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Geochemistry of Granulite Facies Rocks and Problems of their Origin

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Geochemistry of granulite facies rocks and problems of their origin

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Occurrences of granulite facies rocks are widespread in continental regions where they mostly are parts of stable shield areas. Granulite facies terrains are classified as low-, medium- or high-pressure terrains on the basis of critical mineral associations. Special interest is attached to the medium- and high-pressure terrains, as they are representative of the deepest crustal levels available for study in any areal extent on the surface, and may give information about the composition of the lower continental crust. Granulite facies terrains are mainly composed of metamorphic and metasomatic rocks, but magmatic rocks with primary igneous textures interpreted as formed by crystallization of magmas under granulite facies conditions are frequent in some areas. Examples of such rocks are anorthosites, gabbros and mangerites.

The low-pressure–high-temperature granulite facies rocks are chemically indistinguishable from the amphibolite facies gneisses with which they characteristically occur. It is therefore important to make a distinction between these and the higher pressure types. The medium- to high-pressure granulite facies terrains are characterized by a less 'acidic' average major element compositions, and significant depletions in Rb, Cs, Th and U compared with average surface shield compositions. Available data also indicate low initial Sr isotope ratios, even in the gneissic types.

In the author's opinion the important problem associated with granulite facies rocks is not that of their origin, but rather of their importance as constituents of the continental crust, and how they attained their present chemistry.

Introduction

When a paper on 'Geochemistry of granulite facies rocks and problems of their origin' is invited for a symposium on the 'Evolution of the Precambrian crust', it may be for one of the following reasons: (1) granulite facies rocks are restricted to Precambrian terrains; (2) granulite facies rocks are important constituents of the Precambrian continental crust; (3) granulite facies rocks are important constituents of all continental crustal segments which have developed, or 'matured' beyond a certain stage.

Since in this symposium 'granulite facies' has been singled out as something special within the regional metamorphic facies sequence, it must be because it is considered to have some unique properties. This may be related to the first point mentioned above: 'granulite facies rocks are restricted to Precambrian terrains', or it may be related to something specific in their chemistry which makes it important to separate them from other metamorphosed rocks when the chemical composition and chemical evolution of the continental crust shall be evaluated.

In this paper I shall briefly discuss: (1) the regional distribution and age of granulite facies rocks; (2) the term itself and the subdivisions within the granulite facies and the pressure–temperature regions of their formation; (3) some chemical aspects particular to rocks crystallized within a certain field of granulite facies metamorphism; (4) the importance of considering granulite facies rocks when discussing geochemical and geophysical models of the continents.

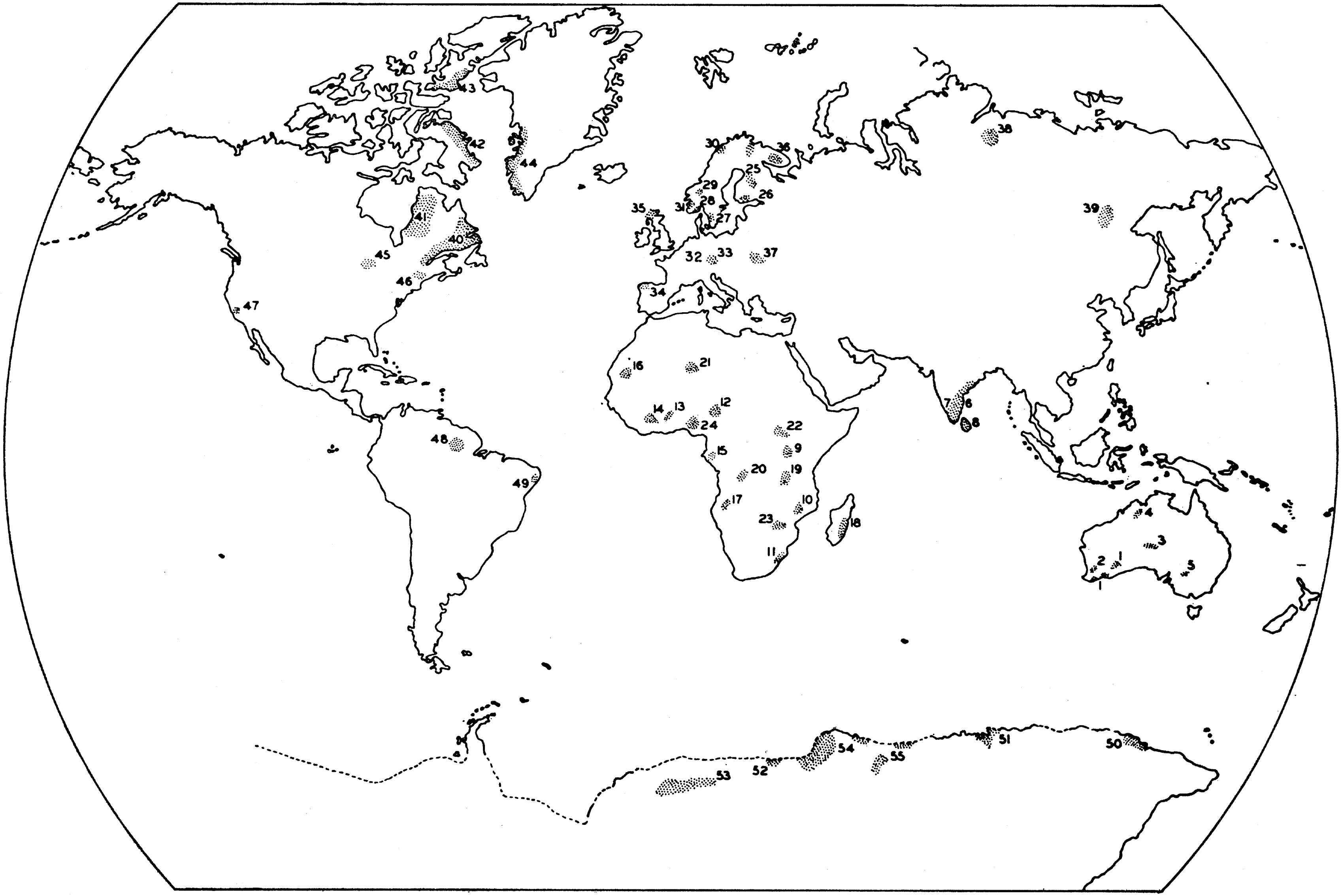

FIGURE 1. Map of the world showing the distribution of granulite facies terrains (shaded). (After Oliver 1969.)

REGIONAL DISTRIBUTION AND AGE OF GRANULITE FACIES ROCKS

Granulite facies rocks are extremely widespread and are found on all continents. Oliver (1969) compiled a map showing the regional distribution of granulite facies rocks (figure 1). Fitting the continents together using the 'best fit models' we get an idea of some large granulite facies provinces. The most impressive of these is North America, Baffin island and Greenland. It is possible that the Lewisian in Scotland and some of the Norwegian granulite facies terrains belong to this same granulite facies province. Nevertheless, however much fine adjustment one makes to the fitting together of continents the impression remains of a very scattered occurrence of granulite facies rocks on the world wide scale. This may be explained by: (1) incomplete mapping; (2) retrograde metamorphism obliterating the granulite facies mineralogy; (3) formation of granulite facies rocks in local 'hot spots' within regionally metamorphosed terrains; (4) granulite facies terrains are associated with large scale faulting whereby they have been tectonically uplifted and are not genetically related to the lower grade metamorphic rocks that are adjacent to them in the field.

Granulite facies rocks are found in all crystalline basement areas, or shield regions, of the world. These are of Precambrian age, and where large areas of granulite facies rocks occur in younger orogenic regions they can generally be recognized as inliers. Possible exceptions are small areas of granulite facies rocks in the Tertiary coast ranges, in California. Palaeozoic K/Ar mineral ages have been reported from different granulite facies terrains (Angino & Turner (1964) and Ravich & Krylov (1964) from Antarctica; Heier & Compston (1969) from Norway), but whole rock Rb/Sr or Pb ages younger than Precambrian have not yet been recorded for granulite facies rocks of significant extent. This may be taken as evidence for special conditions in Precambrian time that favoured the formation of granulite facies terrains. Two important parameters which would control the formation of granulite facies rocks were apparently different from today in the Earth's early history: (1) crustal thickness (thinner in the Precambrian); (2) thermal gradient (steeper in the Precambrian due to more residual heat and higher heat production from radioactive elements). However, our knowledge of present-day heat flows and crustal thickness combined with data from experimental petrology, indicates that conditions for granulite facies metamorphism should prevail up to this day, and were certainly not restricted to the Precambrian. In which case, the occurrence of granulite facies rocks at the surface is related to stage of crustal evolution, depth of exposure through erosion, tectonic uplifting and overfaulting. On all these counts one would expect exposed granulite facies terrains to be geologically relatively old. The condition of formation of granulite facies rocks are briefly discussed below.

Whole rock ages of granulite facies rocks have been found in the range 1000 to 3000 (or 2800) Ma (i.e. 2500 to 2800 Ma in Minnesota (Himmelberg & Phiney 1967); ~ 3000 Ma from Nordland area, West Greenland (Black *et al.* 1971); 2600 to 2900 Ma from the Lewisian of Scotland (Moorbath, Welke & Gale 1969): 2800 and 1800 Ma from Lofoten, Norway (Heier & Compston 1969); 1300 to 1400 Ma from Fraser Range and Musgrave Ranges, Australia (Arriens & Lambert 1969); 1250 and more than 2000 Ma from Ceylon (Crawford & Oliver 1969); 1500 and about 1000 Ma from South Norway (Versteeve 1970; Michot & Pasteels 1969)).

Definition of granulite facies and subdivisions within the facies

The inclusion of the granulite facies rocks in the normal regional metamorphic facies sequence has long been accepted by metamorphic petrologists, and the controls operating in the formation of granulite facies mineral assemblages have been understood in general terms. Eskola (1939) illustrated the metamorphic facies in relation to temperature and pressure as shown in figure 2.

temperature increasing→

pressure increasing ↓

			sanidinite
greenschist	epidote-amphibolite	amphibolite	pyroxene-hornfels
			granulite
	glaucophane-schist		eclogite

Figure 2. Metamorphic facies in relation to temperature and pressure (diagrammatic). (After Eskola 1939.)

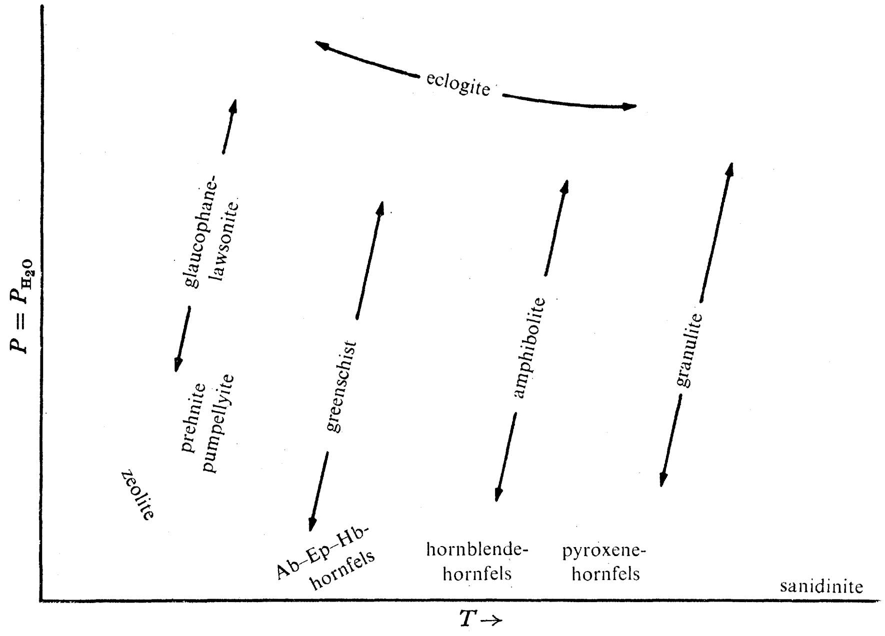

Figure 3. Schematic relation of facies to temperature and pressure ($P_e = P_{H_2O}$). (After Fyfe & Turner 1966.)

A similar presentation was made by Fyfe & Turner (1966), see figure 3. In both presentations one may enter granulite facies from the conditions of amphibolite facies through a simultaneous increase in pressure and temperature or just by an increase in temperature (figure 3). There is also a transition from pyroxene-hornfels facies into granulite facies with increasing pressure or depth of intrusion of a magma, and a move from granulite into eclogite facies merely by change in pressure is indicated. Examples of all these various transitions into, and formation conditions of, granulite facies rocks are known and some of the confusion in discussions of metamorphic petrology possibly relate to the fact that this is not always fully realized. It is also indicated in figure 3 that granulite facies rocks occur over a wide range in pressure conditions, and one would expect mineralogical subdivisions according to high and low-pressure régimes. This latter aspect has particularly been studied in three important papers by Green & Ringwood (1967, 1972) and Ringwood & Green (1966). The reactions taking place on cooling and uplift from eclogite facies into granulite facies and amphibolite facies have lately been intensively studied by a group working in Oslo, i.e. Griffin & Heier (1969), Griffin (1971*a*, *b*) and Mysen & Heier (1972).

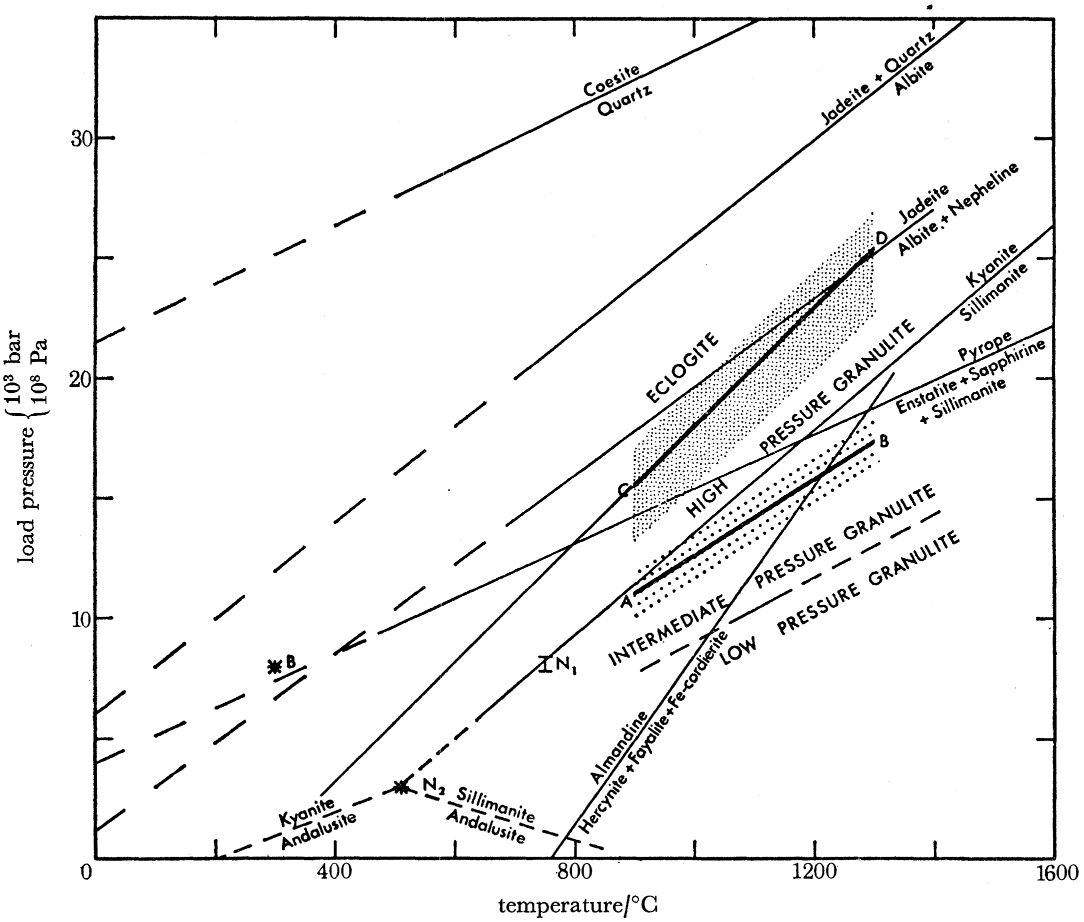

FIGURE 4. Diagram showing the granulite facies subdivisions in a pressure–temperature diagram. (See Green & Ringwood (1967, p. 807, Fig. 8) for explanation of diagram.)

Green & Ringwood (1967) subdivided granulite facies into low-, intermediate- and high-pressure régimes (figure 4) characterized by the mineral assemblages:

(*a*) *Low-pressure granulites* characterized by the association olivine + plagioclase and by the occurrence of cordierite.

(*b*) *Intermediate-pressure granulites* characterized by the association orthopyroxene + plagioclase, but the incompatibility of olivine + plagioclase.

(*c*) *High-pressure granulites* characterized by the association garnet + clinopyroxene + quartz and the incompatibility of hypersthene and plagioclase.

Because of solid solution effects boundaries between the assemblages must be diffuse and the pressure–temperature conditions for a given boundary reaction will depend in part on the rock composition.

Green & Ringwood (1972), mainly discussing their concept of the gabbro–garnet granulite–eclogite transition in the light of new data by Ito & Kennedy (1968, 1970, 1971), published the pressure–temperature diagram shown in figure 5 (see also Ringwood & Green 1966, Fig. 6). The continental geotherm from Ringwood & Green (1966) is shown on the figure.

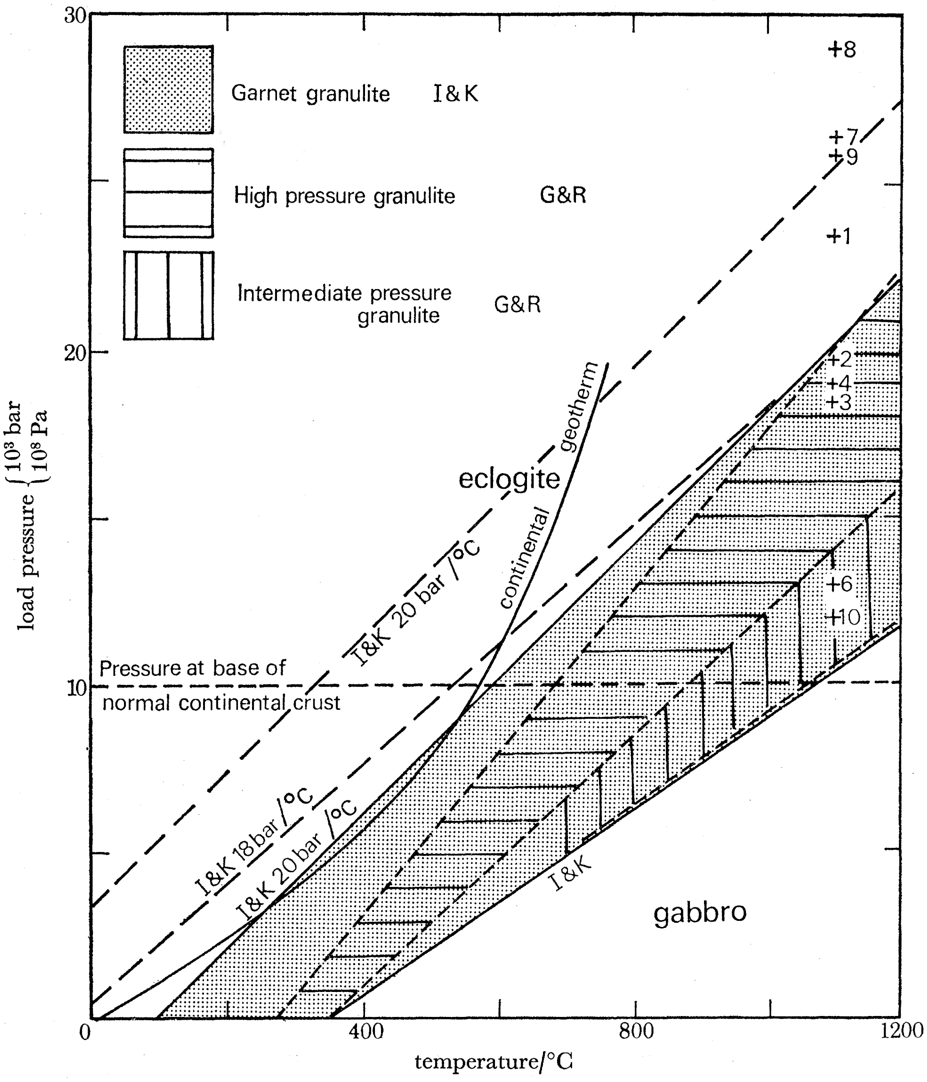

Figure 5. Comparison of extrapolation to lower temperatures of phase boundaries between eclogite, garnet granulite and gabbroic mineral assemblages. (See Ringwood & Green 1966; Green & Ringwood 1972.)

In assessing the experimental data which show that rocks in eclogite facies are stable throughout the entire continental crust, it must be realized that this relates to dry rocks. During the active evolution of continental segments one must consider the reaction taking place in hydrated rocks which are being gradually dehydrated, and a steeper than normal temperature gradient (flatter on figure 5), which thus makes granulite facies rocks the stable assemblage in dry rocks at deep crustal levels. The progressive regional metamorphic mineral reactions are dehydration reactions, and this together with the onset of partial melting in upper amphibolite facies makes the model of a dry deep crust in granulite facies a reasonable assumption. This was first expressed by Heier (1965*a*), Heier & Adams (1965), using geochemical arguments and by Den

Tex (1965) on petrological grounds. It is interesting that studies of fluid inclusions in medium- to high-pressure granulite facies rocks show the presence of large amounts of CO_2 ($\sim$ 2 g/cm^3 in the Lofoten area, W. L. Griffin, personal communication), while H_2O which is always present in such inclusions in lower grade metamorphic rocks is relatively rare in the granulite facies (Touret 1971). Whether granulite facies rocks subsequently transform into eclogite facies depends on the reaction kinetics and is probably to a large extent controlled by the cooling versus uplift (pressure release) history.

Chemical characteristics of medium- and high-pressure granulite facies rocks

The following discussion is restricted to granulite facies rocks which, according to the definitions of Green & Ringwood (1967), would be classified as medium- or high-pressure granulite facies rocks. Low-pressure (high-temperature) granulite facies rocks have not been found to be chemically significantly different from amphibolite facies rocks, with which they are characteristically intimately associated.

The rock types encountered include metasediments and metavolcanics. Recognizable pelitic rocks (previous shales) are relatively rare, possibly due to a pre-history for these rocks which involved migmatization and melting, this would particularly affect rocks of pelitic composition (Heier 1960). Graphite schists, marbles, impure quartzites and quartzbanded iron formations are however abundant. Granites (adamellites) are rare and the general lack of such rocks in medium- to high-pressure granulite terrains has been noted by Groves (1935), Ramberg (1951), Pichamuthu (1953), Wilson (1954, 1960), Heier (1960) from Uganda, Greenland, India, Australia and Norway, respectively. Rocks rather particular to such terrains are those of the anorthosite kindred including mangerites.

The chemistry of medium- to high-pressure granulite facies rocks has been studied by Heier and co-workers from Norway and Australia, and some consistent chemical properties particularly relating to their trace element contents have been defined (Heier & Adams 1965; Heier 1965*a*, *b*; Lambert & Heier 1967, 1968*a*, *b*; Hyndman *et al.* 1968; Heier & Brunfelt 1970; Heier & Thoresen 1971; Green, Brunfelt & Heier 1972).

One consistent feature is the depletion of Th and U in granulite facies rocks compared both with rocks of lower metamorphic grade and with high-level igneous intrusions. Heier & Rogers (1963) demonstrated a geochemical coherence between Th, U and K in crystalline rocks (see also Clark, Peterman & Heier 1966). Thus the potassium content, which is commonly determined in ordinary rock analyses, may serve as a guide to the concentration of Th and U. To ascertain a depletion in Th and U it is, therefore, important to compare rocks of similar K contents. This is shown from the Lofoten area in North Norway, where amphibolite facies and granulite facies rocks occur over a similar K interval (figure 6). The same trend is demonstrated by Lambert & Heier (1968*a*) for the Fraser and Musgrave Ranges in Australia, and by C. M. Gray (personal communication) from the Tomkinson Ranges also in Australia.

A depletion of Rb in granulite facies rocks was indicated by Heier & Adams (1964), and demonstrated by Lambert & Heier (1968*a*), from the Musgrave and Fraser Ranges, and by Heier & Thoresen (1971) from the Lofoten area. The most significant depletion of Rb relative to K was observed in the Lofoten area.

C. M. Gray (personal communication) found no depletion of Rb relative to K in granulite

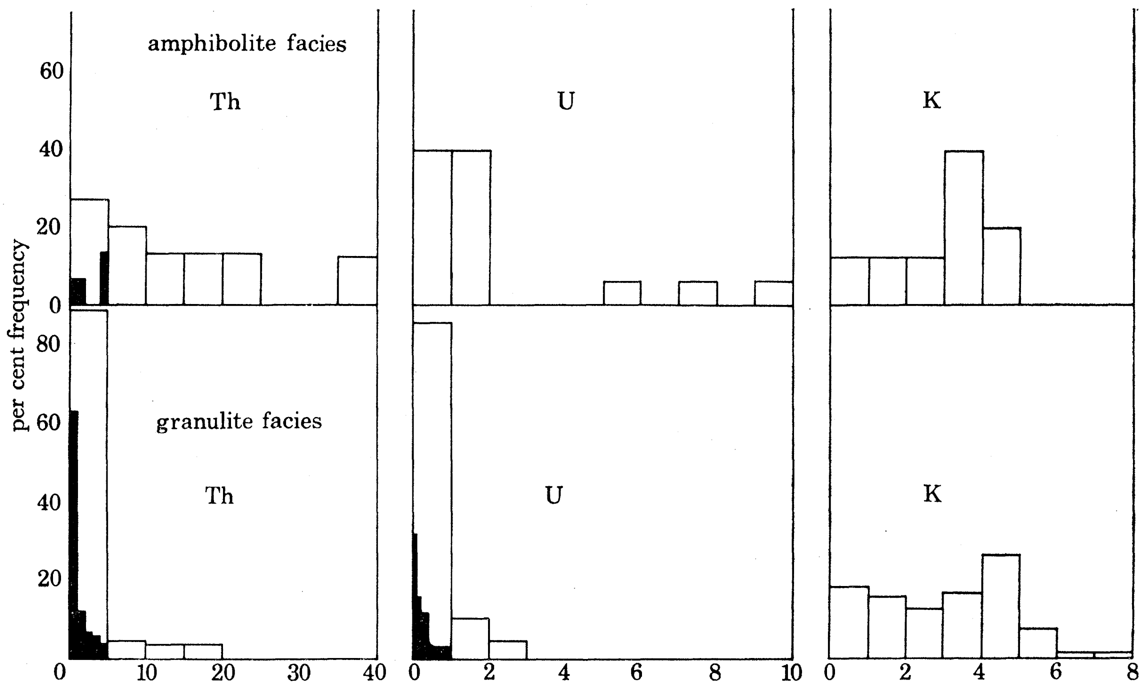

FIGURE 6. Frequency diagrams showing the distribution of Th, U and K in amphibolite facies and granulite facies rocks from the Lofoten–Vesterålen area, north Norway. Dark areas show more detailed distribution; e.g. 90 % of the granulite facies rocks have less than 5 parts/10^6 Th, and 64 % have less than 1 part/10^6 Th. Note the similar distribution of potassium in both metamorphic facies areas.

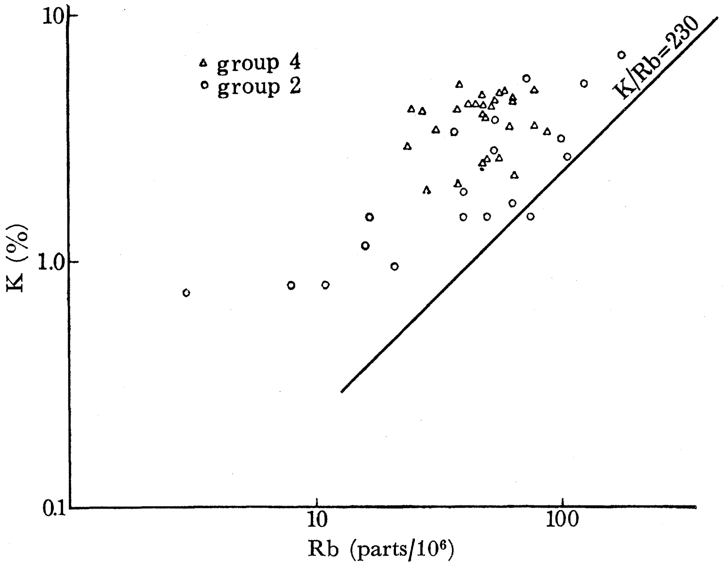

FIGURE 7. Plot of K against Rb for mangerites (group 4) and banded granulites (group 2) from the Lofoten–Vesterålen area in north Norway. (See Heier & Thoresen 1971, Fig. 3.)

facies rocks from the Tomkinson Ranges, Central Australia, although these rocks do show the Th, U depletion. As will be shown below, the loss of Rb on moving from amphibolite to granulite facies metamorphism is predictable, and the results from the Tomkinson Ranges are puzzling. It may be relevant that rocks from the west Australian shield in general appear to be enriched in Rb (characterized by high Rb/Sr ratios) compared with other shield areas.

Rb is plotted against K for mangerites and banded granulites from Lofoten–Vesterålen in figure 7. The assumed average upper crustal K/Rb ratio of 230 (Taylor 1964) is shown for comparison. The high K/Rb ratios of the granulite facies rocks are demonstrated and within the mangerites there appear to be some tendency of increasing K/Rb ratios with increasing K contents. This is quite contrary to the normal trends.

Heier & Brunfelt (1970) demonstrated that Cs is strongly depleted in high grade metamorphosed rocks from Lofoten–Vesterålen. It follows the pattern of Rb, but a fractionation between Cs and Rb is indicated leading to an even more marked depletion in Cs, and loss of Cs is already observed in amphibolite facies rocks. Data for Cs do not exist from any other province.

Mechanism of removal of Th, U, Rb and Cs from medium and high pressure granulite facies rocks

Marowsky & Wederpohl (1971) found a decrease in the concentrations of the very volatile elements Hg, Bi and Cd in a thermal gradient of regional metamorphism from sedimentary to lower amphibolite facies rocks (no data exist for these elements in granulite facies rocks). Apart from this and loss of volatiles, studies of regionally metamorphosed rocks have failed to demonstrate any statistically valid chemical differences until the onset of granulite facies (Shaw 1954, 1956; Chinner 1960; Phinney 1963). In amphibolite facies gneisses the elements Th, U, Rb and Cs are probably mainly present in the lattices of micas and K-feldspar (Rb, Cs) and epidote or zircons (U, Th), though other U and Th minerals must also be considered. The micas tend to break down in granulite facies and to form K-feldspar together with a variety of other reaction products which do not concentrate Rb or Cs. Where micas and K-feldspar co-exist, Rb and Cs are commonly concentrated in the micas rather than in K-feldspar (lower K/Rb and K/Cs ratios in the micas). Breakdown of the micas would either result in low K/Rb and K/Cs ratios in the high-grade metamorphic feldspars, which is contrary to observation, or loss of Rb and Cs from the rocks.

Similarly, epidote minerals are not stable in granulite facies. A number of breakdown reactions involving epidote have been proposed (see Heier 1965*b*, p. 252), but neither of the reaction products have suitable lattices for the incorporation of Th and U.

It is shown above that metamorphic mineral reactions can explain the observed depletion o certain trace elements in granulite facies rocks. Remembering that progressive regional metamorphism involves a series of dehydration reactions, removal of the elements from the rocks could be facilitated by escape of the vapour phase. It was mentioned above that fluid inclusions in the Lofoten granulite facies rocks contain CO_2 rather than H_2O, while CO_2 is not common in rocks of lower metamorphic grade.

If one accepts the argument that the total fluid pressure equals load pressure, the sudden appearance of large amounts of CO_2 in fluid inclusions in granulite facies rocks takes on a special importance. As the fluid pressure cannot exceed the load pressure an increase of the percentage CO_2 in the fluid must result in a decrease in the water pressure. This would induce a more rapid breakdown of hydrous minerals without an increase in temperature (Touret 1970). Liberation and subsequent expulsion of this water could explain the simultaneous loss of certain elements from granulite facies rocks.

Metamorphism and magmatism merge when partial melting begins, generally under upper amphibolite facies conditions. The paucity of acid rocks in the medium- and high-pressure granulite facies areas may be explained by their being the residuum after removal of the melt phase. The relatively minor amounts of acid rocks present in such terrains could represent rocks which for some reason did not melt; melts which did not leave the metamorphic environment; rocks emplaced after the climax of metamorphism in these terrains. Some young granites within these areas are characterized by U and Th depletion, and high K/Rb and K/Cs ratios indicating that they have formed by partial melting of rocks already in granulite facies from which loss of these elements had already occurred (Heier & Brunfelt 1970).

THE IMPORTANCE OF GRANULITE FACIES ROCKS TO CRUSTAL MODELS

It was pointed out above, that conditions for formation of granulite facies rocks could be expected to prevail during the active evolution of the continental crust. A subsequent transformation into eclogite facies rocks will not affect the chemical implications of this statement. Heier & Thoresen (1971) showed that subsequent retrogression, involving hydration, may not noticeably affect the trace element concentrations. The importance one would attach to the chemical observations referred to above will then depend on the volume of rocks in the crust that has been through this metamorphic cycle.

TABLE 1. ESTIMATES OF THORIUM, URANIUM AND POTASSIUM ABUNDANCES IN THE CONTINENTAL CRUST

Th parts/10^6	U parts/10^6	K (%)		
			geochemical estimates	
11.4 ± 2	3.0 ± 0.6	—	Adams *et al.* (1959)	
9.6	2.7	2.1	Taylor (1964)	
			estimates from heat flow	
4.6	1.12	1.84	Clark & Ringwood (1964)	$q = 62.8$ mW/m^2(1.5 μcal cm^{-2} s^{-1})
3.2	0.81	1.31	Clark & Ringwood (1964)	$q = 50.2$ mW/m^2(1.2 μcal cm^{-2} s^{-1})
2.5	0.64	1.05	Clark & Ringwood (1964)	$q = 41.8$ mW/m^2(1.0 μcal cm^{-2} s^{-1})

Heier (1965*a*) first demonstrated the disagreement between estimates of crustal abundances of the heat-producing elements K, Th and U derived from various methods of averaging surface abundances, and from interpretations of heat flow data (table 1). The problem could be resolved if one accepts the postulate of a basaltic lower layer of the continental crust. However, besides making little geological sense, the contention is inconsistent with other measured properties of the lower crust. As shown by Ringwood & Green (1966) dry basic rocks would occur as eclogites or high-grade garnet granulites at these depths with densities between 3.3 and 3.6 g/cm^3, possessing a seismic P velocity of between 7.5 and 8.5 km/s. This is inconsistent with the measured physical properties of the material and the model of a basaltic lower crust must therefore be rejected.

A lower crust compared of rocks of intermediate chemical composition occurring in the eclogite facies would yield seismic velocities and densities which are acceptable for the lower crust (Green & Lambert 1965; Ringwood & Green 1966). Following the discussion above, such rocks would be expected to exhibit the granulite facies depletions of U and Th and from the standpoint of heat production they would then be just as acceptable as basaltic as constituents of the lower crust.

Based on measured surface heat flows; calculated surface heat production from measurements of radioactive element contents; assumption of heat flux from the mantle of 23.0 mW/m^2 (0.55 μcal cm^{-2} s^{-1}) and 18.8 mW/m^2 (0.45 μcal cm^{-2} s^{-1}) in young high heat flow areas and shield areas respectively; deep crust of granulite facies geochemistry, Hyndman *et al.* (1968) computed the distribution of heat production with depth and the concentration of heat-producing elements for an Archaean shield with mainly granitic surface rocks as well as heat production distribution in a shield-greenstone surface layer, and a young high heat flow area with granitic surface rocks (figure 8). The sharp decrease in radioactivity follows our conclusions of a sharp decrease in radioactive element concentrations in medium- and high-pressure granulite facies rocks. The concentration gradients in the lower crust is conjectural. It was assumed that they fall off steadily so that the average concentrations at 20 km depth at 1.1 % K, 0.25 parts/10^6 U, and 1.0 parts/10^6 Th, which are consistent with granulite facies rocks of an overall intermediate composition.

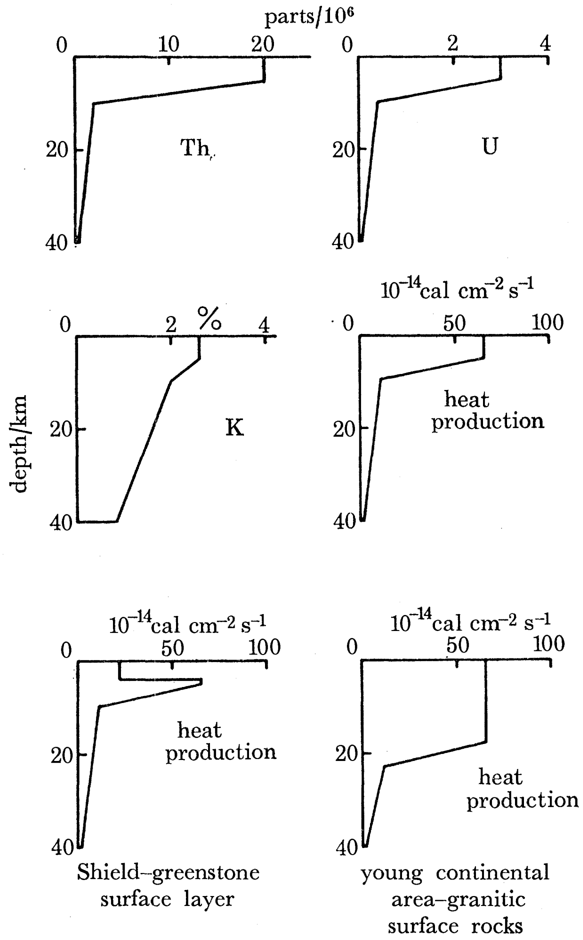

FIGURE 8. Crustal radioactivity and heat production profiles for Archaean Shield areas with mainly granitic surface rocks; shield areas with greenstone surface rocks; young, high heat flow areas with granulite surface rocks. (See Hyndman *et al.* 1969.)

The radioactivity profiles clearly show the strong upward concentration of radioactive elements resulting in a thickness of the surface layer with respect to these elements to less than 10 km (see also Lambert & Heier 1968*b*).

The radioactive elements are unique among the elements in that their crustal abundances may be estimated by two essentially independent means; a geochemical method based on assumptions from surface geological observation, and a geophysical method based on interpretation of heat flow values.

It is possible to estimate the average abundance values of other elements using the model illustrated in figure 8. This has been done for Rb for which we have tentatively suggested 40 to 50 parts/10^6 in the shield crust and 50 to 60 parts/10^6 in the young crust regions (Lambert & Heier 1968*b*).

Hurley (1968), using independent arguments, derived 70 parts/10^6 Rb in the continental crust and 1.75% K. These estimates are compared with those of Taylor (1964) derived from the common type of arguments which in our opinion overemphasizes the chemical composition of the surface rocks in the tabulation of crustal abundances of elements (table 2).

TABLE 2. THE CONCENTRATION OF K, Rb, Th, U IN THE CONTINENTAL CRUST

	this paper	Hurley (1968)	Taylor (1964)
K (%)	1.5–1.6	1.75 ± 0.23	2.09
Rb (parts/10^6)	40–60	70	90.0
Th (parts/10^6)	4.5–7.0	—	9.6
U (parts/10^6)	0.7–1.3	—	2.7

CONCLUSIONS

The problem of granulite facies rock would be to define completely their importance in crustal development through orogenic cycles. If they are important constituents of the crust, studies of their geochemistry show that important errors for a number of elements exist in published abundance tables of elemental concentrations in the continental crust.

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