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WORKSHOP ON

EARLY CRUSTAL GENESIS: IMPLICATIONS FROM EARTH

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WORKSHOP ON

EARLY CRUSTAL GENESIS: IMPLICATIONS FROM EARTH

Compiled by:

William C. Phinney

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Cover: NASA Landsat imagery of the eastern portion of the Pilbara granite-greenstone Craton, Western Australia. Each side of photo represents about 120 km. North is to the top.

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I. Summary

Planetary Implications of the Terrestrial Archean

One of the major scientific advances as a result of the Apollo and planetary exploration programs is an improved understanding of the thermal, chemical, and kinematic evolution of the planets. On November 3, 4, and 5, 1980, a group of 34 geologists, geochemists, and geophysicists from 29 U.S. and Canadian state, provincial, federal, university, and other professional organizations participated in a workshop at the Lunar and Planetary Institute in Houston to consider ways to foster increased study of the early evolution of the Earth considering the planet as a whole. Emphasis was placed on the time interval extending from accretion of the planet until the end of the Archean about 2.5 billion years ago. This report summarizes the results and recommendations of the workshop. The recommendations are directed at NASA with the intent of exploring optimal ways in which NASA could integrate Archean studies with problems of planetary evolution.

The workshop set five goals for any forthcoming project:

1. To improve understanding of the evolution of the terrestrial planets, especially evolution of their crusts.
2. To foster use of global data sets including those collected from Earth orbit.
3. To identify the physical processes, as well as initial and bounding physical and chemical conditions, which determine the main features of the Earth's evolution and its contrasts with other objects in the solar system.
4. To encourage examination of the Earth's Archean crust from a global perspective.
5. To foster cooperative research between those investigators studying the Archean and those studying the planets.

A series of ten problems were identified for emphasis. They were:

1. What evidence exists for changes in the composition and mass of the crust with time, and what evidence exists that certain lithologies, such as high Na/K tonalites and peridotitic komatiites, formed in abundance only during the Archean?
2. How did the crust-mantle system evolve thermally with time? The heat from core formation was liberated in less than a few hundred million years and the heat from decay of ^{238}U and ^{40}K was more abundant during the Archean than subsequently: what were the consequences of this early high heat production.
3. What was the nature of the pre-4.0 b.y. crust, and do any remnants of it exist?
4. Were the tectonic processes that created the Archean granite-greenstone terrains different from those that created modern trenches and island arcs?
5. How did the Archean crust interact with the atmosphere, hydrosphere, and biosphere?
6. What were the effects of core formation on the mantle and crust?
7. How did the planetesimal bombardment prior to 3.9 b.y. affect the Earth?
8. How did juvenile volatiles outgas, and what were their effects on crustal evolution?
9. What were the properties of the Archean mantle, and what were their spatial and temporal variations?
10. What were the effects of formation processes on early evolution of the Earth?

With the intent of focusing on a more manageable number of topics, three themes were selected which embraced the fundamental questions listed above. These themes are inherently planet-wide and draw critically on the skills of the lunar and planetary investigators.

The first of the themes is directed at identifying and analyzing data from the terrestrial Archean to constrain models for planetary evolution. Conceptually this theme is built on the assumption that if one could fully: (1) describe the early temperature distribution in the Earth, (2) detail the spatial variation of the various constituents, and (3) understand chemical fractionation and convection, then it should be possible to fully describe the Earth's subsequent evolution. Conversely, if present or intermediate states can be adequately described, the initial conditions should be constrained. Although a complete quantitative description is far from possible, the correlation in the style and duration of planetary evolution with planet size and inferred bulk composition suggests that a limited number of parameters determine the gross outline of a planet's history. Mercury and the Moon, for example, both appear to have completed their major differentiations within a few hundred million years and have had little igneous activity within the last 3.9 billion years. In contrast, Mars and Ganymede, which are intermediate in size between the Earth and Moon, apparently experienced extensive activity for a few billion years before a major decline in activity.

The key data and observations on which most of the published models for planetary thermal evolution are based on the Moon, which died early, and on the Earth, which is still vigorously active. However, investigations of the Earth are severely limited by the lack of representative data prior to about 3.0 b.y. ago. The available information suggests that terrestrial evolution can be divided into three phases: (1) a phase of vigorous activity from 4.55-3.8 b.y. ago, (2) an early phase of craton stabilization beginning about 3.8 b.y. ago which blends into (3) a plate tectonic phase extending to the present. Considerable debate exists as to whether or not the mantle convection which operated during early fractionation is usefully described in its surface effects as plate tectonics: e.g., were continents subducted? Another debate centers on the extent to which clustering of isotopic ages reflects time episodes in Archean evolution. Evidence exists that the Archean-Proterozoic boundary represents a subtle but pervasive change in both the igneous and sedimentary record and may occur at different times in different locations. Differences of opinion exist as to whether the continental crust grew slowly and progressively or episodically. However, many workers agree that most of the present continents existed at the end of the Archean, although reworking has occurred one or more times subsequent to isolation from the mantle.

The second major theme to address problems of the terrestrial Archean in the planetary context is directed at surface conditions and processes. Most of the record of surface processes during the Archean comes from study of clastic sediments and to a lesser extent from chemical and possibly biological (e.g., graphitic) sediments. Recent oxygen isotope investigations of sediments suggest a surface temperature of 60°C which may explain the extreme silicification of virtually all types of Archean sedimentary rocks. A critical issue is the paleo-distribution of humid and arid zones. Determination of the composition of the Archean atmosphere, particularly its O_2 and CO_2 contents, remains a major subject of research. Processes of weathering, hydrothermal flow and ore formation all represent interactions of the crust with the atmosphere-hydrosphere and are of planetary signficance as well as important aspects of regional geology and mineral exploration. Paleoenvironmental reconstructions are important for identifying the position and nature of major boundaries of the "continents" and hence provide important constraints for tectonic patterns and processes.

The third theme focuses on Archean evidence for physical, chemical and isotopic transfer processes during early crustal evolution. The theme is narrower in scope than the previous two; however, unraveling diffusion and fluid flow processes in the middle and lower crust is important for extracting useful interpretations from the typical partially disturbed chemical and isotopic systematics of Archean rocks. In addition, understanding the nature and magnitude of chemical fractionation, diffusion and solution-redeposition mechanisms is critical in constraining the igneous history of our planet. Much of the work under this theme concerns the role of H_2O and CO_2 in determining diffusion coefficients, in directly transporting chemical components, in altering melting relations and in determining the rheology of the crust.

The workshop participants recommend a three-pronged approach to these research efforts:

1. A research program with funding of peer-reviewed proposals submitted in response to a widely circulated announcement.
2. A series of workshops and conferences on appropriate themes.
3. Cooperative studies involving the participation of both U.S. and foreign scientists using very different approaches. Particular emphasis should be placed on collaboration between groups determining elemental and isotopic compositions of rocks and groups producing geologic maps.

II. Introduction

Over the past 15 years NASA programs have contributed much new data relevant to the origin and evolution of the planets. As a result, a revolution has occurred in our approach to the evolution of crust-mantle systems of planetary bodies, with the appreciation that all but a few small bodies in the solar system probably underwent a period of extensive melting and differentiation during their first few hundred million years. Through combined geological, geochemical, petrological, and geophysical studies of data from the Moon there have been tremendous advances made in development of models for the Moon's thermal history, crustal formation, mantle evolution, volcanic activity, tectonic sequences, early meteoritic bombardment effects, and many other processes. The models, in order to be more generally applied and to be understood in the broader planetary context, must be further tested, modified, and verified by applying them to other planetary bodies of different size, composition, and location. Although various types of imagery, spectral, and potential field data exist for Mercury, Venus, Mars and the Jovian and Saturnian satellites, the extensive geological, geochemical, petrological, and geophysical data necessary for rigorous studies of models of their crust-mantle evolution are not available and probably will not be available for many years.

In contrast, the Earth is a readily accessible planet, and for at least the next decade, will be the only planetary body for which extensive new data sets can be obtained to rigorously test models of planetary evolution. Knowledge gained from the Earth will not only advance our understanding of planetary evolution but will also be of immense importance for planning future planetary missions. In the latter context, it can be used to: (1) narrow the range of planetary models that must be tested in future missions, (2) determine the critical data sets that will test the validity of the models, (3) better define the exploration priorities of planetary bodies and locations on them for which missions should be designed, and (4) select the experiments which will provide the most critical data.

The Early Crustal Genesis Program is a proposed NASA effort that utilizes a multi-disciplinary, multi-institutional approach to the understanding of the early stages of evolution of the terrestrial planets. Topics to be investigated in this program include: planetary formation, crustal features and their development, physical and chemical evolution, volatiles, tectonics, surface processes, metallogenesis, and paleobiology. At present we can characterize the sources of data for this program into four general categories: Earth, Moon, Meteorites, and other planetary bodies. The Earth provides the greatest source of data by far, and is the subject of this document. Additional inputs will be made to the development of the program through further workshops and a steering group to coordinate the workshop results.

We still have a very limited understanding of early Earth history, especially the formation and early evolution of its crust, a major planetary-scale problem. The early evolution of the Earth's crust-mantle system (approximately the first two and one-half billion years, or half of Earth's history) is manifested by the complex geology of the continental shields and has received little benefit from the revolution in the understanding of the genesis of ocean basins and movement of plates associated with the later evolution of the Earth. Thus the testing and modification of relevant models for early earth history have not kept pace with those for more recent Earth history. Inasmuch as the most critical data for planetary models are incorporated in the oldest parts of the Precambrian shields of the Earth's continents, the study of these shields is extremely important to the general application of planetary models for crust-mantle evolution.

The remaining sections of this report outline the overall program goals (Section III), suggest three possible themes, any or all of which could provide a focus for NASA's Earth-oriented part of a planetary program (Section IV), and provide a brief structure and rationale for the program (Section V). Appendix A outlines the major problems of the Earth's early crustal genesis as identified by the workshop participants. Appendix B summarizes the responses to a letter soliciting inputs on the program from a wide group of investigators. A list of the workshop participants is contained in Appendix C.

III. Program Goals

This program should strive:

1. To develop an improved understanding of the evolution of rocky planets, especially the generation of crust. Studies of the Moon, other planets, and meteorites have led to new hypotheses about the melting, differentiation, and energy sources involved in crust-mantle systems. Modeling and testing of hypotheses for the formation and evolution of planetary crusts should receive substantial effort.

2. To encourage the utilization of global data sets, including those collected from Earth orbit, in studying the Earth. Earth orbiting satellites have collected, and will continue to collect, imagery, spectral data and potential field data over a range of resolutions. These data can provide new insights into global-scale processes and patterns.

3. To identify the physical processes and initial physical and chemical conditions which determine the paths of crustal formation and evolution on Earth and other planets: parameters such as size, initial composition, and volatile content should cause significant variations in these paths. The extent to which these and other parameters may determine such paths should be identified.

4. To encourage examination of the Earth's Archean crust from a global perspective as an example of the evolution of a rocky planet. The early crust of the Earth contains petrologic, chemical, isotopic, structural, tectonic, and geophysical data that can be used to test complex models of crustal evolution. The accessibility of new sources of data allows for a continuously iterative process in revisions of models and selection of data, thus making the Archean crust an excellent example for such studies.

5. To foster cooperative research among scientists and organizations studying the Archean and those studying the crusts of other planets. Many national and international research efforts are underway on various aspects of the Earth's crust and other planetary crusts. Communication and collaboration between these investigators should result in a significant enhancement of these individual efforts.

IV. Program Plan

A. Introduction to Program Themes

In its pursuit of planetary exploration goals, NASA has had an extraordinary impact on the geosciences. This includes technical advances from the more precise and sensitive analyses of very small samples needed for study of limited materials from the Moon and meteorites, perceptual advances from comparison of the wider range of planetary characteristics and planetary bodies now available for study, observational advances from the broader range of instruments developed to obtain data for a wider range of planetary characteristics, and scientific advances from formulation of theoretical and empirical models of planetary development. Applications of these advances have already significantly improved our understanding of the Earth.

As part of its continuing pursuit of planetary exploration goals, NASA has the opportunity to extend its positive impact on geo-sciences by means of a program designed to study Earth in a planetary perspective which would add a new dimension to our understanding of planetary evolution. As applied to Earth, a planetary perspective is defined roughly as a viewpoint concerned with those processes that contribute to the spherically symmetric structure and composition of Earth. Clearly it is difficult to draw a sharp distinction between "spherically symmetric" and "broad scale" features such as ocean-continent differences. Certainly NASA programs have contributed greatly to our understanding of such features.

NASA can directly address these problems of understanding the Earth in a planetary persective by bringing together diverse groups of scientists to investigate planetary research themes. These interdisciplinary and intradisciplinary interactions may consist of: (1) field workshops and conferences directed at specific terrain types; (2) workshops and conferences directed at research themes; (3) publications of workshop and conference proceedings in the open, reviewed scientific literature; and (4) funding of appropriate research proposals.

There is a current need to bring together what are generally perceived as diverse groups of scientists (see Appendices B and C). Groups that might mutually profit from such interactions include: (1) field workers who are familiar with occurrences of specific rock types and have an understanding of the complexities of existing stratigraphy and structure; (2) laboratory workers who know the range and complexity of physical, chemical, mineralogic, or isotopic characteristics of these rock types; (3) scientists who are familiar with planetary images, lunar samples, hypotheses of planetary evolution, and spectral data; and (4) theoreticians who have a thorough understanding of idealized planetary development and the limitations on what is theoretically possible.

Consideration of the status of our understanding of problems associated with the development of the early Earth as set forth in Appendix A of this report has led to the definition of three research themes:

1. Archean Contribution to Constraints for Models of Planetary Evolution.
2. Archean Surface Conditions and Processes as Clues to Early Planetary History.
3. Archean Evidence for Physical, Chemical, and Isotopic Transfer Processes in Early Planetary Crusts.

Each of these themes considers the development of the early Precambrian in a planetary context. Each of these themes can be an effective focus of NASA efforts in utilizing our understanding of the Earth's evolution as a basis for understanding the broader problem of planetary evolution. Each theme has been designed so that a substantial research effort over 5 to 10 years will yield significant advances in our understanding of the Earth's crust directly, and of the complexity of planetary processes of crustal formation in general. **We emphasize that these advancements require a substantial research effort.**

By design, these themes focus on the first half of Earth history, because it appears that approximately 2.0 to 2.5 b.y. ago there was a turning point in Earth history. Most observations of rocks younger than 2.0 to 2.5 b.y. can be understood in terms of modern Earth processes. Prior to 2.0 to 2.5 b.y. ago, however, the dominant processes operating to form the Earth's crust appear to have differed in character. These differences affect (1) tectonics, (2) surface conditions, (3) atmosphere and ocean composition, (4) rates of volcanic processes, and (5) intensity of convection. Although Venus, Mars, and Earth are very different today, they might have had similar early developments. In that case the three terrestrial planets may have diverged during that early part of Earth history being addressed in our themes.

B. Theme 1: Archean Contribution to Constraints for Modeling Planetary Evolution

Rationale

One of the major objectives of planetary science is to predict the evolution of various planetary bodies from various sets of initial conditions, or to deduce initial or other prior conditions from observations of evolved conditions. Both approaches should strive to produce compatible results for the evolution of any planetary body. Thermal, tectonic, chemical, and petrologic evolutionary models, all of which are closely interrelated, can be combined; they are constrained by observed or assumed parameters that serve as initial and boundary conditions. Planetary evolution depends on such initial conditions as size, chemical composition, content and distribution of volatiles, abundance and distribution of heat-producing radioisotopes, and flux of impacting materials during accretion and late-stage bombardment. Boundary conditions are constrained by such observable data as chemical and isotopic compositions of materials formed at various times in the body's evolution, structural patterns developed at various stages, surface conditions prevailing (e.g., weathering, atmosphere, ocean) at various stages, and physical conditions occurring (e.g., temperatures, pressures, magnetic fields) at various stages.

The history of crustal processes varies markedly from one planet to another. The surfaces of some planetary bodies indicate an active early history followed by quiescence; these record the processes of early evolution (e.g., Mars, Ganymede). The surfaces of others indicate early quiescence and record whatever processes occurred during and immediately after formation (e.g., Moon, Mercury, Callisto). The surfaces of still others reflect a currently active state and provide insight into processes that are still evolving (e.g., Earth, Io, and, perhaps, Venus). Surely all will eventually run down in some way, but their various stages of evolution provide a panorama of planetary evolution.

Models for evolution of the Moon, an early quiescent body, have been constrained by data from imagery, orbital instruments, sample analyses, emplaced geophysical instruments, and measured meteorite fluxes. Significant advances in modeling include the effects of heating from early accretion, tectonic and thermal effects from early impacts of planetesimal-size bodies, formation and differentiation of an early global magma ocean, tectonic implications of an early magma ocean, variations in chemical composition with depth, and the effect of volatiles on petrogenesis and tectonic stability. Some of the data that helped develop these models comes from observed differences (including isotopic compositions and chemical compositions) in lunar rock types of different ages, comparison of the Moon's present magnetic field with remanent magnetism in lunar rocks, changes in impact fluxes derived from imagery of craters in combination with seismic events and impact pits on returned samples, determinations of crustal and lithospheric structure from seismic and magnetic measurements, and combinations of surface heat flow data and isotopic heat sources in lunar rocks.

Data from planetary bodies other than the Moon are much more limited, and models of their evolution are much less constrained. For those bodies from which there is limited data and where there appears to be little activity beyond the extensive craters produced during the initial period of bombardment, the Moon can serve as a point of departure for preliminary modeling. However, for those bodies that display evidence of a more active history the Moon is less useful. For example, Mars displays terrains of several different ages (from comparative crater densities), huge volcanic structures, extensive canyons, and unusually high contents of Fe and S in surface materials. Venus' surface consists mostly of relatively flat plains with two plateau-like to mountainous continental-sized masses rising above them. At least two categories of surface material detected at three landing sites, one with high K, U, and Th, and another with low K, U, and Th, suggest extensive differentiation of Venus. Correlation of venerean gravity highs with topographic highs indicate compensation at a depth of about 100 km, which requires either severe upward differentiation of heat sources or continuous dynamic activity. Io displays intense modern activity of sulfur-rich volcanoes over much of its surface. Ganymede shows evidence of extensive past tectonic activity over nearly all of its icy surface.

Much of our modeling of planetary bodies relies on ideas developed for the relatively unevolved Moon or the very highly evolved Earth. However, when attempting to incorporate ideas from the more highly evolved Earth one must select from various segments of Earth's history or processes because there is no comprehensive model for Earth's evolution. In particular, processes that occurred during the first half of Earth's history are very poorly understood in comparison with those of its more recent history. Yet it is the first half of Earth's history which should provide the necessary link with the evolution of other planetary bodies, for it is during this time period that the various paths of evolution were determined by the initial conditions. The Moon and Earth are drastically different in such initial conditions as size, content of volatiles, and density. Explanation of the drastic differences in their observed evolutionary trends on the basis of such differences in initial conditions should help provide better models to explain the observed features of other bodies. There has been a well organized effort over the past decade to develop such models for the Moon, but such efforts for the early Earth have been more fragmented and less comprehensive.

It is the intention of the proposed new initiative to focus on quantitative modeling of crust-mantle interactions and to emphasize the as yet inadequately considered constraints placed on evolutionary processes from a clear understanding of: (1) the time dependence of influx of meteorites and its thermal consequences; (2) cosmochemical constraints ... ved from astronomical observations of the solar chromosphere and asteroids, and analyses of lunar samples and meteorites; (3) the transport processes of heat flow, fluid flow, and diffusion within and through appropriate lithologies; and (4) the large scale motions of the crust and mantle.

Problems in Archean Modeling

There are many competing views of the Earth's crustal history. Some suggest that current processes and conditions can be extrapolated backwards in time to the age of the earliest preserved rocks. Others suggest that there has been a secular evolution of crust-forming and crust-modifying processes. Still others suggest that changes did occur, but happened suddenly and possibly synchronously over the surface of the Earth. There is a need for an accurate chronology of crustal events.

The Earth's accretion was dominated by impacts, but post-impact processes produced complementary oceanic and continental crust. Accretion greatly affected the distribution of volatiles and the components that formed the core and mantle. Where these important components of the Earth were located at various times in the Archean is a first-order problem, the answers to which will influence many other hypotheses. Secondarily, the evolution of the mantle strongly influences crustal development, especially in the extent to which convection occurred. The time-frame and effectiveness of the impact process must also influence heterogeneities through addition of energy, and the evolution of the crust through re-working. The post-accretion, post-impact internal evolution of Earth produced units preserved from 3.8 b.y. onwards and possibly earlier. Each of these stages may have contributed observable remnants, that can be studied with varying degrees of difficulty from the existing Archean terrains. A number of key questions on crustal evolution are outlined and discussed in the following paragraphs.

1. Is it reasonable to develop models of Earth history in the following three phases: (a) Accretionary-meteorite impact phase, (b) Early mantle-crust fractionation phase, and (c) The plate tectonic phase to the present?

The major problems of accretionary theories are the size distribution of infalling bodies and their degree of heterogeneity in composition. Both would have mutually affected the chemical profile of the Earth. Determining what actually happened during accretion is important to our understanding of the Archean. It may well be, however, that development of a satisfactory theory for the evolution of the Archean will lead back to an understanding of terrestrial accretion and thence to a clearer understanding of how other planets formed. This feedback would be of considerable scientific importance.

Meteorite impacts should have influenced crustal development for a brief period of time after accretion. A search for evidence for and against this viewpoint must be maintained since that process may strongly influence the interpretation of early Archean rocks.

A major phase of mantle-crust fractionation appears to have occurred during the Archean. The change over to a tectonic regime that includes large basins, troughs, and/or plates is poorly understood; indeed some researchers adopt a strongly uniformitarian view of plate tectonics, applying this model to all Archean complexes, while others claim that few, if any, Precambrian, including Proterozoic, geosynclines can be explained by plate tectonics.

While it is possible to pose general question number 1, and answering it would be aesthetically and scientifically pleasing and important, direct solutions are not to be sought, but rather will be acquired from integration of field, laboratory and theoretical studies which are directed at specifics as in the questions which follow.

2. Are there time episodes for formation of supracrustals, granitoids, stabilized cratons?

Chronologic studies are very important in establishing the relative and absolute order of events that formed the different Archean terrains and in comparing different terrains of the same age. Since gneissic and granite-greenstone terrains in some cases apparently formed in proximity (100 km) to one another, the reasons for the separate but temporally equivalent styles of evolution will place important constraints on any models of their origin. Comparison of chronology for events within and between individual terrains may establish what events are necessary before others can follow, and also may establish the length of time that is required for completion of an event or the interval that is required between events. (Example: Do K-rich granitic rocks occur no sooner than 20 m.y. after the first tonalite is emplaced in a terrain?)

Isotope geochronology, in combination with good field studies, provides the key tools for deciphering Archean geology. The variety of techniques and level of technical perfection in isotopic analysis has risen greatly in the past decade. A great deal of recent effort has been devoted to seeing through metamorphic overprinting to the age of rock formation. This effort has now led to the widespread discovery of rocks formed in the time period 2.9 to 3.8 b.y. Early geochronological efforts, mainly based on K-Ar, Rb-Sr and model lead ages, indicated that there is a strong temporal age grouping on the Canadian Shield and probably on several others, i.e. around 2.6, 1.7, and 1.0 b.y. However, much of the early data certainly represent metamorphic, rather than formational ages. The Ar data, in particular, probably date the time of erosional unroofing of the rocks; i.e., cratonization or the termination of metamorphic history.

To assess questions about timing of crustal processes, it is essential that all types of age determination be considered: formational, metamorphic, and cratonization. Such combined isotope and field studies are needed not only individually to sort out local geological history, but also collectively to decide to what extent the preserved rocks have been subjected to large-scale or even world-wide tectonic processes. Possible projects under this task would be:

(a) Compiling and classifying age data from shields

(b) Filling gaps in the collective age record

(c) Workshops to discuss the interpretation of certain types of isotopic data
(d) Direct or inferential dating of correlateable geological events, e.g. significant uncomformities
(e) Construction of age-province maps, for parts of the world where this has not been done with due regard to the meaning of the data

3. *What evidence is there for secular or episodic evolution of geochemical patterns or petrological processes?*

The most basic data set is that which characterizes the lithology and structure of terrains as they presently exist. The types of rocks present and their relative abundances can be ascertained from field work and petrography. A step beyond this most basic characterization of lithology is establishing the major and trace element chemistry of the rock types. This aspect of Archean terrains has received considerable attention during the last 10 years and a primary data set is available but is very uneven in geographic and lithologic coverage. A more specialized type of geochemical information comes from isotopic tracer studies and includes both stable (O, H, S) and radiogenic (Sr, Nd, Pb) isotopes. This package of lithologic-geochemical data can be, and has been, used for a more limited type of modeling than that hoped for here.

The first geologists who studied the shields perceived at the outset that there are gross differences in structure and lithology between Archean and Proterozoic rocks. Evidence gradually accrued that this extended to geochemical parameters and petrological processes. It is now known that Archean rocks, as exposed at the surface, are characterized by low K_2O/Na_2O, low initial $^{87}Sr/^{86}Sr$, low $^{18}O/^{16}O$, absence of Eu anomalies in shales, and several other differences in well-defined parameters, when compared with Proterozoic equivalents. While some questions remain concerning the data base, these facts seem real enough to be major parameters for consideration in any models. For further refinement the data base needs extension with greater analytical accuracy, choice of first-class material, and careful selection of samples, to obtain systematically comparable suites.

Within the Archean record, it is as yet uncertain whether the changes seen at the Archean/Proterozoic boundary were proceeded by more subtle progressive changes, other than those arising from declining energy sources. It is these smaller-scale effects which will enable to us to approach answers to the questions of recycling and continental growth. Small-scale secular or episodic changes can be established only if inter-laboratory accuracy of analysis exists, if petrological processes can be adequately defined, and if rock systems are properly dated.

The chemical systems which will most quickly reward study in this regard are those where isotopic data can be used to clarify the meaning of their associated element abundances in the rock as seen today. Thus the U-Th-Pb, Rb-Sr, Sm-Nd, Lu-Hf and Re-Os systems merit exceptionally intensive study. $^{87}Sr/^{86}Sr$ has indeed already been used as a base for an hypothesis of slow Archean continental growth and $^{143}Nd/^{144}Nd$ to show that this growth was not strictly uniform but was likely to have been episodic. Again, the data base is small. Isotope data have also been used in developing recycling theories.

Stable isotope ratios and abundances of noble gases have also been used widely, but as yet are not diagnostic in relation to intra-Archean problems. $^{13}C/^{12}C$ and D/H ratios may be anticipated to become more useful. Improvements in instrumental techniques, especially the ion microprobe, will enlarge the scope of stable isotope studies and enhance the possibility of finding intra-Archean variations. Similarly, trace/major element ratios, or trace/trace ratios have been widely used to characterize igneous rock systems and to a lesser extent sediments and their metamorphic derivatives. Trace transition metals and rare earths have so far produced the most useful geochemical results, but secular trends have been difficult to define and are generally controversial. Not only absolute abundances in the reservoirs and their derivatives, but also partitioning constants and igneous fractionation processes must be understood before such data can be applied to secular variation questions.

Finally, it is generally assumed that igneous processes are time-independent, yet the proportion of komatiites and tonalites is far greater in the Archean than in younger terrains and the proportion of alkali basalts is far less. These processes are known to be subject to control by volatiles and thermal gradients. Since the whereabouts of the various volatiles during the Archean is a very open question, a systematic study of igneous processes and compositions of associated fluid inclusions should yield conclusions relevant to secular change. Likewise, thermal gradients in the mantle will control the depth-range of mineral phases, thus controlling the composition of partial melts. Secular change of igneous processes should, therefore, provide information useful for development of models.

To summarize, one very powerful approach to secular or episodic evolution is that of intensive isotopic studies, because these yield both time and tracer information. Continuous development of techniques must be encouraged, especially in applications to small samples, such as via the ion microprobe. Greater cooperation among field and laboratory scientists will improve sample selection procedures and enhance the likelihood of achieving first-class results. A further set of data that needs development is trace-element concentrations in various rocks and minerals and trace-element partitioning between phases, the latter being essential to all studies of mantle differentiation.

4. What is the meaning of the contrasting Archean and Proterozoic sedimentary record?

A common generalization of geological field observations is that Archean rocks contain sediments of the greywacke suite, and limited chemical sediments such as iron formations of volcanogenic association, most deposited in limited sized, rapidly evolving basins. In contrast, the Proterozoic record reveals the first examples of long coastline controlled sedimentary formations: extensive orthoquartzites, carbonates, red beds, and peraluminous pelites deposited in aulocogens or continental margins.

This dramatic change from the Archean to the Proterozoic suggests that tectonic processes produced a change from relatively unstable, perhaps thin, permobile crust to more stable, thicker, platform-geosyncline type crust: clearly a threshold in the evolution of continents. The stabilization, uplifting, erosion, and formation of platform type sediments associated with this transition period lasted hundreds of millions of years beginning as early as 3.0 b.y. ago in southern Africa and about 2.6 b.y. ago in Canada. It has been argued that this gradual stabilization of tectonic activity results from the gradual decrease in heat production associated with radioactive decay of K, U, and Th. Geotherms would migrate downward producing changes in phase relations, volatile concentrations, and convection regimes. The possibility of this transition causing a change from formation of many Archean continental nuclei in some type of active and rapid proto-type tectonic regime to coalescence of the many mini-continents into one, or a few, large stable Proterozoic continents in a less active regime should be investigated. Detailed studies of changes in the Archean to Proterozoic stratigraphic sedimentologic record should reflect changes in stability of continental masses, thereby providing a thermal and structural framework that constrains tectonic processes in models of crustal development.

5. How did differentiation and recycling between crust and mantle proceed?

The significance of this question is partly discussed in question 3 above. It may be said that there are two major schools of thought regarding the origin and history of the Archean continental sialic crust. Either it grew slowly and steadily, or it was present nearly in its current bulk prior to 3.75 b.y. Since many contributors to this subject agree that some 80% of the present continents were present at the end of the Archean, there is clearly a fundamental difference of opinion.

To examine the differentiation aspect further, input is required from natural examples and from experimental petrology. Intensive activity is underway on the former but relevant experiments are as yet neither numerous nor highly definitive. The partial melting of complex ultramafic silicate systems or eclogites in the presence of H_2O is by no means fully understood, whereas the role of CO_2 has been deciphered but is not as yet fully developed. Experimental petrology at ultrahigh pressures is definitely in its infancy and will be relevant to our understanding of what was (and is?) trapped in the lower mantle. Thermal modeling of and experiments relevant to the Archean oceanic crust and upper mantle have already yielded some preliminary conclusions about the origin of komatiites and about the possible thicknesses of mafic and felsic crusts. Modeling and experiments relevant to phase changes and partial melting at 50–100 km depth would appear to be required. This research should examine possible recycling processes in the presence of high geothermal gradients. Of particularly critical importance will be studies on the origin of gravitational instabilities, which will cause recycling and/or differentiation.

The question of whether recycling and differentiation can proceed independently also needs answering. In present-day processes, they are partly linked through ridges and subduction zones, but whether Iceland-type situations involve much recycling is an open question. Archean models will require appreciable physical modeling, based on poorly defined parameters such as geotherms and densities. Because these studies will apply to the post-impact phase, examination of other planetary crusts should influence the choice of models.

Besides the relevant major and trace element studies mentioned in question 3 above, study of the distribution of K, U, and Th is relevant to the rates of recycling and differentiation. The isotopes ^{40}K and ^{235}U were producing between twice and five times as much heat in the Archean. The contribution of primordial heat, i.e., cooling of the interior, also must have been much greater in the Archean than now. All of these factors would have led to higher mean temperature gradients. More speculative is the degree of latent heterogeneity. The distribution of radioisotopes and the geological implications of such distributions merit intensive study.

A combination of intensive development of modeling of dynamic mantle systems with improved experimental petrological techniques is required to address these questions. The rapid extension of experimental capability at pressures > 250 kb (lower mantle) is also necessary.

6. *What stabilized the cratons?*

Most Archean terrains have experienced a substantial amount of tectonic modification. Structural studies are necessary to reconstruct the terrains and establish their primary configuration. Structural studies also serve as an insight into the large scale tectonic or dynamic conditions in which the crust was forming. These tectonic conditions can place very important constraints on crust-mantle dynamic relationships.

An outstanding characteristic of shields (which is implied in the name) is their stability. They are areas where no important, widespread thermal or penetrative deformational events have taken place since early time. Yet the supracrustal rocks of the shield, and particularly the Archean shields, display a history of intense deformation and/or metamorphism. It is fundamental to understanding crustal geology not only to learn what caused the tectonic activity of the shields, but what produced the stabilization (cratonization). Clearly erosion, presumably following substantial uplift of the land surface relative to sea-level, is an important component of the process. Many questions follow from this general topic.

a) When were the various shield areas cratonized?
b) How much relative uplift was involved?
c) What is (are) the mechanism(s) for cratonization?
d) Uplift relates closely to isostasy and roots of the continents. What roots exist under the present continents?
e) We see the preserved rocks. What constituted the remainder and what happened to them?
f) What are the associated upper mantle conditions?
g) To what extent is craton stabilization dependent on low K, U, Th; high Mg/Fe?

Possible projects include: (a) dating of cratonization as distinct from formation and metamorphism and (b) measuring uplift and erosion through downward migration of the geotherm as traced by Ar-Ar isotopic dating, paleomagnetism, petrologic phase relations, and fluid inclusion investigations.

7. *What are the implications of planetary convective models for evolution of the Archean crust?*

The convective regime in the Archean was undoubtedly more vigorous than in the Phanerozoic. 3.8 b.y. ago, the energy output from the mantle was more than twice as great, due to higher radioactivity and cooling rates (primordial heat), but at this time the general character of convection was already much more similar to Phanerozoic convection than to the behavior at formation time 4.5 b.y. ago. This settling down probably occurred fairly early because: (1) core formation was probably completed within the first 0.1 b.y.; (2) planetesimal infall had a comparable decay time; and (3) the rheology of the Earth is strongly temperature-dependent, so that the rate of heat removal adjusts reasonably well to the rate of heat generation.

However, the convection in the early Archean was sufficiently more vigorous to result in some significant differences in tectonic style from the younger Phanerozoic. Most notably, the mean heat flow would have been at least twice as great, leading to attainment of temperatures sufficient for creep, melting, etc. at depths less than half as great as now. Plate velocities would have been moderately greater. More problematical is their horizontal length; the consensus is that it was appreciably shorter, due to greater influence of interior conditions compared to the boundary layer on planforms.

Rigorous thermal evolutionary models have not yet been developed, partly because of the imperfect understanding of the more accessible present-day mantle convection and partly because of large scale computer costs. Such work as has been done is based on boundary layer theories which relate the heat delivered to the Rayleigh number: essentially, the ratio of buoyancy to diffusive effects. These analyses do not answer questions important to interpreting Archean data, such as the length scale, the tendency to oscillations in mantle convection, and the degree of lateral heterogeneity. At present, heat flow varies from $\sim 1/2$ to ~ 3 times the global mean. If the same ratio applied to variations about the higher mean heat flow in the Archean, temperature gradients in the hottest places would have been 160°/km.

Purely mechanical flow models predict that significant lateral heterogeneities in most of the mantle will die away into stratification in a time short compared to the age of the Earth, even for present day conditions. Hence heterogeneities are probably maintained dynamically by heat source variations, etc.—a sort of chicken-and-egg situation most obvious now at subduction zones. When and how oases of low temperature and isostatic compensation first developed to allow craton stabilization is presently quite speculative.

The comparatively rapid decline in energy in the first $\sim$ 0.7 b.y. would have been conducive to sporadicity in behavior. Convective systems have an appreciable degree of memory, i.e., they tend to have patterns reflecting past conditions to some degree, rather than some instantaneous optimum. Hence changes in patterns happen somewhat convulsively, usually as the consequence of the development of a boundary layer instability. If Pangea's breakup in the Phanerozoic is an example of such an instability, it seems unlikely that irregularities of the flow of similar magnitude could have existed in the Archean when the degree of heterogeneity was probably not so great.

In summary, beyond the broad zero-order considerations of long-term energetics, theoretical fluid dynamics can be suggestive although probably not assertive about the character of endogenic effects in the Archean. Geophysical fluid dynamicists should occasionally be brought into contact with Archean geologists and isotopists to be made aware of their problems. As the theory evolves and computers become more effective, NASA should be prepared to support some fairly large scale simulations of "mantle weather" and the consequences for the lithospheric and crustal boundary. But this stage is probably a few years away. Meanwhile, budgets appropriate to models of planetary thermal evolution can be comparatively modest.

Most of the above questions and required data sets involve material that is exposed at the surface. The models that are needed also will require data regarding the rocks, structures, and conditions at depth. These data sets will be furnished by geophysical, field, and petrologic studies. Geophysical studies can establish the third dimensions of the exposed rocks that are critical to the question of relative abundances of rock types. Geophysical and field studies can provide constraints on the structure and composition of the crust and on the physical relationship between the crust and the upper mantle. Petrologic studies can provide insight into P-T gradients necessary for the production of basaltic, tonalitic, and granitic melts representative of the rocks found in Archean terrains.

In order to successfully model the origins of Archean terrains diverse sets of data and theory will be needed from the major fields of geochemistry, geophysics, and petrology. Various parts of the data sets are presently available, but additional information is needed. In fact one beneficial role of the modeling should be to identify information requirements and what is mandatory or desirable to properly constrain the models. If the origin of Archean terrains can be fitted only by several different models, then a very important insight into both the complexity of early planetary evolution and possibly early large-scale heterogeneities in the planet will be gained.

C. Theme 2: Archean Surface Conditions and Processes as Clues to Early Planetary History

Introduction

An understanding of the evolution of planetary surfaces necessarily involves a better knowledge of the early surface history of the Earth. A new and vigorous research effort in this area would rapidly yield significant results and could be readily applied to data already collected from other planets. If guidelines for the evaluation of the resource potential of the Earth and other terrestrial bodies are to be developed, this research effort is essential.

The following research objectives and approaches are particularly ripe for investigation and would provide an immediate advance in an understanding of surface conditions and processes.

1. Archean Climate

A critical parameter affecting the surface character of a planet is the basic nature of its climate. Important questions about the Archean climate are concerned with surface temperatures and the composition and evolution of the atmosphere.

Surface Temperatures Recent investigations of the isotopic oxygen composition of certain Archean cherts have suggested surface temperatures on the order of 70°C at 3.4 b.y. If correct this result places constraints on models for the luminosity history of the sun and/or the evolution of the terrestrial atmosphere, matters of paramount importance for all planets. Additional work coordinating this isotopic data with the associated sedimentary structures and textures (i.e., environment of deposition, source area, and diagenesis) is required to better understand the meaning of oxygen isotope ratios in silicified sediments before the isotopic temperature can be firmly interpreted.

Arid or Humid Atmosphere The moisture content of the early Earth atmosphere is an important question for the temperature history and the overall water cycle of an evolving terrestrial planet. Many aspects of sediments are indicative of humid vs arid climatic conditions. More extensive sedimentologic analyses will supply qualitative information on the overall character of the Archean atmosphere. More detailed petrologic examination of recently discovered evaporite sequences is particularly encouraged.

Chemical Composition of the Atmosphere and Hydrosphere A long standing question of Earth history is the abundance of atmospheric oxygen at the time of the oldest sedimentary rocks. Early models of a reducing atmosphere have recently been challenged by workers noting significant oxidation of certain rocks exposed to the Archean atmosphere. A more detailed mineralogical and geochemical investigation of Archean iron-bearing sediments and Archean weathering profiles is required to resolve this important question. The same analysis will place constraints on the relative levels of other atmospheric constituents.

The present-day chemistry of ocean water is controlled by equilibria between the following fluxes: (a) continental flux composed of the dissolved load of rivers; (b) oceanic crust-sea water exchange; and (c) removal of chemical species via sedimentation. The composition of ocean water at any moment in geologic history reflects the weighted global mean of these fluxes; the record is preserved in chemical sediments such as occur in Archean terranes. Systematic studies of secular variations in the chemical and isotopic composition of carbonate rocks, cherts, and sulfates has revealed first order (10^8–10^9 yrs) changes in $\delta^{18}O$, $^{87}Sr/^{86}Sr$, $\delta^{34}S$, polyvalent metal and alkaline earth metal concentrations coupled with second order (10^6–10^7 yrs) fluctuations in $\delta^{13}C$, $^{87}Sr/^{86}Sr$, and $\delta^{34}S$. Further studies of this type are particularly desirable as the existence of light $\delta^{18}O$ in Archean sediments, considered by some to indicate higher temperatures, may instead be due to a different sea water composition at that time.

Constraints on Planetary Degassing Models Several degassing models for terrestrial planets have recently been generated by research supported by the NASA lunar and planetary programs. A major effort should be made to constrain these models with information derived by direct analysis of early sediments. Conversely, early sediments should be examined for evidence of interaction with atmospheric constituents predicted from degassing models.

2. Interaction of the Crust with the Atmosphere, Hydrosphere, and Biosphere

The bulk of sedimentary products are a result of the interaction of crustal material with a fluid and/or gaseous medium.

Nature of Weathering Rock exposed to the Archean hydrosphere and atmosphere must have undergone significant low-temperature alteration. This process controlled the composition of the sedimentary products and was a major factor in establishing Archean ocean chemistry. The mineralogy and chemistry of the sedimentary products of the water-rock reaction, in particular submarine weathering profiles, will yield data on shale genesis, the temperature of Archean oceans, and chemical gains and losses within the hydrosphere. Geochemical and petrographic analysis of terrigenous sediments will yield information on atmospheric weathering processes. For example, are there any remnants of Archean residual or laterite soils such as bauxites?

Hydrothermal Alteration of Crustal Material In areas of high heat flow, much of the upper crustal regime has been modified by reaction with hydrothermal fluids. The fluids are conventionally believed to be heated marine water, meteoritic water (circulating in the upper crust), and metamorphically-generated fluid, released at lower crustal levels by prograde metamorphism. Study of the reaction products can provide an insight into the physical and chemical nature of these fluids and the dimensions of the thermal regime. Through consideration of the energy requirements for alteration and fluid circulation, the duration and size of shallow plutons that provide the heat energy for these regimes can be estimated. Stable isotope and petrochemical studies would provide data for these investigations.

Ore Deposits from Interactions of the Crust with the Hydrosphere Syngenetic and high-level vein gold deposits, volcanic hosted Cu-Zn-Ag-Au massive sulfide deposits and Algoma-type iron formations are significant resources found dominantly in Archean terrains. These deposits are products of hydrothermal reactions with the crust under specialized local conditions which concentrated upward-moving metal-rich fluids, enabling the formation of anomalous metal concentrations at and near the surface. Examination of these deposits and their environments will yield data significant in interpreting early crustal history in at least three ways:

(a) The chemical and isotopic characterization of the surrounding rocks will indicate the thermal and chemical history of the fluids which generated the deposits, thus contributing to the understanding of crustal fluid-flow regimes. Such data are critical in evaluating and advancing mineral deposit models, thus contributing to the development of guidelines for resource potential evaluation.

(b) These deposits collect lead from variable, but predictable levels within the crust, and commonly shield it from further radiogenic addition; isotopic studies of this lead would assist in evaluating crustal development models and crust-mantle interactions.

(c) The physical environment which enabled focussed fluid flow is produced by specific tectonic regimes. The regime for each deposit type is evidenced by specific sedimentary products. Evaluation of the origin of these products will result in better definition of a pertinent tectonic model at the appropriate stage of Archean development, and will enable refinement of each genetic model.

3. Archean Sediments

Terrigenous clastic sediments provide important information on physical processes operative within primitive water bodies, and chemical sediments provide information on their chemistry.

Physical Processes and Depositional Environments Archean metasedimentary sequences consisting of conglomerate, sandstone, shale, iron-formation, evaporites, and closely related rock types bear such strong resemblance to modern counterparts that it seems likely that environmental conditions then were not totally different from those of today. Detailed field documentation of lithologies, sedimentary structures, and vertical sequences are the basis of interpreting physical processes operative in the Archean, including fluvial and gravity flow processes and the possible existence of waves and tides. Paleoenvironments reconstructed from these investigations provide the necessary framework for any understanding of the origin of the oldest terrigenous sediments.

Archean Provenance Terrains Detailed studies of sandstone petrography and shale geochemistry (especially rare earth elements) are necessary to characterize the composition of Archean provenance terrains as a contrast to those of Proterozoic age. Studies of this type are available for a few occurrences of Archean sediments but are required from various geographic areas to provide information pertaining to such problems as the time of earliest development of potassic granites and the nature of the early crust.

Chemical Sedimentation While the bulk of Archean sedimentary rocks consist of clastic deposits, there do exist some carbonates, iron formations, possible primary cherts, and replaced evaporites. Their paleoenvironments are virtually unknown. The chemical deposits are especially important since they can constrain the composition, temperatures, pO_2, and pH of the water in which they precipitated. These rocks are also thought to be the most likely host rocks for early fossils, and they may be one of the most sensitive indicators of surface conditions on the early Earth. All interpretations must consider the implications of diagenesis as discussed in the following paragraph.

Nature of Diagenesis in Early Sediments A striking aspect of the Archean is the extensive silicification of all types of sedimentary rocks. Many cherts previously thought to be primary have subsequently been found to be silicified volcaniclastics, carbonates, and evaporites. Any analysis of Archean sedimentary rocks must contain a careful consideration of the origin, timing, and significance of silicification. Recent advances in aqueous geochemistry and isotopic composition of authigenic silica should be applied to Archean sediments. This is especially important since silicified rocks will be prime examples for intensive geochemical investigations. The analytical data cannot be meaningfully interpreted without a firm understanding of this silicification overprint.

Tectonic Implications of Land-sea Relationships Terrestrial sediments in Archean terrains imply continental emergence. Documentation of the global distribution of such sediments will indicate the extent of the emergence through the Archean. The geometry and size of associated water bodies can be determined from facies patterns and paleogeographic reconstructions. Lateral and vertical associations of paleoenvironments reflect the tectonic setting of Archean depositories. Thicknesses of sedimentary sequences will place constraints on models of lithospheric thickness. These investigations are also relevant to the question of when the Earth's surface developed topographic bimodality.

4 Recommendations

Long Range The preceding discussion outlines specific research projects which require new field work and laboratory analyses. New funding for such work is the most significant way that NASA can augment the ongoing, individual research efforts.

Short Range In the interval before major funding is available, NASA could make the following positive contributions:

(a) *Field Conference* — A field conference bringing together active workers on early Earth problems could be convened. The Abitibi greenstone belt of Quebec and Ontario is a suggested location because of its size, preservation, accessibility, and the amount of work already done. Many of the problems of interactions of the hydrosphere with Archean rocks could be addressed at this conference. NASA could help by organizing the conference, funding a guidebook, and helping defray travel expenses of participants. Consultation with IGCP 160 is recommended.

(b) *Barberton Mountain Land Guidebook* — The two best teranes for addressing many of the proposed questions are the Barberton Mountain Land and the Pilbara block in western Australia. Neither is feasible as the site of a field conference. However, numerous workers frequently sample in these areas, and require local assistance to conduct field work properly. A guidebook to the Pilbara block is currently available. However, a guidebook to the Barberton Mountains is not available and would significantly help those who travel to this area to collect samples. The geology of the mountain land is sufficiently well understood to allow an excellent guidebook to be prepared. NASA could support those who prepare the guidebook and sponsor its publication.

D. Theme 3: Archean Evidence for Physical, Chemical and Isotopic Transfer Processes in Early Planetary Crusts

Introduction

Planetary crusts provide us with the end results of four and one-half billion years of transfer processes. The initial configuration and various subsequent configurations of planetary crusts and mantles have been modified and obscured by these processes. Any interpretation of planetary evolution, therefore, must utilize present observations in understanding transfer processes that may have occurred in the past. Transfer of material may occur on a variety of scales: e.g., large volumes of material may be moved *en masse*, fluids may diffuse through solids, components may be fractionated from one another by thermal gradients, and isotopes may be separated and reconfigured through melting or recrystallization.

Several categories of transport processes may be outlined in association with igneous, metamorphic, tectonic, and surface events. During igneous events various degrees of partial melting may occur in the mantle or crust. The melted material, with a composition depending on composition of the source rock and the extent of melting, can be transferred. It may all go to the surface as volcanic flows, it may all crystallize beneath the surface in a large magma chamber, or some may crystallize beneath the surface while some continues to the surface. There is the possibility of contamination through reactions with or assimilation of the rocks surrounding the melt, thus adding further transport of material as a by-product of the igneous activity. Separation of volatiles from the crystallizing melt can allow separate transfer processes for the resulting melt and volatiles.

During metamorphic events there may be extensive diffusion of components under the influences of thermal, chemical, and pressure gradients. At the high end of the temperature and pressure gradients there is a merger with igneous and tectonic events. The major transfer processes during metamorphism are almost certainly associated with diffusion of fluids but the details are poorly understood. The composition and state of the fluid may vary from one environment to another; the isotopic and trace elements in fluids may vary from one environment to another; and the nature of exchange of components between fluids and surrounding solids may vary from one environment to another. There may be significant transfer of material by this mechanism from the hotter lower crust to the cooler upper crust or from one rock type to another, or there may be constant additions of some components to the crust from the mantle. There may also be some diffusion of material completely in the solid state but this process is thought to occur on only a relatively small scale and probably does not account for any major transfer of components. However, such solid state reactions can be significant during recrystallization when isotopic and trace element reequilibration can redistribute components between phases and obscure the interpretation of previous systems.

During tectonic events large masses of material may be moved laterally and vertically by convection, subduction, spreading, diapiric upwelling and sinking, folding, and faulting. The scales and rates involved in these processes may be significantly affected by the variables involved in associated igneous and metamorphic events. For example, the amount of fluids present, the extent of partial melting, or the value of temperature gradients can affect these processes drastically.

Surface events may redistribute materials in numerous processes. During the early history of any planetary surface there should be extensive mixing as a result of impacts. Depending on the extent to which atmospheres or condensed fluids develop there may be various types and amounts of weathering, erosion, and deposition. Erosional transport may be primarily as fragments from wind action on arid surfaces or as fragments and dissolved solids when water or other condensed fluids are present.

The extent to which different transport processes have acted on different planets varies drastically. The Moon's igneous activity ceased nearly 3 b.y. ago and transfer of fluids played a very small role in metamorphic events. Condensed fluids and atmosphere played essentially no role in transfer processes on the Moon. However, evidence for transfer of material during the early impact history is abundant. In contrast the Earth has experienced essentially all of the above-mentioned transfer processes. Many Archean terrains have undergone only minor effects of these transfer processes over the past two to two and one-half billion years and thus preserve much of the evidence of these processes that occurred from two and one-half to three and one-half billion years ago. Because many planetary bodies may have experienced transfer processes that are intermediate in their behavior between the Moon and Earth, a study of the Archean processes should lead to a better understanding of other planetary bodies.

Problems of Archean Transfer Processes

In order to better understand the evolution of Archean continental crust, it is essential to outline not only those factors that controlled the original distribution of elements in the crust, but also their redistribution during subsequent events. Various lines of evidence suggest that the interpretation of chemical and isotopic data derived from the upper crust may not be applicable to the lower crust. In particular, the role of fluids where P_{H_2O} is significantly less than P_{TOTAL} is poorly understood. In addition, the role of fluids in processes involving mass transfer, be they physical or chemical, is critical to a better understanding of evolution and tectonics of the early crust.

Although the mineralogy and composition of rocks from early crustal granulitic assemblages indicate that water had a less significant role than in lower grade rocks, the composition of the fluids involved is only vaguely known. In particular, the role of CO_2 in partial melting and complexing of elements remains to be elucidated. Kinetics of metamorphic reactions and crystal growth, metamorphic mineralogy (hydrous vs anhydrous), long-range chemical and isotopic equilibrium, transfer of material to other crustal levels (through solution or partial melting), and deformation processes all depend to a very large extent on the presence and composition of fluid species.

Much controversy surrounds the origin of fluids involved in processes that affected the early high grade terrains. Were they derived from the mantle, from local or regional dehydration processes, or from upper crustal regions? These questions cannot be answered until we understand the role of fluids in the present day lower crust.

Some models of early crustal evolution have assumed that early geothermal gradients were considerably steeper than present gradients. However, limited field and laboratory data would indicate that this may not be valid. The study of mineralogical assemblages from the high-grade rocks of the early crust and experimental calibration of their P and T condition of equilibrium must be vigorously pursued to resolve problems dealing with early crustal geothermal conditions.

One of the most powerful tools in defining source regions of both rocks and volatiles are radiogenic and stable isotope systematics. Conflicting interpretations of isotopic data from early crustal terrains can be resolved only by further studies on the distribution of parent and daughter elements, and on the conditions of isotopic exchange between the crust and the mantle as well as within the crust.

The various lines of approach suggested above should lead to a much improved understanding of the high-grade early crust of the Earth. Results of these studies are a required input into any modeling of crustal evolution. Furthermore, the interpretation of isotopic systems in terms of ages and petrogenesis depends upon the factors that control the redistribution of elements. Interpretation of isotopic data as primary ages or metamorphic ages in older rocks depends critically on a better understanding of isotope systematics.

Our understanding of early crustal tectonics will progress only when we know the composition, role and source of fluids in the lower crust, and their effects on deformation, isotopic exchanges and material transport in general.

We feel that the topics outlined in this section can be addressed most advantageously through detailed field work at selected important localities followed by various laboratory investigations. The latter should include at least the following:

1. Studies of fluid inclusions in order to outline the nature of the volatile species involved in the metamorphism of granulite terrains, and to determine the source of these fluids by measuring the isotopic compositions of S, C, O, and H wherever possible.
2. Analyses of mineral phase assemblages and mineral compositions to outline the physical conditions (P and T) during the formation of high-grade areas and to determine the ambient thermal gradient in Archean crust during metamorphism.
3. Experimental work that focuses on understanding the effects of variable fluid composition and pressure on temperatures of metamorphism and on partial melting.

4. Geochemical studies that focus on the behavior of the various radiogenic isotope systems during granulite grade metamorphism.
5. Geochemical studies on the behaviour of trace elements (in particular the LIL and REE) during granulite grade conditions including partial melting.
6. Laboratory studies aimed at understanding those chemical and physical processes involved in the retrogression of granulite terrains, particularly the relationship between granulites and the formation of lower grade shear zones.
7. Laboratory studies on mineral stabilities and partial melting under granulite grade conditions, specifically mafic and felsic bulk compositions at P_T = 7 10 Kb, $X_{H_2O} < 0.5$ and $T > 700°C$.

Moreover, we urge that the project foster and encourage international cooperation on a scientist to scientist level by means of workshops, field excursions and conferences.

V. NASA Funding to Research

To be most effective in its commitment to an Early Crustal Genesis program, NASA needs to provide substantial support to the following activities:

(a) Conferences, workshops, and perhaps sample collections focused on the research themes discussed in the preceding sections.
(b) Selected research directed at these same topics.

By funding this research, NASA will be in a position to guide the program in directions consistent with the goals of their planetary exploration program in general, and in keeping with the concept of viewing the Earth in a planetary perspective. In particular:

1. NASA can encourage the application of a new understanding of the Earth to other planets, specifically Mars, Venus, Moon and Mercury. NASA can promote the application of new experimental and theoretical techniques developed for terrestrial studies to other planets.
2. NASA can assure the application of ideas of planetary development gained from space missions to understanding the Earth and its evolution.
3. NASA can assure proper, in-depth investigations of processes crucial to understanding planetary development.
4. NASA can assure continued, orderly growth of field and laboratory data sets that are central to models of planetary crustal formation.

Finally, direct funding of research oriented towards high technology, the advancement of experimental techniques, and the development of sophisticated theoretical models is directly within NASA's charter of fostering technological growth.

NASA funded research should include those investigations that (1) collect fundamental data sets related to developing the Earth's spherically symmetric structure and composition and (2) study processes that directly contribute to developing the Earth's spherically symmetric structure and composition. Such data sets and studies will be the test of theoretical and empirical models of planetary development. They will significantly contribute to advancing our understanding of Earth in a global context and from a planetary perspective.

Appendix A

Exposition of Early Crustal Evolution Problems

Outline of Early Crustal Evolution Problems

Secular evolution of crustal composition and mass.

Trends in representative bulk composition for large crustal masses (sampling problems, both lateral and vertical).

Trends in volumes of crust-forming rock types with time (e.g., K-rich granites, komatiites, tonalites, anorthosites, alkali basalts).

Evidence for isotopic recycling between crust and mantle and within crust.

Trends in mineral deposit types.

Temporal changes in mantle composition (development of heterogeneities).

Evidence for changes in distribution and abundance of crustal mass.

2. Thermal evolution of crust-mantle system.

Nature of heat sources.

Changes in thermal gradients with time.

Relative importance of heat transfer mechanisms with time (includes convection, conduction, radiation, mass transport).

Hydrothermal heat transport and development of economic deposits.

Differences between continental and oceanic regimes.

Isotopic constraints (e.g., ^{129}Xe, ^{26}Al).

3. Nature of primordial crust.

Composition.

Mass and distribution.

Persistence in time.

Does any survive?

Chemical and physical effects of accretion and late bombardment.

Comparison with other planets.

4. Evolution of tectonic processes

Cause of contrasting styles among terrains of same age and different age (e.g., granite-greenstone belt style vs gneissic terrain style).

Trends in horizontal vs vertical styles with time.

Trends in lithospheric thickness with time.

Trends in crustal thickness with time.

When did present-day plate tectonics begin and what were its predecessors?

When and how did stabilization of continental masses (cratonization) begin?

5. Interaction of crust with hydrosphere, atmosphere, and biosphere.

Nature of early Precambrian weathering.

Land-sea relations and climate.

Role of hydrothermal processes in production of ore deposits.

Role of atmosphere/biosphere on stabilizing of Fe formations.

Physical processes in early ocean and depositional environments (tides, waves, tectonics).

Relation of temperature and composition of early ocean and surface processes.

Onset of photosynthesis/origin of life.

Recycling of altered surface materials.

Volume and composition of atmosphere/biosphere with respect to past thermal history of Earth including degassing.

6. Effect of core formation on crust.
    Oldest magnetic signatures in crustal rocks.
    Chemical/isotopic evidence for fractionation (e.g., high P partition, K, Pb, S, siderophiles).
    Mechanical/thermal factors (e.g., products of energy release).
7. Effects of impacts on crust.
    Magnitude of effects (pre 3.8 b.y. magnitude still uncertain).
    Archean flux.
    Chemical anomalies (Ir, etc.).
    Identification of inherited or relict structural effects from early Archean impact structures (e.g., early tectonic effects).
    Relict petrographic evidence (e.g., shock textures).
    Extent of thermal anomalies.
    Effects on early atmosphere and ocean.
8. Effect of volatiles on crust.
    Identification of juvenile fluids/gases in rocks (e.g., S).
    Changes in degassing rates with time (e.g., ^{3}He, ^{129}Xe, ^{40}Ar).
    Nature of earliest Archean volatiles (juvenile vs recycled: e.g., what is in komatiites).
    Contribution of juveniles to mineral deposits.
    Rates of recrystallization in various volatile concentrations.
    Rheological effects of fluids during tectonic events.
    Secular or spatial trends in fluid transport (metasomatism).
    Effects on partial melting temperatures during metamorphism.
9. Crust/mantle interactions.
    Nature of Archean mantle in time and space.
    Nature, distribution, and origin of mantle heterogeneities (e.g., continent vs ocean, upper vs lower).
    Are there continental roots in the mantle and, if so, what were their origins?
    Partial melting trends in mantle (abundances of specific crustal rock types derived from mantle: e.g., alkaline basalt, komatiites, tholeiites, tonalites).
    Nature of crust/mantle boundary.
    Nature of transfer between crust and mantle (e.g., rates, scales).
    Mantle contributions to metallogenic provinces.
10. Effects of accretionary processes on primordial differentiation.
    Scale of heterogeneities in accreting bodies.
    Secular trends in composition of accreting bodies.
    Thermal regime during accretion.
    Can a magma ocean form at or near the surface?
    Isotopic constraints on rate of accretion (e.g., ^{129}Xe).
    Comparison of Earth with other planetary bodies.

Problem 1: Secular Evolution of Crustal Mass and Composition

Many authors have argued that the composition and mass of the continental and oceanic crusts have changed over time. Much of the evidence is open to alternative interpretations, but the views proposed can be discussed under several headings.

Bulk concentration changes have been claimed by various authors who argued for an increase (in younger rocks) in total REE, in the ratio LREE/HREE and in the proportion granite/basalt. Increases in REE have also been claimed in sediments. Phanerozoic sediments have been found to be richer in Si, K, Ca and poorer in Al, Na, Mg than Archean ones. Secular changes in shale composition (Archean to Proteozoic) have been noted for many elements, including Hg. K, Rb, Sr, U, Th, Si are more abundant, and Na, Mg, Fe, Ni, Co, Cr less abundant, in Indian Proterozoic basic rocks and sediments, compared with Archean ones.

Conclusions of this kind have not all led to general acceptance, because of the difficulty of devising satisfactory sampling procedures. Conclusions may be valid for a particular region but not amenable to generalization to the whole Earth. Future work should recognize this problem.

Related to the preceding topic is *secular variation* in *isotope ratios*, for example increases in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ in younger rocks. However, the behavior of $\delta^{13}C$ and $\delta^{34}S$ is more complex. The more general question of whether *isotopic recycling* between the crust and mantle occurred has been the subject of many papers, and its proponents have encountered strong opposition from advocates of the view that crustal material is never subjected to rehomogenization in the mantle. Arguments have been advanced from both camps, in recent years, that substantial increases in *crustal mass* have taken place, particularly during the late Archean. Accompanying the analytical studies which provided evidence for these views there have been theoretical studies of mass transfer and isotopic transfer.

Much attention has also been focused on the related question of *time trends in rock abundances* (volumes). Ultramafic komatiites and calcic anorthositic complexes are almost entirely confined to Archean terrains, and K granites have been claimed to be largely absent as have alkali basaltic suites. In addition tonalites are particularly abundant in the Archean as gneisses and granulites. The absence of abundant Archean carbonate sediments has been a problem for years, as has been the apparent restriction of abundant cherty iron formations to Archean and Proterozoic eras.

It is not well understood how *trends in mineral deposit types* have developed. Evidence has been presented by many writers suggesting that major deposits of Ni, Au, Pt metals, and Fe are mostly of early Precambrian origin, whereas deposits of Hg, Sn, and W are mostly younger. In addition the apparent paucity of Pb in Archean massive sulfide deposits and its abundance in younger deposits should be evaluated. It is of course important to consider the factor of erosional exposure in these trends.

Since the crust and mantle must constitute a closed system, it is necessary to recognize that changes in crustal composition and mass must be reflected by *complementary changes in the mantle*. Study of these changes is usually focused on the concepts of pristine mantle and depleted mantle, and their behaviour through time. This, in turn, relates to questions of tectonic and geophysical significance, such as the existence and possible growth of deep continental roots.

Problem 2: Thermal Evolution of the Crust-Mantle System

As the underlying source driving many processes, a planet's thermal regime and its evolution control most aspects of crustal genesis, and so are strongly interrelated with most other problems. Not only does our understanding of thermal evolution affect our interpretations of many observations, but these observations provide important constraints on models of thermal evolution.

Geothermal gradients deduced from studies of metamorphism may yield information about changes in the Earth's heat flux, but such gradients must account for effects of local and regional post-tectonic cooling of the crust and possible ocean-continent differences. Thermal history models also must be consistent with chemical and isotopic compositions of volatiles and with degassing models.

The nature and relative importance of heat sources needs to be better understood. Core formation, accretion, and late stage bombardment act as heat sources and are considered under problems 6, 10, and 7, respectively. The abundances and changes in time of the distribution of long-lived radioactive sources need to be independently constrained: abundances in the lower crust, the mantle and the core are all subject to major uncertainties. The possible role of short-lived radioactivity should be considered, although it is the current concensus that this was important only for very early planetesimals (e.g., the Eucrite parent body).

Heat transport mechanisms should be considered. Although it has become generally accepted that mantle convection is a dominant mechanism, conduction is dominant in boundary layers at the Earth's surface and possibly at the core-mantle boundary and at hypothetical internal mantle boundaries. Although it is believed that radiative transport is insignificant, relevant data are still sparse, especially at high pressures. Other material properties such as the decrease of thermal expansion with pressure may also operate to make convection less dominant in the lower mantle. Hydrothermal circulation plays a significant role in oceanic and continental crusts, and is intimately involved in metamorphism and mineralization. Magmatic transport of heat may have been locally important in the Archean, especially if the early Earth was very hot (notably in a magma ocean).

Continental and oceanic thermal regimes have important differences: oceans have sea-floor spreading, continents have higher radioactivity and possibly thicker mantle roots. The cause of the apparent decline of continental heat flux with tectonic age needs to be established (e.g. the relative importance of erosion and post-tectonic cooling) before reliable interpretations of metamorphic constraints will be possible. The history of continental geotherms may give important constraints on cratonization (problem 4) and on the existence and origin of continental roots (problem 9).

Several important thermal convection problems that could affect Archean conditions require theoretical study. These include: the interaction of the "hysteresis" characteristic of flow systems (i.e., persistence of planforms optimal for earlier conditions) with decreasing energy sources, the nature of boundary layer instabilities with temperature dependent rheology, the interaction with compositional differentiation, and the extent to which all of these may induce sporadic convective behavior.

Problem 3: Nature of the Primordial Crust

The nature of the earliest crust is a long-standing and still unsolved problem, largely because no truly primordial rocks have yet been identified. It is quite possible that the primordial crust has been totally re-melted or metamorphosed beyond recognition. Nevertheless, a number of major questions can be approached in a broad program.

Some theorists favor a global-wide, differentiated primordial crust, others favor isolated bouyant continental nuclei, and still others favor a primitive form of island arc systems. Thickness estimates of the early crust range from a few to several tens of kilometers. The mass and distribution of the early crust remain as major unsolved questions.

Compositions ranging from ultramafic to acidic have been proposed for the earliest crust by various workers. No single lithology may be sufficient to describe the earliest crust, but the chemical and petrographic compositions of the early crust remain a major problem that should be studied. The earliest crust may have been a chilled ultramafic skin on a magma ocean that was rapidly destroyed by foundering and later replaced by a basaltic crust that was itself consumed by subduction. The question of how long the first crust, or series of crusts, persisted in the Archean is also recommended for study, with the realization that no definite answer may be attainable for the very first crust.

Although the oldest rocks yet discovered are only 3.8 billion years old, the possibility must be considered that some older crust yet survives. If it is exposed, presumably normal progress in shield mapping will reveal it. However, the nature of any surviving primordial crust at great depth should be sought in the course of other investigations of the lower continental crust, such as COCORP reflection profiling and xenolith studies. In addition, further studies should be made of the possibility that some existing Archean rocks, such as the "grey gneisses," are remobilized remnants of primordial crust.

Continuing efforts should be made to determine the degree of similarity between the earliest crust of the Earth and those of other planets (e.g., the lunar highland crust). Rock types occurring both on the Earth and on other bodies, such as anorthosites, should be compared in detail. Variations between planets in such characteristics as water content and size will produce different crustal petrogenetic trends which should be studied experimentally, theoretically, and by direct observations. New data on the composition of the lower continental crust should be compared with extraterrestrial data.

It has been proposed that late condensation and accretion of alkalis from the solar nebula may have contributed to formation of the primordial crust. Although the chemistry of the terrestrial continents and the lunar highland rocks does not support simple formation of continental crust by this mechanism, other aspects of late-stage accretion may have had direct or indirect effects on early crustal evolution. For example, the petrologic and tectonic effects of major basin-forming impacts should receive continued study.

Problem 4: Evolution of Tectonic Processes

There are many indications that tectonic processes have changed through time, notably the different scales and styles of tectonic and orogenic units in Phanerozoic, Proterozoic and Archean times, and the absence of pre-Archean rocks. It is not clear to what extent these changes were due to modifications from the present plate tectonic regime versus the existence of different tectonic regimes (such as a thin, non-subducting lithosphere in which vertical movements were more important than at present). The changes, whether minor or major, were presumably strongly controlled by the contemporary thermal regime, and possibly by the extent of differentiation of continental and oceanic crusts and their distribution and thickness.

Major issues involved in these larger questions are the relationships between Archean gneissic terrains and granite-greenstone terrains, the relative importance of horizontal versus vertical tectonic movements, the variation of crustal thickness with time, and the mechanisms and timing of cratonization. For example, some current hypotheses relate the gneiss-greenstone terrains to island arcs and back-arc basins, on the one hand, and to subsiding basins and complementary uplifts, on the other. Much detailed field and laboratory work may be necessary to decide between these hypotheses.

There is a need for well-posed, quantitative modeling to explore the relationship between the thermal regime (problem 2) and tectonic processes. For example, higher global heat flux may result in faster plate motion, thinner plates, smaller plates, thicker oceanic crust (through higher degrees of partial melting of the mantle), or more buoyant oceanic lithosphere (through thicker oceanic crust). In addition continental crustal thickness will be limited by the geothermal gradient which may or may not be related to the global heat flux (see problem 2). Observations relevant to the history of continental crustal thickness, such as geobarometry, would be valuable for evaluating the roles of processes such as underplating and horizontal compression in determining crustal thickness. One of our greatest observational needs is information on the deep crustal structural relations in the old shields.

The mechanism behind the growth and stabilization of cratons is largely unknown, and more detailed documentation of this process for several continents would be important. The relationship of cratonization to crustal thickness and the possible role of mantle roots should be considered.

Problem 5: Interaction of Crust with Hydrosphere, Atmosphere, and Biosphere

Weathering

Rock weathering was initiated on the surface of the Earth at the time the first water molecule was formed. The present-day crust and the underlying mantle are composed primarily of silicate minerals; these are alkaline silicates containing the alkaline earths (Mg, Ca, Sr, Ba) and the alkali metals (Na, K, Rb, and Cs), so they may be viewed as the salts of relatively strong bases and weak acids (silicic acid). The silicates react with water in the process of hydrolysis, with products characterized by strong bases (e.g. $Ca(OH)_2$, $Na(OH)$, KOH, etc.) which give strong alkaline reactions. Alumino-silicic and silicic acid (H_4SiO_4) are relatively insoluble and in the initial stages of weathering may be regarded as a gel of mixed hydrous oxides. The presence of CO_2 and acids such as H_2SO_4, HCl, etc., are effective in reducing the alkalinity; it may be argued that they attack the silicates, but the fundamental process of weathering which procedes in the complete absence of acids, is hydrolysis as outlined above.

Weathering is a chemical process and hence is influenced by the temperature. In early Precambrian time when the temperatures were higher than they are today, we can expect weathering to have been accelerated.

As is the case in modern weathering, the products are clastic and chemical sediments. The oldest are preserved in the Isua area of Greenland and are dated at 3.8×10^9 yrs. The Isua metasedimentary series contain clastic rocks (graywackes) and chemical sediments (banded cherty iron-formation). Carbonates also occur in these rocks, thereby placing strong constraints on the early atmosphere which could have been mildly but not strongly reducing.

Banded cherty iron formations are common throughout the Archean shields of the Earth; these are associated typically with graywacke-slate sequences, conglomerates, and minor carbonate deposits.

Land-Sea Relations

Archean metasedimentary sequences consisting of conglomerate, graywacke, iron formation and closely related rock types bear such strong resemblance to more modern counterparts that it seems likely that environmental conditions did not differ significantly from those of today. If one assumes that the present day volumes of seawater also existed in the Archean, insurmountable problems arise. Present day opinion favors a molten state for the outermost Earth at an early stage in its history. Cooling would have resulted in an equipotential surface which would have been covered to a considerable depth by the present day volume of seawater. Archean volcanic (greenstone) sequences which have been dated back to at least 3.5 b.y. ago, clearly were deposited in water as evidenced by pillow structures and quench (spinifex) textures. Furthermore, the 3.8 b.y. Isua sedimentary sequence must have formed under oceanic conditions. Hence the oceans date back to at least 3.8 b.y. Oxygen isotope data $\delta\frac{O^{18}}{O^{16}}$ determined on chert from iron-formations decrease with time; one interpretation of this secular change is that early Archean seawater was warmer than its modern day seawater counterparts.

The graywacke-slate sequences so common in the volcanic-sedimentary (greenstone) belts commonly appear to have been turbidite sequences derived from either cratonic (granite) terrains or from volcanic (intermediate felsic) centers. Mature clastic rocks and carbonates are generally rare in these sequences, although an exceptional quartzose sequence 3.2 b.y. old (Moodies Group — of tidal origin?) occurs above the Fig Tree turbidite sequence in South Africa. Associated with turbidites in some greenstone belts are conglomerates which were deposited on submarine fans and alluvial fans.

Atmosphere

The banded iron-formations (BIF), composed primarily of silica and iron minerals, are characteristic of the Precambrian. Some deposits of Phanerozoic age have been described, but these appear to be of a different origin than the BIF which are recognized to be chemical precipitates. Large banded cherty iron-formations of Proterozoic age are commonly referred to as the Superior-type because of their outstanding development in the Lake Superior district. These are typically a platform type of deposit, underlain by quartzose sandstones and overlain, in the Lake Superior region, by graywacke-slate sequences.

The Archean deposits are commonly referred to as Algoma-type after deposits in the Algoma district of Ontario; these are commonly associated with graywacke-slate and tuffaceous sediments, overlying thick sequences of greenstone. Some economic geologists attribute the Algoma-type iron-formation to volcanic exhalations on the sea floor but others favor the weathering of iron-rich tholeiitic and komatiitic flows as a source of the iron and silica. In the latter view, the Algoma-type iron-formations were formed during quiescent periods when the areas were relatively stable. Renewal of volcanism terminated these conditions and therefore, in contrast with the enormous extents of Proterozoic iron-formations (e.g. Lake Superior Basin, Hamersley Basin), the Algoma-type deposits are relatively small.

The weathering origin for BIF rests heavily on the assumption that the Archean atmosphere was deficient in oxygen. Abundant and heavy rainfalls under a mild to tropical climate resulted in a lateritic type of weathering leaving a porous and permeable residue of Al, Ti, Fe^{3+}, and some silicates and phosphates of iron and aluminum. Ferrous iron, together with Mg, Ca, Na, K, and other soluble cations, were carried to the depositional basins. The weathered landmasses, because of their permeable textures, were not easily eroded even in the absence of vegetation. This weathering mechanism accounts for the remarkable purity of the BIF, especially the absence of Ti and P, which is not easily explained in any exhalative hypothesis.

The first authenticated evidence of early life was found as algae in black cherts of the Biwabik iron-formation in Minnesota. Later work has revealed much older life in the Fig Tree of South Africa (3.4 b.y.). Carbon isotopes in black carbonaceous rocks of the Isua area suggest that life was present 3.8 b.y. ago. Development of the photosynthetic algae initiated an oxygen-generating system in addition to the small amounts of oxygen found in the upper atmosphere by the dissociation of H_2O, which gradually brought about a change leading to an oxygenated atmosphere that permitted the appearance and development of the metazoans and higher forms of life.

Mineral Deposits

In addition to the Algoma-type iron deposits, there are other Archean mineral deposits of great economic importance, notably deposits of Au. Pt group metals, Ni, Co, Cu, Zn, and Ag. The major mineral deposit types in Archean rocks are stratiform, volcanic-hosted massive Cu-Zn deposits, stratabound and intrusion-hosted vein gold deposits, magmatic Cu-Ni deposits, and the Algoma-type iron formations discussed above. The massive Cu-Zn deposits are related to shallow level (0–2 km), high temperature (350° C) meteoric water circulation, formed in zones of anomalous heat flow. Gold deposits formed at shallow crustal levels, possibly in zones of intravolcanic rifting; the gold-rich, base-metal poor source of fluids may have formed at deep (2–10 km) crustal levels, and were generated by fluid release at the greenschist to amphibolite metamorphic transition.

Both gold and Cu-Zn deposits thus are the products of water-rock interaction at a wide range of crustal levels. Their associated alteration products may yield important indications of intermediate and lower crustal composition and seawater composition during the Archean. Present-day hydrothermal emanations on the sea floor contribute significantly to the sea water composition. The abundant evidence of hydrothermal activity in the Archean may indicate that this process controlled Archean sea water and sea floor sediment compositions.

Recommendations

These short paragraphs summarize widely held views on the interactions of crust and hydrosphere, atmosphere, and biosphere. However, it must be admitted that these views are largely speculative and much research is needed to corroborate hypotheses and to develop new concepts on the interactions between lithosphere, hydrosphere, atmosphere, and biosphere in early Precambrian time.

Research in this area would greatly benefit from an interdisciplinary approach that includes sedimentologists, volcanologists, geochemists, and isotope researchers. Although the geologists would be primarily responsible for the field work, laboratory researchers should be fully aware of field relationships and should assist in the collection of samples. Special emphasis is here placed on obtaining new chemical data which must be more complete and much more precise than that used in previous work.

Problem 6: Effect of Core Formation on the Crust

Most scientists today believe that the Earth's core was formed by segregation, accumulation and settling of metallic Fe-Ni from an Earth that was accreted homogeneously, at least to a first approximation. Core formation in such a model probably began well before accretion was completed and occurred rapidly because of the strong temperature dependence on viscosity and the non Newtonian rheology of the cold center. Because of the gravitational energy released it would represent the greatest single thermal event in the history of the Earth. The bulk temperature of the Earth would be raised by some 2100°C. The metal involved in core formation is thought to be mostly primordial in origin, with possible contribution in the deep mantle from the proposed decomposition of $2Fe^{2+} = Fe^{3+} + Fe^{0}$.

Seismic data indicate that the bulk density of the core is less than that of pure Fe, and that some 8 15 wt. percent of a light element must be present. A number of candidates have been suggested; the most popular contenders are oxygen, sulfur, and silicon, or a combination of sulfur and oxygen. Clearly other elements such as the noble metals, some Cr, carbon, Pb and P must be present in the core in greater abundances than their content in the crust and mantle if chemical equilibrium were even closely approximated during core formation. The suggestion has been made that some K was partitioned into the core. If so, this could provide the heat to drive the Earth's dyanamo. However, it is the informed concensus that solidification of the inner core provides sufficient energy for the geodynamo; there are strong geochemical arguments against K in the core.

Core formation must have removed most of the lead from the mantle so that the age of the Earth as determined by the lead isotope method must actually date the time of core formation. Latest calculations suggest that this was about 100 m.y. after the time of formation of the Earth. Some time after this, but prior to 3.8 b.y. ago the core dynamo originated, thus imprinting the evidence of a magnetic field on the rocks of the crust and mantle.

Core formation is of considerable relevance to our understanding of the primordial crust, and a greater understanding of the processes involved will contribute answers to the following questions involving crust:

1. Did the postulated reaction $2Fe^{2+} = Fe^{3+} + Fe^{0}$ affect the redox state of the early crust through convection of mantle upwards?
2. Was S involved in the core formation process? How does this affect the S budget of the mantle and the process of core formation and ore deposition?
3. What effect did core formation have on the thermal regime of the crust?
4. Was appreciable K involved in core formation? If so, what affect does this have on the Earth's thermal history, mantle convection and plate tectonics?
5. Was core formation a totally catastrophic process, or is it still slowly continuing with additional release of thermal energy?
6. How did the bulk chemistry of the protocrust change as a result of the elemental partitioning involved in core formation?
7. Can we refine our knowledge of the time of core formation?
8. When did the core dynamo turn on, thus magnetizing crustal rocks?
9. How much chemical equilibration occurred during core formation? Can the chemistries of crustal and mantle rocks teach us about the chemistry of the core?
10. If equilibration occurred, why is the crust so oxidized with respect to the core? Was this oxidation a gradual process related to Earth's evolution or to heterogeneous accretion in which the outer Earth accreted material richer in volatiles than the interior.
11. Why is the composition of volcanic gases (H_2O, CO_2, SO_2) oxidized with respect to gases in equilibrium with an assemblage involving metallic iron?

12. Did core formation involve predominantly accreted metal or did substantial reduction by carbon occur as advocated by Ringwood? If so, how did the required massive blowout of gases affect the protocrust?
13. What causes magnetic reversals?
14. How did core formation occur? Is it essentially the process suggested by Elsasser and modified by Stevenson, or is a completely different process involved which may have affected the protocrust in ways that we do not understand? If the Elsasser suggestion is correct, can it be quantified, for as Francis Birch stated it is "reminiscent of removing the vest without the jacket, and cannot well be followed in detail."

Answers to the above questions through research in these areas are necessary to understanding the nature and evolution of the protocrust, as well as understanding the kinetic, chemical and thermal evolution of the mantle and core. Such answers would help greatly in our understanding of the process of core formation on planets other than the Earth. The solution to many of these problems involves all disciplines within the Earth sciences, and a consortium approach would be applicable in many areas. Studies of core formation clearly lie within NASA's charter of understanding the major planetary processes.

Problem 7: Effects of Major Impacts on Crustal Evolution

Any consideration of the Earth as a planetary body must involve speculation as to the role of major impacts in terrestrial evolution. Thus far, no Archean, i.e. pre-2.5 b.y., meteorite impact site has been confidently identified on the Earth. However by analogy with the Moon, Mars, Mercury, Venus and other planetary bodies, the Earth was almost certainly bombarded in a major way in the period prior to 3.8 b.y., the age of the oldest confidently dated rocks on Earth. Because the Earth is such a tectonically active planet all direct traces of this period of mega-impacting may have been subsequently obliterated as a result of tectonic events notably magmatism, metamorphism and deformation. In brief, because it is known that large crater-forming objects swept through the inner solar system prior to 3.8 b.y., this virtually dictates that the Earth must have encountered such objects.

Although no Archean impact sites have yet been discovered, this does not preclude future discoveries, direct or indirect. Since Archean crust is still being discovered especially in more remote parts of the world, the discovery of preserved and exposed evidence of impact in the form of shatter cones and planar structures in minerals is still possible. However, more promising is the identification of preserved, yet buried, impact sites in Archean basement or inherited structures in younger rocks carrying the signature of a former impact structure.

The question arises as to the effects of such major impacting upon the evolution of terrestrial crust. Such impacting naturally affected the crust directly by producing mega-impact structures with accompanying physical and chemical anomalies. Furthermore,such mega-impacts may have induced deep-seated thermal responses in the form of convection currents leading to the development of new crust and/or the modification of existing crust. Effects of such impacts on the evolution of oceans and atmospheres also may be significant. Calculations of the heating effects of ejecta from an impact by one large (> 10 km diameter) object show that the average air temperature can be raised by 10's of degrees and the average temperature of the upper 100 m of the ocean by several degrees. During the early bombardment of the Earth (up to 3.9 b.y. by analogy to the Moon) this effect in combination with higher heat flow and primordial heat suggests that much, or perhaps all, of the Earth's volatiles could have remained in the vapor state for significant periods of time.

Geochemical evidence of Archean meteoritic components may be very difficult to find, but in view of the recently discovered meteoritic trace element concentrations at the Cretaceous-Tertiary boundary, there may be similar anomalies in appropriate Archean environments. Algoma-type iron formations formed during quiescent periods, and have, in some areas, been only slightly affected by metamorphic recrystallization. In addition to preserving early life forms, they may preserve extraterrestrially derived materials which, due to their compositional contrast with iron formations, may be detected and used to determine the rate and composition of meteorite falls on the Archean Earth surface.

Thus the search for direct or indirect evidence of Archean crustal impacting constitutes a worthy target in any global study of Archean crust.

Problem 8: Effects of Volatiles on Evolution of the Crust

Volatiles: What They Are

Volatiles include those low density ($\lesssim 1.5\,gcm^{-3}$) materials which under present surface conditions on Earth exist as gases or liquids (H_2O, CO_2, CO, H_2, N_2, CH_4, NH_3, O_2, noble gases, etc.).

Why They Are Important

The volatile composition of a planet's surface and interior, to a large extent, controls processes which *form* and *modify* their crustal materials. Volatiles are presently being released at the Earth's surface, and it may be inferred that this process has been taking place over the course of geologic time. An obvious result of this is the production of the Earth's extensive hydrosphere and atmosphere (discussed previously under problem 5). It is unclear, however, whether degassing of the Earth occurred in a uniform, continuous manner, or as a sudden, catastrophic event. In either (or neither) case, the *evolution* of planetary volatile systems has fundamental implications for thermal histories, transport mechanisms, and compositions of planetary mantles, crusts and atmospheres. For example, the nature (amount and composition) of volatiles has profound effects on partial melting temperatures, rheological properties of rocks, rates of recrystallization, and origins of mineral deposits. These processes have important implications for stabilization of cratons, nature and location of the base of the lithosphere, and extent of recycling of crustal materials. It is of fundamental importance, therefore, to understand the inventory of planetary volatiles through time.

How They May Be Studied

1. Volatiles are commonly trapped in minerals as fluid filled inclusions. These inclusions represent a sample of the fluid present in the rock at some time during its history regardless of how complex that history may have been. It may be possible, through detailed petrographic study to distinguish primary from secondary fluids trapped in ancient materials, crustal and otherwise. Their compositions can be studied using a variety of techniques, including microthermometry and mass spectrometry.
2. Mineralogical phase equilibria, particularly in metamorphic rocks, can provide information as to the compositions of participating fluids.
3. Experiments carried out using single and mixed volatile species can constrain the effects of these volatiles on magma compositions, melting temperatures, viscosities, densities, and other parameters affecting material transport.
4. Theoretical modeling of the Earth's volatile budget, for example with respect to solar abundances, coupled with modeling of planetary volatile evolution may provide constraints on tectonic evolution of planetary crusts.

Problem 9: Crust-Mantle Interactions

Interaction between crust and mantle is involved in almost every process related to crustal genesis. The role of underlying mantle must therefore be considered whenever we study the genesis of any given section of continental crust.

The base of the crust, the Moho, is defined as the zone where seismic velocity increases to above 7.8km/s. The nature of the crust-mantle transition must be related to crustal genesis. The Moho may be: (1)

a sharp, step-like compositional change from intermediate or mafic rocks to ultramafic rocks, (2) gradational or a broad transition between these two rock types, or (3) a complex interlayering of crustal and ultramafic rock types. These three possibilities may be distinguished by the behavior of seismic waves that impinge on the Moho. The Ivrea zone, which has been interpreted as an upturned section through the crust, displays an interfingering relationship. Such interfingering may be formed by interthrusting of crustal and mantle rocks. The Moho may be investigated seismically in areas of Archean crust and its deduced nature may then be related to the age and tectonic style of the respective Archean rocks. We might also consider that the Moho is a phase change in limited areas only. A phase change would probably lead to a gradational Moho.

The characteristics of the Archean mantle and its relation to continents can be investigated in two broad ways: (1) understanding the characteristics of the present day mantle and how it inherited its characteristics and (2) by investigating mantle-related materials in Archean rocks.

The first approach requires defining the nature and distribution of present-day mantle heterogeneities with depth, both *within* and *between* continental and oceanic mantles. Available petrologic, chemical, and isotopic evidence in basic and ultrabasic rocks from the mantle clearly indicate that the present mantle is heterogeneous petrologically, chemically, and isotopically. Such heterogeneity may have prevailed from its accretion, if the latter was heterogeneous. However, from classical homogeneous or magma ocean hypotheses, the difference between continental and oceanic mantle may have started when the proto-crust was segregated from the mantle. One may imagine that the crust thickened gradually with time. It would be fundamentally important to understand when the mantle-crust differentiation started and what was the thickness of the crust.

Although isotopic evidence clearly shows that a heterogeneous mantle exists at present, it also indicates that oceanic and continental type mantle was established in Archean time. Pb, Sr, Nd, and Hf isotopes provide vitally important constraints on the rate of material transfer from the mantle to the crust.

The interaction between upper and lower mantle is a debatable problem related to the nature of mantle convection. Recent Nd isotope studies in kimberlite and continental flood basalts indicate that the deep mantle (> 200km?) is enriched in lithophile trace elements. Those observations as well as high ^{3}He contents in Hawaiian and Icelandic fumarolic gases have been interpreted as suggesting the existence from the Archean to the present of an undifferentiated primordial mantle at depth.

The second approach requires detailed isotopic and petrochemical studies of selected Archean igneous rocks. Information on the mantle lies in the characteristics of its partial melting products. Is there a recognizable change in such products with time? More information on the abundances of specific rock types, e.g. alkali basalts and komatiites, is required. Why are alkali basalts so rare? If petrology can ascertain the depth of melting for these magmas, isotopic data can provide insights into the existence and distribution of Archean mantle heterogeneites and mantle thermal history. These rocks can also provide other trace element constraints on mantle composition.

It is important to quantify the transfer of material from the crust to the mantle as well as from the mantle to the crust: do the mantle products indeed show any evidence of crustal recycling? Can a rate be determined for such recycling? If so, was it episodic i.e. are there periods when crustal recycling was not apparent? At what scale did crustal recycling occur—was it small-scale and localized or large-scale and general?

Regional variations in metallogenic provinces are found and may be related to corresponding lateral variations in mantle composition. The ultramafic host rocks of most Archean nickel-copper deposits are derived from large scale (10–30%) melting of the mantle. Examination of the sulfides associated with these rocks may yield important information on the degree of mantle homogeneity in the Archean, particularly with respect to lead isotope and platinum-group element compositions. Such relations clearly have major implications for mineral exploration.

Other problems involve emplacement of solid mantle material into the crust. Obduction of ophiolites at convergent margins and tectonic emplacement of ultramafics (such as in the Franciscan) are present day examples of this.

Problem 10: Effects of Accretionary Processes on Primordial Differentiation of the Outer Earth

Early differentiation of the Earth into major units as the crust, mantle and core is strongly dependent upon initial composition and associated thermal regime. In order to utilize these initial conditions in a meaningful way one is forced to consider the following questions: What was the scale of heterogeneity of the bodies that accreted to form the Earth? Were there secular trends in the composition of these bodies (e.g., refractory to volatile)? If so, what was the nature of the trends? By what processes were further homogenization or segregation produced? Was the heat from accretion and late stage impacts great enough to produce total melting or partial melting? How did the rate of heat production by infall compare to the rate of heat removal by convection (particularly in view of the inverse correlation of viscosity and temperature)? Was there enough heat produced, and sufficient inhibition of its removal, to cause melting to depths of hundreds of kilometers on a global scale, or is it more localized?

Answers to these questions rely heavily on the nature of early accretion and the distribution of planetesimal compositions. Meteorites provide the basis for estimates of initial compositions of accreting material. If all of the wide range of meteorite types were involved in the accumulation of a planetary body, then the resulting compositional heterogeneities would provide complications in models of the body's evolution. In addition, this evolution must consider the effects of heat produced by accretion, short-lived nuclides, late-stage impacts, and perhaps other sources that may have been active during the body's formation. Models for the production of heat during accretion and the final impact stages can produce a range of temperature profiles depending on assumptions of size distribution, flux, velocities, and other variables. However, several studies indicate that most of the Earth formed from sizeable planetesimals much of whose energy was buried as large amounts of heat ranging from enough to produce extensive melting through partial melting to high grade metamorphism. From studies of lunar samples there has emerged the possibility of a planet-wide magma ocean (or many large shallow magma chambers) from which differentiation of a model initial melt composition can produce a dense mantle and bouyant crust. Reservations have developed, however, about the extent of such melting. Could there really have been total melting to depths of hundreds of kilometers or only partial melting of a more limited nature. Or is it more reasonable to develop a lunar magma ocean by condensation of material splashed off the Earth by a large terrestrial impact?

Clearly the composition and configuration of any initial planetary units such as crust, mantle and core are heavily dependent on the nature of these processes. How can information about these processes be gained from studies of the Earth?

Any approach to this question is highly dependent on the development of models which must then be integrated with experimental work and tested against structure and chemical data from the field. Validity of the concept of a magma ocean requires experimental and theoretical examination of differentiation via gravity settling and rising of relevant minerals under the proper terrestrial conditions of pressure, temperature and composition. Similar studies must be undertaken on the thermal balances of large bodies of melt including effects of crystallization, conduction, radiation, mixing, etc. Furthermore, there should be comparisons of bulk chemistry, element ratios, and isotopic systems between the earliest known crustal rocks and the products of magma ocean models. Another constraint is knowledge of the composition of the earliest mantle. This would require a concentrated effort to select the earliest known mantle-derived igneous rocks followed by combined petrologic, chemical and experimental studies to estimate the composition of the parent mantle material. Because the oldest rocks with which we can work may postdate the earliest mantle by several hundred million years, it is necessary to devise a means of extrapolating mantle evolution backwards in a reasonable fashion.

Appendix B

Summary of Community Opinion

A letter (reprinted on following pages) describing the proposed Early Crustal Genesis program and soliciting input was sent to many geoscientists in the U. S., Canada, Great Britain, Denmark, Australia, South Africa and India. About 25 responses were received (listed on page 43). All expressed great interest and enthusiasm for such a project, and many described their ongoing research projects which would fit into such a program. Some indicated that NASA is a logical agency for coordinating global efforts of this type, while pointing out that collaborative relations with pertinent other research organizations should be established.

One aspect which was cited by many respondents was the desirability of integrated research efforts (consortia?) among specialists in complementary fields. Support for this research by funding of proposals was indicated by most respondents as a means to achieve the most benefit for the program (some view this as the most fundamental component). Those not eligible for U. S. or NASA funding indicated that collaboration with this project would reinforce their research efforts, both in terms of quality and funding. There were also many suggestions regarding conferences, publications, and workshops, although no consensus on the details was reached. There was strong sentiment, however, favoring field workshops as a fruitful mechanism for focusing on fundamental research problems that require collaborative efforts.

LUNAR AND PLANETARY INSTITUTE
3303 NASA Road 1 HOUSTON, TEXAS 77058 CABLE ADDRESS LUNSI
TEL (713)488-5200

August 25, 1980

Dear Colleague:

This letter is to solicit your input on the development of a NASA program on the early evolution of planetary crusts. The following paragraphs provide background information and the type of input that would be useful.

NASA's programs in lunar and planetary science have provided new data and hypotheses for the early evolution of planetary crusts. Prior efforts in these programs have concentrated mainly on planetary bodies other than the Earth. The Earth, however, is the most accessible planet for further development of these data and hypotheses. Therefore, NASA is exploring the possible ways in which the Earth may play a major role in a proposed program whose objective would be a better understanding of early evolution of planetary crusts.

Because of the lead time necessary for establishing a new program, funding for the proposed program will be quite minimal for the next two years. More substantial funding for proposals may be available by late 1982 or early 1983. In order to commence the development of NASA's involvement and provide a focus for this type of research over the next two years there are several things that can be done with existing funds. A series of small workshops at interesting field locations might develop cooperative efforts that could be discussed and organized while standing on the outcrops and selecting appropriate samples for each type of study. A series of small conferences on specific topics could be convened. Logistical support could be arranged for editing and publishing of a collection of papers from the conferences either as special issues of existing journals or special topical volumes.

As one of the first steps in defining an appropriate program a three-day workshop on "Early Evolution of the Earth's Crust" (EEEC) is planned for November 3, 4, and 5, 1980, at the Lunar and Planetary Institute in Houston. The purpose of this workshop is to help define the manner in which studies of the Earth can contribute to a more general understanding of the origin and early evolution of planetary crusts. This will be one of several topical workshops to be held this fall at the Lunar and Planetary Institute which can have significant influence on the future direction of NASA planetary research programs. For a broader view of the program development activities now underway, please refer to the attached letter on an Early Crustal Genesis (ECG) project by Roger Phillips, Director of the Lunar and Planetary Institute. The specific goal of the EEEC workshop is to prepare a document that would include recommendations on: (1) scientific objectives, (2) organizations that should be involved, (3) mechanisms by which people and organizations could accomplish the objectives, and (4) integration of the EEEC program into the broader planetary crustal evolution project proposed by NASA.

In order to facilitate the writing tasks of participants in the EEEC workshop, other workshops, and sub-discipline groups, we are soliciting written inputs from many persons and organizations who potentially have an interest in such a program. We hope that you will provide us with thoughts that you and your colleagues might have on this program. Some of the topics for which we would appreciate your comments are listed below. However, do not feel constrained to discuss only these topics and, also, do not feel that you must comment on all of the topics. Whatever you can provide will be helpful to the workshop participants.

Following is the list of questions on which we would like your input, from the point of view of either the EEEC program or the ECG project, or both:

1. What should be considered as the major scientific objectives of the program? Both general objectives and more specific objectives within individual disciplines will be developed.

2. What are the best mechanisms for achieving the scientific objectives (workshops, conferences, publications, funded proposals, advisory structure, individual efforts, consortium studies, etc.)?

3. How should the phasing of objectives and mechanisms be developed as the program evolves?

4. What organizations should be involved? In what ways would you or your organization wish to participate?

5. By what mechansims should various groups and organizations be involved (advisory, research activities, information recipients, providing of facilities or funds, collaborative efforts, etc.)?

6. During the interim low budget period of two years or so when there will not be any funds for proposal support, what types of activities could help bring this program into focus and provide for better communication between groups who are interested in this field of research?

7. When funding is available for proposals what types of research should be supported? The program must not appear to usurp the roles of other agencies such as the National Science Foundation. What criteria should be considered for review of proposals?

8. If field workshops are convened, what should be their objectives and what criteria should be utilized for selection of the field areas?

9. If topical conferences are organized what should be the criteria for selection of topics?

10. By what means of publication can we best provide focus and better communications for research on early crustal evolution: special volumes, special issues of journals, volume of extended abstracts for each topical conference, etc.?

An important point to keep in mind is the avoidance of potential conflicts that might arise from the perception of this program as conflicting with ongoing research efforts. Rather, it should provide for a better focus and communication between groups already working in this field of research and it should help develop complementary efforts that contribute to a more complete range of research efforts aimed at a better understanding of the early evolution of the crust.

We look forward to your inputs for this program. It would be appreciated if your comments could be sent by mid-October, 1980 to Ms. Pamela Jones, Projects Office, LPI. With your help we can develop the carefully planned approach and proper communication and cooperation between people and organizations that are necessary for a strong and vigorous research effort on the early crust.

Sincerely,

Jeff Warner

for William C. Phinney
Chairman of Organizing Committee
Workshop on Early Evolution of
the Earth's Crust

Roger Phillips

Roger J. Phillips
Director of the
Lunar and Planetary Institute,
for the Early Crustal Genesis
Steering Group

Respondents to Letter

Thomas J. Ahrens
California Institute of Technology
Pasadena, California

J. Lawford Anderson
University of Southern California
Los Angeles, California

Carl R. Anhaeusser
University of the Witwatersrand
Johannesburg, South Africa

Rodey Batiza
Washington University
St. Louis, Missouri

David Bridgwater
Københavns Universitet
Copenhagen, Denmark

Christopher Brooks
Université de Montréal
Montréal, Québec

Clarence J. Casella
Northern Illinois University
DeKalb, Illinois

Erich Dimroth
Université du Québec à Chicoutimi
Chicoutimi, Québec

Walter F. Fahrig
Geological Survey of Canada
Ottawa, Canada

William S. Fyfe
University of Western Ontario
London, Canada

Robert Hargraves
Princeton University
Princeton, New Jersey

Larry A. Haskin & Klaus J. Schultz
Washington University
St. Louis, Missouri

Lincoln S. Hollister
Princeton University
Princeton, New Jersey

William M. Kaula
University of California, Los Angeles
Los Angeles, California

Cornelis Klein
Indiana University
Bloomington, Indiana

Donald R. Lowe
University of Ottawa
Ottawa, Canada

Paul A. Mueller
University of Florida
Gainsville, Florida

Charles Meyer, Jr.
Johnson Space Center
Houston, Texas

Raymond A. Price
Queen's University
Kingston, Canada

Joseph V. Smith
University of Chicago
Chicago, Illinois

Richard J. Wardle
Department of Mines and Energy
St. John's Newfoundland Canada

John O. Wheeler
Geological Survey of Canada
Vancouver, Canada

Brian F. Windley
University of Leicester
Leicester, England

Peter J. Wyllie
University of Chicago
Chicago, Illinois

Appendix C

Participants

Lewis Ashwal
Lunar and Planetary Institute
3303 NASA Road 1
Houston, TX 77058
(713) 486-2147

Alec Baer
Department of Geology
University of Ottawa
Ottawa, Ontario
Canada K1N 6N5
(613) 231-6571

Robin Brett
EAR, Room 602
National Science Foundation
1800 G Street, NW
Washington, DC 20550
(202) 357-7958

Richard Coles
Earth Physics Branch
Department of Energy, Mines and Resources
Ottawa, Ontario
Canada K1A 0Y3
(613) 889-5625

Geoffrey Davies
Department of Earth and Planetary Sciences
Washington University
St. Louis, MO 63130
(314) 889-5625

Robert F. Dymek
Department of Geological Sciences
Harvard University
Cambridge, MA 02138
(617)495-2083

Kenneth A. Eriksson
Programs in Geosciences
University of Texas at Dallas
Richardson, TX 75080
(214) 690-2409

James Franklin
Mineral Deposits, Geology Section
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
Canada K1A 0E8
(613) 995-4972

Brian Fryer
Department of Geology
Memorial University of Newfoundland
St. John's, Newfoundland
Canada A1B 3X5
(709) 753-1200

Samuel S. Goldich
U. S. Geological Survey
Denver Federal Center
Mail Stop 963
Box 25046
Denver, CO 80225
(303) 234-5531

A. M. Goodwin
Department of Geology
University of Toronto
Toronto, Ontario
Canada M5S 1A7
(416) 978-3022

William M. Kaula
Department of Earth and Space Sciences
University of California, Los Angeles
3806 Geology Building
Los Angeles, CA 90024
(213) 825-1475

L. Paul Knauth
Department of Geology
Arizona State University
Tempe, AZ 85281
(602) 965-5081

Richard St. J. Lambert
Department of Geology
University of Alberta
Edmonton, Alberta
Canada T6G 2E3
(403) 432 3265

Paul D. Lowman, Jr.
Code 922
Goddard Space Flight Center
Greenbelt, MD 20771
(301) 344 7520

Charles Mankin, Director
Oklahoma Geological Survey
University of Oklahoma
Norman, OK 73019
(405) 325 3031

John Maxwell, Chairman
U. S. Geodynamics Committee
Department of Geological Sciences
University of Texas
Austin, TX 78712
(512) 471 5355

Vic Milne
Precambrian Geology Section
Ontario Geological Survey
77 Grenville Street, Room 905
Toronto, Ontario
Canada M5S 1B3
(416) 965 1321

Richard W. Ojakangas
Department of Geology
University of Minnesota
Duluth, MN 55812
(218) 726 7238

T. C. Onstott
Department of Geological and Geophysical Sciences
Princeton University
Princeton, NJ 08544
(609) 452 5011

A. R. Palmer
Geological Society of America
3300 Penrose Place
Boulder, CO 80301
(303) 447 2020

Roger Phillips
Lunar and Planetary Institute
3303 NASA Road 1
Houston, TX 77058
(713) 486 2180

William Phinney
Geology Branch, SN6
NASA Johnson Space Center
Houston, TX 77058
(713) 483 3816

William Quaide
Code: SL 4
NASA Headquarters
Washington, DC 20546
(202) 755 1602

Graham Ryder
Northrop Services, Inc.
Code: LCL
NASA Johnson Space Center
Houston, TX 77058
(713) 483 2666

Denis Shaw
Department of Geology
McMaster University
Hamilton, Ontario
Canada L8S 4M1
(416) 525 4205

Charles Simonds
Northrop Services, Inc.
Code: LCL
NASA Johnson Space Center
Houston, TX 77058
(713) 483 2666

Scott B. Smithson
Department of Geology
University of Wyoming
Laramie, WY 82070
(307) 766-3386

Robert C. Speed
Department of Geological Sciences
Northwestern University
Evanston, IL 60201
(312) 492-3238

Mitsunobu Tatsumoto
U. S. Geological Survey
Denver Federal Center
Mail Stop 963
Box 25046
Denver, CO 80225
(303) 234-3876

Matthew Walton, Director
Minnesota Geological Survey
University of Minnesota
1633 Eustis Street
St. Paul, MN 55108
(612) 373-3372

Jeffrey Warner
Code: SN
NASA Johnson Space Center
Houston, TX 77058
(713) 483-3816

Gordon West
Department of Physics
Geophysics Division
University of Toronto
Toronto, Ontario
Canada M5S 1A1
(416) 978-5175

Joseph Wooden
LEMSCO-C23C
1830 NASA Road 1
Houston, TX 77058
(713) 483-3951