Symposium: Global Sea Level and Plate Tectonics through Time

Peter A. Rona, *Atlantic Oceanographic and Meteorological Laboratories, National Oceanic and Atmospheric Administration, Miami, Florida 33149*
and
Donald U. Wise, *Department of Geology, University of Massachusetts, Amherst, Massachusetts 01002*

The ideas expressed in the symposium "Global Sea Level and Plate Tectonics through Time" are part of the evolution of thought on eustatic theory (Fairbridge, 1961). Many of our predecessors, including Darwin, Chambers, Suess, Grabau, Stille, Bucher, Umbgrove, and Kuenen, recognized that tectono-eustatic processes affecting the cubic capacity of the ocean basins are capable of primary control of eustatic sea-level changes at times other than ice ages. Their ideas were based on limited knowledge of ocean basins and various global tectonic theories that have been largely debunked. An enhanced understanding of global sea level is emerging from the increase in our knowledge of the ocean basins and the development of the theory of plate tectonics.

Laurence L. Sloss, Northwestern University, emphasized the need for caution in discriminating between the effects of cratonal tectonics and of eustatics. The cratons are active and form their own imprint on the total sediment regime manifested in the recognized Sloss cratonic stratigraphic sequences (1963, 1973a, 1973b).

A. Hallam, Oxford University, along with H. W. Menard (1964), was among the earliest to recognize the quantitative importance of reversible changes in the volume of mid-oceanic ridges in the control of global sea level. Using biostratigraphic correlation techniques, Hallam demonstrated the synchroneity of oscillations with periodicities of 10^5 to 10^6 and 10^7 to 10^8 yr superposed on continental epeirogenic movements during Jurassic time. He attributed an apparent emergence of continents over the past approximately 10^9 yr based on the Egyed curve (1956) primarily to the process of "continental underplating" (Hallam, 1963, 1969, 1971, 1973).

Erle G. Kauffman, U.S. National Museum, developed an integrated biostratigraphic geochronologic system for Cretaceous time which provides evidence for a sequence of synchronous world-wide transgressions and regressions on a time scale of 10^6 to 10^7 yr. The transgressive-regressive sequence on island arcs is the reverse of the sequence on cratonic interiors and margins (1972, 1973a, 1973b).

Walter C. Pitman III and James D. Hays, Lamont-Doherty Geological Observatory, Columbia University, demonstrated quantitatively that the world-wide middle-to-Late Cretaceous transgression and subsequent regression may have been caused by a contemporaneous pulse of rapid sea-floor spreading at most of the mid-oceanic ridges between 100 to 85 m.y. The rapid spreading caused the ridges to expand and hence reduced the volumetric capacity of the ocean basins, resulting in as much as 500 m of vertical sea-level change. Cenozoic continental emergence has resulted from a reduction in sea-floor spreading rates (Larson and Pitman, 1972; Hays and Pitman, 1973; Pitman and Hays, 1973).

Nicholas C. Flemming and David G. Roberts, National Institute of Oceanography, United Kingdom, constructed theoretical hypsographic curves corresponding to various distributions of mass between continents and ocean basins. They emphasized the complex interaction between factors affecting the form of the Earth's crust and the total volume of ocean water in determining the magnitude and rate of eustatic movements (1973a, 1973b).

Peter A. Rona interpreted rates of sediment accumulation on subsiding continental margins and in ocean basins as indices of the state of the global plate tectonics system. The rates of sediment accumulation over a time scale of 10^6 to 10^7 yr are related through cyclic eustatic sea-level fluctuations to rates of sea-floor spreading, reversible volume changes of the mid-oceanic ridge system, and net orogenic state of the continents (1973a, 1973b, 1973c).

Donald U. Wise proposed a constant freeboard model in which the relative elevation of continents with respect to sea level is a function of the rate of operation of the plate tectonics system. The Wise freeboard model reflects a precontinental break-up rate during Paleozoic time and a postcontinental break-up rate during Mesozoic and Cenozoic times, as opposed to Egyed's (1956) interpretation of progressive continental emergence throughout Phanerozoic time (Wise, 1972, 1973).

Eustatic changes of sea level manifest volume-area-isostasy relations between continents and ocean basins that are recorded in the curve of continental freeboard. The symposium papers presented evidence defining portions of the freeboard curve and controversial speculation regarding the controlling processes. Definition and interpretation of the continental freeboard curve through time present a unifying challenge to geoscientists.

REFERENCES CITED

Egyed, L., 1956, Determination of changes in the dimensions of the earth from paleogeographical data: Nature, v. 178, p. 534.
Fairbridge, R. W., 1961, Eustatic changes in sea level, Vol. 4, *in* Ahrens, L. H., Press, F., Rankama, K., and Runcorn, S. K., eds., Physics and chemistry of the Earth: London, Pergamon Press, p. 99–185.
Flemming, N. C., and Roberts, D. G., 1973a, Tectono-eustatic changes in sea level and sea floor spreading: Nature, v. 243, p. 19–22.
——— 1973b, Eustatic changes in sea level during the Mesozoic and Cenozoic, causes and effects: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 622.
Hallam A., 1963, Major epeirogenic and eustatic changes since the Cretaceous and their possible relationship to crustal structure: Am. Jour. Sci., v. 261, p. 397–423.
——— 1969, Tectonism and eustacy in the Jurassic: Earth-Sci. Rev., v. 5(1), p. 45–68.
——— 1971, Mesozoic geology and the opening of the North Atlantic: Jour. Geology, v. 79, p. 129–157.
——— 1973, Heirarchical pattern of Phanerozoic eustatic changes: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 650–651.
Hays, James D., and Pitman, Walter C., III, 1973, Lithospheric plate motion, sea level changes and climatic and ecological consequences: Nature, v. 246, p. 18–22.
Kauffman, Erle G., 1972, Evolutionary rates and patterns of North American Cretaceous mollusca: Internat. Geol. Cong., 24th, Montreal 1972, sec. 7, p. 174–189.
——— 1973a, Cretaceous bivalvia, *in* Hallam, A., ed., Atlas of palaeobiogeography: Amsterdam, Elsevier, p. 353–383.
——— 1973b, Stratigraphic evidence for Cretaceous eustatic changes: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 686–687.
Larson, R. L., and Pitman, W. C., III, 1972, World-wide correlation of Mesozoic magnetic anomalies and its implications: Geol. Soc.

America Bull., v. 83, p. 3645–3662.
Menard, H. W., 1964, Marine geology of the Pacific: New York, McGraw-Hill Book Co., 271 p.
Pitman, Walter C., III, and Hays, James D., 1973, Upper Cretaceous spreading rates and the great transgression: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 768.
Rona, Peter A., 1973a, Relations between rates of sediment accumulation on continental shelves, sea-floor spreading, and eustacy inferred from the central North Atlantic: Geol. Soc. America Bull., v. 84, p. 2851–2872.
——— 1973b, Worldwide unconformities in marine sediments related to eustatic changes of sea level: Nature Phys.-Sci., v. 244, p. 25–26.
——— 1973c, Global sea level, plate tectonics and marine stratigraphy: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 785.
Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geol. Soc. America Bull., v. 74, p. 93–114.
——— 1973a, Mode and history of vertical deformation of continental interiors: EOS (Am. Geophys. Union Trans.), v. 54(4), p. 454.
——— 1973b, Tectonic and eustatic(?) factors in late Precambrian-Phanerozoic global sea-level changes: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 813–814.
Wise, Donald U., 1972, Freeboard of continents through time: Geol. Soc. America Mem. 132, p. 87–100.
——— 1973, Constant freeboard deviations and the master equilibrium of tectonics: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 5, no. 7, p. 867.

Symposium: The Unsteady Earth

Marie Morisawa, *Department of Geological Sciences, State University of New York at Binghamton, Binghamton, New York 13901*

Increasing public awareness of geologic hazards has resulted in more earth scientists working to better understand the mechanisms of specific hazards and to communicate their knowledge to urban and regional planners. Such knowledge can be used to protect life and property in future developments and to alleviate damage in areas that are already developed. Certain disciplines within the earth sciences are emerging as being relatively important in studies that enable us to better understand both the geologic hazards that are caused by man's actions and the hazards over which man has little control. One of these disciplines, Quaternary geology and geomorphology, is fast becoming a cornerstone of environmental geology.

A symposium entitled "The Unsteady Earth" was presented by the Quaternary Geology and Geomorphology Division at the 1973 GSA Dallas meeting. The symposium speakers did an outstanding job of demonstrating how thorough, quantitative studies of Quaternary and geomorphic topics can be useful to both scientists and planners.

Papers concerning detection of Quaternary tectonic movements were presented by Carl Wentworth and Edward Helley of the U.S. Geological Survey. Wentworth presented a strong case that geomorphology is an underrated tool for detecting areas of Pleistocene and Holocene tectonic activity, particularly in relation to placement of reactors and other critical engineering structures. Terraces along the California coast were studied with regard to geomorphic processes, Quaternary deposits, structural geology, and geophysical properties. Because the back edges of marine terraces were cut as horizontal lines, there is a sequence of datums to evaluate the types and magnitudes of post-terrace deformation. It was concluded that surface faulting could be reasonably expected near the proposed nuclear reactor site near Point Arena. Edward Helley's work in the San Francisco Bay region is a fine example of applied Quaternary mapping. Soils studies and radiocarbon and paleontologic dating of sediments of different depositional environments distinguish two age groups of deposits, each with distinctive facies. Since 1970, the length of known active faults has been doubled, rates of deposition of bay muds and alluvial fans have been identified (1.0 to 1.5 m per 1,000 yr), rates of tectonic subsidence have been computed locally, and the distribution of fluvial deposits that are graded to a Holocene shoreline has provided a basis for a long-term flood-inundation map.

Quaternary studies of the Cascade Range provide the best approach to volcanic hazards appraisals, according to Dwight Crandell of the U.S. Geological Survey. Volcanic behavior patterns cannot be established by historical records, but the rocks and unconsolidated deposits adjacent to the volcanoes record the events of the last 10,000 to 15,000 yr. Within the last 12,000 yr, 11 volcanic episodes have been recognized at Mount Rainier and more than 30 at Mount St. Helens. Potential hazards that should be planned for include lahars, floods, pyroclastic flows along valley floors, and tephra falls downwind from the volcanoes.

Charles Groat, Texas Bureau of Economic Geology, and Ben Lofgren, U.S. Geological Survey, presented papers about the impact of pumping ground water from Quaternary and older deposits in the Texas coastal zone and the San Joaquin Valley, respectively. Holocene growth faulting has occurred in Texas as a result of gulfward creep of thick piles of deltaic sediments, differential compaction of the deposits, and piercement structures. In the Houston area, as much as 300 ft of head decline has accelerated the rate of compaction, causing as much as 8 ft of land subsidence. Renewed movement has occurred along some of the pre-existing faults. In the San Joaquin Valley and elsewhere, Quaternary deposits have sensitive responses to stress increases caused by man's exploitation of formation fluids. The resulting accelerated compaction affects more than 10,000 sq mi in five states. Horizontal ground movement has also occurred because of horizontal seepage stresses, and may be in part responsible for earth fissures in some basins.

Richard Parizek of Pennsylvania State University pointed out the unique environmental considerations that have to be made in unstable carbonate terrains. The variety of problems that may be associated with carbonate terrains are functions of climate, type and age of rock, and topography. Land settlement may be imperceptible to catastrophic in nature, and sinkholes may develop slowly or in seconds. The quality of ground-water resources may be degraded by agricultural activity, waste disposal, storm-water runoff, highway construction and maintenance, and utility pipelines.

Excellent talks about regional landslide-hazard evaluation were made about Wyoming forested land (Robert Bailey, U.S. Forest Service) and the San Francisco Bay region (Tor Nilsen and Earl Brabb, U.S. Geological Survey). For the landslide-hazard map of the 1,800-sq-mi Wyoming study area, 300 sq mi were classed as unstable and 700 sq mi as partially stable. Landslides in clayey rocks are the most common type of failure, but rockslides, rock falls, and debris avalanches also are common. The results of the study should reduce damage from road construction and logging operations. In the San Francisco Bay region, landslides during the 1968–1969 rainy season caused $25 million in damage to roads, urban housing, and other construction projects. The thousands of landslides that have been mapped by photointerpretation range from small, surficial failures to deep slope failures up to 10 mi wide. One of the results of this intensive study has been the preparation of many slope stability maps for local and regional planners.

These eight presentations were more than summaries of careful studies for a symposium. They are part of a most worthwhile trend at recent GSA meetings of defining and providing solutions for those hazards that may be chiefly the result of man's tampering with the unsteady Earth and those hazards over which man has little control. The need for studies of Quaternary geology and geomorphology is clear, and that need will be reflected in future patterns of education and hiring.

Symposium: Geology and Management in the Coastal Zone: Institutional Perspectives, Area Perspectives

E. G. Wermund, *Bureau of Economic Geology, University of Texas at Austin, Austin, Texas 78712*

The program concerning coastal zone management brought together a state senator, a state land commissioner, a vice president of an international oil company, a university president, three directors of state geological surveys, a geologist from the U.S. Geological Survey, and a research geologist from an academic center to discuss institutional and area perspectives. Some imbalance resulted from the geographic distribution of the speakers, as four of the nine were from Texas; the others were from California, Delaware, Florida, Louisiana, and New York (international). Nevertheless, they were representative of those institutions making decisions or providing information for coastal zone management.

All the speakers emphasized that the coastal zone supports a large population and has a greater density than any other geographic area of the nation. The coastal zone has tremendous competition for space to provide activities such as recreation, commercial fishing, resource production, industrial growth, and land development in general. The natural setting is dynamic, and thorough knowledge of geologic and biologic processes is requisite for wise management.

A balanced morning program on institutional perspectives began as a state senator, A. R. Schwartz, who represents a large coastal constituency, stressed two facts: (1) that a legislator must have the input and guidance supplied by a geologic institution to formulate realistic coastal legislation, and (2) that geologists must not be satisfied with only publishing their coastal research in academic circles but must communicate their results to legislators and ultimately to the public. The land commissioner of Texas, Robert L. Armstrong, reinforced Senator Schwartz's conclusions by anecdotal reference to "flat maps" of the coastal zone which were inherited by his office. "Flat maps" were plats having no management information: no geology, no biology, no topography or bathymetry, and no land use. Thus, decisions dependent on such information could not be made.

T. D. Barrow, senior vice president of Exxon Corporation, summarized coastal zone management from an industrial perspective. He stressed that the technical know-how of geologists and biologists must be integrated with socioeconomical analyses to develop priorities for utilizing the rich attributes of the coast, unconstrained by emotion. Barrow's presentation was followed by that of P. T. Flawn, president of the University of Texas at San Antonio, who provided a viewpoint of academic institutions. Flawn viewed the "emotional" factor of the prior talk as a communications gap, and toward the solution of that impasse he saw the obligation of academic institutions to develop curriculums that provide multidisciplinarians who can unemotionally incorporate scientific, engineering, socioeconomic, and political considerations into the best land use management.

The morning talks provoked lively discussion. One major point made was that industry is less inclined than government to employ a multidisciplinarian specialized in one field and trained in another field of science-engineering and (or) economics-politics-law. Additional discussion compared the contributions of basic and applied research in coastal zones: applied research has not been second-rate; indeed, it has contributed much to our understanding.

During the afternoon session, speakers, primarily from government geological surveys, emphasized area perspectives. R. R. Jordan, state geologist of Delaware, characterized the Atlantic coastal zone as a major geosyncline, the northern coastline of which is submerged glacial deposits, the midportion emergent clastics, and the southern part finer grained and increasingly calcareous. R. O. Vernon, director of a division of the Florida Department of Natural Resources, further emphasized the carbonate terrain of southern and western Florida, where karst processes strongly affect land use. S. M. Gagliano of Louisiana State University's Center for Wetland Resources illustrated a management model for a coastal state dominated by the interaction of deltaic and coastal processes. W. L. Fisher, director of the Bureau of Economic Geology in Texas, described the variable land capability along a coastline having minor progradation, dominated by regression, and buffeted by hurricanes—the Texas coast is wet and humid in the north and hot and dry in the south. K. R. Lajoie of the U.S. Geological Survey, and working in the California coast regions, stressed the significance of seismically active areas upon coastal terrains of bays and steep shorelines.

All the speakers explained how strongly the geology of each coast determined solutions of the major problems of maintaining water quality, recognizing the capability of land to support different activities, and finally, producing mineral resources important to both local and national management decisions. These concerns related directly to perspectives described by the industrial representative in the morning session.

The detracting elements of the symposium were that speakers generally read from texts with insufficient visual aids, that the afternoon session did not develop better discussion, and that the attendance was very poor considering the expertise of the speakers. The two sessions altogether fulfilled the objectives suggested by the title of the symposium; one may be left only to ask, What can any one citizen geologist, unattached to an institution, contribute to coastal zone management?

Symposium: Geology and Geochemistry of the Moon

W. R. Muehlberger, *Department of Geological Sciences, University of Texas at Austin, Austin, Texas 78712, and Center of Astrogeology, U.S. Geological Survey, Flagstaff, Arizona 86001*
and
Harrison H. Schmitt, *Astronaut Office, Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas 77058*

This symposium was designed by its co-conveners to consist of review papers so that any member of the audience, regardless of how little he or she knew about the Moon, would be able to grasp the main essentials without getting bogged down in the details of data presentation that are typical of current lunar studies. This summary should be read in conjunction with the abstracts; many of these talks will appear as papers in *Reviews of Geophysics and Space Physics* in the near future.

Harrison H. Schmitt discussed our knowledge of the Moon as we prepared for the *Apollo* landings. The photogeologic sequence known before the landings was (1) "old" cratered highlands, (2) basin formation, (3) light-plains filling, (4) mare filling, and (5) regolith development, including postmare craters and swirls. This sequence was developed mainly from telescopic studies by the U.S. Geological Survey and later extended by the use of *Ranger, Surveyor,* and *Lunar Orbiter* data.

As summarized by Schmitt, numerous committee meetings produced a set of potential landing sites, mostly in the equatorial belt of the Moon because of operational constraints; the rankings of proposed sites changed as new data accumulated. The first *Apollo* sites were selected within the constraints of a low-energy return trajectory, which dictated sites in the equatorial belt, and an area of low roughness (a mare site). The *Apollo 8* mission was flown as if it were to be a landing (but without a landing module) and was targeted for site 2 (eastern Mare Tranquillitatis). Because this mission was so successful, it was decided to target *Apollo 10* to site 3 in order to enrich the operational experience before an actual landing attempt. *Apollo 11* followed the same path as *Apollo 10* and successfully landed at site 3, now known as Tranquillity Base.

Apollo 12's objectives were to demonstrate pinpoint landing capabilities, as well as to sample a western mare site for comparison. A ray from Copernicus had been recognized at telescopic resolution at this site, and it appears that it was successfully sampled. Later landing sites were determined, with increasing confidence and experience, primarily on scientific grounds, although operational safety requirements were always foremost. *Apollo 13* was targeted to the Fra Mauro site to sample material that on photogeologic grounds could be shown to have been excavated from the Imbrium basin; after *Apollo 13* failed to land, *Apollo 14* completed the mission.

The *Apollo 15* landing target was a high-latitude site, picked to maximize the coverage of the group of new cameras and geochemical sensors aboard the command module and to give the surface geophysical instruments (principally the seismometers and magnetometers) the widest baseline as early as possible in the *Apollo* series. In addition, the mission had the first lunar rover, permitting widespread observation and sampling of geologic features that included a mare unit, a sinuous rille, and the base of a mountain range uplifted during the formation of the Imbrium basin. Ray material from two large craters, Aristillus and Autolycus, several hundred kilometers north of the site, also was sampled.

Light-plains and ridgy constructional forms in the central highlands were the objectives of *Apollo 16*. This mission also completed the seismic and magnetometer network and surveyed a new swath of the Moon with the orbiting photographic and geochemical sensors.

Apollo 17 had two main goals: a search for crustal rocks and basin ejecta older than those already sampled from Imbrium and a test for young volcanics represented by dark mantling deposits. The Valley of Taurus-Littrow at the southeastern margin of Mare Serenitatis was selected for this last manned mission. The widest variety of geologic units yet investigated on the Moon is yielding much information for rivising our entire model of lunar evolution.

Larry Haskin stated that geochemical interpretation of the Moon is constrained by geophysics, solar composition, and the petrology of lunar rocks. Nevertheless, there is wide latitude in acceptable theories. Generally, isotopic and chemical characteristics require that the moon differentiated in part at the time it formed. The moon was subjected to extensive severe impact processes until about 4.0 b.y. ago, then further chemical differentiation produced the mare basalts, the youngest of which sampled are about 3.2 b.y. old. The prime geochemical clues to the nature of these events as seen in the samples include (1) bulk composition, (2) anomalies and shapes in the curves of chondrite–normalized rare earth element abundances, (3) low concentration of volatile siderophile and chalcophile elements, and (4) high concentration of refractory lithophile elements. Geophysical data indicate the existence of crustal layers that limit geochemical inferences. Composition of mare rocks shows that the Moon is as strongly differentiated as is the Earth, and that the mare basalts must have been partial melts to have attained their observed elemental abundances. Mare soils need a 1 to 2 percent meteoritic component to account for the siderophile and volatile element concentration increase over that of mare basalt. Low concentration of Au, Ir, Ni, and Co in crustal rocks suggests iron segregation (a core?). Petrogenetic arguments indicate that garnet is unlikely in the source region of the basalts.

Lunar highlands consist of feldspar-rich rocks, consistent with an earlier hypothesis that feldspar accumulated at the surface of a partly molten Moon. Only a very few of the highland samples, which consist of nearly pure feldspar, retain sufficient chemical and petrographic characteristics for their formation to be consistent with such an origin. Isotopic ratios require separation of these feldspars at the time of origin of the Moon. A more common class of returned highland sample has compositions best understood as KREEP-rich liquid produced by partial melting. (KREEP is an acronym for lunar material rich in refractory and large ion lithophile elements.) Petrographic clues to the original nature of nearly all highland materials are scarce, a consequence of extensive metamorphism. A considerable range in composition of rocks in the lunar highlands indicates that the highlands have not been thoroughly homogenized by impact-related processes, or that those processes have caused differentiation, or both. Mixing lines with feldspar cumulates and KREEP-rich material as end members fail to explain the compositions of many highland rocks. Some anticipated concentrations for Fe, Mg, and Al based on such a model are not found in the samples analyzed. The basic hypothesis of the highlands as feldspathic cumulates may be incomplete, or the highlands may be overlain by a veneer of KREEP-rich material whose origin and nature are not understood.

Keith Howard and his colleagues stated that the physiographic provinces of the whole Moon are, in order of increasing age (1) mare basalt, (2) rejuvenated areas ringing Imbrium and Orientale, (3) older Nectarian-age basin deposits, and (4) heavily cratered highland areas (these are most distant from Imbrium and Orientale, predominantly on the far side). They showed that the most recent basins have recognizable ejecta blankets, whereas the oldest are nearly unidentifiable. The 40 basins now recognized are close to the steady-state limit for the early Moon and thus the upper 20 km of lunar crust, broken up by basin-forming events prior to 4 b.y. ago, could be considered a megaregolith. The largest probable lunar basin recognized is 2,000 km in diameter (larger than the radius of the Moon!) and is in the far side southern hemisphere. The light-plains units, because of their distribution patterns, appear to be related to basin formation.

The original shapes of the basins are difficult to determine because of central uplifts and down-dropped rings that form as a consequence of crater formation. Upthrown mantle was illustrated under central uplifts. The net negative gravity anomaly over unfilled basins may approximate true volume removed by the event.

W. Ian Ridley and his associates pointed out that study of lunar highlands samples is difficult because the original petrographic and chemical characteristics have been modified by metamorphism and by partial to total melting during their later impact history. Most specimens are breccias that were once part of hot ejecta blankets. Lithic clasts give information on the chemistry and earlier history of the sample. Igneous-appearing textures may be magmatic (poikilitic) or due to heat from hot ejecta blankets that cause partial to complete recrystallization (poikiloblastic textures) of the impact-derived breccias. Mineral-inclusion disequilibria, flow textures, and vesiculation in the matrix are clues to the degree of partial melting.

Microprobe analyses of glass fragments in soil permit a chemical definition of possible highland source rocks, which include (1) high-alumina basalt, (2) anorthositic norite, (3) anorthosite, (4) troctolite, and (5) spinel troctolite (the first two being the most abundant). High-alumina basalts give Rb/Sr model ages near 4.3 b.y. and crystallization ages near 3.9 b.y.

J. J. Papike and A. E. Bence reviewed mare rocks and demonstrated that they could be divided into two major groups: older Ti-rich basalts that are confined to the eastern half of the Moon, and younger basalts, less rich in Ti, that are confined to the western half of the Moon. Each of these groups is divisible into several variants. *Apollo 12* olivine basalt (from the western maria) was proposed as being closest to a primary melt.

Clinopyroxene zoning is well displayed, apparently in response to increasing enrichment in iron in the residual liquid as the lavas cooled and to the initiation of feldspar crystallization. The basalts cooled under extremely anhydrous and reducing conditions. A possible source for these rocks is from a residual differentiate composed of olivine and clinopyroxene at depths near 300 km. The nature of the vapor phase that produced the ubiquitous vesicles is still unknown.

E. M. Shoemaker presented a historical treatment of the evolution of the concepts concerning the origin, thickness, and nature of the lunar regolith. The fact that the edge of the Moon is as bright as the center at full Moon means that the surface must consist of pulverized material. The *Apollo* missions gave us samples of this material to study: it is an aggregate of rock and mineral fragments, glass beads, agglutinates (fragments bonded by impact-generated glass), and a small amount of meteoritic material. The thickness of the regolith is approximately equivalent to one-fifth of the diameter of the smallest crater that has a blocky rim. Turnover rates determine the probable lifetime of a rock embedded in the regolith. The *Apollo* landings have produced data to calibrate the curves for regolith formation (impact rates) showing that the rates decreased rapidly, an order of magnitude per 100 m.y., until about 3.7 b.y. ago, but have been essentially constant since about 3.0 b.y. ago.

Symposium: Climate Changes: Patterns and Mechanisms

James V. Gardner, *Deep Sea Drilling Project, Scripps Institution of Oceanography, La Jolla, California 92037*
and
G. Ross Heath, *School of Oceanography, Oregon State University, Corvallis, Oregon 97331*

The CLIMAP Project (Climate/Long Range Investigation Mapping and Prediction) is funded by the office for the International Decade of Ocean Exploration of the National Science Foundation. This symposium at GSA's Annual Meeting in Dallas is a partial report of CLIMAP's progress to date. Among the goals of the CLIMAP Project are (1) quantitative reconstructions of late Quaternary global oceanographic and climatic conditions during periods of maximum, intermediate, and minimum glacial development; and (2) the use of these reconstructions to produce and test models that can explain major climatic change and eventually be used to predict future climatic trends. The climatic interpretations are based on changes in organic and inorganic components of deep-sea sediments.

The importance of the Imbrie and Kipp transfer function technique was evident throughout the meeting. Their method involves deriving equations relating portions of the biologic side of the ecosystem to selected oceanographic parameters (such as sea-surface temperatures and salinities) and using these equations on a stratigraphic succession of samples to make quantitative estimates of past marine conditions. This technique was applied by J. Lozano and his associates and by H. Sachs, using radiolarian assemblages from the Antarctic and North Pacific Oceans, respectively. They suggested that during the most recent maximum glacial conditions—about 18,000 yr ago—year-round circum-Antarctic oceanographic conditions were similar to today's winters, with a northward displaced Antarctic Convergence and summer sea-surface temperatures as much as 10°C cooler than present. During this same glacial maximum, sea-surface isotherms in the central North Pacific were displaced southward 4° to 5° of latitude from their present position.

From a study in the equatorial Atlantic, J. Gardner reported intensified upwelling off the west coast of Africa, as well as increased circulation of the equatorial current system during glacial stages which allowed water 8° to 10°C cooler than occurs today to invade well into the tropical region. During the same glacial stages, according to W. Prell, the western Caribbean showed greater seasonal contrasts in sea-surface temperatures than exists today, with cooler, more saline Sargasso Sea–like sea-surface conditions prevailing. This picture of equatorward shift and acceleration of major oceanic current systems during glacial stages suggested for the Atlantic was also evident from B. Luz's foraminiferal data for the southeast Pacific and from

Sach's North Pacific radiolarian data. However, K. Geitzenauer and his colleagues found little change in equatorial Pacific sea-surface temperatures, although they reported slight evidence for a greater seasonal contrast during glacial maxima.

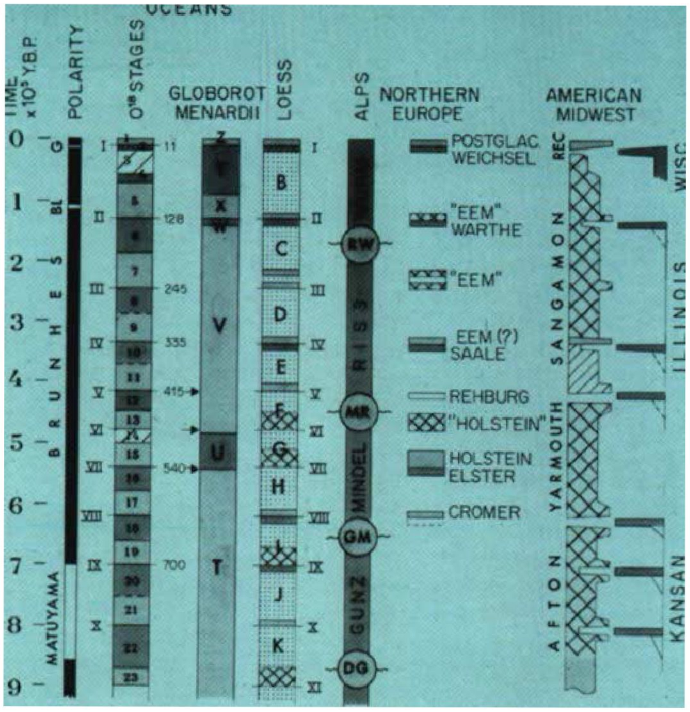

Figure 1. Correlation of deep-sea stratigraphy with central European Standard Loess Sequence (Kukla, 1970, 1974) and with classical European and American glacial stages. ***Oxygen isotope stages*** **(after Emiliani, 1955, 1966, 1972, and Shackleton and Opdyke, 1973). Dark areas = cold; light-gray areas = warm; hatched areas = intermediate. Roman numerals on left stand for terminations after Broecker and van Donk (1970); their absolute ages in millenia (on right) are obtained by averaging set of ages obtained by extrapolation below T II (age from Broecker and van Donk, 1970) with parallel set obtained by interpolation between T II and T IX (Kukla, 1974). Data used from V23-238, P6304-4, P6304-7, and P6304-9.** ***Globorotalia menardii*** **zones of Ericson and three abundance peaks of** ***Globorotalia truncatulinoides*** **(black arrows = probable indication of cold spells) are after P6304-9 core of Emiliani (1966).** ***Standard Loess Sequence*** **(SLS) based on Cerveny Kopec exposure, Czechoslovakia, which overlies Wurm, Riss, Mindel, and Gunz terraces (Kukla, 1970, 1974) and shows that timing of erosional intervals RW, MR, GM, and DG correlates with glacial intervals instead of (as formerly believed) with interglacial intervals. Dotted areas = loess; light-gray areas = interglacial soils; crosshatched areas = polygenetic interglacial soils interpreted as signs of longer duration of forest. Ticklines, equivalents of terminations numbered I through XI and glacial cycles B to K after Kukla (1961). Probable correlation with** ***north European glacials*** **and** ***type interglacials*** **based on terraces of Vltava and Saale (Kukla, 1974) shows type glacials as dark areas, type interglacials as light-gray areas, miscorrelated interglacials as hatched areas, and glacials as white areas. Probable position of sediments representing** ***American glacial stages*** **is estimated, taking into account stratigraphy of Pearlette type O ash of reversely magnetized main Kansan tills (Kukla and Opdyke, 1972), and climatostratigraphic value of type sediments for interglacial stages. Starting phase in development of type Sangamon soil and of recent soil indicated by light-gray areas. Possible time positions of soils, gumbotils, sands, and the like, described as representing interglacials, are crosshatched; the possible miscorrelation is hatched.**

An independent check on the microfossil data was provided by mineralogic analyses of deep-sea sediments. In the North Atlantic off the west coast of Africa, P. Biscaye and his colleagues found higher concentrations of quartz at the 18,000-yr level than at the surface. They attributed the higher concentrations to stronger northeast trade winds during glacial times—a finding consistent with Gardner's foraminiferal results. Similarly, G. R. Heath and his colleagues found that the southern edge of the band of eolian quartz-rich sediments lying across the central North Pacific shifted to about lat 23° to 24° N. during glacial maxima, compared with its 28° N. position today.

The strongest impression that the symposium left was that more energetic oceanographic conditions existed during glacial rather than during interglacial stages, and that these were associated with greater seasonal sea-surface temperature differences, greater equatorial-polar temperature contrast, and intensified winds and compression of the surface oceanic gyres toward the equator during late Pleistocene time.

World-wide correlation of marine Quaternary sections is now a reality. The discovery that most of the variations in the oxygen isotopic composition of calcareous microfossils reflect changes in water volume tied up in icecaps, rather than local changes in surface water temperatures, allows very precise core-to-core correlations, even though the absolute ages of events are still uncertain. Unfortunately, the situation on land is much less satisfactory.

Figure 1 shows G. Kukla's compilation of Northern Hemisphere Quaternary stratigraphic correlations. Clearly, the fourfold (or perhaps fivefold!) division of the Pleistocene, beloved by geologists, has little basis in fact. The correlations between the European and North American stages are still tenuous at best. In the absence of complete stratigraphic sections and of a dating method in the range immediately older than the C^{14} range, the correlations are likely to remain uncertain. Before global climatic patterns covering both land and sea can be compiled for any but the most recent glaciation, much more work remains to be done to relate the major continental glacial events to the complex stratigraphic sequences recognized in deep-sea cores.

REFERENCES CITED

Broecker, W., and van Donk, J., 1970, Insolation changes, ice volumes, and the O^{18} record in deep-sea cores: Rev. Geophysics and Space Physics, v. 8, p. 168-198.

Emiliani, C., 1955, Pleistocene temperatures: Jour. Geology, v. 6, p. 538-578.

——— 1966, Paleotemperature analysis of the Caribbean cores P 6304-8 and P 6304-9 and a generalized paleotemperature curve for the last 425,000 years: Jour. Geology, v. 74, p. 109-126.

——— 1972, Quaternary paleotemperatures and the duration of the high-temperature intervals: Science, v. 178, no. 4059, p. 398.

Kukla, G., 1961, Quaternary sedimentation cycle: Survey of Czechoslowak Quaternary: Warsaw, Czwartorzed Europy Srodkowej i Wschodniej, INQUA VIth Cong., Inst. Geol., Prague, v. 34, p. 145-154.

——— 1970, Correlations between loesses and deep-sea sediments: Geol. Fören. Stockholm Förh., v. 92, p. 148-180.

——— 1974, Loess in central Europe and the age of Pleistocene glacial stages, *in* Butzer, K., and Isaac, B., eds., Stratigraphy and patterns of cultural change in the middle Pleistocene: Edinburgh, Scottish Academic Press—Wenner-Gren Foundation (in press).

Kukla, G., and Opdyke, N., 1972, American glacial stages in paleomagnetic time scale: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 4, p. 569-570.

Shackleton, N., and Opdyke, N., 1973, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale: Quaternary Research, v. 3, no. 1, p. 39-55.