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Petrology and rare earth element geochemistry of clastic metasedimentary rocks from the Isua supracrustal belt, West Greenland

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Abstract

An investigation of the petrology and rare-earth element (REE) geochemistry of clastic metasedimentary rocks from the ~ 3800 Ma Isua Supracrustal Belt has been carried out to provide constraints on the nature of early Archaean metamorphic regimes and on the sources of their sedimentary protolith. The assemblages garnet + staurolite + biotite and biotite + kyanite (both with qtz + musc + plag + ilm) characterize the Isua metasediments and represent types common in younger metamorphic belts. Secondary chlorite and sericite occur in most samples. Garnet-biotite geothermometry indicates T = 541 ± 43°C for prograde metamorphism and T = 464 ± 39°C for retrograde metamorphism. Suggested metamorphic conditions of T ~ 550°C and P ~ 5 Kb imply burial to at least 15 Km with metamorphic thermal gradients < 40°C/Km. These data argue against excessively steep early Archaean crustal thermal gradients.

REE patterns for three muscovite-biotite gneisses are strongly fractionated (Ce_N = 40–100; Yb_N = 2–8) with variable Eu-anomalies (Eu/Eu* = 0.48–0.95), not unlike patterns for Archaean felsic volcanic rocks in other areas. Garnet-biotite schists have less-fractionated light REE, and exhibit a slope reversal for the heavy REE (*i.e.*, $Gd_N < Yb_N$). These most plausibly represent a mixed felsic-mafic (- ultramafic?) protolith. Both sediment types could be the erosion products of a rapidly emergent volcanic structure shedding debris into a shallow basin.

Introduction

We have initiated a program of petrological and geochemical studies on samples from the Isua supracrustal belt of southern West Greenland to follow up field work carried out by us in 1978 and 1979. The purpose of these studies is twofold: to understand the thermal history of this most ancient crustal terrain; and to gain insight into pre-Isua crustal material by examining the compositions of clastic metasedimentary rocks. In this report, we summarize results of petrographic and electron microprobe studies which delineate the nature of early Archaean metamorphism at Isua, and have important consequences for models of terrestrial crustal evolution (cf. Boak & Dymek, 1980). We also report rare-earth element (REE) analyses on seven clastic metasedimentary rocks, which place some limits on the source regions for their sedimentary protoliths (cf. Boak *et al.*, 1981).

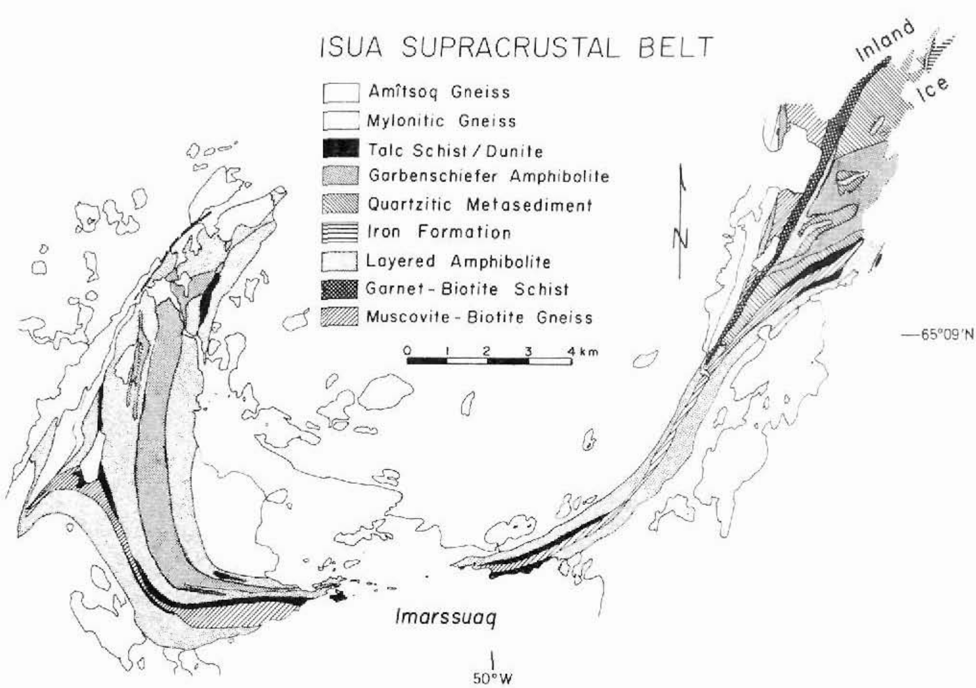

Fig. 1. Simplified geological map of the Isua supracrustal belt (adapted from Allaart, 1976).

Geological overview

The geology of the Isukasia region has been described by Bridgwater & McGregor (1974), Bridgwater *et al.,* (1976), and Allaart (1976). These authors published general descriptions of the stratigraphy and major rock types and established the presence of metavolcanic, clastic and chemical metasedimentary units. More recent detailed mapping by ourselves (Dymek *et al.,* 1981) and Nutman *et al.* (1983), have largely confirmed the earlier mapping and has established a coherent stratigraphy for the whole belt (Nutman *et al.,* in press). A generalized map of the supracrustal belt is reproduced in figure 1, which is used as a framework for discussion in this report.

The volcanic and sedimentary protoliths of the Isua supracrustal rocks were deposited at $\sim$ 3700–3800 Ma, and underwent amphibolite-grade metamorphism before $\sim$ 3600 Ma. There is some ambiguity to the Isua chronology, since the uncertainty in the age determinations is typically $>$ 50 Ma. (see Hamilton *et al.,* 1977, for a recent summary of isotopic studies). However, these results clearly establish the antiquity of the Isua supracrustal belt and of the mainstage of regional metamorphism which affected it.

The Isua supracrustal belt is surrounded and locally intruded by *c.* 3750 Ma Amîtsoq orthogneiss, although most contacts between gneiss and supracrustal lithologies are strongly tectonized, obscuring original relationships. Deformation of the supracrustal rocks is generally intense: two periods of folding, the first one isoclinal, were followed by open folding responsible for the arcuate form of the belt (James, 1976; Nutman *et al.,* 1983).

The principal rock types in the Isua supracrustal belt include: (1) banded, black to green amphibolite with tholeiitic composition containing the assemblage hornblende-plagioclase-quartz; (2) massive to layered gray-green, Mg- and Al-rich leucoamphibolite with common garbenschiefer texture containing the assemblage hornblende-anthophyllite-chlorite-plagioclase-quartz; (3) quartz-rich chemical metasediments ranging from banded magnetite ironstone to types rich in carbonate (commonly with tremolite and only rarely diopside) or Fe-silicates (principally grunerite ± garnet ± actinolite); (4) clastic and volcanogenic metasediment (garnet-biotite schist and muscovite-biotite gneiss); and (5) talc schist and serpentinite with local dunitic and harzburgitic relics. As illustrated in figure 1, several of these lithologies form continuous units throughout the belt, but there is a remarkable amount of mixing among them such that units which are dominant in one part of the region may occur only as thin layers or inclusions elsewhere. This lithological heterogeneity occurs down to the scale of single hand-specimens, and the mineralogical diversity that we have encountered belies the apparent simplicity inferred from field observation.

Sample description

We have focussed our studies initially on the volcanogenic and clastic metasedimentary rocks since their bulk compositions may yield mineral assemblages which are useful for characterizing the conditions of metamorphism in the Isuakasia region. Moreover, these rocks should provide important information on the nature of the source regions of the original sedimentary material, possibly including pre-Isua crustal rocks.

The volcanogenic units are greyish-white, fine-grained, banded muscovite-biotite gneisses. These are described by Dimroth (unpublished manuscript) as felsic graywackes, and have an apparent rhyodacitic to rhyolitic composition. Unusually high K_2O (up to 10 wt %) and low Na_2O (< 0.10 wt %) in some samples (Bridgwater *et al.,* 1978), suggest the possibility of hydrothermal alteration.

These gneisses locally contain both conglomeratic and agglomeratic structures and fine-scale layering indicating that their protolith included weakly to thoroughly reworked felsic volcanic rock, including tuffs. In at least one coarse clastic horizon, angular fragments are well-preserved.

Petrographically, these rocks are relatively simple and monotonous. In addition to abundant muscovite and biotite, they contain substantial quartz and plagioclase, and less-commonly microcline. Trace amounts of allanite, zircon, epidote and carbonate are present in most samples. Retrogressive metamorphism appears to have caused local enrichment in white mica and carbonate as well as chloritization of biotite, although the textures are complex and commonly ambiguous.

This lithology probably occurs at more than one stratigraphic level in the belt (Nutman *et al.,* 1983). The presumed lower unit appears in the northeastern part of the supracrustal belt, whereas the upper unit extends from the east side of the lake Imarssuaq up to the margin of the inland ice. The two units are separated by a tectonic slide (Nutman *et al.,* 1983).

Above the north-eastern unit are a series of dark garnet-biotite schists comprising mafic to semi-pelitic to pelitic clastic metasediments. The contact between this unit and the underlying muscovite-biotite gneisses is gradational and characterized in a general way by meter scale interlayering of the two lithologies, although the details of the contact are more complex. The garnet-biotite schists are typically massive units, but include abundant sections which are layered on a cm to m scale. Variations in color, grain size, and proportions of minerals serve to distinguish individual layers.

Mineralogically, the garnet-biotite schists are highly variable. The most common type is a quartz-plagioclase-biotite-garnet-ilmenite rock. Primary muscovite is found in perhaps half of the samples. Staurolite occurs in five samples, and kyanite in two. Thus, the garnet-biotite schists are generally K- and Al-poor. Hornblende, with or without muscovite, is also present in some samples. Accessory apatite, zircon, sulfide, graphite, tourmaline, and ilmenite occur in nearly all samples investigated. In addition, epidote and carbonate may occur as accessory phases in more calcic types. The effects of retrogression are widespread, and include chloritization of garnet and biotite, and seriticitization of plagioclase and staurolite. The wide range of observed mineral assemblages and the apparent complete gradation among them, indicates that the protolith for the garnet-biotite schists was not a simple homogeneous aluminous pelite, but a mixture of several different types of sediment.

Mineralogy

We have analyzed the principal phases in each of 30 samples using electron microprobe techniques and found that mineral compositions reflect the variability implicit in sample

Table 1. Microprobe analyses of muscovite and biotite, Isua metasediments

	158538		167679		IS 629-7C	
	M	B	M	B	M	B
SiO_2	47.20	36.80	47.28	38.80	46.00	35.89
Al_2O_3	32.36	18.25	36.18	18.68	37.75	18.96
Cr_2O_3	0.03	0.04	0.00	0.00	0.07	0.34
TiO_2	1.10	2.39	0.44	1.35	0.20	1.60
MgO	1.73	12.87	0.81	14.04	0.50	8.91
FeO	1.79	15.23	0.81	13.20	1.25	20.76
MnO	0.02	0.13	0.00	0.09	0.00	0.00
BaO	0.05	0.08	0.00	0.00	0.82	0.26
Na_2O	0.22	0.05	1.12	0.16	0.67	0.14
K_2O	10.59	9.52	9.69	8.95	8.04	8.91
F	0.00	0.00	0.00	1.09	0.00	0.00
Cl	0.01	0.13	0.20	0.01	0.00	0.19
Total	95.10	95.46	96.33	95.91	95.30	96.06

M = Muscovite; B = Biotite

1. *GGU 158538 = Muscovite-biotite gneiss w/ microcline*
2. *GGU 167679 = Muscovite-biotite-kyanite schist w/ garnet*
3. *IS 629-7C = Garnet-biotite-staurolite schist*

Table 2. Microprobe analyses of garnet and staurolite, Isua metasediments

	GARNET				STAUROLITE	
	1	2	3	4	5	6
SiO_2	38.90	39.29	37.01	37.75	27.55	27.92
Al_2O_3	20.55	20.97	20.77	20.41	53.08	53.70
Cr_2O_3	0.14	-	0.02	0.11	0.19	0.32
TiO_2	0.13	0.03	0.05	0.02	0.48	0.65
MgO	0.49	2.50	0.95	1.76	1.23	1.25
FeO	17.55	28.26	39.16	37.65	12.53	14.04
MnO	11.36	8.85	1.44	0.35	0.03	0.05
CaO	12.19	2.91	1.75	3.19	0.00	0.00
ZnO	-	-	-	-	2.93	1.15
Total	101.32	102.80	101.14	101.24	97.98	99.08

1. *IS 706-1A Garnet-biotite-hornblende schist*
2. *GGU 167679 Muscovite-biotite-kyanite schist w/ garnet*
3. *IS 707-6 Garnet-biotite schist*
4. *IS 629-7C Garnet-biotite-staurolite schist*
5. *IS 629-7C " " " "*
6. *IE 726-2 Garnet-biotite-staurolite schist*

petrography. However, compositional variation within individual samples is rather limited and quite systematic-features that we interpret to be consistent with metamorphic recrystallization under largely equilibrium conditions.

The compositions of muscovite and biotite are highly variable, but systematically related to mineral assemblage. Micas occurring with staurolite or kyanite are more aluminous than those found with garnet alone, whereas the least aluminous micas coexist with potassium feldspar or hornblende. Similarly, Fe/(Fe+Mg) in biotite (Total range = 0.3–0.8) varies systematically with mineral assemblage. Representative analyses of muscovite and biotite from three samples are listed in Table 1.

Garnet is invariably rich in Fe(almandine) and poor in Mg(pyrope), but includes types with up to 40 per cent Ca(grossular) and Mn(spessartine). Despite an extremely large total range in measured compositions, garnet in individual samples has a much more restricted compositional range, and is only slightly zoned, with rims being more Fe-rich than cores. Garnet coexisting with staurolite is relatively Ca- and Mn-poor, whereas those found with hornblende are Ca-rich. Garnet that occurs with kyanite is exceedingly Mn-rich (~ 8–9 wt % MnO), which probably accounts for its presence in these samples. Representative garnet analyses from four samples are listed in Table 2.

Staurolite has a rather limited compositional range [Fe/(Fe+Mg = 0.85–0.90] and includes types with up to 3 wt % ZnO. Two analyses are listed in Table 2.

Plagioclase has an extremely large compositional range (An_2-An_{80}). However, variation in a single sample is smaller (~ 15 mole % An). There does not appear to be any systematic relationship between plagioclase composition and rock type.

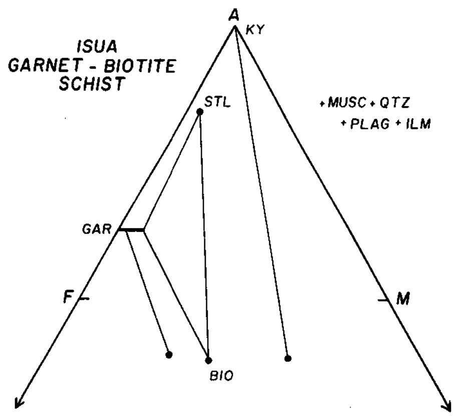

Fig. 2. Schematic phase relationships in Isua garnet-biotite schists.

Metamorphism

The important phase relationships for the Isua supracrustal rocks are illustrated in simplified form in figure 2, which is a standard AFM projection from muscovite in the presence of quartz, plagioclase and ilmenite. Many samples cannot be portrayed on this diagram due either to the absence of muscovite or the presence of non-AFM components such as Ca and Mn in garnet.

Of critical importance in assessing the nature of regional metamorphism of the Isua supracrustal belt are the assemblages biotite-kyanite-muscovite and biotite-staurolite-garnet-muscovite. The occurrence of these assemblages indicates that the Isua rocks were metamorphosed at Stl-Ky zone conditions, which is typical of Barrovian-type metamorphic environments such as the Scottish Dalradian or the Vermont Appalachians. Hence, there is nothing 'special' about the early Archaean metamorphism at Isua, since mineral assemblages that formed during this event resemble those found in Paleozoic metamorphic belts.

We have calculated temperatures of metamorphism from Fe-Mg partitioning between garnet and biotite using the experimentally calibrated results of Ferry & Spear (1978). As recommended by these authors, we have restricted ourselves to Ca- and Mn-poor assemblages. Temperatures obtained from garnet cores are 541 $\pm$ 43°C (1σ for mean of 44 pairs), which we associate with mainstage prograde metamorphism; temperatures obtained from garnet rims are lower (464 $\pm$ 39°C; 1σ for mean of 64 pairs), and probably reflect re-equilibration during retrogressive metamorphism.

Physical conditions for metamorphism of the Isua supracrustal rocks are illustrated schematically on figure 3, in which the boundaries for the aluminosilicate polymorphs are taken from Holdaway (1971). The temperature ranges shown in figure 3 are based on the Fe-Mg partitioning data discussed above, whereas the pressure of main-stage metamorphism is constrained to lie within the field of kyanite. We feel that T $\sim$ 550°C and P $\sim$ 5 kb is a reasonable estimate for the main-stage of regional metamorphism, and will apply these values in the following discussion.

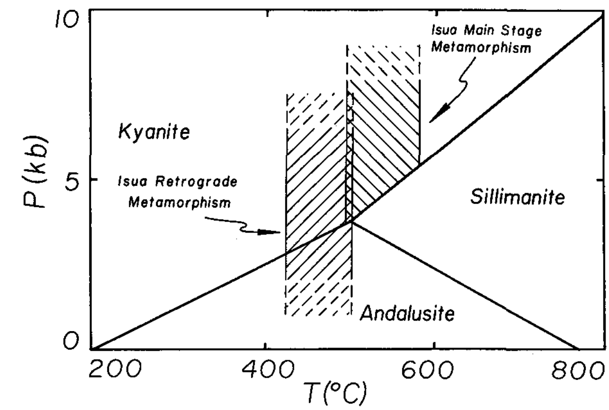

Fig. 3. Inferred *P-T* conditions for early Archaean metamorphism of the Isua supracrustal belt. Temperatures shown are based on the Fe-Mg partitioning data discussed in the text; aluminosilicate phase boundaries adapted from Holdaway (1971).

Discussion: metamorphism

Our estimates for the physical conditions during main-stage metamorphism of the Isua supracrustal belt (see above) are consistent with thermal gradients and depths of burial on the order of ~ 30–40°C/km and ~ 15 km respectively. These results permit the existence of substantially thickened early Archaean crust (> 30 km), and are consistent with the interpretations of Griffin *et al.* (1980) for metamorphism of the early Archaean Akilia association in the region south of Godthåb, ~ 150 km distant. However, our interpretations of the Isua metamorphism (as well as those of Griffin *et al.*), are critically dependent on the assumption that we are studying mineral assemblages that equilibrated in an early Archaean (> 3600 Ma) metamorphic event.

The isotopic studies alluded to previously support an early Archaean age for this metamorphism, or more appropriately, they do not argue against it. The key mineral phases used in our interpretation (i.e. kyanite, garnet, staurolite) are intergrown with fabric-forming micas. This fabric is common to all lithologies, including those without the indicator minerals, and predates the last open-folding of the belt. Moreover, the Ameralik dikes, which crosscut both the Amîtsoq gneiss and Isua supracrustal rocks, are neither deformed nor metamorphosed to the same degree as the supracrustals. Hence, the Isua main-stage metamorphism is definitely pre-Ameralik dike emplacement, at the youngest. Additional discussion of this question, based on detailed structural data, can be found in Nutman *et al.* (1983).

We interpret the growth of staurolite, garnet, kyanite, etc. as being part of an early pre-3600 Ma main-stage dynamothermal metamorphic event. The alternative explanation, that the fabric in all samples of garnet-biotite schist and muscovite-biotite gneiss is a result of later (though demonstrably ancient) deformation and metamorphism, is less appealing and probably incorrect. We prefer to ascribe to a later retrogressive matamorphism such features as the growth of chlorite and local inclusion-free Fe-rich euhedral rims on garnet.

Rare earth element (REE) geochemistry

Seven samples have been analyzed for eight REE using isotope dilution mass spectrometric techniques, and results are illustrated in figure 4A and 4B. All samples have REE concentrations that are slightly to moderately enriched with respect to chondritic abundances (~ 4–100X), and can be divided into two groups according to the general shapes of their REE patterns.

The first group is shown in figure 4A, in which 8 and 9 represent the 'matrix' and 'boulder' from the major conglomerate horizon within the muscovite-biotite gneiss unit near the shore of the lake Imarssuaq. Both samples show strong relative depletion of the heavy REE, and have small negative Eu-anomalies (Eu/Eu* = 0.95 and 0.72). The near equivalence of the REE in both 'boulder' and 'matrix' (except for a small dilution by REE-deficient phases such as quartz and carbonate) suggest derivation from the same source material. These data are in general agreement with results reported previously for samples form this locality by Moorbath *et al.* (1975).

The third data set shown in figure 4A (7A) is for a sample of kyanite-bearing gneiss. The REE pattern for this sample is remarkably parallel to those of the two muscovite-biotite gneisses – suggesting a possible relationship – although the kyanite-bearing gneiss has higher overall concentrations and a substantial negative Eu-anomaly (Eu/Eu* = 0.48). These REE data, together with the aluminous nature of the kyanite-bearing gneiss, suggest that its protolith was a strongly-weathered equivalent of the muscovite-biotite gneisses.

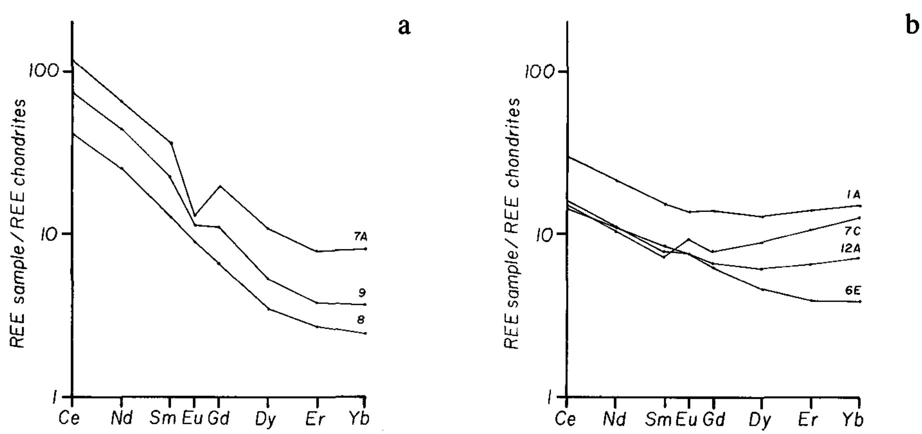

Fig. 4. Chrondrite-normalized rare-earth element (REE) patterns for Isua metasedimentary rocks.

(A) 7A (IS 629–7A), muscovite-biotite-kyanite gneiss;
8 (IS 717–8), muscovite-biotite gneiss ('conglomerate matrix');
9 (IS 717–9), muscovite-biotite gneiss ('conglomerate boulder').

(B) 1A (IS 629–1A), garnet-biotite-muscovite schist;
7C (IS 629–7C), garnet-biotite-staurolite-muscovite schist;
12A (IE 722–12A), garnet-biotite-staurolite-muscovite schist;
6E (IE 725–6E), garnet biotite-muscovite-epidote schist ('quartz-pebble conglomerate', ~ 35 per cent pebbles and 65 per cent matrix).

The second group (fig. 4B) includes three garnet-biotite schists (1A, 7C, 12A) and a quartz-pebble conglomerate with a garnet-biotite schist matrix (6E). All four samples are muscovite-bearing; 7C and 12A contain staurolite, and 6E has accessory epidote.

The four garnet-biotite schists have subparallel, moderately fractionated light REE, and small but variable Eu-anomalies. The heavy REE in three samples (1A, 7C, 12A) are fractionated with differing degrees of reversal in slope; 6E (the quartz pebble conglomerate) has relatively unfractionated heavy REE (i.e. Er and Yb).

Discussion: REE data

The REE data for the two muscovite-biotite gneisses and the kyanite-bearing schist (fig. 4A) are most easily explained in terms of dominance by a REE component from a single source. Variations in the level of the Eu-anomaly can be ascribed to weathering of feldspar and accompanying loss of Eu during original sedimentation.

Field occurrence, chemistry and sample petrography indicate that the Isua muscovite-biotite gneisses are volcanogenic graywackes derived from felsic volcanic rocks. The REE data (pattern shapes and concentrations) for the Isua samples (8 and 9; fig. 4A) are not unlike those reported for the felsic volcanic rocks from Archaean greenstone belts (e.g. Minnesota – Arth & Hanson, 1975; Zimbabwe – Hawkesworth & O'Nions, 1977). This similarity suggests that greenstone belt-like felsic volcanic rocks contributed material to Isua sediments.

We have already remarked on the gradational nature of the contact between the garnet-biotite schist and muscovite-biotite gneiss units. This suggests that felsic volcanic rocks should have contributed a component to the sedimentary protolith of the garnet-biotite schists. It is interesting to note in this regard that the kyanite-bearing schist occurs as an interlayer in garnet-biotite schist, but has REE characteristics of the muscovite-biotite gneisses (cf. fig. 4A).

We interpret the fractionated light REE in garnet-biotite schists (fig. 4B) as resulting from a contribution from felsic volcanic rocks. The other component(s) appear to have an overall depletion in light REE, and moderate enrichment in heavy REE. The presence of abundant garnet, biotite and hornblende in many of these samples suggests a contribution from mafic and/or ultramafic sources. Basaltic to komatiitic volcanic rocks found in Archaean green stone belts have REE characteristics (e.g. Hawkesworth & O'Nions, 1977) appropriate for such source material. In either case, the REE data indicate a mixed protolith for Isua garnet-biotite schists, consistent with interpretations based on field relationships and sample petrography.

Summary and conclusions

The Isua supracrustal belt contains the oldest rocks yet recognized on Earth, and as such, serves as the starting point for discussions on the evolution of the Earth's crust. Several lines of evidence, including radioactive element budgets and eruption of peridotitic komatiites, indicate higher heat production during the Archaean era. If this high heat production had been dissipated by conduction through the crust, then it would have left its mark on early Archaean metamorphic rocks. However, our petrological study of the Isua supracrustals seems to contraindicate high crustal heat flow. Therefore, our results are in conflict with models for Precambrian geological history that invoke thin hot sialic crust. Other mechanisms for removing 'excess' heat from the Earth during the early Archaean, such as more rapid convection and production of 'oceanic' crust, provide attractive, alternative explanations.

Our REE study of Isua metasediments suggest source regions for these rocks dominated by felsic to mafic (perhaps including ultramafic) volcanic rocks. This type of source terrain appears similar *lithologically* to Archaean greenstone belts. However, the Isua belt occurs in a classic Archaean high-grade gneiss terrain (cf. Windley & Bridgwater, 1971), and is stratigraphically and sedimentologically unlike a low-grade greenstone belt. This apparent dichotomy between the geological setting of the Isua belt, and the inferred source region for the clastic sediments within it, poses intriguing questions concerning the formation and growth of Archaean crust. At the present time, our preferred interpretation involves deposition of Isua sediments in a shollow basin adjacent to an emergent volcanic structure, followed shortly thereafter by syntectonic emplacement of Amîtsoq gneiss, which also could have provided a thermal source for metamorphism.

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