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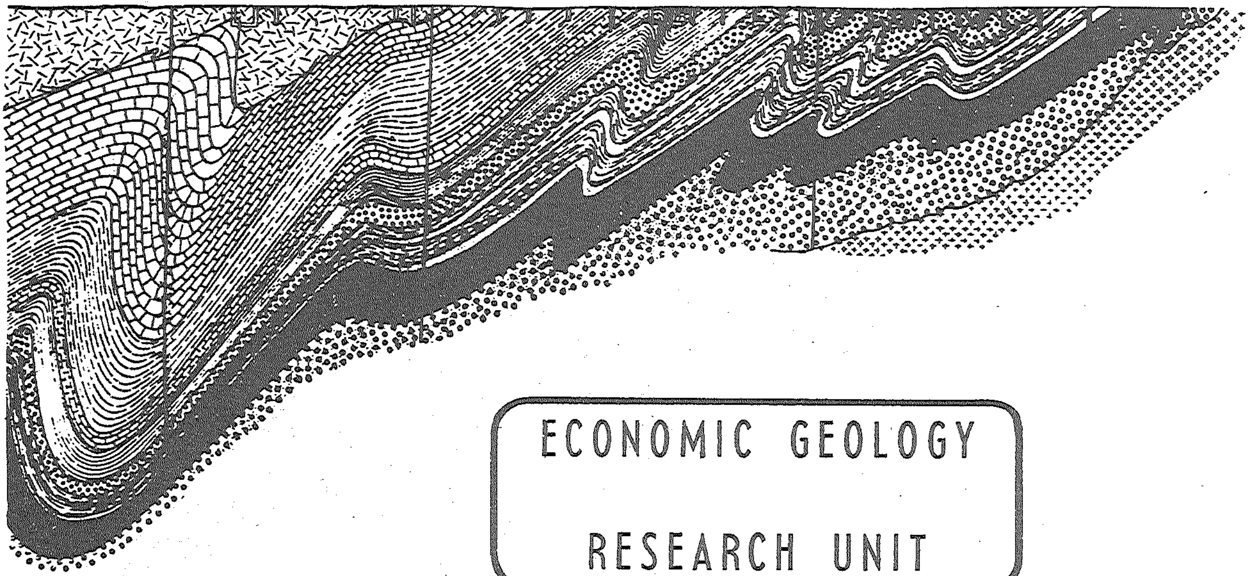

ECONOMIC GEOLOGY

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THE BARBERTON MOUNTAIN LAND : CLUES TO THE DIFFERENTIATION OF THE EARTH

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THE BARBERTON MOUNTAIN LAND : CLUES TO THE DIFFERENTIATION OF THE EARTH

by

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ABSTRACT

The Swaziland System is typical of the ancient greenstone belts of the world. Basal parts of these belts (Onverwacht-type) are strikingly like emergent island arcs, and must have evolved upon a thin, unstable crust. In contrast, the succeeding parts of most greenstone belts (Fig Tree and Moodies types) have been derived from, and deposited upon, a progressively more stable, thickening, granitic crust. Moreover, at present, the greenstone-granite terrains of the Barberton-type form the thickest, coolest, and most stable shield areas of the world. The enveloping granites exceed the greenstones in volume by an order of magnitude. Some are over 3000 million years old, and most surficial granite exceeds 2500 million years in age.

Granite must have been added to the greenstone-granite terrains during both orogenic and anorogenic periods. Much of it has apparently been passively accreted from below.

The basalts and peridotites of the Onverwacht-type are depleted in the ratiogenic nucleides K, U, and Th. Lavas of this composition have been erupted from the mantle in island-arc environments for over 3000 million years. They may represent the only primary mafic magma-types. Their constancy in composition throughout decipherable geologic time suggests that their source in the upper mantle also has been of uniform composition. This indicates that the first-order differentiation of the upper mantle and protocore preceded the emplacement of the Onverwacht lavas. The small amounts of K, U, and Th in them indicate that similar, localized source-regions of the mantle cannot have been the source of the associated granites. The origin of the widespread granite appears to be the result of large-scale melting in the mantle prior to, and during, Onverwacht times.

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THE BARBERTON MOUNTAIN LAND : CLUES TO THE DIFFERENTIATION OF THE EARTH

INTRODUCTION

The Barberton Mountain Land offers the geologist a unique opportunity to study early stages in the evolution of the Earth. This paper represents an attempt to explore several of the many facets of terrestrial differentiation, especially the incipient evolution of continental crusts, as suggested by features of the Barberton Mountain Land.

A knowledge of the general geological features of the Barberton Mountain Land is presumed. The geology of this region has been the subject of continuing interest since Hall's pioneering reconnaissance (Hall, 1918). Recent, important contributions include the Barberton Memoir of the Geological Survey of South Africa (Visser et al, 1956) and the work of local mine geologists (Cooke, 1965; Steyn, 1965), of the Swaziland Geological Survey (Hunter, 1957; Hunter, 1965; Urie and Jones, 1965), of the Bernard Price Institute for Geophysical Research (Allsopp et al, 1962; Nicolaysen, 1962; Nicolaysen et al, 1965), and of the Economic Geology Research Unit (Ramsay, 1963; Anhaeusser, 1965; Anhaeusser and Viljoen, 1965; Roering, 1965).

The continuing studies of the Onverwacht Series by M.J. and R.P. Viljoen, as part of South Africa's contribution to the International Upper Mantle Project, are invaluable.

DIFFERENTIATION OF THE EARTH

A. DIFFERENTIATIVE EPISODES

The studies of Nicolaysen (1962), and Allsopp and his colleagues (1962) suggest that the Swaziland System, and many of the enveloping granites, may exceed 3000 million years in age. On other continents, the oldest granites and migmatites surrounding greenstone belts appear to be some 300 to 600 million years younger Lowden, 1961; Lowden et al, 1963; Giletti and Gast, 1961; Goldich et al, 1961; Wilson et al, 1961).. Few of these old crustal fragments are as well exposed as the Barberton belt, or as free of dynamic metamorphic overprint. This conjunction of extreme age and preservation in the Barberton area raises the question whether this entire fragment of continental crust was formed earlier than most, if not all, of the other greenstone-granite belts of the world; or whether it is a remnant that survived, while its contemporary analogues in Australia, North America, and other continents were largely obliterated by more recent granite-forming orogenic episodes.

Existing geologic data suggest that, in any given terrain, the oldest greenstone belts, as well as the enveloping granites, vary in age. Reasoning from this, via uniformitarianism, one might conceive of all the old greenstone-granite belts as a second, or subsequent, generation of volcanic-greywacke complexes, the predecessors of which are now the mafic screens and ghost-like streaks within the oldest granite gneiss. Via this actualistic approach, the onset of continental evolution also might be envisaged with the birth of the first rift volcanoes, or island arc-like welts in much earlier, primeval seas (Macgregor, 1951). These initial volcanic edifices may have evolved upon, and from, a protocrust even more primitive in its chemical characteristics than the modern ocean basins (Engel et al, 1965; Tatsumoto et al, 1965). In South Africa, the oldest Barberton granites and migmatites may thus be regarded as extracts from, at least, several preceding cycles, each involving volcanism, weathering, sedimentation, and orogeny. Each cycle could have added, in turn, some ultimate differentiate, granite, and migmatite, to the spreading and thickening sial. This hypothesis predicates the evolution of the greenstone-granite terrain as crudely linear with time, or, at least, the by-product of many granite-forming, orogenic episodes, similar in kind and not too dissimilar in degree. Although this interpretation has the merits of uniformitarianism philosophy, it will be seen that it encounters serious difficulties in explaining features of the Barberton Mountain Land.

The accumulating mass of age and field data certainly suggests that the major granite-forming and orogenic cycles are episodic. The major episodes appear to have occured at intervals of several hundred million years. Reading backward from the present, major granite-forming orogenic events in the crust are dated at about (in millions of years) : 100, 400, 1000, 1500, 1900, 2600, and 3200 (Gastil, 1960; Engel and Engel, 1964). The granite-forming episode at about 2600 million years is defined by the ages of many of the granites in the oldest greenstone-granite belts of Western Australia (Wilson et al, 1961; Leggo et al, 1965) and of the Canadian shield of North America (Goldich et al, 1961; Lowden, 1961; Engel and Engel, 1964). The oldest clearly recognizable granite-forming episode on the Earth, at about 3200-3400 million years, has, as its most decipherable rocks, the granites of the Barberton Mountain Land.

Crustal regions that are stabilized and welded to pre-existing shield areas of each continent by the succession of granite-forming orogenic events may be designated provinces. In North America, the provinces, as thus defined, form a striking, accretionary pattern, the younger enveloping the older (Engel and Engel, 1964; Figure 1). In Australia, the provinces decrease in age from west to east (Wilson et al, 1961). In South Africa, the provinces tend to decrease in age towards the Cape (Nicolaysen, 1962). A plot of the area of each of the provinces of North America, including in these "areas" the known initial overlap of each province into adjoining younger provinces, is given in Figure 2. This plot suggests that each of the provinces is of approximately equivalent area, and that the growth of the stable shield areas of the North American continent is crudely linear with time.

But the question of continental differentiation also involves the volumes of sialic constituents that have been contributed directly from the mantle, and the rates at which this took place, not only during the successive stabilizing granite-forming orogenies, but also during anorogenic periods. Was this direct contribution from the mantle fairly uniform, or was there a major early effusion of sialic materials, followed by quite subordinate more recent additions?

The migration of sialic materials from the mantle into the crust is but a part of the broader differentiative history of the Earth into core, mantle, and crust, for it is inevitable that the differentiation of the Earth's core and mantle are reflected in important geologic events and processes in the crust.

B. <u>RATES OF DIFFERENTIATION</u>

At present, there exist widely divergent concepts of the rate, magnitude, and nature of the successive episodes of differentiation of the Earth. Examples of two extreme interpretations are the hypotheses of Runcorn (1965) on one hand, and Patterson and Tatsumoto (1964) on the other.

Runcorn (1965) has suggested that the differentiation of the Earth from a cold, essentially homogeneous agglomerate began about 3000 million years ago, that is, at the onset of the first clearly recognizable granite-forming episodes in continental crusts. His plot of the growth of the Earth's core, or, more precisely, of the ratio (n) of the radius of the core to the radius of the Earth is shown in Figure 3. Runcorn (1965) has attempted to relate a spherical harmonic analysis to certain of the major granite-forming episodes, which he infers are crustal manifestations of core growth and mantle convection. It can be seen in Figure 3 that Runcorn's Curve (R) involves the series of granite-forming episodes from about 2700 million years, and that the earth is almost completely differentiated at present. However, a most critical aspect of Runcorn's scheme is that, in Onverwacht time, the Earth was essentially undifferentiated!

In contrast, Patterson and Tatsumoto (1964) have interpreted a continent-wide array of lead, uranium, and thorium isotope data, derived from potassium felspars of North America, to mean that there was an early major migration of Pb, U, and Th from the Earth's interior to the crust. This initial differentiative pulse appears to have been followed by a sharp decrease in the rates of transport of these elements during, or near the end of, the first thousand million years after the Earth was formed. The strong coherence of potassium with lead, uranium, and thorium is well demonstrated. Implicit in these studies, therefore, is the conclusion that the rate of migration of the critical sialic constituents K, Pb, U, and Th, from the interior of the Earth is more nearly as shown by Curve E in Figure 3, or by Curve P in Figure 4.

The accumulating data from the Barberton Mountain Land, and other greenstone-granite terrains seem to support a differentiative history more like that suggested by Patterson and Tatsumoto (1964), and to invalidate the proposal of Runcorn (1965). The data also suggest that the first-order differentiation of the Earth into core, mantle, and sialic crust involved a major thermal event in the mantle. The resultant activation and migration of K, U, Th, and Pb from the Earth's interior to the surface is an intrinsic part of the evolution of the enveloping sea of granites. Comparison of the Onverwacht Series of the Swaziland System in South Africa with more recent volcanic suites also indicates that, since some 3000 million years ago, the upper mantle has not changed appreciably in its chemical composition, although the interior of the Earth has continued to degas and supply amounts of sialic constituents to the crust at lower rates (Figure 4, Curve P).

The oldest greenstone-granite analogues of the Barberton Mountain Land in North America form the Superior-Wyoming and Slave Provinces — an area exceeding half-a-million square miles. These are described in numerous reports, especially those of the Canadian Geological Survey, the Ontario Geological Survey, and the Bulletin of the Geological Society of America. Brief summaries appear in (Engel and Engel, 1964; Lowden, 1961; Lowden et al, 1963; Stockwell, 1962; Wilson, 1956).

The oldest greenstone-granite provinces of Australia constitute roughly half-a-million square miles of Western Australia (Low and Connelly, 1957). This region is the subject of considerable investigation at present. Constituent areas are described in publications of the Geological Survey of Western Australia. A brief summary appears in Wilson (1958). Knowledge of the oldest greenstone-granite regions of South America and Asia is less complete. Obviously no extended synthesis is possible until these areas are described in detail.

It is clear, however, that, in each of the continents, the greenstone-granite regions now form the oldest, thickest, stablest, and coolest crustal fragments (Clark and Ringwood, 1964). Therein, the sial, plus subjacent sima, is from 30 to 45 km thick (Press, 1961). Half of this appears to be "granitic", with the bulk chemistry of a granodiorite (Poldervaart, 1955). Heat flow is invariably low, of the order of 0.8×10^{-6} cal/cm^2/sec (Clark and Ringwood, 1964). Hence, temperatures at the base of these old crustal fragments may be inferred to be about 350°C, with some 60 to 80 per cent of the important heat-producing, long-lived, radio-active nucleides now concentrated from the mantle into this composite crust (MacDonald, 1959, p. 1982).

This implies that the mantle under these areas is largely depleted in the elements K, U, Th, and Pb (MacDonald, 1963; Clark and Ringwood, 1964). The present quest is for the rate of, and the major episodes involved in, this migration of the heat-producing large cations K, U, and Th, and their chemical cogeners, from the interior of the original homogeneous Earth and their concentration in its continental crust.

C. CRUSTAL THICKENING

A start will be made, as near the beginning as possible, with the Onverwacht Series at the base of the Swaziland System. Many features of the Onverwacht, and analogous basalt units in other old greenstone belts, imply an origin on a relatively thin crust. Specifically, the closest analogies to these old volcanic series are the recently-evolved island arcs of the circum-Pacific (Adams, 1962; Australasian Petroleum Company, 1961; Byers, 1959; Coats, 1959; Goryatchev, 1962; Liechti et al, 1960; Pergament, 1958; Raitt et al, 1955; Routheir, 1953; Schmidt, 1957; Shor, 1962; Yerokhov, 1960), and of the Caribbean (Dengo, 1962; Ewing and Ewing, 1959; Maxwell, 1948; Officer et al, 1957; Talwani et al, 1959). Recent detailed studies of these arcs suggest that their thickness is a function of their degree of differentiation and age. The Onverwacht-type assemblage of rocks, if considered separately, has analogies in parts of the Kurils and Aleutians, where crustal thicknesses are about 12 to 15 km (Coats, 1959; Goryatchev, 1962; Shor, 1962). The Swaziland System, taken as a whole, has its closest recent analogies in parts of the Philippines (Durke and Pederson, 1961), New Caledonia (Routhier, 1953), Kamchatka, and some island in the Caribbean (Burk et al, 1964; Dengo, 1962; Maxwell, 1948). These regions have crustal thicknesses ranging from 15 to 25 km (Officer et al, 1957; Talwani et al, 1959).

In effect, the degree of differentiation of the crust, or its age, may be plotted as a function of its thickness, as in Figure 5. The thinnest, youngest (?), most primitive crusts are under the oceans (Engel et al, 1965; Press, 1961). The thickest, oldest, and most granitic crusts are now the ancient greenstone-granite shields of the continents.

The Onverwacht Series, considered as an isolated crustal complexes, would plot in the area of the island arc-like assemblages (Figure 5); but, if the entire Swaziland System is considered, this complex falls much farther up the slope of the plot, in the area between the island arcs and continental borderlands. Hence, the data that are synthesized in Figure 5 imply that, as the Swaziland System evolved from the basal Onverwacht Series to the topmost Moodies Series, this area of crust, and adjacent source regions of detritus, also thickened, stabilized, and became more granitic. Certainly, this is what the lithologic features of the succession Onverwacht — Fig Tree — Moodies reveals — an upward progression through more differentiated and highly weathered sediments, which show an increase in the ratios of potassium felspar to plagioclase, clay minerals to chlorites and micas, potassium to sodium, and silica to magnesium. These upward-changing sedimentary attributes are accompanied by a marked decrease in the ratio of volcanics and tuffs to residuate sediments, and by abrupt decreases in landslides, debris flows, and other evidence of crustal instability. The ultimate rock-types are the essentially clean quartzites of the upper portion of the Moodies Series (Steyn, 1965; Visser et al, 1956).

These general characteristics of the Swaziland System are repeated with striking similarities in the more mature island arcs, and in all the older greenstone belts of the world. Yet, the extreme stability of the oldest of these greenstone-granite terrains during the past 2500 to 3000 million years also indicates that the associated crust must have grown sufficiently strong (thick ?), and the underlying mantle sufficiently quiescent (depleted in K, U, Th, Pb ?) to prevent the onset of orogenic episodes.

Other characteristics of the Barberton rocks suggest their emplacement on a crust much thinner than the present. An example is the telescoped nature of the metamorphic aureoles at contacts with the younger granites, and the bimodal nature of the mineral facies (Figure 6). In many of the greenstone-granite contacts, the zones of obvious contact metamorphism are no more than a few thousand feet wide (Urie and Jones, 1965; Anhaeusser and Viljoen, 1965). At the granite, the greenstones are reconstituted to amphibolite-facies rocks; yet, in the greenstone away from the granite, the grade of metamorphism drops abruptly to the greenschist facies, as illustrated in Figure 6. Telescoped metamorphic aureoles of this kind are known, from studies of much more recent geological environments, to be products of granite invading and enveloping near-surface parts of the crust. Buddington (1959) has characterized the nature of these epizonal granites and their host-rocks in North America. Some of the most illuminating examples are found in the Great Basin of North America, where it is sometimes possible to reconstruct the amount of rock that covered the rising granite, as Hunt (1953) has done in the Henry Mountains, Utah. From studies of this sort, it may be inferred that the "younger" granites which envelop, cut, and reconstitute the Onverwacht - Fig Tree, and most old volcanic-greywacke (greenstone) belts were emplaced at depths of 5 miles or less; and that the heat of these intrusions was dissipated very rapidly upward to the surface by convective streaming along faults and other fractures in the thin overlying crust.

These observations also imply a steeper thermal gradient in the crust and upper mantle 3000 million years ago than now. This is consistent with other evidence of a major thermal event in the upper mantle just preceding Onverwacht times (Figures 4 and 7).

GRANITES AND THE DIFFERENTIATION OF THE SIAL

A. ORIGIN AND EMPLACEMENT OF GRANITES

A third source of information about the ancient Barberton crust is the enveloping granites. The thoughtful, detailed work of Hunter (1957 and 1965), Roering (1965), and Anhaeusser and Viljoen (1965) indicates the oldest granites are either pre-Onverwacht or were emplaced during, and immediately after, its development. The mapping of M.J. and R.P. Viljoen (personal communication, 1966) clearly shows that some of the quartz-porphyries of Hall (1918) are felsic tuffs and thus part of the Onverwacht Series, whereas some are intrusives into the Onverwacht (Steyn, 1965). There are also major pulses of granite emplaced during, and immediately after, the deformation of the Swaziland System (Hunter, 1957). These syn- and late-orogenic granites appear to be at least 3000 million or more years old (Nicolaysen, 1962; Allsopp et al, 1962). Finally, there has been appreciable passive emplacement of high-level, young, anorogenic granite at some 2200-2500 million years ago (Allsopp et al, 1962).

This means that an enormous flood of granite, some four times the volume of the existing greenstone belts, was emplaced, in part, orogenically, and, in part, anorogenically (Roering, 1965). The anorogenic granites may be merely the surface manifestations of a widespread sialic accretion from below — a passive sialic underplating and thickening of the crust, accomplished by convective streaming of granite-forming constituents from the mantle. The earlier synorogenic granites, and the very old granitic gneisses certainly appear to mark a major flood of granitic fluids from the mantle. Before evaluating this major episode, it should be noted that evidence for the active, and passive, sialic underplating of continental blocks is by no means confined to the Barberton Mountain Land. Both orogenic and relatively young anorogenic granites appear in all the old greenstone-granite regions. The similarities are worldwide. The greenstone belts have the geological characteristics of rocks known to be emplaced on thin, relatively primitive crusts; yet, they float in a sea of granite, and now, with the granite, constitute the thickest, most stable parts of continental blocks.

More indirect, but important, arguments for secular, sialic underplating also are implicit in the studies of Rubey (1951), Holland (1962), Patterson and Tatsumoto (1964), and many others. These investigators have marshalled a vast array of data that suggests that differentiation and degassing of the Earth has continued up to the present. All of these data seem to require a secular thickening of continental crusts, complementary to a deepening of the oceans. The concept of isostatic equilibrium dictates that, if a secular increase in the depth of the oceans has occurred, the sialic continents have thickened to maintain "freeboard" above sea-level.

B. VOLUME OF OLD GRANITES

The rise of plateaus, and the appearance of intracratonic basins suggest that a passive sialic underplating at one site may be preceded or accompanied, by subcrustal erosion or thinning of other areas. In general, however, the amount of anorogenic granite, and the amount of sialic underplating seem to have decreased from Onverwacht time to the present. Most granite emplaced during the last thousand million years of the Earth's history seems to be of the classical, orogenic variety — an anatectic melt in the roots of evolving geosynclines. It is the older granites that require the most explanation, as Roering (1965) has pointed out. There are too many of them, and this volume relationship, as well as the anorogenic granites, cannot be explained as a product of the conventional geosynclinal-orogenic cycle (Roering, 1965).

For example, in the Barberton region it appears that a near-surface zone of granitic rock, at least one mile thick, perhaps 10 miles thick, was emplaced by about 3000 million years ago. The existing ratio of granite to greenstone is more than 4:1. Let it be assumed that, at Onverwacht time, the ancient sial of South Africa was about 5 miles thick, more than 80 per cent granitic rock, and less than 20 per cent Onverwacht and other greenstones. The average amounts of the critical sialic elements K, U, Th, and Pb in this old granitic crust may be readily inferred from the potassium content. The analytical data of Hunter (1957) and van Eeden and Marshall (1965) suggest that this ancient sialic crust contained about (in ppm) : K, 30,000, and, hence, also about Th, 15; U, 4; and Pb, 20.

Very similar ratios of granite to greenstone, and equivalent, or larger, amounts of K, U, Th, and Pb exist in the old granite-greenstone regions of other continents. In South Africa, the area of this ancient granitic crust probably exceeded half-a-million square miles. In general, in all the continents, this oldest granite-greenstone terrain appears to have covered at least one-fifth of the area of present-day continents, and, perhaps, even much more of a crust now reconstituted into, and obliterated by, succeeding orogenic episodes in the adjoining, younger provinces. These data on area and volume are minimal, and may be low by a factor of two or more.

The choice of a widespread thermal, differentiative event in the Earth to explain this old granitic crust also is dictated by the conception of the composition of the upper mantle from Onverwacht time to the present. The limiting, and critical, conditions appear to be imposed by the composition of the basalts and peridotites in the Onverwacht and younger volcanic series.

BASALTS AND THE DIFFERENTIATION OF THE SIAL

A. PARENTAL BASALTS

It is generally agreed that basalt is the one magma erupted from the mantle in great volumes, essentially ubiquitous in time and in geologic environment. At least two primary basaltic magmas have been postulated — one of tholeiitic basalt, and the other alkali-rich (Kushiro and Kuno, 1963; Yoder and Tilley, 1962). Recent studies on both continents and oceans suggest, however, that tholeiitic basalts are the predominant, if not the only, mantle-derived basalt (Engel et al, 1965). In fact, alkali-rich basalts constitute less than one per cent of the total volcanic sequence in the oceans, and appear to be limited largely to the surficial carapaces of the larger volcanoes. In the continents, the volume and structural relations are much the same. There are essentially no alkali-rich basalts in the Precambrian, which constitutes some four-fifths of geologic time (Engel et al, 1965).

The dominant tholeiitic basalts show only moderate, but apparently significant, variations in composition. The variations of interest at present are the amounts of K, U, Th, and Pb. These, with silica, vary systematically with the crustal environment in which the tholeiitic basalts are emplaced. In the oceans, where the great floods of tholeiitic basalt are extruded through a thin, basaltic crust, the average values are (in ppm) : K, 1,000; U, 0.1; Th, 0.2; and Pb, 0.8 (Tatsumoto et al, 1965).

In the island arcs and old greenstone environments, the values for K, U, Th, and Pb rise to double or triple these amounts. In the stable continental regions, the flood basalts and swarms of diabase and dolerite have an average potassium value of about 7000 parts per million (Walker and Poldervaart, 1949) with proportional increases in U, Th, and Pb. There is, accordingly, an increase in these elements in flood basalts that is closely correlative with the increasing thickness, age, and degree of differentiation of the crust which they intrude (Figure 5).

One interpretation of these data is that the upper mantle source of all flood basalts had initially about the same low amounts of K, U, Th, and Pb. If this is true, the systematic environmental increase is due to an increasing contamination of the rising basalt melt by K, U, Th, Pb and Si from the progressively thicker, more sialic crust. An alternative possibility is that the primary basaltic melt under the continents is blended with the continent-thickening, sialic constituents that are rising from the interior of the Earth.

The point of immediate interest is that the compositions of these tholeiitic basalts seem to place limiting conditions on the amounts of K, U, Th, and Pb in their mantle source-regions under the relatively thin, primitive oceanic, island-arc, and greenstone crusts (Engel et al, 1965). Moreover, for these specific crustal environments, the conditions in the subjacent mantle do not appear to have varied much with time. The present analytical studies of Onverwacht rocks are far from complete, but it is clear that the constituent pillow basalts average about (in ppm) : K, 1500; U, 0.15; Th, 0.3; and Pb, 1.0. Similar concentrations of K, U, Th, and Pb exist in the basalts of both of the old greenstone belts of North America, and in the tholeiitic basalts of young island arcs in analogous, incipient stages of development.

Because seismic data imply that the composition of the upper mantle is peridotitic, the tholeiitic flood basalts are probably partial melts, originally blended with peridotite, in ratios of perhaps 3:1 or 4:1 (Clark and Ringwood, 1964). If this is correct, the concentrations of K, U, Th, and Pb in the mantle under the oceans, evolving island arcs, and greenstone belts, throughout the last 3000 million years has, been about (in ppm) : K, 400; U, .04; Th, .08; and Pb, 0.3.

A test of this inference is possible through studies of the K, U, Th, and Pb in peridotites of the Onverwacht and younger greenstone and island arc environments. The agreement is good. These peridotites contain on the average about 250 to 400 ppm K, and appropriate very low concentrations of U, Th, and Pb, often so low, in fact, as to defy accurate analysis by contemporary techniques.

Almost surely, both the pillow basalts and ultrabasics of these sequences offer the upper and, probably, the lower limits of K, U, Th, and Pb in the upper mantle from which they have been derived; the basalts are partial melts, the peridotites are total melts, or residuates from which some basalt already has been extruded.

Summarizing these conjectures : (1) the composition of the upper mantle from which the basalts and peridotites of specific crustal environments have been derived has not varied significantly in composition for at least 3000 million years, and (2) during this time the concentrations of the elements K, U, Th, and Pb in the upper mantle under oceanic, island-arc, and greenstone belts have been low, of the order of K, 400; U, .04; Th, .08; and Pb, 0.3 (in ppm).

B. DIFFERENTIATION OF THE SIAL

Because numerous lines of evidence point to a primordial Earth composed of far more primitive material, perhaps a mix of stony and iron meteorites in ratios of 4:1 to 7:1 (Birch, 1964), it may be readily inferred that the differentiation of this primordial mix into iron-rich core and silicate-rich mantle and crust preceded Onverwacht time. If the mantle source of the Onverwacht volcanics was much more primitive than at present, the partial and total melts extruded therefrom would clearly indicate this primordial legacy.

The second conclusion, that the amounts of K, U, Th, and Pb in the mantle below greenstone belts were low in Onverwacht and succeeding times, follows from the first. If these elements were abundant in the upper mantle, they would be abundant in its partial and total metls extruded as island arc and greenstone volcanics.

The implications of this fact are crucial to the problem of the old granites. The derivation of the old granitic crust, some 5 miles thick, that has been inferred for the Barberton Mountain Land, and for other old greenstone-granite terrains, would require almost complete extraction of the K, U, Th, and Pb from an underlying zone of the mantle some 100 miles thick. If the thickness of the old South Africa granites has been appreciably underestimated, then their total K, U, Th, and Pb, would have to come from the nearly complete extraction of these elements from much of the upper mantle. Hence, there is a prejudice in favour of a major, early differentiation of the Earth, accompanied by a major, large-scale, thermal event in the mantle in the period preceding Onverwacht time.

The similar requirements of the lead-uranium isotope data from North America have been emphasized. Further support for this differentiative event is derived from recently analyzed thermal models of the Earth (Reynolds et al, 1966). The conclusions are summarized in Figure 7. Conditions suggested by the "uniform terrestrial model" of the Earth's composition seem to require partial, or total melting of a large zone in the upper mantle, during the early history of the Earth. Reynolds and his colleagues suggest that a zone of the mantle some 400 km thick, reaching to within 200 to 250 km of the surface, was molten during the period of generation of the older granites, some 2500 - 4000 million years ago.

It appears that independently derived geochemical and geophysical data point to a partial or complete melting of the outer Earth early in its history. This process would greatly accelerate the differentiation of core, mantle, and crust by permitting the iron to settle into the Earth's core, and the more volatile constituents, together with K, U, Th, Pb, and other granite-forming elements to rise towards the surface.

Elsasser (1963) in a discussion of the Earth's differentiation attempts to explain why this upward streaming of sialic constituents was concentrated on one side of the Earth and retarded in oceanic areas. If this protocontinent was Gondwanaland, the Barberton Mountain Land was near its centre. It may be speculated that upward convective streaming of sialic material began here, and that the sial grew laterally with time, thus accounting for the great age of the South African crust relative to that of Australia and North America.

But these are more speculative aspects of the Earth's history that cannot now be tested. It is possible, however, to evaluate, at this time, the concept of passive sialic underplating, and to further quantify the scale of the several, early granite-forming events in the Barberton Mountain Land. Deep drill-holes into the Nelspruit, Kaap Valley, and old Swaziland granites would produce cores from which more exact volumes and ages of the several granites could be determined as a function of depth. Such deep sialholes may prove as fruitful a source of the Earth's history as oceanic moholes. South Africa is, indeed, a critical region.

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List of References Cited

Adams, R. D.	1962	Thickness of the Earth's Crust beneath the Campbell Plateau. New Zealand Journ. Geol. Geophysics, Vol. 5, p. 74.
Allsopp, H. L., Roberts, H. R., Schreiner, G. D. L., and Hunter, D. R.	1962	Rb-Sr Age Measurements on Various Swaziland Granites. Journ. Geophys. Research, Vol. 67, No. 13, p. 5307-5313.
Anhaeusser, C. R.	1965	Wrench Faulting and its Relationship to Gold Mineralization in the Barberton Mountain Land. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.
Anhaeusser, C. R., and Viljoen, M. J.	1965	The Base of the Swaziland System in the Barberton-Noordkaap-Louw's Creek Area, Barberton Mountain Land. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.
Australasian Petroleum Company Proprietary	1961	Geological Results of Petroleum Exploration in Western Papua. Journ. Geol. Soc. Australia, Vol. 8, Pt. 2, 113 pp.
Birch, F.	1964	Density and Composition of Mantle and Core. Journ. Geophys. Research, Vol. 69, p. 4377-4388.
Birch, F.	1965	Speculations on the Earth's Thermal History. Geol. Soc. America, Bull., Vol. 76, p. 133-154.
Buddington, A. F.	1959	Granite Emplacement with Special Reference to North America. Geol. Soc. America, Bull., Vol. 70, p. 671-747

Burk, C. A., et al.	1964	A Study of Serpentinite : the AMSOC Core Hole near Mayaguez, Puerto Rico. National Acad. Sciences—National Research Council, Pub. 1188, 175 pp.
Byers, F. M.	1959	Geology of Umnak and Bogoslof Islands, Aleutian Islands, Alaska. U.S. Geol. Survey, Bull. 1028-L, p. 267-369.
Clark, S. P. Jr., and Ringwood, A. E.	1964	Density Distribution and Constitution of the Upper Mantle. Reviews of Geophysics, Am. Geophys. Union, Vol. 2, p. 35-88.
Coats, R. R.	1959	Magma Type and Crustal Structure in the Aleutian Arc. in The Crust of the Pacific Basin, Am. Geophys. Union, Monograph 6, p. 92-109.
Cooke, R.	1965	The Pre-Fig Tree Rocks in and around the Moodies Hills, Barberton Mountain Land. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.
Dengo, G.	1962	Tectonic-Igneous Sequence in Costa Rica. in Petrologic Studies, Buddington Volume, Geol. Soc. America, p. 133-161.
Durke, E. F., and Pederson, S. L.	1961	Geology of Northern Luzon, Philippines. Am. Assoc. Pet. Geol., Bull., Vol. 45, p. 137-168.
Elsasser, W. M.	1963	Early History of the Earth. in Geiss, J., and Goldberg, E. D., Editors, Earth Science and Meteorites, North Holland Publishing Co., Amsterdam, p. 1-30.
Engel, A. E. J. and Engel, C. G.	1964	Continental Accretion and the Evolution of North America. in Advancing Frontiers in Geology and Geophysics, Krishnan Volume, Indian Geophys. Union, Hyderbad, p. 17-37.
Engel, A. E. J. and Engel, C. G., and Havens, R. G.	1965	Chemical Characteristics of Oceanic Basalts and the Upper Mantle. Geol. Soc. America, Bull., Vol. 76, p. 719-734.
Ewing, J. T., and Ewing, W. M.	1959	Seismic Refraction Measurements in the Atlantic Ocean Basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea. Geol. Soc. America, Bull., Vol. 70, p. 291-317.
Gastil, G.	1960	The Distribution of Mineral Dates in Time and Space. Am. Journ. Science, Vol. 258, p. 1-35.

Giletti, B. J., and Gast, P. W.	1961	Absolute Age of Precambrian Rocks in Wyoming and Montana. Annals, New York Academy of Sciences, Vol. 91, p. 454-458.
Goldich, S. S., Mer, A. O., Baadsgaard, H., Hoffman, J. H., and Krueger, H. W.	1961	The Precambrian Geology and Geochronology of Minnesota. Minnesota Geological Survey, Bull. 41, 193 pp.
Goryatchev, A. V.	1962	On the Relationship between Geotectonic and Geophysical Phenomena of the Kuril-Kamchatka Folding Zone at the Junction Zone of the Asiatic Continent with the Pacific Basin. in The Crust of the Pacific Basin, Am. Geophys. Union, Monograph 6, p. 41-49.
Hall, A. L.	1918	The Geology of the Barberton Gold Mining District. Geol. Survey S. Africa, Memoir 9.
Holland, H. D.	1962	Model for the Evolution of the Earth's Atmosphere. in Petrologic Studies, Buddington Volume, Geol. Soc. America, p. 447-477.
Hunt, C. B.	1953	Geology and Geography of the Henry Mountain Region, Utah. U.S. Geol. Survey, Prof. Paper No. 228, 234 pp.
Hunter, D. R.	1957	The Geology, Petrology, and Classification of the Swaziland Granites and Gneisses. Trans., Geol. Soc. S. Africa, Vol. 60.
Hunter, D. R.	1965	The Precambrian Granitic Terrain in Swaziland. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.
Kushiro, I., and Kuno, H.	1963	Origin of Primary Basalt Magmas and Classification of Basaltic Rocks. Journ. Petrology, Vol. 4, p. 75-89.
Leggo, P. J., Compston, W., and Trendall, A. F.	1965	Radiometric Ages of Some Precambrian Rocks from the Northwest Division of Western Australia. Geol. Soc. Australia, Journ., Vol. 12, Pt. 2.
Liechti, P., Roe, F. W., and Haile, N. S.	1960	The Geology of Sarawak, Brunei, and the Western Part of North Borneo. Geol. Survey Borneo, Bull. 3, 360 pp.

Low, G. H., and Connelly, R. R. — 1957 — Geological Sketch Map of Western Australia. Geol. Survey Western Australia, Aust. Comm. Bureau Min. Resources.

Lowden, J. A. — 1961 — Age Determinations by the Geological Survey of Canada. Geol. Survey Canada, Paper 61-17, 127 pp.

Lowden, J. A., Stockwell, C. H., Tipper, H. W., and Wanless, R. K. — 1963 — Age Determinations and Geological Studies. Geol. Survey Canada, Paper 62-17, 140 pp.

MacDonald, G. J. F. — 1959 — Calculations on the Thermal History of the Earth. Journ. Geophys. Research, Vol. 64, p. 1967-2000.

MacDonald, G. J. F. — 1963 — The Deep Structure of Continents. Reviews of Geophysics, Am. Geophys. Union, Vol. 1, p. 587-665.

Macgregor, A. M. — 1951 — Some Milestones in the Precambrian of Southern Rhodesia. Trans., Geol. Soc. S. Africa, Vol. 54, p. 27-71.

Maxwell, J. C. — 1948 — Geology of Tobago, B.W.I. Geol. Soc. America, Bull., Vol. 59, p. 801-854.

Nicolaysen, L. O. — 1962 — Stratigraphic Interpretation of Age Measurements in Southern Africa. Petrolotic Studies, Buddington Volume, Geol. Soc. America, p. 569-598.

Nicolaysen, L. O., et al. — 1965 — Age Measurements on Rocks from Swaziland and the Area Around Barberton. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.

Officer, C. B., Ewing, J. I., Edwards, R. S., and Johnson, H. R. — 1957 — Geophysical Investigations in the Eastern Caribbean–Venezuelan Basin, Antilles Island Arc, and Puerto Rico Trench. Geol. Soc. America, Bull., Vol. 68, p. 359-378.

Patterson, C., and Tatsumoto, M. — 1964 — The Significance of Lead Isotopes in Detrital Felspar with Respect to Chemical Differentiation within the Earth's Mantle. Geochim. Cosmochim. Acta, Vol. 28, p. 1-22.

Pergament, M. A. — 1958 — Upper Cretaceous Rocks of Northwestern Kamchatka. Proc. Acad. Sci. U.S.S.R., Vol. 120 (in English translation), Consultants Bureau, New York.

Poldervaart, A.	1955	Chemistry of the Earth's Crust. Geol. Soc. America, Special Paper 62, p. 119-144.
Press, F.	1961	The Earth's Crust and Upper Mantle. Science, Vol. 133, p. 1455-1463.
Raitt, R., Fisher, R. L., and Mason, R. G.	1955	Tonga Trench. Geol. Soc. America, Special Paper 62, p. 237-254.
Ramsay, J. G.	1963	Structural Investigations in the Barberton Mountain Land, Eastern Transvaal. Trans., Geol. Soc. S. Africa, Vol. 66.
Reynolds, R. T., Fricker, P. E., and Summers, A. L.	1966	Effects of Melting upon Thermal Models of the Earth. Journ. Geophys. Research, Vol. 71. p. 573-582.
Roering, C.	1965	The Tectonics of the Main Gold Producing Area of the Barberton Mountain Land. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.
Routhier, P. P.	1953	Nouvelles Donnees sur l'Histoire Geologique de la Cote Ouest de Nouvelle Caledonie. Proc. 7th Pac. Sci. Congr. Vol. II, Geology, p. 47-61.
Rubey, W. H.	1951	Geologic History of Seawater. Geol. Soc. America, Bull., Vol. 62, p. 1111-1147.
Runcorn, S. K.	1965	Changes in the Convection Pattern in the Earth's Mantle and Continental Drift : Evidence for a Cold Origin of the Earth. Royal Soc. London, Philos. Trans., Series A, Vol. 258, p. 228-251.
Schmidt, R. G.	1957	Geology of Saipan, Mariana Islands : Petrology of the Volcanic Rocks. U.S. Geol. Survey, Prof. Paper 280B, p. 127-174.
Shor, G. G. Jr.	1962	Seismic Refraction Studies of the Coast of Alaska : 1956-57. Geol. Soc. America, Bull., Vol. 72, p. 721-730.
Steyn, M. v. R.	1965	Basal Rocks of the Swaziland System in the Steynsdorp Valley and Fairview Areas of the Barberton Mountain Land. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.

Stockwell, C. H. 1962 A Tectonic Map of the Canadian Shield. in The Tectonics of the Canadian Shield, Royal Soc. Canada, Spec. Pub. No. 4, p. 6-15.

Talwani, M., Sutton, G., and Worzel, J. 1959 A Crustal Section Across the Puerto Rico Trench. Journ. Geophys. Research, Vol. 64, p. 1545-1555.

Tatsumoto, M., Hedge, C. E., and Engel, A. E. J. 1965 Potassium, Rubidium, Strontium, Thorium, Uranium, and the Ratio of Strontium-87 to Strontium-86 in Oceanic Tholeiitic Basalt. Science, Vol. 150, No. 3698, p. 886-888.

Urie, J. G., and Jones, D. H. 1965 Metamorphic Zones of the Archean Fold Belt in Northwestern Swaziland. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.

Van Eeden, O. R., and Marshall, C. G. 1965 The Granitic Rocks of the Barberton Mountain Land in the Transvaal. Annexure Trans., Geol. Soc. S. Africa, Vol. 68.

Visser, D. J. L. et al. 1956 The Geology of the Barberton Area. Geol. Survey S. Africa, Spec. Publ. No. 15.

Walker, F., and Poldervaart, A. 1949 Karroo Dolerites of the Union of South Africa. Geol. Soc. America, Bull., Vol. 60, p. 591-706.

Wasserburg, G. J., MacDonald, G. J. F., Hoyle, F., and Fowler, W. A. 1964 Relative Contributions of Uranium, Thorium, and Potassium to Heat Production in the Earth. Science, Vol. 143, p. 465-467.

Wilson, A. F. 1958 Advances in the Knowledge of the Structure and Petrology of the Precambrian Rocks of South-Western Australia. Royal Soc. Western Australia, Proc., Vol. 41, p. 57-83.

Wilson, A. F., Compston, W., and Jeffery, P. M. 1961 Radioactive Ages from the Precambrian Rocks of Australia. Annals New York Acad. Sci., Vol. 91, p. 514-520.

Wilson, M. E. 1956 Early Precambrian Rocks of the Timiskaming Region, Quebec and Ontario, Canada. Geol. Soc. America, Bull., Vol. 67, p. 1397-1430.

Yerokhov, V. F. | 1960 | New Data on the Age of the Neogene Formations of the Northeastern Part of Iturup Island (Kuriles). Doklady Acad. Sci. U.S.S.R., Earth Sci. Sec. 130, p. 1-15.

Yoder, H. S., and Tilley, C. E. | 1962 | Origin of Basalt Magmas : an Experimental Study of Natural and Synthetic Rock Systems. Journ. Petrology, Vol. 3, p. 342-532.

Key to Figures

Figure 1. Gross patterns and ages of geologic provinces in North America, as defined by major granite-forming, mountain-building events. Numbers refer to ages of emplacement of major granites, in thousands of millions of years.

Figure 2. Graphic representation of the crudely linear rate of continental evolution in North America, as indicated by ages of emplacement of most granites in each geologic province. The area of each block reflects the known extent, and overlap, of the several geologic provinces.

Figure 3. Diagram indicating two alternative rates of growth of the Earth's core (modified from Runcorn, 1965). n is the radius of the Earth's core to the radius of the Earth. The curve R is based upon a hypothesis of convection, correlated with specific spherical harmonics (Runcorn, 1965). The Curve E appears to be more consistent with the geological features of the oldest granite-greenstone terrains.

Figure 4. Curves indicating two possible rates of radioactive heat generation in the Earth, related to relative rates of continental growth. The curve marked "chondritic" is derived from concentrations of radioactive elements in chondrites. The curve designated "crustal" is derived from the terrestrial concentrations of K, U, Th, and Pb, inferred by Wasserburg et al (1964). The solid line encloses the areas of continent shown in Figure 2 which imply a linear rate of continental growth. The dashed line enclosing the ruled area indicates the addition of sialic constituents to the crust, as proposed by Patterson and Tatsumoto (1964) and suggested by the studies of old granites (diagram from Birch, 1965; Engel and Engel, 1964; Patterson and Tatsumoto, 1964).

Figure 5. Graph of the interrelations between the degree of differentiation of the Earth's crust, its thickness, and known age.

Figure 6. Diagrammatic cross-section of an old greenstone-granite terrain, illustrating the strongly bimodal metamorphic facies, and the telescoped nature of the metamorphic aureoles that are formed in the greenstone by the invading granite.

Figure 7. Plot of the variation of temperature in the Earth as a function of time and depth, using the data employed in deriving the "terrestrial" curve in Figure 4. The cross-hatched zone may have become partially or entirely molten due to heat from the Earth's radio-activity (from Reynolds et al, 1966).

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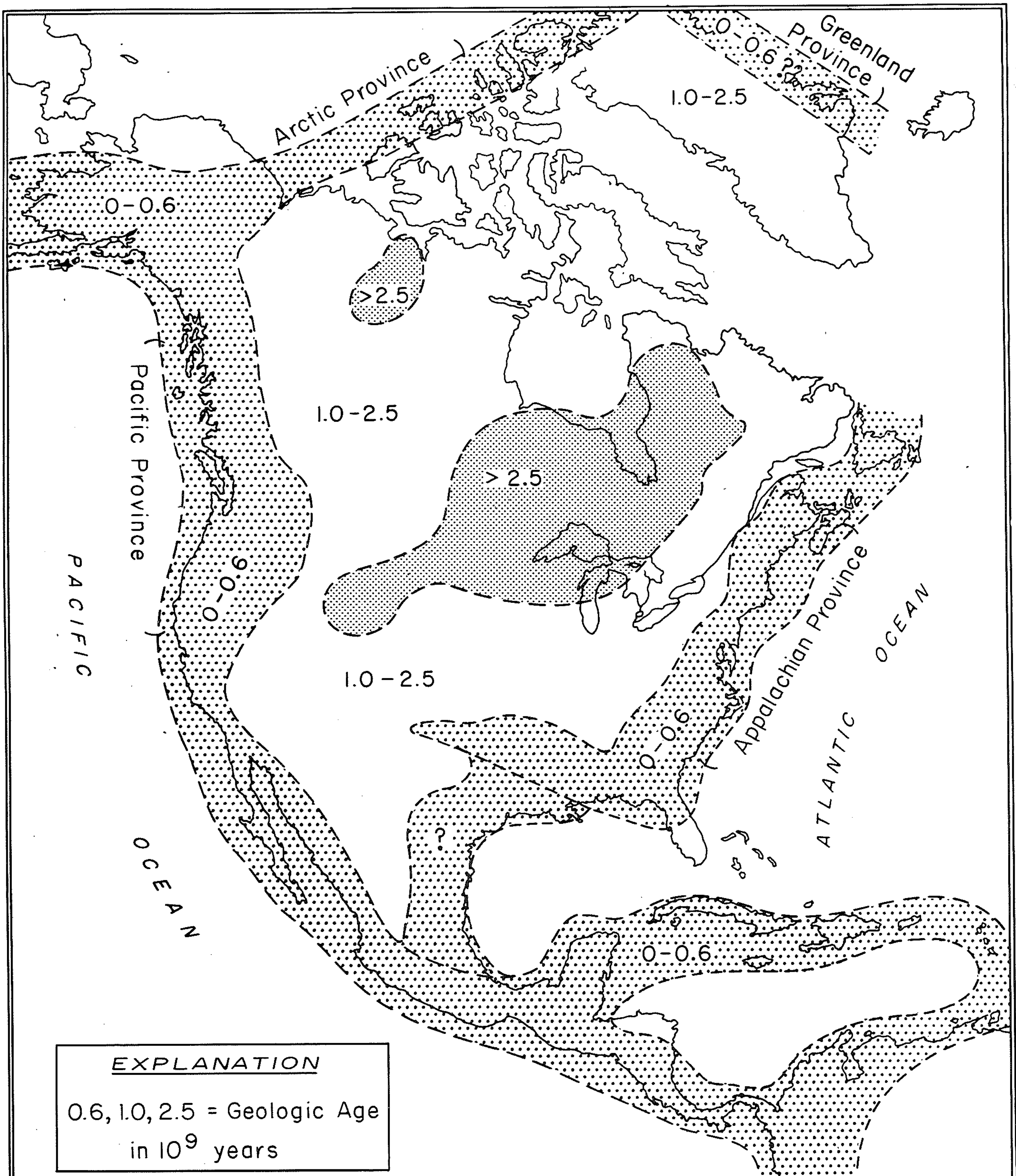
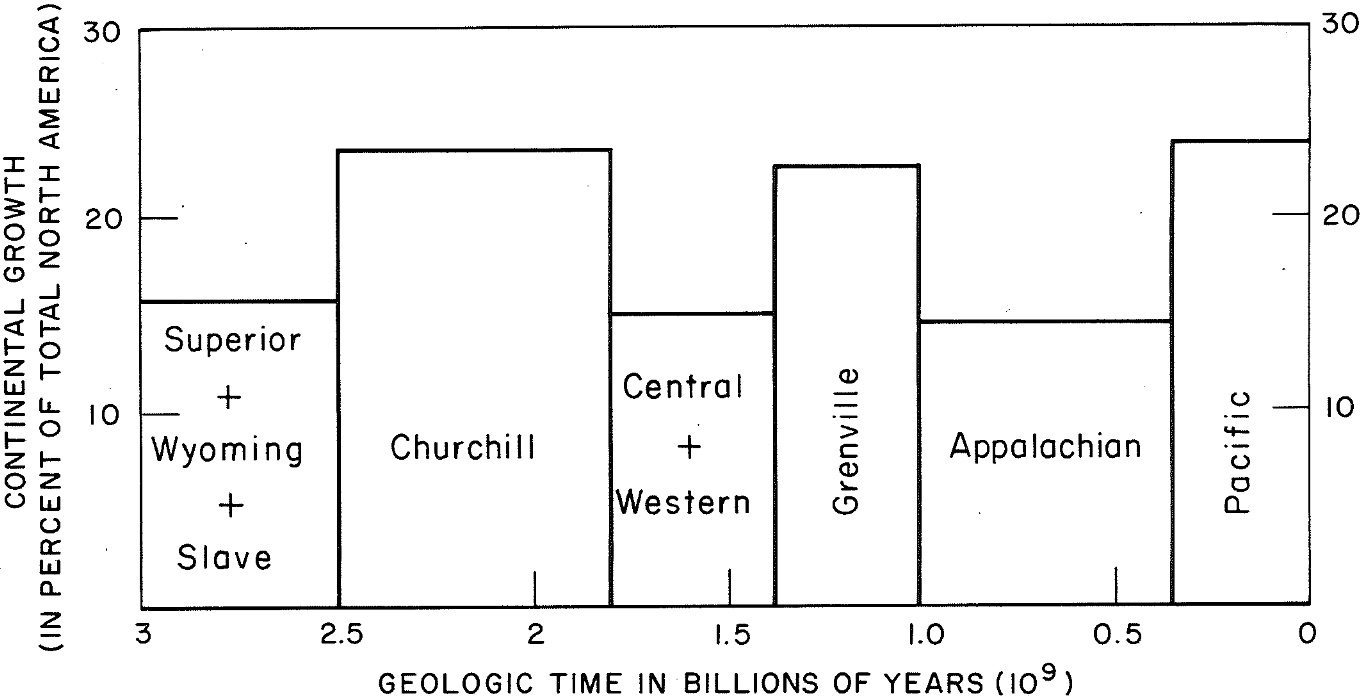
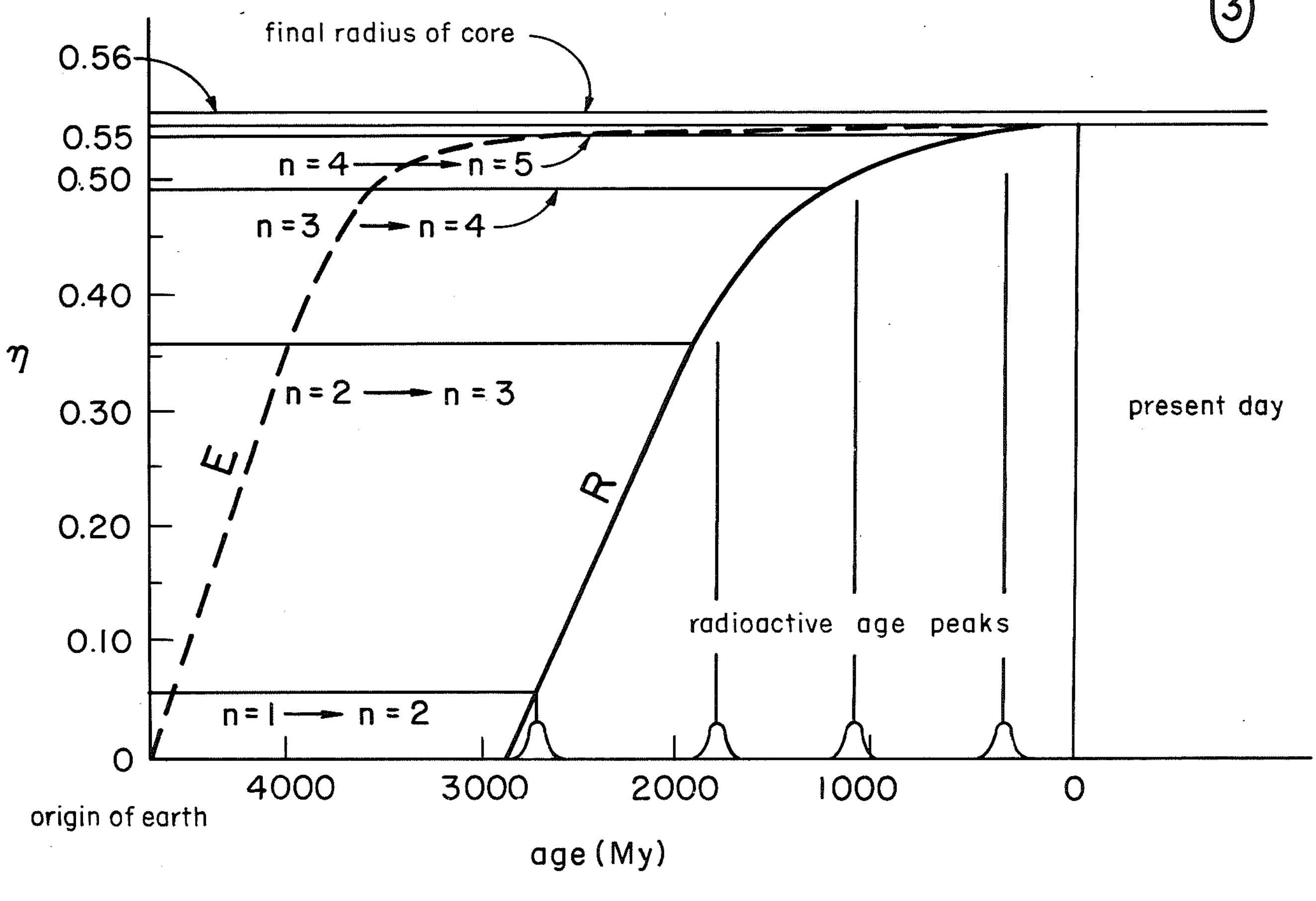

Arctic Province
Greenland Province
0-0.6 ??
1.0-2.5
0-0.6
>2.5
1.0-2.5
Pacific Province
>2.5
0-0.6
PACIFIC OCEAN
1.0-2.5
0-0.6
Appalachian Province
ATLANTIC OCEAN
?
0-0.6
EXPLANATION
0.6, 1.0, 2.5 = Geologic Age in 10^9 years

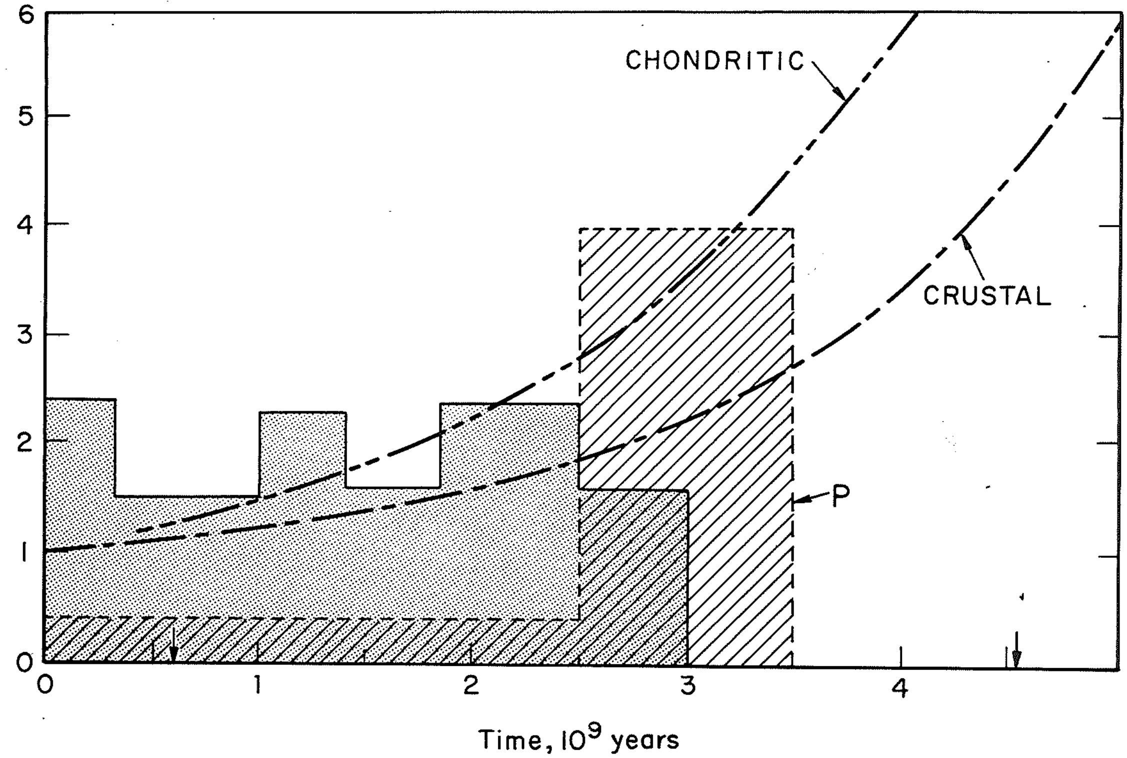
2


CONTINENTAL GROWTH
(IN PERCENT OF TOTAL NORTH AMERICA)
30
20
10
Superior
+
Wyoming
+
Slave
Churchill
Central
+
Western
Grenville
Appalachian
Pacific
3
2.5
2
1.5
1.0
0.5
0
GEOLOGIC TIME IN BILLIONS OF YEARS (10^9)

3

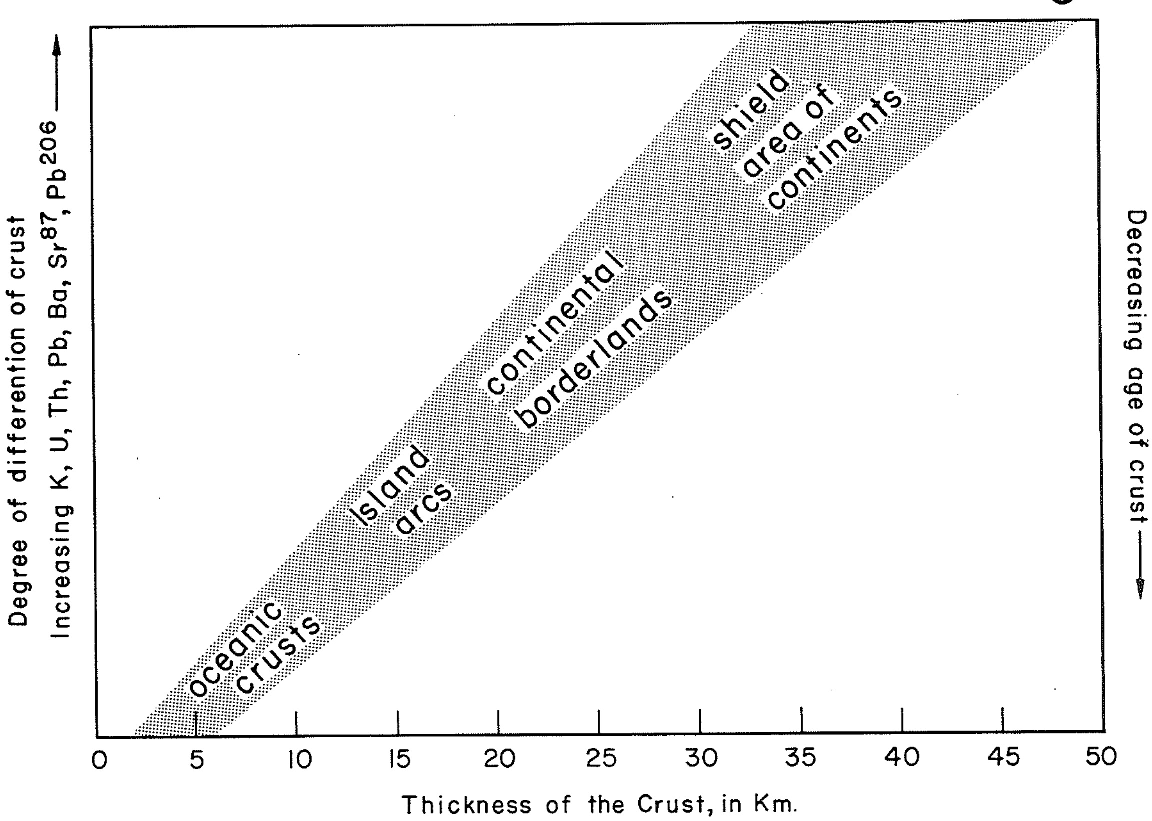

final radius of core
0.56
0.55
0.50
0.40
0.30
0.20
0.10
0
η
n = 4 → n = 5
n = 3 → n = 4
n = 2 → n = 3
n = 1 → n = 2
E
R
present day
radioactive age peaks
4000
3000
2000
1000
0
origin of earth
age (My)

(4)



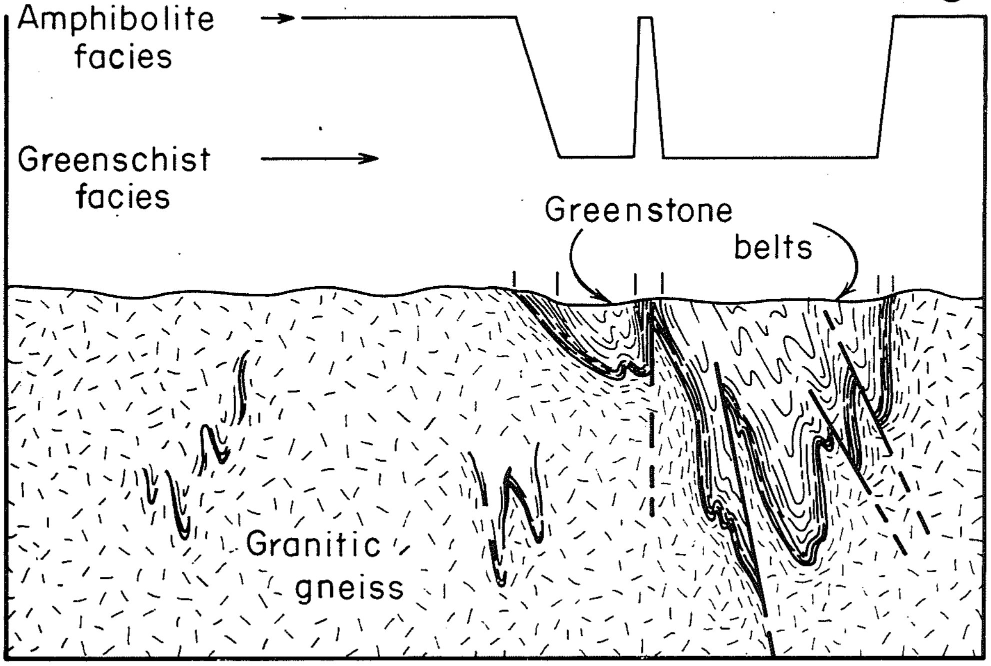
CHONDRITIC
CRUSTAL
P
6
5
4
3
2
1
0
0
1
2
3
4
Time, 10^9 years

(5)

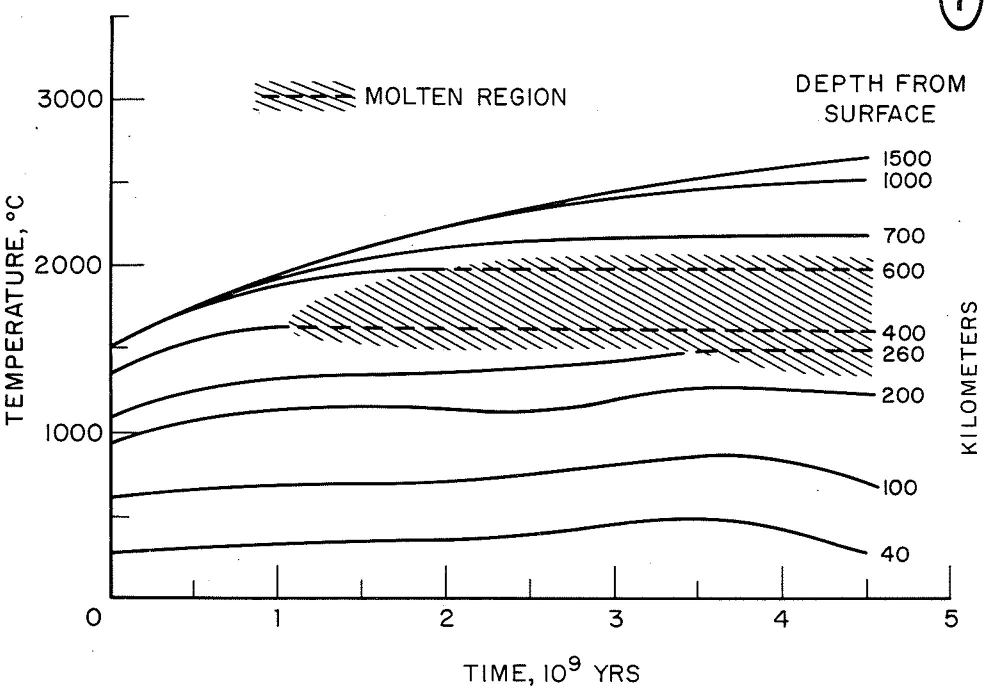


Degree of differention of crust
Increasing K, U, Th, Pb, Ba, Sr^{87}, Pb^{206}
Decreasing age of crust
oceanic crusts
island arcs
continental borderlands
shield area of continents
0
5
10
15
20
25
30
35
40
45
50
Thickness of the Crust, in Km.

6


Amphibolite facies
Greenschist facies
Greenstone belts
Granitic gneiss

7


MOLTEN REGION
DEPTH FROM SURFACE
KILOMETERS
1500
1000
700
600
400
260
200
100
40
TEMPERATURE, °C
3000
2000
1000
0
1
2
3
4
5
TIME, 10⁹ YRS