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THE CONTRIBUTION OF GEOPHYSICAL INVESTIGATIONS TO OUR GEOLOGICAL UNDERSTANDING OF THE DEEP CRUST

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ABSTRACT

The paper reviews briefly the various methods employed in the investigation of the nature of the deep continental crust. The methods include seismology, gravity, magnetism, heatflow, experimental petrology, isotope and trace element geochemistry, studies of "deep seated" inclusions.

The merits of the different methods are discussed, and it is concluded that a deep continental crust under shield areas of medium to high pressure granulite facies affinities is consistent with all existing data.

1. INTRODUCTION

To introduce this paper the system under discussion must be closely defined. In recent literature some confusion has been introduced because the "lithosphere" has been assumed to be synonymous with the earth's crust. However, the lithosphere includes both the crust and that portion of the upper mantle that lies above the low-velocity zone. The lithosphere therefore may contain the Moho discontinuity as well as other less pronounced discontinuities, especially in seismically active belts.

The lithosphere is distinguished from the underlying asthenosphere primarily on the basis of differences in physical properties. The upper surface of the lithosphere is generally well defined whereas its lower boundary is not at all distinct in a number of critical places and probably varies with time.

The lower boundary of the lithosphere is the most significant discontinuity to the concept of plate tectonics. When discussing the composition of the lithosphere we must not adhere too strongly to the Huttonian principle of "the present is a key to the past." Most probably the initial lithosphere was formed through

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processes that were much different from those that are presently taking place. Much evidence exists suggesting that the earth differentiated early in its history. It is possible that a fully developed lithosphere formed within the first billion years. This should be remembered when we try to account for the present concentrations of alkali metals and those minor elements which are concentrated in the continental lithosphere, or continental crust.

Also in a discussion of the composition and geology of the deep crust we must take into consideration that new lithosphere appears to be continuoulsy forming as well as disappearing. The plate tectonic concept shows that new lithosphere forms along midocean ridges and world rift systems. The rocks being produced are principally basic volcanics and ultrabasics. In an effort to better understand these processes, and to determine the nature of the parent material of the rocks produced, much interest to day is focussed around mantle-related rocks such as ophiolites which occur both in ocean basins and in old geosynclinal belts. Although most of the rocks along the midocean ridges are basic volcanics and ultrabasics, major lateral variations in physical properties occur through most of the lithosphere. These variations are roughly symmetrically about ridge axes. The ridge system varies in character along its length, with significant variations in igneous rock chemistry along the ridge axis.

It is a necessary requisite of the plate tectonic concept that lithosphere must be consumed. This destruction is associated with the discontinuities that exist along the seismically active belts associated with island arcs and continental margins. The destructive earthquakes associated with these belts apparently are due to thrusting of the lithosphere into the underlying astenosphere. How deep must the lithospheric plate be depressed before it is destroyed? The extent of underthrusting is inferred from the depths at which earthquakes occur. The maximum known depths are approximately 700 km. It must be emphasized that it is not known whether this maximum represents the depth of underthrusting reached in the last rapid cycle of plate movement, whether it represents the maximum depth at which the lithosphere can maintain its identity before assimilation into the asthenosphere, or whether it is a function of these and other unknown factors.

Perhaps the most striking seismic discovery of the last several years has been the recognition of a widespread low-velocity zone (LVZ) in the upper mantle. The term low-velocity layer has occasionally been used. A summary of the principal results were given by Anderson (1967). As pointed out by Magnitsky and Zharkov (1969) it is possible that there are areas on the globe where no such layer exist. In Iceland, Japan and the Kuril arc, and some regions in the western United States unusually low seismic wave velocities have been observed immediately below the Moho. In these areas there appear to be no low-velocity layer in the strict meaning of the term; instead a continuous increase in velocity with depth would be expected, although the increase begins with abnormally low velocities (Magnitsky and Zharkov, 1969). In trench areas there is a continuous transition between crust, lithosphere and LVZ.

This paper is concerned with the nature of the deep continental crust. Therefore, to treat this subject we have to trace the descending lithosphere in the subduction zone under the continents. Many diagrams could be selected to illustrate this situation. Figure 1 is from Ringwood (1971).

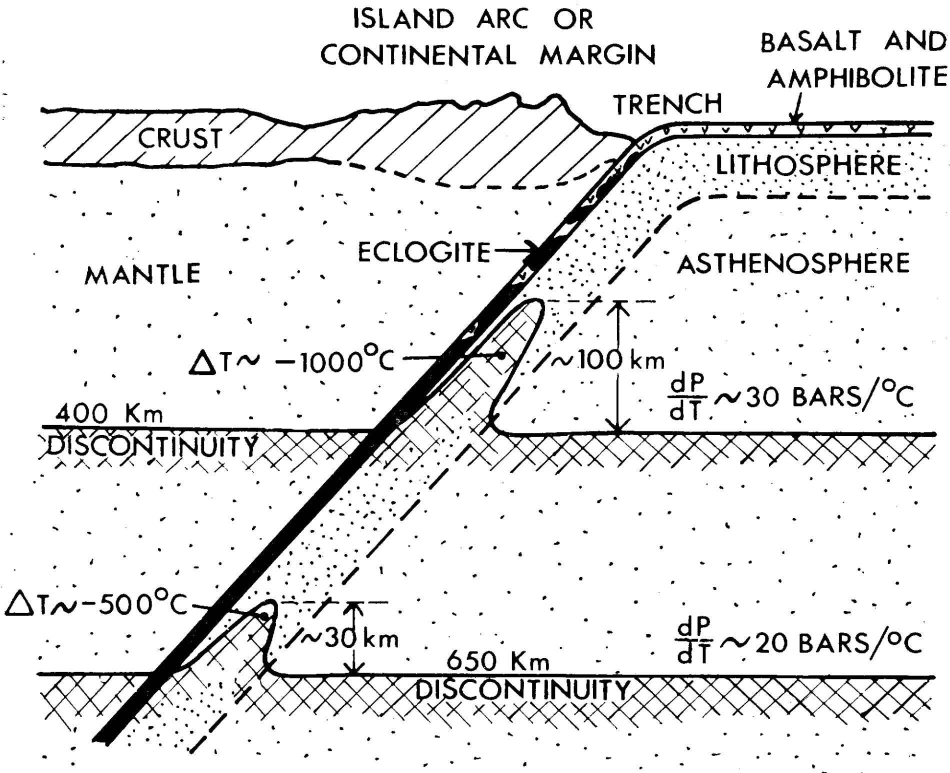

FIG. 1. — *Sketch showing possible relationship between sinking lithosphere plate and phase transformations. ΔT is the maximum temperature difference between interior of sinking slab and normal mantle at given depth (not to scale) (from Ringwood, 1971).*

Figure 1 also illustrates another important seismic conclusion namely that there is always a region of relatively high velocity (HV) overlying the LV zone, and that this zone is thinner beneath the oceans than beneath the continents. It is also important to our discussion to know to which depth the LVZ extends. Is it for instance synonymous with the depth of destruction of the lithosphere? It appears that under the oceans and normal continental regions the LVZ is terminated by the "Lehman discontinuity" at a depth of 220 km (Lehman, 1964). However, Anderson and Toksøy (1963) and Anderson (1964) show that a discontinuity is present at less depth in oceanic regions. Though it is of course important to note differences in depth where the LVZ terminates under ocean and continents it is more important for our discussion of the continental crust to note that while the SLVZ appears to be world wide in nature (Nuttli, 1963) a world wide existence of a PLV layer is considerably more in doubt (it should be noted that the PLV layer is more difficult to detect because surface wave velocities are insensitive to or independent of V_p). According to Clark and Ringwood (1967) apparently the PLV zone is almost certainly present in tectonically active regions

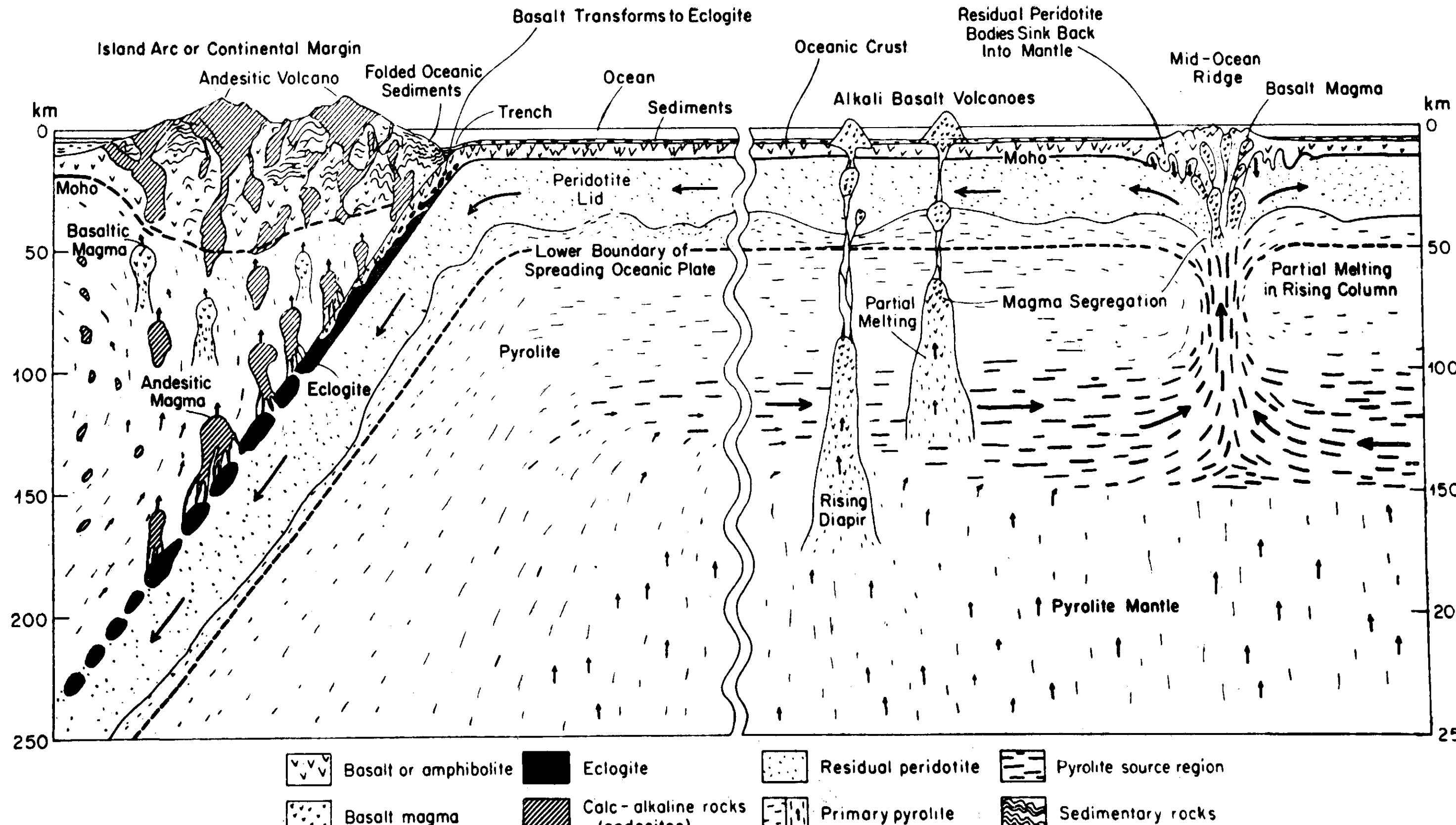

FIG. 2. — *Modified version of ocean-floor spreading hypothesis (not to scale) (from Ringwood, 1969).*

(regions of high heat flow). It is probably present in "normal" continental regions, although deep and with a relatively small decrease in velocity in the channel. It is most probably absent beneath Precambrian Shields. This paper will be devoted entirely to the subject of the deep crust in shield areas.

Before we enter into a discussion of the geology of the deep crust in shield areas it is necessary to take one further look at the geological consequences of the plate tectonic hypothesis (fig. 2, Ringwood, 1969). The important thing to note here is that newly generated continental crust is usually of andesitic composition derived by partial melting of predominantly basaltic, oceanic crust intermixed with some oceanic sediments. Part of the heat necessary for the partial melting could be the result of viscous dissipation in the upper mafic boundary layer of the sinking slab as was suggested by Oxburgh and Turcotte (1968). Green and Ringwood (1968) suggested that the upward rise of calc-alkaline magmas referred to above may trigger convective instability in the wedge-shaped region between the surface and the sinking slab of oceanic crust, leading to fractional melting in this region and the generation of basaltic magmas which also enter the growing continental margin (or island arc).

According to this model the new formed continental crust should have an andesitic-basaltic composition diluted with an unknown and probably spatially variable amount of sedimentary material derived from a pre-existing continent.

2. METHODS TO OBTAIN INFORMATION ABOUT THE NATURE OF THE DEEP CRUST UNDER SHIELD AREAS

The methods one can use to obtain information about the deep crust under shield areas may be classified as geophysical, geochemical and geological. I was asked to give a paper on the contribution of geophysical investigations to our geological understanding of the deep crust. However, all of the various methods used and the conclusions one may derive from them are so closely interdependent, that they cannot be treated separately.

The methods used are:

— Seismology;
— Gravity;
— Magnetism, including magnetotelluric studies;
— Heat flow;
— Experimental petrology;
— Studies of deep seated rocks carried to the surface;
— Studies of fluid inclusions;
— Isotope and trace element geochemistry.

3. SEISMOLOGY

Within shield areas it is possible to derive some conclusions based on seismic evidence alone. However, even when our studies are restricted to shield areas

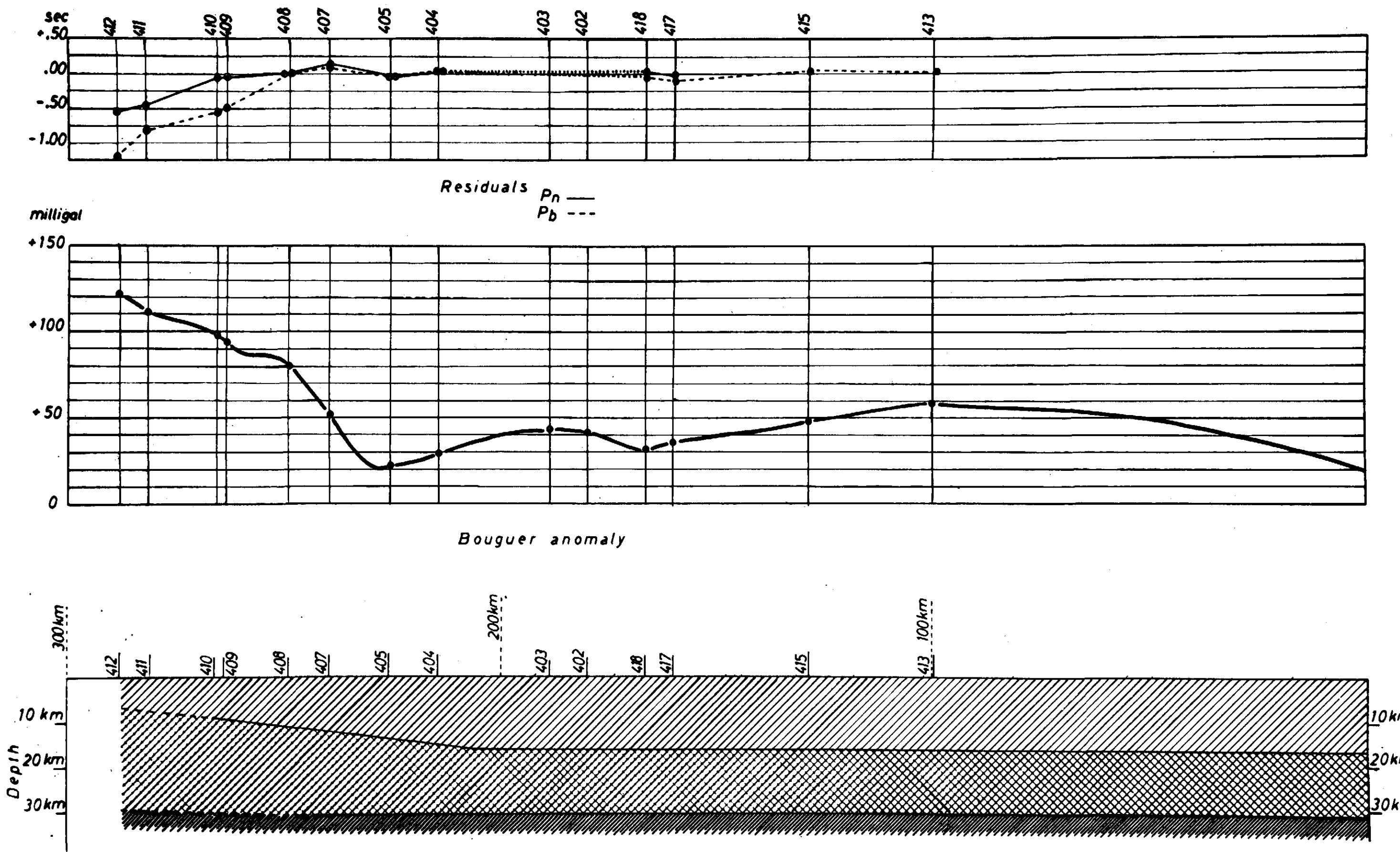

FIG. 3. — *A correlation between travel time residues. Bouguer anomalies and crustal structure in the Lofoten-Vesterålen region (from Sellevoll, 1968).*

difficulties are encountered when making broad generalizations about these structures because velocity distributions vary. The depth to Moho, which defines the thickness of shield areas, is generally well known. It varies between 35 and 45 km. Seismic velocities in the upper crust are commonly between 5.8 and 6.3 km/sec (Steinhardt and Meyer, 1961). It is generally assumed that they increase with depth and velocities of 6.6 to 7.2 km/sec are inferred for the lower crust. A very important problem is the nature of this downward increase. In some areas there is clear evidence for a discontinuity—the Conrad discontinuity—whereas in others the increase appears to be continuous, and even with zones of lower velocities in between. Where the Conrad discontinuity is indicated it appears to be situated at a depth of from 15 to 20 km. An exception is shown by a seismic profile in northern Denmark where an exceptionally shallow depth of less than 10 km is indicated for the Conrad discontinuity (Closs, 1969). Results obtained by the Seismological Observatory in Bergen, of studies carried out in Lofoten-Vesterålen area of North Norway are illustrated in figure 3 (Sellevoll, 1968). This data is of considerable importance to a discussion of the nature of the lower crust. The surface rocks in the area are composed of medium to high pressure granulite facies rocks partly retrograded to amphibolite facies. The Conrad discontinuity here appears to be very close to the surface.

One problem with the interpretation of seismic data is the retention of old ideas in the construction of models. It has been fashionable to interpret data assuming a layered crust where the individual layers are separated by discontinuities. These interpretations were stimulated by the success of seismologists in unravelling the gross structure of the earth, subdividing it into crust, mantle, outer core, and inter core, all seperated by discontinuities. The seismic solutions for the crust also were greatly influenced by petrologic notions of the time, for instance Daly's postulate of a world encompassing basaltic layer; thus a lower basaltic and an upper granitic crust.

The prevailing situation regarding the interpretation of seismic data for subdividing the earth's crust is well summed up in a statement from the U.S. program for the geodynamics project (1973).

"The earth's crust is often depicted as being separated from the mantle at a sharp boundary, the Mohorovicic (Moho) discontinuity. Occasionally, seismic refraction results are interpreted as indicating that there are several more discontinuities in the lower crust and upper mantle. These discontinuities are not well defined by seismic techniques, nor is their existence strongly confirmed by other evidences. If they are real, the contrast in physical properties is much smaller than the contrast at the Moho, hence they are overlooked in data that are rather difficult to interpret.

Should, however, one or more of these discontinuities prove to be real, calculations of depths to other horizons may have to be revised. More importantly, this might imply evolution of the continental crust from the primitive mantle in a much more complex manner than hitherto suspected. Conversely, the interpretation of crustal evolution may be simplified: The Mohorovicic discontinuity might be only the most prominent suite of such evolutionary schemes. Despite the fact that considerable debate about the nature of crustal differentiation exists to day, the character of these debates may undergo a considerable change in the future with availability of more detailed information regarding this interface region."

The seismic data available at this time for the crust in shield regions indicates a metamorphic modelling for the continents rather than an igneous layering. The variations indicated in crustal structure from one locality to the other, as well as the nature of the Conrad discontinuity which in some places is expressed by a sharp discontinuity in seismic velocities, and at other locations as a gradual increase, plus the second order discontinuities that have been indentified at different depths, corresponds to a metamorphic model of crustal evolution.

Interpretations of seismic data by Pakiser and Robinson (1966) indicate that the continental crust is significantly more mafic (or denser) than the continental crust suggested by Vinogradov (1962) and Taylor (1964). We shall return to these observations later but they are in harmony with the views stated by this author during the last ten years.

4. GRAVITY

It is generally assumed that regional changes in values of Bouger gravity anomalies are related to changes in the thickness of the earth's crust. Also, where the surface varies considerably from the normal, elevation of the crustal thickness has anomalous values (Wollard, 1969). If the gravity anomalies are positive, it is assumed the crust is thinner than normal; if they are negative, it is assumed that the crust is thicker than usual. However, the interpretation of regional anomalous gravity values in terms of anomalous crustal thickness is predicated on the constancy of the mean density of the crust and of the mantle. If these densities do not remain constant, the anomalous value of crustal thickness can be different from what is usually assumed. (Local anomalous gravity values are attributed to the near surface mass distribution, and the interpretation of local anomalies is generally logical.) For gravity studies to assist us in our understanding of the geological nature of the deep crust they have to be closely correlated with seismic observations.

It appears from the available data that approximately 65 per cent of the seismically defined crustal thicknesses have a "normal" relation to surface elevation which suggests a fairly uniform density contrast between the crust and underlying mantle. For the remaining 35 per cent crustal thickness values as determined from surface elevations and Bouguer anomalies are not reliable within 10 km (Wollard, 1969). It is important to note that seismic evidence suggests that the anomalous values of crustal thickness generally are not caused by a lack of isostatic equilibrium, but rather by significant changes in the density contrast between the crust and mantle.

5. MAGNETISM, AND MAGNETOTELLURIC STUDIES

Even though it is generally accepted that the major part of the geomagnetic field originates within the earth's core, where electric currents are generated by heat energy and the earth's rotation, studies of geomagnetism tell us little about the geology of the deep continental crust. This is due to what is generally known as "the Curie depth." Below this depth (temperature) ferrimagnetic minerals are paramagnetic and possess so little magnetization that they can be assumed to be nonmagnetic when interpretations are made of magnetic anomaly data. Mundt (1966) estimated the Curie depth in northern Germany to be 20-25 km, with an interval of uncertainty of ± 5 km.

The most widely applied techniques for deep electrical measurements have involved measurements of the electromagnetic fields produced by the dynamo effects in the ionosphere, by Alfvén waves generated in the magnetosphere or at its boundaries, and by drift motions of ionized particles trapped in the earth's magnetic field and also perhaps driven by magnetospheric electric fields. Electrical studies using these natural electromagnetic fluctuations have generally used two techniques. When using the first technique the three fluctuating components of the magnetic field are simultaneously measured at several points in the area being investigated. This method is known as the "geomagnetic variation method" (Rikitake, 1969). The method is probably not useful for crustal studies because the mechanical properties of rocks are not sensitive to slight changes in temperature, but it holds promise as an independent means of detecting anomalous conditions within the mantle.

The other technique uses fluctuations in the horizontal components of both the electric and the magnetic fields. This is known as the "magnetotelluric method." A modification of both methods known as the "telluric method" is also used. In the telluric method simultaneous measurements of the horizontal electric fields are made at several points.

To the author's knowledge these methods have not yet been employed to solve problems dealing with the nature of the deep crust. They may be useful in delineating the border between sedimentary basins and the crustal substratum. However, the magnetotelluric measurements will perhaps be most useful in making quantitative comparisons of the upper mantle underlaying various tectonic regions and to outline the transition zones separating such regions.

It is clear from measurements of geomagnetic variations and the pattern of electrical conductivity in southwestern Australia that the zones underlying shield areas have lower electrical conductivity than elsewhere. This suggests that the temperature gradient here is less, which agrees with the low heat flow values measured in shield areas (Everett and Hyndman, 1967).

6. HEAT FLOW

In the last 10 years considerable interest has been focused upon heat flow measurements from various geological provinces. Interpretations of crustal structure and the distribution of heat producing elements are based on these measurements. To obtain heat flow data from the ocean bottom is relatively simple and the increase in oceanographic research in the years after the second world war has produced much heat flow data from ocean areas. Measurements from continental areas have been fewer and largely restricted to mining areas where boreholes of sufficient depth have been available. It is generally realized that the heat producing elements (U, Th, K) are concentrated in the continental crust.

It was therefore, somewhat surprising to discover that the average heat flow from the oceans and continents is very similar; in the range of from 1 to 2 HFU (1 HFU = 1 μcal cm^{-2} sec^{-1}) (fig. 4—Lee, 1970). The histograms are of equal area grid averages where N equals 95 % for the continents (total number of samples 597) and 591 for the oceans (total number of samples 2 530).

The hypothesis of sea floor spreading may explain why the continental heat flow is not significantly larger than that from oceanic areas, as it implies that a large proportion of the oceanic heat is carried upward by convection rather than conduction. Part of this heat may be " orignal heat" inherited from an early high temperature stage of the earth's history. Also part may come from deeply buried radioactivity, but the important thing is that there is no necessity to assume that the ultimate source should permanently lie in the oceanic upper mantle. Accordingly, there is no longer any justification for assuming that average chemical compositions beneath continents and oceans when extrapolated to considerable depths are identical. It would be more reasonable to construct models with much lower abundances of U, Th and K in the oceanic upper mantle than

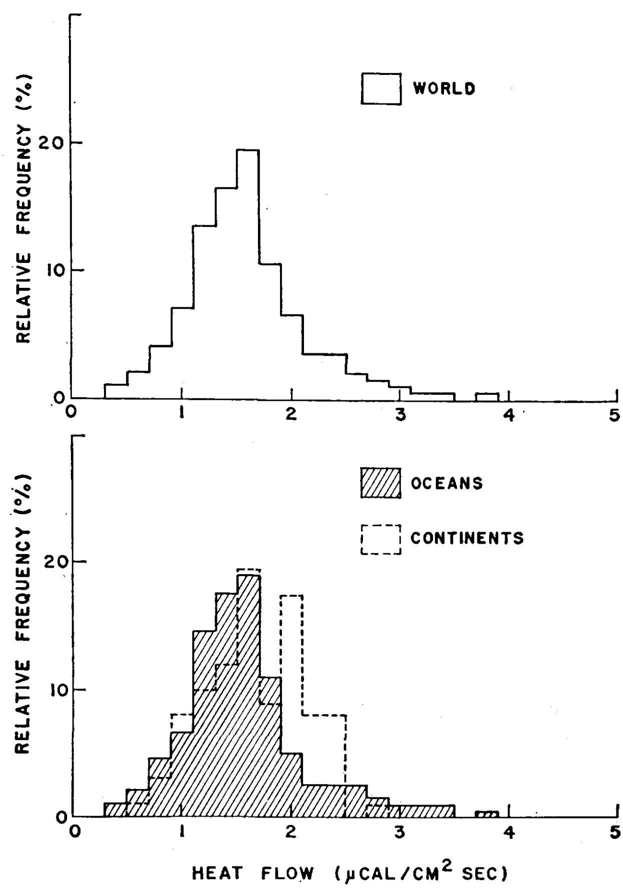

FIG. 4. — *Histograms of equal-area grid averages of heat-flow for the world, continents and oceans (from Lee, 1970).*

previously appeared possible. This is supported by the widespread occurrence of oceanic tholeiites with distinctive trace element chemistry and low abundance of U, Th and K (Ringwood, 1969).

The heat flow distribution for various continental tectonic provinces are illustrated in figure 5. The Precambrian shields (214 samples) have the lowest heat flows with their arithmetic mean being 0.98 and their S.D. 0.24.

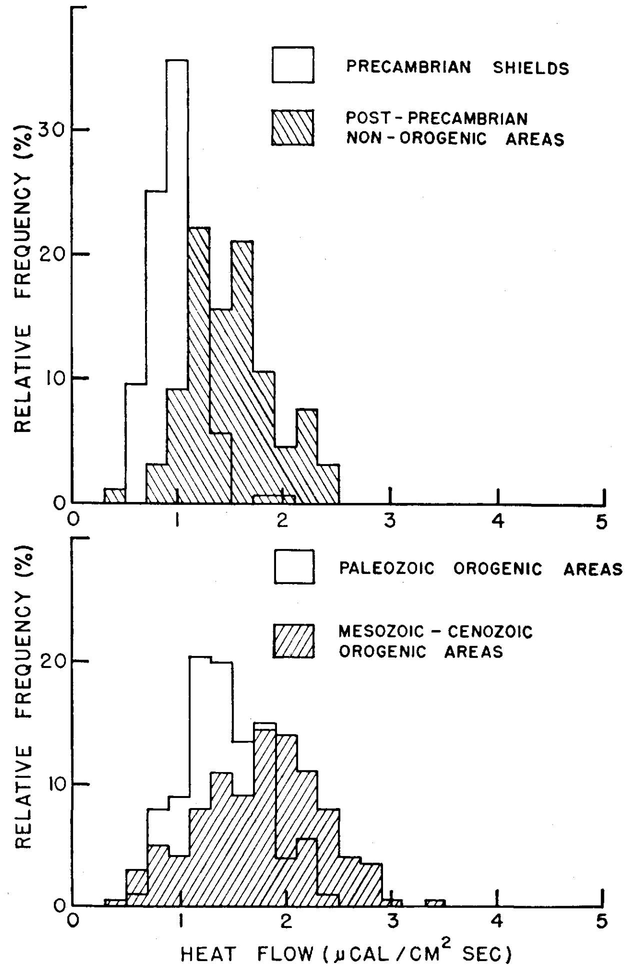

FIG. 5. — *Heat-flow histograms for various tectonic provinces on land (from Lee, 1970).*

Together with Lackenbruch (1968, 1970), Roy *et al.* (1968), we at the Australian National University were the first ones independently to point out the necessity of knowing the surface heat production in order to obtain the maximum amount of geological information from heat flow data. Most of this work has been summarized by Heier (1973*a*).

Our early approach was to find a correlation between heat flow and surface radioactivity by assuming particular crustal models for the various tectonic environments under discussion (Hyndman *et al.*, 1968; Lambert and Heier, 1968*a*). This procedure was used in the West Australian shield area where the surface heat flow and heat production was known. Taking into account the frequently documented evidence that the depletion of U and Th takes place rather abruptly as medium to high pressure granulite facies rocks are encountered, and assuming that after this there is a slight gradual loss of the heat producing elements down to the base of the crust, the thicknesse of the upper "granitic" crust may be calculated by assuming that the surface radioactivity continues to a depth (X) where the medium to high pressure granulite facies begins (fig. 6).

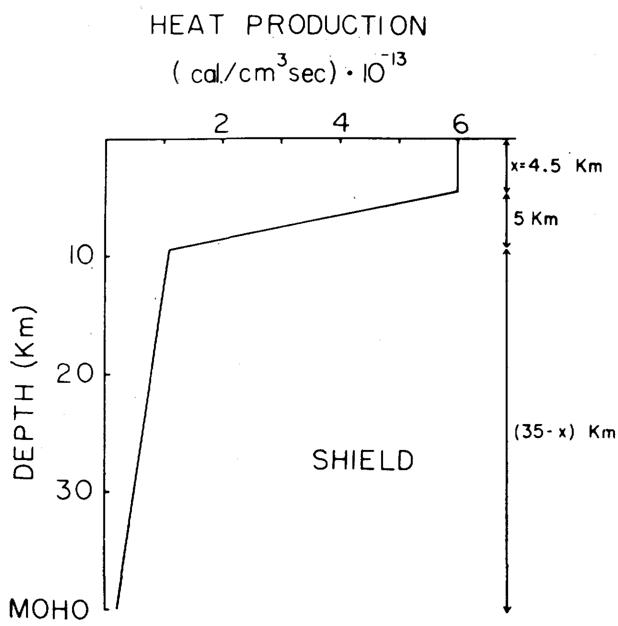

FIG. 6. — *Heat production at various depths within the stable southwest Australian shield (from Lambert and Heier, 1968*a*).*

We can then calculate X from the relation:
α shield $+ 1/2\,(\alpha$ shield $+ \alpha$ gran.$)\,.\,5 + 1/2\,(\alpha$ gran. $+ \alpha$ Moho$)\;(35 - X) =$ total surface heat flow $-$ heat flow from the mantle; where α shield $=$ heat produced by surface radioactivity, etc. In this particular model it is further assumed (based on seismic evidence) that the total crustal thickness is 40 km, and that the transition from surface to granulite facies heat production takes place over a transition zone of 5 km. The calculation indicates an "upper" crust of 4.5 km thickness. Roy *et al.* (1968) have shown that in many regions which they designate as heat flow provinces, there appears to be a linear relation of the form:

$$Q = a + bA.$$

In this equation Q and A are surface heat flows and heat generations respectively within a geological province. The simplest model which would fit this formula is that of a layer of thickness b in which the heat generation at every point has the surface value A, while there is uniform flow of heat a (Q_0) into the bottom of the layer from the low crust and upper mantle. At this stage it seems apropriate to quote Jaeger (1970) "Without wishing to impute any particular geological value to this model, it provides an extremely convenient method of visualizing and discussing results."

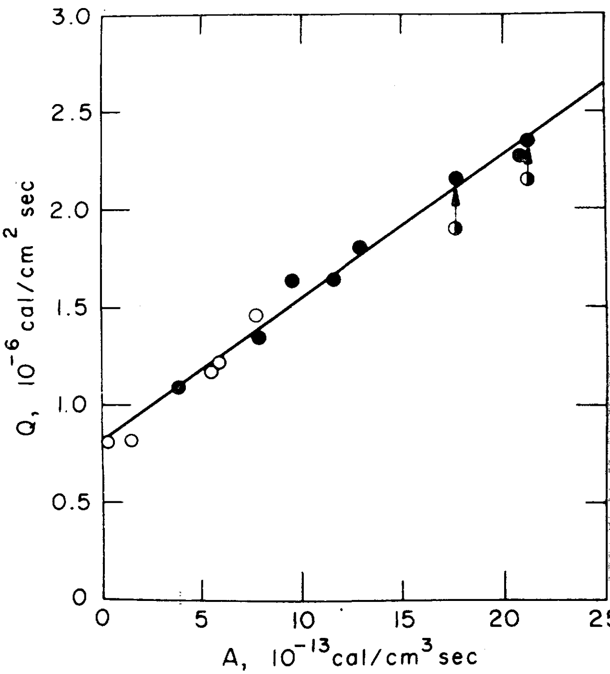

FIG. 7. — *Heat flow and heat productivity data for plutons in the New England area (solid circles) and the Central Stable Region (open circles). The line is fitted to both sets of data (from Roy* et al., *1968).*

Roy *et al.* (1968), Jaeger (1970), Swanberg *et al.* (1974) illustrate this model with examples from North America, Australia and Norway respectively. Figure 7 is from Roy *et al.* (1968) and shows the heat flow and heat productivity data for plutons in the New England area and the Central Stable Region of U.S. The heat flow arising from the mantle and lower crust are given by the intersections on the Y axis, while the slope of the line (b) represents the thickness of the crust corresponding to the values of A. Data published so far and interpreted in this manner show that for the Sierra Nevada, $b = 10.1$ km; the Eastern U.S. $b = 7.2$ km; the Basin and Range province $b = 9.4$ km; Australia $b = 4.5$ km; Norway $b = 8.4$ km. Equally as interesting as the thickness of "the surface crust" as indicated by line slopes are the values of a (Q_0)—the amount of heat coming from the mantle and lower crust. However, a discussion of the real significance of this is presently premature.

In Norway these studies are intensively carried out largely through contributions from the Norwegian Research Council for Science and the Humanities to the Norwegian Geotraverse Project, and by a cooperative study with the Niedersächsisches Landesamt für Bodenforschung W. Germany aimed at heat flow determinations in inland lakes. The first results of these studies are presently in presse (Swanberg *et al.*, 1974; Hänel *et al.*, 1974). The mean value obtained so far is 0.96 ± 0.21 HFU, in good agreement with our earlier results.

7. STUDIES OF DEEP SEATED ROCKS BROUGHT UP TO THE SURFACE

Seismic data gives clear evidence of a deep crust composed of denser material than average shield rock at the surface. The increase in density is greater than that which would be expected as the result of the pressure due to the weight of the overlying rocks alone. Likewise interpretations may be made from the heat flow data of a fairly thin upper crust (max. 10 km thick) containing the bulk of the heat producing elements, and by inference containing the bulk of the strongly oxyphile elements in the earth. The geochemistry of the deep crust has been discussed in several earlier papers (e.g. Heier, 1973*a*). As pointed out above the rather irregular seismic structure of the crust in shield areas is as expected assuming that metamorphic processes have largely been responsible for the formation of the shield. It is probable that regional metamorphism during orogenesis leads to the development of a high pressure granulite facies layer throughout much of the lower crust (Heier, 1965; Heier and Adams, 1965; Lambert and Heier, 1967, 1968*b*). Terranes of medium to high pressure granulite facies rocks appear to represent the deepest crustal material available in any reasonable extent at the surface.

There are much evidence that medium to high pressure granulite facies rocks do indeed constitute the material of the lower crust. Three illustrative examples are given below.

a) The Lofoten-Vesterålen area

This area was treated above in figure 3 used to illustrate where the "Conrad discontinuity" comes very close to the surface. Work in the area has progressed for a number of years, and the granulite facies nature of the rocks has been amply demonstrated (Heier, 1960; Griffin and Heier, 1969, 1973; Green and Jorde, 1971; Romey, 1971; Griffin *et al.*, 1974; Devaraju and Heier, 1974). Works now in progress show that mangeritic rocks intruding the granulite facies gneisses, crystallized at $P \sim 10$ kb and $T \sim 800$ °C (Ormaasen, pers. comm.) based on coexisting Cpx and Opx, and the stability of the assemblage iron rich Opx/olivine/quartz (Smith, 1971). Another intrusion, the Raftsund mangerite (Griffin *et al.*, 1974) crystallized at a pressure estimated to be approximately 8 kb (based on the presence of iron rich pyroxenes) and at a temperature close to 900 °C. The age of the intrusions are approximately 1 700 m.yr.

b) The Hardangervidda-Ryfylke nappe system

This area in the south central Norwegian highlands has been studied by Naterstad and coworkers. Andresen *et al.* (1974) have shown that in a sequence

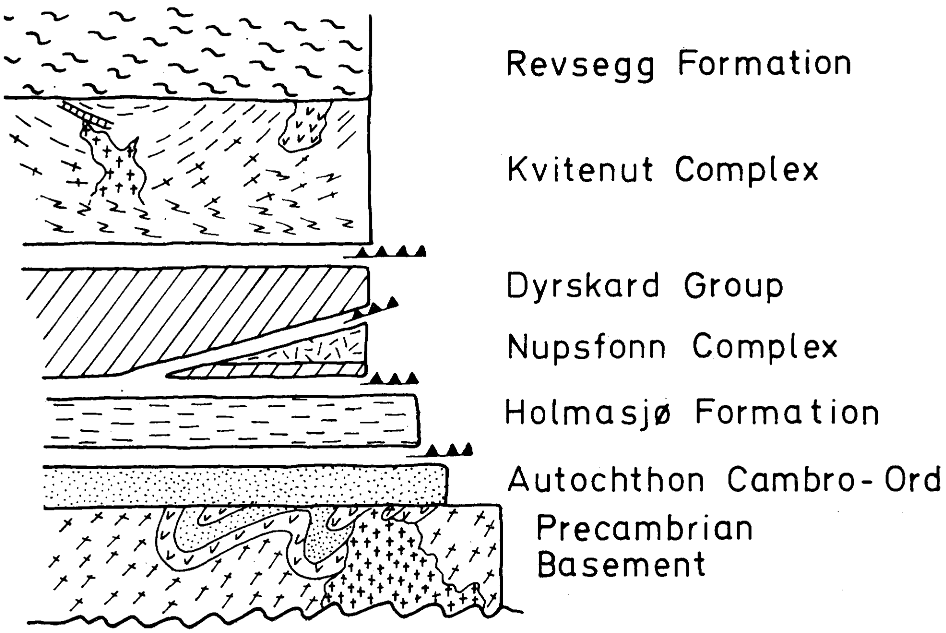

FIG. 8. — *The Hardangervidda-Ryfylke nappe system; age and degree of metamorphism increasing upwards (from Andresen* et al., *1974).*

of nappes the degree of metamorphism and age of crystallization increase upwards (fig. 8). The uppermost crystalline rocks are mostly retrograded granulite facies rocks with an apparent age $1\,643 \pm 88$ m.yr.

The large uncertainty in age reflects the complex post granulite facies history. Our interpretation of the geological structure is that successive sheets were sliced off and thrusted one over another. What to day occurs on the top of the pile represents the deepest layer of the crust taking part in the thrusting.

c) Crystalline rock fragments in the Moses Rock Dike, Colorado Plateau

It has long been recognized that kimberlite pipes contain samples of the upper mantle and deep crust, and numerous occurrences have been described in the literature. Most interest has been focused on the xenolithes believed to represent samples of the mantle. However, the diverse suite of rock fragments contained in the pipes indicates that extensive sampling has taken place also from crustal layers. In this paper attention is focused on one such pipe.

McGetchin and Silver (1972) described a crustal—upper-mantle model for the Colorado plateau based on observations of crystalline rock fragments occurring in the Moses Rock Dike. It should be noted that the authors consider the crust underlying the Colorado plateau to have evolved predominantly through igneous rather than sedimentary processes which is somewhat contrary to the two other areas discussed above where metasedimentary and igneous rocks occur together.

The following notes summarize their observations.

(1) Metabasalts and granite are abundant and form the largest fragments. They are inferred therefore to be abundant in the upper part of the crust.

(2) Gabbro and diorite fragments are moderately large and have suffered no more than modest retrograde metamorphism; hence they are interpreted to be young or shallow or perhaps both.

(3) In general, low-rank metamorphic rocks are larger than high-rank metamorphic types; basic metamorphic compositions are more abundant than more acidic (or pelitic) types. Sillimanite was observed but not kyanite or andalusite. Many of the metamorphic rocks show the effect of retrograde metamorphism.

The authors feel that these rocks constitute a pile of metavolcanic and metaplutonic rocks (mainly basalts and gabbros) which increase in metamorphic grade with depth from greenschist facies assemblages near the surface, amphibolite grade rocks at intermediate depths, and granulite grade rocks (garnetiferous metagabbro) at depth. They also feel that this pile of rocks probably grade downward more or less continuously to plagioclase bearing eclogitic rocks, eclogites and pyroxenites.

The authors consider that some of the eclogites may have a crustal origin. The *M* discontinuity in this region is at 43 km and may be petrologically complex.

8. EXPERIMENTAL PETROLOGY

The thickness of the crust in shield areas, as defined by the depth to the *M* discontinuity, is usually between 35 and 45 km. Seismic velocities in the upper crust are between 5.8 and 6.3 km/sec as compared to velocities between 6.6 and 7.2 km/ sec commonly inferred for the lower crust. The nature of this downward increase has been discussed above but may not be the same for different parts of the earth. The increase from $\sim$7 km/sec in the lower crust to $\sim$8 km/sec in the upper mantle is assumed to occur within a narrow depth interval of a few kilometres. However, there is some debate about the detailed nature of this transition.

A layered crustal model is now generally discarded by geologists, but geophysicists still tend to retain aspects of it. The seismic velocities commonly observed in the upper crust correspond to those of acidic, igneous and metamorphic rocks. This has led to the inference that the upper crust is generally of "granitic" composition—an assumption that is probably correct as most students of the Precambrian shield will verify. Average chemical compositions of crystalline rocks from shield regions have been summarized by a number of workers. For instance Poldervaart (1955) assumes a seismic *P*-wave velocity of about 6.2 km/sec which corresponds to a rock composed principally of quartz, feldspar, micas, and/or amphibole (Table I). This mineral assemblage is thermodynamically stable under the conditions of pressure and temperature existing in the upper crust (Ringwood and Green, 1966*a*).

The velocities quoted for the lower crust are similar to those for basic rocks such as gabbros, diabases, dolerites and basalts. Moreover it has been widely accepted among geophysicists that the lower crust has this composition because it also fits the heat flow data.

The concept of a basaltic or gabbroic lower crust, however, is most certainly wrong (Green and Ringwood, 1966, 1972; Ringwood and Green, 1964, 1966*a*, 1966*b*). In shield areas characterized by heat flow of 1.0 HFU the temperature at the *M* discontinuity is probably lower than 450 °C. The general conclusion is that if substantial water pressures were present, basaltic rocks would occur dominantly as amphibolites, probably in the almandine-amphibolite facies. They would then be composed mainly of amphibole, plagioclase, epidote and almandine-rich garnet having a seismic *P* velocity of about 7.0-7.6 km/sec

TABLE 1. — *Average composition of continental shield crystalline surface rocks (Poldervaart, 1955).*

Component	Weight per cent
SiO_2	66.4
TiO_2	0.6
Al_2O_3	15.5
Fe_2O_3	1.8
FeO	2.8
MnO	0.1
MgO	2.0
CaO	3.8
Na_2O	3.5
K_2O	3.3
P_2O_5	0.2
Density (estimated), 2.69 g/cm^3	
V_p (estimated) 6.25 km/sec.	

and densities of 3.0 to 3.25 g/cm^3. This is too large for values characteristic of the very lowest part of the crust in shield areas. On the other hand if the lower crust is relatively dry and basic it should be composed of eclogite ($V_p = 8.4$ km/sec, $Q = 3.5$ g/cm^3). Even when maximum allowances are given for experimental errors, dry basic rocks in the higher grades of the garnet-clinopyroxene-granulite subfacies would have velocities in the vicinity of 7.0 to 8.0 km/sec and densities of 3.2 to 3.4 g/cm^3. This is again considerably higher than believed to be valid for the lower crust. The only reasonable conclusion possible assumes that the lower crust is relatively "dry" and if chemical equilibrium is approached the lower crust cannot be of basic composition. Studies by Green and Lambert (1965) of the phase assemblages in an anhydrous granite at high temperatures and pressures show that the incoming of garnet in any rock of acid, intermediate or basic composition will cause appreciable increase in velocity. This data together with that reported by Ringwood and Green (1966*a*) caused them to conclude that rocks approaching quartz diorite in chemical composition should provide the best match to the physical properties of the lower crust. Their data is given in Table 2.

TABLE 2. — *Compositions, mineral assemblages, and estimated densities and seismic velocities of typical acidic-intermediate rocks at low pressures and at high-pressures*

Component	Chemical Composition, weight per cent	
	Diorite	Granodiorite
SIO_2	60.4	65.6
TiO_2	0.7	0.7
Al_2O_3	17.3	16.2
Fe_2O_3	2.0	1.4
FeO	4.3	3.6
MgO	3.5	1.8
CaO	7.2	4.9
Na_2O	3.3	3.6
K_2O	1.3	2.2

Mineral	Mineral Assemblage weight per cent			
	Low Pressure	High Pressure	Low Pressure	High Pressure
Quartz	14.8	20.2	21.7	27.8
Orthoclase	7.7	7.8	13.0	12.8
Plagioclase	56.5	–	52.0	–
Clinopyroxene	5.8	47.2	2.3	41.6
Hypersthene	11.0	–	7.7	–
Garnet	–	8.4	–	4.6
Kyanite	–	15.6	–	12.5
Ore minerals	4.2	0.7	3.3	0.7
Density, g/cm^3	2.83	3.20	2.78	3.07
Vp, km/sec (approx.)	6.6	7.6	6.4	7.3

9. CONCLUSIONS

It has been demonstrated in this paper that:

(*a*) Rocks on the surface in shield regions are not representative of the total crustal volume in these areas;

(*b*) The lower crust is most probably of intermediate chemical composition, and under conditions of T and P corresponding to the granulite facies.

This paper has not discussed the geochemistry of granulite facies rocks, but reference may be given to Heier (1973*a*, *b*), where it was demonstrated that:

(*c*) Medium to high pressure granulite facies rocks are strongly depleted in the heat producing elements (U and Th). Therefore they are consistant with the material underlying "granitic" shields characterized by low surface heat flows.

(*d*) Many intermediate to silicic granulite facies rocks are characterized by low Rb/Sr ratios. Therefore granitic magmas formed by anatexis of the lower crust will have low initial $^{87}Sr/^{86}Sr$ ratios.

One interesting problem is that most surface shield regions are terranes of igneous granitic rocks, migmatites and metamorphics. This implies that at an early stage of crustal evolution temperatures within the upper 15 km or so of the crust must have been at least 400 to 600 °C. At the same time temperatures in the lower crust must have been higher and in the range of 600 to 1 000 °C. This would cause partial melting and the generation and upward movement of granitic magmas. If large amounts of melts were formed only dry residual basic rock would remain. At granulite facies conditions this residual rock would have a mineralogical composition too dense to fit the known properties of the lower crust.

If only minor amounts of granitic magmas were formed and at the same time should be responsible for the depletion of U, Th, and related elements from the lower crust we would expect to find numerous granites extremely enriched in these elements.

Fyfe (1973) stated that it is rare to find rocks trending towards the pyroxene bearing granulite facies which do not show the effects of "sweating out of granitic components." It is generally accepted by students of granulite facies terranes that they are on the average less silicic (granitic) than the average surface shield rock shown in Table 1. Moreover "true" granites rarely occur in such areas.

Even so, I do not think that the complete answer to the nature of the deep crust is found in the anatectic process, and we should focus our attention to the chemistry of fluid inclusions.

In the Lofoten area of North Norway fluid inclusions taken from medium- to high-pressure granulite facies rocks contain large amounts of high density CO_2 (~ 2 g/cm^3, W. L. Griffin, personal communication). H_2O which is always present in inclusions in lower grade metamorphic rocks is relatively rare in rocks of the granulite facies (Touret, 1971). If one accepts the argument that the total fluid pressure equals load pressure, then the abrupt appearance of large amounts of CO_2 in fluid inclusions from granulite facies rocks becomes particularly significant, since because the fluid pressure cannot exceed the load pressure, an increase in the percentage of CO_2 in the fluid must naturally result in a decrease of water pressure. This would cause hydrous minerals more rapidly to breakdown without a simultaneous increase in temperature (Touret, 1970). Liberation and subsequent expulsion of this water could explain the simultaneous low concentrations of certain elements from granulite facies rocks without invoking the process of partial melting and removal of the melt.

It could be querried if an escaping fluid phase consisting of H_2O and CO_2 is capable of removing the elements we find depleted from granulite facies rocks. It has been stated, in the geological literature that an upward concentration of radioactive elements is unlikely to take place unless a molten phase is present. However, the contact metasomatic aureole surrounding many granite intrusions demonstrate that a fluid phase is capable of transporting these elements in large quantities. Experimental data for water given by Holzapfel and Franck (1966) shows that water becomes increasingly dissociated at high temperature and pressures, and is about 10^{-4} at 600 °C and 6 kb. Under such conditions the solubility of quartz increases to 1.3 wt. % (Ganayev and Rumyantsev, 1969;

Anderson and Burnham, 1965). This suggests that as water becomes a stronger electrolyte, uranium and its host minerals will become increasingly soluble.

The CO_2 source is an open question. It could be derived from the mantle, or it could be the result of the PT field where the reaction

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 \pm CO_2$$

takes place.

A possible implication is that the granulite facies rocks have been subjected to a different PT gradient than migmatites constituting "normal" surface rocks in shield areas. This would allow them to be dehydrated before the beginning of incipient melting by the introduction of CO_2. The expelled water phase containing many "granitic elements" would be carried away with this phase and concentrated in the granitic melts, or "collection zone" of Fyfe (1970). Apparently this method of transporting the elements would be more capable of dispersing them throughout the overlying crust, than the removal of melt. Another possibility is that the granulites followed the normal PT gradient but CO_2 was introduced into the rocks by the intrusion of gabbroic magma (Touret, personal communication).

The attention of experimental petrologists, geochemists, and geophysicists has in the last 15 years or so been concentrated on the mantle, and mantle derived rocks as basalts and ultramafics; and on the moon. I believe that in the next decade we will see renewed attention and interest directed towards unravelling the nature of the deep crust. We can expect that new exciting data will be produced when the sophisticated instrumentation constructed for lunar work is applied to terrestrial problems.

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