AND S. D. MAY

Multichannel seismic-reflection profiles in the northern Chukchi and Beaufort Seas suggest that three pulses of rifting created the first-order geologic structures and localized the sedimentary basins of the continental margin north of Alaska. A Late Triassic-Early Jurassic pulse isolated shelf deposits of the Mississippian to Triassic Arctic Alaska Basin from their sourceland in the present area of the Arctic Ocean and created the east-westerly trending Dinkum graben. This graben, which underlies the eastern half of the Alaskan Beaufort shelf, contains 2 to 4 km of inferred Jurassic to Paleogene clastic rocks.

Late Neocomian to Albian rifting completed the process of continental breakup and formed the Canada Basin of the Arctic Ocean by sea-floor spreading. From 4 to 10 km of submarine-fan and abyssal-plain deposits partially fill this ocean basin. Clastic sediment from southern sourcelands overstepped the newly rifted margin by Albian time and prograded the present continental-terrace sedimentary prism. This prism, more than 13 km thick, is dominated structurally by growth faults and rotational megaslumps; off northeastern Alaska it contains large syndepositional diapiric-shale ridges and Quaternary detachment folds.

Both late Neocomian(?) and latest Cretaceous or early Paleogene pulses of rifting between Wrangell Island and the Chukchi Continental Borderland appear to have thinned the continental crust into which the North Chukchi Basin subsided. The earlier pulse is recorded by marked basinward thickening of Cretaceous strata, and the later one by numerous antithetic faults and foundered fault blocks in the Cretaceous strata. Sediment in the basin is more than 12 km thick. Because the basin underlies the shelf only adjacent to the borderland, these contiguous features may be tectonically related.

THE ARCTIC PLATFORM IN THE NATIONAL PETROLEUM RESERVE IN ALASKA—DEPOSITION, DEFORMATION, AND PETROLEUM POTENTIAL

BY C. E. KIRSCHNER

The National Petroleum Reserve in Alaska (NPRA) covers an area of 93,240 km² or about half of the Arctic slope in the west-central part of northern Alaska. This paper outlines the major elements of the geology and a few aspects of the stratigraphic history and structural development of the Arctic platform that have a significant bearing on the oil and gas potential of the region. The Arctic platform was originally defined as a pre-Albian tectonic feature that occupied the northern part of the present coastal plain and the adjacent area of the Arctic Ocean. I view the area of the platform as extending southward in the subsurface across the NPRA at least to the north front of the Brooks Range.

The stratigraphy is subdivided into three major Phanerozoic sequences: the Franklinian, the Ellesmerian, and the Brookian. The Franklinian sequence, of pre-Mississippian age, consists primarily of metamorphosed sedimentary rocks that are complexly deformed and thus constitute economic basement for petroleum exploration.

The Ellesmerian sequence, of Mississippian to Early Cretaceous age, consists of clastic, bioclastic, and associated sediment in part derived from a northern provenance (Barrovia) that was partly rifted away by the end of Neocomian time. In the following discussion, this sequence is subdivided into three distinct subsequences: lower, middle, and upper. The lower Ellesmerian subsequence, of Mississippian to Early Permian age, consists of nonmarine clastic rocks overlain by marine-shelf bioclastic strata that fill grabens and overlap adjacent horst blocks and uplifts on the Franklinian basement. This subsequence is very thick in the riftlike graben lows and thins rapidly by time-transgressive onlap in a northerly direction.

The middle Ellesmerian subsequence, of Late Permian and Triassic age, includes fluvial to marine-shelf clastic and bioclastic strata that form a sheetlike package across the Arctic platform. This subsequence is relatively thin and, like the underlying lower Ellesmerian subsequence, is also time transgressive northerly on the platform. The distribution of sandstone facies dictates a proximal northerly-provenance terrane. There are no similar shelf deposits on the Arctic platform in post-Triassic time. These sandstone and bioclastic limestone beds are the reservoirs for the giant Prudhoe Bay oilfield east of the NPRA, where these reservoirs are sealed by the overlapping pebble-shale unit of Neocomian age. Only the Barrow gasfields in the NPRA have a similar tectono-stratigraphic setting. The early and middle Ellesmerian reservoir beds in the NPRA are interpreted not to form traps because the rocks are time transgressive on the platform, and so petroleum probably migrated updip with the strandline facies.

The upper Ellesmerian subsequence, of Jurassic and Early Cretaceous (Neocomian) age, includes marine shale, minor sandstone, and mudstone that form a blanketlike package across the platform. The distribution of sandstone facies and southerly prograding foreset beds in the Kingak Shale is interpreted to define a distal northerly provenance that ceased to supply detritus to the platform by late Neocomian time. Other workers have stated that the upper Ellesmerian rocks were deposited in a shallow-marine shelf environment. However, paleontologic bathymetric indicators, core lithologies, electric-log characteristics, and seismic-stratigraphic interpretation all suggest a deep-water basinal environment in which suspended-load or turbidite processes were involved. The upper part of the Ellesmerian sequence is interpreted to have been deposited in a southerly, southwesterly, and southeasterly prograding turbidite fan complex. The sandstone beds that make up the potential reservoir rocks are composed of turbidite channel sandstone that commonly fines upward and of suprafan sandstone sequences that are cyclic and thicken upward. Following this line of reasoning, the Kuparuk River oilfield reservoirs are interpreted to be turbidite sandstone in a combined structural-stratigraphic trap in which the pebble-shale unit forms the overlying stratigraphic seal. In the northwestern part of the NPRA, significant gas shows were penetrated in the Tunalik well within a setting that may be similar to the Kuparuk field. The concept of turbidite reservoirs enhances the potential for primarily stratigraphic entrapment, although these reservoirs may also consist of low-porosity and low-permeability fine-grained silty sandstone with low producing capabilities. Furthermore, oil shows are more common east of the Meade arch, whereas gas shows are more common west of the arch. The latest Neocomian beds are distal pyritiferous shale, rich in organic material, and mudstone deposits. Seismic stratigraphy suggests that these beds were derived from the south in the Brooks Range provenance and indicates that "flip" in provenance to the Arctic platform was completed by the end of Neocomian time.

The Brookian sequence, of Early Cretaceous to Holocene age, includes the latest Neocomian strata and all post-Neocomian formations. The sequence consists mainly of thick flysch and molasse deposits flushed from the rising Brooks Range orogen and dumped into the Colville foredeep to prograde northward and eastward across the Arctic platform and the present Barrow arch. Lowermost Brookian sequence rocks of the Torok Formation are deep-water prodelta turbidites deposited on the platform and over the Barrow arch before uplift during post-Albian time. The turbidite sandstone may offer reservoir targets in a variety of structural and stratigraphic settings. Upper Brookian sequence rocks of the Nanushuk and Colville Groups are delta-plain sandstone and shale that are marine in the east and nonmarine and coal bearing in the west. They offer reservoir sandstone targets that are generally at shallow depths and on small structures, so that the economics of these plays may not be attractive unless a local need is developed.

The Arctic platform province is defined by seismic and well data beneath the Arctic Coastal Plain. The platform dips regionally south beneath the northern foothills province and is interpreted to continue to dip south beneath the southern foothills province at least as far as the north front of the Brooks Range thrust belt. The platform also dips regionally west and east from the north-south-trending Meade arch in the central part of the NPRA.

The northern foothills province is a broadax-shaped wedge incorporating a wrinkled-carpet pattern of detachment folds in Brookian rocks that overlie the regionally south-dipping homoclinal Ellesmerian sequence.

The southern foothills province encompasses two contrasting styles of complex structure. Subparallel to the north front of the Brooks Range thrust belt, the structure, in mainly Lower Cretaceous shale and graywacke, involves very complex bed crenulation, isoclinal folding, and thrust faulting. Northwest of this band, broad ridge-forming bathtub-shaped synclines, which appear to float on a shale substrate (Torok Formation), are separated by long narrow faulted diapiric anticlines. Seismic data do not appear to define evidence of the style of frontal thrust folds in Ellesmerian rocks that are productive, for example, at Turner Valley in Alberta or the Painter Creek reservoir in Wyoming.

The Brooks Range province in the NPRA is characterized by imbricately stacked and folded thrust sheets in mainly Ellesmerian rocks. Current interpretation suggests that these thrust sequences have been involved in very large scale tectonic transport and crustal shortening in the range of 250–600 km. The data suggest that vertical uplift and subhorizontal tectonic transport of Ellesmerian rocks in the western Brooks Range may be at least twice as great as in the Canadian Rockies west of Turner Valley and thus that diagenesis of the source and reservoir beds may be significantly greater.

Because of the structural complexity and the disappointing history of the few wells drilled in the foothills and thrust-belt provinces, it is difficult to develop enthusiasm for their petroleum potential. However, the region is only lightly explored, and new concepts and new data could require a reevaluation in the future. The potential for deep to very deep reservoirs on basement-controlled structures of rather large areal dimensions is untested. These include such features as the Oumalik, Umiat, and Utukok platforms, where reservoir objectives might be present in the depth range of 2,400–7,600 m. Although present concepts of the generation and preservation of hydrocarbons suggest that reservoirs may be gas prone only below depths of about 3,600 m and there may also be serious question as to the presence of adequate reservoir facies, these are apparently large structures that would seem to warrant serious consideration as candidates for future drilling.

Three unique catastrophic-type structures on and adjacent to the Barrow arch are the Avak structure on the Barrow high, Simpson paleocanyon beneath Dease Inlet, and the Fish Creek paleolandslide east of the Fish Creek platform. The Avak structure is situated on the crest of the Barrow high. It is a semicircular feature, 13 km in diameter, that contains severely disrupted beds in the core zone and distinct listric slump faults around the periphery. Gravity and seismic data define a circular low within the boundary of the structure and a central high. The Avak well, which was drilled near the crest of the high, has a large number of core dips ranging from 40° to 90°. Seismic data, lithology, and paleontology define severe bed disruption and uplift of about 100 to 500 m in the core. Oil shows were common, and there is no lithologic or petrographic evidence for high-temperature/high-pressure metamorphism. Previous reports have suggested that this structure was formed by meteorite impact, as a cryptovolcanic structure, or simply by submarine canyon erosion and landsliding. There are major difficulties, however, with all these interpretations. The enigma is, what geologic force could uplift about 11 km^3 of semiconsolidated sediment as much as 500 m with no disruption of the flanking sediment that now contains the South and East, postdisruption, Barrow gasfields?

The Simpson paleocanyon trends northeasterly across the Simpson Peninsula between Dease Inlet and Smith Bay. There is very good seismic, well, and corehole control onshore to define the canyon configuration on the southeast. A total of 32 shallow core tests were drilled in the vicinity of the East Simpson Nos. 1 and 2 wells and the Simpson No. 1 well. On the west beneath Dease Inlet, mud-gun seismic data are poor in quality, but these data in combination with well control establish reasonable constraints on the northwesterly canyon margin. The canyon was cut in Early Cretaceous time in the Nanushuk delta-plain and Torok prodelta sequences. Some data indicate that the canyon axis may reach as deep as the top of the pebble-shale unit near the present coastline. The canyon was backfilled by shale of the Upper Cretaceous Colville Group. The core tests partly define the Simpson oilfield, and a few tests penetrated the basal canyon beds, which have a chaotic structure typical of a submarine-canyon wall. The shallow Simpson oilfield reservoirs are in Nanushuk sandstone, trapped by a leaky seal at the canyon margin. The potential for deeper, possibly economic reserves in turbidite sandstone of the lower part of the Torok trapped at the canyon wall has not yet been explored. It has also been suggested that reservoir sandstone beds may be present in the canyon axis; no data are available to confirm or deny this possibility. Offshore data show a complex of listric gravity faults that may have a headwall scarp near the present coastline. I conclude that this faulting may indicate the presence of a submarine landslide which localized the headward erosion of the canyon.

The Fish Creek paleolandslide covers an area of about 1,200 km^2 on the east-southeast flank of the Fish Creek platform in the northeasternmost part of the NPRA. The boundary of the area is irregular but broadly simple; its internal structure as defined by seismic and well data is very complex and has not yet been mapped in detail. The disrupted beds involved in the slide are the Neocomian pebble-shale unit and the prodelta and turbidite beds in the lower part of the Torok Formation. An interpretation by Tetra-Tech, Inc., concluded that the seismic-diffraction pattern was universally symmetrical and probably due to gas-charged turbidite sand bodies. This interpretation is suspect because there are not only symmetrical diffractions but also one-sided bed-termination diffractions, and well data define 20°–40°-W.-dipping beds in the Torok Formation that are antiregional in comparison with the regional eastward dip. These west-dipping beds are confined to the disrupted part of the Torok Formation and occur in wells where the pebble-shale unit is missing. The pebble-shale unit is interpreted to be cut out by normal listric faulting, which also causes the antiregional panels of westward dip. Although some gas or oil accumulations may be present within the slide complex as interpreted by Tetra-Tech, Inc., the larger potential could be related to turbidite reservoirs of the lowermost part of the Torok trapped at the periphery of the slide. Similar but younger normal listric faulting traps the small Fish Creek oil accumulation. The disruption caused by the Simpson paleolandslide is clearly established as having occurred early in Torok time. The ages of the Simpson paleocanyon and the Avak structure are not so well defined but could be about the same as that of the Fish Creek paleolandslide.

All three of these catastrophic-type structures are, broadly speaking, situated on the Barrow arch. There may be a common casual mechanism, possibly the disruption of gas-hydrate deposits during the beginning of uplift on the Barrow arch. In the case of the Fish Creek paleolandslide, a broadly simple but internally complex landslide resulted. In the case of the Simpson paleocanyon, landslumping triggered the rapid headward erosion of a large submarine canyon. Lastly, in the case of the Avak structure, the disruptive force must have been phenomenal, to uplift the beds of the Neocomian pebble-shale unit at least 500 m. The Jurassic sandstone reservoirs of the Barrow gasfields are overlapped by the pebble-shale unit on the northwest. This zero line probably produced an areally large petroleum reservoir in the early history of the development of the Barrow high. When the Avak structure breached this high, the accumulation was flushed into the Arctic Ocean.

OIL AND GAS RESOURCES OF THE NORTH SLOPE, ALASKA
BY KENNETH J. BIRD

After 40 years of oil and gas exploration by Government and industry, the North Slope is now known to contain resources of both conventional and unconventional oil and gas. Conventional oil is currently the only economic resource, but an important one that contributes one-fifth of daily U.S. production. Unconventional oil resources include heavy oil, tar, and oil shale; unconventional gas resources include tight-gas sand, gas hydrates, coalbed methane, and geopressured methane. Our current understanding of these resources is based on two Government exploration programs, combined with information from U.S. Geological Survey (USGS) onshore and offshore studies, the literature, and industry drilling results.

North Slope oil and gas resources occur in a region of similar geology, informally referred to herein as the North Slope petroleum province, greater than 260,000 km² in area, that includes all lands north of the Brooks Range, an undetermined part of the Brooks Range, and the continental shelf and slope adjacent to the North Slope (fig. 5). This province displays a complex geologic history that includes marine and nonmarine sedimentation from the Precambrian to the Holocene interrupted by unconformities, some of which represent periods of orogeny. Although oil indications are known from pre-Mississippian metamorphic rocks, these rocks are generally considered nonprospective for petroleum and, therefore, economic basement. The petroleum-prospective sedimentary rocks in this province consist of two depositional sequences: an older (Mississippian to Early Cretaceous) relatively thin northern-derived sequence and a younger (Early Cretaceous to Quaternary) relatively thick southern-derived sequence. A long-lasting tectonic event, which began in the Late

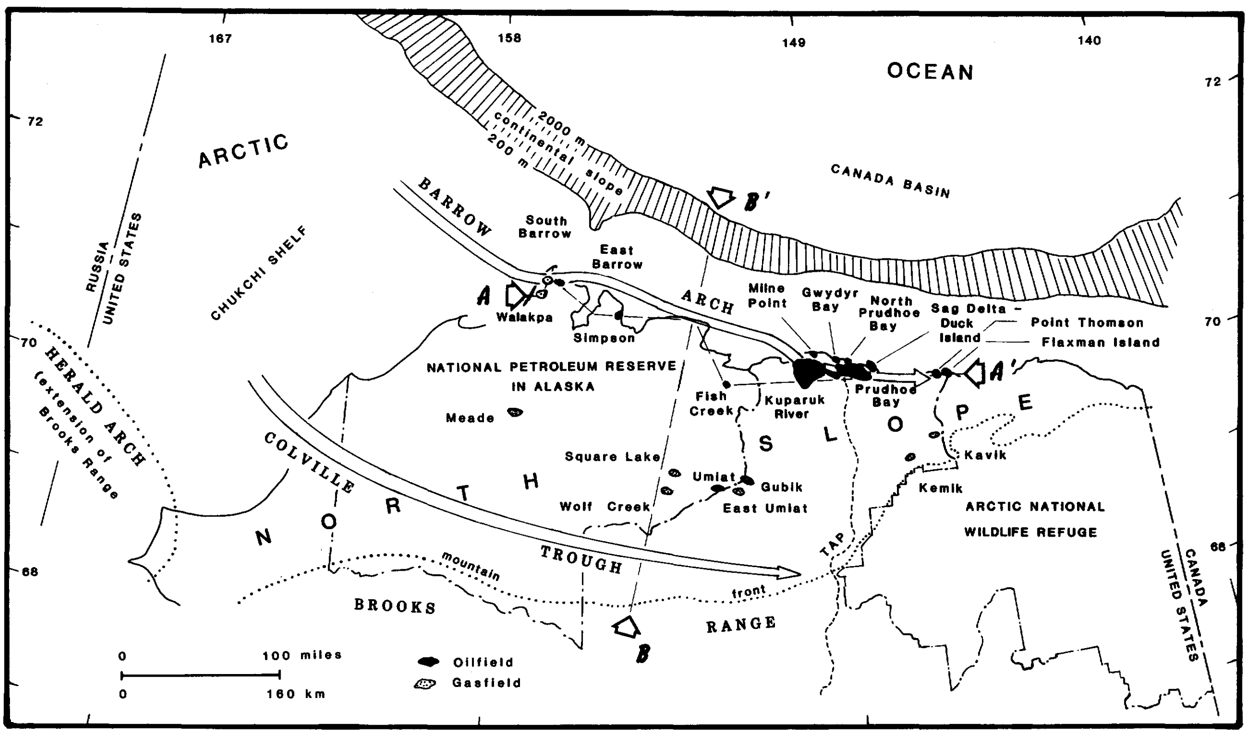

FIGURE 5.—North Slope of Alaska petroleum province, showing oilfields and gasfields, major structural features, Trans-Alaska Pipeline (TAP), and locations of cross sections (A–A′, B–B′) in figure 6.

Jurassic or Early Cretaceous, initially transposed the sediment-source areas and later formed most of the structural features observed in the region today. The time of generation and the locations of most, if not all, North Slope petroleum accumulations are thought to have been controlled by Cretaceous and Tertiary tectonics and sedimentation.

The northern-source assemblage of sedimentary rocks (Ellesmerian sequence), which averages about 2 km in thickness but locally may be three times as thick, was deposited on and partly derived from an erosionally subdued Late Devonian orogenic landmass (economic basement). This assemblage is characterized in the north by good to excellent reservoir rocks (including those in the Prudhoe Bay field) composed of compositionally mature sandstone and dolomite deposited during several transgressions and regressions in nonmarine to shallow-marine environments along an east-west-trending shoreline. These rocks grade southward into finer grained relatively deep marine rocks that are potential source rocks. The most important petroleum-source rocks in this assemblage are marine shale units deposited during transgressions of the sea: the Shublik Formation, the Kingak Shale, and the pebble shale unit (fig. 6).

Rifting during Jurassic and Early Cretaceous time formed the proto-Canada basin and an uplifted basement ridge, part of which is the southeast-trending Barrow arch. This feature later became the focus of migrating hydrocarbons and is now the site of most North Slope oil and gas accumulations in both Ellesmerian and Brookian reservoir rocks. To the south, continental subduction and mountain building, possibly linked to the rifting event, formed the ancestral Brooks Range. During middle Neocomian time, renewed uplift of the rifted margin to the north created a regional erosional unconformity in northernmost Alaska and the offshore areas. Sandstone reservoirs beneath this unconformity locally show improved porosity by leaching. During late Neocomian time, a northward transgression of the sea in response to subsidence of the rift margin resulted in the deposition of a thin marine shale, rich in organic material, that capped the regional unconformity and thus sealed several important reservoir rocks and terminated deposition of the northern-source Ellesmerian-sequence sediment.

In the south, a rising orogenic landmass characterized by low-angle northward-directed thrust faulting (the ancestral Brooks Range) shed debris into an adjacent foredeep (the Colville trough). A prograding wedge of sediment, characterized by a distinctive shelf-slope-basin geometry, filled the foredeep with at least 6 km of deep-marine to nonmarine clastic sediment (Brookian sequence) and eventually overlapped the now-submerged Barrow arch. Reservoir rocks in this sequence consist of sandstone rich in lithic fragments, deposited in nonmarine to deep-marine environments. The reservoir quality of these rocks is generally poorer than that of Ellesmerian reservoir rocks. The petroleum source rocks consist of marine prodelta, slope, and basinal shale units. Basin filling, maximum sediment loading, and the deformation of these rocks into a series of long linear fault-cored detachment folds proceeded from the southwestern part of the North Slope during Albian(?) time to the northeastern part of the North Slope during late Tertiary time. Deposition of the Brookian sequence is believed to have provided the deep burial and subsequent heating of source rocks necessary for the generation of oil and gas in this province. Folding and faulting of reservoir rocks accompanying deposition of the Brookian sequence provided traps for migrating oil and gas. Oil and gas indications are known in nearly every reservoir rock in the province.

To date, 21 oilfields and gasfields have been discovered on the North Slope and nearby offshore areas, but only two oilfields, the Prudhoe Bay and the Kuparuk River, are economic. These two oilfields are among the largest in the United States and currently produce 1.6 million barrels of oil per day via the Trans-Alaska Pipeline. All North Slope gasfields are subeconomic—including the 29 trillion ft^3 of gas in the Prudhoe Bay field, representing about 14 percent of 1981 U.S. gas reserves. However, gas is produced from the South and East Barrow fields for local consumption by the village of Barrow. The South Barrow field, discovered in 1949, is distinguished as the earliest Arctic gas to be discovered and produced.

The latest USGS estimates of petroleum resource remaining to be discovered in the entire onshore and offshore North Slope petroleum province (mean value of recoverable resources) are 14.4 billion barrels of oil and 73.2 trillion ft^3 of gas. The area of most exploratory interest is currently the Barrow arch, particularly its offshore extension.

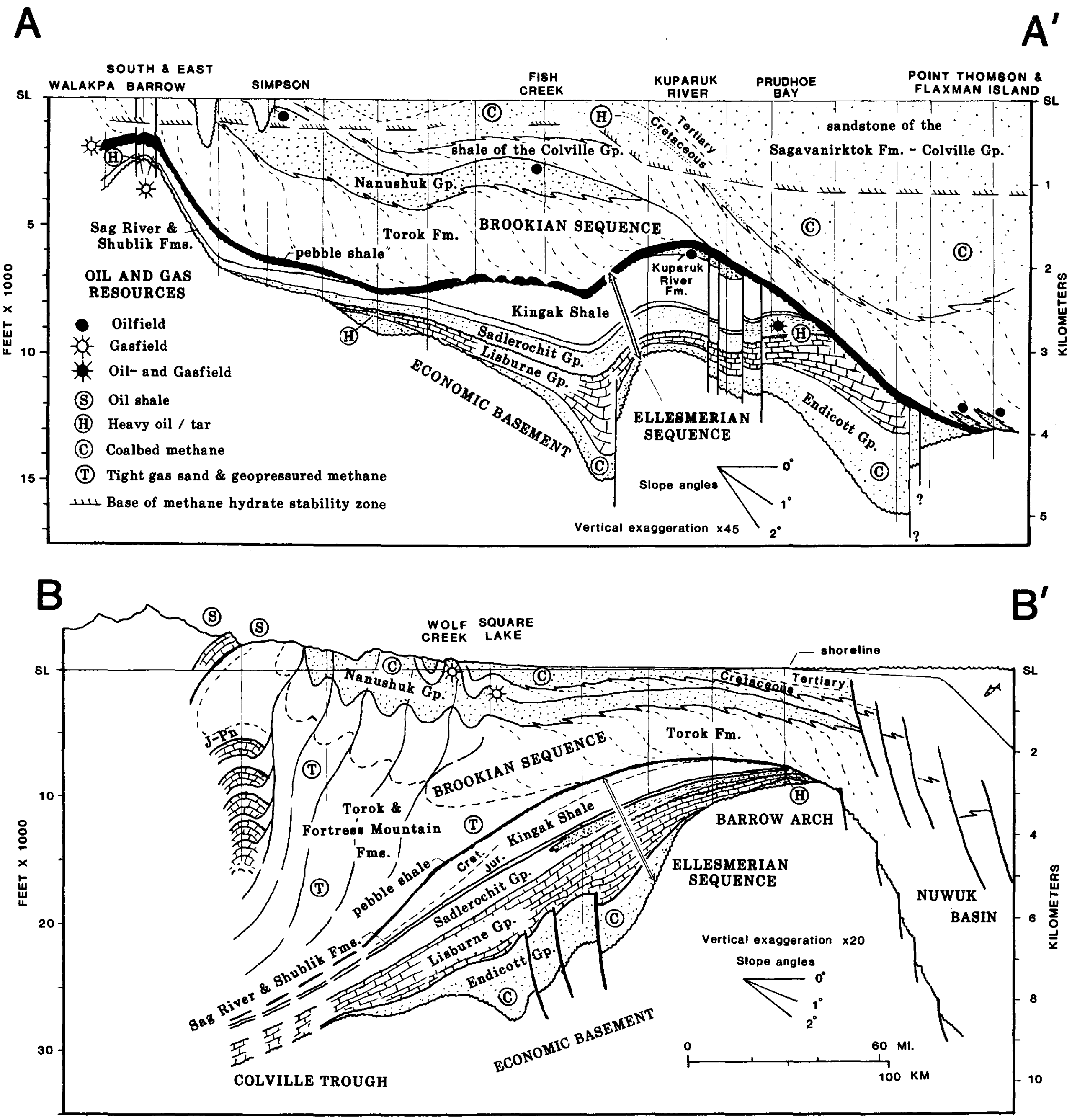

FIGURE 6.—Cross sections of North Slope petroleum province, showing occurrence of oil and gas resources. Thin vertical lines are selected wells. Horizontal scale and resource symbols are the same for both sections. See figure 5 for locations.

As reserves of conventional oil and gas resources decline and their replacement becomes more difficult, more interest is generated in unconventional oil and gas resources to meet the need for replacement. These resources or the requisite physical conditions for their existence are known to occur in the North Slope petroleum province. Figure 6 shows the locations of these resources or the places where the requisite physical conditions exist. General evaluation of these resources, however, is in only the very earliest stages. Heavy oil and (or) tar, which reportedly amounts to 18–40 billion barrels in place, occurs in shallow Upper Cretaceous sandstone reservoirs overlying the Kuparuk River field; an additional 2 billion barrels in place is reported at the base of the oil column in the Prudhoe Bay field. Small amounts of heavy oil have been recovered from several wells in other areas of the Barrow arch. Oil-shale occurrences are limited to small isolated surface exposures in the foothills of the Brooks Range. These oil-shale occurrences, which apparently represent basinal condensed deposition during Mississippian, Triassic, and Jurassic time, are tectonically displaced and of limited areal extent. Tight-gas sand and geopressured methane are known in several areas of the Colville trough in Brookian and uppermost Ellesmerian rocks. Gas hydrates were reportedly cored in an industry well near Prudhoe Bay, and the pressure and temperature conditions necessary for the existence of hydrates occur over a wide onshore area generally within 50 km of the shoreline. Coalbed methane potential is limited to the relatively shallow occurrences in the nonmarine part of the Brookian sequence and the relatively deep occurrences in the lowermost part of the Ellesmerian sequence. Brookian coal volumes are very large, whereas Ellesmerian coal volumes are largely unknown.

The role of the USGS in the exploration and development of North Slope oil and gas resources continues to be important. From the earliest general North Slope studies at the turn of the 20th century to the current focused studies of oil and gas resources, the USGS has provided the public with an impressive body of useful scientific data and interpretations pertinent to hazard identification, land classification, and resource evaluation.

PETROLEUM SOURCE ROCK RICHNESS, TYPE AND MATURITY FOR FOUR ROCK UNITS ON THE ALASKAN NORTH SLOPE—ARE THEY SOURCES FOR THE TWO OIL TYPES?

BY LESLIE B. MAGOON AND GEORGE E. CLAYPOOL

Since 1976, the U.S. Geological Survey (USGS) has been engaged in a comprehensive petroleum geochemical study to assess the petroleum resources on the Alaskan North Slope. This study involves the collection and interpretation of geochemical data not only from exploratory wells drilled in the National Petroleum Reserve in Alaska (NPRA) but also from wells drilled to the east in the Prudhoe Bay area and from rocks exposed in the Arctic National Wildlife Refuge and in the Brooks Range from Cape Lisburne to the United States/Canadian border. More than 17 different kinds of rock analyses, eight different oil analyses, and three gas analyses are being used to evaluate rock (outcrop samples, core, drill cuttings), oil (seeps, drill stem test, oil-stained core, producing well), and gas (drill stem test, producing well) samples on the North Slope. To date, the more than 60,000 analyses completed on these samples have been placed into a computer-based file for storage and retrieval in tabular, graphical, or map form; numerous graphical software programs have been written to facilitate interpretation and publication. So far, these petroleum geochemical data have been used to map and evaluate the organic matter content, type, and thermal maturity of the major rock units and to characterize the known oil and gas occurrences.

This evaluation of petroleum source rock richness, type, and thermal maturity on the Alaskan North Slope is based on five petroleum geochemical analyses (organic carbon content, C_{15+} hydrocarbon content, elemental analysis, visual kerogen, and vitrinite reflectance) that were routinely performed on rock samples from 63 Government-drilled wells within or adjacent to the NPRA. Samples were selected from rocks ranging widely in depth and age: from surface to 20,000 ft and from Tertiary to Ordovician. Sample material includes drill cuttings, sidewall cores, and conventional cores. Contour maps to evaluate the petroleum source rock richness, type, and thermal maturity were drawn for 12 of the stratigraphic units penetrated.

Organic carbon content (wt %), C_{15+} hydrocarbon content (ppm), elemental analysis, and visual kerogen type indicate that the Shublik Formation (Triassic), the Kingak Shale (Jurassic), the pebble shale unit, and the Torok Formation (both Cretaceous) are petroleum source rocks. Even though rock units younger than the Nanushuk Group (Cretaceous) have organic carbon contents higher than 1 wt %, they are so immature that they can be considered only potential source rocks. The Nanushuk Group and the Sag River Formation (Triassic) include shale that, in most places, resembles the source shale within the Torok Formation and the Shublik Formation/Kingak Shale, respectively. The Endicott (Devonian and Mississippian), Lisburne (Mississippian and Pennsylvanian), and Sadlerochit

(Permian and Triassic) Groups, though not source rocks, contain migrated hydrocarbons.

Thermal maturity, measured by vitrinite reflectance (% R_0), increases from north (the Barrow high) to south (the Colville trough). Within the Colville trough, for a given stratigraphic depth, the western part of the NPRA region has a higher reflectance value than the eastern part. Within the NPRA, well control is sufficient to indicate that the Upper Cretaceous and Tertiary rocks are in the diagenetic stage (¼0.6% R_0) of petroleum generation. Substantial volumes of the Jurassic and Lower Cretaceous rocks have reached the liquid window or catagenic stage (0.6–2.0% R_0), whereas most of the pre-Jurassic rocks are in the metagenetic stage (½2.0% R_0) of petroleum generation.

A total of 40 oil samples from across the North Slope have been analyzed by the U.S. Bureau of Mines and the U.S. Geological Survey. Results of these analyses suggest two distinct genetic oil types. The first, the Simpson-Umiat oil type, occurs in reservoir rocks of Cretaceous and Quaternary age and includes oil from seeps in the Skull Cliff, Cape Simpson, Manning Point, and Ungoon Point areas, and oils from Wolf Creek test well no. 3 and the Cape Simpson and Umiat oil fields. These are higher gravity, low-sulfur oils with no, or only slight, odd-numbered *n*-alkane predominance and pristane-to-phytane ratios greater than 1.5. Also, these oils have ^{13}C values ranging from −29.1 to −27.8 permil and ^{34}S values ranging from −10.3 to −4.9 permil.

The second type, the Barrow-Prudhoe oil type, occurs in reservoir rocks of Carboniferous to Cretaceous age and includes oils from South Barrow gas field, Prudhoe Bay oil field, and Fish Creek test well no. 1. Physical properties of the Barrow-Prudhoe oil vary, but generally the oil is a medium-gravity high-sulfur oil with slight even-numbered *n*-alkane predominance and pristane-to-phytane ratios less than 1.5. This oil has ^{13}C values of −30.3 to −29.8 permil and ^{34}S values of from −3.0 to +2.1 permil.

The next phase of this work is to determine which rock unit may have generated a particular oil type. Toward this goal, a unique 2-year study has been carried out by 30 research groups from Government, industry, and academia, representing the United States and seven other countries, to analyze the same 15 rocks and nine oils from the North Slope. This study, conceived and organized by the USGS and sponsored by the American Association of Petroleum Geologists (AAPG), included a 4-day research conference in 1983, a 1-day short course at the AAPG 1983 Annual Meeting in Dallas, and a symposium volume that will be published in 1984. There were three objectives: (1) to provide similar data on the same samples from various research groups for interlaboratory comparison; (2) to compare various analytical techniques used by different research groups in evaluating petroleum source rocks and oils; and (3) to determine which shale units penetrated in the NPRA could have been sources for North Slope oils. Research methods, results, and interpretations varied widely. One method that was commonly used was a conventional one—gas chromatography. In addition, other groups applied the more advanced technology of computerized gas chromatography/mass spectrometry (GC-MS), which enabled the researchers to examine both saturated and aromatic hydrocarbons in greater detail; carbon isotope, fluorescence, and pyrolysis were other methods employed. Results from a few groups indicated no correlation between any of the shale units and oils. However, the consensus was that the Shublik Formation and the Kingak Shale correlate with the Barrow-Prudhoe oil type and the pebble shale unit and, possibly, the Torok Formation are the source for the Simpson-Umiat oil type.

Future work for our group will include (1) further investigation into oil-rock correlation to refine our understanding of the origin of North Slope oil and (2) interpretation of the large number of petroleum geochemical data on samples acquired in the Brooks Range thrust belt. Results of investigations should provide clues to the oil and gas potential of the thrust belt and reveal how this belt relates to the oil accumulations in the north.

EMERGING RECOGNITION OF THE NONFUEL MINERAL RESOURCES OF ARCTIC ALASKA

BY DONALD GRYBECK

Some of the most exciting new mineral discoveries in Alaska during the past two decades have been in the Brooks Range, yet conventional wisdom 25 years ago was that northern Alaska was rather unpromising, if not geologically unfavorable for mineral deposits. Nonetheless, what has emerged in the Brooks Range is a mineral frontier, largely as a result of detailed geologic mapping, systematic mineral exploration, better accessibility, and new ore-deposit models.

In 1898, a wave of prospectors began moving through northern Alaska in their quest for gold, and by 1909 they had discovered all the gold placer districts that are known today—Chandalar, Koyukukk, and Kiana—as well as several lode prospects. Also in 1898, the U.S. Geological Survey (USGS) began its geologic exploration of northern Alaska and by the early 1940's had mounted several expeditions that defined the basic geographic and geologic framework of northern Alaska. In 1944, the USGS began extensive geologic studies of Naval Petroleum Reserve Number 4, and by 1953 had a good understanding of the geology of the Arctic Coastal Plain and the Arctic foothills. But by 1950, in spite of more than a half-century of work, the geologic map of the Brooks Range still had large blank areas, most of the range remained essentially inaccessible, and relatively little mineral exploration had been done. In the early 1950's, helicopters were first used for geologic mapping in the Brooks Range. Although their introduction produced no immediate breakthroughs, in retrospect it was pivotal. Systematic geologic mapping and mineral exploration became practical for the first time and has continued unabated since.

In 1957, Bear Creek Mining Co. began exploration of the bornite copper deposit in the Ambler district and soon after began mineral exploration throughout the Brooks Range. Their first world-class discovery was the Arctic copper-zinc massive sulfide deposit in 1965. Further work by several companies has now detailed a belt of copper-zinc massive sulfide deposits more than 160 km long along the south flank of the Brooks Range. Similarly, the initial discovery of zinc-lead mineralization in the De Long Mountains by I.L. Tailleur of the USGS in 1969 has led to delineation of the Red Dog deposit, a large volocanogenic massive sulfide deposit now being developed by Cominco Ltd., as well as several smaller similar deposits, and to recognition of widespread potential for other volcanogenic deposits along the northwest flank of the Brooks Range. Though not so noteworthy, numerous other deposits of various types have been found in the past 20 years, including several porphyry copper deposits, one porphyry molybdenum deposit, several barite deposits, and many others.

In view of the naivete of past projections, it may be premature to suggest how many mineral deposits yet lie undiscovered in northern Alaska, or their locations. However, even if some of the larger deposits have already been found, large areas have yet to be examined in any but cursory fashion and the expanding geologic data base and catalog of identified types of deposits strongly suggest that many other large deposits do exist in the Brooks Range.

COAL OCCURRENCE, QUALITY, AND RESOURCE ASSESSMENT, NATIONAL PETROLEUM RESERVE IN ALASKA

BY GARY D. STRICKER

Field studies by U.S. Geological Survey personnel in 1977 and 1978 of the Cretaceous Torok, Kukpowruk, and Corwin Formations in the western portion of the NPRA (National Petroleum Reserve in Alaska) and Cretaceous Torok, Tuktu, Grandstand, and Chandler Formations in the eastern portion of NPRA indicate that two major delta systems are responsible for most of the coal accumulation in this area. The Corwin delta in the western portion of NPRA was an early Albian to Cenomanian, north and east prograding system, whereas the slightly younger mid-Albian to Cenomanian Umiat delta system prograded north and northeast in the eastern portion of NPRA. Investigations of the lithologies, fossils, and primary depositional structures of these formations indicate that the Corwin system was deposited as a large, high-constructional, "birdfoot" shaped delta on which thick (as much as 10 m) and numerous coals developed on splay and interdistributary bay platforms away from the influence of the Cretaceous epicontinental sea. The Umiat delta started out as a high-constructional system but in time became wave dominated, and its shape changed to lobate. Boreholes indicate that north of the outcrop belt, the rocks of the Umiat delta quickly lose their non-marine characteristics. Because of the small size of the Umiat delta and marine influences on it, coals were laid down in sparse, thin, and discontinuous beds.

Eighty-six coal samples have been collected from NPRA as part of a comprehensive program by the U.S. Geological Survey to describe the chemistry of United States coal. These samples consist of face channel, grab, auger, and drill core samples. Proximate and ultimate analyses, heat-of-combustion, air-dried loss, and forms-of-sulfur determinations were run on 36 samples; major and minor oxides and trace element analyses were performed on all 86 samples to determine coal quality. An additional 20 proximate and ultimate analyses were determined by the U.S. Bureau of Mines. In a total of 106 samples, 10 samples are from the eastern portion, 9 samples from the central portion, and the remaining 87 are from the western portion of NPRA.

Apparent coal rank ranges from lignite A to high volatile A bituminous coal, with the highest ranked coals located in the southern half of NPRA. Sulfur content ranges from 0.10 percent to 2.0 percent, which appears comparable to that of other Western United States coals of similar rank. The concentrations of trace elements of environmental concern such as As, Be, Hg, Mo, Sb, and Se also appear similar to major Western United States coals.

Published estimates of unidentified coal resources in NPRA range from just over 100 billion to 3.3 trillion short tons. Based on published data, there are approximately 50 billion short tons of identified coal resources in NPRA. For an area as large as NPRA, available data are insufficient to indicate any realistic potential coal resources.

PERMAFROST AND THE GEOTHERMAL REGIME

BY ARTHUR H. LACHENBRUCH AND B. V. MARSHALL

Permafrost is the region in the solid earth where the temperature is below 0°C summer and winter. Within this region, water usually occurs as ice, often in massive segregated forms, although capillary water, brines, and gas hydrates also occur. The frozen condition renders permafrost impermeable to water flow, subject to brittle fracture under seasonally induced thermal stress, and subject to mechanical failure and flow when thawed by natural processes or disturbed by man. Hence an understanding of the factors controlling the geothermal regime is necessary for an understanding of geomorphic processes and for successful design of engineering structures such as roadways, heated buildings, pipelines, and oil wells in permafrost terrains. Studies of these factors are greatly simplified by the general absence of heat transfer by flowing ground water; temperatures can be estimated with confidence from heat-conduction theory if the ground surface temperature, regional heat flow, and thermal properties are known.

The equilibrium thickness of permafrost varies inversely with regional heat flow and directly with thermal conductivity, and the subzero value of mean surface temperature. Thus the heat flow and surface temperature are similar at Barrow and Prudhoe Bay, but permafrost is twice as thick at Prudhoe Bay (620 m) because the thermal conductivity of the ice-rich siliceous sediments there is twice as great. The primary cause of variable permafrost thickness at NPRA (200–400 m) is probably local variation in thermal conductivity. However, work in progress by our colleagues, John Sass and Robert Munroe, suggests that there might also be important lateral variations in heat flow, possibly associated with migration of fluids deep in the sedimentary basin.

The periodic variation in surface temperature from summer to winter determines the position of the top of permafrost, as it generates the active (seasonally thawed) layer upon which man's activities take place. The thickness of the active layer is very sensitive to its thermal properties and to the mean and annual range of surface temperature. Modification of the surface, whether by natural processes or by man, generally changes all three parameters and the thickness of the active layer as well. Seasonal temperature variations also cause visco-elastic thermal stress in permafrost which results in networks of recurring tension cracks, meters deep and tens of meters apart. Seasonal freezing of meltwater in the cracks results in the growth of networks of massive ice wedges; differential settlement of the tundra surface above these wedges under changing active layer conditions, controls surface drainage patterns and is a principal cause of damage to engineering structures.

Recent systematic changes in the mean annual surface temperature leave tell-tale curvature in the geothermal profile from which the surface change can be investigated by conduction theory. Observations in wells along the Alaskan Arctic Coast indicate a surface warming of 1½ to 3°C in the last 100 years or so with a net accumulation of heat by the solid earth surface of 5–10 Kcal/cm^2 during the event.

Surface bodies of water such as lakes, rivers, and shallow seas that do not freeze to the bottom represent hot spots on the surface in permafrost terrain. In northern Alaska, such bodies deeper than 2 m have mean bottom temperatures close to 0°C, about 10°C warmer than the emergent surface beyond their shores. The configuration of these bodies continually changes as lakes are drained or shorelines migrate as a result of thermal erosion. Two- and three-dimensional transient conduction models permit a calculation of the configuration of the underlying thawed region for application to water-supply problems, or a reconstruction of the shoreline history from the lingering thermal effects at depth. According to a recent synthesis by David Hopkins, rising sea level and thawing ice-rich sea cliffs probably caused the shoreline of the Beaufort Sea to retreat tens of kilometers in the last 20,000 years inundating a part of the Alaskan continental shelf that is presently the target of intensive oil exploration. A simple transient conduction model applied to the Prudhoe Bay area suggests that this recently inundated region is underlain by near-melting, ice-rich permafrost to depths of 300–500 m; its presence is important to seismic interpretations in oil exploration and to engineering considerations in oil production. When permafrost configurations are confirmed by offshore drilling, heat-conduction models should yield reliable new information on the chronology of arctic shorelines.

GLACIATION IN ARCTIC ALASKA
BY THOMAS D. HAMILTON

The glacial record of arctic Alaska includes advances of late Tertiary age, a complex sequence of Pleistocene fluctuations, and minor expansions of cirque glaciers during the Holocene. Glaciers originated mainly within the Brooks Range, a 150-km-wide mountain chain that extends across northern Alaska. The range evidently supported extensive ice caps during late Tertiary and early Pleistocene glaciations, because erratics of Brooks Range provenance indicate that large ice streams and piedmont glaciers fed from alpine sources extended far to the north across the Arctic Slope. Glaciers of middle and late Pleistocene age were successively less extensive; they were mainly confined to mountain valleys and flowed only short distances beyond the north flank of the range. A second ice source, probably in the Canadian Arctic, was responsible for ice-rafted erratics in late Cenozoic marine deposits along the Arctic coast east of Barrow. A third ice source may be indicated by erratics of unknown provenance in Tertiary(?) gravel near the Colville River delta. Only the record produced by Brooks Range glaciers will be considered here (fig. 7).

Pre-Pleistocene(?) Glaciation. The oldest glacial interval in the Brooks Range is represented by the informally named "Gunsight Mountain" erratics—isolated boulders of highly resistant rock types beyond the limits of recognizable drift of Pleistocene age. These erratics typically occur on uplifted plateaus along the north flank of the Brooks Range; they cannot be traced to existing mountain valleys. The extent of erratics north of the range suggests that much of the precipitation that nourished the glaciers may have been derived from the north, probably prior to formation of the present sea-ice cover over the Arctic Basin.

Early(?) Pleistocene Glaciation. The oldest recognizable drift sheet in the Brooks Range is assigned to the Anaktuvuk River Glaciation. Glaciers of Anaktuvuk River age flowed through mountain valleys at levels generally 100 m or more above their modern floors. Extensive moraines beyond the mountains are fairly continuous but subdued, with low slope angles, mature drainage networks, complex thaw-lake basins, and sparse erratics. The drift sheets have been dissected by streams that flowed 40–65 m above modern levels and eroded valleys as wide as 10 km within the glacial deposits.

Middle Pleistocene Glaciation. The complex of drift sheets assigned to the Sagavanirktok River Glaciation was deposited after a long interval of valley enlargement and pedimentation that followed Anaktuvuk River time. Drift extends into valley centers, where it generally stands within 40 m of modern stream levels. Moraines retain much of their original morphology, but deposits are deeply oxidized, subdued by mass wastage, and dissected by streams. Two separate drift sheets assigned to the Sagavanirktok River Glaciation are present locally.

Late Pleistocene Glaciation. Glacial deposits of late Pleistocene age occupy modern valley floors and generally are little eroded; their stony surfaces lack deep weathering. The drift sheets are divisible into older and younger complexes, assigned respectively to the Itkillik and Walker Lake Glaciations of early and late Wisconsin age. Itkillik deposits are slightly oxidized, and are somewhat subdued by postglacial solifluction and patterned-ground formation. Walker Lake deposits, dated by radiocarbon at between 24,000 and 11,500 yr B.P., are morphologically fresh, have little solifluction cover, and still are partly ice cored.

Holocene Glaciation. An interval of milder

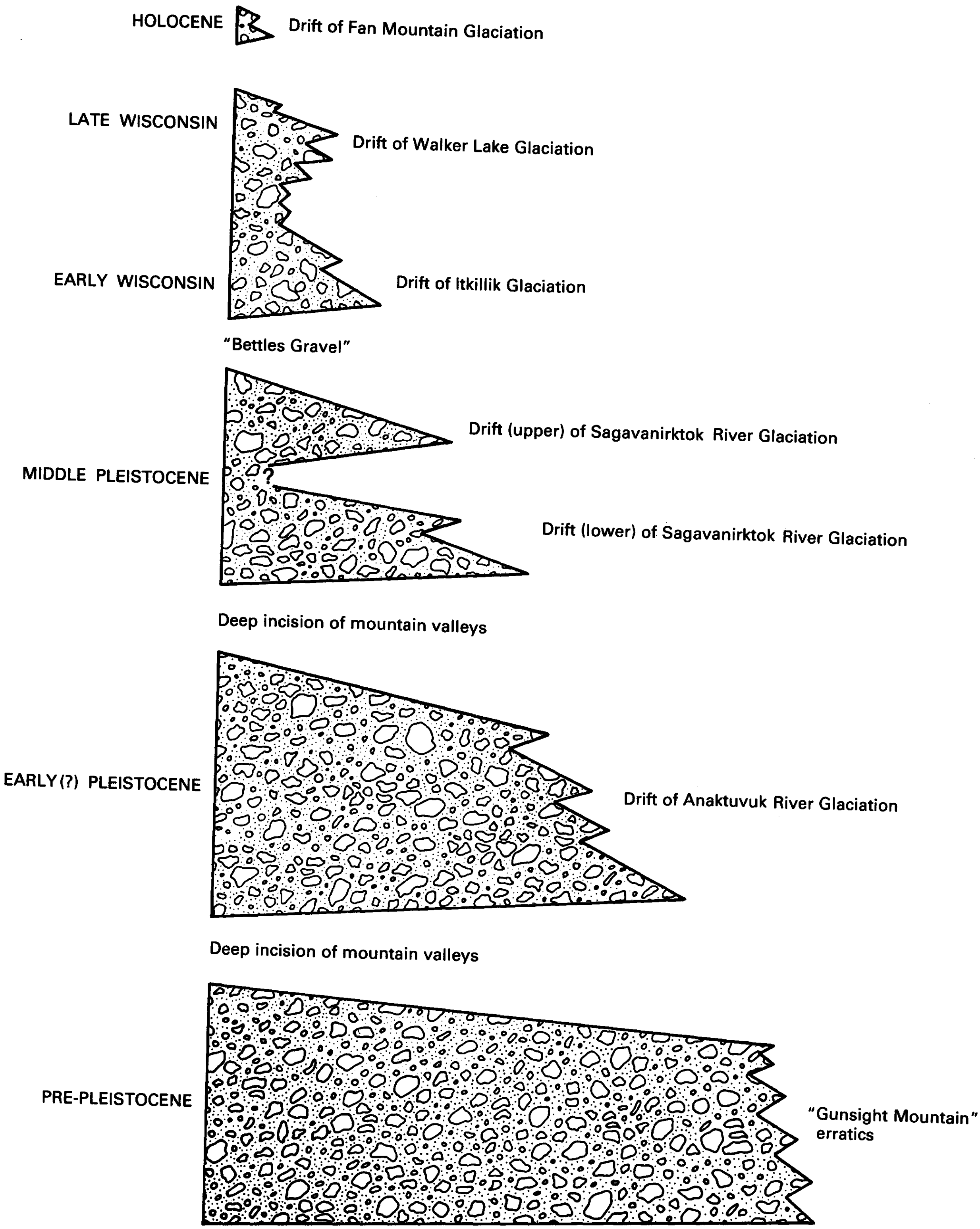

Figure 7.—Time-distance diagram, showing late Cenozoic events and glacial deposits of the north-central Brooks Range, Alaska. Horizontal axis (not to scale) shows distance north of modern valley heads along Continental Divide.

climate in northern Alaska was followed by ice advances and alluviation of mountain streams beginning around 4,500 to 3,000 yr B.P. Drift formed by expanded cirque glaciers in the Brooks Range is assigned to the Fan Mountain Glaciation, which occurred in two phases separated by a milder interval between about 2,000 and 1,000 years ago.

A PLEISTOCENE SAND DESERT IN ARCTIC ALASKA

BY L. DAVID CARTER

A sand desert composed of large dunes and barren sand plains extended across a significant part of Arctic Alaska north of the Brooks Range during late Pleistocene time. The dunes occupied about 11,600 km^2 of the Arctic Coastal Plain west of the Colville River, and the sand plains extended at least 100 km northeast of the dunes. This sand desert was part of an eolian system that extended about 400 km from sediment sources on outwash plains and fans in the east to where waning winds deposited loess along the margin of the Arctic Foothills southwest of the dunes.

Linear dunes, as much as 20 km long and 1 km wide (Carter, 1981), make up the eastern 7,000 km^2 of the dune field, but dune types in the rest of the area have not yet been classified. All the Pleistocene dunes are obscured by a thin cover of younger eolian sand that includes small stabilized longitudinal and parabolic dunes, identified during earlier U.S. Geological Survey fieldwork (Black, 1951). In addition, the Pleistocene dunes have been extensively modified by thermokarst processes.

Radiocarbon ages of herbaceous plants from eolian and lacustrine sand within the dune field indicate that the dunes were active from before 36,000 to nearly 12,000 yr B.P. Bedding attitudes, dune-ridge orientations, and measurements of pseudocrosslamination formed by climbing adhesion ripples demonstrate a wide regime similar to that of the present and indicate that the dominant directions of sand-moving winds were easterly to northeasterly.

Former barren-ground and dry-surface conditions upwind of the dunes are indicated by fossil sand wedges, as much as 7 m deep and 3 m wide (Carter, in press). Observations of modern sand wedges in Antarctica indicate that these wedges develop beneath vegetation-free surfaces in the most arid regions by the repeated formation of thermal-contraction cracks and subsequent filling with loose sand. The Alaskan fossil sand wedges are composed of sand that is texturally distinct from the host materials but similar to the sand composing the dunes. The loose sand that filled the thermal-contraction cracks evidently was derived from wind-driven sand moving across the coastal plain toward the dunes.

The linear dunes and sand wedges thus define a zone of mobile sand that was dry, barren, and windswept during middle and late Wisconsinan time and, possibly, throughout the Wisconsinan. During this same period, however, large lakes formed south of this zone where drainage from the Arctic Foothills was blocked by the dunes; and in the loess terrane south and west of the lakes, surface moisture was sufficient to create syngenetic ice wedges. Extensive tracts of barren ground may have been limited to the zone of mobile sand during much of this period because radiocarbon dating of fossil bones indicates that before 28,000 years B.P. vegetation in the loess terrane was sufficient to support such large herbivores as mammoth, horse, and bison (Carter, 1982). However, none of the dates on these mammals is less than 28,000 years B.P., and few organic remains have been found in coastal-plain deposits between 14,500 and 28,000 years old relative to both older and younger deposits. Desert conditions may have expanded beyond the zone of mobile sand during the late Wisconsinan cold phase to include most of the Arctic Coastal Plain and the Arctic Foothills. Steppe-tundra vegetation and large mammals may not have persisted into late Wisconsinan time throughout this vast region.

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SEDIMENTARY FACIES ON AN ICE DOMINATED SHELF, BEAUFORT SEA, ALASKA

BY PETER W. BARNES AND ERK REIMNITZ

Sea ice is a major factor influencing the character of high latitude shelf deposits today and has been throughout the Quaternary. Ice impacts sedimentation by physically disrupting the sea floor, by influencing wave and current regimes, by rafting sediments to depocenters and by affecting the erodability of seabed materials. As a result of this interaction distinctive facies are developed in the surficial sediments.

The ice environments affecting the shelf stratigraphy can be divided into three zones. Inshore of about 20 m is the semistationary fast-ice, which is inundated with flood waters near rivers in the spring. Between about 20 m and 40 m a zone of grounded ice ridges composed of seasonal and multiyear ice (called stamukhi) is present during the winter and often lasts into the summer months. Seaward of the stamukhi zone, polar pack ice is in motion through much of the year, its depth of penetration onto the shelf is controlled by seasonal weather pattern and ice draft.

The ice zonation has resulted in a characteristic sedimentary facies in the different ice environments as follows:

1) Delta facies—The normal interplay of sediment supply and marine reworking is seasonally interrupted by ice flooding and vertical drainage through the ice canopy (strudel) creating scour depressions whose fill becomes the dominant delta facies. Bedding is laterally discontinuous due to repeated strudel scouring. The stratigraphy is characterized by alternating layers of sand and finer materials and layers of fibrous organic matter. Gravel is notably absent in the marine part of modern delta facies.
2) Fast ice zone facies—Although ice gouging in this zone occurs at a rate high enough to completely rework the surficial sediments in less than 200 years, hydraulic processes are responsible for the sedimentary structures observed in this zone. These processes infill gouges with finely laminated sands and mud while unbedded sandy mud is derived from the gouging and mixing processes. The resulting facies is a bedded sequence of sand and finer material with finer grained beds often contorted, mottled and structureless. Laterally discontinuous beds are composed of ice gouge infill which results in linear "shoestring" deposits characterizing this part of the shelf.
3) Stamukhi zone facies—Ice gouging becomes the dominant agent in forming sedimentary structures plowing and replowing the seafloor mixing the sediments into a heterogeneous mass. The resulting facies in this zone grades seaward from the fast ice zone facies through a zone of contorted bedded sequences to completely heterogeneous sequences of gravelly muds in waters 30 to 40 m deep.
4) Outer shelf facies—In waters deeper than 50 m, few ice ridges grow large enough to interact with the seafloor and hydraulic processes dominate sedimentary structures. The resulting outer shelf facies is characterized by bedded sequences of muds and sandy muds which are laterally continuous.

During the transgressions and regressions of the Quaternary these facies extended to deeper water on the arctic shelves and would have been a part of the facies on subarctic shelves where sea ice was present. These facies would also be present in glacial lakes where lake ice formed and interacted with the lake beds.

QUATERNARY SEDIMENTATION ON THE ALASKAN BEAUFORT SHELF: SEDIMENT SOURCES, GLACIOEUSTATISM, AND REGIONAL TECTONICS

BY DAVID A. DINTER

Shallow sedimentary strata underlying the middle and outer continental shelf of the Alaskan Beaufort Sea compose, in general, a sequence of wedges, each of which thickens seaward to the shelf break. At least seven such wedges, with maximum seaward thicknesses on the order of 15 to 40 meters, are recognized on high-resolution seismic reflection profiles. The wedges are bounded by disconformities that presumably represent successive subaerial exposures of the shelf during Quaternary glacioeustatic sealevel minima. Many of these surfaces are intermittently channelled beneath the middle shelf, and some are overlain by thin, discontinuous, acoustically chaotic layers inferred to be nonmarine or shallow marine in origin.

Seaward of several river mouths foreset sequences less than 15 meters thick are intercalated between some of the wedges.

Several of the wedge-shaped strata die out inshore beneath the middle shelf. At least three, however, persist in thicknesses of 2 to 10 meters at the shoreward ends of seismic profiles, which typically lie close to the 25-meter isobath some 20 to 30 kilometers from shore. Tentative correlations with shallow boreholes seaward of the barrier islands (Peggy Smith and David Hopkins, personal commun., 1983) support the interpretation that these strata are primarily marine, and accumulated in late Quaternary time during relative highstands of the sea.

Lithologies of surficial gravel samples from seabottom exposures of the top of the youngest wedge are exotic to Alaska, but similar to Paleozoic suites exposed on the shores of Coronation Gulf in the Canadian Arctic Islands. Rodeick (1979) has proposed this area as the probable source of the gravels and suggested ice-rafting as the most feasible transport mechanism. A great volume of sediment-laden icebergs must have been shed from the Canadian Arctic Islands into the Arctic Ocean during the decay of the Laurentide Ice Sheet in late Wisconsin/early Holocene time. This period coincides with the early phases of the reinundation of the shelf subsequent to the latest glacioeustatic sea level minimum approximately 18,000 years ago and so appears to be a likely time of deposition for the now-relict gravels on the shelf. It is possible that earlier Canadian Arctic ice sheets were significant sediment sources for the older Quaternary wedges underlying the Alaskan Beaufort shelf.

An exception to the idealized shallow stratigraphic geometry discussed above occurs on the eastern part of the Alaskan Beaufort shelf, where a persistent structural high some 30 km wide and 60 km long trends northeast from Camden Bay. The youngest sedimentary wedges on the shelf onlap the flanks of this arch, and nearly every earthquake recorded from the shelf has an epicenter in the area marked by a paucity of late Quaternary sediment (Grantz and Dinter, 1980; Dinter, 1982). Near the axis of the arch strongly deformed strata of unknown age are exposed within 1 meter of the seafloor.

Seaward of the shelf break, slides and slumps pervasively disrupt the shallow sedimentary strata such that stratigraphic horizons prominent over great distances beneath the shelf cannot be traced further downslope on reflection seismic profiles.

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PERMAFROST AND RELATED ENGINEERING PROBLEMS ON THE NORTH SLOPE AND BEAUFORT SHELF, ALASKA

BY OSCAR J. FERRIANS, JR.

The critical need for finding and developing new and dependable sources of hydrocarbon resources has caused a tremendous increase in exploration and development activities on the North Slope of Alaska and on the shelf of the Beaufort Sea. These regions pose special engineering problems and are environmentally "sensitive." Consequently, they require careful study and consideration to ensure the integrity of engineering structures and to minimize adverse environmental impacts. One of the most important factors to be considered in these northern regions is permafrost.

Permafrost, or perennially frozen ground, is a widespread natural phenomenon. It underlies approximately 20 percent of the land area of the world, and 85 percent of Alaska is within the permafrost region. In Alaska, the known permafrost thickness ranges from about 600 m near Prudhoe Bay to less than a meter at the southern border of the permafrost region. On the North Slope, permafrost thickness generally is greater than 200 m. Locally, however, it is absent under large lakes deep enough so that they do not freeze to their bottoms in the winter.

The distribution and character of subsea permafrost is still poorly understood; however, ice-bonded permafrost is known to be widespread under the shelf of the Beaufort Sea. This subsea permafrost generally differs from the adjacent onshore permafrost by being warmer and containing less ice. Most of the subsea permafrost is relict, having formed under subaerial conditions at a time when sea level was much lower than it is today.

Thawing of ice-rich permafrost, the most serious permafrost-related engineering problem, results in a loss of strength and a change in volume of the ice-rich soil. Under severe conditions, the ice-rich soil can liquefy and lose essentially all of its strength. A more common occurrence is differential settlement of the ground surface.

Proposals to chill the natural gas in buried pipelines as a means of mitigating the problems caused by the thawing of permafrost pose different problems—the most difficult to solve is frost heaving caused by the freezing of unfrozen soils surrounding the pipe.

The two basic methods of constructing on permafrost are (1) the active method and (2) the passive method. The active method is used in areas where permafrost is thin and generally discontinuous, or where it contains relatively small amounts of ice. The object of this method is to thaw the permafrost and, if the thawed material has a satisfactory bearing strength, then to proceed with construction in a normal manner.

The object of the passive method is to keep the permafrost frozen so that it will provide a firm foundation for engineering structures. Obviously, the passive method has wide application on the North Slope where permafrost is widespread, thick, and generally ice rich near the surface. When using this method, every effort should be made to minimize disturbing the ground surface, and when the ground surface is disturbed, to take carefully planned mitigative measures immediately. Various techniques used to help keep the permafrost frozen include using different kinds of insulation (both natural and man-made), elevating heated structures above ground, and using refrigeration.

QUATERNARY MICROFOSSILS ON THE ARCTIC SHELF

BY KRISTIN McDOUGALL

Late Pliocene and Quaternary marine transgressions on the Arctic Coastal Plain are each defined by a particular sea level stand and by temperature changes relative to the present conditions. Microfossils are common and generally well preserved in the marine strata. Foraminifers which are sensitive to depth, temperature, salinity or oxygen, can be used to identify the transgressive-regressive cycles through faunal changes which correspond to the environmental changes.

Benthic foraminifers have been identified in a series of offshore boreholes along the Arctic Coastal Plain. Transgressions represented in these boreholes range from Berringian to Holocene in age. Foraminiferal faunas in the oldest transgressions (Berringian to Fishcreekian) are poorly represented as material of this age is rarely encountered. The younger transgressions (Kotzebuan through Holocene) are well represented, and microfossils associated with these transgressions can be described and traced throughout the Arctic Coastal Plain.

Kotzebuan and Pelukian faunas are characterized by moderate foraminiferal numbers, moderate diversities, indigenous Pacific and Atlantic species, warmer temperatures and deeper waters. Kotzebuan faunas generally indicate greater water depths and a greater Pacific and Atlantic influence than during the Pelukian.

Kotzebuan assemblages are recognized only in boreholes seaward of the barrier island chain from Flaxman Island to Prudhoe Bay. Although the strata are of variable thickness, Pelukian assemblages are present in most boreholes on the Arctic Coastal Plain between Flaxman Island and the Jones Islands. Both Kotzebuan and Pelukian assemblages contain common occurrences of *Cassidulina teretis, C. norcrossi, C. islandica, Elphidium orbiculare, E. incertum,* and *Buccella frigida.* Outer neritic and deeper water species such as *Stainforthia concava* are sparse, whereas elphidiums and other inner neritic species are more common in the Pelukian than in the Kotzebuan, reflecting the higher stand of sea level in the Kotzebuan. *Elphidiella groenlandica, Elphidium asklundi, Eggerella advena,* and *Gordiospira arctica* are present as a result of the warmer temperatures and the influx of Atlantic and Pacific waters.

Faunas of the early Wisconsin, Flaxman transgression, have moderate foraminiferal numbers, lower diversities, and indicate that water depths and temperatures were shallower and cooler than during the Pelukian or Kotzebuan transgressions, but deeper and warmer than at present. Cassidulinids decrease significantly in abundance and constitute only a minor component of the Flaxman faunas. *Elphidiella groenlandica, Elphidium* *asklundi*, and *Elphidium excavatum alba* also become increasingly rare as the temperatures cool.

The Flandarian transgression is marked by low foraminiferal numbers, low diversities and cold shallow waters which were less saline than at present. *Elphidium clavatum* is the dominant species in most Flandarian faunas.

Holocene faunas are best preserved and most variable. In general, the foraminiferal numbers are high and species diversities are moderate to low. *Elphidium orbiculare* and *Elphidium excavatum alba* are the most common species. Since the Holocene record is most complete, faunal changes are numerous and correspond to increasing water depths associated with the transgression. Shallowing is observed in several of the boreholes and related to the migration of the barrier islands or deltaic deposits.

A COMPARISON OF NUMERICAL RESULTS OF ARCTIC SEA ICE MODELING WITH SATELLITE IMAGES

BY CHI-HAI LING AND CLAIRE PARKINSON[1]

The results of a dynamic/thermodynamic numerical model of Arctic sea ice are being compared with satellite images from the Nimbus 5 electrically scanning microwave radiometer (ESMR). The model combines aspects of two previous sea ice models—those of Parkinson and Washington (1979) and Ling, Rasmussen, and Campbell (1980). It is a solid/fluid model basically following the formulation of the Parkinson and Washington model with the addition of the constitutive equation and equation of state from the Ling et al. model.

The Parkinson and Washington model simulates the seasonal cycle of sea ice thicknesses and concentrations with a horizontal resolution of roughly 200 km and a timestep of 8 hours. The thermodynamics are calculated through energy balances at the interfaces between ice and air, water and ice, and water and air. The ice dynamics are calculated through a momentum equation balancing air stress, water stress, dynamic topography, and Coriolis force, with an adjustment for internal ice resistance. This model has yielded results which compare favorably with observed Arctic and Antarctic sea ice variations.

The Ling et al. model treats sea ice as a large-scale fluid. It uses a viscous fluid constitutive equation that specifies the relationship between stress and strain, and an equation of state that relates the sea ice pressure to the ice concentration, thickness, and velocity. It lacks a complete energy equation, although thermodynamic effects are treated parametrically.

The numerical scheme of the combined model keeps track of the amount of ice entering each grid square. In locations with a net inflow of ice, the concentration increases according to the inflow values as long as the concentrations do not exceed 99.5%. When calculated concentrations exceed 99.5%, the Parkinson and Washington model reduces all inflow velocities to the relevant grid squares. The current model, however, with the Ling et al. formulation, retains the originally calculated ice velocities and appropriately thickens the ice to conserve ice volume. A fluid-type stress-strain relationship is used in the formulation of internal ice stress, in which the normal stress, or the sea ice pressure, is postulated to be proportional to the concentration and velocity convergence. The momentum equations, which are second order partial differential equations, are solved using successive over-relaxation and a nine-point finite difference method.

Atmospheric inputs are mean monthly surface-air temperatures, surface dew points and sea level geostrophic winds from Jenne et al. (1969), while the initial ice extent is from the ESMR data for January 1, 1974. The ESMR sea ice extent data for the remainder of 1974 is then used for comparison against the model results. Model calculations and ESMR data correspond well in the central Arctic but reflect the lack of oceanographic inputs in the marginal ice zone regions. For instance, the model fails to produce the prominent indentation of open water often observed along the west coast of Greenland, which is presumably due to the warm West Greenland current.

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ARCTIC SEA ICE BY PASSIVE MICROWAVE OBSERVATIONS FROM THE NIMBUS-5 SATELLITE

BY WILLIAM J. CAMPBELL, PER GLOERSON[1], AND H. JAY ZWALLY[2]

Observations made from 1972 to 1976 with the Electrically Scanning Microwave Radiometer (ESMR) on board the Nimbus 5 Satellite provide sequential synoptic information of the Arctic sea ice cover. This 4-year data set was used to construct a fairly continuous series of 3-day average 19-GHz passive microwave images which has become a valuable source of polar information, yielding many anticipated and unanticipated discoveries of the sea ice canopy observed in its entirety through the clouds and during the polar night. Interpretation of the passive microwave satellite data set was performed by comparing selected sequential images with corresponding microwave profiles and images acquired by the NASA CV-990 airborne laboratory and with various "in situ" microwave and physical observations. These aircraft and surface microwave programs were performed as part of the Arctic Ice Dynamics Joint Experiments (AIDJEX) of 1972, 75, and 76. Mesoscale microwave images of the AIDJEX manned drifting station array (Triangle) were obtained by aircraft during every season, and extensive aircraft transects covering major portions of the Arctic Basin in spring, summer, and fall. At the main camp within the AIDJEX triangle detailed multifrequency passive microwave observation, ice crystallographics, and dielectric properties were measured in three test areas with areas of approximately 1.5×104 m^2.

Analysis of this three-level, three-resolution data set has shown how satellite passive microwave observations can be used to map key sea ice parameters on synoptic scales at time scales ranging from several days to interannual: ice edge position, ice concentration, multiyear ice, first-year ice, mixtures of these two ice types, and snow melt on the ice. Significant variations of ice concentration are found to occur in various parts of the Arctic during all seasons. During every August–September period of the 4 years ESMR operated, large areas of low microwave radiances, attributed to low ice concentration, formed deep within the ice pack. In 1972, 73, and 76, these extensive zones of low ice concentration occurred generally along the Transpolar Drift Steam. The anomalous distribution was in 1975 when they appeared in a ring of 85° N. cutting across the Beaufort Sea Gyrc with another array along the Transpolar Drift Steam between the North Pole and East Greenland Sea. See figure 8.

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LAND COVER AND TERRAIN MAPPING FOR THE DEVELOPMENT OF DIGITAL DATA BASES FOR WILDLIFE HABITAT ASSESSMENT IN THE YUKON FLATS NATIONAL WILDLIFE REFUGE, ALASKA

BY MARK B. SHASBY[1], CARL MARKON[2], MICHAEL D. FLEMING[1], DENNIS L. MURPHY[1], AND JAMES E. YORK[1]

The U.S. Geological Survey's EROS Field Office and the U.S. Fish and Wildlife Services's Refuges Division, both in Anchorage, Alaska, are currently working together on the use of Landsat multispectral scanner (MSS) data and digital elevation model (DEM) data to develop and test digital land cover and terrain data bases for assessing wildlife habitat in Alaska's National Wildlife Refuges (NWR). The inventory and assessment of resources for all NWR's in Alaska are being carried out under the mandates of the Alaska National Interest Lands Conservation Act of 1980, which requires the development of a comprehensive management plan for each refuge by 1987. The work reported here was performed on the Yukon Flats NWR under an Interagency Support Agreement that provided for the cooperative development of land cover and terrain digital data bases.

The Yukon Flats NWP consists of approximately 8.63 million acres of land and water in the upper watershed of the Yukon River in northeastern Alaska. Portions of seven summer and five winter Landsat scenes were digitally registered to a 127-meter Universal Transverse Mercator (UTM) grid and processed to derive land cover information for the refuge and an additional 4.5 million acres of adjacent lands. DEM data acquired from the U.S. Geological Survey's National Cartographic Information Center for the ten 1:250,000-scale USGS quadrangles comprising the study areas were mosaicked and registered to the same 127-meter UTM grid. From the registered DEM data, slope and aspect information was derived to complete the terrain information portion of the data base.

Landsat and DEM digital data were processed by computer in the EROS Field Office Digital Analysis Laboratory. Land cover was classified on summer Landsat MSS data utilizing a modified cluster-block approach followed by postclassification stratification. The winter Landsat data were used to more accurately identify water and riparian areas. Using terrain information (elevation, slope and aspect), certain spectral/information

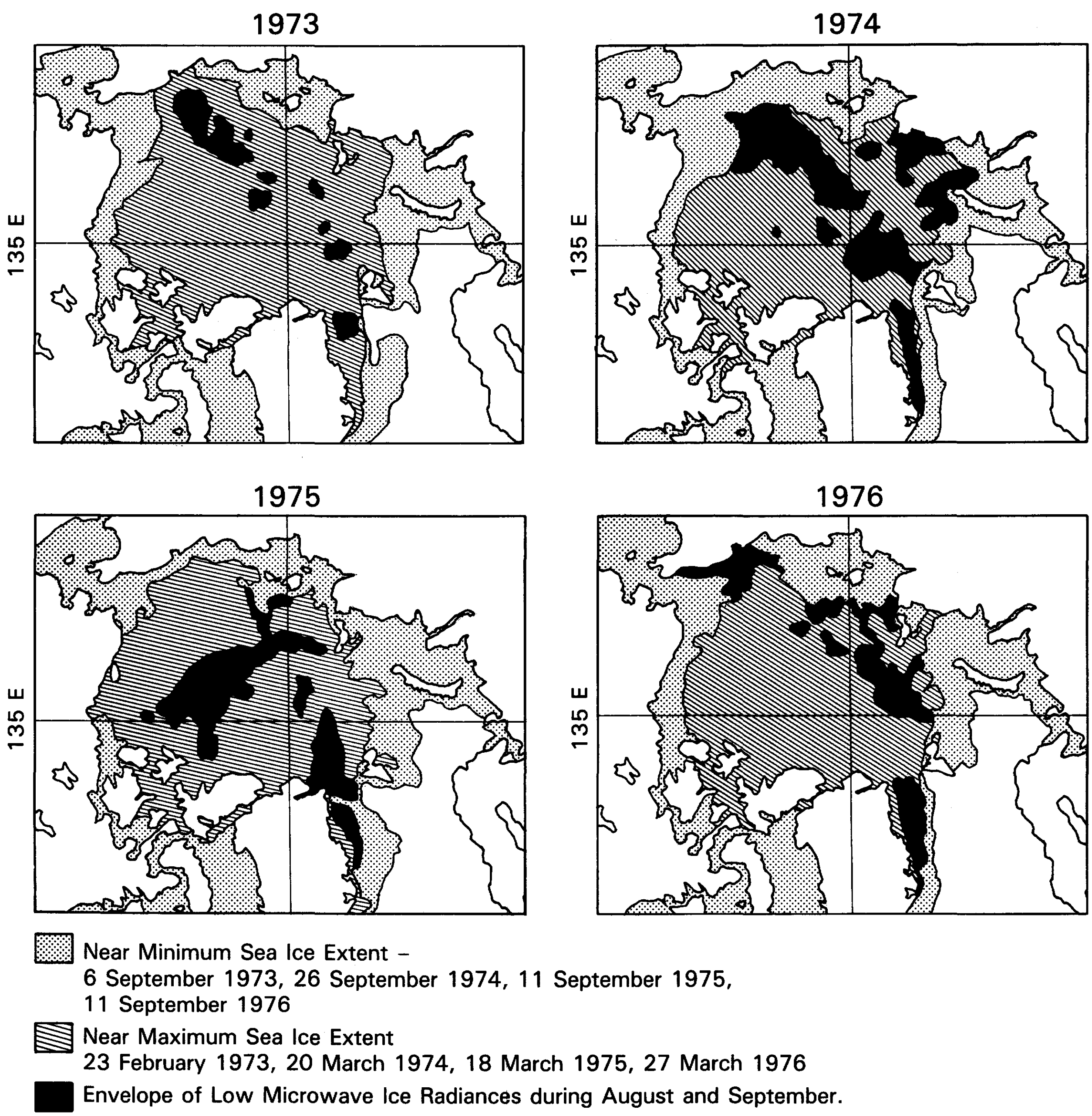

FIGURE 8.—Arctic sea ice parameters for 1973–76.

classes were stratified into more meaningful map classes.

The resultant digital data base containing land cover information and the three terrain variables provides a flexible tool for subsequent wildlife habitat assessment and resource inventory. Monitoring and assessment of waterfowl habitat and waterfowl populations are of primary importance on the Yukon Flats Refuge. To address this information need, a computer-aided procedure for building a lake inventory data base was developed for assessing the current status of water bodies within the refuge and as a basis for future monitoring activities.

The lake inventory data base is developed through a series of computer programs which extract all water bodies from the land cover layer of data in raster format, to produce a new layer comprised only of water, and then convert the raster file to a vector data file from which a data base file is produced. In the data base, each lake is identified with a unique number and is associated with the following variables: latitude and longitude coordinates for the centroid of each lake, surface area estimated in acres, and a water quality class based on sediment loads or depth derived in the Landsat-analysis phase of the project. Information from the data base can be queried and summarized based on user specified criteria. For particular lakes or regions, additional data variables can be added or derived. Options exist for output in tabular form or in a plotted map format from the data base. Potential uses include investigations relating waterfowl population to lake densities, size, proximity to different cover types, and other parameters. These investigations will help managers gain a greater understanding of the resource they are managing.

[1]Technicolor Government Services, Inc., work performed under U.S. Geological Survey Contract Number 14-08-001-20129.
[2]U.S. Fish and Wildlife Service.

GEOCHEMICAL DETECTION OF PROSPECTIVE PETROLEUM AREAS IN ARCTIC REGIONS

BY A. A. ROBERTS, T. J. DONOVAN, J. D. HENDRICKS AND K. I. CUNNINGHAM

Geochemical prospecting for petroleum is based on the premise that microseepage of compounds from oil and gas reservoirs does occur and that these compounds subsequently migrate to the Earth's surface. These techniques involve the detection of epigenetic alteration of near-surface rocks due to the presence of these seeping hydrocarbons, or the detection of alterations of the chemical composition of the near-surface soils and soil gases themselves. Two geochemical exploration techniques that have been developed for use in the contiguous United States have been investigated for their applicability in the permafrost environment of the Arctic coastal plain.

The first of these involves the detection of anomalously high concentrations of the noble gas helium in near-surface permafrost. Owing to its small molecular size, chemical inertness, and extreme mobility, helium is one of the components of oil and gas reservoirs most likely to escape and subsequently migrate to the surface. Because helium is not of biogenic origin, its presence in anomalous concentrations near the surface is an indication of a subsurface source. Permafrost samples are collected and hermetically sealed in aluminum cans, leaving 5–10 cc of air above the sample. The helium in the permafrost is then allowed to equilibrate with the air in the head space. Subsequently, the helium in the head space is analyzed and the concentration of helium in the original sample is calculated through the use of corrections for temperature, pressure, pore volume, and water content. Normal concentrations of helium were observed in the permafrost overlying a variety of nonproductive areas in the National Petroleum Reserve in Alaska and in an area subsequently drilled as a dry hole. Abnormally high helium concentrations were observed on the Simpson Peninsula over the Simpson oil field and around the subsurface Simpson Canyon and are interpreted as being related to seepage of gases in areas where gently dipping Cretaceous strata have been truncated by the canyon.

The second technique involves the detection of anomalous shallow-subsurface occurrences of magnetic minerals through the use of low-altitude (90 m), special purpose, aeromagnetic surveys. These magnetic materials are interpreted to be the result of chemical reduction of normally fully oxidized iron minerals to magnetite in the presence of seeping hydrocarbons. The magnetic contrast between typical sedimentary rocks and those enriched with this epigenetic magnetite results in distinctive high wave-number and low-amplitude total field anomalies. Detection of these shallow magnetic mineral occurrences is strongly enhanced through the use of a horizontal-gradient magnetic survey, which concurrently greatly reduces interpretation problems associated with diurnal variations and solar storms present at these high latitudes. Surveys over the Arctic Coastal Plain revealed magnetic anomalies over the Barrow gas fields, over the Simpson Canyon area of Cape Simpson, and slightly offshore in the Dease Inlet off the National Petroleum Reserve. In addition, surveys over the Arctic National Wildlife Refuge revealed a large area of anomalously high magnetic gradients over the Marsh Creek anticline suggesting that it may be a prime petroleum prospect.

HYDROLOGY OF THE NORTH SLOPE, ALASKA

BY CHARLES E. SLOAN

The hydrology of the North Slope is dominated by the cold, dry climate and permafrost. Streamflow virtually ceases during the long winter. Precipitation occurs mainly as snow from September to May and is stored in the snowpack until breakup, a dynamic flow period in late May and early June. Most of the annual runoff occurs in the brief 2- to 3-week breakup period. The estimated mean annual runoff on the North Slope averages about 0.5 cubic feet per second per square mile and ranges from about 0.3 on the Coastal Plain to about 2.0 in the mountains. Peak flows usually occur during spring breakup when the height of the flood flow is significantly increased by the presence of ice jams. Maximum evident floods range from about 7 to 80 and average about 40 cubic feet per second per square mile in large streams on the North Slope.

The water quality of streams is generally excellent. However, during periods of high flow the streams carry high concentrations of suspended sediment and during periods of low or zero flow dissolved solids may become concentrated and the water may become depleted in dissolved oxygen.

Lakes are the most conspicuous hydrologic feature on the North Slope, in places composing as much as 40 percent of the surface area of the Coastal Plain. The lakes range in size from Teshekpuk Lake which covers about 315 square miles, to small pounds of less than an acre. There are estimated to be more than 40,000 lakes greater than 1 acre in size in the National Petroleum Reserve in Alaska (NPRA) alone. Most of the lakes on the Coastal Plain are shallow and freeze to the bottom during winter. Teshekpuk Lake is about 20 feet deep and stores about 4 million acre feet of water, which is equivalent to about 2 years of average flow from the Colville River. A number of deep lakes to the south of Teshekpuk Lake range in depth from 20 to more than 70 feet.

Water quality in the lakes is generally very good. Shallow lakes may become turbid when wind and wave action stirs up the bottom sediments. Glacial lakes in the mountains and southern foothills also have varying degrees of turbidity. In shallow lakes that freeze nearly to the bottom the water can become so concentrated in dissolved solids by late winter that it would be unacceptable as a potable supply.

The widespread occurrence of permafrost on the North Slope acts as an impervious barrier to the movement of ground water, limiting its availability, preventing the infiltration of surface water, and consequently accelerating runoff. Ground water is present beneath lakes and pools in rivers that do not freeze to the bottom. However, water in the fine-grained sediments beneath lakes is generally saline, and there is limited storage in the unfrozen sediments beneath deep river pools. Most water beneath the permafrost is also saline. Thawing of permafrost creates thaw lake depressions. Thermal erosion of ice-rich permafrost also leads to rapid and spectacular erosion of coastal bluffs and riverbanks, as well as rapid enlargement of lakes.

A significant ground-water resource exists in carbonates of the Lisburne Group and in coarse clastic rocks of the Sadlerochit Formation in the eastern part of the Brooks Range near the mountain front. Numerous springs, some quite large, occur in this area. Sadlerochit Spring, which has a discharge of about 35 cubic feet per second, the Shublik Spring, which flows at about 25 cubic feet per second, are individual springs that flow from bedrock. Discharge from the springs freezes in winter to form large icings (aufeis). Icings are quite conspicuous and easily discernible on Landsat imagery. The source at springs can be found by going upstream from the icings. Tributaries of the Ivishak River, including the Echooka River, Flood Creek, Saviukviayak River, and the main stem of the Ivishak, have a cumulative discharge of more than 300 cubic feet per second from springs near the mountain front.

Snow and ice are important as construction materials for roads, workpads, and airfields, and as sources of water supply. Snow accumulation can be managed through use of snow fences and other wind barriers that influence snow deposition. Snowfall may occur during any month of the year, but usually sticks to the ground starting in September and remains until late May or early June. Drifts along river and lake banks frequently persist until late summer. Lake and river ice attains an average thickness of about 6 feet by late winter and occasionally is 8 to 9 feet thick.

PALEOGEOGRAPHIC AFFINITIES AND ENDEMISM OF CRETACEOUS AND PALEOCENE MARINE FAUNAS IN THE ARCTIC

BY L. MARINCOVICH, JR., E. M. BROUWERS, D. M. HOPKINS

The Arctic Ocean is the last of the world's oceans whose paleobiogeographic history is largely unknown. The general configuration of the Arctic Ocean and the presence or absence of major connecting seaways to the North Pacific and North Atlantic influenced the composition of Late Cretaceous and Cenozoic shallow-water arctic marine faunas. New finds of early Cenozoic marine faunas in onshore stratigraphic sections along the arctic margin of North America are providing fresh insights into the early history of the Arctic Ocean.

An unusual assemblage of Paleogene mollusks, ostracodes, brachiopods, benthic foraminifers, dinoflagellates and palynomorphs occurs at Ocean Point, northern Alaska (fig. 9). The endemic nature of this assemblage suggests the possibility that the Arctic Ocean was not then in communication with the world ocean. Tentative correlation based on mollusks and ostracodes can be made with the early Paleocene Cannonball Formation of North and South Dakota, but not with some other approximately coeval northern high-latitude faunas; this suggests a geographically restricted arctic faunal realm. The molluscan and ostracode faunas of the Ocean Point and Cannonball deposits have relatively low species diversities, in strong contrast to the highly diverse approximately coeval faunas of tropical aspect in the Gulf of Mexico embayment, West Greenland (Disko), and northwestern Europe. Faunal composition and low

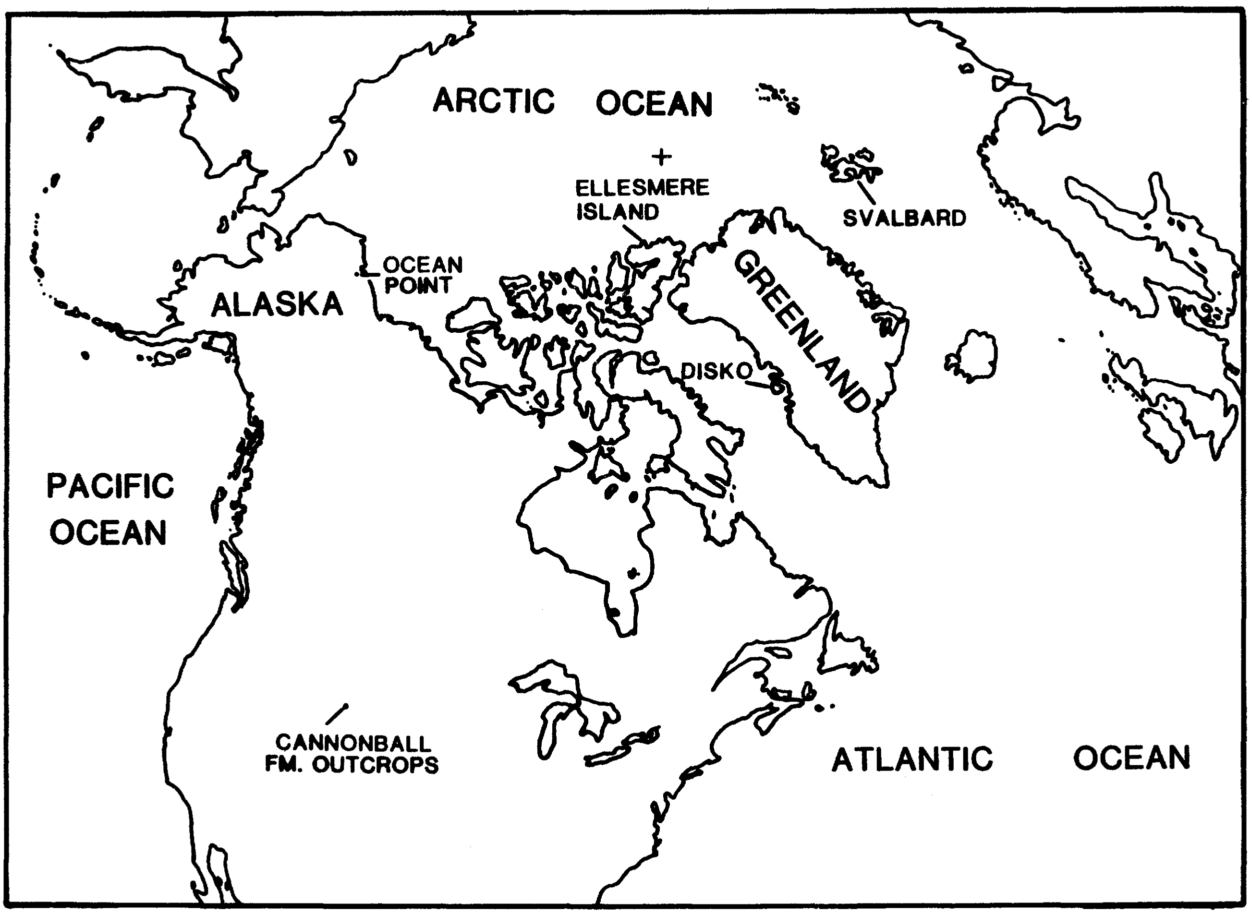

FIGURE 9.—Location of areas with Upper Cretaceous or Paleogene marine faunas noted in text.

species diversity suggest a temperate rather than tropical aspect for the Ocean Point and Cannonball faunas and imply a major separation of Arctic and Atlantic faunal realms in the early Tertiary. Paleogene molluscan faunas on Svalbard (fig. 9) are of moderate diversity and of probable Atlantic affinities. The Ocean Point and Cannonball beds are approximately coeval with the upper part of the Eureka Sound Formation of the Canadian Arctic Archipelago, which contains Paleocene and Eocene vertebrates, megaflora and pollen (West and others, 1981). Marine mollusks are known from the dominantly nonmarine Eureka Sound deposits on Ellesmere Island, but have not been extensively collected or studied, and are thought to be of relatively low diversity. Because the Eureka Sound Formation contains the thickest accumulation of arctic Paleogene deposits, study of its marine mega- and microfaunas is central to an understanding of the early Tertiary history of the Arctic Ocean. Sparse information available on Eureka Sound marine fossils allies them with the endemic low-diversity Ocean Point and Cannonball faunas and suggests that this formation was also deposited in an Arctic Ocean largely or entirely separated from the world ocean during part of the Paleogene.

The history of connecting seaways between the Arctic and Pacific Oceans is poorly known. Most current plate-tectonic models suggest closure of marine connections between these oceans during the Late Cretaceous (Churkin and Trexler, 1981), although few paleontologic data are available to test this idea.

Paleontologic research done to date on Late Cretaceous and Paleogene marine faunas from the onshore arctic margin of North America has been limited by the small amount of collected fossils available for study. Still, the endemic character of the faunas is clear and supports the hypothesis of a geographically isolated Arctic Ocean during some portion of Paleogene time.

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REMOTE SENSING STUDIES OF DYNAMIC ENVIRONMENTAL PHENOMENA IN ICELAND

BY RICHARD S. WILLIAMS, JR

In 1966, the U.S. Geological Survey (USGS) began a geological remote-sensing project in Iceland to study and to monitor various types of dynamic environmental phenomena. By mid-1983, more than 50 abstracts, papers, and maps, mostly in collaboration with Icelandic scientists, have been or are about to be published on the following topics: thermal-infrared surveys of volcanoes and geothermal areas; volcanology; glaciology; geomorphology; geologic hazards, marine geology, and bibliography of the geological literature of Iceland.

During the course of three aerial thermographic (airborne thermal-infrared) surveys, two by the Air Force Cambridge Research Laboratories in 1966 and 1968 and one by the National Aeronautics and Space Administration in 1973, surface patterns of thermal emission were recorded of all of the known high-temperature geothermal areas and of several volcanoes in Iceland. In 1973, color and color-infrared aerial photographs were also acquired. A series of preliminary papers on the analysis of the aerial thermographic data has been published, and preparation of a USGS Professional Paper, "Remote Sensing of High-Temperature Geothermal Areas of Iceland," in cooperation with the National Energy Authority of Iceland, is nearing completion.

Volcanological studies have included analysis of thermal data of an effusive eruption on Surtsey recorded by the Nimbus 2 spacecraft and publication of a USGS scientific leaflet on diversion of lava by water cooling during the course of the eruption of Eldfell on Heimaey, Vestmannaeyjar, Iceland. Satellite imagery of Iceland's glaciers established that variations in the termini of ice caps and outlet glaciers could be measured by Landsat imagery. This research provided the catalyst for the initiation, in 1977, of a USGS-sponsored international project to prepare a

"Satellite Image Atlas of Glaciers (of the World)." Analysis of satellite imagery resulted in the publication of two 1:500,000-scale Landsat image maps of Vatnajokull ice cap, preparation of a special computer-enhanced image, and new knowledge about poorly known or unknown glaciological, structural, and tectonic features under and adjacent to the Vatnajokull ice cap.

Geomorphological research involved the use of aerial thermographs and color-infrared aerial photographs to map periglacial phenomena in Iceland, including frost-crack polygons and palsas (frost mounds). Comparative planetology studies established that concentric ridges on the Arsia Mons volcano on Mars are best explained by the analog of recessional moraines in Iceland. Moreover, comparative planetology research, in a joint effort with the late Sigurdur Thorarinsson and Elliot C. Morris, resulted in a new classification for the 27 types of Iceland's volcanoes. The classification is based on the nature of the volcanic activity, environment during formation, and configuration of feeder conduit, for the three primary compositional classes of Icelandic volcanoes.

A new classification scheme has been developed for the four principal geologic hazards of Iceland: geomorphic, geothermic, seismic, and volcanic. Historically, seismic (earthquakes and rifting) and volcanic (lava flows, tephra falls, volcanic gases, maars (explosion craters), jokulhlaups (glacier-outburst floods), and other floods) hazards have had the most impact on Iceland and its people.

In marine geology, analysis of a Landsat multispectral scanner (MSS) band 4 image off the southwest coast of Iceland has revealed the complex pattern of coastal currents in this area, including eight large eddies (40 km in diameter), all apparently made visible by variations in the concentration of phytoplankton in near-surface waters.

A "Bibliography of the Geological Literature of Iceland: 1777–1983" is also nearing completion, with approximately 5,000 citations already prepared and indexed. The multilanguage geoscience literature of Iceland is particularly rich in the topics of volcanology, goethermal activity, geochemistry, geophysics, tectonics, tephrochronology, glaciology, petrology, and geologic hazards, and having the extant literature available in English will make it more widely known to English-speaking scientists.

CORRELATION OF LATE CENOZOIC MARINE TRANSGRESSIONS OF THE ARCTIC COASTAL PLAIN WITH THOSE IN WESTERN ALASKA AND NORTHEASTERN RUSSIA

BY JULIE K. BRIGHAM

Six distinct marine transgressions of Pliocene (?) and Pleistocene age have been differentiated within the Gubik Formation across the western part of the Alaskan Arctic Coastal Plain (fig. 10; Brigham, 1983). The recognition of these superimposed but lithologically similar marine units is based on the detailed stratigraphic study of unconsolidated sediment in coastal and river-bluff exposures and the amino-acid geochemistry of mollusks from these deposits (table 1). The extent of isoleucine epimerization (aIle/Ile) in free (naturally hydrolyzed)- and total (free plus peptide bound)- amino-acid fractions in *Hiatella arctica* (Linne), *Mya truncata Linne*, and *M. arenaria* Linne from Gubik deposits cluster into groups of ratios that differentiate temporally distinct high-sea-level events (table 2).

Amino-acid data have also been acquired from mollusks representing the transgressions documented by Hopkins (1967, 1973) along the west coast of Alaska and from similar sequences described on the Soviet coasts of the Bering and Chukchi Seas (Petrov, 1966, 1976, 1982; Khoreva, 1974). AIle/Ile ratios (G. H. Miller, unpublished data, 1976) in *Hiatella* and *Mya* provided by D. M. Hopkins from the Nome region approach racemic equilibrium in the free-amino-acid fraction of the oldest unit (table 2). Similarly, aIle/Ile ratios in shells from the Soviet coast (provided by O. M. Petrov, Geological Institute of Moscow) gradually increase over time (table 2; Brigham, 1981). In general, the higher aIle/Ile ratios in mollusks from the Kamchatka deposits reflect more rapid epimerization resulting from the relatively warmer thermal regime (current mean annual air temperature, CMAT, −0.9 to 1.5°C) affecting the peninsula throughout the late Cenozoic. Latitudinal temperature gradients along the Soviet and Alaskan coasts today are sharp (1.4°C per degree of latitude), although the Soviet shore averages 2°–6°C cooler than the Alaskan coast at similar latitudes. All the sites sampled, except those from Kamchatka, lost most of their maritime influence during

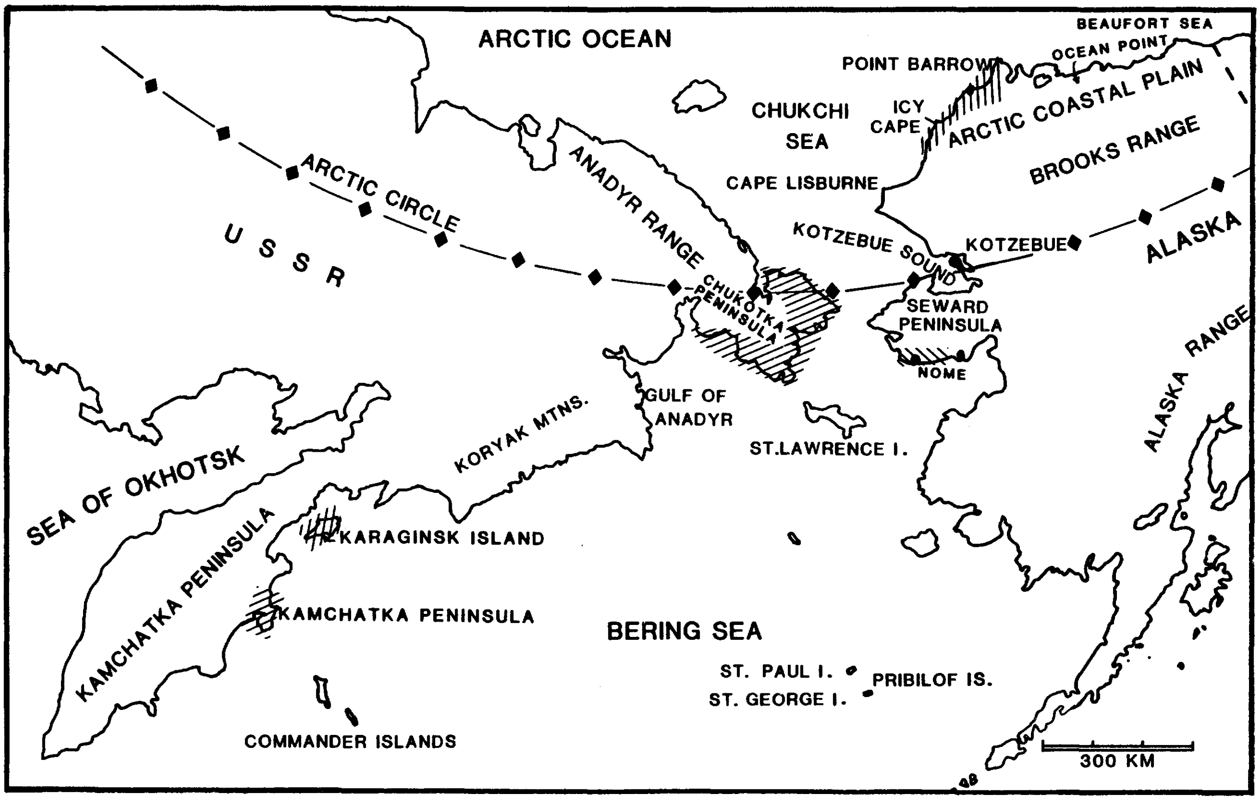

FIGURE 10.—Western Alaska and northeastern Russia, showing locations of sample sites (shaded areas) on either side of the Bering and Chukchi Seas.

the glacial episodes of low sea level and presumably had significantly lower mean annual temperatures (e.g., Brigham and Miller, 1983).

The correlation of marine units within Alaska and across the Bering Strait to the Kamchatka and Chukotka Peninsulas (table 3, fig. 11) is based on the relative differences in aIle/Ile ratios and on assumptions concerning the integrated thermal history of the samples since deposition. The low aIle/Ile ratios suggest that the Attarmen beds of Kamchatka may be only 35,000–40,000 yr old, rather than 125,000 yr old as suggested by Hopkins (1973), Gladenkov (1981), and Petrov (1966, 1982). If the Attarmen beds are assumed to be as old as 125,000 yr, then the aIle/Ile ratios require an effective diagenetic temperature of −9°C, some 8°C cooler than today. This thermal term seems much too cold, especially in light of CLIMAP (Climate/Long Range Investigation, Mapping and Predictions) reconstructions for the North Pacific (Moore et al., 1980) that indicate sea-surface temperatures only about 2°C cooler than those 18,000 yr B.P.

A major middle Pleistocene interglacial transgression is recognized along numerous reaches of the Bering and Chukchi Seas, as indicated by the Kotzebuan, Karmuk, Karaginsk, and Pinakul' marine units (table 3).

The los aIle/Ile ratios in shells from the Pinakul' suite off Siberia (0.035, total) preclude the correlation by Khoreva (1974), who suggested that this suite correlated with the highly epimerized Alaskan Anvilian deposits (0.47, total). Moreover, similar aIle/Ile ratios in shells from the Val'katlen, Kresta, and Pinakul' beds suggest that any age differences between these beds are small.

The correlation of deposits older than middle Pleistocene, however, is less certain. AIle/Ile ratios in the upper (0.22, total) and lower (1.04, total) parts of the Olkhovaya suite on the Kamchatka Peninsula indicate that this unit spans a great deal of Pliocene and Pleistocene time. The lower part of the Olkhovaya suite is probably much older than the Beringian transgression in western Alaska, especially in comparison with total-amino-acid ratios in Pliocene shells from Britain (CMAT,

TABLE 1. Pliocene and Pleistocene marine stratigraphy and sea level history of the Gubik Formation on the Alaskan Arctic Coastal Plain west of Barrow, Alaska

Informal units of Gubik Fm.	Stratigraphic Position (Locations, Fig. 1)	Marine Environment	Estimated Age (years)	Evidence for Age	Correlation with Western Alaska (Hopkins 1967, 1973)
(youngest deposits) unit not preserved along Chukchi Sea Coast	Distribution limited to Beaufort Sea coast at $\leq$7 m above sea level	Arctic waters similar to today	80,000-105,000	Correlation with oxygen-isotope record beyond radiocarbon dating	------
Walakpa beds	Extensive beach and barrier deposits at Barrow, Walakpa Bay, Wainwright, and coast south of Wainwright up to 12 m above sea level	Marine environment slightly warmer than today. Numerous extralimital species	120,000-125,000	Amino-acid age estimate; associated with relatively warm fauna; correlation with oxygen-isotope record; beyond radiocarbon dating	Pelukian
Karmuk beds	Blankets the upper half of bluffs along parts of Skull Cliff, deposits at Karmuk Pt., and beach deposits 30-33 m above sea level south of Icy Cape. Reworked shells in alluvium 25 km south of Atkasook. Unit locally folded	Arctic waters like today; no extra-limital or extinct species	250,000-500,000	Amino-acid age estimate; tentative correlation with Kotzebuan that is K-Ar dated at ≈250,000 yr	Kotzebuan
Tuapaktushak beds	Extensive exposures along Skull Cliff, between Barrow and Peard Bay; also near Milimankavi, south of Wainwright; reworked shell samples at 60 m above sea level along Kukpowrik River. Unit locally folded	Marine conditions much warmer than today; includes several extinct mollusk and ostracode forms, as well as extremely extra-limital species	?	---	?
Killi Creek	Discontinuous basal marine unit along Skull Cliff. Extent above present sea level unknown	do.	1,700,000-2,200,000	Similar faunal elements and stage of evolution of fossil sea otter found in deposits at Ocean Pt. with similar alle/Ile ratios (L.D. Carter, unpublished data, 1982)	Probably Anvilian
Nulavik	Discontinuous basal marine unit along Skull Cliff. Transgressive extent unknown	conditions not well documented	2.5-3.5 m.y.	Differentiated only on the basis of alle/Ile ratios. Oldest unit recognized therefore correlated with	Beringian

Table 2. Aminostratigraphy of marine transgressions in northwestern and western Alaska and on the Kamchatka and Chukotka Peninsulas, U.S.S.R.

Unit	Species[1] analyzed	No. of valves	aIle/Ile[2] FREE	TOTAL
		northwestern Alaska (CMAT, -10° to -13°C)		
Modern ------------	Ha	3	ND[3]	0.011±0.002
Walakpa beds ------	Ha	16	ND	0.014±0.002
	Ma	2	ND	0.018±0.001
Karmuk beds -------	Ha	26	0.40±0.052	0.038±0.007
	Mt-Ma	19	0.37±0.085	0.038±0.006
Tuapaktushak beds -	Ha	4	0.51±0.025	0.086±0.009
	Mt-Ma	15	0.54±0.057	0.086±0.013
Killi Creek beds --	Ha	4	0.50±0.072	0.15±0.007
	Mt-Ma	3	0.52±0.057	0.15±0.023
Nulavik beds ------	Ha	3	0.75±0.067	0.23±0.016
		Nome, western Alaska (CMAT, -4.7°C)		
Pelukian ----------	Ha	2	0.16±0.001	0.040±0.002
	Mt	4	0.28±0.03	0.042±0.005
Kotzebuan ---------	Mt	2	0.46±0.04	0.093±0.001
Anvilian ----------	Ha	3	0.90±0.02	0.47±0.03
Beringian ---------	Ha	3	1.04±0.03	0.56±0.07
	Mt	2	0.94±0.03	0.56±0.04
		Chukotka Peninsula (CMAT, -7.5° to -10°C)		
Val'katlen beds ---	Mt	3	0.17±0.011	0.018±0.002
Kresta suite ------	Ha	1	0.23	0.022
	Mt	2	0.22±0.02	0.020±0.002
Pinakul suite -----	Ha	1	0.26	0.031
	Mt	1	0.21	0.035
		Kamchatka Peninsula (CMAT, -0.9° to -1.5°C)		
Attarmen beds -----	Ha	1	0.17	0.038
	Mt	1	0.14	0.027
Karaginsk beds ----	Mt	3	0.43±0.05	0.115±0.013
Upper Olkhovaya --- suite	Mt	3	0.44±0.01	0.22 ±0.012
Tusatuviam beds ---	Mt	2	1.16±0.03	0.577±0.004
Lower Olkhovaya --- suite	Ha	2	1.38±0.03	1.04 ±0.06
	Mt	2	1.28±0.03	1.04 ±0.05

[1] Ha, Hiatella arctica; Mt, Mya truncata; Ma, Mya arenaria; Mt-Ma, Mya truncata and M. arenaria results combined

[2] Values represent the mean ±1σ for peak-height measurements.

[3] ND, not detectable

Table 3. Aminostratigraphic correlation of late Cenozoic marine-transgressive units across the Bering and Chukchi Seas

Estimated Absolute Age (m.y.)	Kamchatka, U.S.S.R.	Chukotka, U.S.S.R.	Nome, W. Alaska	Coastal Plain, NW. Alaska
0.035-0.040	Attarmen beds	----------	--------	--------
0.08-0.100	-------------	----------	--------	Youngest deposits
0.125	?	Val'katlen	Pelukian	Walakpa beds
0.150	-------------	Kresta	---------	---------
0.25-0.50	Karaginsk	Pinakul'	Kotzebuan	Karmuk beds
?	Upper Olkhovaya (?) suite	(no older	---------	Tuapaktushak beds
1.7-2.2	Tusatuviam(?) beds	samples	Anvilian	Killi Creek beds
2.5-3.5	--------------	analyzed)	Beringian	Nulavik beds
>3.0	Lower Olkhovaya suite		---------	---------

+10°C) of 1.20±0.002 (Miller et al., 1979). This interpretation differs from the correlation proposed by Gladenkov (1981, p. 20), who equated the entire Olkhovaya suite with marine deposits younger than the Anvilian transgression.

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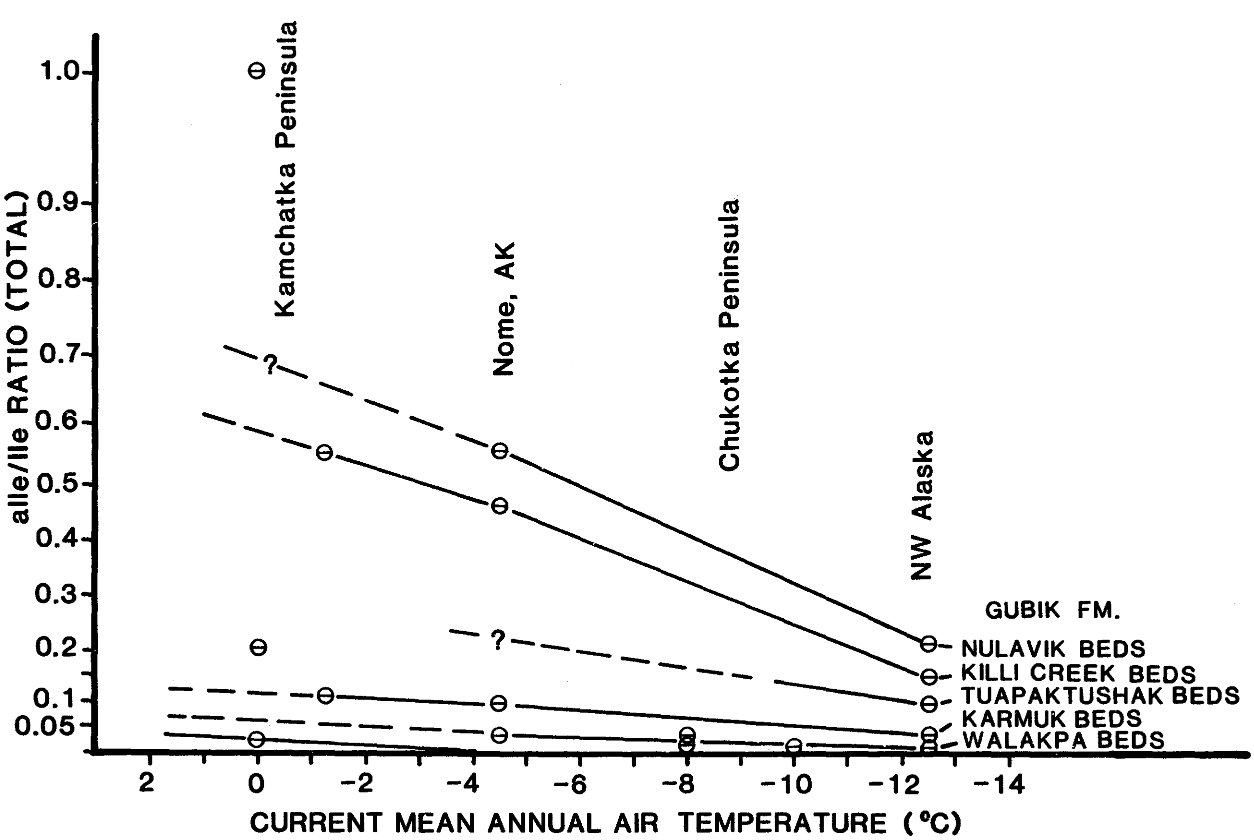

FIGURE 11.—Tentative correlation of transgressive marine units between Alaska and northeastern Russia, based on total-amino acid aIle/Ile ratio plotted against current mean annual temperature.

ABSTRACTS NOT PRESENTED AT THE SYMPOSIUM

POSSIBLE ORIGINS OF PLACER GOLD IN KOVUKUK AND CHANDALAR DISTRICTS, BROOKS RANGE, ALASKA

BY JOHN C. ANTWEILER, JOHN R. WATTERSON, JOHN B. CATHRALL, AND ELWIN L. MOSIER

In regions of permafrost, gold nuggets may form when mineral or organic acids dissolve, transport, and then deposit finely divided gold on spores of psychrophilic (cold-loving) bacteria. As an example, in the Kovukuk and Chandalar districts, Brooks Range, Alaska, gold-quartz-antimony-arsenic-sulfide veins have been suggested as the source of gold in a number of placer deposits. In addition to the gold-bearing veins, gold often occurs as tiny particles disseminated in schists and in igneous rocks such as diorites. There, as elsewhere in Alaska, gold in those veins is of smaller grain size than that in the placers and is also of much lower fineness. Typically, grains of gold in the veins occur as small, discontinuous blebs, wires, stringers, or crystals that weigh only a few milligrams at most and have a fineness of 800–825. Nuggets in nearby placers, however, sometimes exceed an ounce in weight and have a fineness of 900–970.

Finely disseminated gold that occurs in schists, veins, stringers, and blebs in many Alaskan gold fields can be dissolved by several agents. These include cyanogenic compounds in organic materials, organic acids in the layer of humus-rich muskeg over permafrost and bedrock exposures, and sulfuric acid with traces of arsenic and antimony in pyrite-rich zones. In addition, various microbiological processes may contribute to the solubilization of gold.

The spores of bacteria can precipitate gold from solution. In laboratory experiments, suspensions of *Bacillus cereus* spores added to 1,000 micrograms/milliliter solutions of gold chloride have been shown to bind gold chemically. They have also been shown to be nucleation centers for the growth of microscopic 8- and 12-sided gold polygons similar to small crystalline gold nuggets found in placers. X-ray diffraction and scanning electron microscope confirmed the crystalline nature of gold fixed to bacterial spores.

We therefore propose the following: finely divided gold may be solubilized in several ways and is carried to solution through channels or fractures in permanently frozen ground. The same channels may also transport psychrophilic bacteria that thrive at temperatures near 0°C. The spores of these bacteria at favorable sites may be nucleation centers for the growth of crystalline gold nuggets.

PERMAFROST STUDIES IN ALASKA

BY ROBERT F. BLACK[1]

During the period 1945–1952 detailed studies of permafrost were carried on in central and northern Alaska, and reconnaissance was made of many areas throughout the region. The main focus of the initial work was to resolve the opposing viewpoints of E. de K. Leffingwell and Stephen Taber. Leffingwell in 1919 published the contraction hypothesis for origin of ice wedges in permafrost. In this concept ice wedges at the top of the permafrost table were initiated by ground-contraction cracking in early winter, the cracks filling with snow, hoar frost, and freezing water during the spring thaw. Moisture came from the atmosphere and surface. Taber in 1943, however, denied this was an active process and proposed that the ice wedges were fossil features that grew at the time of the formation of the permafrost by water being drawn up from below. Thus, the age, significance, and engineering implications of the ice wedges were thrown into doubt.

It is interesting to note that Leffingwell's study was done over a period of many years while he lived year-around in extreme northern Alaska—a region of continuous permafrost. In contrast, Taber's work had been concentrated on seasonal frost in connection with highway construction and maintenance and on simple laboratory experiments with the freezing of small samples. His one summer in Alaska was confined essentially to the discontinuous and sporadic zones of permafrost—a time when the contraction cracks of the previous winter were obscured by thaw and luxuriant vegetation.

The need for quick assessment of permafrost conditions during World War II demanded better understanding of the age and origin of the processes involved in the growth of ice in the ground and of the significance of surface features, particularly polygonal patterns, in evaluating the character of the permafrost. My work through the change in seasons at Barrow substantiated fully the observations and interpretations of Leffingwell. Precise measurements of ground contraction showed that the ground responded to temperature changes as would be expected and that cracking and partial filling did occur. The average rate of growth in width of the ice wedges was about 1 mm/year. Modified techniques and equipment of glaciologists and petrologists also were used to prepare and study numerous thin sections of the ground ice. Interpretation of the detailed fabrics of ice wedges corroborated and reconstruction of their manner of growth and of the thermal stresses and strains that took place seasonally.

Buried, inactive ice wedges also were studied in the field and laboratory, but they were not amenable to dating in those earlier years. Samples for radiocarbon dating, collected recently in northern Alaska, show the wedges to be very old, probably spanning most if not all the Wisconsinan Stage. The deeply truncated roots of buried wedges are rising very slowly, like diapirs, because of horizontal stresses from the growth of large surface wedges and from thermal changes. The permafrost is active in its upper part.

A knowledge of ice wedges in Alaska has aided immeasurably in identifying true ice-wedge casts in the temperature regions of the United States. Permafrost climates associated with the margins of former ice sheets have been postulated on the basis of wedge structures that have been misidentified in many places, such as southern New England.

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PLEISTOCENE OF NORTHERN GREENLAND

BY WILLIAM E. DAVIES

North of 79 degrees, a zone of ice-free land, 100 to 200 km wide, extends across the north part of Greenland. In this area are coastal alpine mountains south of which are high, dissected plateaus. The land is segmented by long fjords extending from the sea to the inland ice sheet.

In the area of ice-free land there is evidence of three pre-late Wisconsinan glacial advances. The features related to the oldest advance and retreat are numerous ice-marginal channels that are not in accord with the geometry of features developed by later Wisconsin glacial events. A later stage of glaciation is in Knud Rasmussen Land north of Hyde Fjord where the mountains are cut by interconnected cirques many of which have been truncated at their heads or toes by younger glaciers moving across them. Some were buried by later ice sheets and at present are partially exhumed or are recognizable from the surface configuration of the ice cover.

Two large terminal moraines extend along Independence Fjord in the vicinity of Hagen and Danmark Fjords. The northernmost is a ridge over 50 km long and up to 200 m high formed of unweathered clayey and silty sand with cobbles and boulders. Bordering this moraine to the south is one of similar but deeply weathered material which has been planed off by overriding of more recent glaciers.

During Wisconsinan glaciation there were six major ice centers. The inland ice sheet of Greenland expanded north to Independence Fjord, J. P. Koch Fjord and westward towards Nares Strait. The ice sheet in Nares Strait and to the north did not connect with the one on Ellesmere Island and only snouts of valley glaciers extended into the strait. The ice caps of Hans Tausen Land and Nordkronnen expanded southwards coalescing with and buffering the inland ice sheet in Independence Fjord as well as moving northeastward down Hyde Fjord. North of Hyde Fjord there is no evidence of extensive overriding by an ice cap. At the time of maximum extent of glaciers there were extensive mountain icefields with valley glaciers coalescing to form piedmont glaciers along the north coast of Greenland. The center of another local ice cap was on the north side of Hyde Fjord near its mouth. Similar conditions existed in a greatly expanded Flade Isblink east of the mouth of Danmark Fjord. The area between Independence and Hyde Fjords appears to have been free of ice cover, and there remain a number of high level, interlaced valleys that carried meltwater from the ice sheet to the Greenland Sea.

Based on marine terraces, the retreat of the ice in Nares Strait and to the north began 7,000 to 8,000 years B.P. During the retreat of the inland ice sheet and smaller ice caps, movement from the ice centers was concentrated in long valley glaciers occupying the major valleys. Successive retreatal positions follow valleys and are more or less parallel to present ice fronts. Uplift since retreat began varies from 25 m on the northern Arctic coast to a maximum of 129 m between Independence and Hyde Fjords.

During retreat of the ice, varved clay and silt deposits 20 m or more thick were laid down in most of the large, interconnecting valleys in lakes formed behind ice-tongue dams. Extensive marine deposits formed along the coast of the Greenland Sea and were reworked into seven main levels of raised beaches and delta terraces. End moraines are well developed in valleys and on coastal plains but are generally not well developed on the upland.

THERMODYNAMICS AND OCEANOGRAPHY OF THE SEA ICE EDGE

BY EDWARD G. JOSBERGER

Sea ice melting at the ice edge is one of the primary processes that determines the ice edge position; the melting results from the upward heat flux from the underlying upper ocean. The melting process occurs during both the winter and the summer because the adjacent open ocean in the Marginal Ice Zone (MIZ) is at a temperature above the salinity determined freezing point. The ice is then either blown out into this relatively warm water or this water flows under the ice. This melting produces the large horizontal gradients of temperature and salinity that characterize the MIZ. Melt rate measurements from the winter Bering Sea and the summer Greenland Sea show that the melt rates reach 20 mm per hour for typical upper ocean temperature, salinity and velocity conditions. Figure 12 shows the melt rates and sea water temperature and speed 2 m below the ice from the winter Bering Sea experiment.

A properly formulated model of ice melting in sea water must include the eutectic relationship between temperature and salinity and both the heat and salt transfer from the underlying upper ocean. The results of such a model show the following: first, the ice-sea water interface temperature is within 10% of the far-field salinity determined freezing point not at 0°C nor at the far-field freezing point; second, the melting rates are of the order of 1 m/day; finally, the effect of the melting on the upper ocean dynamics, as characterized by the Obukov length, are minimized by the upward salt flux reaching the ice. In this case the Obukov lengths are greater than the planetary boundary layer depth.

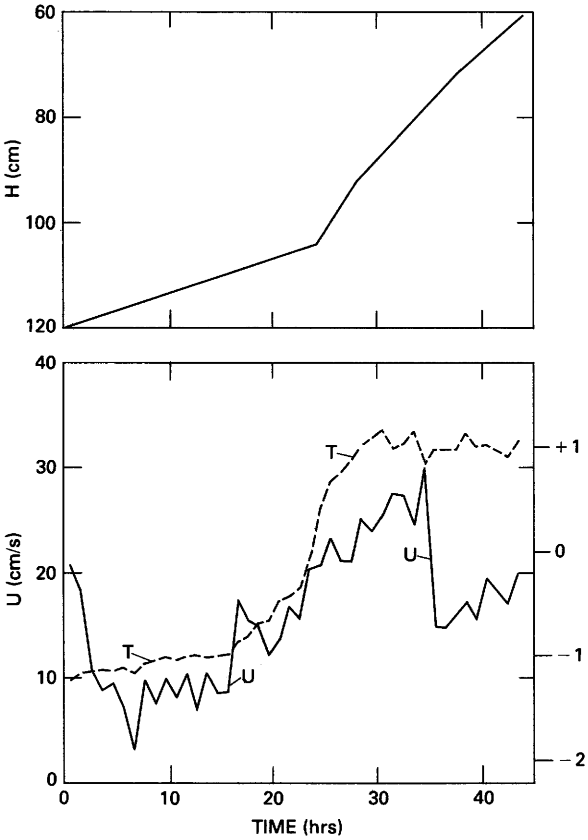

FIGURE 12.—Ice thickness, ocean temperature, and ocean speed taken during the Bering Sea MIZEX experiment, February 1983. The closing of switches set at increasing depths in the ice gave the ice thickness during the experiment. A current meter suspended 2.5 m below the ice gave the ocean temperature and speed. Initially the ice was in water at −1°C and was melting at 7 mm/hr. Then the ice moved into water at +1°C, and the melting increased to 20 mm/hr.

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