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A model for the composition of the deep continental crust

By

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With 6 figures and 5 tables

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Abstract: The paper discusses the nature of the deep crust under stable shield areas. Earlier estimates of the composition of this material is briefly reviewed, and their shortcomings are demonstrated. The data on the distribution of heat-producing elements and heat-flow are then considered and a simplified model for the evolution of shield areas is presented. It is demonstrated that our present knowledge of the physical properties, chemical compositions and mode of formation of medium to high pressure granulite facies rocks fit all known constraints put on the nature of deep crustal material. Combination of heat flow and heat generation data from different parts of the world indicates a thickness of the upper crust of less than 10 kilometers. Previous estimates of continent composition refer, at best, to the composition of this upper layer.

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Introduction

From being largely a science concerned with the description of phenomena at the surface of the earth, geology and geologists have in the later years been increasingly concerned with the interior structures of the earth, and the interaction between the earth's crust and mantle. The integration of geophysical, geochemical and experimental petrological disciplines into the classical geology departments has proved to be a great stimulant to the science. International research programmes, aimed at combining different disciplines in the study of a common problem, have proved very successful; e.g. the upper mantle project and the international geodynamics project.

In this paper we shall propose a possible model for the composition of the deep portion of the stable continental crust.

Definition

We define the continental crust as that part of the continents which extends vertically from the atmosphere and to the mantle (Moho), and laterally to the continental rises. This material constitutes only about 0.3%

of the earth's total mass. However, the strong upward concentration of many elements in the earth gives the crust a geochemical importance which is out of all proportion to its mass. Several of the elements which are most strongly concentrated in the crust, notably U, Th, K, Rb, Sr, Pb, are also most important for the consideration of various earth models and comparisons with extraterrestrial materials. An exact knowledge of their terrestrial abundances and the ratios between them is therefore of prime importance. We understand from crystal chemical principles why some cations concentrate upwards in the earth (Fig. 1), but the concentration factors indicated in the figure are uncertain.

In this paper we shall be concerned with the deep crust under shield areas, which is not such an easily definable concept. Typical crustal thicknesses in shield areas are 35 to 45 kilometers with seismic velocities ranging from 6 to 7.2 km sec⁻¹ underlain by a mantle with seismic velocities of about 8.2 km sec⁻¹. There is, however, no general agreement about the broad structure of the continents, and the existence and nature of the seismic Conrad-discontinuity separating an upper (granitic) from a lower (basaltic) crust is currently in debate. It will be shown later that the com-

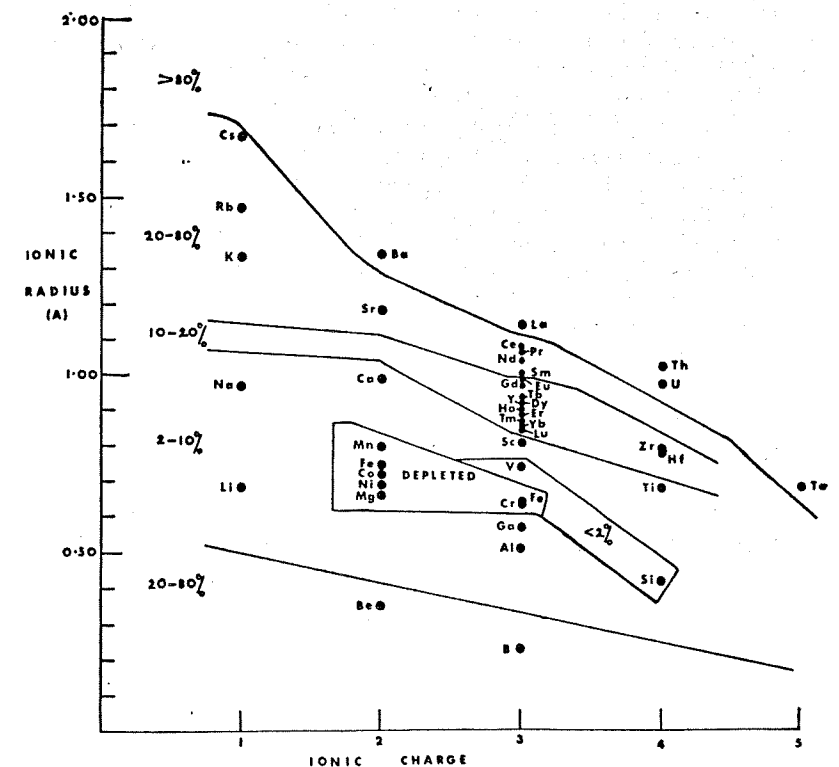


Fig. 1. A plot of ionic charge versus ionic radius for some elements. The assumed concentration of the elements in the continental crust is indicated (from TAYLOR, 1964a).

bination of heat-flow measurements with the determination of surface radioactivity may prove the most successful tool in defining the depth to the lower crust. These data and data from experimental petrology, combined with isotopic evidence, plus geochemical investigations of certain high grade metamorphic rocks exposed at the surface may make it possible to make quantitative statements about the extent and composition of the deep crustal layer.

The age of the continent

An understanding of the age of the continents, the mechanism of concentrating elements in the crust and crustal growth is most important when estimates of continental composition are to be attempted. Our knowledge of these factors is rapidly increasing though still only sketchy.

Studies in geochronology during the last ten to fifteen years have shown rocks in the age range 2.6 to 3.0×10^9 years to be present on all continents. Possibly the bulk of the continental mass was already brought to the surface at that time.

On the other hand, other geochronological and geochemical evidence together with geological observations are interpreted to favour a continuous growth of the continents at much the same rate throughout earth history. If present day volcanic activity represents true addition of material to the crust, and remembering the Huttonian axiom that the present is a key to the past, a continuous growth of continents at a constant rate is demonstrated. To equate addition of material with continental growth may not be correct, in that possible return of material back into the mantle is then totally neglected. The mechanism of the return could be by way of the subducting plates in the plate tectonic model. The professed geological evidence for continental growth may rather be evidence of continuous crustal remodelling. The radiogenic strontium-⁸⁷ model of continuous continent formation proposed by HURLEY et al. (1962) has not been verified, and we are faced with the problem of a continental crust and upper mantle continuously changing in composition. Studies of radioactive isotopes and their daughter products are important tools for our understanding of the trend and rate of this continuous process (e.g. HART & BROOKS, 1970; HURLEY, 1968).

Earlier estimates of the composition of the continental crust

Previous estimates of the composition of the continental crust have been based on one of these three approaches:

1. surface sampling and averaging rock compositions over surface areas;
2. average igneous rock type;
3. material balance computations.

The different estimates were reviewed by TAYLOR (1964, 1967), HOLLAND & LAMBERT (1972), and will only be presented very briefly here.

The average composition of Precambrian shield surface rocks has been considered particularly important for consideration of crustal compositions (i.e. POLDERVAART, 1955). Table 1 gives estimates of such composition from different shield areas. Excluding column 2 which has been superseded by the estimate of SHAW et al. (1967) of the same area (column 1), there is a general agreement between all the estimates from different parts of the world. These compositions (with some allowance for a general basification towards depth) are frequently considered not only typical of shield areas, but of the entire shield crust.

Table 1. Major element estimates (wt.%) of Precambrian shields.

	1	2	3	4	5	6	7
SiO ₂	64.93	57.76	67.45	69.7	67.0	64.0	66.2
TiO ₂	0.52	1.37	0.41	0.7	0.5	0.58	0.6
Al ₂ O ₃	14.63	16.52	14.63	14.1	14.5	15.4	15.4
Fe ₂ O ₃	1.36	3.16	1.27	1.4	1.5		
FeO	2.75	4.72	3.13	2.6	3.0		
Fe ₂ O ₃ *	4.42	8.40	4.75	4.3	4.8	6.1	4.9
MnO	0.068	0.08	0.04	—	0.2	0.1	0.1
MgO	2.24	2.75	1.69	1.7	2.5	3.1	2.0
CaO	4.12	4.07	3.39	2.8	4.0	5.3	3.8
Na ₂ O	3.46	3.68	3.06	3.3	2.5	3.7	3.5
K ₂ O	3.10	2.82	3.55	3.6	3.0	1.7	3.3
P ₂ O ₅	0.15	0.21	0.11	0.3	0.2		0.2

1. Canadian Precambrian Shield (SHAW et al., 1967).
2. Canadian Precambrian Shield (GROUT, 1938).
3. Finnish Precambrian Shield (SEDERHOLM, 1925).
4. Average Norwegian Precambrian Rocks (BARTH, 1961).
5. Average SW Australian Shield (LAMBERT & HEIER, 1968).
6. Average analysis of the Lewisian, Scotland (HOLLAND & LAMBERT, 1972).
7. Average crystalline Shield (POLDERVAART, 1955).

* Total iron.

Different estimates, which may broadly be termed attempts to derive an average igneous rock, are presented in Table 2. The significance of the average igneous rock to our problem is that the ultimate origin of the material building up the continents is igneous, and that metamorphic and sedimentary rocks are derived from this material.

The classical estimate of the average igneous rock is that of CLARKE & WASHINGTON (1924), column 1, Table 2. Their estimate was based on a compilation of 5159 "superior analyses", and is possibly still today one of the most commonly quoted compositions of the continents.

GOLDSCHMIDT pointed to the similarity between the average igneous rock and granodiorite exemplified by the Opdalite from the Norwegian Caledonides (Column 2, Table 2). Both of them compare well with GOLDSCHMIDT's average analysis of 77 samples of glacial clay purporting to give the average

Table 2. The average igneous rock.

	1	2	3	4	5	6
SiO ₂	59.14	61.94	59.19	60.3	63.11	60.1
TiO ₂	1.05	0.95	0.79	1.00	0.75	0.7
Al ₂ O ₃	15.34	15.30	15.82	15.4	15.21	17.2
Fe ₂ O ₃	3.08	0.94				
FeO	3.80	4.64				
Fe ₂ O ₃ *	7.30		6.99	8.0	6.65	6.8
MnO	0.12				0.13	
MgO	3.49	4.10	3.30	3.9	3.10	3.5
CaO	5.08	4.66	3.07	5.8	4.14	7.1
Na ₂ O	3.84	3.42	3.05	3.2	3.37	3.3
K ₂ O	3.13	3.39	3.93	2.5	3.01	1.3
P ₂ O ₅	0.30	0.16	0.22	—	0.21	

1. Average igneous rock (CLARKE & WASHINGTON, 1924).
2. Opdalite (GOLDSCHMIDT, 1954, average of 2).
3. Norway glacial clay (GOLDSCHMIDT, 1933).
4. 1:1 Granite / basalt ratio (TAYLOR, 1964).
5. 2:1 granite / basalt ratio (VINOGRADOV, 1962).
6. Average andesite (TAYLOR & WHITE, 1965).

* Total iron.

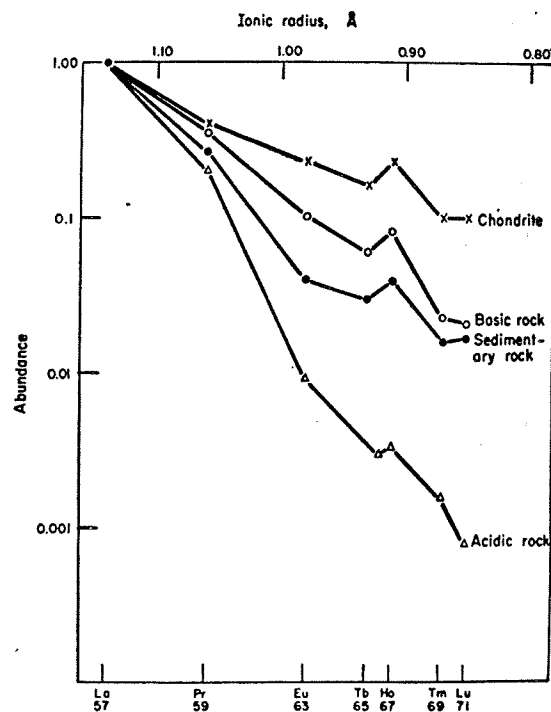


Fig. 2. The abundances of the rare earth elements of odd atomic number, normalized to La = 1.00 (weight ratio) in basic, acid and sedimentary rocks, and in chondrites (from TAYLOR, 1964b).

surface composition of Fenno-Scandia (column 3). This estimate is free from the human subjectiveness in estimating relative rock abundances and averaging chemical analyses. Unfortunately, the clays are not only products of the mechanical processes of scraping and mixing, but are also affected by chemical processes. Among the major elements the effects of hydration and solution resulting in leaching of sodium and calcium and the absorption of potassium to clay particles are most noticeable.

A similar brilliant approach, which would avoid sampling and human errors, was suggested by TAYLOR (1964b). The La-normalized REE-distribution patterns of sedimentary rocks had been shown by HASKIN & GEHL (1962), to be identical irrespective of sediment age, type and geographic location. TAYLOR pointed out that the pattern of sediments was intermediate between the patterns of granite and basalt, the two most abundant igneous rock types (Fig. 2). He calculated that a mix of one part granite to one part basalt would explain the sedimentary pattern. Unfortunately, later work has not substantiated the argument mainly because of considerable range and overlap of basalt and granite REE patterns. TAYLOR used this mix to calculate the abundances of most elements in the crust. The calculated abundances of the major element are listed in column 4, Table 2. They are today widely used as reference data but for the reason stated above this should be discontinued.

VINOGRADOV (1962) estimated on a different basis a continental crust composed of two parts granite and one part basalt (column 5, Table 2).

Present day continental volcanism is dominantly andesitic, and TAYLOR & WHITE (1965, 1967) argued that the continental crust grew mainly by addition of this material, and that the diverse rock types observed on the continents were largely derived from remodelling of andesitic source material. The average andesite composition is shown in column 6, Table 2.

Comments on the estimates given in Tables 1 and 2

It is not the intention to comment extensively on the estimates given above. Their relative merits and weaknesses should be evident. Common to all the estimates is that they either over emphasize the present, or the near surface most easily available to us for inspection. The andesite model certainly overextends the uniformitarian approach to geology. Heat flow and heat production in the first two billion years of earth history were radically different from today. Much of the material concentrated in the crust and upper mantle was probably emplaced in this period. Also, as for instance demonstrated by HART & BROOKS (1970), the indications are that the mantle is continuously changing its composition with a corresponding change in magma compositions derived from it.

Estimate of surface composition and average igneous rocks describe at best the top layer and the geological arguments for this to continue to the mantle are not given or are not convincing.

The calculation which assumes that the crust consists of average igneous rock calculated as a mixture of granite and basalt is lacking one factor.

Most geologists would agree that while basalt are derived from the mantle and represent true addition to the crust, granites are largely derived from the deep crust. Such a calculation must, therefore, make allowances for a third rock type, the residual rock which remains in the low crust when granite magmas form and migrate towards the surface.

Most authors accept a basification of rocks with depth and attempt to adjust their surface estimates, i.e. POLDERVAART (1955). However, without any well defined model for crustal evolution and the nature of the deep crust, the adjustments can not be more than guesswork. CLARKE & WASHINGTON (1924) stated that their average igneous rock could only be taken as representative of the continental crust to a depth of ten miles or so. On the other hand, SHAW (1968) in a discussion of radioactive elements in the Canadian Precambrian shield states "it is here accepted that the Canadian Precambrian shield averages may be taken as representative of the continental crust".

Evidence of the nature of the deep crust from radioactive elements and heat-flow data

The heat producing elements in the earth are ^{40}K , ^{232}Th , ^{235}U and ^{238}U . Their abundances in the crust may be derived from two essentially independent methods; geological estimates similar to those discussed above, and geophysical estimates based on heat-flow data. HEIER (1965) pointed out that the abundances derived from the two methods differed by a factor of two or more, Table 3. He also pointed out that as crustal abundances in general are derived from premises similar to those used to obtain the geochemical estimates in this table, it is possible that the abundances of the most "granitophile" elements in the crust are overestimated (Fig. 1).

Table 3. Estimates of thorium, uranium and potassium abundances in the continental crust.

Th ppm	U ppm	K percent	
11.4 ± 2	3.0 ± 06		Geochemical estimates
9.6	2.7	2.1	ADAMS et al. (1959)
			TAYLOR (1964)
			Estimates from heat flow
4.6	1.12	1.84	CLARK & RINGWOOD (1964) q = 1.5 H.U.
3.2	0.81	1.31	CLARK & RINGWOOD (1964) q = 1.2 H.U.
2.5	0.64	1.05	CLARK & RINGWOOD (1964) q = 1.0 H.U.

The abundances of K, Th and U derived from heat flow data are based on the following premises:

1. measured surface heat flow;
2. assumed heat flow from the mantle;
3. assuming that heat transfer takes place through conduction rather than convection or other form of transport.

The number of heat flow determinations in shield areas have multiplied in the last ten years and it seems a valid contention that heat transfer takes place through conduction in such areas. From geophysical data, geological observation on material brought up from the mantle, and information from experimental petrology on the composition and mineralogy of the mantle, it should be possible to bracket fairly closely the value of heat flow from the mantle. In shield areas the best estimates are between 0.45 and 0.55 $\mu\text{ cal cm}^{-2}\text{ sec}^{-1}$ with a preference for the lower value (it should be noted that the greater the assumed heat flow from the mantle, the greater the discrepancy between the two sets of K, Th and U values in Table 3).

It is difficult to understand how the heat flow derived total radioactive element concentration in the shield crust can be significantly in error. However, it must be emphasized that the value for the three elements given in Table 3 may be wrong in that the ratios between them may be different in the deep and upper crust. It will be shown later that on the proposed model U and Th may be relatively more depleted in the lower crust than K.

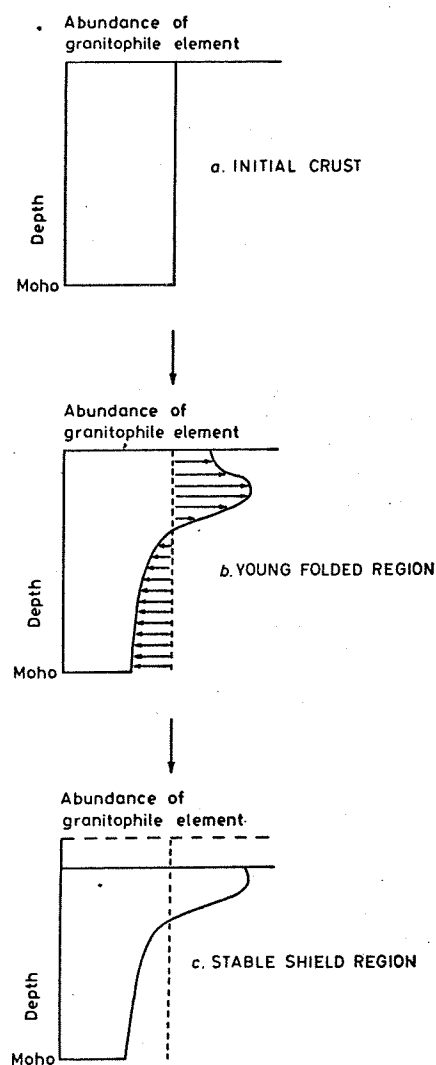
The evidence suggests that either there is an upper crust concentrating the heat producing elements underlain by a deep crust low in these elements, or there is a gradual transition from the surface to the mantle.

The problem now is to define the nature of the material of the low crust, and to derive the relative thicknesses of upper and lower crustal material. Our model assumes a rather sudden transition from high to low crustal material.

The model

Irrespective of the origin of the primordial crust or the nature of the material added to the crust during later processes, it is assumed here that the stable shields have formed through periods of mountain building, metamorphism, faulting, folding and erosion. The net effect on a vertical column of homogeneous material is to subject it to processes of regional metamorphism whereby not only recrystallization of the rocks, but also migration of elements takes place. In the upper levels, the migration of elements is associated with the dehydration of the rocks, first by loss of pore water and later through the dehydration reactions characteristically associated with progressive metamorphism. Elements which are easily leachable and/or unstable in the new mineral structures formed under the higher pressure and temperature conditions will be concentrated upwards in the crust through these processes.

Later on partial melting with the formation and upwards migration of granitic melts will take place whereby elements with partition coefficients strongly in favour of the melt will be concentrated upwards in the column. The process is schematically illustrated on Fig. 3, where "content of granitophile elements" (x-axis) is plotted against depth (y-axis). The bulk of the granitic material does not reach the surface, but crystallizes at some intermediate depth, where melts are no longer stable. This is the amphibolite facies terrains characteristic of the stable shield surface rocks and represent-



ing a maximum of granitic material in the crust. The residual zone left behind is depleted in "granitic" material and is in high metamorphic grade characterized by "dry" mineral assemblages. It is considered to consist largely of medium to high pressure granulite facies rocks.

The theory that the deep crust should largely be composed of granulite facies rocks was first argued by HEIER (1965), HEIER & ADAMS (1965) and DEN TEX (1965).

Fig. 3. Schematic model for the evolution of the continental crust.

Physical properties and radioactive element concentrations in medium to high pressure granulite facies rock

Medium to high pressure granulite facies rocks (GREEN & RINGWOOD, 1967) represent the highest grade of regionally metamorphosed rocks exposed at the surface to any areal extent. For these rocks to be the material of the deep crust they must satisfy the seismic criterion of a denser lower crust, and they must have low concentration of the heat producing elements to comply with the heat flow data.

RINGWOOD & GREEN (1966) using data from experimental petrology, demonstrated that the average composition of the lower crust should be acid to intermediate. GREEN & LAMBERT (1965) argued that anhydrous granulite facies mineral assemblages should be generated in the lower crust during orogenic periods. They demonstrated that basic granulites (i.e. metamorphosed basalts) would be too dense to satisfy the seismic velocity measurements, and that granulites with an overall intermediate composition would best fit the seismic data (see also HEIER, 1965; HEIER & ADAMS, 1965; DEN TEX, 1965).

Extensive geochemical studies of granulite facies rocks with particular emphasis on the distribution of heat producing elements have been carried out in Australia and Norway (HEIER & ADAMS, 1965; LAMBERT & HEIER, 1967, 1968a, b; HEIER & THORESEN, 1971).

Th and U contents of granulite and amphibolite facies rocks are compared over the same K-range in Fig. 4. The depletion of U and Th relative to K in the granulite facies rocks is evident.

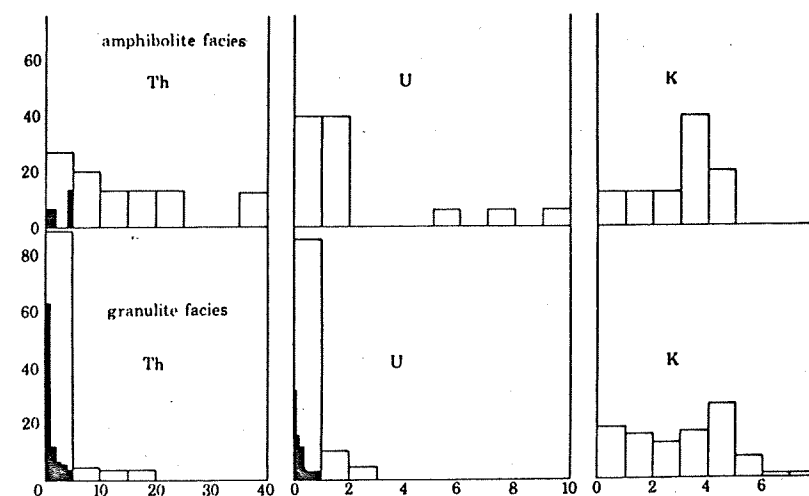


Fig. 4. Comparison of Th, U and K distributions in neighbouring amphibolite facies and granulite facies terrains, Lofoten-Vesterålen area, North Norway.

In Table 4 areal averages of two granulite facies terrains from Australia are compared with an adjacent amphibolite facies terrain (Musgrave Ranges) and the whole S. W. Australian shield. The depletion of the heat producing elements in the granulite facies rocks is again evident.

The granulite facies deep crust model

We consider the incoming of granulite facies rocks to be fairly sudden, and believe the depletion of U and Th in them to be associated with the beginning of melting and subsequent removal of the melt. We have as yet

Table 4. Radioactive element concentrations in granulite and amphibolite facies rocks, Australia (from LAMBERT & HEIER, 1968a).

	Frazer Range granulites	Musgrave → granulites	← Range amphibolite	SW Shield all rocks
% K	1.4	2.2	2.8	2.6
ppm Th	1.8	2.1	11.0	20.0
ppm U	0.3	0.4	1.0	3.0

Table 5. Radioactive element abundances and heat productions at three different levels in the continental crust under shield areas (from LAMBERT & HEIER, 1968b).

	Th (p.p.m.)	U (p.p.m.)	K %	Heat production (cal/cm ³ sec. 10 ⁻¹³)
Surface shield crust	20	3	2.6	6
Medium to high pressure granulites	2	0.4	2.0	1.1
Base of crust	0.4	0.1	0.4	0.2

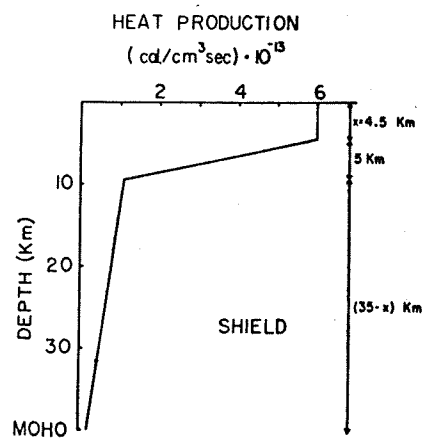


Fig. 5. Heat production at various depths within the stable southwest Australian shield (LAMBERT & HEIER, 1968b).

seen no evidence for a gradual decrease in the concentrations of these elements with progressive metamorphism until the onset of granulite facies.

On our model (Fig. 3) the shield crust is best approximated by a granitic layer on top of granulite facies rocks. The concentration values used in our model for the different surfaces are illustrated in Table 5. (The concentrations at the base of the crust are conjectural and derived from the assumption that a slight decrease may be expected.) For the calculation of the thickness of the upper granitic crust, it is assumed that the surface radioactivity continues to a depth (x) where the medium to high pressure granulite facies transition begins.

We can calculate x from the relation

$$a_{\text{shield}} \cdot x + \frac{1}{2} (a_{\text{shield}} + a_{\text{gran}}) \cdot 5 + \frac{1}{2} (a_{\text{gran}} + a_{\text{Moho}}) \cdot (35-x)$$

= total surface heat flow — heat flow from mantle. Here a_{shield} = heat produced by surface shield radioactivity etc. In the model it is assumed that the total crustal thickness is 40 kilometers, and that the transition from surface to granulite facies heat production takes place over a transition zone of 5 kilometers. The resulting profile is shown in Fig. 5 (LAMBERT & HEIER, 1968b; HYNDMAN et al., 1968). The depth to which the high radioactivity granitic layer persists (x) can, according to this, only be of the order of 4.5 km, and the total thickness of what in this terminology could reasonably be called upper crust, for which the estimated average compositions discussed earlier may be approximately valid, should be 10 km or less.

Further evidence from heat flow data for the thickness of the upper „granitic“ crust

In recent years more data on surface heat flow and surface heat production have become available (BIRCH et al., 1968; HYNDMAN et al., 1968; LACHENBRUCH, 1968, 1970; LAMBERT & HEIER, 1967, 1968a, b; ROY et al., 1968; SWANBERG, 1972). A linear relation between heat flow and heat generation was first observed by BIRCH et al. (1968) and ROY et al. (1968). It is of the form

$$Q = Q_0 + bA$$

where Q is surface heat flow (1 hfu = 10^{-6} cal/cm² sec), A is surface heat generation (1 hgu = 10^{-13} cal/cm³ sec), and b and Q_0 are constants. The slope of the line (b) constrains the vertical distribution of heat generation (LACHENBRUCH, 1968; SWANBERG, 1972), and Q_0 is the steady state heat flow below the radioactive layer. It has been regarded as mantle heat flow, but is here considered to be the sum of mantle and lower crust heat flows; i.e. (b) is the thickness of what in this paper has been termed the upper crust. Typical relationships of Q vs. A is shown in Fig. 6 (ROY et al., 1968).

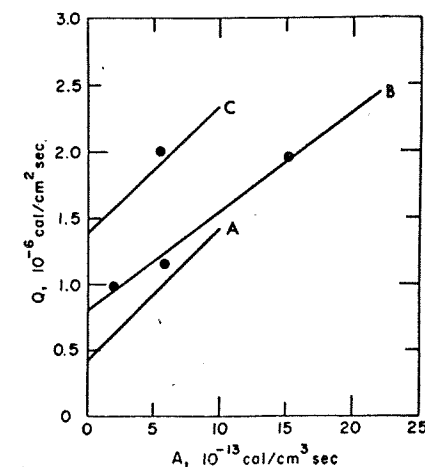


Fig. 6. Relationship between heat flow and surface heat production in the Sierra Nevada (A), eastern United States (B), and Basin and Range province (C) (from ROY et al., 1968). The data points are from Australia (see text and ROY et al., 1968, p. 7).

The slope of the line A from Sierra Nevada corresponds to $b = 10.1$ km, and the intercept (Q_0) (mantle + lower crust heat flow) is 0.4 HFU; B from the eastern United States corresponds to $b = 7.2$ km with an intercept (Q_0) of 0.84 HFU; C is from the Basin and Range province with b corresponding to 9.4 km with Q_0 equals 1.4 HFU. The data points shown on the figures are earlier Australian data. The plot on the C curve is from the Snowy Mountain area, which represents a younger Paleozoic crust, while the three plots along the B curve are from the Australian shield. Recent data from Norway, based on work carried out at the Mineralogisk-Geologisk Museum in Oslo in cooperation with Professor SIMMONS at M.I.T. (SWANBERG et al., 1973), suggest b to equal 8.4 km with a low Q_0 of 0.48 HFU.

All data so far available from shield areas substantiate, therefore, a thickness of the upper "granitic" shield crust of 10 km or less, while the granulite facies model for the nature of the deep crust agrees with all known constraints on this material.

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