Origin of Granulite Terranes and the Formation of the Lowermost Continental Crust

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Differences in composition and pressures of equilibration between exposed, regional granulite terranes and suites of granulite xenoliths of crustal origin indicate that granulite terranes do not represent exhumed lowermost crust, as had been thought, but rather middle and lower-middle crustal levels. Application of well-calibrated barometers indicate that exposed granulites record equilibration pressures of 0.6 to 0.8 gigapascal (20 to 30 kilometers depth of burial), whereas granulite xenoliths, which also tend to be more mafic, record pressures of at least 1.0 to 1.5 gigapascals (35 to 50 kilometers depth of burial). Thickening of the crust by the crystallization of mafic magmas at the crust-mantle boundary may account for both the formation of regional granulite terranes at shallower depths and the formation of deep-seated mafic crust represented by many xenolith suites.

As a result of its inaccessibility, the petrogenesis and evolution of the lower continental crust are, at best, poorly understood. Because of the high pressures recorded in exposed regional granulite terranes (metamorphic rocks exposed over thousands of square kilometers that equilibrated at 650° to 900°C and 0.5 to 0.9 GPa) and their depleted character (low activity of H_2O and commonly observed low abundance of heat-producing elements), these terranes generally have been thought to represent exhumed portions of the lower continental crust. However, application of well-calibrated mineral barometers generally indicates that the rocks in many exposed granulite terranes equilibrated at depths of only 20 to 30 km (*3*). Large granulite-grade terranes whose exposure is not limited to narrow belts along tectonic boundaries (for example, the Adirondacks, Napier Complex, and south Indian granulites) are now underlain by 20 to 30 km of apparent crustal material; this implies crustal thickness of ~60 km before uplift.

Some amphibolite-granulite terranes have been thought to represent cross sections through the lower crust [for example, Fraser Range, southwestern Australia; Ivrea Zone, Italian Alps; Kapuskasing Zone, Ontario, Canada; Pikwitonei Domain, Manitoba, Canada (*1, 2*)]. However, the rocks now exposed in these terranes equilibrated at depths no greater than 30 km (*3*) (Table 1). Crustal rocks that apparently equilibrated at pressures significantly higher than those of most exposed regional granulite terranes are represented in a large number of suites of granulite grade xenoliths (*4, 5*). In this report we show that most granulite xenoliths are indeed derived from levels deeper than those represented by exposed regional granulite terranes and propose that the differences in pressure, as well as chemical composition, can be understood in the context of a model that relates the evolution of regional granulite terranes to the synchronous formation of lowermost crust by magmatic underplating.

Most estimates of pressures recorded in xenoliths have been deduced from equilibria in the model system CaO-MgO-Al_2O_3-SiO_2 (*5*). As the compositions of most crustal xenoliths are not well represented by this model system, the pressures inferred could be imprecise. For this reason and to facilitate comparison with metamorphic conditions recorded in regional granulite terranes, we reevaluated the pressures recorded in xenolith suites using the same geobarometers, well calibrated by experiment, for both xenoliths and granulite terranes.

Pressure-sensitive equilibria that are represented in nearly all regional granulite terranes and in most suites of crustal xenoliths include: orthopyroxene-plagioclase-garnet-quartz (*6, 7*), ilmenite-Al_2SiO_5-quartz-garnet-rutile (*8*) and ilmenite-plagioclase-quartz-garnet-rutile (*9*) (Tables 1 and 2). Application of the same calibrations of these barometers with similar solution models (*10–12*) in all rocks allows accurate determination of relative pressure differences because systematic errors in solution models or imprecision in the experimental calibrations and thermodynamic parameters are eliminated. To further facilitate comparisons, we have calculated equilibration pressures for xenoliths at 800°C, a metamorphic temperature common to most regional granulites. Most crustal xenoliths likely equilibrated at significantly higher temperatures, perhaps between 900° to 1000°C. Such temperatures would increase inferred pressures for such rocks by 0.1 to 0.2 GPa.

As can be seen in Table 1, metamorphic pressures from most regional granulite terranes cluster around 0.75 ± 0.05 GPa, and there are as few estimates above this cluster as below (*13*). In contrast, pressures deduced from crustal granulite xenoliths (Table 2) are generally 1.0 GPa or higher. Suites of xenoliths that yield pressures comparable to those of granulite terranes contain abundant inclusions of metasedimentary rocks (Kilbourne Hole, Tallante). Such xenoliths were most likely dislodged from parts of the crust that are equivalent to these represented by exposed regional granulite terranes (*14*). Some granulite terranes contain rocks that equilibrated at pressures approaching those inferred for xenoliths. Such terranes (Doubtful Sound, Furua, Napier Complex and, possibly, Kapuskasing, Lofoten) may represent levels of the crust that are transitional to those represented by xenoliths. However, the overall differences between regional granulite terranes and granulite xenoliths (Tables 1 and 2) are minimum differences. Not only are the xenoliths likely to have equilibrated at temperatures well in excess of 800°C, but those for which pressures were determined probably represent the highest crustal levels (lowest pressures) in the suite. In order to apply the same well-calibrated barometers in both granulites and xenoliths, plagioclase-bearing rocks have been selected. At high pressures, plagioclase components dissolve in pyroxenes and garnet. As a result, plagioclase-free xenoliths (commonly a majority of any given suite), which are of similar bulk composition as plagioclase-bearing rocks, must have equilibrated at pressures higher than those listed in Table 2. Pressures of 1.2 to 2.0 GPa (based on barometers other than those employed in our analysis) have been reported for various suites of crustal xenoliths (*4, 5, 15*).

The dissimilarities in pressures recorded in granulite terranes as compared to crustal xenoliths as well as differences in overall bulk compositions of the two groups of rocks can be related to processes by which the continental crust was generated and evolved. The generation of many regional granulite terranes (representative of middle to lower-middle levels of the crust) and the formation of lowermost crust (as represented by crustal xenoliths) may be inextricably

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related. Bohlen (3) and Mezger *et al.* (16) have suggested that several characteristics of regional granulite terranes are consistent with the addition of substantial volumes of magmas (probably mantle derived) at the base of and to existing crust:

1) "Peak" metamorphic pressures in most granulites do not differ significantly from those of associated upper amphibolite facies rocks. This similarity suggests that granulites were metamorphosed at higher temperatures but were not necessarily more deeply buried than amphibolites.

2) Pressure-temperature-time paths of metamorphism in many regional granulite terranes where prograde mineral textures are preserved are consistent with the formation of sillimanite from andalusite in metasedimentary rocks and initial, nearly isobaric cooling from peak conditions (for example, the Adirondacks, Arunta Block, Namaqualand, Pikwitonei, and Willyama granulites; Fig. 1).

3) In many regional granulite terranes maximum pressures and temperatures of the granulite facies events were attained at approximately the same time (Fig. 1).

4) Geochronologic data for well-dated granulite terranes (for example, the Adirondacks, Pikwitonei, and Napier Complex granulites) suggest that metamorphic minerals such as garnet grew only during discrete episodes of a protracted regional metamorphism coeval with or slightly after emplacement of intrusions. The data also show that granulite metamorphism occurred after the continental crust that forms these terranes was assembled, not during the assembly.

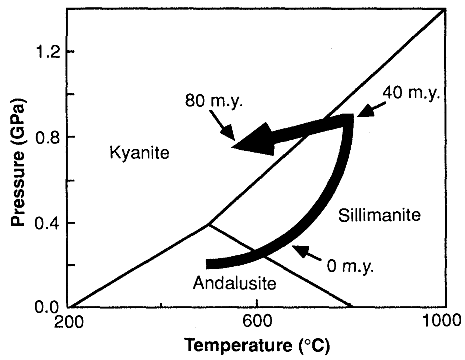

Fig. 1. A portion of counterclockwise, pressure-temperature-time path for regional granulite terranes as deduced from petrologic and geochronologic considerations; see (3) and (16). The path shown is that deduced from the Adirondacks and Pikwitonei granulites and is semiquantitatively like those for the Arunta Block, Namaqualand, and Willyama granulites, and, possibly, the Napier Complex and Inarijarvi granulites. Ages in million years (m.y.) give the duration of the tectonothermal episode in the Pikwitonei granulites, Manitoba (16); Al_2SiO_5 phase relations after Holdaway (36).

5) Cooling from peak conditions in many terranes occurred at rates of <5°C per million years for a period of a few hundred million years.

These observations are all consistent with metamorphism caused by episodic events that led to rapid increases in temperature, moderate increases in pressure, and a steepened geothermal gradient during metamorphism. They require that advective heat transport, most likely by underplating and intrusion of magmas, was the dominant process governing the thermal regime. Because some basaltic magmas are too dense to rise above the crust-mantle boundary (17), episodic underplating of multiple batches of such magmas at the base of the existing crust could account for the long metamorphic histories observed in some regional granulite terranes and the formation of deep, mafic crust. The melts would provide a heat source for high-grade metamorphism and partial melting. The advection of heat by upwardly migrating melts would produce rapid temperature increases during metamorphism. Differentiation of magmas ponded at the crust-mantle boundary would give rise to a variety of cumulate rocks (including anorthosites) that would impart a layered structure to the lowermost crust, as revealed by seismic studies (18). Such features also agree with petrologic studies of xenoliths [see (5) for a review]. Furthermore, if regional granulites are related to crustal thickening by magma underplating, then cross sections of the crust should reveal a decrease in supracrustal rocks and a general increase in the mafic character of the crust with depth. Such predictions of the model are generally supported by observation. The deepest rocks exposed in those terranes thought to represent crustal cross sections (Doubtful Sound, Fraser Range, Ivrea, and Kapuskasing) include abundant, and in some places thick, sequences of mafic rocks at their bases. Terranes such as the Napier Complex, Furua Complex, and Doubtful Sound that may represent levels of the crust

Table 1. Characteristics of granulite terranes; see (3) for primary references except where otherwise indicated; *n* is the number of samples from which pressures were calculated; CCW refers to a counterclockwise pressure (P)-temperature (T)-time path of metamorphism, qualitatively similar to that shown in Fig. 1; IBC refers to initial, nearly isobaric cooling from high P-T conditions; the last column gives estimate of abundance of felsic granulite (fg, tonalites and other granitoids), mafic granulite (mg, metabasalts and related rocks), and metasedimentary rocks (s); percentages of each given in parentheses; Ma = million years ago.

Locality	Age (Ma)	T (°C)	P (GPa)	*n*	P-T-time path	Lithology
Adirondacks, New York	1150 to 1000	750 to 825	0.70 to 0.85	40	CCW, IBC	fg (70) mg (20) s (10)
Arunta Block, Australia (31)	1800	800 to 850	0.70 to 0.90	*	CCW, IBC	fg (50) mg (15) s (35)
Bamble, Norway	1500	750 to 850	0.75 to 0.90	17	IBC	fg (70) mg (20) s (10)
Buksefjorden, Greenland	2800	800	0.74 to 0.83	6	IBC	fg (40) mg (50) s (10)
Doubtful Sound, New Zealand†	120	750	1.04	2		fg (30) mg (60) s (10)
Furua Complex, Tanzania	1800?	800	0.96 to 1.04	12	IBC	fg (45) mg (50) s (5)
Hebei Province, PRC	2600?	750	0.60 to 0.68	3		
Inarijarvi, Finland	2150	750	0.70 to 0.75	2	CCW?	fg (30) mg (10) s (60)
Ivrea Zone, Italy†	270	710	0.68 to 0.74	4	IBC	fg (30) mg (40) s (30)
Kapuskasing, Ontario	2700 to 2600	750	0.89 to 1.01	12	IBC	fg (65) mg (25) s (10)
Labwar Hills, Uganda	?	950	0.65	1		
Lofoten, Norway	2000 to 1800?	800	0.80 to 0.95	6		fg (70) mg (20) s (10)
Madras, India	1100	800	0.70	2	IBC	
Molodezhnaya Station, Antarctica	1100	700	0.57	3	IBC	
Namaqualand, South Africa	1200	800 to 850	0.50	4	CCW, IBC	fg (50) mg (10) s (40)
Napier Complex, Antarctica (32)	3100 to 3000	900 to 950	0.85 to 0.92	3	CCW, IBC	fg (40) mg (35) s (25)
Nilgiri Hills, India	2500	750 to 850	0.77 to 0.92	4	IBC	fg (70) mg (10) s (20)
Otter Lake, Ontario	1100	700	0.70 to 0.84	11	IBC	fg (60) mg (10) s (30)
Pikwitonei, Manitoba	2700 to 2600	700 to 850	0.70 to 0.78	15	CCW, IBC	fg (50) mg (40) s (10)
West Ussimaa, Finland	1800	800	0.50	1	IBC	fg (40) mg (30) s (30)
Willyama, Australia	1700	650 to 800	0.55 to 0.65	6	CCW, IBC	fg (30) mg (10) s (60)

*Values of pressure taken directly from (31). †Not Precambrian regional granulite terranes, but included as examples of crustal cross sections.

Table 2. Characteristics of xenolith suites. See (*5*) for primary references except where otherwise indicated; pressures are calculated at 800°C; *n* is the number of samples from which pressures were calculated. The last column gives the lithology of xenoliths in decreasing abundance (mg, mafic granulite, metabasalt, and related rocks; um, ultramafic rocks; fg, felsic granulite, tonalite, and other granitoids; s, metasedimentary rocks). The xenolith suites without abundant mafic rocks yield the lowest pressures.

Locality	P (GPa)	*n*	Lithology
Big Creek, California (*33*)	1.20 to > 1.25	4	mg, um, fg, s
Camp Creek, Arizona	> 1.04	2	mg
Colorado-Wyoming	> 1.18	2	mg
Eifel, West Germany	> 1.00	1	mg
Kayrunnera, NSW, Australia	> 0.80	1	mg
Kilbourne Hole, New Mexico	0.72 to 0.81	8	fg, s, mg
Lesotho, South Africa	0.98 to > 1.50	7	mg, fg
Moses Rock, Utah (*34*)	1.12	1	mg, fg, s
North Queensland, Australia	1.04 to 1.13	2	mg, um, s, fg
North Queensland, Australia (*35*)	0.86 to 1.16	8	mg, fg, s
Stockdale, Kansas	> 1.03	1	mg
Tallante, Spain	0.60 to 0.70	3	s, fg

approaching those represented by crustal xenoliths are generally more mafic in overall bulk composition and contain relatively fewer supracrustal rocks than granulite terranes recording lower pressures and hence representing higher levels of the crust (Table 1) [see also (*14*)].

Underplating of magmas may occur in a rift environment, above a hot spot or along an active continental margin. Synmetamorphic compressional features that generally predate the thermal peak are widespread in granulite terranes (*19*). The long duration of high-grade metamorphic conditions (typically >100 million years) and the multiple episodes of mineral growth separated by quiescent intervals of no apparent mineral reactions (*16*) indicate that metamorphic conditions in regional granulite terranes changed episodically during protracted periods of high-grade metamorphism. These features imply that many regional granulite terranes were metamorphosed in a tectonic setting that prevailed for long periods and where large amounts of magmas were added to the crust episodically. The most likely setting for such a scenario is an active continental margin setting (*20, 21*).

As shown in Table 1, most of the metamorphic terranes, for which information on the retrograde path is available, underwent initial, nearly isobaric cooling. This type of cooling history implies that the terranes had to be close to isostatic equilibrium in the waning stages of the tectonothermal event and the uplift rates had to be relatively low. Typical uplift rates of <100 m per million years and low cooling rates of <5°C per million years (*16, 22*) are consistent with the relaxation of geotherms perturbed as a result of the underplating and intrusion of magmas (*23*). Geochronologic studies of amphiboles, biotites, and rutiles (*16, 22*) indicate that the time scale of the relaxation is on the order of 100 to 300 million years (*23*). The density of the lower crust will be enhanced by cooling and by mineralogic reactions that cause the formation of garnet-rich rocks in the lowermost crust. The increase in density will limit isostatic uplift, thereby reducing topographic relief and rates of erosion. The relatively high density of the lowermost crust might help to account for why most regional granulite terranes were exposed several hundred million years after high-grade metamorphism by processes that seem to be unrelated to those that caused metamorphism.

Because many granulite terranes were apparently exposed accidently by later tectonic or magmatic activity, they most likely represent somewhat random samples of the middle crust. In that xenoliths are likely random samples of the lower crust, we suggest that significant parts of the lowermost crust have formed by the underplating of mostly mafic magmas and such underplating was likely associated with the same tectonothermal events that led to the formation of regional granulites. The heat from underplated and intruded magmas would have contributed significantly to the heat budget during the formation of regional granulites.

This model implies that regional granulite terranes are not underlain by additional felsic and minor metasedimentary material like that in granulite terranes themselves, but by a variety of cumulus rocks, anorthosites, dunites, pyroxenites, websterites, and peridotites in addition to eclogites, pyroxene granulites, and garnet granulites, as indicated by the dearth of xenoliths of sedimentary origin (*24*). This mafic material may have a total thickness of as much as 15 to 25 km and is represented by the suites of crustal xenoliths that record pressures higher than those of granulite terranes. If this model is representative, the role of magmatic accretion beneath existing continental crust, as opposed to the lateral accretion of arc material at continental margins, has been underestimated as an important mechanism for the growth of the continental crust (*25*).

The model predicts that the igneous and metamorphic age of lowermost crustal xenoliths (not their subsequent entrainment in magma) will be the same as, or at least similar to, the age of granulite facies metamorphism in the overlying crust. Such predictions are consistent with the geochronologic data on the xenolith suites from northwestern Queensland and Mexico. The U-Pb ages of metamorphic zircons extracted from granulite xenoliths from northwestern Queensland having a supracrustal precursor most likely date the time of high-grade metamorphism. The ages are identical to U-Pb ages obtained on zircons extracted from xenoliths crystallized from mantle-derived melts (*27*). Furthermore, Sm-Nd mineral–whole rock ages determined on garnet-biotite gneisses in a xenolith suite from Mexico indicate a Grenville age for granulite facies metamorphism. The ages are consistent with Nd model ages determined on xenoliths from the same area (*27*). Eclogite xenoliths from Tanzania have Sm-Nd mineral ages of 1.75 billion years ago (*28*). These metamorphic ages are consistent with emplacement ages of precursor mantle-derived melts (now exposed as eclogite in the Vissury Mine). The ages also coincide with the emplacement of granites in the central part of the Tanzanian craton, suggesting that high-grade metamorphism and partial melting was triggered by emplacement of basaltic melts into the lower crust (*28*). In these cases, the melts bringing the xenoliths to the surface are unrelated to the processes that formed the lower crust. More detailed age information deduced from garnet and other minerals (*29*) combined with barometry is needed to test further the relation of magmatic underplating to granulite formation. The best localities for such evaluations would be those in which xenoliths typical of regional granulites and lowermost crustal granulites were entrained in the same volcanic eruption.

Most continental crust was stabilized during the Archean and Proterozoic (*30*). If this were caused by underplating of mafic melts, then either the average composition of the continental crust must be more mafic than is widely believed (*30*) or large parts of this underplated material must have been recycled back into the mantle. Alternatively exposed granulite terranes may not be typical representatives of the middle to lower crust. That they are exposed may indicate that they are somewhat atypical. However, if such were the case, the proposed model for the evolution of the lowermost crust should be still valid for regional granulite terranes.

Our model also implies that the lowermost crust is younger than the crust it underplates. In addition, the newly formed lowermost crust will not necessarily be depleted chemically and could therefore be the source region for large amounts of felsic to intermediate magmas. Thus model ages for the separation of crust-forming material, deduced from rocks derived from this underplated reservoir, will be younger than those from the overlying crust.

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13. Relatively small terranes exposing kyanite-bearing granulites are widespread in Phanerozoic orogenic belts (the Bohemian massif, for example). Such terranes are relatively limited in extent and seem to have been exhumed and cooled rapidly in contrast with many regional granulite terranes. Although such granulite terranes are important in the understanding of Phanerozoic orogenesis, they do not seem representative of large areas of the continental crust and therefore have been excluded from our discussion. In so doing, we recognize that not all granulites form by the same tectonic or geologic processes. Other workers [for example, S. Harley, *Terra Cognita* **8**, 267 (1988)] have emphasized that different kinds of Precambrian regional granulite terranes may form by different tectonic processes. In this report we focus on a significant number of regional terranes that have in common several unifying characteristics that place important constraints on their formation and the formation of related lowermost crustal material.
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Template-Directed Oligomerization Catalyzed by a Polynucleotide Analog

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A pyrophosphate-linked analog of polycytidylic acid has been synthesized and shown to catalyze the oligomerization of the complementary monomer 2′-deoxyguanosine 3′,5′-bisphosphoimidazolide. Analogs of polynucleotides are of interest in studies of the origins of life as possible precursors of the first RNA molecules. These results demonstrate that such molecules are capable of serving as templates for further synthesis.

ENZYMATICALLY SYNTHESIZED POLYcytidylic acid [poly(C)] catalyzes the synthesis of oligoguanylic acids [oligo(G)'s] from an activated form of guanosine 5′-phosphate (*1*). This system has been considered as a possible model for prebiotic replication of RNA. However, the inhibition of the reaction observed when both stereoisomers of the mononucleotide are present is not consistent with this role (*2*). Poly(C) has also been shown to catalyze the oligomerization of both 2′-deoxyguanosine 3′,5′-bisphosphoimidazolide (ImpdGpIm) and an acyclic analog of guanosine not based on ribose (*3–5*). In these latter template-directed reactions, the oligomers produced are linked by pyrophosphate, rather than phosphodiester linkages. Acyclic nucleic acid analogs with pyrophosphate backbones are possible precursors of the first RNA molecules (*6*). It is important, therefore, that these molecules be capable of acting as templates for oligomerization. We have synthesized a pyrophosphate-linked polynucleotide analog based on 2′-deoxycytidine 3′,5′-bisphosphate (pdCp) and now report that this product serves as a catalyst for template-directed oligomerization.

The monomer *N*-4-diphenylacetyl-2′-deoxycytidine 3′-*O*-phosphate 5′-*O*-(*S*-4-methylphenyl)phosphorothioate (structure 1 in Fig. 1A) was synthesized and subjected to oligomerization (*7–12*). In the absence of other nucleophiles, reaction of the activated 5′-phosphate can only occur with a free 3′-phosphate group. After removal of the diphenylacetyl protecting groups (*13*), therefore, the major products expected were the cyclic pyrophosphate (structure 2 in Fig. 1A, produced by intramolecular cyclization of the activated intermediate) and a series of 3′,5′-pyrophosphate–linked oligomers of pdCp (structure 3 in Fig. 1A). The crude products were fractionated, and oligomers were subjected to alkaline phosphatase treat-

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