X-644-73-342
PREPRINT

NASA TM X-70539

EVOLUTION OF THE EARTH'S CRUST: EVIDENCE FROM COMPARATIVE PLANETOLOGY*

PAUL D. LOWMAN, JR.

*Review version; submitted to The Journal of Geology.

OCTOBER 1973

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

(NASA-TM-X-70539) EVOLUTION OF THE EARTH'S CRUST: EVIDENCE FROM COMPARATIVE PLANETOLOGY (NASA) 80 p HC $6.00 CSCL 08E
N74-13098
Unclas
G3/13 24657

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ABSTRACT

Geochemical data and orbital photography from Apollo, Mariner, and Venera missions have been combined with terrestrial geologic evidence to study the problem of why the earth has two contrasting types of crust (oceanic and continental). The problem is frequently considered that of the origin of continents, but is actually inseparable from the origin of ocean basins and from the general question of how the terrestrial planets have evolved geologically. The approach presented here has been to compare the crustal evolution of the moon, Mars, Venus, and earth in that order, which is one of increasing mass, internal activity, and degree of geologic evolution.

Analyses of returned lunar samples, orbital photography, and remote sensing data (especially X-ray fluorescence) indicate that the moon developed a global igneous crust of feldspathic gabbro and its differentiation products early in lunar history. This crust is now partly overlain by mare basalts, partly localized by major impacts that formed the mare basins. The moon's geologic evolution was essentially completed by about three billion years ago, except for external events such as cometary or meteoritic impacts and mass wasting.

Infrared spectra and orbital photography from Mariner spacecraft suggest that Mars also developed, early in its history, a global igneous crust of basic or intermediate composition, possibly basaltic, part of which still survives as the cratered highlands. Later igneous events produced lava flows, now comprising the smooth plains of the northern hemisphere, and the shield volcanoes and associated flows of the Tharsis region. The latter class of feature is geologically young, indicating that the geologic evolution of Mars is continuing. Mars has also developed a large series of tension-produced depressions, of which the Coprates canyon is the most prominent; these features appear analogous to terrestrial rift valleys, and probably represent incipient crustal fragmentation.

Gamma-ray spectra transmitted from the surface of Venus by Venera 8 indicate potassium, uranium, and thorium contents similar to those of granite, implying extensive differentiation of Venus if the landing site is representative of the

surface in general. High-resolution earth-based radar imagery of the surface reveals cratered terrain similar to the highlands of the moon and Mars. Such terrain is probably primitive, implying that planetary differentiation was a very early event.

Terrestrial geologic evidence on the origin of continents and ocean basins includes, in part, the relative youth of oceanic crust, the wide extent of Precambrian basement in several continents, the ensialic nature of Precambrian eugeosynclines, and the demonstration that large areas of continental crust have subsided to oceanic depths in areas such as the Mediterranean Sea. This evidence argues against lateral continental growth by accretion of geosynclines, orogenic belts, or subduction zones.

The following outline of terrestrial crustal evolution is therefore proposed. A global crust of intermediate to acidic composition, high in aluminum, was formed by igneous processes early in the earth's history; portions survive in some shield areas as granitic and anorthositic gneisses. This crust was fractured by major impacts and tectonic processes, followed by basaltic eruptions analogous to the lunar maria and the smooth plains of the north hemisphere of Mars. Seafloor spreading and subduction ensued, during which portions of the early continental crust and sediments derived therefrom were thrust under the remaining continental crust. The process is exemplified today in regions such as the Andes/ Peru-Chile trench system. Underplating may have been roughly concentric, and the higher radioactive element content of the underplated sialic material could thus eventually cause concentric zones of regional metamorphism and magmatism. Radiometric ages in these zones, of which the Grenville province is typical, were reset, leading to age distributions previously interpreted as evidence of lateral continental growth. The net result of these various processes has been a decrease in area of continental crust, but an increase in its thickness and a lithophile element content. Lateral continental growth, though probably demonstrable in examples like the ensimatic Franciscan assemblage of California, has been dominated globally over geologic time by oceanization.

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INTRODUCTION

The exploration of space has also been the exploration of the earth. Interplanetary flight in particular has at last made it possible for us to approach the great problems of geology by comparing the earth in detail with other planets. This paper is an attempt to apply new knowledge of the moon, Mars, and Venus to the problem of the origin of continents.

The very phrase "origin of continents" tends to shape one's approach to a more fundamental question: Why does the earth have two contrasting types of crust, oceanic and continental? Most previous work in this field has been oriented toward the concept that continents have grown laterally at the expense of ocean basins. I shall propose here instead that the dominant process of terrestrial crustal evolution has been growth of the ocean basins, or "oceanization." The general concept is of course not new, dating back at least into the 19th century. But there has been no attempt to apply new discoveries in comparative planetology and plate tectonics to it or to the broader problem of crustal evolution in general. This paper is such an attempt, in which I shall compare the geologic evolution of the moon, Mars, Venus, and the earth, a sequence of increasing mass (Table 1), internal energy, and apparently degree of geologic evolution. This approach also permits an evaluation of the importance of atmospheric/hydrospheric processes in the origin of continents: on the moon, such processes are non-existent; on Mars, significant but not dominant; and on the earth, superficially dominant. The nature of surficial processes on Venus is essentially unknown.

This paper, like most scientific papers, is a progress report rather than a finished product. Although based on some ten years of work in lunar and terrestrial geology, it has taken definite form only in the last two years and will doubtless require revision as new knowledge becomes available.

The theory of crustal evolution presented here was first published as an appendix to "The Third Planet" (Lowman, 1972a), a collection of orbital photographs intended to give an overview of terrestrial geology. Many of the structures and areas to be discussed in the present paper are illustrated in this book or in similar ones by Nicks (1970) and Cortwright (1966).

Table 1

Characteristics of the Terrestrial Planets and the Moon

	Equatorial Diameter (km)	Mass Relative to Earth	Density (gm/cm^3)	Gravitational Acceleration at Surface Relative to Earth
Moon	3476	0.01	3.3	0.16
Mercury	4680	0.05	5.7	0.40
Mars	6796	0.11	3.9	0.38
Venus	12,320	0.90	5.0	0.87
Earth	12,756	1.00	5.5	1.00

Note: Figures for earth and Venus from "Planets," by E. Novotny and R. W. Fairbridge, in Encyclopedia of Atmospheric Sciences and Astrogeology, R. Fairbridge, editor, Reinhold Publishing Co., New York, 1967, 1200 p.

Diameter for Mars from Dollfuss (1972).

Figures for moon and Mercury from TRW Space Data, J. B. Kendrick, editor, TRW Systems Group, Redondo Beach, California, 1967, 127 p.

CRITICAL REVIEW OF PREVIOUS WORK

The scientific literature on the origin of continents extends back well over a century, and therefore can be summarized only briefly. This critical review is intended to throw light on the nature of the problem, rather than simply summarize the chronology of research. Previous studies can be grouped in three categories, the first two focussed on continental growth and the last on ocean basin growth:

I. External Derivation of Crust

   A. Meteoritic accretion
   B. Zoned accumulation

II. Internal Derivation of Crust

   A. Early, rapid growth
   B. Continual growth, essentially steady-state

III. Oceanization

I. External Derivation of Crust

Theories of this class hold the material of the primordial continental crust to be fundamentally extraterrestrial. The simplest concept of extraterrestrial derivation, as summarized (but not advocated) by Howell (1959), is that the early continents were the remnants of extremely large bodies that fell onto the earth. This theory has been advanced by Alfven (1963), Safronov (1972), Van Bemmelen (1971), and Donn, et al (1965); the latter stressed that the present continents are the result of much mixing and modification of the original meteoritic material, followed by marginal accretion. There are a number of fundamental objections to this mechanism, discussed at length by Howell, which need not be recounted here. Furthermore, evidence from lunar exploration provides new arguments against it. The most important of these is that the circular mare basins, such as the Imbrium basin, probably represent large impact craters that localized later vulcanism, so that we now have some first-hand knowledge of the results of major impacts. It has not yet been possible (Anderson, et al, 1972) to positively identify material in Imbrian ejecta (the Fra Mauro formation sampled by the Apollo 14 astronauts) that might be the remnants of the hypothetical impacting body, although this might be accounted for by similar compositions for it and the moon (Morgan, et al, 1972). There is, in any event, no evidence for the former existence of large acidic circumterrestrial bodies; and the result of a major impact is a large crater, not a discrete addition to the target body. This theory for the origin of continental nuclei can probably be safely discarded.

A variation of the impact theory proposed by Urey (1953) and in detail by Salisbury and Ronca (1966) should be mentioned here. These authors suggested that major impacts might have produced large craters which, after filling by volcanics and sediments, and uplift, would form the nuclei of continents. The mechanism proposed for uplift and subsidence involves the gabbro-eclogite phase change theory of the Mohorovicic discontinuity, which has been the subject of continuing controversy since development in its modern form by Kennedy (1959); Wyllie (1971) presents a comprehensive review of the problem. The Salisbury-Ronca theory is hard to evaluate, partly because of its dependence on the phase change mechanism. However, it is clear that nothing like continental nuclei were formed on the moon or Mars by this mechanism, assuming the large craters and mare basins to be impact-formed.

Another school of thought holds the continents to be formed by what Turekian and Clark (1969) have labeled "zoned accumulation." This theory, based partly on Larimer's (1967) compilation of the condensation sequence to be expected in the primitive solar nebula, is that the alkali silicates would be accumulated by the earth after the iron and nickel (forming the core) and iron and magnesium silicates (forming the mantle). To quote Turekian and Clark: "... high density turns out to be associated with low volatility, enabling planets to accrete in a way that is automatically stable gravitationally." This theory is classed as external derivation somewhat arbitrarily, since the whole earth is "external" in a broad sense. However, it is fundamentally different from the "internal derivation" theories to be discussed in that the earth's core, mantle, and crust are considered the result of initial stratification, rather than differentiation of an originally homogeneous body.

This theory is primarily chemical rather than geological, and can not be fully evaluated in this paper. However, Boettcher (1971) has pointed out that uranium, thorium, and the rare earths are relatively non-volatile, but are concentrated in the earth's crust. Philpotts, et al (1972) and Taylor (1973) have applied similar reasoning to the lunar highland crust, concluding that its chemistry is typically magmatic. There seems to be no strong need to postulate zoned accumulation for either the terrestrial or lunar crusts, although Gast (1972) has given arguments for a more diffuse accretionary zoning in the moon.

II. Internal Derivation of Crust

The great majority of theories focussed on continental growth involve derivation of the sialic crust from the mantle, differing primarily on the time and rate of this process, and on whether it was primarily by igneous or sedimentary mechanisms. This critical review will treat them on the basis of the time at which the continents are thought to have been formed, following the treatments of

Taylor (1967) and Engel (1963). To save needless repetition of qualifying adjectives and adverbs, it should be stated here that some parts of "continents" are obviously young (neglecting crustal re-cycling); examples include features like the wedge of sediments in the Mississippi embayment, chains of active volcanoes such as the Cascades, and lava plateaus such as the Columbia River basalts. The term "continents" as used in this paper refers chiefly to the older rocks which underly most of their area, chiefly the Precambrian basement but including Paleozoic and Mesozoic rocks of major physiographic provinces.

This review will omit most of the older theories, proposed by Dana, Green, and others, based largely on contraction, although they are of historic interest.

The theory that the earth's continental crust was formed rapidly at a very early period by igneous processes has been advocated by authorities such as Daly (1933). The general process favored by many petrologists (e.g., Buddington, 1943) is large-scale magmatic differentiation, analogous to that evident in large layered intrusives (Hamilton, 1960) like the Palisades sill, which produced a granitic layer from a largely or entirely molten earth. A specific theory for the early formation of granitic continental nuclei, proposed by Joly (1925), Hills (1947) and Vening Meinesz (1948) among others, involves convection in the primitive earth. The continental nuclei were formed by accumulation of sialic material at convergence sites where the convection currents turned down. According to Hills, this would have occurred at the poles, producing two proto-continents, Laurasia and Gondwanaland.

This theory, in which the continents are considered to form as patches of granitic scum on basaltic magma, can be refuted decisively on petrologic grounds. First, granite is the last product of the differentiation of basaltic magma (except for minor features such as hydrothermal vein deposits), not the first. Second, and more important, is the fact stressed by Bowen (1928, p. 197ff and p. 309) that solid granite is dissolved by reaction with basaltic magma. Because of these critical weaknesses, this theory will not be considered further.

The other concept of primitive late stage sial as the igneous differentiate of basaltic magma is on firmer ground petrologically. One problem pointed out by Bowen (1928, p. 319) is that the present thickness of continental crust, about 25 kilometers (Bowen's figure), would require a basaltic layer about 200 kilometers deep for its production, since the granitic differentiates would form a minor proportion of the original volume. This difficulty may be avoided if the primitive sialic crust was much thinner than 25 kilometers. Details of just how, where, and when the supposed differentiation took place are naturally obscure. However, substantial if subordinate quantities of granitic or syenitic magma have been produced by essentially igneous processes in many large intrusions and volcanic fields; the case of Iceland is especially relevant. The igneous differentiation mechanism for the origin of primitive sial has something to recommend it in general, even if the concepts advocated by Joly and Hills are both over-simplified and petrologically incorrect.

The most widely-favored theory for the origin of continents is "continental accretion," the term used by Engel (1963) in a comprehensive review of the subject. This concept, also termed marginal, peripheral, or lateral accretion, has a long history, and several workers have found it quite compatible with sea-floor spreading (Dietz, 1972). Therefore, it must be evaluated in some detail.

The theory of continental accretion was first conceived as long ago as 1856 by J. D. Dana, who considered North America to have grown outward from the Canadian shield toward the Atlantic and Pacific Oceans: "Thus the enlargement went on to the southward, each period making some addition to the main land, as each year gives a layer of wood to the tree." The motive force he suggested was contraction of the earth. Although contraction has fallen into disfavor in recent years, this general concept has been brought forth by many geologists since Dana, including Lawson (1932), Kay (1951), Wilson (1959), (King, 1959), (Hess, 1962), Engel (1963), Badgley (1965), Taylor (1967), and Dietz (1963, 1972). In modern terms, the theory is that continents have grown laterally by accretion of orogenic belts formed from island arcs and eugeosynclines. The immediate motive force is, in Lawson's words, "underthrust due to landward creep of sima," or sea-floor spreading and subduction in the "new" global tectonics.

Evidence for the continental accretion theory has been well-summarized by Engel (1963) with reference to North America: (1) similarity between old rock complexes (greenstone belts — ancient eugeosynclines (PDL)) in the heart of the continent and modern island arc complexes; (2) increasingly continental nature of rocks in successively formed geologic provinces; (3) concentric patterns of radiometric ages (Tilton, et al, 1962) indicating orogenies and granite-forming events (Figure 1). Related but independent evidence from strontium isotope studies has been presented by Hurley, et al (1962), who find that sial has apparently been added, as igneous intrusions and related rocks, to the crust from the mantle at an essentially constant rate through geologic time. These studies are an extremely important part of the support for secular continental growth, and will be discussed at more length later. A convincing example of continental accretion may be the Franciscan assemblage of California, a eugeosynclinal suite of great thickness apparently deposited on oceanic crust (Bailey, et al, 1964). The arguments for continental accretion will not be further elaborated here; instead, weaknesses in the theory will be discussed in order to demonstrate the need for a new attack on the problem.

The main direct terrestrial evidence against continental accretion can be summarized as follows.

1. Extent of Precambrian Continents—A massive compilation of radiometric basement dates by Muehlberger and his colleagues (Goldich, et al, 1966; Muehlberger, et al, 1967) put well-defined limits on the extent of lateral growth of North America by showing that more than half of the present continent's area was in existence 2.5 billion years ago and considerably more by 1 billion years ago. Goldich, Muehlberger, Lidiak, and Hedge (1966) concluded that North America was "very nearly" its present size 1.7 billion years ago. This group suggested that the concentric radiometric age pattern generally interpreted as lateral accretion could mean instead crustal stabilization by thermal and igneous events. Wassenberg (1966) has arrived at a similar interpretation.

2. Ensialic Nature of Eugeosynclines—A key element of the continental accretion theory is the belief, clearly stated by Dietz (1972), that eugeosynclines (Dietz's "eugeoclines") are deposited on oceanic rather than continental crust, i.e., that they are ensimatic rather than ensialic. Although this can be fairly well-demonstrated for the Franciscan assemblage (Bailey, et al, 1964), there is a growing body of evidence that eugeosynclines are in general ensialic, including the work of the following authors:

(a) Anhaeusser, et al (1969), presented detailed field evidence from Southern Africa and cited published work from other shield areas showing that Precambrian "greenstone belts" (equivalent to eugeosynclines — PDL) have been formed on pre-existing granitic crust, admittedly thinner and less stable than the present crust. They stated forcefully that "The concept of geosynclines ... cannot be applied to the early Precambrian shields." and further that "The granites are not the result of, nor do they in any way appear to be associated with, the type of orogeny and consequent granite formation of a geosyncline in the classical sense." Reports given at a 1971 Penrose Conference (Barker, 1971) indicate that other workers share this view for the Canadian, Fennoscandian, and African shields.

(b) The ensialic, or intracratonic, nature of eugeosynclines advocated by Anhaeusser and his colleagues for Africa was strongly supported for the Canadian Shield in a collection of papers edited by Baer (1970). Papers were presented covering eight Precambrian geosynclines, orogenic belts, or related features. Most of these geosynclines, despite their age, could be interpreted in terms of Phanerozoic principles as proposed by Kay (1951). The various authors uniformly considered all of them, including those of undoubted eugeosynclinal nature, to have been deposited on continental crust, although this crust may have been thinner and less stable than the present one. The exceptionally detailed work of E. Dimroth and his colleagues in the Labrador trough deserves particular mention. This feature, also called the Circum-Ungava geosyncline, is early Proterozoic, or between 1.6 and 2.5 billion years old, but is well-preserved and exposed. It is clearly a classic mio-eugeosyncline couple, essentially identical to the northern Appalachians as described by Kay (1951). Field relations show it to have been formed on continental crust, and to have been flanked on east and west by sialic land-massed that supplied arkosic sediments in the initial sedimentation. The Labrador trough appears to be the best demonstration available that eugeosynclines can form on continental crust.

(c) C. A. Hopson (1964) published an extremely detailed report on crystalline rocks of the Maryland piedmont. Although a local study, Hopson's work has major implications for the continental accretion theory because this area must be in the long-sought eugeosynclinal portion of the former central Appalachian geosyncline (itself the classic geosyncline); King (1959) and Dietz (1972) specifically interpreted this area, the "crystalline Appalachians," as the former eugeosyncline, or "eugeocline" in Dietz's terminology. However, the facies relations of the Glenarm metsedimentary rocks (late Precambrian or early Paleozoic) worked out by Hopson show decisively that the Glenarm Series, the supposed eugeosynclinal part of the Paleozoic Appalachian geosyncline, must have deposited on sialic crust, since the Piedmont area he studied is underlain by the older Glenarm Series and related metasediments, which in turn rest on the 1.1 billion years old (Figures 2, 3) Baltimore gneiss. The pre-metamorphic nature of the Baltimore gneiss is not definitely known (Hopson considered it metamorphosed intermediate to acidic volcanics), but the gneiss is clearly not oceanic crust (cf. Dietz, 1963).

(d) The thickness of continental crust under former eugeosynclines (chiefly Precambrian) seems too great for them to represent a simple lateral accretion to the continent (Tilton et al, 1962). An example is found in the Colorado Front Range, in which O'Connor (1963), Garawecki (1963), and others have interpreted Precambrian metasediments about 1.7 billion years old as former eugeosynclinal assemblages. However, the crustal thickness in this area is on the order of 40 kilometers (e.g., Quershy, 1960). Even if the lower 10 kilometers of this is gabbroic (i.e., possibly former oceanic crust) and the entire thickness of former eugeosynclinal sediments is preserved without deformation, some 30 kilometers of sediment must have been deposited in one geosynclinal cycle. This is far greater than any verified stratigraphic thickness (the

Franciscan assemblage is estimated by Bailey, et al, as over 50,000 feet thick, with considerable uncertainty).

(e) Although a detailed summary of field evidence for orogenic belts on several continents would obviously be beyond the scope of this paper, it should be noted that several authorities with wide experience consider most if not all geosynclines to have formed on continental basement. Rutten (1969), for example, states that Precambrian continental crust can be found under all European orogenic belts (former geosynclines), and for that reason specifically rejected accretion of continental crust. Clifford (1968, 1970) came to the same conclusion for Africa, although he suggested "progressive cratonization." Wood (1970) similarly stated that, although evidence for four major orogenic events up to the early Phanerozoic could be found, that "no marginal accretion of crustal material has occurred in the past three billion years." Wood also stated that Archaean Africa was at least as large as present-day Africa, a conclusion similar to that reached by Muehlberger and his colleagues for the extent of Precambrian North America.

3. Relative Amount of Granitic Rock in Continental Crust—In the continental accretion theory as presently conceived by most geologists, the granitic part of continental crust was developed by anatexis of the accreted eugeosyncline (e.g., Badgley, 1965). Under this theory of magma generation, the granite should comprise a relatively small proportion of the rocks eventually exposed, corresponding to the low-temperature trough of the albite-orthoclase-quartz-water system studied by Tuttle and Bowen (1958). However, geologic maps of most Precambrian areas demonstrate, and orbital photography (Figure 4) suggests, that in fact granite or granodiorite predominates in volume. (Much of this granite may be in mantled gneiss domes (Eskola, 1949) rather than true igneous intrusions, but if so it only reinforces the argument that the orogenic belts were formed on pre-existing granite crust.) Gilluly (1955) has reached similar conclusions about the United States part of the Cordillera. See also Turner and Verhoogen (1960, p. 383).

4. Relative Ages of Continental and Oceanic Crust—It seems so well-demonstrated that the oceanic crust is far younger than continental crust that one may overlook the fact that continental accretion as formulated in the 1950's implied that the oceanic crust was older (Wilson, 1954), and was being gradually encroached upon by the growing continents. Although the concept of continental accretion involving sea-floor spreading and subduction (e.g., Hess, 1962) suggests a possible reconciliation of the youth of oceanic crust with continental growth, it should be remembered that the gross age relations, taken by themselves, do not suggest continental growth.

5. Direct and Indirect Evidence for Very Old Granitic Crust—There is a growing body of evidence (to be discussed later) indicating that considerable areas of continental (granitic) crust were formed before 3 billion years ago. Direct evidence includes the numerous radiometric dates greater than 3.0 billion years published since 1955, when Ahrens reported the oldest exposed rocks to be probably 2.7 billion years, culminating in the recent announcement of 3.8 billion years old rocks from Greenland (Oxford Isotope Laboratory, 1971). These very old rocks of course are but a minor part of the area of continental crust, as demonstrated by the compilation of Hurley and Rand (1969). Nevertheless, they prove that at least some of the continental crust formed in the first billion years of the earth's existence.

The question of why more of this early crust has not been found can be answered in several ways. Orogeny, erosion, and sedimentation all would tend to destroy or at least render it unidentifiable; the radiometric effects of regional metamorphism have been stressed by Wasserburg (1966). However, another reason, so obvious as to be easily overlooked, is that as shown by Tuttle and Bowen (1958) and Winkler, et al (1958), granites are not only the residua system but also the first-formed liquid in anatexis. A primitive granite crust, therefore, would either melt completely, or at least tend to flow plastically, during the first regional thermal event to affect a segment of crust.

III. Oceanization

By "oceanization" is meant the overall growth of ocean basins at the expense of the continents. Since it is the thesis of this paper that oceanization is in fact the dominant process by which the earth's crust has evolved, the evidence for it will be presented in some detail in a later section. Accordingly, this review, unlike those of internal and external derivation of continents, will stress the historical development of the concept, to avoid unnecessary repetition.

The theory of oceanization in something like its modern form was first proposed by Eduard Suess, in "Das Antlitz der Erde" (1885-1909) which begins "If we imagine an observer to approach our planet from outer space, . . ." (Sollas translation, The Face of the Earth, 1904). Suess considered the outer part of the earth to be in contraction, producing tangential folding and vertical subsidence. Structures produced by vertical subsidence ranged from fault troughs such as the African rift system to the ocean basins themselves: "It is to subsidence and collapse that the Mediterranean seas (sic) and the largest oceans owe their origin and enlargement." (Sollas translation, v. 1, p. 604).

The evidence cited by Suess is far too voluminous to be cited here. Perhaps the major weakness in Suess's theory is that it was necessarily based upon the supposed contraction of the earth, being conceived before the discovery of radioactivity raised the possibility that the earth may be heating up and thus expanding.

The "undation" theory proposed by Van Bemmelen (1972), intended primarily as an explanation of mountain building, involves crustal foundering. As applied by Van Bemmelen to the evolution of the Indonesian mountain systems, the undation theory calls for breakup and partial subsidence of the Indonesian "Primeval Continent," probably in the Silurian, followed by geosynclinal sedimentation which localizes the generation and rise of "asthenoliths," in mantle-derived bodies of acid magma that form batholiths. This sequence of events happened in arcs successively from the South China Sea southwest to the Sumatra-Java arc, from the late Paleozoic to the present. (This "lateral migration of the waves of orogenesis" suggested the name "undation.") Locally, the net result of this process has been the thickening and consolidation of the crust, even though it began with partial foundering of a primitive sialic crust, so that the undation process can also be considered a process of internal derivation and growth of continental crust.

The most specific modern theory of oceanization has been that of Beloussov (Beloussov and Rudich, 1961), who terms the process "basification." Beloussov and Rudich, although recognizing continuing crustal growth by differentiation, deduced that the ocean basins have in general grown laterally at the expense of the continents. Their main lines of evidence included the following:

1. Relative youth of the ocean basins (noted by Beloussov in 1951)
2. Source areas for terrigenous sediments that are now deep ocean
3. Land connections indicated by Gondwanaian floral distribution
4. Granite-bearing Paleozoic glacial tills in India apparently derived from now-oceanic areas
5. Evidence from oceanic geology indicating deepening of the ocean basins and subsidence of seamounts.

In the 1961 paper, Beloussov and Rudich presented a detailed outline of the geologic history of the Sea of Japan, with detailed evidence that the area now at oceanic depths was land until the Miocene period, when it began to subside. The mechanism primarily responsible, they propose, was the rise of superheated basaltic magma from the mantle and basic metasomatism.

Beloussov's theory differs sharply from present western tectonic thought in denying the existence of large horizontal crustal movements, mantle convection, and sea floor spreading. This of course does not necessarily invalidate his theory, but it suggests that an effort should be made to reconcile new evidence for these phenomena with it. Petrologic aspects of Beloussov's oceanization process seem questionable, in particular the need for superheated basaltic magma and its role in generating andesitic magmas, and the importance of basic metasomatism. Bowen (1928, p. 182ff.) showed that basaltic magmas have little superheat (except for the surface effects of exothermic chemical reactions). Beloussov's explanation for the origin of andesitic magmas seems over-general and, in the light of recent work (summarized by Wyllie, 1971, p. 168ff.), unnecessary. Basic metasomatism is quantitatively unimportant as a petrologic process, except as a local contact effect or a "basic front" complementary to metasomatic granitization (Turner and Verhoogen, 1960, p. 572ff.).

STATUS OF THE PROBLEM

Of the three main schools of thought on the origin of continents and ocean basins, that involving external derivation of the sialic crust appears to be the weakest. Apart from the specific problems summarized here, there is no absolute need to invoke an exterrestrial origin for sial since there are several terrestrial processes which are known to produce at least some such material. Iceland, for example, demonstrates that purely igneous processes can produce acidic magmas, even if they appear quantitatively inadequate to account for all the continental crust. The andesites of island arc/trench systems similarly demonstrate that processes probably involving remelting of underthrust sediments and oceanic crust can produce great volumes of intermediate rock corresponding rather closely to the composition of average continental crust (Taylor, 1967).

Theories of internal derivation of sial are clearly preferable. However, the most-favored such theory — continental accretion — appears to have been critically weakened by field mapping and radiometric studies of Precambrian rock carried out in the last decade. Attempts to fit continental accretion into what is now called the new global tectonics, exemplified by the work of Hess (1962) and Dietz (1972 and earlier), actually bring nothing new to the problem; the concept of continental growth proposed by Lawson in 1932 ("underthrust due to landward creep of sima") is essentially similar.

Theories of oceanization seem consistent with a wide range of evidence, despite the geophysical difficulties of converting continental to oceanic crust. However, with the exception of recent work by Van Bemmelen (1972), there has been no attempt to such review theories in the light of plate tectonics. Since youth and mobility of the oceanic crust are key elements of plate tectonics, this is obviously desirable.

CRUSTAL EVOLUTION OF THE MOON

Although much remains to be learned about the moon, the main features of its geologic history now appear fairly clear, and are summarized in Table 2. Since even the first samples returned proved older than almost any terrestrial rocks, it is obvious that the crustal evolution of the moon has important implications for the origin of terrestrial continents. A pre-Apollo discussion of these implications was presented by Lowman (1969); although the arguments of that paper have since been partly invalidated by more recent discoveries, especially the moon's general depletion in volatiles, the present paper is based on it.

The most important general conclusion about the moon's geologic development is that it formed a differentiated global crust, by igneous processes, very early in its history. Evidence for this conclusion follows.

Global Distribution of Early Crust

Most of the moon's early crust survives as the lunar highlands, or terrae. Although now partly buried on the earthward face by mare basalts, this crust was originally of global extent. This is shown, first, by the generally uniform highland crater population (Figure 5). Although some regional differences exist, there are clearly no patches of unusually old crust that might correspond to terrestrial continental nuclei, nor is there any suggestion of concentric zonation in crater populations except for mare basin ejecta blankets.

The X-ray fluorescence experiment flown in lunar orbit on Apollo 15 and 16 (Adler, et al, 1972a, 1972b) provides further evidence that the early lunar crust was global in extent, rather than forming nuclei. As shown in Figure 6, there is no obvious compositional zoning of highland crust except for, again, mare basin ejecta blankets. This is also demonstrated by the relatively uniform highland albedo (at least for the front side), which has proven to be directly correlated to aluminum (and hence plagioclase) content (Figure 7). The γ-ray spectroscopy experiment does show lateral concentrations of radioactive elements over the western maria (Metzger, et al, 1973). However, this appears to be related to formation of the Imbrium basin, perhaps by excavation or magmatic transport of KREEP. There is no marked lateral concentration of radioactivity on the far side, which is of course almost entirely highland crust.

Further evidence for the global distribution of highland crust, primarily of a structural nature, comes from the wide occurrence of multi-ring craters similar in form to the Orientale system. Such multi-ring craters are not abundant, but they do occur in all parts of the moon (Hartmann and Wood, 1971). The mechanism of their formation (assuming an impact origin) is not understood. Van Dorn (1968)

Table 2

Geologic Evolution of the Moon*

Stage	Events	Mechanism/Cause/Source
I (4.7-4.6 b.y. ago)	(a) Formation of moon	(a) Precipitation, fission, or capture; mechanism unknown.
	(b) Strong heating, to temperatures over 1000°C, of outer part of moon.	(b) Energy of accretion, fission, and tidal interaction of earth; short-lived isotopes possibly important.
II (4.6-3.7 b.y. before present)	(a) First differentiation, forming global crust of aluminum-rich gabbroic rocks and differentiates	(a) Partial melting, forming primary aluminum-rich basaltic magma; magmatic differentiation formed subordinate quantities of anorthosite and felsite. KREEP possibly formed by initial melting.
	(b) Heavy cratering	(b) Infall of bodies related to origin of moon, from vicinity of earth-moon system.
	(c) Shear faulting	(c) N-S compression caused by slowing of moon's rotation during recession from earth.
	(d) Mare basin formation	(d) Infall of large objects from vicinity of earth-moon system, possibly proto-moons.
	(e) Formation of Archimedian craters	(e) Infall of objects from vicinity of earth-moon system, after mare basin formation but before mare filling.
	(f) Formation of highland volcanics such as Cayley formation	(f) Generation and eruption of high-aluminum basaltic magmas. Volcanic origin of Cayley formation uncertain; interpreted as deposits related to mare basin formation by some.
III (3.7-3.2 b.y. before present)	Second differentiation of moon; mare filling.	Generation of basaltic magmas by partial melting of deep interior; maria formed by repeated eruptions, partly localized in circular mare basins.
IV (3.1 to present)	Post-mare events; concurrent impact cratering by asteroid-belt bodies and comets, minor mare and highland vulcanism, tension faulting, and mass-wasting.	

*Condensed and modified from Table 2 in Lowman (1972).

explained the origin of the Orientale system as resulting from transient gravity waves in a low-density surface layer 50 km thick that had been formed by impact brecciation. Seismic velocities (Latham, et al, 1973) are now known to be far too high below about 10 kilometers depth for the rubble to be such an impact breccia. Nevertheless, Van Dorn specifically predicted the discovery, by seismic methods, of a wide-spread 50 km discontinuity outside the maria, a prediction now essentially fulfilled by the detection of a crustal layer 60 kilometers thick (Latham, et al, 1973). When added to the work of Oberbeck and Quaide (1968) explaining formation of small multiring craters by mare stratification, it seems clear that such craters are in some systematic way related to the thickness of the lunar crust. Their widespread occurrence then suggests the global extent of this crust.

Igneous Origin of Early Crust

It has until recently been difficult to characterize the highland crust, not only because the early landing sites were on the maria, but also because the highlands are intensely brecciated, presumably by the innumerable impacts responsible for the many craters; very few unfractured rocks have so far been found in the highlands. However, the X-ray fluorescence data indicated as early as Apollo 15 that the dominant rock type indicated by Al/Si and Mg/Si ratios over both near and far-side highlands was a plagioclase-rich pyroxene-bearing rock, probably anorthositic gabbro or feldspathic basalt (Figure 8). This general description has since been proven essentially correct in the light of samples collected by Apollo 15, 16, and 17 crews and by Luna 20, but more detailed classifications are now possible. The Lunar Sample Analysis Planning Team (1973) recognized three broad compositional classes of highland rocks:

Anorthositic rocks — over 25% Al_2O_3

KREEP-poor norites and troctolites — 20-25% Al_2O_3

KREEP-rich norites — 15-20% Al_2O_3.

The petrology and inter-relationships of these rock types, which apparently grade into each other, are not understood. However, as the LSAPT pointed out, all are differentiates, produced by magmatic processes.

It was suggested by Gast (1972) that the moon is radially zoned, with the outer parts enriched in refractory elements, especially aluminum. This naturally leads to the question of whether the highland crust is the result of late-stage accretion of such elements rather than internal, igneous, processes. There is much to recommend Gast's proposal, as discussed by Brett (1972). However, Philpotts, et al (1972) and Taylor (1973) have demonstrated clearly that the chemistry of the lunar highland samples (Table 3) depends on characteristics such as ionic radius and valence rather than volatility. This shows that the highland crust itself is the result of igneous processes, although there may well have been a general enrichment in refractory elements as proposed for Gast for the outer 2-300 km of the moon from which the aluminum-rich highland magmas were derived.

The details of these igneous processes are poorly understood, to say the least. Fractional crystallization of plagioclase from aluminum-rich basaltic magma is almost certainly responsible for formation of the widespread anorthosites, as shown not only by long-established petrologic behavior (e.g., Dana, 1846) but also by the pervasive europium deficiency (Schuetzler and Philpotts, 1971; Nava and Philpotts, 1973) of lunar samples. The main question here is whether complete melting of the outer part of the moon was necessary, or if fractionation of magma bodies produced by repeated partial melting was sufficient. It should be stressed here that monomineralic anorthosites are a subordinate, though widespread, constituent of the lunar highlands, as shown first by the X-ray fluorescence experiment (Adler, et al, 1972a) and later by returned samples. The bulk highland composition (Table 3) corresponds to a basalt unusually high in aluminum, and it seems possible that a magma of this composition might be generated by partial melting from the initially aluminum-rich lunar mantle postulated by Gast. Clarification of this problem would be valuable in further refinement of models for the moon's thermal history; Toksoz and Solomon (1972, Figure 11) have shown that complete melting of the outer part of the moon meets many but not all constraints.

Another major petrologic problem related to the highland crust is the relation between KREEP-rich rocks and other highland rock types. This problem is intimately involved with the question of radiometric highland ages, and will therefore be discussed in the following section.

Age of the Highland Crust

The lunar highlands clearly predate the maria, as shown by their greater crater density, and are therefore older than 3.85 billion years (the greatest mare basalt radiometric age). However, radiometric dates of highland samples have proven hard to interpret. Model ages (based on BABI) of about 4.5 billion years are common for soils and rocks from both highlands and maria (Schonfeld and Meyer, 1972), but crystallization ages greater than about 4 billion years are scarce; no truly primordial material has yet been identified or dated.

Highland samples from Apollo 15 and 16 and Luna 20 show a remarkable tendency to cluster around 3.85 to 4.05 billion years before present (Tera, et al, 1973).

Table 3

Composition of the Lunar Crust vs. the Terrestrial Crust

	Maria				Terrae				Earth	
	Apollo 11[1]	Apollo 12[2]	Apollo 15[3]	Apollo 17[4]	Apollo 14[5]	Apollo 15[6]	Apollo 16[7]	Apollo 17[8]	Continental[9]	Oceanic[10]
SiO_2	40.2	45.6	46.4	38.8	47.9	45.9	45.1	45.2	60.2	48.7
TiO_2	11.4	3.0	2.2	12.1	1.7	1.2	0.6	1.0	0.7	1.4
Al_2O_3	9.9	9.8	8.6	9.1	17.6	16.0	26.7	21.7	15.2	16.5
Fe_2O_3	0.0	0.0	—	—	0.0	—	0.0	—	2.5	2.3
FeO	18.7	19.7	22.8	18.8	10.4	12.9	5.5	7.9	3.8	6.2
MnO	0.3	0.3	0.3	0.3	0.1	—	0.1	—	0.1	0.2
MgO	7.3	10.9	9.5	8.4	9.2	11.2	5.9	9.7	3.1	6.8
CaO	11.1	10.0	9.8	10.9	11.2	11.1	15.4	13.1	5.5	12.3
Na_2O	0.6	0.3	0.3	0.4	0.7	0.4	0.5	0.4	3.0	2.6
K_2O	0.2	0.1	0.1	0.1	0.6	0.2	0.1	0.2	2.9	0.4

Sources for compositional data, by column:

1. Lowman, 1972, Table 1 (references cited therein); average of 13 Type A or B basalts.
2. Cuttitta, et al (1971); average of 6 basalts.
3. Mason, et al (1972); average of 6 basalts.
4. Rhodes (1973); average sub-floor basalt.
5. Rose, et al (1973); average of 6 Fra Mauro soils.*
6. Apollo 15 Preliminary Science Report, NASA SP-289; average of comprehensive soil samples 15101 and 15301, from stations 2 and 7 on the Apennine Front.
7. Rose, et al (1973); average of 6 soils from several Apollo 16 stations.
8. Rhodes (1973); average composition of 3 massif-derived (highland) categories of sample: light mantle, KREEP-like breccia, and anorthositic gabbro.

9, 10. Ronov and Yaroshevsky (1969), Table 5; total continental and total oceanic compositions.

*For highland compositions, except Apollo 17, soil analyses are used instead of rock analyses, because the low variance of soil compositions indicates that they provide a reasonably good composite sample with respect to major elements.

This appears to be the result of either extremely wide distribution of Imbrium ejecta or, more probably, melting and recrystallization caused by the cataclysmic impacts generally considered responsible for the formation of the circular mare basins. (From stratigraphic evidence (Lowman, 1972, Table 2), these basins are inferred to have been excavated in a short discrete period after the formation of the highland crust.) Despite this pervasive reheating, primary crystallization ages much greater can be identified; Papanastassiou and Wasserburg (1972) have reported ages of 4.40 AE to 4.48 AE for Apollo 16 sample 65015. Model and formation ages of about 4.4 billion years have been derived, using a two stage evolution model, for KREEP by Schonfeld and Meyer (1972), implying that KREEP is the oldest class of lunar rocks; this would also meet thermal requirements for early upward segregation of radioactive elements (Toksoz and Solomon, 1973). However, Nava and Philpotts (1973), from chemical data, inferred KREEP to have been formed by local partial fusion of feldspathic highland cumulates, implying that the latter are the oldest. The origin and age of KREEP are obviously still not resolved.

Summary

It is now clear that despite its small mass, depletion in volatiles, and relatively low present internal energy, the moon underwent major differentiation to form a global igneous crust within about the first tenth of its existence. A few additional observations should be made because of their implications for the crustal evolution of the earth. First, the moon's crust is remarkably thick; as mentioned before, Toksoz, et al, (1972) report a 60 kilometer thickness on the near side, from seismic evidence. Second, the laser altimetry (Sjogren, et al, 1972) indicates that this crust is about twice as thick (LSAPT, 1973) on the far side, i.e., that the moon's center of mass is displaced about 2 kilometers toward the earth from its center of figure. Despite its pre-mare global distribution, therefore, the crust is now notably assymetric.

This assymetry of figure and crustal thickness is presumably related to the surprising concentration of mare basalts on the earthward side of the moon. Generation of these basaltic magmas represents a second differentiation period (Lowman, 1972, Table 2). It is therefore natural to wonder if eruption of the lunar maria may not be analogous to what Hess (1962) termed the "great catastrophe" — formation of the earth's supposed primordial single continent by toroidal convective overturn as conceived by Vening Meinesz. Such an analogy is not valid; it should be emphasized that the formation of the maria represented a process of "oceanization," to the extent that it was growth of mafic crust at the areal extent of less-mafic crust. It was not analogous to the supposed formation of the earth's primordial single continent, but instead, perhaps, to the creation of a primitive Pacific basin.

CRUSTAL EVOLUTION OF MARS

Crustal evolution on Mars can be treated along the same general lines as lunar crustal evolution. An outline of Martian geologic history will not be presented, however, until the evidence on which it is based has been covered. The main conclusion toward which the following discussion is oriented is that, like the moon, Mars formed a differentiated global crust, by igneous processes, early in its history. This early crust was later partly flooded by volcanics in a process analogous to eruption of the lunar maria, or to oceanization. The bases for this conclusion follow.

Evidence for Differentiation

Mars has generally been considered undifferentiated (e.g., Hanks and Anderson, 1969), an opinion initially reinforced by the Mariner IV pictures that revealed a surface resembling the lunar highlands, one which implied a primitive, inactive planet. It is therefore necessary to review recent evidence that geochemical differentiation has actually occurred. The first direct evidence (Figure 9) was produced by the infrared spectroscopy experiment (Hanel, et al, 1972a) flown on Mariner 9, which indicated immediately after the spacecraft entered Martian orbit that the suspended dust had a relatively high SiO_2 content, corresponding to that of an intermediate igneous rock. This was later estimated, from comparison of the IRIS spectra with laboratory spectra, at 60% ±10% (Hanel, et al, 1972b). For comparison, the average SiO_2 content (by weight) of chondrites is about 47% (Wood, 1968), of the earth's oceanic crust 49%, and of the continental crust 60%. It has since been found that the extremely small grain size of the Martian dust, on the order of a few micrometers, complicates interpretation of the infrared spectra (Conrath, et al, 1973), but it is believed that the initial conclusion is essentially correct.

Indirect but abundant evidence of differentiation appears on the Mariner 9 television pictures of the many volcanic landforms. These include the unmistakable calderas and lava flows of Nix Olympica (Figure 10) and the Tharsis region, and even more important, parts of the smooth plains unit (McCauley, et al, 1972; Carr, 1973). Field evidence from both earth and moon, combined with petrologic experience, shows that magma generation, chiefly by partial melting, is the primary internal mechanism of planetary differentiation; vulcanism means differentiation.

The martian gravity field, as determined from the orbital data of Mariner 9, is consistent with a differentiated crust, although not providing independent evidence of differentiation (Phillips, et al, 1973; Hartmann, 1973a). Taken together, the spectral, photographic, and geophysical evidence show convincingly that Mars is differentiated at least to the extent of having a chemically and physically distinct crust.

Global Extent of Differentiated Crust

Infrared spectroscopy data have been to date interpreted only for suspended dust, rather than the martian surface. Accordingly, the inference of global extent of the crust must rest on other evidence.

Turning first to the Mariner 9 television pictures, we see that landforms of probable volcanic origin are not confined to conspicuous features like the large shield volcanoes and their immediate surroundings. As mentioned previously, lobate scarps typical of lunar basaltic lava flows are visible in the smooth plains area surrounding Nix Olympica; McCauley and his colleagues suggested that "much of the smooth plains consist of superposed volcanic flows." This unit dominates the northern hemisphere outside the polar regions and itself implies geographically extensive differentiation. However, the plains are clearly younger than the cratered terrain and would not necessarily represent early differentiation. The most important features, for the purposes of this discussion, are the ridges resembling the lunar mare ridges occurring in the cratered terrain of Mars. First seen on Mariner 6 pictures (e.g., 6N20, B camera), in the cratered area south of Meridiani Sinus, these ridges have now been found in abundance in the Hesperia region (Figure 11), which is also cratered terrain. The martian features closely resemble two-sided mare ridges. The origin of the latter is not fully understood. However, they are invariably found in mare (i.e., volcanic) terrain (including highland maria such as the Schiller basin), and are probably formed over fissures that supplied the mare lavas; an illustrated discussion of this theory was presented by Lowman (1969, Figures 62 and 84). If they are in fact igneous features and analogous to the similar structures on Mars, the occurrence of the latter in the cratered highlands implies that the martian cratered highlands (the oldest crust) are also lava flows.

Further morphologic evidence for the global extent of a crust comes from the several multi-ringed basins found in the cratered highlands (Figures 12, 13). Wilhelms (1973) lists six: Hellas, Libya, Argyre, Edom, Iapygia, and "Schrodinger," ranging in diameter from 200 to 2000 kilometers, and proposed that there were analogous to the lunar ringed mare basins. As discussed previously, in relation to the moon's crust, it seems clear that the formation of such features depends on the existence of subsurface layering in the terrain hit by the assumed impacting body. The best interpretation of such layering in Mars seems to be volcanic flows or intrusives. If correct, this and the wide distribution of the multi-ringed basins support the idea that the cratered terrain of Mars represents a widespread igneous crust.

A final category of evidence for global differentiation in Mars comes from orbital data. As previously mentioned, these data have been interpreted by as consistent with the explanation that the cratered highlands are a differentiated crust. Masursky (1973) specifically compared them with the lunar highlands, and suggested that Martian highlands of the southern hemisphere were the "more siliceous 'continental' crustal rocks." Hartmann (1973a) arrived at the same conclusion from the bimodal distribution of elevations on Mars.

In summary, both major physiographic divisions on Mars have been found to display landforms indicating a volcanic nature, and the cratered highlands show both layered structure and geophysical properties indicating their differentiated nature.

Age of the Highland Crust

The absolute chronology of Mars is in the same stage as that of the moon before returned samples were available for radiometric dating. The greater crater density of the cratered highlands shows that they are relatively the oldest visible crustal division, but their absolute age must be estimated from assumed cratering rates. Hartmann (1973b) has made such an estimate, finding that the oldest terrain, such as Deucalionis Regio, is 3 to 4 billion years old. However, he stressed the uncertainty, by a factor of at least 3, of the assumed cratering rates. Despite Hartmann's reservations, there is little doubt that, from a broad viewpoint, the cratered terrain of Mars represents a very early if not primordial crust, corresponding to the early Precambrian crust of the earth.

Oceanization on Mars

The smooth terrain of the northern hemisphere is probably of volcanic origin, though now mantled with aeolian deposits; it is younger and lower, and thus probably denser, than the cratered terrain. Broadly speaking, this crustal division resembles the lunar composite mare, Oceanus Procellarum. If it is actually analogous, this implies that a major period of oceanization, as previously defined, was an important stage of Martian crustal evolution. A problem with this suggestion is that although the center of figure of Mars is offset about 1 kilometer (Schubert and Lingenfelter, 1973), the direction of offset is toward Tharsis, implying a thicker crust in what would seem to be an ocean basin. This discrepancy may be explained if the Tharsis volcanic region is similar to the East Pacific Rise, and represents a third period of differentiation. The beginning of crustal fracturing leading to further oceanization may be present in the Coprates canyon (Figure 14).

Summary

The geologic evolution of Mars is of course not as well known as that of the moon. Nevertheless, using the same principles, except for the radiometric dates, the major events can be summarized as follows:

Stage I	(4.7-4.6 billion years ago) — Formation and rapid heating;
Stage II	(4.6 to 3 billion years ago) — First differentiation to form highland crust; formation of multi-ringed basins (e.g., Argyre) and smaller craters;
Stage III	(3 billion to ? years ago) — Second differentiation to form smooth plains of northern hemisphere by eruption of basaltic(?) lavas;
Stage IV	(Stage III to present) — Tension faulting in equatorial region (Coprates Canyon); localized vulcanism over mantle plumes (Tharsis, etc.); superficial geologic processes including aeolian erosion and deposition, glaciation in polar regions and associated effects, intermittent fluvial erosion, undermining by ground water and/or ice.

The geologic evolution of Mars from internal causes is not over, as shown by the relative youth of the Tharsis volcanic region. However, the planet has obviously not undergone the extensive and active evolution of the earth, and much of its early crust survives. Mars appears to be geologically intermediate between the earth and the moon. The most important aspect of its geology is that despite its lower internal energy and volatile content, Mars has undergone an early period of widespread differentiation that formed an initially global crust. There is no evidence of continental nuclei or of a single nucleus analogous to "Pangea." Instead, there is strong evidence that the dominant martian tectonic process, on a global scale, has been crustal fragmentation and oceanization.

CRUSTAL EVOLUTION OF VENUS

Venus comes close to being the earth's twin in mass and density (Table 1), and its crustal evolution should in principle have implications for that of the earth. Recent discoveries from American and Soviet spacecraft, and from earth-based radar, now make it possible to explore those implications with a much firmer foundation of evidence than before. New evidence on the geologic evolution of Venus concerns its surface composition and topography. Since this evidence, impressive as it is, still represents but a small sample of the planet's surface, the following discussion of crustal evolution must be shorter and much more speculative than those for the moon and Mars.

Evidence for Differentiation

Mueller (1963) reasoned a priori that the igneous petrology of Venus should be grossly similar to that of the earth, and further suggested (1969) that because the high surface temperatures would raise mantle temperatures, partial melting and differentiation should be more thorough than in the earth. Thermal gradient calculations by Fricker and Reynolds (1968) imply a similar conclusion. The first definite evidence of differentiation, however, came from the Soviet spacecraft Venera 8, which landed on Venus in 1972. The spacecraft carried a gamma ray spectrometer that transmitted data for 42 minutes (Vinogradov, et al, 1973). The spectra were calibrated by 2π geometry laboratory simulations over granite, granodiorite, and andesite-basalt, and allowance made for atmospheric pressure (90 atm, at 470°C). The surface elemental composition was thus estimated in weight percent, with an estimated maximum error of 30% of the amount determined: potassium, 4.0%; uranium, $2.2 \times 10^{-4}\%$; thorium, $6.5 \times 10^{-4}\%$. This composition was considered closest to granite, and interpreted by Vinogradov and his colleagues as indicating endogenic differentiation, possibly supplemented by surficial weathering and partial melting.

As Vinogradov, et al, stressed, the Venera 8 measurements are for one point only, and it is obviously impossible to infer global differentiation. However, extensive differentiation had been previously predicted by the authors mentioned above; and it is statistically unlikely that Venera 8 happened to land on a rare rock type. Viewed in this context, the results are encouraging to the theory that Venus has an extensive granitic crust.

Age of the Crust

Although nothing of the surface of Venus has ever been seen from earth, Doppler radar observations made in 1972 with the 210 and 85 foot antennas of the Jet Propulsion Laboratory's Goldstone tracking station have revealed details (Figure 15) as small as a few kilometers across (Goldstein, et al, 1973) in a strip 1450 kilometers long on the equator. The topography thus seen is heavily cratered, resembling the lunar highlands. A dozen craters were found, ranging in diameter from 34 to 160 kilometers. Interestingly, the craters were all unusually shallow for their depth, with the 160 kilometer crater being less than half a kilometer deep. For comparison, the lunar highland crater Theophilus, with a diameter of about 100 kilometers, is over 4 kilometers deep at the lowest part of the floor (Kopal, 1962, Figure 18). This tends to confirm Mueller's prediction (1969) that, because of lower mantle viscosity resulting from higher temperatures, topographic relief would be less on Venus due to better isostatic adjustment.

Like the Venera 8 measurements, the radar observations so far are but a small sample of the surface of Venus, and inferences must be drawn very tentatively. However, it appears that Venus has a crater population typical of a very early stage of crustal evolution, representing perhaps the last stages of planetary accretion (Hartmann, 1972). The reason this crust has survived is probably that there are no oceans and fluvial processes operating to destroy or cover them with sediments, as has happened on the earth. It should not be denied, however, that the discovery of a heavily cratered terrain on a presumably active planet with a hot, dense, atmosphere was a surprise.

Summary

Despite the still-restricted extent of our knowledge about Venus, it appears quite possible that this planet too has undergone early and geographically extensive geochemical differentiation. Whether there has been crustal subsidence and oceanization analogous to that of the moon and Mars is unknown; there is no obvious evidence in the radar images of tension fracturing such as that probably responsible for the Coprates canyon. It is in fact not clear whether such features should be expected, since the high surface temperatures have apparently had effects on the mantle to considerable depths. Should such features be discovered, for example by an orbital radar, it would strengthen the parallelism among the moon, Mars, Venus, and the earth.

A final point should be brought out about the implications of the apparent differentiation of Venus. Many authorities consider the granites that make up the bulk of the earth's continental crust to be essentially superficial in origin, in being produced by anatexis of sedimentary rocks; Paige (1955) and Barth (1962) stated specifically that the earth's continents were ultimately sedimentary in origin. The lateral accretion theory for the origin of continents depends largely on sedimentation, aided by internally-driven processes such as sea-floor spreading and subduction. But if large amounts of granitic crust have formed on Venus, a point needing confirmation, it will demonstrate that granite, and continents, need not be tied to water-laid sediments, which could not form on Venus. More specifically, it will imply that the formation of continental crust on the earth could have been essentially by igneous processes, well before the beginning of sedimentation.

EVOLUTION OF THE EARTH'S CRUST: A WORKING HYPOTHESIS

There are of course great physical differences among the various silicate planets. But the early geologic evolution of the moon and Mars seems to have followed similar courses, and we see definite indications that Venus too has undergone somewhat the same kind of development, with deviations explainable by the high surface temperature. It is my belief that terrestrial geologic evidence can be interpreted to support an evolutionary path grossly similar to but much further advanced than that followed by the moon, Mars, and Venus. The following working hypothesis (actually a synthesis of several concepts) is therefore proposed for the crustal evolution of the earth.

Before discussing the evidence for this hypothesis, a few qualifications should be mentioned. First, the sub-events of each stage are listed in general order of occurrence, but this does not necessarily imply separation in time; it seems obvious that there must have been much overlap. Second, this outline is extremely general, and is focussed on internally-caused processes. Sedimentary processes, for example, began about 3.5 billion years ago, but are omitted from the sub-events, chiefly because sedimentation seems to be a result of subsidence, not its cause (Bucher, 1933, p. 61). Finally, it will be apparent that whatever value this outline (and in fact this paper) may have is the light it throws on the period between 4500 and 600 million years ago, i.e., Stages II and III. Stage I is largely the province of astrophysics and geophysics, and hence will be discussed only selectively. Stage IV, Phanerozoic time, is the subject of historical geology, and in detail is beyond the scope of this paper.

Stage I

The earth is now generally believed to have formed by accretion from the gas and dust of the primordial solar nebula, about 4.6 billion years ago. The proposal of Urey (1951), that the terrestrial planets were relatively cool when formed and only warmed up later, has in recent years been rejected by most workers, such as Ringwood (1966) and Hanks and Anderson (1969), except for the earlier stages of accretion. The latter paper is of particular interest in relation to the early crustal evolution of the earth. Hanks and Anderson based part of their calculations, on the early thermal history and accretion rate of the earth, on the belief that Mars was undifferentiated. Despite this assumption, they concluded that the earth had accreted rapidly (in less than 500,000 years) and largely at temperatures between 1200°K and 1450°K; Safronov (1972) has reached similar conclusions.

Independent evidence from returned lunar samples now indicates that such conditions also describe the origin of the moon rather well (Lowman, 1972), and we have seen that the moon is extensively differentiated. But the moon has only 1/81 the mass of the earth, and the temperature of accretion (from conversion of gravitational energy) is roughly proportional to the square of the final radius:

$$\Delta T = \frac{\rho \frac{4}{3} \pi r^2}{Cp},$$

Table 4

Crustal Evolution of the Earth

Stage	Event	Mechanism/Cause/Source
I (4.6 b.y. ago)	(a) Formation of earth	(a) Condensation and accretion from solar nebula, possibly leading to initial chemical stratification by zoned accumulation.
	(b) Rapid heating and initial reduction of silicates to metallic iron	(b) Heat sources include energy of accretion, solar radiation (incl. particulate), short-lived isotopes, adiabatic compression, possibly electromagnetic resistive heating.
	(c) Formation of moon	(c) Mechanism unknown; possibilities include precipitation, fission, and capture. Process may have raised temperature of earth still further.
II (4.5 to 3.5 b.y. before present)	(a) First differentiation, forming global crust, complementary to segregation of iron core; initial degassing to form atmosphere of CO_2, N_2, etc.	(a) Crust formed by repeated eruption and intrusion of intermediate composition magmas, high in Al. Core formation raised temperature of earth by several hundred degrees or more. Process probably overlapped by later stages of accretion, i.e., intense but declining infall of planetesimals.
	(b) Infall of several large protoplanetary bodies or fission fragments, disrupting global crust	(b) Bodies formed simultaneously near earth from solar nebula, or possibly by fission of earth to form moon.
	(c) Initial oceanization and beginning of second differentiation by generation of basaltic magma	(c) Large impact basins localized eruption of basaltic magmas, by deep fracturing, possibly addition of heat to earth, and relief of pressure under impact basins. Basaltic eruptions possibly assymetric, concentrated in Pacific hemisphere.
III (3.5 b.y. to 600 m.y. before present)	(a) Initial tectonic oceanization, by fragmentation and subsidence of crust along global fracture systems	(a) Tension faulting, caused by mantle processes similar to those operating at present to form rift valleys and mid-ocean ridge system.
	(b) Sea-floor spreading and subduction of oceanic and some continental crust, leading to decrease in area but increase in thickness of continental crust.	(b) Sea-floor spreading probably result of some form of mantle convection and diapiric intrusion along oceanic ridges. Decrease in area of continental crust due to direct or indirect erosion and underthrusting of sialic crust at continental margins.
IV (600 m.y. ago to present; Phanerozoic Era)	Continuation of processes of Stage III, but at a slower rate, perhaps decreasing. Some secular addition of material to continents. Net result is enlargement of ocean basins.	Secular addition of material to continents by partial melting of subducted oceanic crust, continental vulcanism, minor emplacement of mantle-derived acidic magmas, and subordinate local accretion of eugeosynclinal sediments and volcanics.

where

ΔT = maximum surface temperatures from gravitational accretion,

ρ = density

r = final radius of earth

Cp = heat capacity of material.

(Derived from Figure 1, p. 21, Hanks and Anderson.)

Mars, which has 1/10 the mass of the earth, is also now known to be extensively differentiated, although Hanks and Anderson show that the maximum surface temperature for Mars would be only about 14,000°K, contrasted with 48,000°K for the earth. The argument can now be applied to the earth. The evidence for differentiation in two much smaller bodies implies that they formed hot; clearly, the earth must have been formed much hotter, and extensive early differentiation in the earth becomes highly probable.

The formation of the moon is presumably important to any theory of the earth's early crustal evolution regardless of what mechanism is involved, because almost all theories involve considerable exchange of energy in the process. Furthermore, no other terrestrial planet has a satellite of comparable size, complicating comparisons among them. It is quite conceivable, for example, that capture of the moon, which would deposit considerable heat in the body of the primitive earth (Kaula, 1969), triggered the initial differentiation of the earth, as suggested by Cloud (1968). Furthermore, two convergent theories for the moon's origin, fission (Wise, 1963; O'Keefe, 1969) and precipitation (Ringwood, 1970) derive the moon from the earth. However, the origin of the moon is by itself still a problem of great difficulty, and a full discussion beyond the scope of this paper. I shall therefore simply note the complications mentioned above, with the comment that independent evidence from lunar samples at least permits estimation of the moon's age (4.6 billion years) even if it has not yet shown just how the moon formed. In addition, the apparent absence of lunar radiometric dates less than 3.1 billion years puts an upper limit on the time when the moon was very close to the earth.

Stage II

The major event of Stage II was the formation of a global crust, of intermediate composition (ca. 60% SiO_2), by generation and eruption of magmas corresponding to basalt (possibly high in Al_2O_3) and andesite, with minor quantities of differentiation products such as anorthosite and rhyolite. Formation of this original crust is listed first in the outline, but it probably took several hundred million years as did the moon's crust, involving repeated episodes of magma generation and vulcanism.

Evidence for formation of this global primitive crust is both indirect and direct. The chief indirect evidence is the existence of such crusts, formed by internal processes, on the moon, Mars, and possibly Venus. In view of the thermal considerations previously discussed, it seems likely that a body as massive as the earth would have reached high temperatures, sufficient for crust formation by igneous processes, from the energy of accretion alone. Furthermore, the earth has a large core, whose formation would have added to the already high temperature of the primitive earth. The importance of core formation has been discussed by Urey (1951), Birch (1965), and Hanks and Anderson (1969), and there is general agreement on the magnitude of its effects.

Direct evidence, which I shall define as evidence from the earth itself, comes from several sources. First among these are studies of lead isotopes, chiefly those by Patterson and Tatsumoto (1964). From the apparent fact that lead isotopes in accessible rocks evolved in a system whose U/Pb ratio has been essentially constant, they concluded that the earth differentiated into a core, mantle, and "protocrust" shortly after its formation. The "protocrust" was not the present continental crust, but a precursor more than 100 kilometers thick from which the present continents (or at least North America) developed between 3.5 and 2.5 billion years ago. A similar sequence of events has been derived from lead isotope studies more recently by Robertson (1973), who also distinguishes "protocrust" from true continental crust formed after 3.5 billion years ago.

The inference of very early differentiation, from lead isotopes, appears to be contradicted by the evolution of strontium isotopes. Hurley, et al (1962) showed that the ratio (radiogenic Sr87)/Rb87 is essentially inversely proportional to geologic age for rocks ranging from 3000 to 400 million years, from which they concluded that "there has been continuous generation of primary sial from subsialic source regions that has caused the continental areas to grow roughly in proportion to the extent of the geological age provinces." They further concluded that reworked crust older than 1-2 billion years could be only a minor proportion of typical newer basement, partly from the relatively low ^{87}Sr/^{86}Sr ratios, which are for many granites close to those of mantle-derived basalts.

A promising attempt to reconcile this conflict between the strontium and lead isotopic results, which is discussed in some detail by Faure and Powell (1972), has been made by Armstrong (1968), and termed by him the "steady-state model." At the risk of oversimplification, the model can be summarized as involving, first, early differentiation of the earth into core, mantle, and crust; next, mixing of the crust and upper mantle along subduction zones, with crustal material, supplied as continent-derived sediments, being returned to the continent by magma generation. The process was considered to decrease exponentially with geologic time, and the continents to maintain essentially constant volume. The strontium isotope data are explained by re-equilibration with mantle strontium during the subduction/magma generation process, which gives isotopic ratios that appear to indicate mantle derivation. As Faure and Powell (1972, p. 138) point out, the problem is partly one of semantics, in particular definition of "crust." Also, Hurley and Rand (1970) state that the apparent low mean age of the continental crust, less than 1000 million years, could be misleading if radiogenic Sr has been lost to the mantle as suggested by Armstrong.

In summary, it appears that Armstrong's model, which has since 1968 been quantitatively tested (Armstrong and Hein, 1973), supports the concept of very early formation of the continental or "protocontinental" crust. It should be mentioned here, before leaving the subject of evidence from strontium isotopes, that even if the steady-state model is discarded (see discussion by Hart, 1969), the recent compilation of strontium data by Faure and Powell (1972) shows that about 20% of granites from all over the world show $^{87}Sr/^{86}Sr$ ratios high enough (Figure 16) to indicate derivation from pre-existing sial (p. 44-48), and 50% show low ratios indicating (on the Hurley assumption) mantle derivation.

Returning to the general subject of evidence for an early sialic crust, several lines of evidence should be cited. First is the recently-demonstrated existence of crustal rocks (from West Greenland) nearly four billion years old (Oxford Isotope Geology Laboratory, 1971), a date since revised downward to 3.85 billion years (C. C. Schnetzler, personal communication). The importance of this discovery can hardly be exaggerated, since the period between the earth's origin (4.5 billion years ago) and the age of the oldest previously known rocks (3.5 billion years) appeared to have left no geologic record, and this gap played a central role in several discussions of early crustal evolution (e.g., Cloud, 1968). The West Greenland rocks, which are described as feldspathic gneisses of amphibolite facies, are "the first direct evidence for the existence of a granitic crust so early in the earth's history," to quote the Oxford authors.

Even before the discovery of the very old West Greenland rocks, considerable evidence had accumulated for a major granite-forming event or events about 3.5 billion years ago and perhaps earlier. Engel (1969) has presented a valuable discussion of the geology of the Barberton Mountain Land of South Africa, based in part on the work of the Economic Geology Research Unit whose publications have already been cited (Anhaeusser, et al, 1969). Rocks of the Barberton Mountain Land consist of a typical greenstone-granite association representing the oldest granite-forming episode, 3.2-3.4 billion years ago, known at the time of publication. Engel concluded, from field relations and the chemistry of the Onverwacht Series, that the differentiation history suggested by Patterson and Tatsumoto (1964), involving early crust formation, was more likely than one with much later crustal evolution. Engel's conclusion is of more than ordinary significance, since his earlier paper (1963) is generally considered a classic presentation of the continental accretion theory. (It should be noted, however, that he did suggest a possible "cataclysmic granite-forming event" before 3 billion years ago.)

A comprehensive collection of evidence for an early granite crust has already been cited, namely that by Donn, et al (1965). In addition to radiometric dates as great as 3.5 billion years, these authors compiled from the literature many reports, from several continents, of extremely old sedimentary or metasedimentary rocks with minerals or rock fragments indicating derivation from a preexisting sialic crust. They concluded that a substantial sialic crust was present in one of the "earliest recognizable stages of geologic history," around 4 billion years ago since considerable time must be allowed for development of the geosynclinal piles in which the sial-derived sediments occur. A similar conclusion was reached by Condie (1967), on the basis of his studies of Precambrian graywackes.

In summary, it seems now well-demonstrated that although truly primordial crust, 4.5 billion years old, has yet to be found (and, realistically, probably never will be), there was a major period of sialic crust formation well before 3.5 billion years ago, and that portions of this old crust underly several continents. Let us now turn to the question of what this crust was like.

The problem of describing the composition of the early sialic crust is extremely difficult for several obvious reasons. First among these is the fact that in most shield areas, the original composition has been altered by metamorphism/metasomatism accompanying the events that reset the radiometric dates. The main effect of these processes, on a regional scale, has probably been to increase the SiO_2 and alkali content — "granitization" in a very broad sense. A second problem is that, as shown by the absence until very recently of radiometric dates greater than 3.5 billion years, there are very few exposures of the earliest sial; most of it must be in the deeper parts of the crust if it survives at all, and we can infer its composition only by derivative magmas and perhaps by xenoliths.

In view of these problems, the early crust can be only generally characterized. It was probably intermediate in composition, i.e., about 60% SiO_2; this suggestion is based on the pervasive granitizing effects referred to above, implying a less granitic initial composition, and on the fact that the continental crust as a whole averages about 60% SiO_2 (Ronov and Yaroshevsky, 1969). It may be further speculated that the early crust was relatively high in Al_2O_3, i.e., higher than the 15% figure derived by Ronov and Yaroshevsky for average continental crust. In mineralogical terms, this implies a high plagioclase content. Support for this suggestion is found in the demonstration by Windley (1970) that high-calcium anorthosites more than 3 billion years old, found in Greenland, Africa, India, and elsewhere, are strikingly similar to those of the lunar highlands. It is interesting to note in this connection the proposal by Buddington (1943) and Anderson (1969) that the more sodic massif anorthosites (e.g., in the Adirondacks), which generally have ages between 1.2 and 1.7 billion years (Herz, 1969), were derived from a pre-existing plagioclase-rich layer in the deep crust.

The actual mode of formation of the proposed early sialic crust is still more obscure. A possible clue is Engel's (1969) observation that many of the old granites (actually gneisses) of the Barberton Mountain Land are anorogenic, and Eskola (1948) and others have noted the importance of mantled gneiss domes in Precambrian terrains. These rocks are not, therefore, epizonal magmatic rocks, but could have been derived by metamorphism of volcanic piles; Hopson (1964) suggested that the Baltimore gneiss (admittedly only one billion years old) had been formed from a thick series of rhyodacitic to basaltic sediments. By elimination, it seems that the most likely mode of origin for the early crust was repeated eruption of flows and pyroclastics of mafic to intermediate composition, accompanied by coeval acidic intrusions; a sequence of this sort 20-40,000 feet thick 2.7 billion years old has been described in the Vermilion district of Minnesota by Ojakangas (1972).

A second major event in Stage II, but one which largely coincided with formation of the early crust, was an exponentially-declining infall of innumerable bodies associated with the origin of the earth-moon system. Indirect evidence for these impacts is the extensively cratered terrain of the lunar and Martian highlands, and of the small part of Venus so far studied with high-resolution radar. Absolute ages are available, however, only for the lunar highlands, and these are obscured by the Imbrium event, as previously discussed. As pointed out by Short (in press), heavy impact cratering is evidently a normal stage in the early evolution of the terrestrial planets, and since bodies nearer to and farther from the asteroid belt than the earth have undergone such cratering, we should expect a priori that the earth did too. There is of course also direct evidence for at least the later stages of terrestrial impact cratering, in the 18 impact structures, up to 65 km in diameter (Figure 17), found on the Canadian shield (Dence, 1968); the Hudson Bay arc, with a 400 km diameter, may also be of impact origin. Some old impact craters may not be easily recognized as such because the impact served to localize a complex series of later igneous events. The best example of this is the Sudbury lopolith, which Dietz (1963) and French (1968, 1970) have shown to be probably of impact origin, supporting Lowman's (1963) suggestion that terrestrial lopoliths are analogous to the lunar circular maria.

It may be objected that there is no evidence in Precambrian terrains of the chaotic rubble that would be produced by intense bombardment, except for the few discrete impact structures found to date. However, orderly layering has survived in the lunar highland crust, as shown by exposures along the Apennine Front (Figure 18), despite the evidently high impact rates, although these layers may be ejecta blankets from mare basins. Furthermore, the heaviest bombardment was very early in the earth's history, and the impacted crust of that period is probably still in the lower layers of the present crust. Finally, later regional metamorphism would probably have completely reconstituted the early impact breccias into gneisses and schists.

Although the largest terrestrial feature generally accepted as of impact origin, the Manicouagan structure, is only 40 miles in diameter, the abundance of much larger impact craters on the moon and Mars (e.g., Wilhelms, 1973) implies that very large bodies struck the earth as well. These impacts must have disrupted the primitive global crust. They were followed, probably after a significant time, by eruption of basaltic magmas, as happened at Sudbury (French, 1968) and on a much larger scale in the lunar mare basins. This process was not simply one of puncturing the primitive crust; a discrete time interval between formation of the lunar mare basins and eruption of the mare lavas can be demonstrated (Lowman, 1969), and a similar interval probably occurred on the earth.

These early lava eruptions, localized at the sites of major impacts, can be considered the beginning of oceanization. If the magmas were of basaltic composition, these events can also be considered the beginning of a second differentiation, analogous to formation of the lunar maria. This suggestion is based on the assumption that these basaltic magmas differed in composition from the parent mantle material, which seems well-grounded in geophysical, field, and experimental data (Wyllie, 1971).

It seems reasonable to postulate a concentration of these early basins in what is now the Pacific Ocean, despite the fact that the Pacific basin seems no older than other ocean basins, simply because of the resemblance of the earth's topographic assymetry to that of the moon. The cause of such assymetry, which seems related to a more fundamental assymetry of figure in at least the moon, in not understood. By the end of Stage II, the earth probably resembled the present moon in general, but Mars in detail, since it has been shown that the oceans and a reducing atmosphere were forming by about 3.5 billion years ago and possibly earlier; accordingly, surficial erosion and deposition were underway by then.

Stage III

The division between Stages II and III is to some extent an artificial one, since some Stage II events, such as generation of basaltic magma and the infall of large bodies, continued to the present, or at least to much later times; the Sudbury impact, for example, has been dated at approximately 2 billion years ago (French, 1970). However, it is not until about 3.5 billion years ago that the general geologic record begins to take recognizable form. Some sedimentary rocks survive from this time, and terrestrial life evidently also began then (Barghoorn and Schopf, 1966). Superficial conditions were of course different, in particular the composition of the atmosphere, which probably consisted largely of CO_2 and N_2 (Rubey, 1955; Cloud, 1968). However, from an overall viewpoint, uniformitarianism becomes clearly applicable around 3.5 billion years ago, in that geologic processes occurring today became dominant over those whose reality is at least partly speculative. Accordingly, Stage III is considered to begin then.

The dominant process of Stage III was internally-caused oceanization. Unlike the initial oceanization of Stage II, that of Stage III is thought to have begun with tension fracturing and down-faulting of the early crust. Present examples of this process are the continental parts of the world rift system, such as the Gulf of California (Figure 19), the African Rift Valleys (Figure 20), the Rhine Graben, and the Baikal-Kosogol Rift Valley of eastern Asia. The Coprates Canyon of equatorial Mars is a probable extraterrestrial analogue. There are no plausible lunar analogues; although tension fracturing has been abundant on the moon, it is chiefly related to the formation of mare basins. The Alpine Valley is a good example of this relation. Because of the absence of non-mare graben, therefore, the moon is believed not to have evolved as far as terrestrial Stage III.

Formation of these early rift valleys was followed by sea-floor spreading, driven or accompanied by formation of mid-ocean ridges by creation of new (oceanic) crust, and the complementary crustal destruction in subduction zones. This sequence is now a familiar one, and needs little elaboration. Examples of the relation between rift valleys and mid-ocean ridges are present in the Gulf of California and the East Pacific Rise, and the Red Sea and Indian Ocean Ridge.

The question of continental drift must of course be mentioned. The evidence in its favor is in the opinion of many conclusive (e.g., Hurley, 1968), although a substantial group whose views are represented by Maxwell (1968) and Meyerhoff and Meyerhoff (1972) remains doubtful. I shall try to evade the problem here, offering as justification the opinion expressed by Dewey and Bird (1970) that continental drift is from a broad viewpoint "merely a corollary" of sea-floor spreading and plate motions.

A more profound question that can not be avoided is that of whether continental areas can be converted into oceanic areas. This problem has been generally put as that of conversion of continental crust into oceanic crust, which I feel is misleading. A more specific question is whether the relatively low-density continental crust can somehow subside and be disposed of so as to form an ocean basin, since it seems apparent that not all basins can be formed by separation of continents, if indeed any are.

The best way to answer this question is a condensed summary of the work of several geologists who have studied the problem.

1. M. Kamen-Kaye (1967 and personal communication, 1973) has compiled examples of subsidence of the basement by several kilometers. Those exceeding 5 kilometers, classed as hypersubsidence, include the Gulf of Mexico, the Persian Gulf, and the Karroo Basin. Many others with lesser but still significant (over 3 km) degrees of subsidence are well-known, since they include major oil fields: the Williston, Congo, Middle Amazon, and Great Artesian (Australia) basins are examples. The thin crust under the Gulf of Mexico indicates that in some cases crustal subsidence may lead to actual thinning of continental crust, which is at least partway to conversion of continental to oceanic crust.

2. J. C. Maxwell (1970) has summarized a wide variety of evidence indicating that the Mediterranean Sea (meaning of course the basin) has been formed by subsidence and oceanization of pre-existing sialic crust formerly connecting Africa and Europe. The oceanization was accompanied by injections of mantle material now making up the ophiolite suite exposed at many places in and around the Mediterranean. Maxwell's paper is of further importance to the theme of this discussion because he points out that the Alpine, Hercynian, and Caledonide mountain belts all developed on pre-existing continental crust, thus contradicting by implication lateral continental growth by accretion of geosynclines.

3. V. V. Beloussov, as mentioned previously, has long championed the theory of oceanization. Of particular interest is his demonstration (with Ye. M. Rudich, 1961) that the Sea of Japan appears to have been formed by conversion of continental to oceanic crust; island arcs of this sort are customarily considered to represent growth of the continents, rather than their destruction. Beloussov and Rudich also cited seismic evidence for oceanic crust under the Black Sea and Caspian Sea, and gravimetric evidence for oceanic crust under the Tyrrhenian Sea.

4. H. W. Menard (1967) has presented a useful discussion of "small ocean basins," such as the Black Sea, Gulf of Mexico, and Aleutian basin. These basins, which are of oceanic depth (deeper than 2 km) but generally isolated from the main ocean basins, appear to be geophysically intermediate between oceanic and continental crust in many cases. Menard concluded that they could represent either conversion of oceanic crust to continental crust, by sedimentation, which he felt most common, or of continental to oceanic crust. The possibility that such basins have contributed substantially to continental growth, however, seems contradicted for at least some major basins, in particular the Mediterranean, Black, and Caspian Seas by geologic evidence cited by Maxwell and Beloussov and Rudich.

5. J. Gilluly (1955), in a previously-cited paper, discussed both sides of the continental growth controversy. Although he concluded that the evidence required addition of new sial to the crust through geologic time, he also presented arguments for the conversion of continental to oceanic crust. These were based on the existence of large volumes of sediment in the Appalachian, Alpine, and Cordilleran geosynclines that must have been derived from lands oceanward, in areas now oceanic. From this and other evidence, Gilluly concluded that despite the great problems involved in turning continental crust into oceanic crust, "... it seems quite indisputable that such transformations have taken place, ...". Noting that there seemed insufficient evidence of volcanism for injection of heavier basic material to be responsible for subsidence, he suggested subcrustal erosion and lateral transport of sialic material as the mechanism responsible.

Viewed collectively, the work of these authors suggests very strongly that oceanization has occurred over large areas in Phanerozoic time, and is occurring now. A plausible mechanism for the initial stage of the process, namely depression of continental crust, remains to be found; extrusion of dense ophiolitic material, and crustal thinning by subcrustal erosion, appear most promising. The later stages of oceanization appear accounted for by sea-floor spreading and subduction. It should be noted that subduction, or down-thrusting of oceanic crust, which appears to be the best established phase of the "new" global tectonics, provides a demonstration that crustal segments can be driven down into denser mantle material. This gives at least qualitative support to the opinions expressed above that continental crust can be depressed to oceanic depths.

The fate of subducted oceanic crust and associated materials (including perhaps some continental crust and terrigenous sediments) after they have been thrust under continents is crucial to the question of continental growth vs. oceanization.

Advocates of continental accretion, such as Dietz (1972), consider the net result to be continental growth by vulcanism and wedging of the "eugeoclinal" sediments against the continent. However, as I have pointed out earlier (Lowman, 1972b, pp. 94, 162), the presence of old rocks at the very edge of, for example, western South America (Figure 2), argues against lateral continental growth since at least the late Paleozoic. This region and by analogy other subduction zones can be interpreted as the sites of continental destruction, by subcrustal erosion, crustal subsidence, or down-thrusting of terrigenous sediments as proposed by Armstrong (1968). However, at least some of the underthrust sial comes up again as andesitic magmas; the result is, as in South America, thickening of the continental crust at the expense of its area. Following Gilluly (1955), it seems reasonable to postulate a general underplating of the continent in other areas by dominantly horizontal subcrustal transport of sial.

This underplating, which is admittedly much more hypothetical than the crustal thickening in island arcs, may provide an explanation for the undoubtedly real concentric pattern of radiometric dates in North America, Australia, and perhaps other continents, which has been a major element of theories of continental growth since the work of Wilson (1954). The underplated sialic material may have accumulated concentrically, and its greater content of radioactive elements could have eventually produced corresponding concentric zones of regional metamorphism and subordinate magmatism in the overlying crust. As Wasserburg (1966) has shown, such zones as the Grenville "province" probably represent areas in which radiometric dates in pre-existing crust have been reset by thermal events (rather than belts of continental accretion — PDL). His interpretation is strongly supported by the demonstration by Wynne-Edwards (cited by Wyllie, 1971) that rocks in most of the Grenville province are much older than the Grenville "event" 950 million years ago, and that the province thus represents considerable tectonic overprinting rather than continental growth.

Stage IV

The boundary of Stage IV is placed at the bottom of the Cambrian period, or the beginning of Phanerozoic time, to which Stage IV is equivalent. In terms of biological and to some extent atmospheric evolution, this boundary is of course a very real one. However, there is no good evidence that late Precambrian crustal evolutionary processes were radically different from Phanerozoic ones; in that respect, the division between Stage III and IV is somewhat arbitrary.

It has been shown, from radiometric dates, that most of the continental crust was in existence by the beginning of the Cambrian period. This fact, and the ensialic nature of most orogenic belts, implies that crustal evolution in Stage IV was dominated by fundamentally oceanic processes, with essentially superficial sedimentation and subsequent tectonism occurring on the continents. The general result, from a global viewpoint, of the oceanization process during Stage IV was a continuing decrease in continental area with a corresponding increase in the thickness of continental crust. Differentiation of the earth continued by generation of basaltic magmas, but formation of new sial directly from the mantle was relatively minor. However, at least some andesitic and rhyolitic magmas have probably been produced by fractional crystallization of basaltic magma or partial melting of subducted basaltic crust; to this extent, there has been indirect formation of new sial throughout Stage IV. It may be suggested, in fact, that the earth could eventually develop a sialic crust by these processes alone, although the thesis presented here is that most of it was formed rapidly at a very early date.

DISCUSSION AND SUMMARY

The objective of this paper has been to advocate a particular theory for the evolution of the earth's crust, not to present an encyclopedic summary of the entire problem and attempts to solve it. It should be plainly stated here that I have not presented a well-balanced account of the oceanization vs. continental growth controversy; in particular, a much stronger case exists for continental growth by lateral accretion than an uncritical reader might think. For example, S. R. Taylor (1967) has marshalled an impressive body of geochemical and geological evidence for secular continental growth by andesitic vulcanism in island arcs. The concentric arrangement of successively younger orogenic belts in Indonesia (Holmes, 1965, p. 1138ff.) certainly suggests continental growth by just such a process. On the opposite side of the Pacific, the gradation eastward along the Aleutian arc from active volcanoes into Mesozoic batholiths on the Alaskan mainland is undoubtedly suggestive of continental growth along strike, while the decreasing age southward of successive orogenic belts in Alaska itself can also be explained as continental growth. Similar age relationships are found in Australia from west to east.

I have interpreted these patterns as the result of interaction between young, actively spreading oceanic crust and old, passive continental crust, whose net result has been progressive shrinkage in area, but increase in thickness, of the continents. Horizontal subcrustal transport of sial from the continental borders seems to have resulted in a still poorly-defined concentric underplating, expressed in surficial rocks by belts of radiometric dates and associated magmatism. I have relied heavily on the work of Wasserburg (1966) and Armstrong (1968) for my belief that the collective isotopic evidence on crustal evolution can be explained by this very general model.

The arguments for what might be called the modernized oceanization theory can be briefly summarized as follows.

First, and most important, is the indirect evidence from other planets. The moon in particular shows that even a small body, depleted in volatiles, and with a presently low level of internal activity, has a thick and originally global differentiated crust. This crust, formed early in the moon's history by igneous processes, was later disrupted and partly covered by basalt, a process amounting to oceanization, though different from sea-floor spreading. The geologic evolution of Mars seems to have followed much the same course, although unlike the moon, Mars is still evolving internally, by volcanic activity and tension fracturing. The evidence from Venus, fragmentary and preliminary though it is, indicates a granitic crust of considerable extent; and if the newly-discovered craters represent early intense bombardment, this crust is probably primitive.

On at least two planets, then, we see no evidence of crust formation in discrete nuclei or in single proto-continents analogous to the still-hypothetical Pangaea. Planetary differentiation was global; the present assymetry on both Mars and the moon is the result of something equivalent to oceanization in that it was disruption and flooding of early crust by basalt.

Turning to the origin of the earth's continents, several important generalizations now seem fairly well-established. First, the earth underwent a major period of differentiation early in its history, and most of the present continental crust was in existence by the beginning of the Cambrian period. Second, most eugeosynclines appear to be ensialic, not ensimatic, as required by the lateral accretion theory of continental growth; exceptions to this relation appear to be rare, with the California Franciscan being perhaps the best example of an ensimatic eugeosyncline. Third, examples of Cenozoic oceanization, independent of possible ocean basin formation by continental drift, appear to be surprisingly widespread, including the Mediterranean, Black, and Caspian Seas, the Gulf of Mexico, the California continental borderland, and the Sea of Japan. Pre-Cenozoic oceanization is implied by the inference, from stratigraphic evidence, of sialic source areas in what are now oceans on the west and east coasts of the United States.

To summarize the conclusions of this paper, I believe that the dominant process of crustal evolution on the earth, over geologic time, has been growth of the ocean basins, not growth of the continents. The present continents, in this view, are the much-altered and thickened remnants of an originally global crust that was formed by igneous processes shortly after the earth itself was formed. Additions to this continental crust have been essentially limited to mantle-derived basalt and the products of partial fusion of subducted basaltic oceanic crust; the sialic crust is largely primitive, though not radiometrically identifiable as such now.

The crustal evolution of the earth is, in this theory, fundamentally similar to that of the other terrestrial planets, with unique features explainable by specific characteristics such as mass, internal energy (itself a function of mass), and retention of volatiles, in particular water.

ACKNOWLEDGMENTS

This paper covers an extremely general problem, and has been in preparation for nearly three years; consequently, it is difficult to thank adequately all those who have given me help of one sort or another. The reference list itself is a form of acknowledgment, since the paper is largely a synthesis of the work of others. I am also indebted to the following people for discussions, suggestions, or unpublished material: R. L. Armstrong, H. W. Blodget, P. E. Cloud, J. F. Dewey, R. S. Dietz, B. M. French, H. V. Frey, D. C. James, M. Kamen-Kaye, B. M. Lowrey, J. C. Maxwell, J. M. Mead, A. A. Meyerhoff, J. A. O'Keefe, J. A. Philpotts, R. S. Saunders, P. K. Sims, B. F. Windley, and J. A. Wood. My understanding of the lunar X-ray fluorescence experiment and the martian infrared spectroscopy experiment was greatly aided by discussions with team members for each, and I thank the respective principal investigators, Dr. I. Adler and Dr. R. A. Hanel, for permission to reproduce material. I also wish to thank G. Faure, C. A. Hopson, and G. R. Tilton for permission to reproduce illustrations from their publications, and R. M. Goldstein for unpublished radar images of Venus.

Through the support of the Carnegie Institute of Washington, I was able to attend the William W. Rubey Conference on Crustal Evolution at Santa Barbara, California, in June, 1973. This conference was invaluable to me both as a source of information and as a stimulus to finishing the paper. Dr. L. T. Silver distributed to conference members translations of the report by Vinogradov and his colleagues on the Venera 8 results.

Student readers may find of some interest that this paper is the long-delayed but nevertheless direct outgrowth of a term paper on the origin of continents done in 1953 under the direction of the late D. I. Blumenstock of Rutgers University; comments by him and by B. L. Smith, also of Rutgers University, were incorporated in the present paper.

Finally, I wish to thank my wife, Karen, for encouragement and for a quiet and well-equipped retreat in which most of the paper was written.

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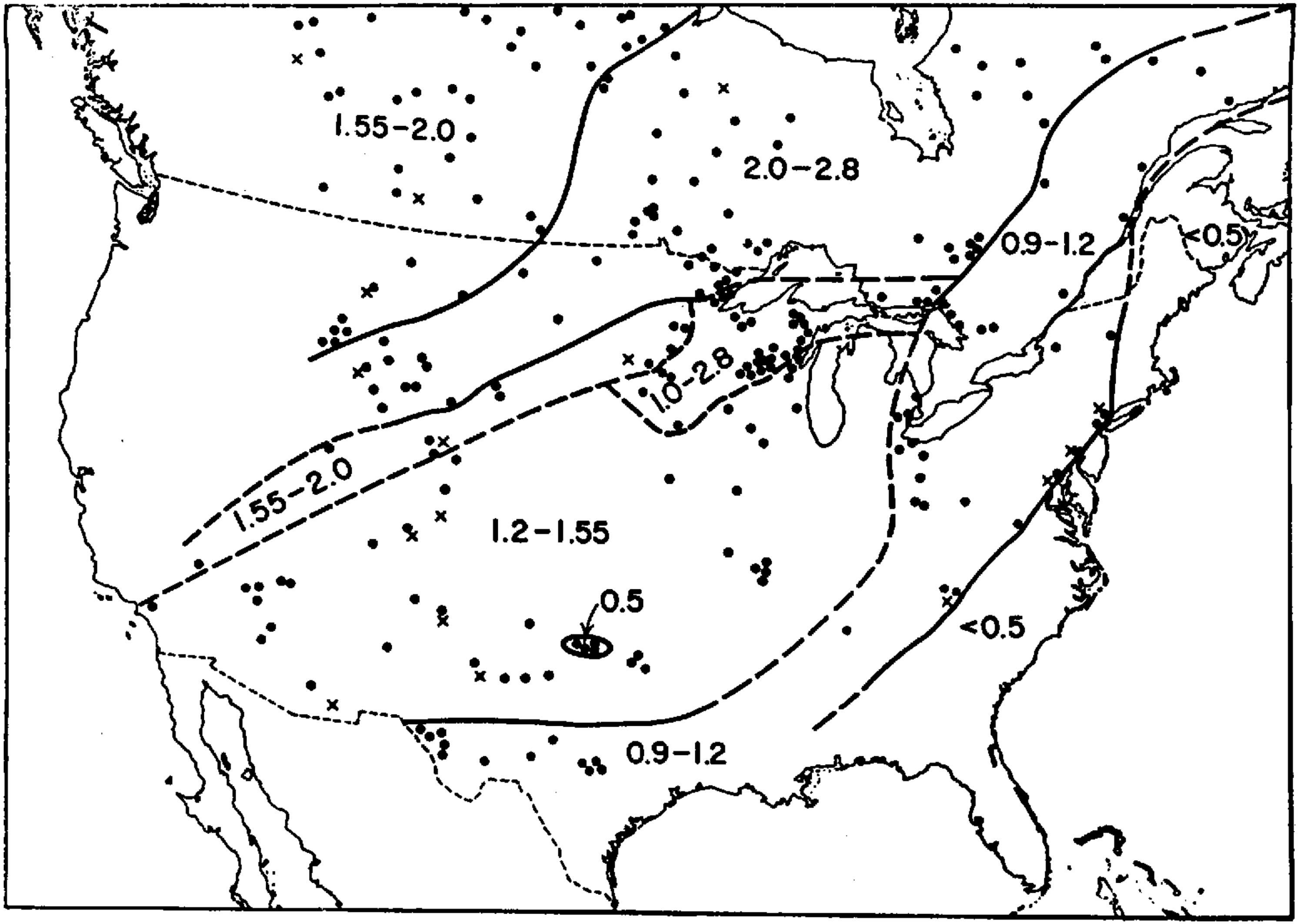


Figure 1. Radiometric dates in North America, in billions of years (aeons). From Tilton, et al, 1962; reproduced by permission.

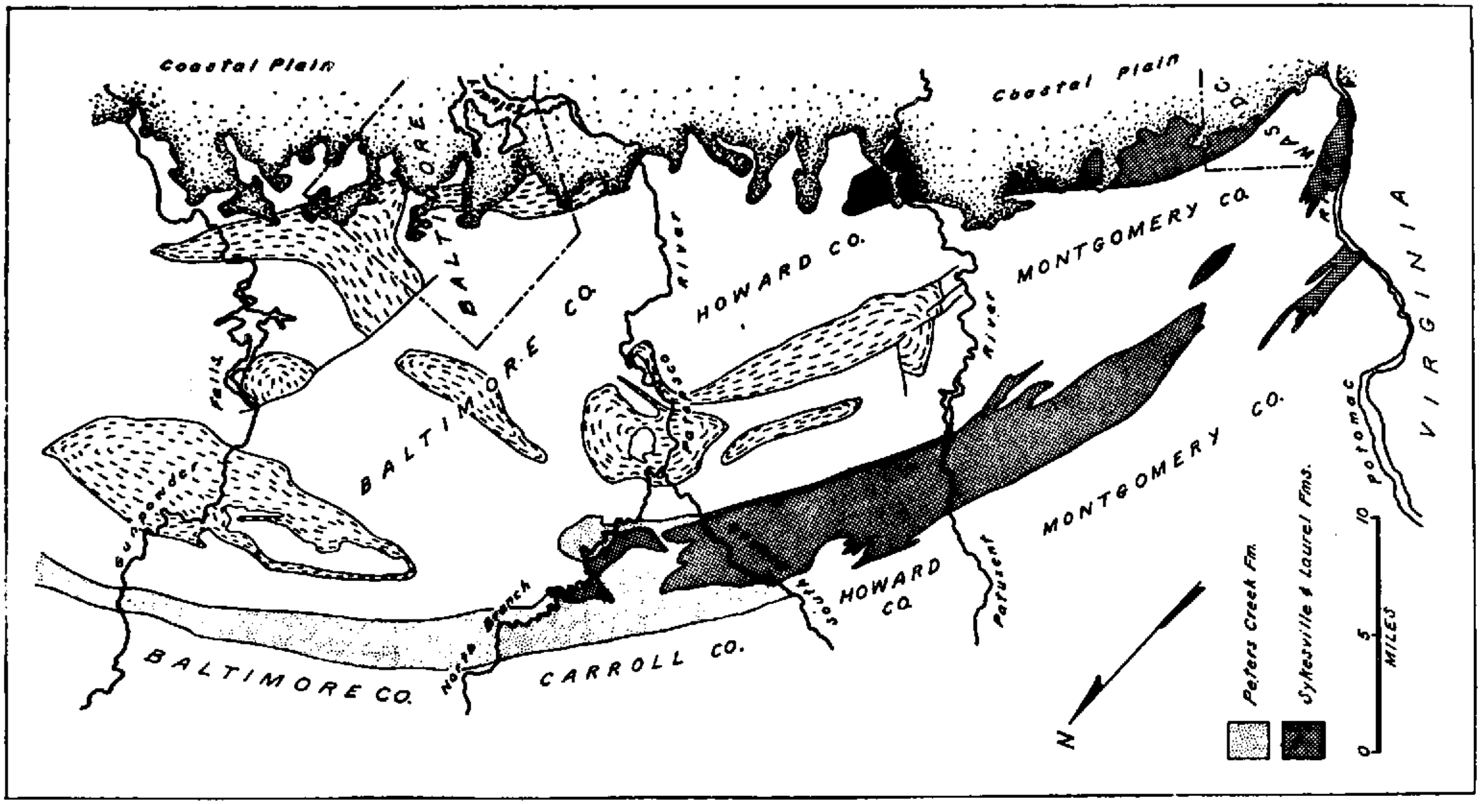


Figure 2. Baltimore gneiss domes of Maryland, from Hopson (1964), shown with dashed pattern. Radiometric age of Baltimore gneiss is 1.1 billion years (Wetherill, et al, 1966). Unpatterned rocks surrounding gneiss domes are Lower Pelitic Schist member of Wissahickon Formation; Hopson's Sykesville, Laurel, and Peters Creek Formations now considered members of the Wissahickon (Cleaves, et al, 1968). Wissahickon Formation shown by Higgins (1972) to be probably of lower Paleozoic age. Reproduced by permission.

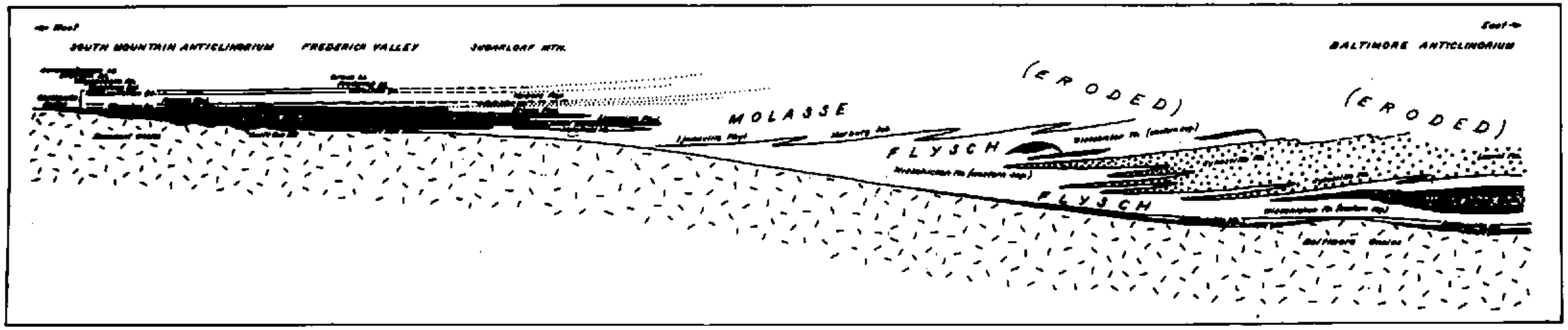
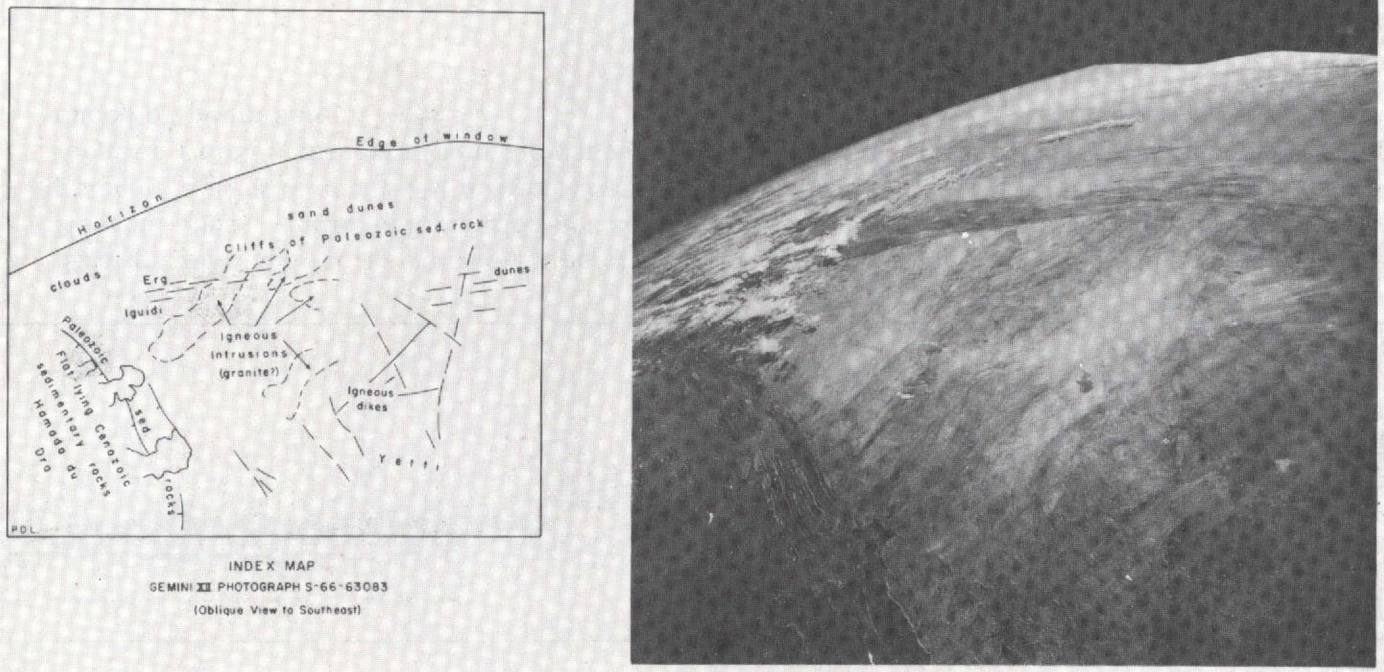


Figure 3. Stratigraphic and facies relationships of the Maryland Piedmont, as deduced by Hopson (from Hopson, 1964). Later deformation not shown. Baltimore gneiss in east thought to have been emplaced plastically about 440 million years ago (Hopson, 1964, p. 207), but originally formed basement on which sediments from the east (now the Wissahickon formation) were deposited. Reproduced by permission.



INDEX MAP
GEMINI XII PHOTOGRAPH S-66-63083
(Oblique View to Southeast)

Figure 4. Precambrian rocks of the Yetti plain, or Dorsal Reguibat, of the western Sahara, as shown by a Gemini XII photograph; described in detail by Lowman (1972b, p. 110). Light-toned Precambrian rocks of the Yetti plain possibly granitic gneiss domes similar to Baltimore gneiss and "gregarious batholiths" of Rhodesia (in Holmes, 1965, p. 1185 ff). Areal predominance of granitic rock, if representative of volume relations, argues against anatectic origin for granites if magmatic.

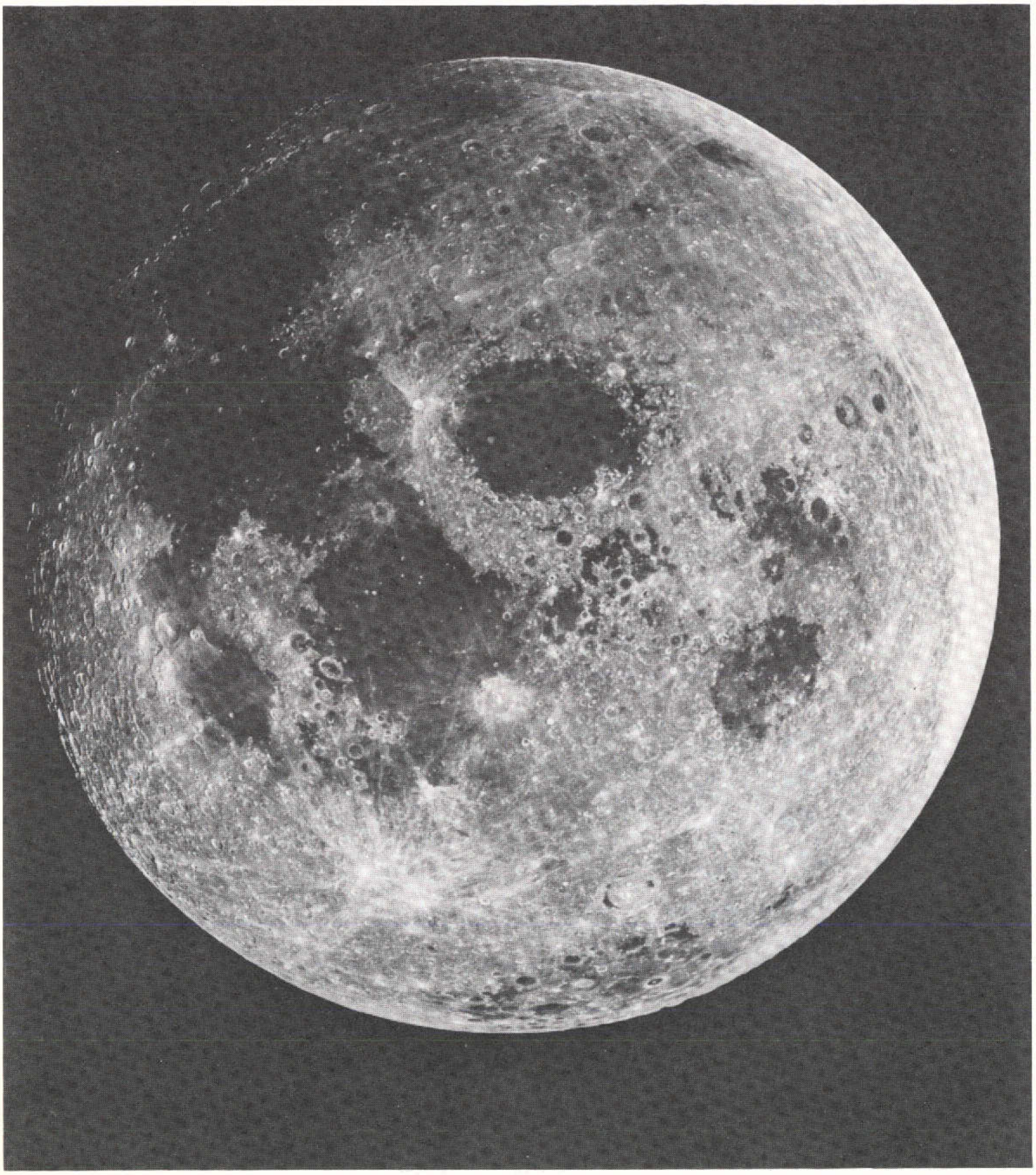


Figure 5. Apollo 16 view of east limb of moon, taken after trans-earth injection; north at top, with Mare Crisium on limb at center. Homogeneous crater population of highlands indicates similar age of most of lunar pre-mare crust, implying global differentiation as opposed to formation of crustal patches analogous to supposed continental nuclei. Relatively uniform albedo of highlands (not shown well here) interpreted as due to high plagioclase content and uniform areal distribution.

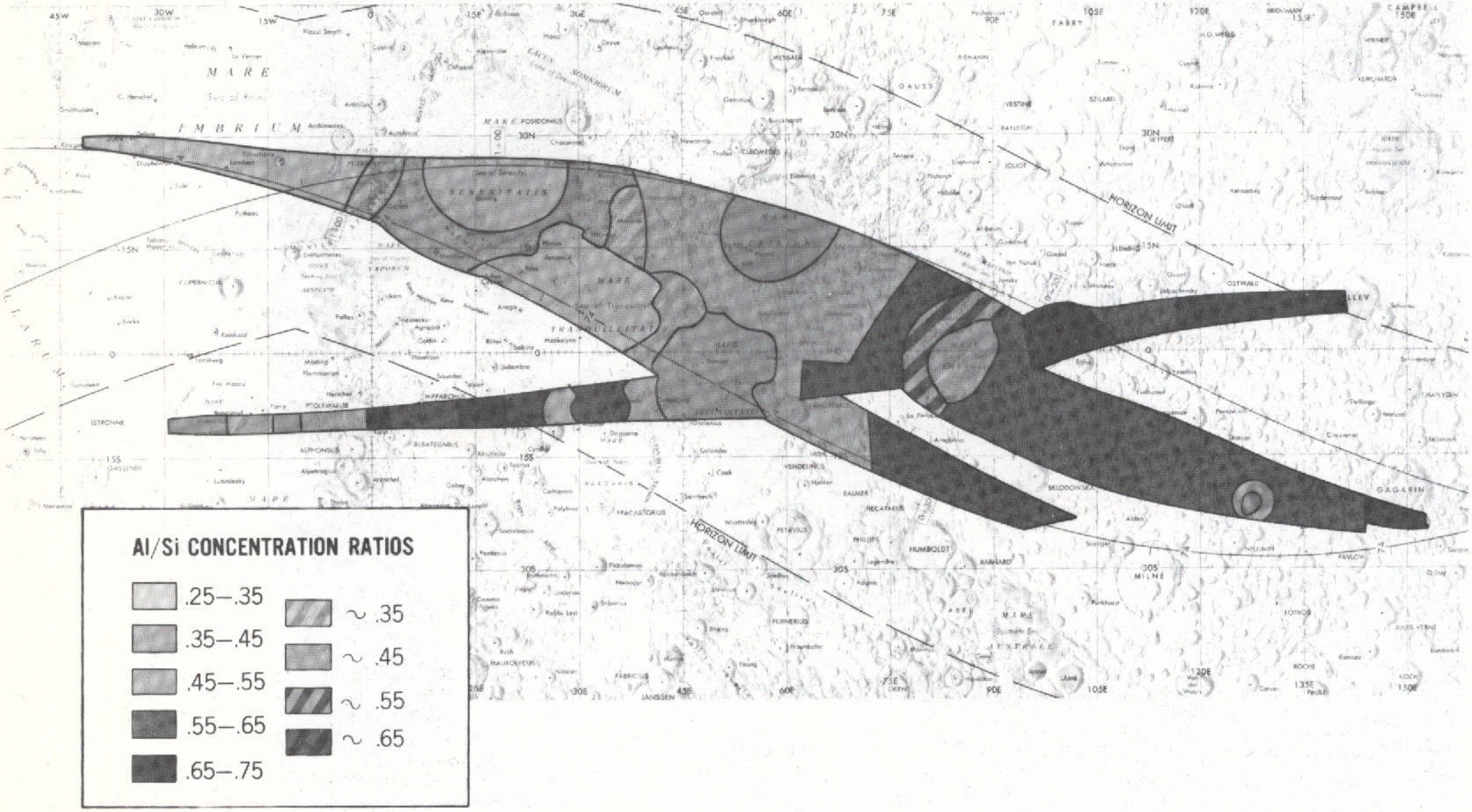


Figure 6. Al/Si concentration ratios as measured by the X-ray fluorescence experiment from lunar orbit during Apollo 15 and 16 missions (Adler, et al, 1972a, 1972b). Measurements cover over 180° in longitude, including much highland terrain on the far side (right).

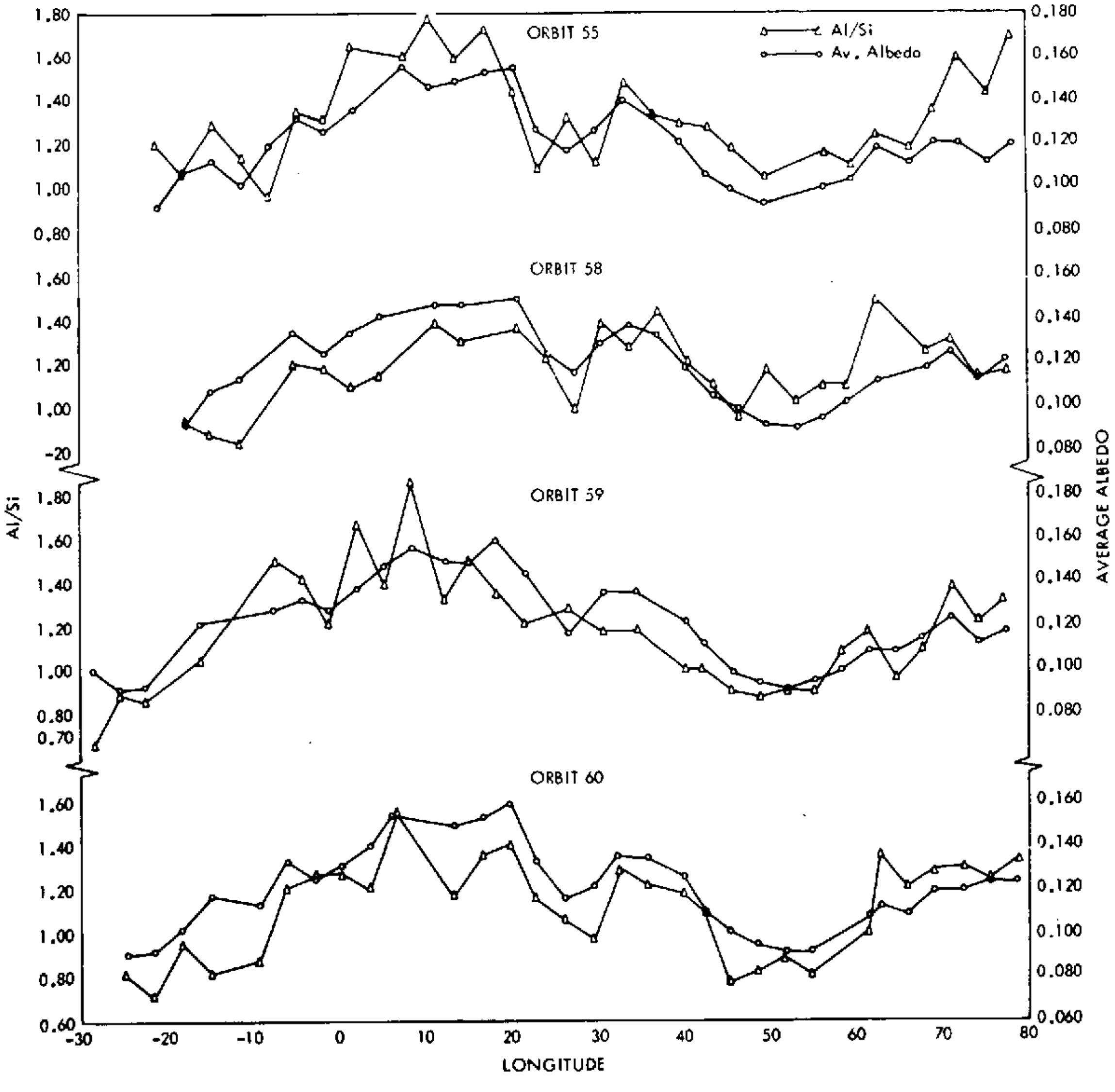


Figure 7. Optical albedo and Al/Si X-ray fluorescence intensity ratios plotted against longitude along Apollo 16 flight path (Adler, et al, 1972b). Positive correlation between Al content and albedo interpreted as meaning that high albedo of terrae result from high plagioclase content, except for bright, Copernican age craters and rays.

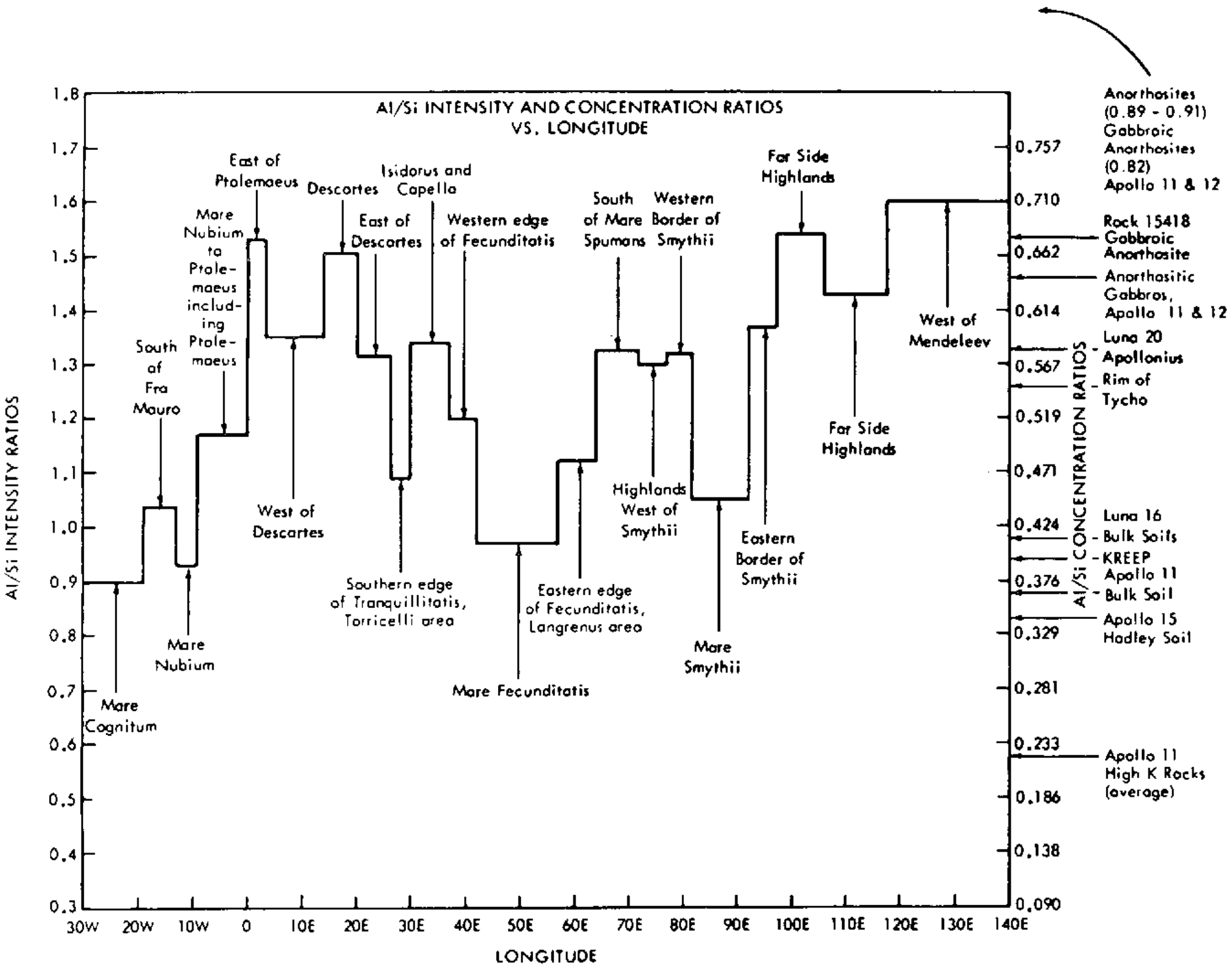


Figure 8. Al/Si intensity and concentration ratios from X-ray fluorescence measurements plotted against longitude along Apollo 16 flight path. Highland ratios are too low for anorthosites and gabbroic anorthosites, indicating that these materials are subordinate constituents of the highland crust. Gamma-ray measurements (Metzger, et al, 1973) also rule out KREEP as major constituent despite Al/Si ratios.

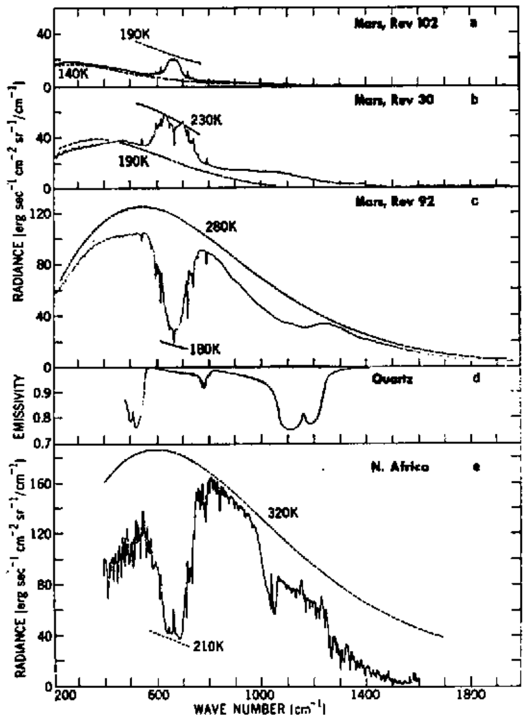


Figure 9. Thermal emission spectra of Mars and terrestrial materials for comparison: radiance or emissivity as a function of wave number (wave length in micrometers = 10,000/wave number, e.g., 1000 cm^{-1} is 10 micrometers). From Hanel, et al, 1972b.

(a) Spectrum measured by Mariner 9 IRIS of Martian north polar hood, with 140°K blackbody curve for comparison; main features are CO_2 bands in emission.

(b) Spectrum of Martian south polar region. Prominent emission features in 600-800 cm^{-1} region are CO_2 bands. Broad feature centered on 1100 cm^{-1} are caused by silicate dust suspended in atmosphere.

(c) Spectrum of Martian midlatitude region; features seen in absorption rather than emission because of different atmospheric temperature profile. Note broad silicate feature centered on 1100 cm^{-1}, interpreted as implying a SiO_2 content of about 60% (Hanel, et al, 1972b).

(d) Laboratory emissivity measurements of fractured quartz.

(e) IRIS spectra from Nimbus 4 taken over the Sahara; features not found in Martian spectra are chiefly water and ozone bands. Absorption feature centered on 1100 cm^{-1} is caused by suspended dust, presumably silicates. (Prominent feature at 1042 cm^{-1} is ozone.)

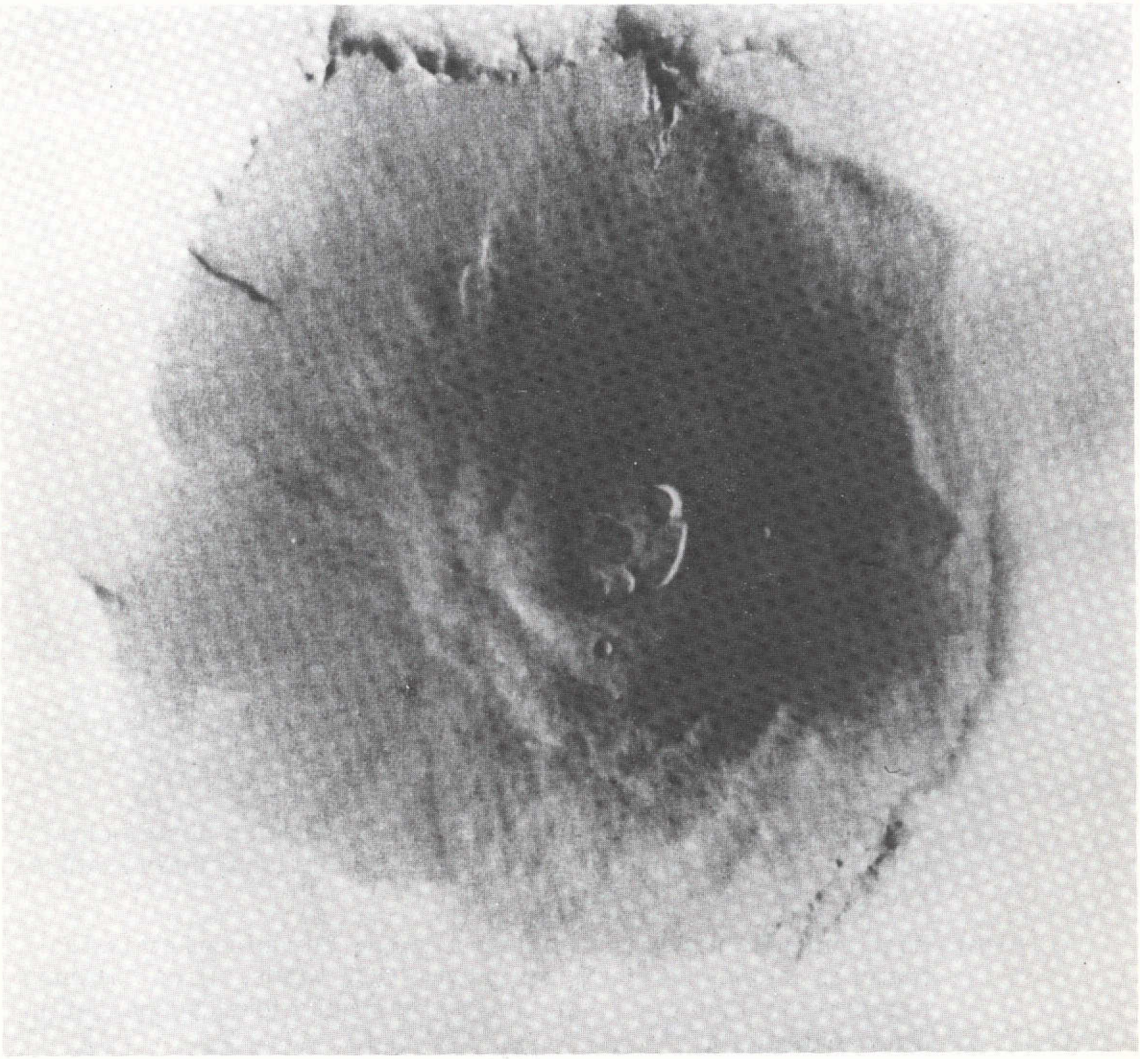


Figure 10. Mariner 9 mosaic of Martian shield volcano Nix Olympica (see map of classic features, Fig. 12); total width of structure about 600 km, with summit caldera 65 km wide (Carr, 1973). Bounding scarps about 2 km high; origin not known. High resolution pictures, not included, show flanks to have topography identical to that of basaltic lava flows of terrestrial volcanoes.

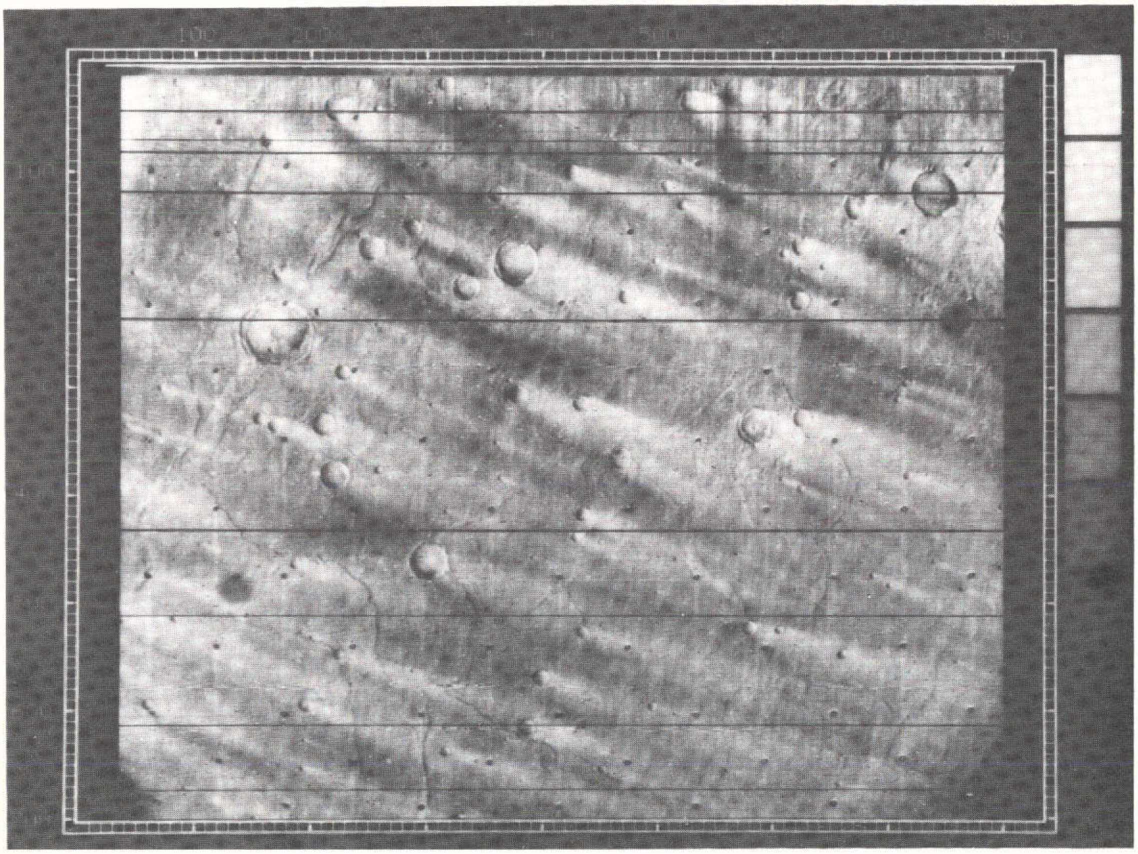


Figure 11. Mariner 9 A-camera picture of Hesperia region, covering area about 400 km wide in cratered terrain of midlatitudes. Light and dark streaks generally considered eolian features (Sagan, et al, 1972). Note abundant two-sided ridges, interpreted here as analogous to lunar mare ridges, and thus implying a volcanic nature for the cratered highland crust.

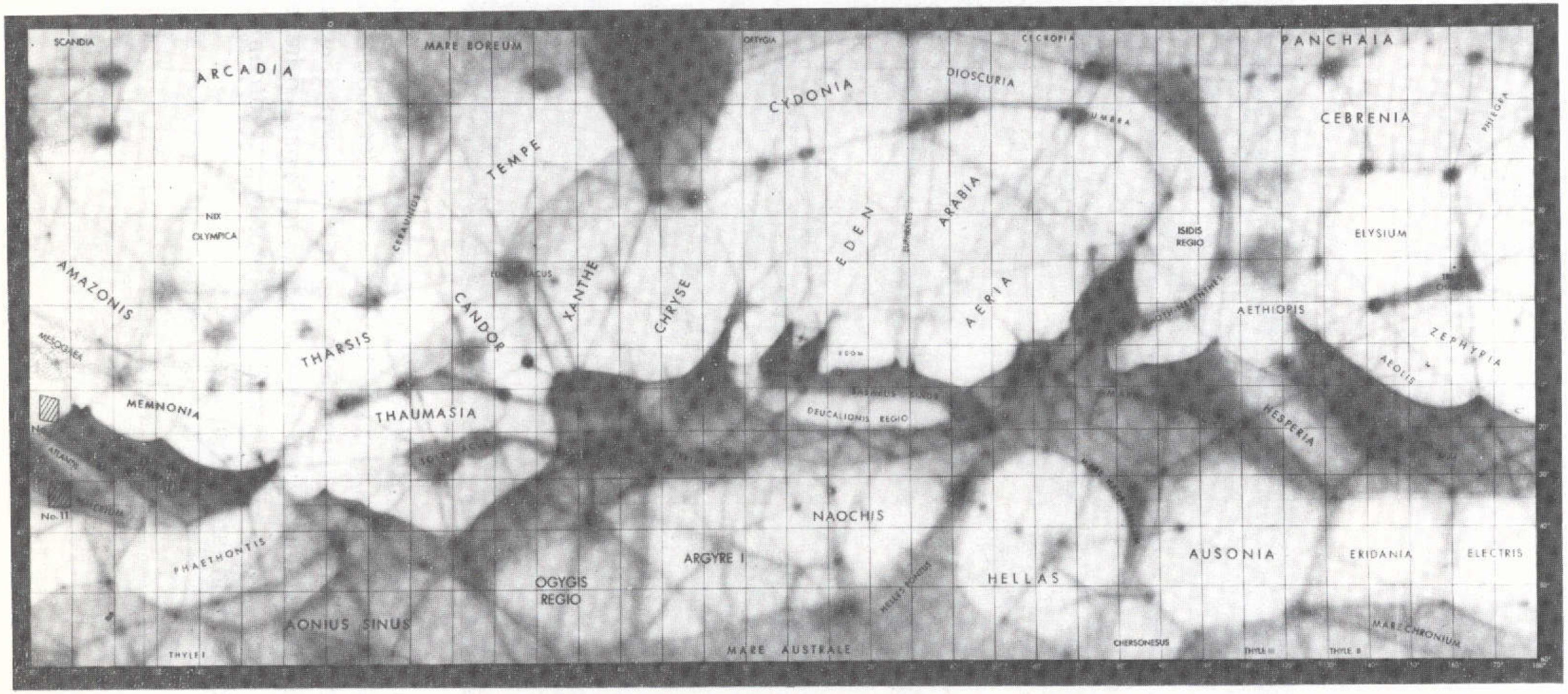


Figure 12. Portion of USAF Aeronautical Chart and Information Center Map of Mars, MEC-1 (1962), showing classical (telescopic) features. Most canals now known not to exist. Map presented primarily for geographic purposes; compare with shaded relief map, based on Mariner 9 pictures (Fig. 13).

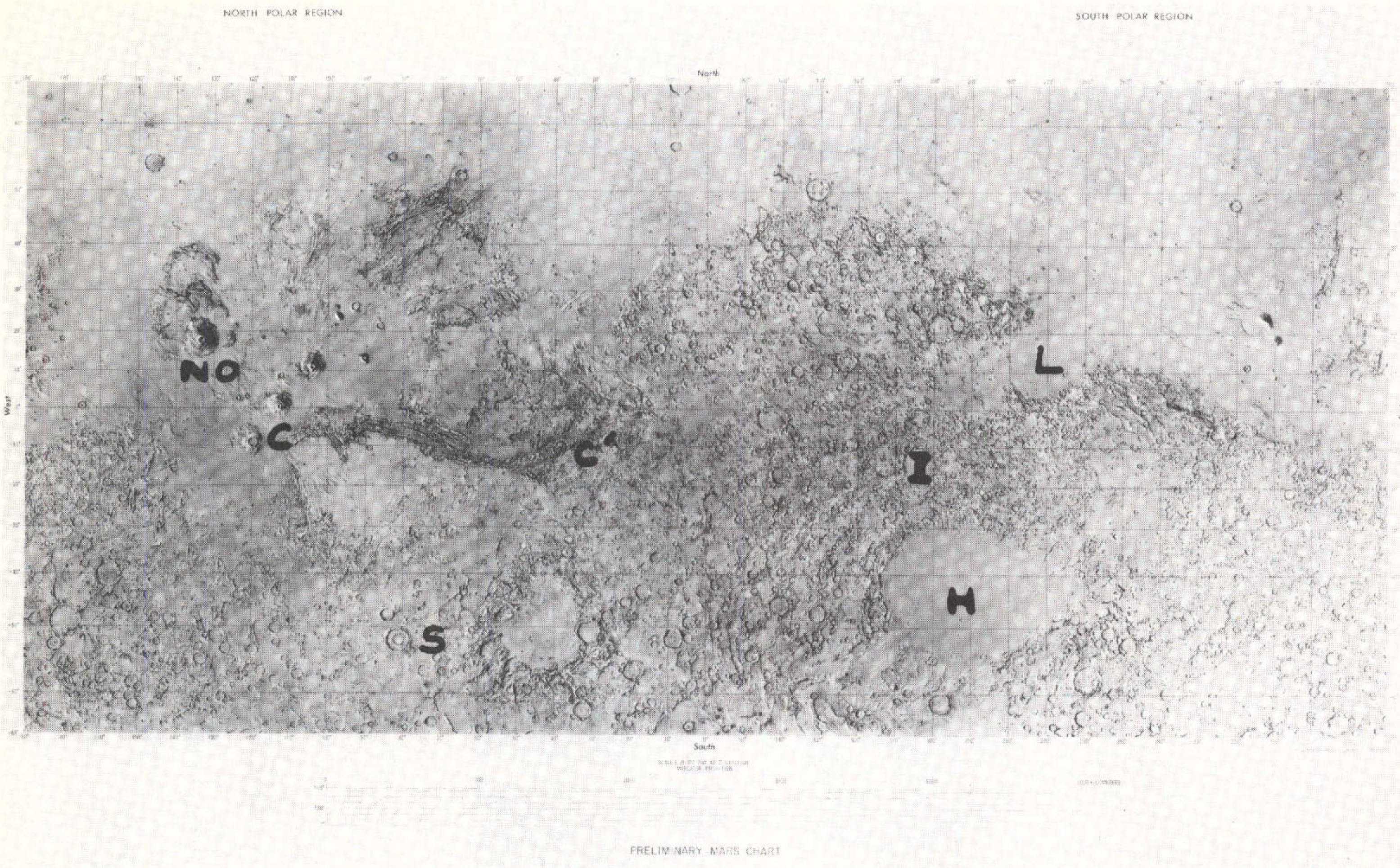


Figure 13. U.S. Geological Survey shaded relief map, Mercator projection, of 65°N-S latitude band. Multiringed basins discussed by Wilhelms (1973) labeled: "Martian Schrodinger," S; Argyre, A; Edom, E; Iapygia, I; Hellas, H; Lybia, L. Sizes range from 200 km ("Schrodinger") to 2000 km (Hellas). Concentric structure interpreted as implying existence of one or more layers, possibly including crust-mantle boundary; wide distribution implies wide extent of crust. Other labeled features include Nix Olympica, NO, and Coprates canyon, C-C'.

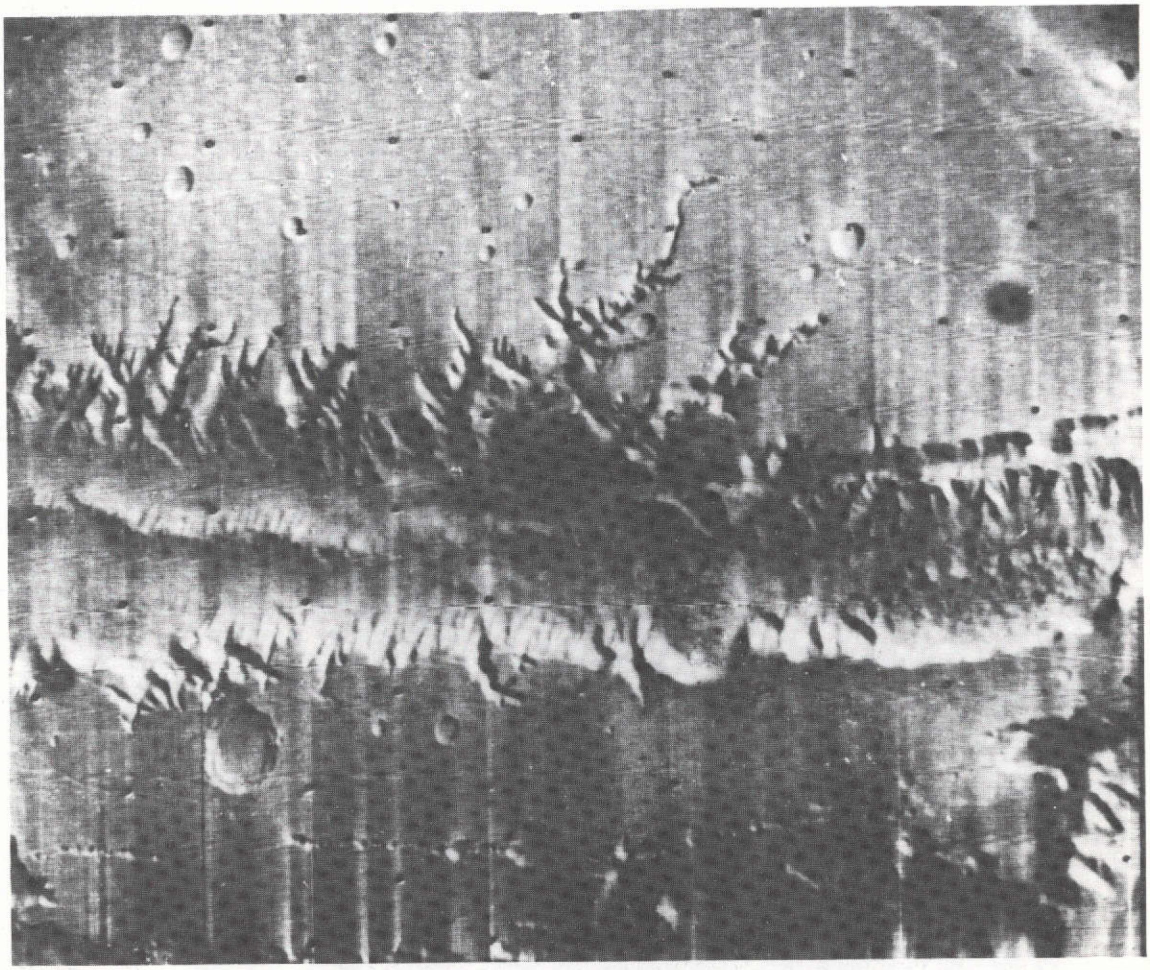


Figure 14. A vast chasm with branching canyons eroding the adjacent plateaulands appears in this view of Mars taken by Mariner 9 on January 12. Located in Tithonius Lacus, 100 miles south of the equator, these features represent a type of landform evolution apparently unique to Mars. The resemblance to the tree-like tributaries of a terrestrial stream system is probably superficial, for many of the "tributary" canyons are closed depressions. Subsidence along lines of weakness in the crust, and possibly deflation by Martian winds, have sculptured this unique pattern. The picture was taken with Mariner 9's wide-angle TV camera from 1977 km (1225 miles) and covers an area 376 by 480 km (235 miles by 300 miles).

Figure 15a

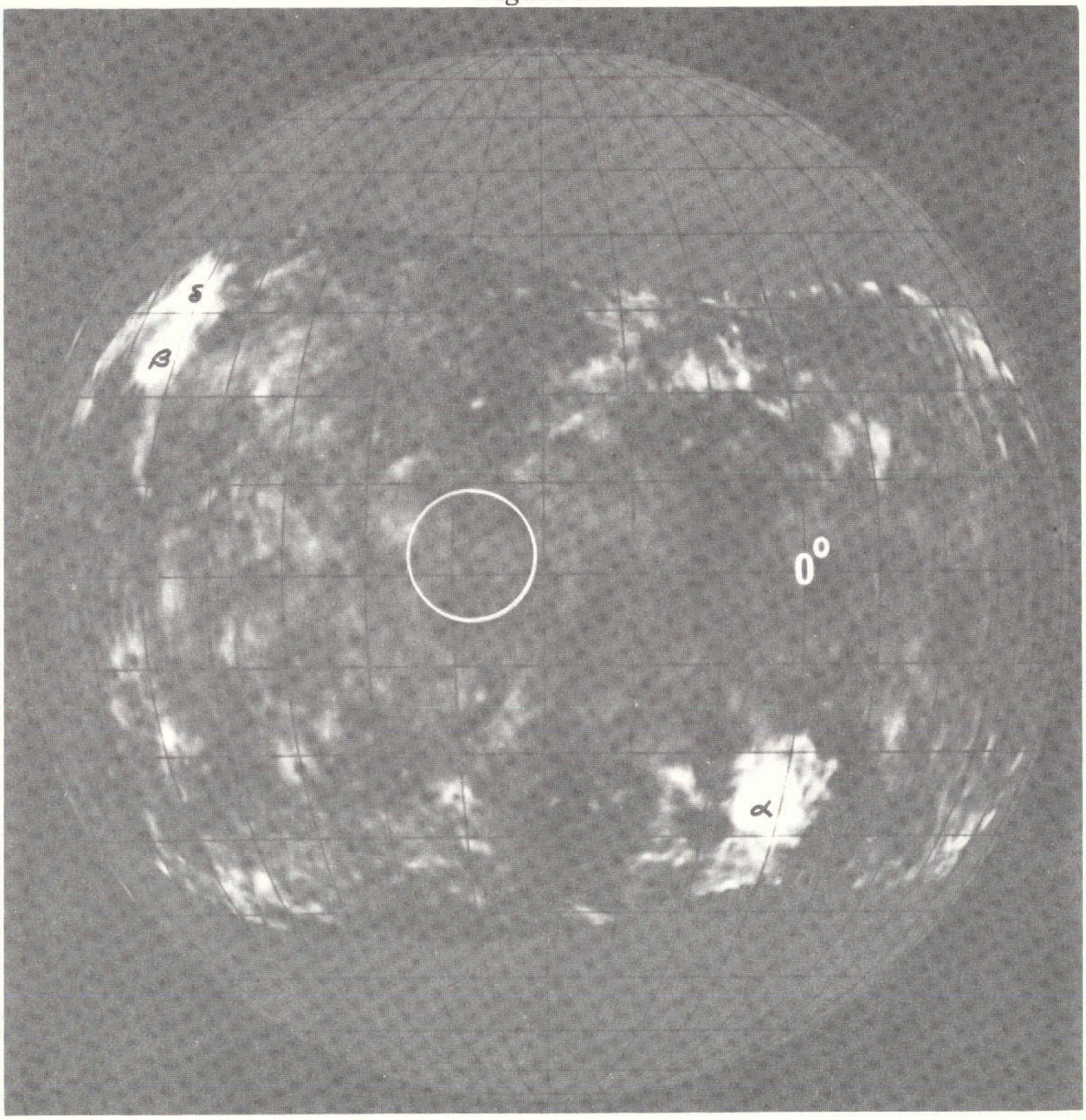


Figure 15. Earth-based radar maps of Venus, courtesy of Richard M. Goldstein (Jet Propulsion Laboratory). Technique used was range-Doppler measurements, described by Goldstein and Rumsey (1970); mapping elements are range-Doppler cells. Fig. 15a gives overview with 80 km ground resolution; features alpha, beta, and gamma are high reflectivity areas. Blurred equatorial area is locus of sub-radar points, with poor resolution; blacked out area in Fig. 15b is corresponding feature. Circle in 15a gives location of Fig. 15b, which has 10 km ground resolution, showing craters between 35 and 160 km in diameter.

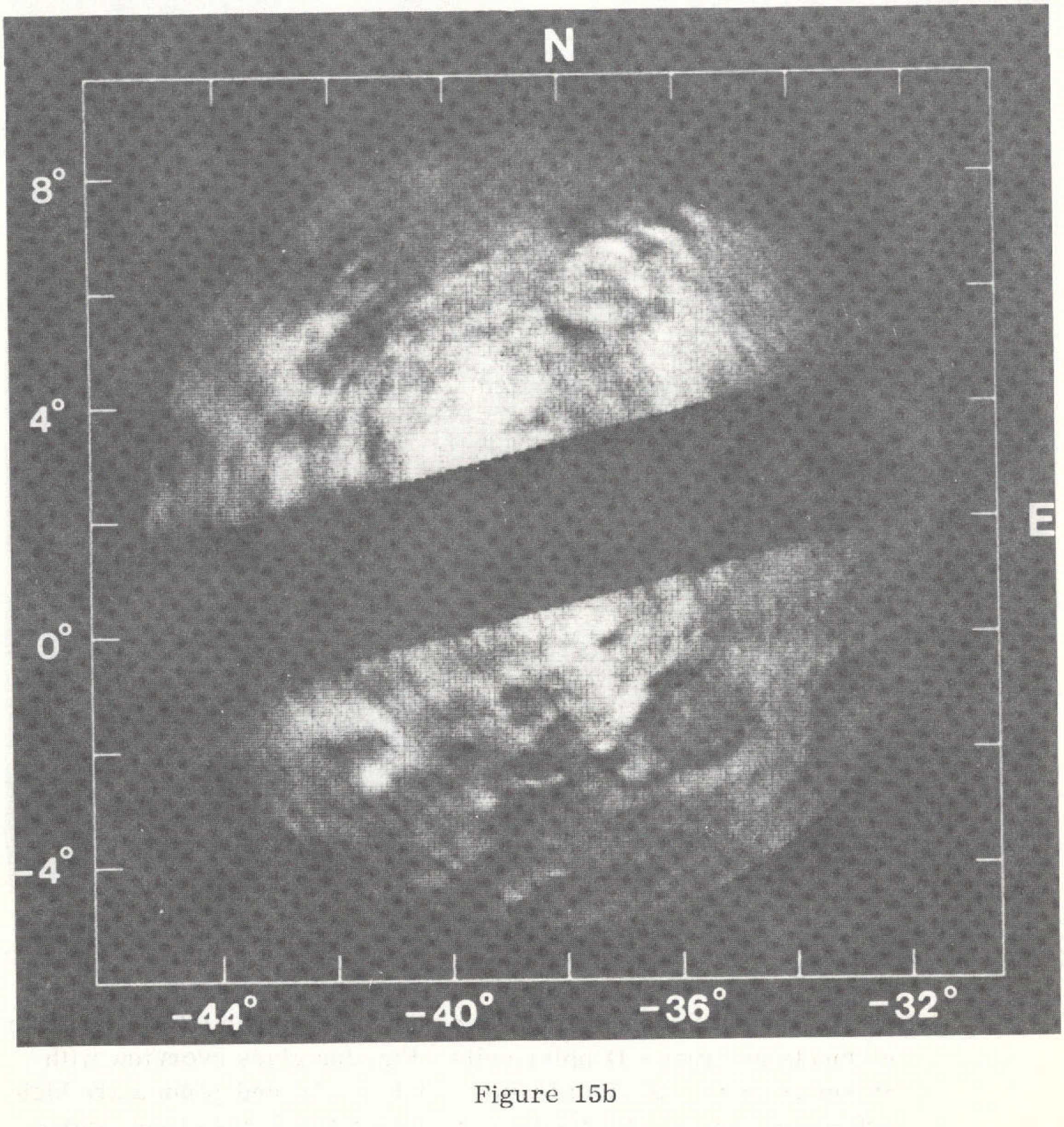


Figure 15b

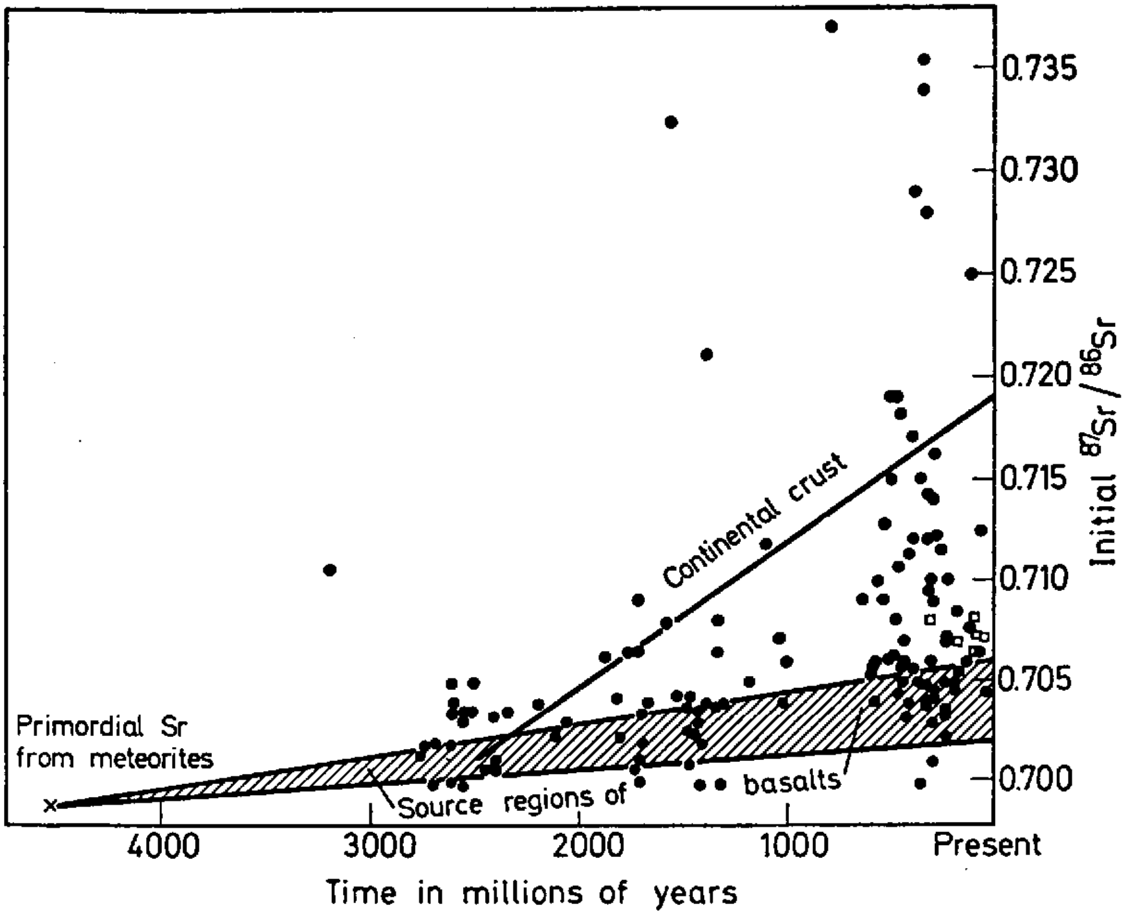


Figure 16. Plot of initial $^{87}Sr/^{86}Sr$ ratios of granites vs. age, from Faure and Powell (1972). Low ratios, in shaded region, suggest derivation of granites from mantle (source region of basalts); about 50% of plotted points fall here. High ratios, above continental crust Sr isotopic ratio development line, suggest at least partial derivation of granite from pre-existing sial; about 20% of granites fall on or above line. Intermediate ratios include Phanerzoic batholiths of North America (e.g., Sierra Nevada), and can be explained by several mechanisms discussed by Faure and Powell. For recent interpretations of Sierra Nevada isotopic ratios see Kistler and Peterman (1973) and Doe and Delevaux (1973), for Pb and Sr, respectively. Reproduced by permission of Springer-Verlag and the authors.

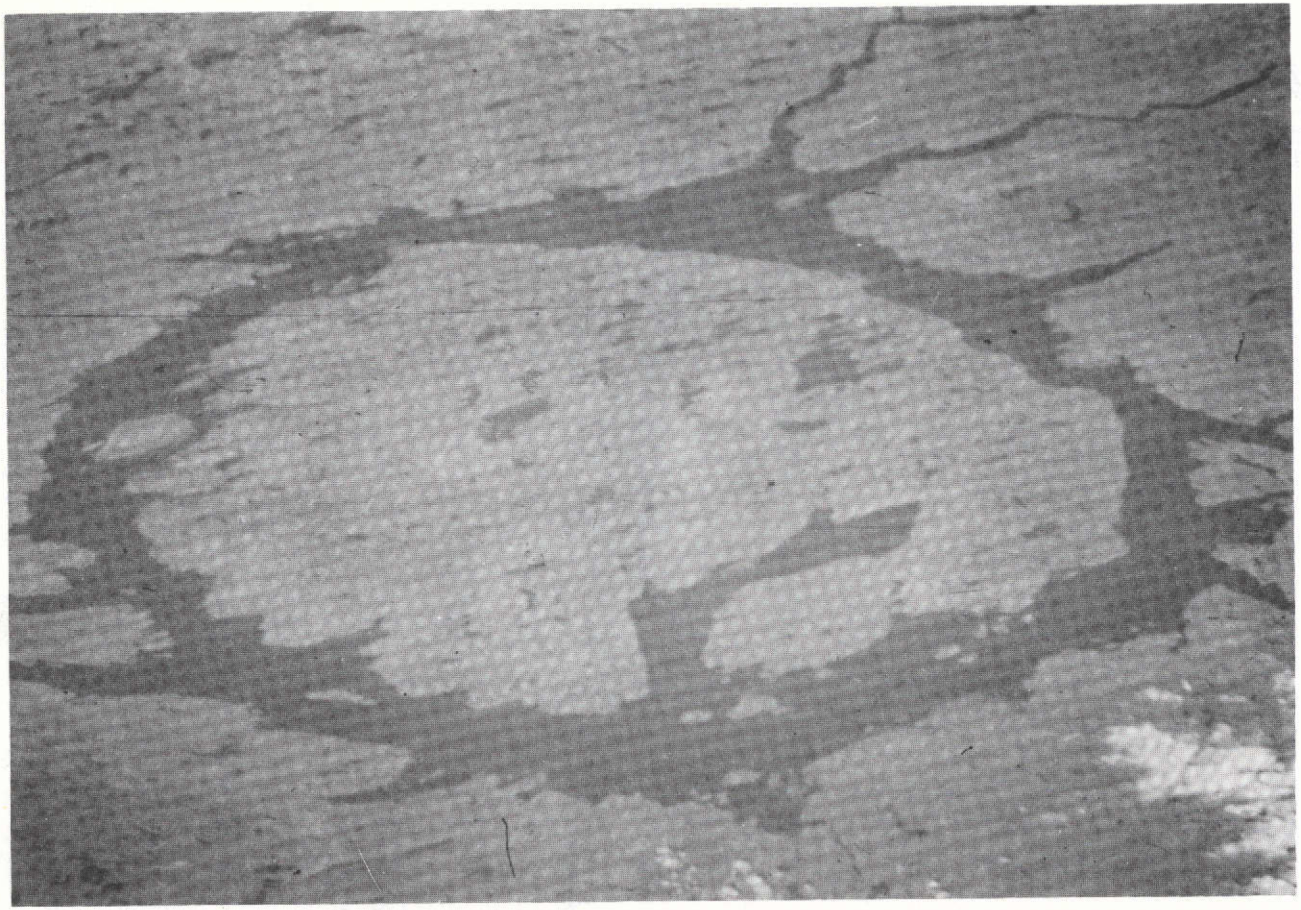
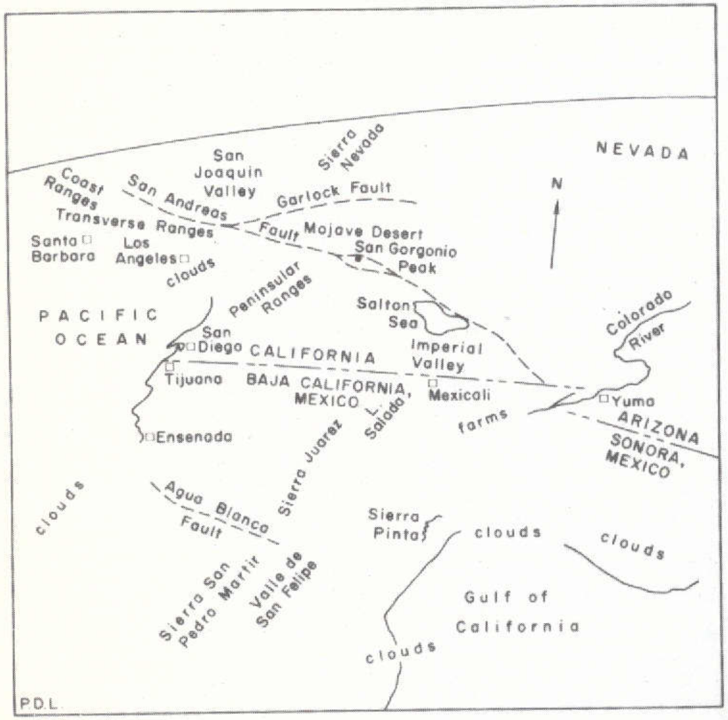


Figure 17. Skylab 2 70 mm photograph 65 km wide of Manicouagan impact structure, Canada, about 350 miles northeast of Quebec. Structure is in Precambrian rock, and is considered to be of impact origin from structural and petrographic evidence, with an age of 200-300 million years (Wolfe, 1971). Impact may have been followed by impact-induced igneous activity, producing monzonite. Circular lake, occupying ring graben, was formed from Manicouagan and Mushalagan Lakes by recent damming of Manicouagan River, and differs from appearance of most maps.

Figure 18. Apollo 15 photograph made with 500 mm lens from Lunar Module by D. R. Scott, showing Silver Spur, 800 meter high cliff on Apennine Front. Survival of layering, interpreted elsewhere (Lowman, 1972a) as volcanic flows of pre-Imbrian crust, suggests that similar layering in early terrestrial crust could have survived intense bombardment.



INDEX MAP

APOLLO 9 PHOTOGRAPH AS 9-21-3263

Note: Scale variable; San Diego-Yuma distance 145 miles.

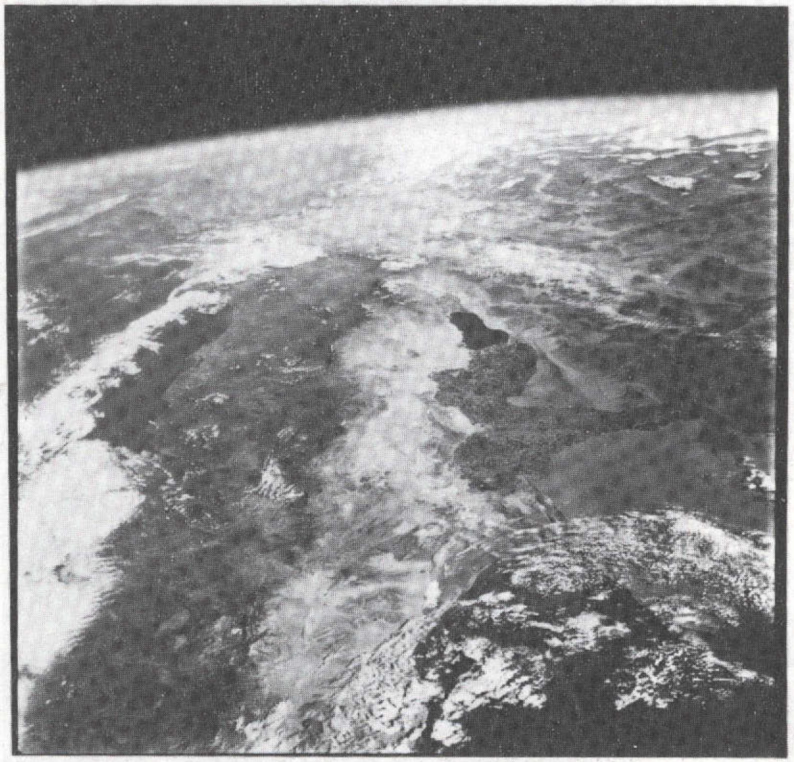
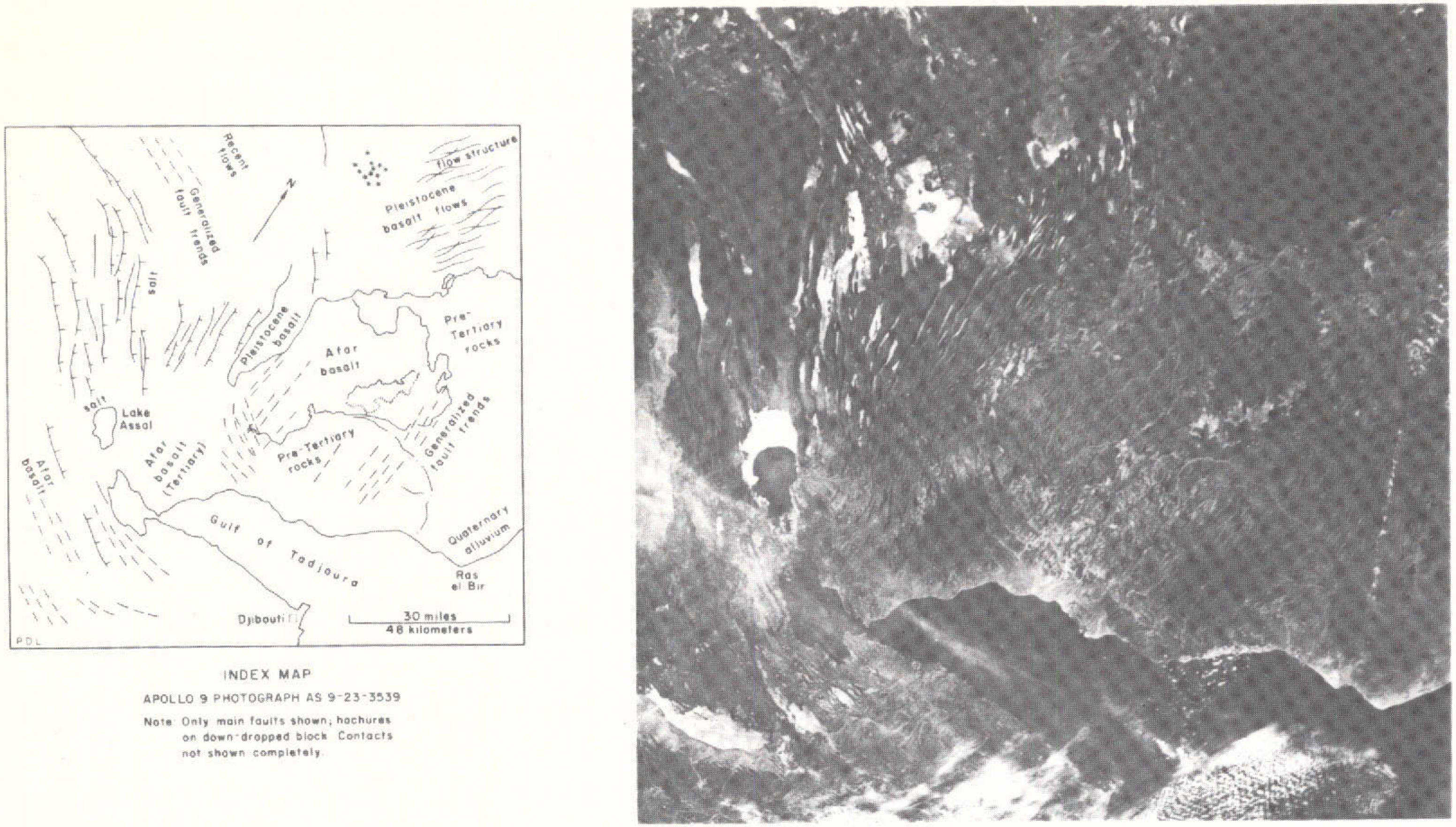


Figure 19. Apollo 9 photograph looking north over Gulf of California and Salton trough, an area of active sea-floor spreading illustrating present-day example of early stages of oceanization. (See Lowman, 1972b, p. 26, for detailed discussion.)



INDEX MAP

APOLLO 9 PHOTOGRAPH AS 9-23-3539

Note: Only main faults shown; hachures on down-dropped block. Contacts not shown completely.

Figure 20. Apollo 9 photograph of southern part of Afar depression, at about 42°E, 12°N. Afar depression is structural branch of the Red Sea, and interpreted as incipient crustal fragmentation leading to sea-floor spreading and eventual oceanization (or continental drift in some interpretations). (See Lowman, 1972b, p. 132 for discussion.)

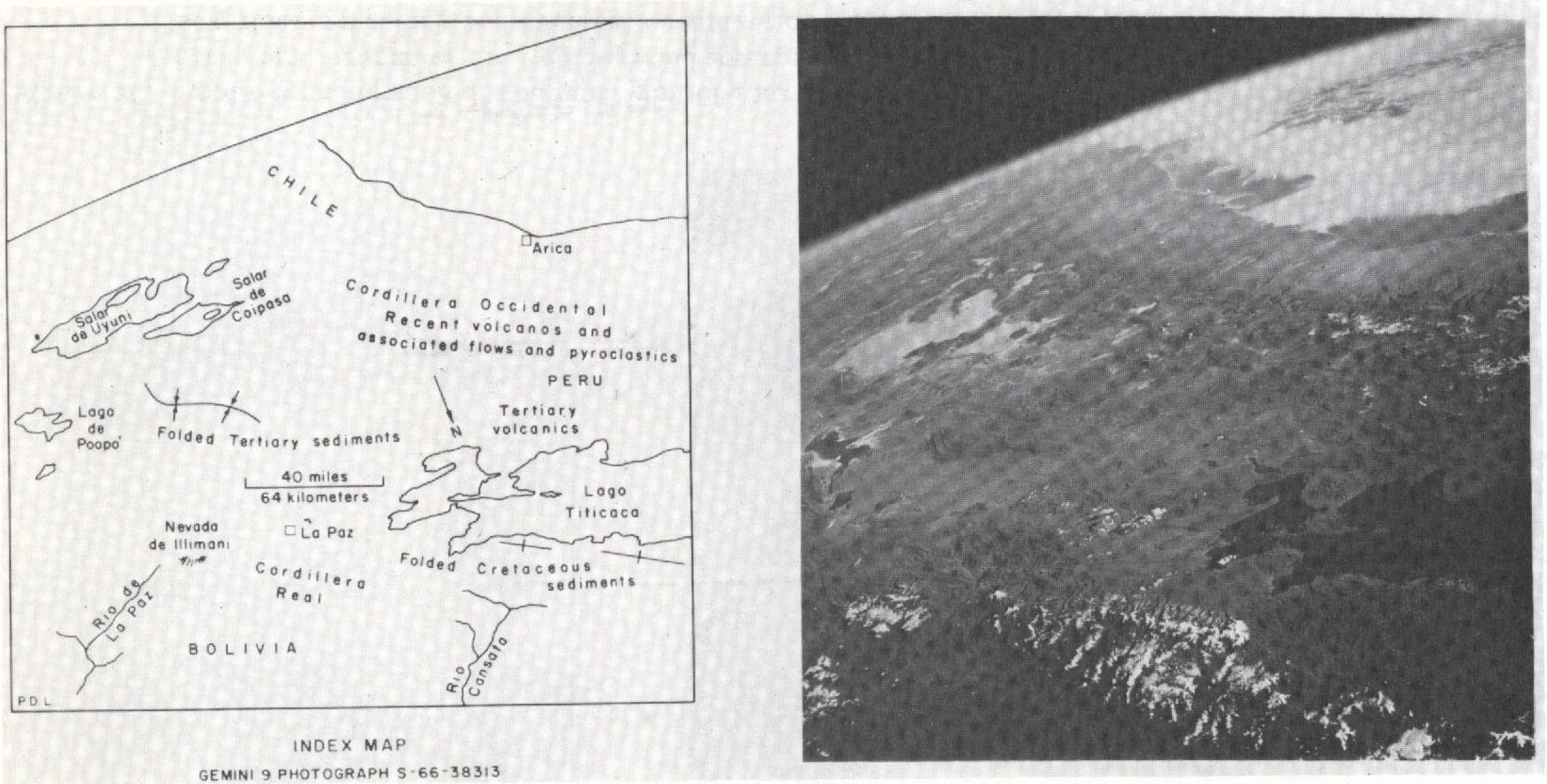


Figure 21. Gemini 9 photograph looking south over Andes, showing spatial relations between trench-subduction zone (off coast), volcanic belt, and older (pre-Mesozoic) rocks between volcanic belt and trench. Area interpreted here as one of oceanization and continental thickening. See James, 1973, for plate tectonics interpretation of Andes, and Lowman (1972b, pp. 90-95 for detailed discussion of photograph.