

GEOLOGICAL SURVEY CIRCULAR 602



Sand and Gravel on the Continental Shelf off the Northeastern United States

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By John Schlee

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United States Department of the Interior

STEWART L. UDALL, Secretary



Geological Survey

William T. Pecora, Director



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SAND AND GRAVEL ON THE CONTINENTAL SHELF OFF THE NORTHEASTERN UNITED STATES ¹

By JOHN SCHLEE

ABSTRACT

Most of the continental shelf off New England, Long Island, and New Jersey is mantled by sand associated with lesser amounts of gravel in a quantity probably sufficient to constitute an economic asset. The mantle extends eastward onto Georges Bank and the Scotian Shelf. The sand is quartzose and fine to coarse grained. Gravel is associated with drowned river-terrace deposits of the ancestral Hudson River off New Jersey and with glaciofluvial deposits off Rhode Island and Massachusetts. A few shallow drill holes on the shelf indicate that the sand is as much as several meters thick. Shallow continuous seismic profiles show that uppermost layers on the inner shelf are fairly continuous over much of the area, though the layers vary in thickness.

INTRODUCTION

Increasing interest has been directed toward the continental shelf as a future source of sand and gravel (Schlee, 1964; Emery, 1965; Duane, 1968a; Rexworthy, Simon, unpub. data). Future needs in the United States for sand and gravel have been projected to $1,800 \times 10^6$ short tons per year by 1980 (Cotter, 1965), as compared with a consumption of 934×10^6 short tons per year in 1966 (D'Amico, 1967). In long-term growth, the present production figure represents about a fourfold increase over the past 20 years, and, using Cotter's figure, a twofold increase in the next 20. The question is, Where will the new deposits come from? If the surficial deposits of the continental shelf are to be a potential source, sand and gravel producers will need to know the location, grain-size distribution, composition, and thickness of deposits.

¹ Contribution 2173 of the Woods Hole Oceanographic Institution. Based on work done under a program conducted jointly by the U.S. Geological Survey and the Woods Hole Oceanographic Institution and financed by the U.S. Geological Survey.

As a result of a 6-year cooperative program between the Woods Hole Oceanographic Institution (WHOI) and the U.S. Geological Survey (USGS), approximately 1,000 samples (fig. 1) have been collected on a grid (18 kilometers on a side) over the northeastern U.S. continental margin. As previous investigators have noted (Shepard, 1932; Stetson, 1938), most of the shelf is covered by sand, gravel, and silty clay. Deposits of possible economic interest for the whole Atlantic continental margin have been pointed out by Emery (1965); deposits in selected areas have been noted by Schlee (1964) and Pratt and McFarlin (1966). Emery (1965, 1966) emphasized the wide distribution of sand and gravel on the shelf and the probability that much of it was deposited during a period of lowered sea level in the Pleistocene. Schlee (1964) described a sandy gravel deposit on the shelf off New Jersey in water depths of 20 to 40m (meters); he likened the deposit to upland gravel of fluvial origin in southern Maryland. Many studies not concerned with economic aspects have shown distribution of bottom sediment over restricted areas or along profiles; among these are reports by Trowbridge and Shepard (1932), Shepard, Trefethen, and Cohee (1934), Shepard and Cohee (1936), Stetson (1938), Hough (1940, 1942), McMaster (1960, 1962), Wigley (1961), Moore (1963), Rvachev (1965), Garrison and McMaster (1966), and King (1967). Inventories of the inner shelf sand deposits have been started by the Coastal Engineering Research Center (CERC) of the U.S. Army Corps of Engineers (Taney, 1965, 1966) for selected areas off New

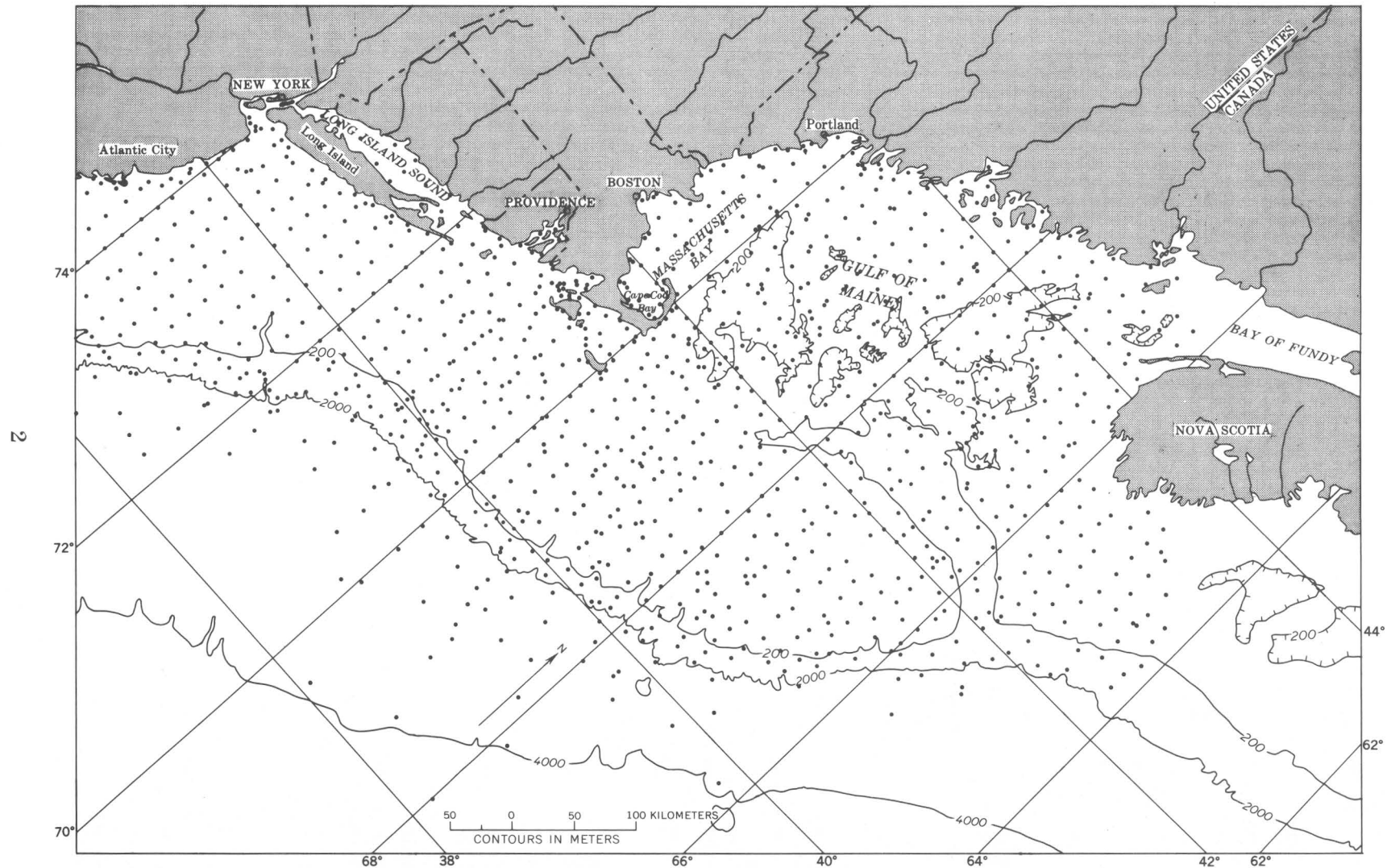


FIGURE 1.—Sample localities on the continental margin off northeastern United States.

Jersey, Long Island, and New England; studies include shallow seismic profiling and vibrocore sampling of the deposits. CERC investigations (Duane 1968a, b; written commun., Aug. 1968) have disclosed considerable quantities of sand within 5 miles of the coast off the northeastern United States and in water depths less than 100 feet.

Many of my colleagues at Woods Hole have contributed to this study through their discussions and in collecting and analyzing the samples. Among these are K. O. Emery, J. R. Frothingham, Jr., J. C. Hathaway, Carlyle R. Hayes, Jobst Hülsemann, R. H. Meade, Jr., R. M. Pratt, J. V. A. Trumbull, and Elazar Uchupi. R. H. Meade, Jr., D. B. Duane, J. P. Minard, and Elazar Uchupi kindly reviewed the manuscript.

METHODS AND DEFINITIONS

The Wentworth scale (Wentworth, 1922) is used here to define grain size classes. Gravel size extends from 2 mm (millimeters) ($\frac{1}{12}$ inch) on up; sand size ranges from $\frac{1}{16}$ to 2 mm. Modal size means the largest amount of sediment (in weight) occurring within a particular size range— $\frac{1}{4}$ to 1 mm or $\frac{1}{16}$ to $\frac{1}{4}$ mm. Depending on its dominance, the modal size generally will give an idea of the appearance of the sediment in terms of relative coarseness. Bottom-sediment samples were collected with a variety of sampling gear. Many samples were collected by personnel from the U.S. Bureau of Commercial Fisheries, using a Smith-McIntyre bottom sampler and a Dietz-LaFond snapper. Those samples collected on the joint WHOI-USGS program were obtained by a Campbell grab bucket or Van Veen sampler. To determine grain size, the gravel fraction was sieved, and sand was sized with a settling tube; silt and clay were pipetted. Statistical parameters, including the principal modes, median, standard deviation, and skewness, were calculated on a digital computer. Where sufficient pebbles were available, rock types were tabulated in the 8- to 16-mm size class to map the areal variation in composition; 50 to 100 pebbles were counted at each of 125 sampling points. Roundness was determined (by R. M. Pratt) on 20 pebbles from the same size class for each sample, using the Krumbein scale.

SAND

As shown in figure 2, most of the sand is on the continental shelf. Except for shallow banks and nearshore areas, it is less abundant in the Gulf of Maine and on the continental slope and rise. Although the sand map is contoured on a partial interval of 25 percent, most of the samples on the shelf in areas marked as greater than 75 percent are 100 percent sand. Hence, the 90- or 95-percent contours would fall nearly on top of the 75-percent contour for most of the region. A few areas on the shelf are deficient in sand; gravelly areas (fig. 3) off New Jersey, Nantucket Shoals, and Georges Bank are examples. Fine-grained sediment in the Hudson Channel area and on the central and outer shelf south of Rhode Island probably veneers older fluvial and marine transgressive sands (Emery and Garrison, 1967). Also apparent in figure 2 is a broad alternating of modal grain size on the shelf. In a festoon pattern, sand with coarse modal size forms a discontinuous thin band along the shelf edge and a much broader band across the central shelf south of Long Island, where it is associated with gravelly areas on Nantucket Shoals and Georges Bank. Sand with a finer modal grain size occupies the areas between the bands of coarser sand and fills transitional zones to finer grained sediment; two such transitional zones are the silty area south of Rhode Island and a sandy apron of fine sand along the northern edge of Georges bank.

The sand is angular to subrounded and quartzose; it contains minor amounts of feldspar, heavy minerals, glauconite, and shell fragments. Weight percent of heavy minerals (specific gravity > 2.85 grams per cubic centimeter) is mainly 1 to 4 percent (Ross, 1969). Areas of abundant sand such as Georges Bank and Nantucket Shoals generally have less than 2 percent heavy minerals. Shell debris is less than 2.5 percent of the sandy sediment, judging from percentages of calcium carbonate determined by Hülsemann (1967, fig. 3); exceptions are on the northeast edge of Georges Bank where shell debris exceeds 20 percent. Throughout much of the shelf, particularly Georges Bank, the ratio of feldspar to quartz is small—1:16 (Hathaway, J. C., oral commun., July 1968)—though in some areas on the outer shelf, the ratio is greater than 1:8. On the

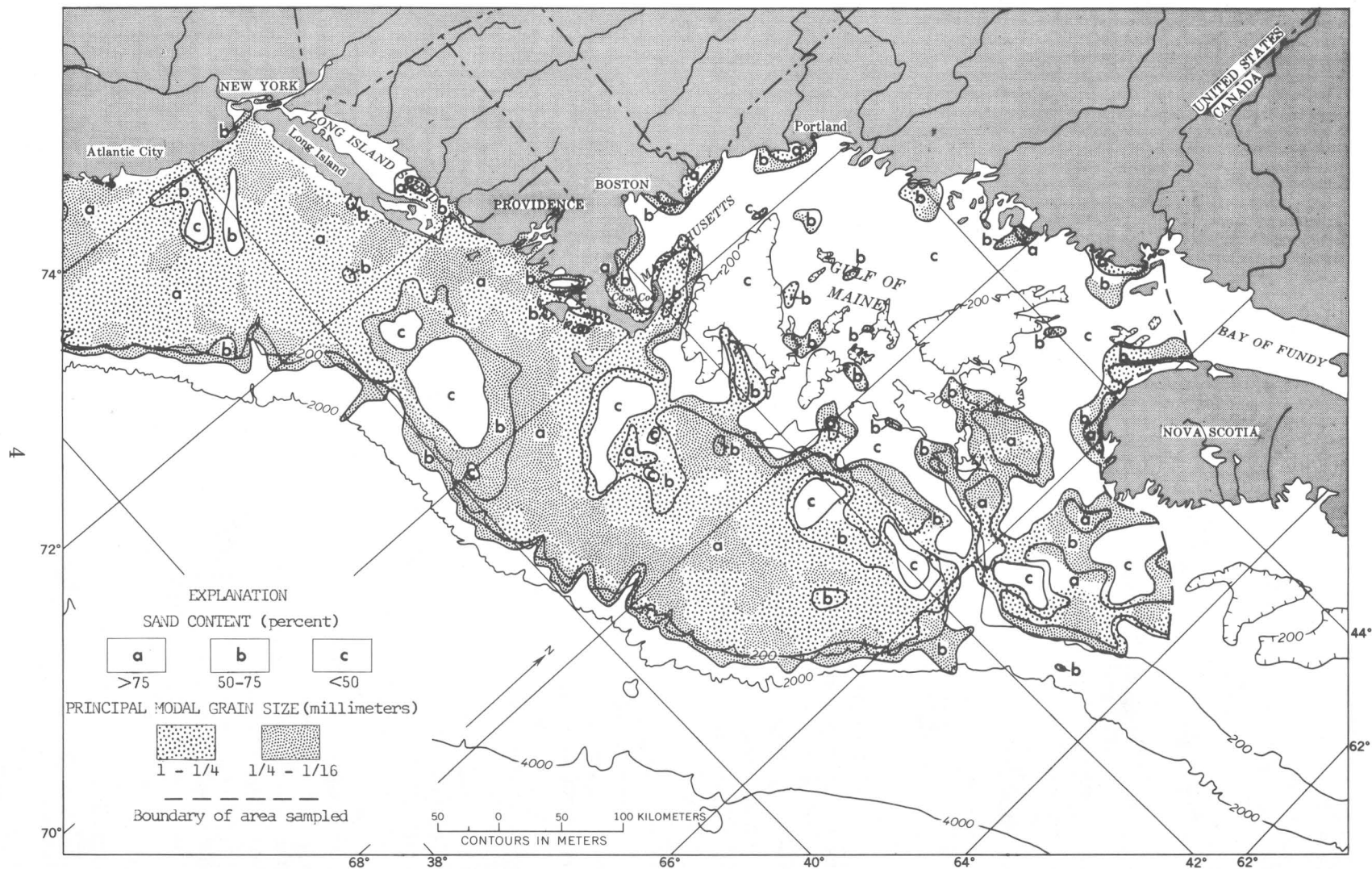


FIGURE 2.—Distribution and principal modal grain size of sand on the continental margin off northeastern United States.

Scotian Shelf, feldspar is much more abundant, in part because of the granitic terrane from which it was derived.

Though most of the continental shelf is mantled with sand, the sea floor of the Gulf of Maine is not. Sand is more patchy there, being restricted mainly to shallow isolated banks and to shallow nearshore areas like Cape Cod Bay. It is mixed with silt, clay, and gravel in some hummocky areas in the central gulf and is almost lacking from the very fine grained sediments in basins of the gulf.

Thus, for metropolitan areas such as Boston and Portland, offshore sources of sand are less plentiful than they are for New York and Providence. Shallow coastal shelves, particularly around Cape Cod and Massachusetts Bays, would be likely areas to investigate. Rhode Island Sound and the inner shelf adjacent to Long Island and New Jersey also are prime areas meriting more detailed study. Indeed, the Army Corps of Engineers tried an experimental pumping operation off Sea Girt, N. J., in 1966 to show the feasibility of the offshore sand as a source to replenish that lost by coastal erosion along the beaches (Mauriello, 1966).

Little is known about the thickness of sand that mantles the shelf. Coast Guard site foundation borings for the Ambrose Light Station and Scotland Light towers at the approaches to New York Harbor show wide variation in thickness of surficial sand and gravel (McClelland Engineers, Inc., unpub. data, 1963); one borehole went through 20 feet of silty sand before entering gray clay. In another hole, 49 feet of sand and gravel were penetrated before entering gray clay. In a third hole, 196 feet of sand and gravel overlies shaly clay. On a Texas Tower site drilled in 185 feet of water 60 miles south of Moriches Bay, Long Island, the log revealed 70 feet of coarse sand and fine gravel overlying silty clay (Athearn, 1957). In a similar-type boring made on Nantucket Shoals, 80 to 90 feet of well-sorted sand and gravelly sand overlie a silty clay bed (Livingstone, 1964; Groot and Groot, 1964). On Georges Shoal, 100 miles to the northeast, as much as 120 feet of fine- to coarse-grained sand with stringers of silty sand and gravel have been penetrated in drilling (J. M. Zeigler, written commun., July 1968). All these holes, with the exception of the first

Texas Tower site, are in shoals where concentration of coarse-grained sediment through reworking would be likely.

Seismic profiles across the shelf (Knott and Hoskins, 1968; McMaster and others, 1968) show a fairly uniform covering, as much as a few meters thick, of the most recent sediment, mantling buried channels, deltas, drift, glacial moraines, and older strata of probable Tertiary and Cretaceous age. The lack of drill-hole data does not permit specific reflectors on the profiles to be identified and correlated. Hence, thickness of the sand cover on the shelf is incompletely known.

GRAVEL

Gravel deposits have a much more restricted distribution (fig. 3) than sand. Even though several large patches are shown, gravel distribution is probably much spottier than is represented here. In part this reflects the complexity of topography in gravelly areas and in part the texture of the gravelly sediment.

Most of the gravel on the shelf south of the Gulf of Maine and New England is associated with sand in a bimodal grain-size distribution (fig. 3). The gravel fraction is quartzose, and fragments are subrounded (Schlee and Pratt, 1969). On photographs of the bottom, gravel can be seen as diffuse patches associated with sand or in troughs with shell debris between sand ripples. Obviously, bottom currents from wave surge and longshore drift have winnowed the sediment and tended to concentrate the coarse detritus in the low areas. On Georges Bank, most of the gravelly samples from shoal areas were collected between sand ridges. Hence, any anomaly showing abundant gravel needs to be taken as a general representation only, realizing that the actual areal pattern may be more restricted by interareas of sand as tidal ridges and sand waves; some of these features are actively being reworked (Stewart and Jordan, 1964).

Gravel in the Gulf of Maine is associated with a poorly sorted matrix of sand, silt, and clay in till-like deposits (fig. 3). Not only does the matrix constitute much of the sediment, but gravel fragments may reach a maximum diameter of several meters; fragments tend to be angular, and the variety of rock types is large. Only along the shallow edges of the Gulf of

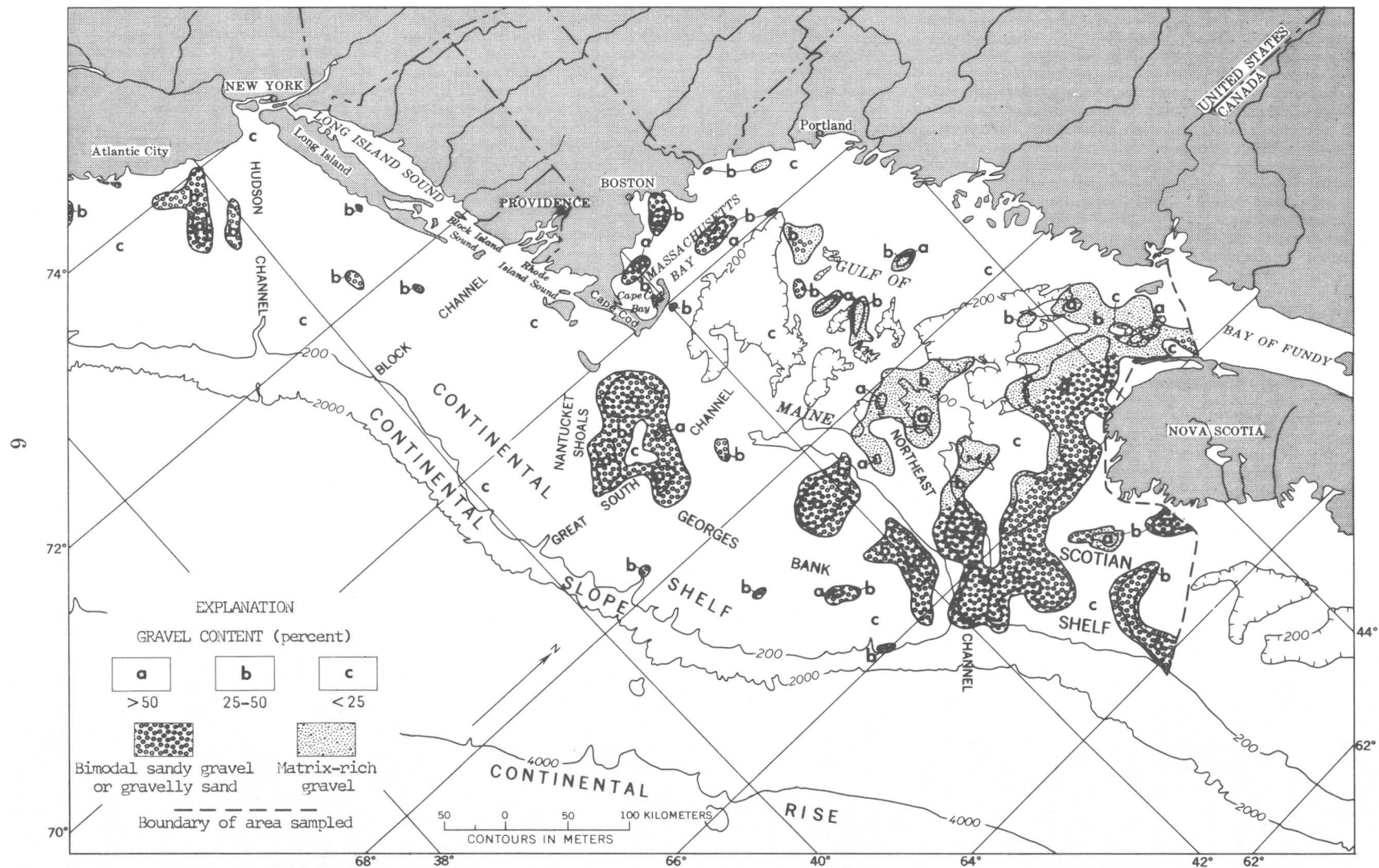


FIGURE 3.—Distribution of gravel on the continental margin off northeastern United States.

Maine and on isolated banks and ledges in the central gulf have currents reworked the glacial till and removed the fine detritus to leave behind a lag of coarse gravel and sand. Reworking of glacial drift is well illustrated on the rocky inner coast adjacent to Nova Scotia and off coastal Massachusetts, where Stetson (1935) described the process many years ago.

Sources of gravel fairly close to land are largely restricted to the deposit off New Jersey, isolated patches in 60 m of water south of Long Island, patchy remnants of glacial moraines in Block Island and Rhode Island Sounds (McMaster, 1960; Schafer, 1961), and isolated occurrences on ridges and banks near Boston and Plymouth. As reworked glacial debris, the gravel adjacent to New England is more likely to have a large size range and to be more patchy in exposure than is shown on the map. It may also have a matrix of fine-grained sediment at depth below the sea floor. The largest areas of gravel are off Nova Scotia and near Nantucket Shoals. The gravel close to Nova Scotia is probably a thin covering over a rocky shelf, to judge from numerous rock ledges and

small islands that dot the offshore area. On the Scotian Shelf, deposits are mainly in the banks; profiles taken by King (1967, p. 21) indicate the reworked sand and gravel lag to be 10 to 20 m thick.

ORIGIN OF SAND AND GRAVEL

Figure 4 indicates the ultimate source of sand and gravel and its probable history since erosion by glacial and fluvial agents. Most of the shelf sediment is relict in that the rivers and ice that brought it to the shelf ceased transport many thousands of years ago. Reworking of the outwash and fluvial terrace deposits during Holocene time has partly masked the gravel and has resulted in the system of sand shoals well described by Uchupi (1968) and mapped by Franklin Stearns and L. E. Garrison (U.S. Coast and Geod. Survey and U.S. Bur. Commercial Fisheries, 1967). On the shallowest parts of the shelf, the process of redistribution and dispersal of sand continues; hence, exploitation of these deposits may tend to alter the budget of sand and its transport through the area. Beyond 20 m, reworking is diminished,

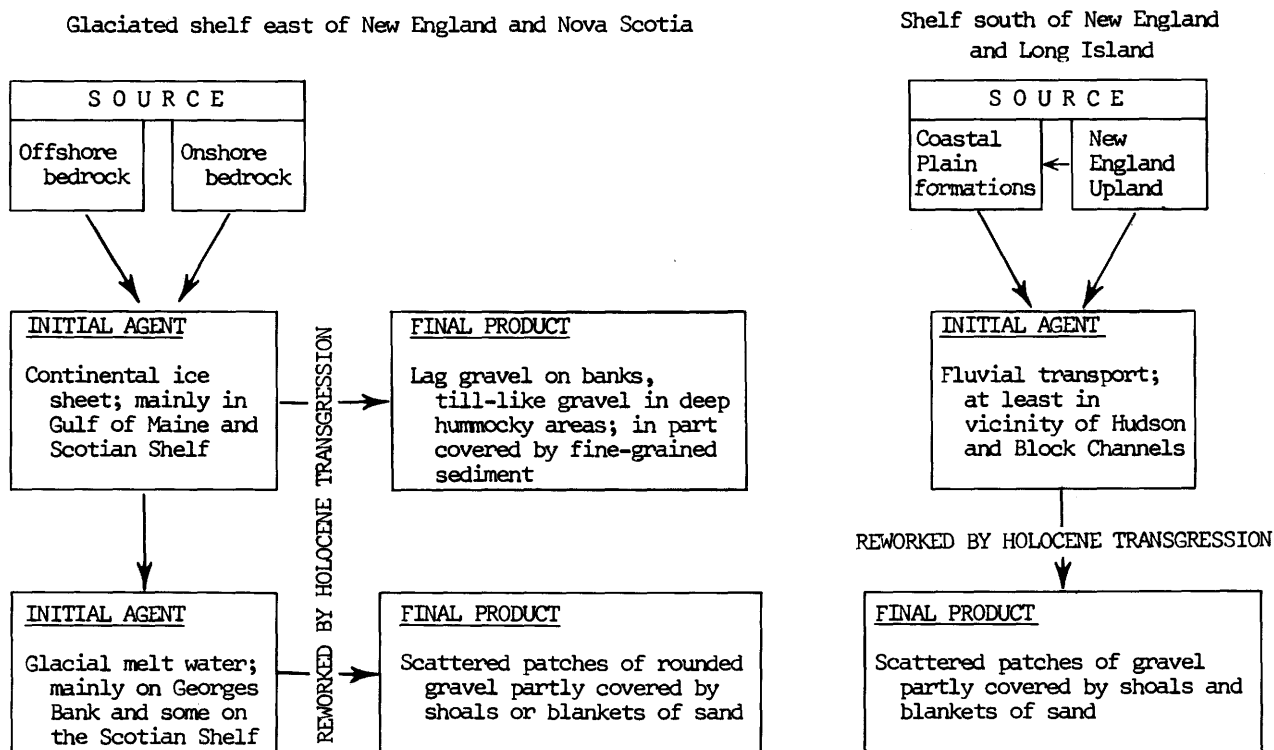


FIGURE 4.—Summary of sources and distribution agents for sand and gravel on the continental shelf off northeastern United States.

and Holocene strand-line deposits are preserved. Preservation of these older sand deposits may explain the alternation of coarse and fine modal sand zones subparallel to the bathymetric contours.

CONCLUSIONS

The study indicates that the most of the shelf off the northeastern United States is covered by fine- to coarse-grained sand probably to a depth of several meters. Sand is much less abundant down the continental slope and in the Gulf of Maine. Most of the sand and associated gravel seems to have been brought to the shelf by rivers and glaciers during lowered stands of sea level and to have been reworked by the ocean as sea level rose after retreat of the glaciers.

As the sand and gravel are near the large metropolitan areas of New York, Providence, and Boston, they merit exploration by shallow offshore drilling to determine their thickness and areal distribution over restricted areas of the sea floor. Newly published bathymetric charts (U.S. Coast and Geod. Survey and U.S. Bur. Commercial Fisheries, 1967) at a scale of 1:125,000 and a contour interval of 1 fathom should aid such exploratory investigations.

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GEOLOGICAL SURVEY CIRCULAR 640



A Strategy for the Geologic Exploration of the Planets

Julian

A Strategy for the Geologic Exploration of the Planets

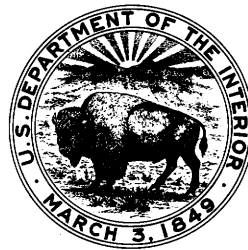
By M. H. Carr, *Editor*

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*Prepared on behalf of the
National Aeronautics and Space Administration*



United States Department of the Interior
WALTER J. HICKEL, *Secretary*



Geological Survey
William T. Pecora, *Director*



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A Strategy for the Geologic Exploration of the Planets

By M. H. Carr, *Editor*

INTRODUCTION

By M. H. Carr

Scope and Purpose

The geology of the planets bears directly on three basic aims of lunar and planetary exploration: determination of the origin and evolution of the solar system; determination of the origin and evolution of life; and clarification of the nature of the processes shaping man's terrestrial environment (National Academy of Sciences, 1966). The purpose of this report is to suggest guides to the orderly geologic exploration of the planets and the assignment of priorities to specific experiments and to indicate where supporting Earth-based research can be most profitably pursued. The kinds of data that are most relevant to geologic interpretation are specified, and the sequence in which these data should be acquired is outlined. The report does not provide detailed consideration of the engineering problems involved in acquiring the data, but the exploration suggested appears practical in view of present flight plans and probable future flight opportunities.

The strategy is concerned almost exclusively with geologic problems; other topics are discussed only where they relate to geology and only insofar as they illuminate a particular geologic problem. The term "geology" is used in its broadest sense and is considered to mean study of the solid parts of the planets. Geophysics, geochemistry, geodesy, and other disciplines concerned with the solid planets are

all included in the general term. Planetary atmospheres are almost completely disregarded, not because they lack relevance but because they are not normally studied by geologic techniques. This limitation restricts much of the discussion to the terrestrial planets and to the solid satellites of the outer planets. Jupiter and Saturn in particular are difficult to consider in geologic terms because they may have no solid surfaces. Attention is focused on the inner planets because they are closest to Earth and are easiest of access. Successful flyby missions have already been made to Mars and Venus, and missions to Mars, Venus, and Mercury are in advanced planning stages.

The strategy proposed is intended as a supplement to earlier more general papers. It has been written largely within the framework of recommendations of the Woods Hole Conference (National Academy of Sciences, 1966) and the MacDonald Committee on Space Research (National Academy of Sciences, 1968). We have relied heavily on several earlier reports, particularly those of the Space Science Division of the Jet Propulsion Laboratory (Adams and others, 1967a,b, and Mackin and others, 1969). This paper differs from the aforementioned largely in the emphasis on geologic problems. The work was supported by NASA (National Aeronautics and Space Administration) contracts W-12, 650 and W-12, 872.

Relevance of Geologic Studies

Before examining in detail what specific experiments best fulfill geologic requirements,

the more general question of the importance of geology in planetary exploration will be examined.

Origin and Evolution of the Solar System

Adams and others (1967a,b) examined the problem of the origin and evolution of the solar system and reduced it to these questions:

1. Are the individual terrestrial planets and satellites chemically uniform or nonuniform?
2. Did final accretion result in the present array of planets or satellites, or in an array that was subsequently altered?
3. Was the cloud chemically homogeneous at the time of final accretion?
4. What was the state of the sun-cloud system when it first appeared as a recognizable unit.
5. Were there large-scale elemental and isotopic nonuniformities in the contracted nebula?

Because all these questions concern determination of the stage (or stages) in solar-system evolution when chemical fractionation took place, answers must ultimately depend on chemical measurements. Many of the necessary measurements will be made on planets and their satellites, to interpret them we are confronted with the problem posed by the first question. Are the planets and satellites chemically nonuniform? We cannot assume *a priori* that a planet is chemically homogeneous and that a given analysis is representative of the whole planet. This is not true of the Earth and is not true of the Moon (see section "Surface heterogeneities"). To determine whether a planet is homogeneous will require observations that will permit inferences regarding the structure of the interior. Moreover if general conclusions are to be drawn from specific measurements, it is not sufficient merely to establish nonuniformity; the nature of the nonuniformity must be defined. To document nonuniformity, we cannot simply assume random variability and sample a planet statistically, because the only accessible part of a planet, its near surface, may be totally nonrepresentative of the planet as a whole. We must have a general understanding of the planet, and this can be achieved effectively only by

studying the processes that have caused, and may yet be causing redistribution of materials within the planet. Only if the processes are understood can valid general conclusions be made regarding the significance of specific measurements. The sampling or type of measurement made on a planet should therefore be guided by geologic priorities based on this need to understand geologic processes, rather than cosmogonical considerations, because we cannot proceed from the specific to the general without the geologic knowledge.

Geophysics is concerned largely with documenting internal heterogeneities and conditions. Chemical determinations on materials from the interiors obviously cannot be made directly; nevertheless, inferences are possible from measurements of physical properties. The value of any particular physical parameter is not important in itself, since it depends on local conditions; its importance lies in the fact that it places limits on chemical composition and internal conditions and provides data on internal processes. Stratigraphy is concerned directly with documentation of crustal heterogeneity. Even though the surface rocks constitute a minute part of the total mass of the planet, it is the part on which virtually every measurement is made. For this reason an understanding of surface materials is crucial. We must know how variegated the surface rocks are and how they were formed. The mode of formation is particularly important, for different processes vary in the extent to which they cause chemical change. Consequently, to understand the broader implications of surface analyses, the distribution and mode of formation of the rocks analyzed should be known, as well as the degree to which they typify all the materials of the planet.

Origin and Evolution of Life

The geology of planetary surfaces bears directly on the origin of life. This paper has been written largely on the assumption that, in our solar system, life will not be found on other planets. But if life is found elsewhere, then the significance of geology will be enhanced and this strategy will need drastic revision. With life on a planet, the mode of rock formation, the physical

conditions of deposition, and the relative age will take on new significance. Not only will they reflect past conditions and events, but they will reveal the evolutionary path of life on the planet and the conditions under which life thrived. Paleontology, which has been totally ignored in this strategy, would become of paramount importance, and different types of missions would be required to meet its needs.

Man's Terrestrial Environment

One important result of planetary exploration will be increased knowledge of the Earth. Many fundamental geologic problems could be solved by detailed comparison of the Earth with other planetary bodies. The relative effects of size, original composition, and the presence of an atmosphere and hydrosphere on the evolution of the Earth are of particular geologic importance, and comparison of the Earth with other bodies will allow these effects to be assessed.

Probably the most important result of planetary exploration from the point of view of Man's terrestrial environment will be an improved understanding of the early history of the Earth. Features on the surface of the Earth are subject to relatively rapid destruction and modification largely as a result of the erosive action of water, and also as the result of tectonic and volcanic activity. As evidence of events and processes that took place early in Earth's history rarely survives, very little is known of the first 2 billion years of the Earth's history. Mars, Mercury, and the Moon on the other hand, have no oceans, and the erosive effects of water are therefore virtually absent. Furthermore, because of their smaller size, we can expect less tectonic and volcanic activity than on Earth (Anderson, 1969). Primitive features are likelier to survive on these planets, allowing their early history to be defined. Analogy with these more primitive planets may be the only way to arrive at an understanding of the Earth's early history.

Geology will play a vital role in achieving the three basic aims of planetary exploration. A detailed discussion on how best to pursue the geologic studies in concert with other types of investigations follows.

STRATIGRAPHY AND STRUCTURE

By M. H. Carr and J. F. McCauley

Stratigraphy is the study of rock sequences; structural geology is the study of rock deformation and the features it has produced. The ultimate aim of both is to determine the history of the planet and the mode of its formation. A planet is not static and unchanging; its constituents are constantly being rearranged to form new rocks with new distributions. Changes may be only surficial, resulting from external mechanism such as meteorite impact. Or the changes may result from internal processes such as volcanism and tectonism. Whatever the processes, a partial record of successive events is preserved in the surface rocks and structures. The role of stratigraphy and structural geology is to reconstruct from this fragmentary record the sequence and nature of the events that have affected the planet and to devise a model for the evolution of the planet that is consistent with the observations.

Applicability to the Planets

Correct interpretation of any surface measurement depends on knowledge of the degree of heterogeneity of the planet, of the processes and sequence of events causing the heterogeneities, and of the local geologic environment at the site of measurement. One purpose of the study of stratigraphy and structure is to provide this necessary background information, and its relevance to the planets will be examined in this light.

Surface Heterogeneities

The immediate aim of stratigraphy and structure is to reduce the enormous complexity of a planet's surface to comprehensible proportions by dividing the near-surface rocks into units and mapping their distribution and attitude. The complexity of the Earth's crust is well known, but the variegated nature of other bodies in the solar system is less widely

appreciated. The Moon is the only other body in the solar system whose surface has been studied in any detail; its heterogeneity is now well established. The basic distinction between mare and terra has long been recognized. Gilbert (1893) pointed out the existence of a blanket of material surrounding Mare Imbrium; several additional widespread terra units such as the Orientale blanket (McCauley, 1967) and the Cayley Formation (Morris and Wilhelms, 1967) have since been recognized and mapped from telescopic observations. Subtle differences in the color and reflectivity of the maria documented from telescopic observations (Whitaker, 1966, McCord and Johnson 1969) showed that the maria also are heterogeneous and susceptible to subdivision (Carr, 1966). It was with the acquisition of Lunar Orbiter IV photography that different provinces of the terra could be fully recognized and differences in the maria adequately documented (Wilhelms and McCauley, 1969). Wilhelms and McCauley ascribe some of the regional differences to volcanism, but whatever the cause of the differences, they are real and exemplify the heterogeneity of the terra. Similarly detailed but larger scale mapping of the Apollo landing sites (Trask, 1970) shows that differences also occur within the maria and that the mare material cannot be treated as a single homogeneous unit. The Moon therefore shows considerable heterogeneity and stratigraphic studies are essential for its orderly scientific exploration.

Much less is known about the surfaces of other planetary bodies, but telescopic observations do reveal markings on all bodies whose surfaces can be observed. The surface markings of Mars, which probably result from albedo variations, are especially well known from the extensive observations of Lowell (1908), Slipher (1962), and deVaucouleurs (1965). Recent Mariner photography has shown that the Martian surface is, in addition, topographically variegated. The Mariner Mars '69 experimenters have pointed to cratered areas much like the lunar highlands, to crater-free areas such as Hellas, and to areas of "chaotic" terrain. Markings have also been observed on Mercury and on the Jovian satellites Europa, Io, Ganymede, and Callisto (Katterfeld and others, 1968). Color differences have been detected on

Mars and some Jovian satellites and the differences have been attributed to chemical heterogeneity (McCord and Adams, 1969). The surfaces of many planetary bodies appear to be heterogeneous. It will be necessary to establish the nature of the differences so that the events and processes leading to the present configuration can be understood.

Nature of Processes

Data from the surface of a planet must be interpreted in the light of processes that resulted in its present configuration. Processes affecting a planet can be classified into two broad categories; those such as volcanism and tectonism, related to internal forces, and those such as impact and erosion, related to external forces. If a planet is internally inert, and has always been inert, and if the geology of the surface is controlled solely by external processes, then stratigraphic studies will be of limited value. If, however, the planet has experienced any internal activity, then chemical fractionation is likely and the significance of analytical data will depend directly upon the local geology. Stratigraphic studies are required therefore, first, to determine whether internal processes, particularly volcanism, have affected the surface, secondly, to document the geology in detail if internal effects are present.

The first close look at Mars provided by the Mariner IV photography indicated that Mars is more Moon-like than Earth-like. Meteorite impact appears to have played a prominent role in sculpturing the surface, and it is expected that the same is true of Mercury. This does not, however, imply that internal effects are absent. One result of impact on the Moon is to mask volcanic effects; nevertheless, such effects have long been recognized from telescopic and orbital observations (Shoemaker and Hackman, 1962; McCauley, 1967) and the volcanic nature of mare materials is now confirmed by direct examination of lunar samples. The fact that volcanism has occurred on the Moon strongly suggests that it has also occurred on planets of comparable or greater size, thereby greatly enhancing geologic interest in these bodies.

Sequence of Events

The significance of any event on the surface must be viewed in its historical context. If, for example, volcanism ceased 1 billion years after the planet formed, the implications regarding bulk composition are far different than if volcanic processes are still active. Stratigraphy is largely concerned with placing rock units in historical sequence and relating them to specific events in the past. This historical perspective distinguishes stratigraphy and the discipline of geology in general from most other natural sciences. In the absence of fossils and as a result of the difficulty of getting absolute ages, geometrical relations as observed by photography will be the principal source of the data on relative ages. On the Moon, geometrical methods have been highly successful in establishing a global stratigraphy, largely because there are extensive marker horizons in relation to which other units can be dated. Two examples are the Imbrian blanket (Fra Mauro Formation) and the Orientale blanket. Both are extensive deposits that appear to have formed during a very short period of time. Structures have a similar importance for dating purposes, and in some areas of the Moon the presence or absence of Imbrian sculpture is the dominant criterion for determining relative ages. The now well-established techniques used on the Moon (Shoemaker and Hackman, 1962; Wilhelms, 1966) are directly applicable to planetary imagery, and we can expect the same degree of success in unraveling crustal stratigraphy given photographic data of comparable quality. Definitive information on stratigraphic relations will however finally depend on surface-based observations; crucial relations inferred from the imagery must be checked at some stage by man, or by means of automatic roving vehicles or drilling techniques.

Geologic Framework

The stratigraphy and structure of a planet are fundamental in that they provide the framework within which all other measurements must be evaluated. A chemical analysis, a heat-flow measurement, or a seismic profile can

be understood and correctly interpreted only if the geology near the place of measurement is known. A chemical analysis of a salt dome in Texas does not give the composition of the surface of the Earth in the south-central part of the United States, nor can a value for heat flow in Yellowstone National Park be extrapolated to the whole of the western United States. For any measurement to be understood, the geologic context must be known. This is so fundamental to geologic thinking that to state it appears trite and obvious, yet it is a concept that has found only limited acceptance with regard to the exploration of other bodies in the solar system. Without geologic analysis, the surface of the planet is in danger of being treated as a homogeneous unit; a chemical analysis is likely to be considered as indicative of the chemistry of the whole surface, and the mineralogy of one part might be considered as the mineralogy of the whole. Such interpretations are demonstrably nonsensical for the Earth and the Moon, and there is little reason to think that they will prove any more valid on other planets. Measurements made on the surface of a planet must be interpreted in light of the local stratigraphy; and to do otherwise could lead to gross errors in interpretation.

Methodology

Because of dependence on remote-sensing data, the techniques of stratigraphic and structural analysis of the planets differ from those normally used on the Earth. Terrestrial rock units are defined on the basis of lithology, chemistry, and mineralogy as seen at an outcrop. The relative ages of different units are determined largely by relations observed in vertical sections or in outcrop patterns; correlations are made by comparison of successions of lithologies, by tracing specific horizons on the ground, by diagnostic fossils, and by absolute dating methods. In general the stratigrapher proceeds from particular observations seen at specific outcrops to a synthesis of general patterns. The reverse procedure must be used in studying the geology of a remote surface. General patterns are observed from remote-sensing data and the

significance of the patterns is later checked and supplemented by measurements and observations at a restricted number of ground sites. The procedure is similar to that used terrestrially in geologic exploration of remote regions, such as the Canadian shield, where initial reconnaissance is by aerial photography, aerial gravity, and magnetic surveys; areas of interest are located from the remote-sensing data and a restricted number are checked on the ground.

The techniques used in analyzing the surface of the planets will be similar to those already used on the Moon. For stratigraphic purposes, photography has been the most valuable source of remote-sensing information. Nearly all basic lunar stratigraphic units and relations have been determined from the visual imagery. On the basis of differences in topography and reflectivity, the surface of the Moon has been divided into many units on the assumption that those differences result from differences in the materials exposed at the surface. The relative ages of adjacent units are determined by superposition and intersection relations, and a Moon-wide chronology has been established by dating units with respect to extensive marker horizons such as the Fra Mauro Formation. Variations in gravity, emissivity in the infrared spectrum, radar reflectivity, and color have had value largely as interpretative aids, but not in defining and mapping units because they have not been determined with the same linear resolution as the visual black and white image.

Stratigraphic techniques are successful on the Moon because the lunar surface does not undergo regional variations in external conditions. The surface of the Earth is greatly affected by external conditions such as those produced by climate and vegetation; as a result, a specific rock unit may exhibit a variety of surface properties. On the Moon the principal external process modifying the surface is bombardment by meteorites, and because this is essentially isotropic, differences in properties of the lunar surface must reflect differences in the properties intrinsic to the surface materials. Similar conditions probably hold for Mercury. On Mars and Venus regional climatic patterns

may affect surface forms, and geologic interpretation must be made in light of possible climatic effects.

The techniques that have been applied to the Moon are directly applicable to Mars, Mercury, and many planetary satellites, but additional techniques may prove useful. In particular, color, being partially dependent on mineralogical composition, may prove to be a valuable aid in identifying and characterizing geologic units on planetary surfaces.

Once the geologic units have been defined and their relations to one another determined, the results can be portrayed on geologic maps. Although the geology of the Moon has been interpreted largely in the light of surface landforms and albedo, the resulting maps are truly geological, for they incorporate the three basic ingredients of a geologic map: rock units, age relations, and geometric position. They are quite distinct from topographic maps, terrain maps, and physiographic maps, which are concerned with surface form. Unless the surface topography is controlled entirely by surficial effects, such as wind action in a thick debris layer, we can expect to make geologic maps of several of the planets.

Complete characterization of the rock units recognized from the imagery will require ground-based measurements. A major purpose of a lander will therefore be to determine the lithology, texture, mineralogy, and petrology of the rocks at the landing site. Another objective should be to determine the vertical and lateral variations in these properties so that the stratigraphic relations at the site can be compared with those inferred from the vertical imagery. The choice of site for establishing ground control will clearly be critical. In the initial stages of exploration, sites should be located on geological units that have a wide distribution and in areas where there is the minimum of stratigraphic ambiguity. Subsequently, sites may be chosen to clarify a specific scientific problem, such as presence of volcanic activity, or they may be located in an area where a vertical section is accessible, as near a fresh crater or steep vertical wall. In late stages of exploration, surface units and their mutual relations will be most efficiently studied by some kind of traversing vehicle.

Data Requirements

The first stage in the geologic exploration of a planet is to identify and outline the distribution of the basic units of the crust from the visual imagery supplemented by other remote-sensing data. The second stage is to establish "ground truth" at critical locations by obtaining chemical, mineralogical, and petrological data from landers. It is important that sufficient data be obtained in the first stage so that landing sites can be effectively chosen and the data obtained related to a regional framework. No matter how many landers are deployed, determination of the geologic environment at each site and interpolation between the sites will depend on the quality and coverage of the available regional imagery. If adequate imagery is lacking, the subsequent exploration program could be jeopardized by lack of the basic information needed to interpret or extrapolate data from individual sites. It is therefore pertinent to examine in detail what photographic data are required to meet the needs of later exploration.

Flyby Photography

The initial photographs of any planet will surely be from flybys. These missions will be reconnaissance in nature, and no systematic coverage can be expected, the purpose being in large part to determine crustal style and identify general problems. For optimum utility, an early reconnaissance mission should strive for imagery at a wide range of scales and broad coverage at low resolution. The ideal plan would result in photographs of the whole disk during approach and in subsequent photographs each at a larger scale and nested within the previous frame. This has two advantages over a plan in which all photographs are taken at the highest resolution: the broad geography of the body is established, and the nature of the terrain at different scales is determined. The second advantage is important, as there is no way of knowing in advance the optimum scales for obtaining information on landforms. Systematic stratigraphic studies are not possible from flyby photography; for this purpose, orbital coverage is required.

Orbital Photography

Orbital photography will be the single most important source of stratigraphic information; its usefulness for stratigraphic purposes depends on three main factors: resolution, areal coverage, and illumination. Color, polarization, photometric fidelity, and stereo overlap, though useful, are of secondary importance in the very early stages of exploration.

Illumination

Imagery is a source of information on two basic properties of the surface of a planet, topography and reflectivity; detailed information on both properties is necessary for stratigraphic work. Albedo differences are best seen at or near vertical illumination; topography is best observed at low angles of illumination when contrast and resolution are enhanced and shadows bring the topography into relief. The optimum illumination angle depends on the roughness of the terrain. For lunar terrain, illumination in the 5° – 15° range has proved best. In very smooth terrain, illumination at the low end of the range is desirable so that low-relief elements can be discerned, whereas in rough terrain higher angles are necessary to prevent too much of the image being in shadow. The optimum angle must be determined from preliminary terrain analysis. Ideally, vertical photography at both low and high illumination should be obtained. Oblique photography has very limited use for systematic work because of geometric distortions, scale and resolution changes within a single frame, and because distant features may be hidden by near features.

Resolution

The term "resolution" as it is applied to visual imaging experiments often leads to confusion with regard to system capability. Photographic resolution has traditionally been given in terms of separable white and black line pairs per millimeter of the image. In vidicon imaging experiments, on the other hand, the scale width of a single TV line, or in other cases

the width of two TV lines, at a particular altitude, is often given as an index of system resolution. The size of the smallest objects about which something can be said either in a topographic or geologic sense is considerably larger than the width of two TV lines, and is a function of overall target contrast (fig. 1). In any given television picture, for example, small high-contrast objects such as young fresh craters will be more detectable than larger, subdued, older craters. In the ensuing discussion resolution is meant to imply the smallest relief element that can be recognized, acknowledging

that resolution is not fixed by the imaging system alone, but depends also on illumination and the character of the surface being photographed.

The importance of resolution is easily understood, as the finer surface details that can be seen at higher resolutions permit more refined stratigraphic analysis. The Zond III pictures of the far side of the Moon, with resolutions of 10 km (kilometers) allowed little more to be deduced than the location of mare areas and the largest craters. No stratigraphic work was possible because surface textures

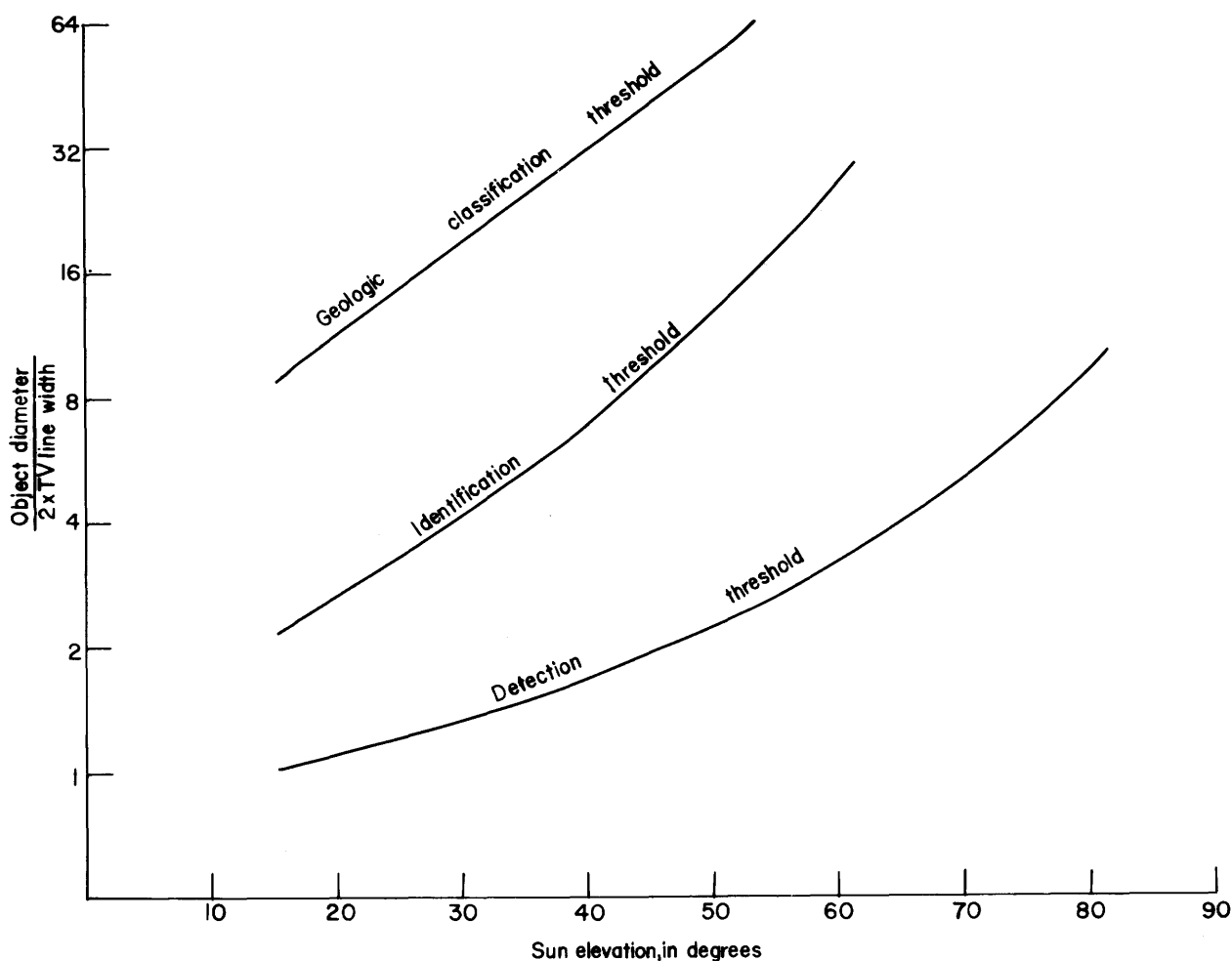


Figure 1.—Dependence of feature recognition on illumination angle (after Keene, 1965).

could not be seen. Stratigraphic work was possible from early telescopic photography of the near side, with resolutions of approximately 2 km, but the only recognizable units, were those such as the Imbrian blanket (Fra Mauro Formation) that have very coarse surface textures. The big breakthrough in lunar stratigraphy came with the acquisition of the Herbig photography (taken by the Lick 120-inch reflector), with resolutions of approximately 200–400 m (meters). This photography revealed the highly variegated nature of the lunar uplands as well as differences in the mare. Lack of broad contiguous coverage however prevented analysis of the entire front side at these resolutions. This was later rectified by Lunar Orbiter IV, which provided nearly complete coverage of the front side at even better resolutions. This latter mission was ideal from a stratigraphic point of view, since complete coverage at fairly constant resolution and illumination was provided. For the Moon, improvement in resolution beyond 20 m does not significantly improve geologic interpretation because regolith variations rather than the underlying rock units control the fine-scale topography. The optimum resolution at which to systematically photograph each planet must be established from earlier flybys, but on the basis of Moon and Mars experience, 0.5- to 1-km detection resolution appears to be a reasonable goal for early orbital imagery. .

Areal Coverage

The study of stratigraphy and structure from aerial photography hinges on recognition of regional patterns. Broad regional coverage at resolutions such that surface patterns can be recognized is therefore essential. Photography of restricted areas, even if of excellent quality, has limited usefulness unless the general geologic context of the areas is known. The Mariner IV photography of Mars, for example, cannot be used for stratigraphic purposes because the individual frames cannot be placed in regional context. The importance of areal coverage results from the importance of distributional patterns in the study of stratigraphy. The distribution of a rock and its relation to adjacent units often tells more about the origin and age of many rock units than does the surface

morphology. The fact that the Fra Mauro Formation on the Moon occurs all the way around the Imbrium basin is far more indicative of its origin than is its surface texture. Similarly, very detailed photography of a particular fault scarp in the Southern Highlands might reveal very little concerning the origin of the scarp, whereas wide photographic coverage could show it to be part of a system of fractures radial to Mare Imbrium and therefore related in origin to the formation of the Imbrium basin. Distribution patterns are an essential element in geologic analysis, without which image analysis is reduced to inefficient exercises in comparative geomorphology.

The success of any landing mission will depend in part on the scientific merit of the site and the suitability of the terrain. In order to make judgments on both these factors and to ensure that choice is made within the broadest range of possibilities, wide photographic coverage at moderate resolutions is required. Despite the importance of wide areal coverage, it is useful only if acquired at adequate resolution. Lunar experience suggests that increased coverage cannot justify degradation in resolution beyond 2 km and that the early photographic effort should be directed toward getting the broadest possible coverage resolution of 0.5–2 km (6–8 TV-line widths).

Color

Despite the reservations stated above, information on color should be obtained on early orbital missions if coverage and resolution are not prejudiced. Color as a means of distinguishing chemical differences in the surface materials has been applied with moderate success to the Moon. This topic is covered more fully in the section "Geochemistry."

Polarimetry

The usefulness of photography through polarizing filters has yet to be demonstrated for the Moon, the Earth, or experimental surfaces. Polarimetry therefore should not be attempted at the expense of other potentially more useful aspects of a mission.

A strategy for advanced orbital missions cannot be formulated effectively until the early reconnaissance program has been completed. Nevertheless, certain needs can be anticipated. After most of the planet has been photographed at a resolution of approximately 1 km, limited areas will need to be photographed at higher resolutions. Specific sites would be chosen for features typical of a given class or the solution of some specific geologic problem. Such detailed photography will bridge the gap in scale between observations on the ground and the reconnaissance orbital photography and will provide a basis for extrapolation of the reconnaissance photography to finer scales. The mission would resemble in part the Lunar Orbiter V mission, but should have additional capabilities, in particular, the capabilities of convergent stereophotography and multiband photography.

Following a Lunar Orbiter V type of mission, emphasis should shift away from imagery toward other remote-sensing techniques, with particular emphasis on techniques that provide information on the chemical and mineralogical properties of the surface rather than those more dependent on physical properties. Possible remote-sensing techniques are discussed in the sections on "Geophysics" and "Geochemistry."

Lander Photography

A landed photographic system has three main geologic purposes:

1. To examine in detail the lithology, texture, and attitude of the surface rocks at a specific site.
2. To determine the topography in the vicinity of the spacecraft.
3. To provide supplementary information for other experiments on the spacecraft.

Lithology, Attitude, and Texture of Surface Rocks

Since Mars and Mercury are not protected from meteorite bombardment by thick atmospheres, their surfaces are probably covered, at least partly, by a debris layer or

regolith similar to that on the Moon. The Martian regolith is of particular interest because processes other than impact are likely to have played an important role in its formation. Aeolian erosion and deposition, permafrost, carbon-dioxide "glaciation," and atmospheric weathering may all have left their imprint on the regolith. Detailed examination of the lithology, texture, and structure of the regolith in order to determine what processes have been most active in its formation will be one of the main tasks of a landed imaging system.

On Mars, in contrast to the Moon, coherent rocks may be accessible in places for analysis and observation. The yellow clouds, widely interpreted as dust storms, may remove the regolith in places and expose bedrock. Coherent rock material will almost certainly be available for inspection, if not in place, then as blocks in the regolith. Much can be learned from the fine-scale texture and lithology of rocks. Layering suggests a sedimentary process, either in a magma chamber or on the surface. A texture of interlocking crystal forms indicates a crystallization stage during rock formation, either as a result of derivation from a melt or as a result of post-depositional recrystallization. Euhedral phenocrysts point to a magmatic origin, rounded grains to a sedimentary origin. Textures of this type are generally visible at 1-mm resolution and cameras can achieve this resolution without special optics. The ability to discern these fine-scale textures will depend on lighting; repeated photography of the spacecraft environment at different lighting conditions will bring out all the observable features.

Optical microscopy is the most widely used technique for examining rocks. By no other single technique can a rock be so completely characterized or its origin so reliably determined. Petrographic microscopes have been successfully combined with TV systems and compact lightweight microscopes have been designed specifically for spaceflight programs so that petrographic work can be done remotely. But the utility of remote petrographic microscopy is likely to depend more on the effectiveness of sample preparation than on the ability to design flight-qualified instruments. Thin-section work is the most informative type of microscopy; examination of crushed rock or fragmental debris from the regolith are far less

essential geologically and alone would not merit an elaborate microscope experiment. Making thin sections must be considered an integral part of the design of a petrographic microscope experiment and needs to be actively supported.

A less desirable alternative to remote microscopy is visual examination of a sawed surface, perhaps coated with a wetting agent to improve contrast. A device to cut a very small flat surface and a spray coater should not present great technological difficulties. If the material is reasonably coarse grained, then in addition to textural relations modal analyses may be made by point counts on pictures of the surface. Provision for sampling selected areas on the surface for chemical and mineralogical tests would greatly enhance the value of the device.

The gross features of rocks in place are also related to origin. Bedding, cross-cutting relations, faults and folds are all necessary for understanding sequential relations, yet they cannot be examined adequately from a stationary vehicle nor from an orbiter. Some mobility is required because of the scale of the features involved and because a sufficiently large number of relations must be observed to confidently interpret them. An automated mobile vehicle to test the heterogeneity inferred from the orbital imagery and to sample a variety of geologic units for chemical and physical study must be considered for advanced missions.

Surface Topography

The conditions necessary for topographic reconstruction from landed imagery are given in the section "Geodesy and Cartography." The topography of any planet's surface is likely to be constantly changing as a result of contending destructional and constructional processes; evidence of the character of the processes will be preserved in the landforms. All features, irrespective of origin, will be modified by impact, and their state of preservation will indicate something about the rate of landform development. Detailed photography of the surface therefore provides basic information on the rate and nature of surface modifying processes.

Analytical Support

One of the main functions of a landed imaging system is to provide support for other analytical instruments. The environment around the spacecraft will almost certainly be geologically diverse. Rocks of various types may be present both in the regolith and in the bedrock. An imaging system provides an essential means of monitoring what is being analyzed and what is available. When used in conjunction with a surface sampler, the imaging system will greatly improve the versatility of many analytical instruments on board inasmuch as it changes the sampling from a random process to one of intelligent control and selection. This applies both to the geological instruments and to the biological and engineering instruments.

Drillhole Measurements

The capability of drilling a hole and making in-hole measurements is of prime importance for stratigraphic studies. In addition holes are also needed for heat flow measurements, for detection of subsurface water, and for penetrating the regolith. Vertical sections may be observable also on crater walls, or fault scarps, and some of these *may* be accessible to roving vehicles, but a section is *always* available to a vehicle with drilling capability. A large number of in-hole measurements are feasible once a hole is dug. Resistivity, conductivity, porosity, and natural and induced radioactivity all can be logged to reveal stratigraphic discontinuities. Existing logging techniques require only the minimum of adaptation for use on planets. The principal technological difficulty lies not in logging but in drilling, as no satisfactory technique for remote drilling is available. A drillhole is so important that maximum efforts should be made to develop drilling techniques and to insure that advance systems will have a drilling capability.

SUMMARY

1. Stratigraphic studies are concerned with documenting the nature, extent, and mutual relations of surface rocks in order to

determine the history of the planet's surface and the nature of the processes controlling its evolution and to provide a framework for interpreting surface measurements.

2. The basic data requirement is imaging, visual or radar, at a wide variety of scales, with substantial contiguous areal coverage at each scale. Initial requirement is global coverage at ground resolutions no worse than 1-2 km, then contiguous coverage of selected areas, constituting approximately 1 percent of the planet, with ground resolutions no worse than 100 m. Imaging should be at both low-angle illumination (10° - 25°) for maximum topographic discriminability and high-angle illumination for albedo characterization.
3. Colorimetric, photometric, and polarization demands on the imaging system should be secondary to the requirement for wide areal coverage at useful resolutions, but colorimetric characterization of the surface should follow acquisition of the initial imagery or be done concurrently if resolution and areal coverage are not jeopardized.
4. Once moderate-resolution global coverage and higher resolution coverage of selected areas has been acquired, then emphasis should shift toward remote-sensing techniques other than imaging, particularly those such as visual and infrared spectroscopy that are sensitive to chemical and mineralogical differences.
5. Lander imagery and direct chemical and mineralogical determinations on the surface, while essential for interpreting the nature of units identified from orbital photography, are of limited stratigraphic value unless accompanied by mobility or drilling capability. Development of the hardware necessary for drilling should be supported.

GEODESY AND CARTOGRAPHY

By D. W. G. Arthur, R. M. Batson,
and F. J. Doyle

Definition of Objectives

The literal meaning of geodesy is to "divide the Earth." In application it has come to mean

the determination of the size and shape of the physical Earth and the location of a network of control points on the Earth's surface in fixed coordinate systems. Because of the instrumental techniques employed for measurements on the Earth's surface, geodesists have had to concern themselves with the positions of celestial bodies and with the gravity field. Their activities and interests overlap with those of astronomers and geophysicists, and as a consequence, geodesy has been divided into three nearly distinct subjects: geometric geodesy, geodetic astronomy, and gravimetric (physical) geodesy.

For most of its history, geodesy has had to depend on observations made from the surface of the Earth. The restricted range of these observations made possible the preparation of highly detailed and precise maps of localized areas, but expansion of dimensions and reference systems to continental and global areas was accomplished only with great difficulty, and some unresolved ambiguities still exist. The capability of observing from and to artificial satellites, available only in the past 10 years, has completely revolutionized geodesy. When applied to the planets, the new techniques will make feasible the scientifically preferable approach of proceeding from the general to the specific in an orderly fashion, with the possibility of review at each level before proceeding to the next.

Geodesy and cartography are intensely practical disciplines. They provide an indispensable reference system for recording and correlating the observations and deductions of all other planetary sciences. Because of this general utility, they are often looked upon as an exercise in technology and the inherent scientific content of the data obtained is neglected.

The techniques of geodesy, photogrammetry, orbit analysis, and cartography can provide information on the following:

- The basic planetary dimensions.
- A mathematical figure of reference.
- The orientation of the body in the celestial coordinate system.
- The rotational constants.
- A defined system of coordinates.

The location of any number of surface points in the defined coordinate system.
The gravity potential expressed in spherical harmonics.

Topographic and thematic maps:

At small scales for synoptic coverage.

At intermediate scales for regional coverage.

At large scales for landing areas and other sites of particular scientific value.

Surface albedo in various wavelengths.

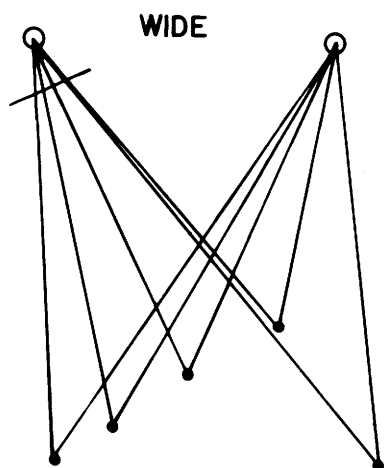
The size, shape, and rotational constants contain geophysical information about moments of inertia, internal composition, and rigidity. The harmonics of the gravity field contain information about anomalous mass distribution within the body. Regional and local topography imply internal and external mechanism of formation. Albedo measurements give information on regional and local differentiation and composition of materials. Coordinate systems and point locations are necessary for correlation of all other data, for specification of site locations, for navigation and guidance of eventual landers and surface mobile vehicles. Geodetic studies are therefore essential for the study of any planetary body with a solid surface.

Data-Acquisition Systems

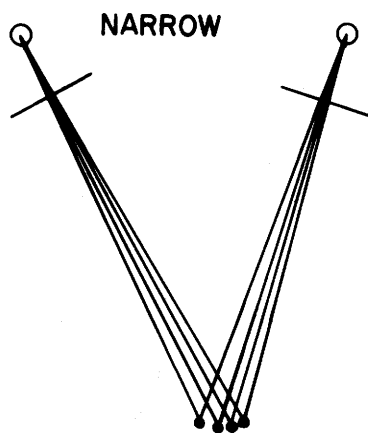
It makes sense to consider the commonality of geodetic and cartographic sensors with those employed for other planetary sciences. The basic sensors—imaging systems, tracking systems, stabilization systems—are essential to all disciplines, and minor concessions in optimization for one application can immeasurably increase the utility for another. An excellent example is the Lunar Orbiter Program, which was designed essentially to provide surface photographic coverage at medium and high resolution. That function is performed beautifully, but when landmark positions, elevations, terrain slopes, and control geometry were required, the system was grossly inadequate. Imaging systems on future planetary missions must be designed and used in such a manner that accurate reconstruction of surface geometry is possible.

Both geodesy and cartography depend in large part on scaled reconstruction of the surface by means of some form of imagery. It is appropriate therefore to review the conditions which are necessary for the photogrammetric reconstitution of models from photographs. In pure photogrammetry, only the photographs themselves are used; all external data are excluded. This is preferred, as camera position and attitude errors may be encountered. Also preferred for geodetic purposes are wide-angle cameras because their greater geometric strength results in much less restrictive reconstitution conditions. For wide-angle photography the necessary conditions for reconstitution are that five points must be identified on two photographs and that no three of these should lie in one plane containing the two camera positions. This is the well known Fourcade correspondence theorem. Base height ratios of 0.2–1.5 are usable, 1.0 being about the optimum. The Fourcade correspondence theorem cannot be applied to narrow-angle photography, but pure photogrammetric reconstitution is possible if a minimum of three pictures with considerable convergence ($< 30^\circ$) is acquired, with the same four points measured and identified on all three pictures (fig. 2). Reconstitution is possible from two strongly convergent photographs provided accurate orientation and positional information on the camera is available so that the correspondence settings can be performed and provided the camera's internal geometry is appropriately calibrated. Despite their disadvantages for geodetic purposes, narrow-angle cameras have been used on previous lunar and planetary missions and will be used on planetary missions presently planned because only with these cameras can acceptable ground resolutions be achieved from normal orbital altitudes.

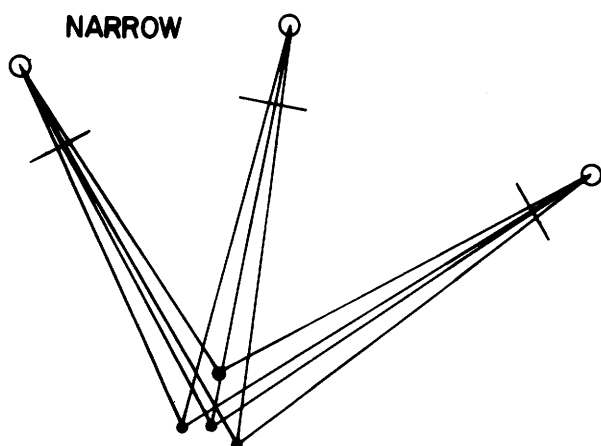
Given a choice, geodesists and cartographers will always opt for physical film return because of the inherently simpler and more accurate data reduction. Physical film return, while not impossible, is unlikely for unmanned missions other than to the Moon. High-resolution vidicon systems and combination film-scanning transmission systems such as on Lunar Orbiter can currently produce image-plane resolutions



1. Reconstitution generally possible

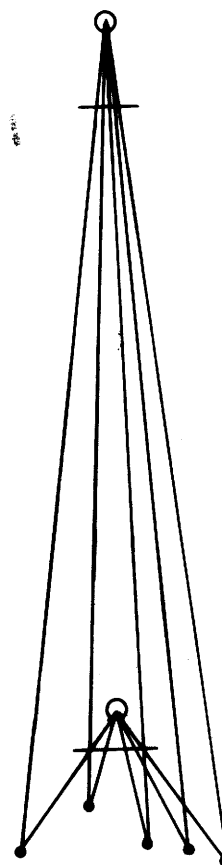


2. Reconstitution not possible without external data



3. Reconstitution generally possible

NARROW AND WIDE



4. Reconstitution generally possible

Figure 2.—Conditions for photogrammetric reconstitution.

approaching 300 lines per millimeter. Development of such systems will certainly continue. The quality of the possible imagery is likelier to be restricted by transmission capabilities than by camera design. A high-quality terrestrial aerial photograph contains approximately 10^8 to 10^9 bits; to obtain wide coverage at comparable quality, enormous amounts of data must be transmitted.

Other Imaging Systems

Infrared and microwave imaging systems may be useful for other planetary sciences but their inherent geometric problems and gross resolution make them undesirable for geodetic and cartographic applications. If, however, they are the only imaging sensors to be carried on a mission, their geometry should be analyzed and the system geometrically calibrated. Some useful geodetic information may be extracted under such circumstances.

Planets with a visually opaque atmosphere (Venus) may be amenable to radar imagery. Again, geometric analysis and calibration beginning with sensor-system design are required. Radar imagery is susceptible to the same kind of reduction as optical imagery, but additional techniques are also available. In particular, the ranging capability of radar may be utilized for reconstruction of surface topography.

Support Data

Detailed tracking, timing, and attitude data are especially important if narrow-angle cameras are used because reconstitution requires this external data. As a general rule, the precision of the time and tracking should permit vehicle location with an accuracy comparable to the surface resolution of the image. Usually sensor attitude can be determined to nearly an order of magnitude better than the sensor can be aimed. A particularly useful reference for attitude is the stellar field recorded either photographically or by star trackers. Properly time-coupled and calibrated with surface photography, this may permit measurement of the celestial orientation of the pole and the rotational constants of the

body. Altimeter data (laser or radar, depending upon planetary conditions) provide a scale restraint for photogrammetric solutions, and in the absence of geometric imaging systems, can provide data on the size and shape of a planetary body.

Flyby and Approach Photography

The most useful photography for geodetic purposes is approach photography that encompasses all or most of the disk. In addition, the photographic period should be extended to provide continuity in scale between full disk and detailed photography of the surface. The main aims of approach photography are:

- Measurement of the profile of the disk to determine ellipticity.

- Determination of the relative three-dimensional positions of surface markings.

- Fitting of the surface markings to an oblate spheroid and fixing the axis of rotation with respect to surface markings.

- Determination of the position of the axis of rotation with respect to the celestial sphere.

The aims are pertinent to all sizeable bodies in the solar system except those that have no solid surface. Two situations are encountered. Mars yields an example of the first, in which the planet rotates relatively rapidly; Mercury is an example of the second, where the planet rotates relatively slowly. For rapid rotation it is possible to make good use of the long-focus characteristics likely to be enforced by the requirements of other fields of study and to depend on the planets rotation to provide a baseline. In this case the inclination of the vehicle trajectory to the plane of the planet's equator is important. Clearly if the spacecraft is on the polar axis during approach, then as viewed from the surface of the planet it is not displaced by rotation. The spacecraft's position remains fixed and a three-dimensional triangulation is not possible. To utilize the planets rotation, the trajectory must be in a plane close to the equatorial plane of the planet.

To establish a baseline for triangulation on a slowly rotating planet, the planet's rotation is of

no assistance and image displacement must be caused entirely by spacecraft motion. Since this motion is almost directly toward the planet, the position in the sky, as seen from the planet, will change slowly so that poor geometry will result until near encounter. At encounter the direction of spacecraft motion is at a significant angle to the line joining the spacecraft and the planet's center, and so the spacecraft moves rapidly across the planet's sky and good geometry is possible.

A similar geometric problem is encountered in establishing the position of a rotation axis with respect to the celestial sphere from approach photography. The approach trajectory is close to a straight line, and the position of the spacecraft on the line alone is insufficient to define the geometry since the planet and the cameras can be rotated as one around the trajectory without violating the tracking data or the photographic measures. To rigidly define the geometry, the orientation of the camera must be known. This can be determined from the spacecraft orientation provided the geometric relation between spacecraft and camera has been previously determined. The precision of the measurements will then depend on the precision that the spacecraft orientation can be determined. For successful geodesy the relation between camera orientation and spacecraft orientation must be precisely determined (in gravity-free environment to offset flexing of structural members) and the in-flight orientation of the spacecraft to the stars must be accurately known.

Orbital Photography

Systematic mapping of fixed surface features is necessary for guidance and navigation, for location of landing sites or sites for more detailed orbital examination, and to provide a base for portraying and correlating other analytical data. In order to achieve the appropriate resolutions, such systematic mapping must be done from orbital altitudes. For the Moon, a map series was recommended by the Geology Panel at the 1967 Conference on Lunar Science and Exploration at Santa Cruz, as follows:

Orthographic, Mercator, and Polar Stereographic projections of the whole Moon at a scale of 1:5,000,000.

Complete topographic coverage of the Moon at a scale of 1:1,000,000.

Coverage of approximately 20 areas of scientific interest for landing sites and traverses at a scale of 1:250,000.

Coverage of central parts of 20 areas of special interest at a scale of 1:50,000.

Coverage of landing locations in the central part of science sites at a scale of 1:5,000.

This series may be considered representative of what might be desired for other planetary bodies, although the requirements may vary in detail according to size and surface configuration.

Standards for the positional accuracy of maps at various scales, for the surface resolution required to produce the necessary content, and for the elevation accuracy required for various contour intervals are as follows:

Map Accuracy requirements, in meters

<i>Map scale</i>	<i>Horizontal standard error</i>	<i>Optical resolution</i>	<i>Contour interval</i>	<i>Vertical standard error</i>
5,000,000	1,520	250	1,000	300
1,000,000	300	50	500	150
250,000	76	12.5	100	30
50,000	15	2.5	25	8
5,000	1.5	.25	3	1

For camera systems with strong geometry, the accuracy of positions and elevations established photogrammetrically will be one to three times the surface resolution. This means that a planimetric map having compatible resolution and horizontal positional accuracy as given in the above table can be produced from camera systems of relatively weak geometry.

Elevation Determinations

Although accurate planimetric maps are possible with weak geometries, the conditions for determining elevations are more restrictive and should be considered in more detail. Photogrammetry is the only rigorous photographic method. With the camera systems being flown, useful vertical resolutions can be achieved with convergent stereophotography, but those achievable by vertical stereophotography are marginal. Because of the difficulty of systematic coverage by convergent stereophotography, other methods of measuring elevations, such as photoclinometry or the traditional shadow-analysis technique, must be considered.

Vertical Stereophotography

In vertical stereophotography, the optical axis of the camera remains vertical and the baseline is fixed by the viewing angle of the camera and the overlap. Typical camera systems used so far on lunar and planetary missions incorporate a vidicon tube with a 10 mm square format and optimally 35 optical resolution elements per millimeter. The smallest elevation difference that can be measured is given by the following equation:

$$\Delta H = \frac{H \Delta \theta}{\sin \alpha}$$

H = height of camera,

$\Delta \theta$ = angle in radians subtended at the lens by the smallest resolution element in the image,

α = intersection angle at ground point formed by two homologous rays from two cameras.

For a camera with a focal length of 50 mm

$$\Delta \theta = \frac{1}{35} \times \frac{1}{50} = \frac{1}{1750}$$

For vertical cameras with 50 percent overlap

$$\sin \alpha \approx 0.1,$$

$$\text{therefore } \Delta H \approx \frac{H}{175}$$

The smallest differences in elevation that can be measured are 5.7 km for an orbital altitude of 1,000-km and 11.4 km for a 2,000-km orbit. These figures are independent of camera focal length if the overlap remains the same, since maintaining the overlap keeps the base/height ratio constant. The measurable differences are inadequate for most mapping purposes. Systems with wider angle lenses or higher resolutions than previously used must be flown if useful vertical stereophotography is to be obtained.

Convergent Stereophotography

Photogrammetrically useful stereophotography pairs can be obtained by convergent stereophotography even if the camera system is inadequate to provide useful vertical stereophotography. Instead of taking overlapping vertical photographs, the camera is tilted and multiple oblique photographs are taken of the region of interest. For vertical photographs the base/height ratio is fixed by the viewing angle of the camera and the overlap. With convergent stereophotography the base/height ratio depends on the tilt of the camera and some latitude is possible in choosing an appropriate ratio.

Consider the case of two photographs of the same area, one vertical, the other taken with a tilt angle, t :

$$\text{As before } \Delta H = \frac{H \Delta \theta}{\sin \alpha}.$$

$\Delta \theta$ remains the same, being $\frac{1}{1750}$ for a 50-mm lens. α , the intersection angle at the ground formed by homologous rays from each camera position, is now the tilt angle t ,

$$\text{therefore } \Delta H = \frac{H}{1750 \sin t}.$$

For a 1,000-km orbit:

$$H = 2.2\text{-km } 15^\circ \text{ tilt}$$

$$H = 1.1\text{-km } 30^\circ \text{ tilt}.$$

The vertical resolution improves proportionately with the focal length of the camera, since $\Delta \theta$ becomes smaller without a corresponding decrease in α as in the vertical case. The increased resolution is of course accompanied by a decrease in the area covered.

The disadvantages of convergent stereophotography with long-focal-length cameras are that a high pointing accuracy is needed and that systematic coverage requires a large number of frames to cover a relatively small area. The technique may be practical only for limited areas such as landing sites or sites of unusual scientific interest.

Photoclinometry

Photoclinometry is a method of extracting topography for nonstereoscopic photography obtained from orbiting vehicles (Watson, 1968). It is based upon the assumption that, if surface albedo is constant, variations in photographic density are functionally related to the surface slope. The relation is expressed by the photometric function required before the technique can be applied. Slope data is acquired on profiles across the photograph and integrated to provide elevations from which contours can be interpolated. While theoretically attractive because it does not impose severe restraints on

angular field or stereoscopic overlap, the method is not truly practical because the normal albedo is not constant, the photometric function is not adequately known (particularly in the case of planets), and the data reduction effort is enormous. Although photoclinometry has been successful in characterizing different types of lunar terrain by statistical slope analysis (Rowan, McCauley, and Holm, 1969), the technique has had only limited success in terrain reconstruction to form topographic maps. The technique should be regarded as a stopgap measure to be used where other methods have failed. Since the data required for its implementation (zero phase and oblique-illumination photography) coincide with requirements for other purposes, no specialized photography is required. The only special requirement is that of photometric fidelity and this coincides with other scientific needs.

Radar Altimetry

One possible way of making elevation measurements over wide areas is by means of radar altimetry. Profiles of the surface can be determined to accuracies of 10–100 m with existing systems which have only modest weight and telemetry requirements. A simple radar-altimeter experiment would also provide valuable calibration data for photogrammetric purposes.

Soft-Landing Missions

Imaging systems on soft-landed planetary probes present a "man's eye" view of the landing site and provide a frame of reference for the various measurements made by other instruments in the probe. A landing site can be reconstructed from pictures provided the imaging system is specifically designed for making photogrammetric measurements and the optical geometry of the system has been precisely calibrated. However, the difference in ground resolution between pictures taken from orbit and pictures taken from a planetary surface is so great that the meaning of much of the information in pictures taken by a landed system is lost, unless the location of the lander is precisely known and photographed from orbit.

If an orbiter is present, a symbiotic relation between orbiter and lander can be developed from which highly detailed interpretations of planetary surfaces can be made. Even without support from an orbiter, considerable topographic information can be extracted from the lander imagery. Because the soft lander is stationary during data acquisition, the photographic problems are generally simpler than for orbiting spacecraft.

Photography

Imaging systems for planetary landers fall into two main categories: slow-scan television and optical-mechanical scanners.

Slow-scan television pictures are geometrically similar to pictures taken by conventional film cameras. Panoramas can be taken with a slow-scan camera by rotating it about its perspective center some angle less than the field of view between each picture until the entire panorama has been covered. The resulting pictures can be pieced together as a mosaic.

Optical-mechanical scanners are similar to the facsimile systems used by news services to transmit photographs from one facility to another. A camera of this kind suitable for surface planetary exploration incorporates a small mirror which rotates about vertical and horizontal axes and which reflects images into the lens of the system. A tiny hole in the image plane, on the axis of the lens, admits light to a photosensitive device that converts luminous flux to an electrical signal for processing and transmission to receiving stations. As the mirror rotates about one of its axes, the focused image of the landing site moves across the pinhole above the photosensor, thereby transmitting the luminance along a narrow band of the scene. A picture is taken by making adjacent sweeps with the mirror until the complete panorama has been transmitted. Entire panoramas or segments of panoramas are recorded as single pictures without making mosaics.

There are several advantages in using facsimile cameras on planetary landers. Their design is so much simpler, mechanically and electronically, than slow-scan television cameras that they are inherently more reliable. Optical design is simplified because the pinhole is on the lens axis and optical aberrations outside the

paraxial region need not be considered. They are capable of producing pictures of very high resolution from relatively small systems.

Stereoscopic coverage, permitting topographic mapping of the area photographed, requires photographs from two different points of perspective. This can be achieved by—

Moving the imaging system physically from one station to the other.

Photographing the object space directly and then photographing its reflection in a mirror appropriately located.

Providing two imaging systems separated by an appropriate baseline.

Stereoscopic baselines may be either vertical or horizontal. Horizontal baselines present the most natural view of the scene, but vertical baselines are equally useable from a geometric point of view.

In all cases the accuracy and extent of mapping depend on the length of baseline and the height of the perspective centers above the planetary surface. If the baseline is calibrated in advance, it will permit the establishment of a local coordinate system and map scale without reference to external control provided by orbital photography. Under certain circumstances the lander imaging system can photograph identifiable stars from which azimuth and perhaps position can be established.

Spacecraft shadows provide data from which topographic measurements can be made. The location with respect to the imaging system of a shadow on a planetary surface can be computed as a function of the known size and orientation of the part casting the shadow and the angle the shadow subtends from the imaging system. A second method of spacecraft shadow measurement is the computation of shadow location as a function of the illumination angle, the angle subtended at the imaging system between the shadow point and the spacecraft part casting the shadow, and the distance between the imaging system and the spacecraft part.

Statistical slope information can be gathered by measuring shadows of natural features, and, theoretically, systematic slope measurements could be connected to provide map data. The geometric conditions for mapping by this method are so varied and complicated, and the number of observations required are so great,

that this approach should be considered as an emergency solution rather than a primary procedure.

A mapping method called "Phototrig" may be used when the same surface features can be identified in pictures taken by both lander and orbiter. Feature heights relative to the imaging system are computed as a function of distance from the lander (measured on orbiter pictures) and vertical angle (measured on lander pictures). Contour lines are then interpolated between the spot elevations thus computed. As with all imaging systems from which map data are to be produced, geometric analysis and system calibration are indispensable.

Data Reduction

The camera focal lengths and picture formats useful for planetary exploration from spacecraft—whether flyby, orbiter, hard or soft lander—will generally be different from those employed in conventional aerial or terrestrial mapping. They may therefore be expected to be more or less incompatible with the photogrammetric procedures and equipment generally available. In addition, information about camera position and attitude—available through orbital tracking and attitude sensors—provides geometric constraints on triangulation not available to usual aircraft situations. This means that computer programs designed for conventional aerial control extension will be inadequate for planetary missions.

It is therefore necessary that consideration be given from the initiation of a planetary exploration program to the complete system design, which includes not only the spacecraft, the sensors, and the mission, but also the hardware and software for extracting the maximum geodetic and cartographic information from the records obtained. Unfortunately, this has not been the case through the lunar program and the planned planetary flights.

SUMMARY

1. Geodesy and cartography provide a reference system for navigation and guidance

and for correlation and compilation of all data from the surface.

2. The basic requirement for geodesy is geometrically true, low to moderate resolution, wide-angle photography of the whole planet. For cartography the basic requirement is high-resolution wide-angle photography of areas of interest, the resolution depending on the intended map scale.
3. Resolution demands and weight constraints have forced, and are likely to continue to force, the use of undersirable narrow-angle camera systems for which reconstitution requires accurate knowledge of external data such as camera orientation and position. The narrow-angle cameras demand more stringent calibration procedures, a more restrictive imaging strategy, and more precise knowledge of camera orientation and position than wide-angle cameras; these factors must be considered in total system design at the initiation of any imaging experiment.
4. The most necessary attribute of the imaging system, without which no metric analysis is possible, is geometric fidelity. The widely used vidicon system are notoriously prone to distortion, ground-based work should therefore concentrate on developing geometrically more reliable systems, preferably film.
5. Useful photogrammetric determinations of elevations with narrow-angle cameras from orbital altitudes is possible only with convergent stereophotography and then only with precisions of the order of several hundred meters for most camera systems now being considered for planetary exploration.
6. Nonvisual imagery can be used for geodetic and cartographic purposes, and with radar, the additional ranging capability can be utilized for elevation measurements.
7. Metric analysis of lander imagery is complicated by rapid scale changes, uncertainties of orientation and masking by shadows, but facsimile cameras promise to provide geometrically stable imagery for quantitative work.

GEOPHYSICS

By M. H. Carr, G. G. Schaber, and
R. L. Wildey

Geophysics is concerned with the study of the planets by the methods of physics; it includes consideration of the structure, dynamics, and physical conditions of planetary interiors. Fundamental studies that can be related very directly to processes involved in the history and evolution of the planet are detection of radial subdivisions such as core, crust, and mantle; characterization of seismic activity; measurement of heat flow; and mapping the gravity and magnetic fields. Of lesser importance, but still of geologic significance, are measurements of the physical properties of near-surface materials. Abundant ground-based data cannot be expected from any planet as relatively few ground stations will be established. Even a very few surface geophysical measurements will enormously improve our knowledge of the planet, for little is known of the interiors of any planet other than the Earth. Many geophysical parameters such as size, shape, dynamical figure, surface reflectivity, and emissivity at various wavelengths can be determined remotely, either from spacecraft or from the Earth, and these are the measurements on which most data will be obtained early in the exploration program.

Size, Shape, Mass, and Rotational Constants

Size, shape, mass and rotational constants are of interest because they place constraints on two important properties of a planet, the internal mass distribution and internal viscosities. The internal distribution of mass may reveal compositional differences, implying that differentiation has taken place; internal viscosities are important in that they place limits on the temperature and pressure conditions in the interior. Information on these parameters is derived largely from deviations from radial symmetry and the effects of the asymmetry on the planet's rotation.

The radius and geometry can be determined from radar measurements, approach photography, and occultation experiments (Ash

and others, 1967). Radius is important as a constraint on the internal mass distribution, and viscosity estimates are made from deviations of the geometrical figure from hydrostatic equilibrium.

The dynamical figure of a planet is the shape of its gravitational field as determined from the orbital parameters of satellites. If the rate of rotation of a planet is great enough to cause significant polar flattening, then the moments of inertia can be determined from the dynamical figure, assuming hydrostatic equilibrium. Since the moment of inertia severely constrains values of internal densities, precise determination of the dynamical figure is fundamental. Very accurate determination of the dynamical figure requires tracking of several satellites, preferably in tight orbits with different inclination, but determination of the lower order harmonics results from normal tracking of an orbiter around a planet and will follow from any orbiter program. Higher order harmonics of the dynamical figure, similar to those encountered on the Moon (Muller and Sjogren, 1968), can result from near-surface anomalous mass distributions and may have important implications concerning the structure of the crust. These anomalies can be determined only by precise tracking of satellites unaffected by drag. For this purpose, a tracking transponder, preferably incorporating a nul-type accelerometer, should be placed in orbit around the planet.

Moments of inertia can be derived from the dynamical figure only if the rate of rotation is great enough to cause significant polar flattening. If the rotation rate is too slow, then the moment of inertia must be determined from the response of the planet's motion to torques. The principal response is a librational or precessional motion; precise determination of these motions is needed for moments of inertia calculations. Location of axes of rotation by approach photography and extended terrestrial radar observations will aid in defining the planet's motion.

The moments of inertia of Mercury, although of great interest from a dynamical point of view because of its spin-orbit coupling (Goldreich and Peale, 1967), are difficult to determine owing to the slow rotation. However, refinement of figures for the mass and radius

will result from a flyby, and extended observation of an orbiter will give precise information on the geometrical and dynamical figures. Full-disk photography should be undertaken from all spacecraft so that the axis of rotation can be accurately located and any librational motion defined.

The slow rotation of Venus prevents direct determination of its moment of inertia from the flattening. However, determination of the dynamical figure is still extremely useful for analyzing gravity anomalies and other indications of dynamic imbalance. Because the atmosphere of Venus will cause significant drag on a satellite, a tracking transponder incorporating a nul-type accelerometer should be orbited to precisely determine the dynamic figure. Determination of the libration of Venus is necessary for determination of the axial moment of inertia, and this appears possible from extended radar observations of the planet from Earth. The moment of inertia of Venus is of particular importance because of similarity to the Earth in mass and size. Analysis of the internal mass distribution will reveal to what extent the evolution of their interiors has been different.

Mars rotates fast enough to cause significant polar flattening. At present the geometrical flattening is not well known, and the best figure conflicts with the dynamical flattening determined from the orbits of Deimos and Phobos. Precise values of the optical flattening and radius will be obtained from the far-encounter photography and occultations of planned orbiters. Tracking of these orbiters will lead to more precise determinations of the dynamical figure and, as a result, of the moment of inertia and the internal-mass distribution. Later orbiters containing a nul-type accelerometer and tracking transponder should be flown to analyze local gravity anomalies and the general structure of the crust.

Anomalous internal mass distributions may occur, especially for Venus and Mercury, which exhibit spin-orbit coupling. Nonradial symmetry would be revealed by noncoincidence of the centers of the geometrical and dynamical figures and by comparing their deviations from sphericity. This can be achieved by radar altimetry from an orbiting vehicle. Therefore inclusion of a radar altimeter, which is needed

for accurate analysis of topography also, should be considered in advanced missions.

Seismology

The seismicity of a planet provides indirect evidence concerning the thermal and dynamical state of its interior. Seismology provides the most effective way of measuring the dimensions of a core, crust, or any other subunit of the interior and is the most simple and direct way of locating internal discontinuities and internal movement. This information is of such importance in determining the origin and evolution of a planet that a seismic experiment should be given a very high priority and included early in any exploration program.

The ideal seismic experiment requires a global network of seismic stations each with a wide variety of seismic detectors and the necessary power and facilities for data handling. The possibility of establishing such a network on any planet other than the Earth is exceedingly remote, but this does not rule out a meaningful scientific experiment. Much can be learned from a relatively simple seismic experiment which would not only provide basic scientific data but enable subsequent more complex and comprehensive systems to be better designed.

The simplest experiment involves placing a single seismic detector on the surface of the planet, preferably a short-period (1 second) single-axis seismometer, or, if telemetry and weight restraints permit, a short-period three-axis type. From such a detector, the seismicity or aseismicity of the planet could be established and estimates made of the magnitude and frequency of seismic events. The general level of seismic noise could be measured, and from the separation of the S and P waves approximate distances of events from the station could be inferred. In addition to its intrinsic scientific worth, the data would permit an accurate assessment of the advisability of more complex seismic stations for future missions and provide design constraints on such systems. A simple seismometer should be deployed at the earliest possible opportunity, preferably on the first lander to any planet.

A second-generation seismic station should include both long- and short-period

three-component seismometers. From such a station, a far more complete picture of the seismic properties of the planet can be obtained than from records of a single short-period instrument. Comparison of the amplitude and separation of surface and body waves enables distances and focal depths to be estimated. Distances and directions can be established with far greater accuracy than with a single short-period instrument, and better determinations of attenuation rates are possible. In addition, the seismic properties of the "crustal" materials can be deduced from the dispersion of surface waves resulting from the wave-guide effect (Press and others, 1960).

The effectiveness of a seismic station is vastly enhanced by the simultaneous operation of a duplicate station. Many of the ambiguities of interpretation are removed by having duplicate records, and seismic events can be more accurately located by using widely spaced stations. Far better estimates can be made of the variation of seismic velocity with depth than from a single station, and under certain conditions shadow zones can be detected and the presence of a core determined. Consideration, therefore, should be given to the simultaneous operation of two distantly spaced stations early in the exploration program. Gravity-, tilt-, and strain-variometer experiments to examine free oscillations, tidal effects, and secular deformation should be deferred until at least two six-component stations have been established on the planet.

The internal constitution of Mercury is of special interest because of the planet's high density. Although no landers are planned at present, a lander is feasible, and a simple seismic experiment should have high priority on the first lander.

A thorough comparison of Venus and Earth is necessary for an understanding of what factors control planetary evolution. A primary objective is to determine whether Venus, like the Earth, is divided into core, mantle, and crust. This is a problem that can be solved by seismic experiments, and the feasibility of designing a seismic experiment to survive in the 700° C and 100 atmospheres pressure that prevail on Venus should be explored.

A successful seismic experiment appears to be particularly promising for Mars. Mars landers

are already planned, and a simple seismic experiment should be carried on the first landers, preferably three-axis short-period seismometers capable of operating for 6 months, to be followed later by six-component seismometers.

Development of lightweight, compact, low-noise seismometers is well advanced. Instruments have been designed that weigh less than 5 pounds and can withstand loadings up to 25 g. Such instruments developed for operation on the Moon can be adapted with little modification. The principal problem in establishing a seismic station is not in detecting and recording the signal but in transmitting the information. Most of the planned seismic experiments for the Moon are based on technology of data analysis derived from our earth-based experience. To obtain relatively few numbers, we analyze thousands of data bits from a seismogram. There are many possible ways to reduce the quantity of information required for transmission and these ways should be explored. One possibility is an event-triggered mode of operation. Initial operation could be continuous to determine the general seismic noise and appropriate trigger level; long-term operation would be event triggered.

A seismic station must of necessity operate for a considerable length of time before a statistically significant number of events are recorded. No estimate can be made of this time until the level of seismicity of each individual planet is obtained. A minimum 6-month operation time should be aimed for, and the appropriate power sources for such lengthy operation should be developed.

Active seismic experiments are normally used to study near-surface discontinuities and near-surface seismic velocities. These are of considerably less importance than analysis of natural seismic events, and this type of active seismic experiment is given low priority on a seismically active planet. However, active seismic experiments can be used to study the interiors of planets where the number of natural seismic events is not adequate for analysis. Very little effort has been expended in attempting to define realistic active experiments for the Moon and other planetary bodies, and it may be possible to carry out these experiments by using abandoned delivery vehicles. In anticipation of

some planets being aseismic, study of possible active experiments should be undertaken.

Heat Flow

The most significant geothermal measurement is that of the internal heat flow. From its value, much can be deduced concerning the thermal regime of the planet's interior and the thermal evolution of the planet (MacDonald, 1964; Lee, 1967). A heat flow measurement is particularly difficult on a remote surface because the measuring devices must be placed in a hole drilled in the surface. Temperatures and thermal conductivities must be measured in the natural state at depths sufficient to avoid appreciable diurnal and seasonal temperature variations. The depth required depends on variations in surface temperature, the length of days and seasons, and the local thermal properties. In order to make the necessary measurements, drilling of a hole at least 5 to 10 m deep is required. Because strong lateral gradients in both temperature and surface properties could cause strong lateral flux components, several heat-flow measurements may be needed to evaluate the significance of these shallow observations. The greatest technical difficulty lies in drilling the hole. The actual measuring devices are already developed; they are lightweight and compact, draw very little power, and have very modest telemetry requirements. Such a hole would be useful for a wide variety of experiments other than heat flow, and the feasibility of drilling on different planetary surfaces should be vigorously explored. Until drilling is practical, attempts to make in place heat-flow measurements should be deferred.

Monitoring of the near-surface temperature regime by emplacement of temperature-sensing devices at shallow depths can give information on diurnal and seasonal temperature variations. From the damping of these variations as a function of depth, and from the phase lag, local values of thermal diffusivity can be estimated. Although these shallow thermal measurements are not as fundamental as the internal heat flow, they can yield very useful data on the thermal environment for other experiments and on the heat-exchange process at the planetary surface.

Determination of near-surface thermal properties at a landing site can be used to calibrate infrared radiometric measurements from an orbiting spacecraft. Because of the likelihood of lateral inhomogeneity, however, a number of measurements should be made, and they must be used with caution in the interpretation of radiometric data.

Magnetics

Detection of a planetary magnetic field significantly larger than that of the interplanetary medium indicates the presence of an electrically conducting and convective core within the planet. The existence of such a core would show that the planet has undergone some differentiation in the past and that the present conditions of the core are such that the mobility of the core materials is possible. If the presence of a core is demonstrated by seismic methods yet no magnetic field is detected, then we can infer that either the core is nonconducting or that conditions in the core are such that motion of the materials is not possible or that the forces necessary to cause motion within the core are absent. Should remanent magnetism be detected in surface rocks despite the present lack of a field, then the conditions within the core must have been different in the past. Magnetic measurements therefore have important implications concerning both the history of the planet and the present conditions deep in the interior.

Magnetic field measurements are relatively simple and can be made remotely from flybys or orbiters with sensitivities limited only by the magnetic properties of the supporting vehicle. The simplest magnetic experiment is measurement of total field strength with a three-axis magnetometer from a flyby. The experiment has very modest weight, power, and telemetry requirements and should be included on all first looks at a planet. Subsequent strategy will depend on the results of the first look. If a field is detected, then followup experiments will be concerned with mapping the structure of the field since this will reflect the flow pattern within the core. If no field is detected, then consideration should be given to methods of improving the sensitivity of the measurements.

Jupiter is the only planet on which a magnetic field has been detected. An early spin-stabilized flyby or preferably a "tight" orbiter carrying a three-axis magnetometer to map the magnetic field would provide sufficient information for harmonic analysis to reveal details of magnetohydrodynamics processes in the core and the possibility of other magnetic sources. As appropriate instruments are available, no new developments are needed. Should strong fields be detected on other planets, a similar program of magnetic mapping should follow for these also.

Magnetic fields have not been detected on Mars and Venus from flybys (Fawcett and others, 1965; Brandt and Hodge, 1964), and if fields are present on either planet more sophisticated experiments are required than have been tried in the past. The possibility of using demagnetized spacecraft to improve sensitivity of magnetic measurements and to place more stringent limits on the magnetic fields should be explored. In the case of Mars, where a series of landers is planned, the feasibility of making magnetic field measurements at some distance from a landing vehicle by projecting the magnetic experiment away from the spacecraft should be studied. However, detection of magnetic fields of very low intensity is of secondary importance and should not preempt more fundamental and less risky experiments such as seismic and chemical measurements.

The absence of a magnetic field at present does not preclude the existence of a field in the past. Evidence of the past field will be preserved in the surface rocks, and a simple experiment to determine to what extent surface rocks are magnetized should be made on an early lander to all planets. The simplest experiment would require a single-axis magnetometer and a sampler similar to the one carried on Surveyor. Magnetometer readings are taken as samples are moved toward it. Since the experiment is being conducted in the absence of a field, changes in magnetometer readings would indicate some rock magnetism and hence that a magnetic field existed in the past. Success of the experiment would imply the existence of a core and would further imply that present conditions within the core are static.

Physical Properties of Near-Surface Materials

Several remote-sensing techniques are available for measuring the properties of near-surface materials. These techniques have had only limited applicability to terrestrial geologic problems, largely because the appropriate measurements can commonly be made more accurately on the ground. But, because of the limited availability of ground-based information on planets, the importance of remote-sensing techniques as geologic tools is greatly enhanced. Some of the parameters susceptible to remote measurement, for example, porosity, density, and thermal conductivity, are difficult to relate to mineralogy and petrology of the underlying rocks; the absolute values of these properties have limited geologic significance. Nevertheless, the measurements are geologically useful, since their variation across the planet's surface can be used for mapping and for interpolation between ground measurements. Undue reliance on the optical response of the surface is thus avoided. Furthermore, although remote-sensing measurements rarely offer unique solutions, they do add to the bank of data with which any interpretation of the surface must be consistent.

Infrared Radiometry

Infrared radiometer measurements on the Moon (Shorthill and Saari, 1966) have proven extremely useful in interpreting the nature of the lunar surface and the relative age of craters. Systematic radiometric mapping will be similarly useful on Mars and Mercury. Of particular interest is the detection of thermal anomalies and correlation of these anomalies with optical features. Anomalies detectable on the nightside result principally from differences in the rates of decay of surface temperatures due to local differences in thermal inertia. Since thermal inertia is dependent on lithology, variations in nighttime temperatures are related to variations in rock lithologies. Thermal anomalies could result from internal heat sources, and although this is likelier, anomalies of this type would be most readily observed just to the darkside of the morning terminator, where surface temperatures

are lowest. Systematic radiometric mapping from an orbiter of nighttime surface temperatures, including the temperatures immediately before dawn, is therefore recommended for Mars and Mercury and should follow acquisition of broad photographic coverage at useful resolutions (≈ 500 m) in the visible.

Microwave Emission

A planet undergoes both diurnal and seasonal variations in surface temperature. A thermal wave communicates these temperature fluctuations to subsurface layers, but with depth the wave becomes progressively damped in amplitude and retarded in phase. Because the overall microwave opacity of solids generally decreases toward longer wavelengths, microwave radiometers turned to lower frequencies can observe at progressively greater depth (Pollack and Sagan, 1965). With increasing wavelength we should therefore expect a decrease in the amplitude of the diurnal temperature oscillations and an increase in the phase lag. Furthermore, if the sole source of heat is the sun, and if the albedo is constant, then the mean surface temperature should be the same for all wavelengths. If the mean surface temperature is not the same, discontinuities in thermal properties with depth or an internal source of heat can be inferred.

The geologic interest in passive microwave measurements results from the possibility of determining internal heat flow and from determination of near-surface properties (Drake, 1966; Kaula, 1968). Theoretically the internal heat flow can be measured from the variation in mean surface temperature as measured at different wavelengths, provided the thermal conductivities of the near-surface materials are known. In practice, surface properties may rarely be sufficiently well known that thermal gradients will be unambiguously measured; but in view of the importance of internal heat flow, development of microwave measuring techniques at several wavelengths and possible applications to planetary problems should be supported.

Bistatic Radar

Study of planetary surfaces by means of bistatic radar methods has been suggested by Fjelbo (1964) and Tyler (1966); such methods were applied to the Moon in a preliminary manner during the Lunar Orbiter I and Explorer 35 missions (Tyler, 1968). In the bistatic mode, radar signals transmitted from the Earth are received by an orbiting spacecraft after the signals are reflected from the planet's surface. The nature and intensity of the signal depend on the configuration and properties of the near-surface materials. Surface roughness is particularly important in controlling the signal, as it affects the proportions and intensities of the specularly and diffusely reflected components. Surface roughness in the radar sense could be mapped bistatically with resolutions of several hundred wavelengths (Tyler, 1966); this is considerably better than what is possible by systems totally Earth based and is particularly useful for Venus, whose surface topography cannot be characterized visually. An early vehicle to Venus should test the feasibility of mapping in the bistatic mode by using the S-band radio system. If mapping appears feasible in this mode then a spacecraft of the Pioneer/Imp class should be assigned to bistatic mapping of the Venusian surface.

Radar measurements of the surface roughness of Mars and Mercury are less important than for Venus because the topography of these planets can better be described from visual observation. Radar reflectivity measurements are, however, of interest on Mars and Mercury because of the possibility of mapping dielectric constants and of detecting subsurface discontinuities. The dielectric constant is of particular interest as a means of detecting water. Dry materials rarely have dielectric constants in excess of 10, yet values can be much greater than 10 if moisture is present. A radar receiver could therefore detect and map near-surface water, and, if the vehicle had an extended lifetime, the changes in the distribution of near-surface water with the seasons could be followed. The wavelength should be as long as compatible with instrument design (10^5 – 10^7 hertz) since penetration is a

function of wavelength and surface roughness is of lesser interest.

Detection of subsurface discontinuities is of geologic interest especially if the surface is covered with a debris layer. The surface configuration of the debris layer on Mars, for example, may be in part controlled by atmospheric effects so that geologic mapping from the visible imagery alone may be difficult. Since radar signals penetrate to much greater depths than optical signals, radar measurements will be useful for detecting variations in the properties of rocks below the debris layer and variations in the thickness of the layer. The feasibility of bistatic mapping of Mars and Mercury at various wavelengths should therefore be examined.

Radar Topographic Mapping

From a geologic viewpoint the most important aspect of radar is that it provides a means of mapping the topography of a planet whose surface is obscured by the atmosphere. This is particularly important for Venus, which is very similar in radius to the Earth and so might reasonably be expected to have followed a similar evolutionary path. We know, however, that the atmosphere of Venus is drastically different from the Earth's and it is essential to know whether the solid parts of the planets exhibit comparable contrasts. Comparison of the topography of Venus with that of the Earth is an essential first step in evaluating the nature and causes of difference between the two planets. The presence on Venus of orogenic belts, rift zones, and sedimentary basins similar to those on Earth will have particular geologic significance. The necessary imagery could be obtained from either terrestrial measurements or orbital measurements.

Terrestrial Observations

Radar imagery, with spatial resolution comparable to telescopic optical photography (≈ 2 km), has already been obtained of the Moon. With improved receivers and data-handling techniques, comparable resolutions are achievable for Venus from

terrestrial observations. The hemisphere ambiguity problem has already been solved, and rudimentary imagery has been obtained with existing techniques. Resolution is presently limited only by the ratio of signal to noise, and it is expected that this ratio can be significantly improved in the near future. Support of terrestrial radar observation of Venus with particular emphasis on improving spatial resolution is recommended. This has higher priority than any other measurement of Venus and is comparable in priority to obtaining orbital photography of Mars. A necessary supporting effort is to improve knowledge of the rotation and orbital constants of the planets and particularly of Venus.

Coherent Side-Looking Radar

Side-looking radar is the only means of obtaining high-resolution (100 m) imagery of the surface of Venus or any other planetary body obscured by clouds. A side-looking radar system measures the reflectivity of the scattering medium as a function of position, and it uses the information to construct an image of the surface. The transmitter and receiver are both within the spacecraft and a signal is transmitted to the target surface at a fixed angle (generally $45^\circ - 60^\circ$). The reflected signal varies in intensity, largely according to the relation between surface slopes and the spacecraft. The signal is measured as a function of track position, azimuth, and range. The positional and intensity information are combined to construct a radar image, which strongly resembles an optical image of the surface under oblique illumination. Use of synthetic aperture techniques permits high-resolution images to be formed from orbital altitudes without need of physically impossible antennas (Brown, 1969). The imagery can be interpreted by standard optical techniques, including stereophotography, provided the appropriate imagery is obtained, but several additional techniques unique to radar can also be applied. Since the side-looking radar is a ranging device rather than an angle-measuring device, such as a standard camera, topographic information can be extracted from the range data. It is not yet

possible to determine elevations from range data on a single radar image alone, but ranging techniques are being developed for construction of topographic maps (LaPrade and Leonardo, 1969). Depth effects can be discerned with the use of multifrequency systems and imaging at different radar wavelengths.

Utilization of side-looking radar will depend on rate of development of terrestrial radar techniques. Moderate-resolution (2 km) radar imagery of Venus must be obtained during the next decade. If this appears unlikely from terrestrial measurements, then side-looking radar imagery must be obtained, even if this requires all the payload of a Mariner-class vehicle. Side-looking radar of Mars and Mercury is not recommended for the foreseeable future unless obscuration of surface features from atmospheric effects proves to be a greater problem than anticipated.

SUMMARY

1. Precise determination of rotational constants and the optical and dynamical figures are required for analysis of internal mass distributions and internal viscosities. Radar observations of all the planets should therefore continue for better definition of motions and diameters in addition, orbiting tracking transponders, possibly with nul-type accelerometers should be flown to determine precisely the dynamic and optical figures and perhaps to identify near-surface mascons.
2. The first landers to any planet should carry seismometers, preferably three-axis short-period instruments, and plans should be made for simultaneous operation of at least two widely separated stations. Depending on the earlier results, second-generation stations may include long-period instruments, more elaborate short-period instruments, or be capable of operating in an active mode.
3. Plans for heat flow measurements should be deferred until a remote drilling capability is established, but high priority should be attached to developing the necessary technology.

4. A first look at any planet should include measurement of the magnetic field. If there is no present field, then the first lander should carry a simple magnetometer experiment to measure the magnetization of surface rocks for evidence of past fields. If a significant field is detected, it should be mapped with a three-axis magnetometer on a "tight" orbiter.
5. Measurement of the physical properties of near-surface materials by remote-sensing techniques such as infrared radiometry or bistatic radar, while less important than determinations on interiors, is useful for understanding the nature and origin of near-surface materials, especially for Venus, where cloud cover prevents direct visual observations.
6. Improved radar imagery of Venus is of highest priority; resolutions of 2 km are highly desirable. If these resolutions do not appear feasible from terrestrial observations within the next decade, then side-looking radar imagery must be obtained from an orbiting vehicle.

GEOCHEMISTRY

By M. H. Carr, Priestley Toulmin, 3d, and
I. A. Breger

An important concern of geochemistry is the bulk composition of the planets. Because chemical differences between the planets may reveal the nature of chemical heterogeneities in the original solar nebula and the mechanism of planetary accretion, it is important to acquire the data necessary for evaluation of their bulk composition. Obviously there is no way to chemically analyze a body as large and heterogeneous as a planet at a single gulp. Nor can chemical homogeneity be assumed. The earth is certainly not homogeneous and most evidence points to a heterogeneous Moon. The overall bulk composition can be determined only by devising a sampling and analytical program designed to evaluate and allow for compositional variability. To do this statistically on the assumption of random variability is both inefficient and, because only the very near

surface part can be sampled, subject to great error. A plan must be devised that is based on an understanding of the geochemical regularities and geologic relations among the various rock types of the body. We should begin by determining the mineralogic and petrologic relations in order that the processes by which the major rock units have been formed can be inferred and the relative proportions of different rock types can be deduced. Only when we have a fairly detailed understanding of the geochemical and petrogenetic processes that have operated on the planet and the history of their action, together with a satisfactory model for the internal structure of the planet, will we be in a position to arrive at a reasonable estimate of the bulk chemical composition.

The most effective strategy for the geochemical study of a planet is to proceed systematically with the mineralogical and chemical characterization of its materials in accordance with geologically determined priorities. It is insufficient merely to chemically analyze the surface rocks. Determination of mineralogy, texture, lithology, and other properties of the rock that might be relevant to origin is necessary. Mineralogic composition is particularly important, as the mineral assemblage reflects both the chemical composition and conditions of formation and is far more diagnostic of rock type and formative processes than chemical composition alone. Mineralogy has been greatly neglected in the exploration of the Moon; it must be included as a major aspect of the exploration and scientific study of the planets. Indeed if a choice must be made between a mineralogic and a chemical analysis, the geologist will generally opt for the mineralogic analysis because it contains much chemical information and a great deal more. Such a choice should not be necessary, for mineralogical and chemical experiments can be readily integrated to provide a complete analysis.

The exploration strategy for the planets must be more comprehensive than that for the Moon, whose exploration has been conducted with the expectation of early return of lunar samples to the Earth. Difficult experiments could therefore be conveniently deferred until a sample was available on Earth. Since return of

samples from any of the planets presents far greater technological difficulties than from the Moon, we cannot anticipate early return. Difficult experiments such as age determinations, petrologic characterization, and isotopic and trace-element analyses cannot be delayed until samples are returned to Earth; the instruments necessary for performing these experiments remotely must be developed and deployed.

The success of any geochemical exploration program will depend largely on how intelligently sites are chosen for analysis. A chemical analysis on the surface of a sand dune on Mars, for example, will not reveal much about petrologic processes. Information from orbiters will be crucial in selecting sites. Photography is likely to be most valuable but other techniques more sensitive to chemical composition, such as multizonal photometry, should also be used. The usefulness of these techniques depends not so much on the precision with which they can determine surface chemistry, but on their ability to detect differences. Because orbital measurements are important in giving areal dimension to specific surface analyses the orbital and landing programs should be planned in concert and strategies employed such that each mission plan can be modified by information gained from the other program.

In summary, data from a lander should include both chemical and mineralogical information supplemented by information of petrologic importance such as texture, lithology, and structural position. The general significance of such information gathered at a restricted number of landing sites should be evaluated in light of all available geologic information, including geophysical measurements on properties of the interior and orbital measurements of the variation in surface properties. The following sections contain more specific discussions evaluating different methods of acquiring the necessary fundamental data.

Elemental Composition

Sampling

Some of the broader aspects of the sampling problems were discussed in previous section, but

additional problems are encountered in the immediate vicinity of the spacecraft. Because of possible local variations, an analytical instrument must have the capability of making measurements on any nearby object of interest and of visually monitoring such measurements. This requires that a sampling tool be available and that the analyses be conducted in close conjunction with the imaging system, as was done successfully with Surveyor.

Accuracy and Precision

It serves very little purpose at this time to specify accuracies and precisions for possible chemical determinations. This will depend on what is technologically feasible and also on the variability in surface chemistry of the planet under consideration. Efforts to achieve extreme

precision with relatively few analyses would be justifiable only in the unlikely case of a homogeneous planetary surface, whereas more analyses with lesser precision might be desirable on a planet with variable surface composition. In the table given below, the precisions listed are those adequate to characterize most terrestrial rock types. For even the most homogeneous of terrestrial rocks, the natural chemical variability generally exceeds the listed precisions (Landy, 1961) so that to more accurately define the chemistry of the rock, multiple analyses are required as well as increased analytical precision. This is somewhat academic for the planets because the presently achievable precisions fall far short of those listed in the table, and we are not likely to be presented with the choice between extreme precision on few analyses or moderate precision on many analyses early in the exploration program.

First priority elements

<i>Element</i>	<i>Expected range (percent)</i>	<i>Precision needed to define most terrestrial rocks (percent)</i>
Na-----	0.5-4.5	10
Mg-----	.5-20	10
Al-----	2.5-20	10
Si-----	15 -35	3
K-----	.5-5	5
Ca-----	.5-6.5	10
Fe-----	.5-20	5
H ₂ O-----	---	---

Second priority elements

S, Ti, Mn, Ni, Cr, U, and Th

Third priority elements

Ba, Sr, Cu, Pb, Li, P, B, Cl,
F, and Zn

Priorities have been assigned to elements in the table. This could be done in a more sophisticated way if available chemical data were more carefully evaluated. A wealth of chemical data is available in terrestrial rocks, yet little systematic work has been done in organizing the data to separate natural variations from analytical errors and to determine what

abundances or what elemental ratios are most diagnostic of specific rock types or meteorites. The Geochemistry Group at the Santa Cruz conference sponsored by NASA suggested intensive study of existing data with the intent of evaluating the diagnostic value of specific abundances and ratios. This group stated that "The K/Ca ratio a much better index by which to classify chemical variations than analysis for Al, Mg, Si, and Fe. The K/Ca ratio varies by a factor of 500 in common rock types, where Mg/Si or Mg/Fe ratios vary by less than a factor of 10. Similarly, the Al/Si or Ca/Si ratios are a much better index for distinguishing chondritic material and ultramafic rocks from other rocks than the Mg/Fe or (Mg or Fe)/Si ratios. Probably

the most distinctive chemical characteristic of chondrites is the Ni content or Ni/(Mg or Fe) ratio." (National Aeronautics and Space Administration, 1967) The study recommended should be undertaken to avoid making chemical determinations of limited diagnostic value.

The importance of specific elemental ratios as indices of bulk differentiation of the planet or heterogeneities in the solar nebulae should also be explored. Adams and others (1967a) have approached this problem and have pointed to the importance of the Fe/Si ratio in determining homogeneity of the original nebulae, internal uniformity of the planets, and formation of preplanets. Other ratios may have comparable significance.

Analytical Techniques

A detailed evaluation of different analytical techniques is beyond the scope of this report, and the following discussion is included more to illustrate problems than to suggest solutions. No one technique can be used to determine all the necessary major elements satisfactorily; different techniques may need to be combined if we are to have an adequate analysis. And since a mineralogic analysis is absolutely essential for understanding any chemical analysis, compatibility with phase-detecting devices is a principal criterion in evaluating the relative merits of the different techniques.

The alpha-backscatter, the only fully flight-qualified instrument now available (fall 1969), has been used successfully on the Surveyor program. The technique gives good results for the light elements, especially O, Mg, Al, and Si, which constitute most of any likely rock, but it has poor precision for heavier elements. Lack of precision for the heavy elements is particularly limiting for the highly diagnostic elements Ca, K, and Fe. The technique will encounter problems on Venus because of atmospheric absorption, but it might be appropriate for Mercury and Mars.

X-ray fluorescence is a versatile technique with a high degree of compatibility with various methods of phase analysis and one by which both light and heavy elements can be examined, depending on the excitation source. The standard technique of using a high-energy primary X-ray beam to excite the sample is

sensitive for all elements heavier than Al. To determine the lighter elements, advantage can be taken of the rising alpha-particle excitation function with decreasing atomic number. An alpha-emitter such as Cm242 or Po210 can be used to excite the sample. The excited X-rays may be detected dispersively by means of goniometers or nondispersively by solid-state detectors. Continuing development of small multichannel analyzers and higher resolution detectors makes the nondispersive methods potentially very attractive because the instruments are mechanically simple and the resolution of present detectors (< 200 electron volts) already permits unambiguous determination of adjacent elements heavier than Mg.

Neutron activation may be of value in determining elements whose determination is not possible by one of the more general techniques or in low-level determinations of specific elements. The technique is particularly sensitive for Na, Al, Si, Ca, K, Mn, and Be and could be conveniently combined with an X-ray fluorescence unit using the same analyzer and the same detector (appropriately biased). The only additional requirement would be some form of neutron source. The sensitivity of neutron activation depends on the particular element and on the flux available to excite the sample, but potentially the technique can be used for trace-element analysis not possible by either α -scatter or X-ray fluorescence.

Optical emission spectrometry, the traditional method of trace-element analysis, holds considerable promise for remote applications. The development of linear arrays of closely spaced photodetectors may have provided the key to utilization of this technique in space, but photography and subsequent photometric scanning is still a possibility. The method is sensitive to a large number of elements, can deal with very small samples, and has a wide range of response. Calibration to provide quantitative data may be the main problem with the technique.

It is evident from this brief discussion that no single technique will fulfill all geochemical needs. Emphasis should be placed on integrating various methods and exploring the commonality of different components so that a complete geochemical package can be assembled, similar

in concept to the ALSEP (Apollo Lunar Surface Experiment Package) for the Moon.

Isotopic Composition and Age Determinations

The principal interest of isotopic compositions of the condensed part of a planet is that they provide a means of determining ages. Sequence and age are of fundamental geologic concern. Only by placing rocks in proper sequence can we achieve some order out of the complexity of a planet's surface and arrive at some understanding of the processes that resulted in its formation. It is of obvious geologic importance to know whether the surface of a planet that formed 4.5 billion years ago has been dead ever since or is still undergoing endogenetic change. Each alternative has vastly different implications concerning the chemistry and conditions of the interior.

The isotopes of most interest are those of Rb, Sr, A, U, and Pb, and the only satisfactory technique of determining isotopic compositions of these elements is mass spectrometry. Flight instruments are being developed that utilize a sputtering ion source and a double-focusing system, but precisions now achievable permit only the crudest of geochronological measurements. Mass spectrometry is potentially a very versatile analytical instrument, as it can be used for measuring elemental abundance as well as isotopic abundances. A major effort should be to obtain flight-qualified instruments.

Mineral Composition

X-ray diffraction is the only satisfactory technique for determining mineralogy. No other technique can provide the same combination of generality, specificity, and quantitative data. X-ray diffraction patterns of polycrystalline material can be interpreted (1) to identify most phases present with little or no ambiguity, (2) to determine quantitatively the composition of most solid-solution series, and (3) to determine quantitatively or semiquantitatively the modal proportions of phases in aggregate. The phase compositional data can be recalculated into an elemental analysis which, though somewhat less

precise than that obtained by direct methods, is nevertheless useful for most interpretative purposes. (Interpretation of an elemental analysis involves, at least implicitly, calculation of a hypothetical mineralogical composition.)

Several different diffraction techniques are possible. A procedure commonly used is to change the angular position of a detector with respect to the sample and X-ray source and measure the intensity of X-rays at different angular positions. Although this technique has been adapted for space-flight applications, the instruments are delicate and mechanically intricate and several simpler alternatives are feasible. One promising approach is to use a curved position-sensitive proportional counter (now being developed at Illinois Inst. Tech. Research Inst., Chicago). The counter is in a fixed position, subtending an angle with respect to the sample such that X-rays from the sample hit different parts of the counter according to the angle through which they are diffracted. The resulting pulses are attenuated by the central wire of the detector with the result that pulse height depends on where the X-ray entered the detector and hence on the diffraction angle (monochromatic X-radiation is assumed). D-spacings in the sample can therefore be derived from the pulse-height distribution in the detector output. Photographic methods are also possible; film could be wound through an appropriate camera, then developed and scanned. Another possible diffraction technique is to have a nondispersive detector in a fixed position with respect to the sample and source. The diffracted X-rays are then dispersed electronically with a multichannel analyzer rather than mechanically by means of a goniometer. All the above alternatives should be explored to avoid placing disproportionate reliance on goniometer systems.

Another technique of mineralogic determination that deserves mention is differential thermal analysis (DTA). This technique, although of limited use for systematic mineralogy, can provide very useful mineralogical data. It is particularly important for identification of clay minerals, carbonates, and other minerals that undergo low-temperature transformations. The devices are compact and lightweight and have low power

and transmission requirements; they may therefore still be feasible when a more comprehensive mineralogical experiment is not possible.

Organic Radicals

A major objective of planetary exploration will be the search for extraterrestrial life. Efforts of the organic geochemists will be primarily devoted to recognition, identification, and analysis of organic matter on the planetary surface or in its atmosphere. Should living substances not be detected, then such organic material might provide clues as to extinct life processes, or it might reflect compounds formed abiotically. Such substances may in turn provide evidence, by analogy, of substances similarly formed on Earth which ultimately were the progenitors from which life arose on our own planet. Abiotically-formed compounds could provide information on the chemical radicals that exist within the space of our solar system.

The organic geochemist cannot ignore the environment in which the organic matter he has under study has been formed or found. Problems involving mineralogy, catalysis, and radiation chemistry, as well as the condensation or polymerization of organic compounds, are all interrelated. Organic matter may be formed biogenetically or may represent the abiotic products derived from condensed fragments such as C, CH, CH₂, CH₃, CO, N, NH, NH₂, and other radicals interacting in planetary atmospheres or on planetary surfaces. The occurrence of high fluxes of cosmic radiation (Mercury and Venus in particular) or of ultraviolet radiation could readily provide the energy necessary to create the radicals in the vicinity of the planet or to convert low-molecular-weight compounds to high polymers on the planetary surfaces. Search for such compounds must be made.

Gases expelled from a sample can be analyzed, quantitatively if desired, by infrared absorption or mass spectrometry with or without gas-liquid chromatography. Infrared techniques are also available for determining C¹³/C¹² ratios in carbon dioxide that may be given off. Establishment of the C¹³/C¹² ratio would be significant in determining whether the

organic matter had the same ratio as the atmospheric carbon of the planet. A significant variation would lead one to suspect that the organic matter was produced by a chemical or "biochemical" reaction accompanied by isotopic fractionation. Microscopic examination will also be necessary to determine the association between minerals and organic matter and to provide information as to whether the organic matter was deposited in place or was fluid at some time and flowed into its present location, where it then condensed or polymerized.

Most of these techniques have already been developed for adaptation to landers, or are now under development. A package capable of performing gas-liquid chromatography, differential thermal analysis, mass spectrometry, microscopy, and possibly infrared analysis would provide a powerful set of tools for evaluation of the nature of the organic matter, its source, and its relation to other constituents of the planet being examined. It could also provide complementary information on isotope ratios and mineral species.

Orbital Measurements

Precise chemical and mineralogical determinations are not possible from orbiting vehicles. Nevertheless, extremely useful geochemical information can be gained from orbital programs. To evaluate the general implications of a few precise analyses from landers, we must have some knowledge of the geochemical variability of the planet's crust, and this is practically obtained only from orbital vehicles. By utilizing a variety of remote-sensing devices, geochemical variations can be mapped, geochemical anomalies identified, and limits placed on chemical and mineralogical compositions over wide areas. Unique chemical and mineralogical determinations cannot be expected from such measurements; in precision and generality, the results will be more like those of terrestrial gravity and magnetic maps and subject to a limited set of interpretations.

Multiband Photometry

Multiband photometry in the visible and near infrared is promising as a technique for

mapping surface chemical and mineralogical differences. The technique has already been applied with some success to the Moon (McCord and Johnson, 1969). The method involves measuring the reflectivity of the surface at different wavelengths and utilizes the fact that the color of light reflected from crystalline material depends on the elemental and mineral species in the material. The method has several limitations, some practical and some theoretical. One practical limitation is that its utility is dependent on areal resolution and the number of wavelength channels in which measurements are made. Each spot measurement requires a large number of bits—because of the large number of channels—so that to build a mosaic of a planet's surface with useful resolution, say 5 km, would require enormous transmission capabilities. This limitation applies to other spectral measurements discussed below. A theoretical limitation of the method is that the characteristic peaks are very broad and therefore not very specific, and any given spectrum is susceptible to a wide number of possible interpretations. Despite these reservations, development of the method should be supported, certainly for telescopic work, but also in anticipation that orbital measurements will be practical.

Far-Infrared Spectroscopy (5–50 μ)

The far-infrared spectrum, being partly dependent on Si-O polymerization, is in general more sensitive to different rock types than the visible and near infrared (Salisbury and Hunt, 1969). Acid, intermediate, and basic rocks are readily distinguishable and measurements in the far infrared could be used to map the distribution of these rock types. In application it suffers from essentially the same limitations as measurements in the visible.

γ -Ray Spectrometry

γ -ray spectrometry from orbiting vehicles is an attractive possibility for a planet where gross differentiation of the crust is suspected. Because of atmospheric absorption, however, the technique is relevant only to Mars and Mercury.

Measurements are made of surface variations in natural γ -ray activity, which are largely the result of variations in the U, Th, and K contents. These elements are particularly diagnostic of "oceanic" and "continental" rocks on Earth and will have similar diagnostic importance on other planets. Other major elements may be detected as a result of γ -ray activity induced by radiation from the sun. This is particularly likely for Mercury.

X-Ray Spectrometry

X-ray spectrometry may be possible on Mercury from an orbiter because of the high solar flux and thin atmosphere. The purpose of such an orbiter would be to map compositional differences as revealed by the differences in X-ray spectra as a result of excitation of the surface by the sun's radiation.

Supporting Earth-based Research

The first and most obvious earth-based activity is in the field of instrument development, discussed above. As stated, the main thrust should be toward exploring the commonality of components between different techniques and toward producing an integrated package for elemental and mineralogical analysis.

The second, and in a sense more fundamental, kind of ground-based study should be devoted to acquiring basic scientific data needed to interpret the experiments performed at the planets. In part, this consists of the obvious direct calibration of instruments and simulation of experiments under conditions similar to those to be encountered on the planet's surface. The DTA response of a dehydration or decarbonation reaction, for example, may be quite different in the Martian environment than in a terrestrial laboratory. Effects of this sort may be evaluated in much the same way that flight hardware must be tested for operation under expected conditions. This work is properly part of the development procedure for specific instruments and experiments and can be done only in conjunction with experimental design.

A thin line separates these from other research programs that are designed to gain a better understanding of the conditions and processes on the planetary surface so as to predict and define the most significant measurements as well as to aid in their interpretation. For example, we need much more extensive data on the stabilities of phases that are curiosities on Earth but may be important constituents of the surface materials of other planets. We need especially to study minerals whose stabilities may be greatly enhanced or restricted by atmospheres very different from ours in composition, pressure, oxidation potential, content of H_2O , CO_2 , CO , and NH_3 , and other parameters.

To take a specific example, we know that the Martian atmosphere, with a surface pressure of 7 millibars, is largely CO_2 . Such an atmosphere is so different from our terrestrial atmosphere that we cannot predict with certainty the nature of the weathering products that would result from its interaction with even common terrestrial rocks. We can predict that the mineral phases in equilibrium with the Martian atmosphere are likely to be more reduced and perhaps more carbonate-rich than their terrestrial counterparts, but we are not in a position to make any quantitative predictions. A program of direct experimentation in low-temperature reactions between common terrestrial rock types and simulated Martian atmospheres is one desirable route of attack, but it should be supplemented by systematic measurement, compilation, and evaluation of equilibrium data on the low-temperature regions of pertinent simple systems under similar reducing conditions. Carbonal compounds and oxalates, quite rare in terrestrial occurrences, may be much more common on Mars. The properties and stabilities of those containing the major rock-forming cations should be investigated. Similar stability studies are needed for conditions on other planets, especially Venus and Mercury.

The extent to which the atmosphere has influenced more deep-seated rock-forming processes depends largely on the history of the planet. If a mobile interior and high rates of erosion and sedimentation have allowed accumulations of weathered debris to sink to sufficient depth to be metamorphosed, or

partially or completely melted, the character of the weathering products will obviously affect the resulting metamorphic or igneous rocks. Even if this has not occurred, volcanic rocks interact directly with the atmosphere in the process of their formation, and the resulting mineral assemblages may show the effects of the volatile constituents, especially those affecting the oxidation states of the magma. Again, both direct simulation and carefully controlled studies of selected key systems are desirable. Fortunately, the effect of fugacity on the crystallization of basaltic melts is of great terrestrial importance, and studies recently completed or currently underway may suffice, but their status should be evaluated from a planetologic point of view and supplementary work supported as needed.

SUMMARY

1. Geochemical work should begin with determining mineralogical and petrological relations so that the processes by which major rock units formed can be inferred and the relative proportions of different rock types deduced.
2. Mineral assemblage is as important as bulk chemical composition for the mineralogy reflects both chemical composition and conditions of formation and is far more diagnostic of rock type and formative processes than composition alone.
3. Difficult measurements such as isotopic and trace-element composition cannot be deferred with the expectation of early sample return to Earth but must be performed remotely. The necessary hardware should be developed.
4. Since no single analytical technique can make all the necessary chemical and mineralogical determinations, emphasis should be placed on exploring the commonality of different systems so that an integrated chemical package can be assembled.
5. Orbital chemical measurements such as multiband photometry and infrared spectroscopy, although imprecise and subject to a variety of interpretations, are essential for interpolation between ground

stations and for choosing the best places for ground measurements. Detailed chemical mapping from an orbiter should follow acquisition of surface imagery.

6. Concurrently with instrument development, theoretical studies on stability relations under planetary conditions should continue both to aid in instrument design and to ensure correct interpretation of the resulting data.

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