CONTINENTAL CRUSTAL COMPOSITION AND LOWER CRUSTAL MODELS.

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The composition of the upper crust is well established as being close to that of granodiorite (Table 1, col A). The upper crustal composition is reflected inthe uniform REE abundances in shales[1] which represent an homogenisation of the various igneous REE patterns (Fig. 1). This composition can only persist to depths of 10-15 km, for heat flow and geochemical balance reasons. The composition of the total crust is model dependent. One constraint is that it should be capable of generation the upper granodioritic (S.L.) crust by partial melting within the crust. One proposed composition is given in Table 1 Col. B. This composition is based on the "andesite" model, which assumes that the total crust has grown by accretion of island arc material. However, the relationship between the generation of island arc magmas and subduction zones implies that a plate tectonic regime was operative during the formation of the bulk of the continental crust. The evidence for such processes does not extend clearly beyond the late Proterozoic, by which time perhaps 80% of continental growth had probably been accomplished. Figure 3 shows a representation of the growth rate of the continental crust[1]. It can be noted that freeboard constraints, reflecting essential constancy of continental and oceanic volumes, clearly apply, in this type of model, well back into the Proterozoic. but are not necessarily valid in the Archean[2]

Archean upper crustal compositions, derived from REE sedimentary rock patterns, show a more basic upper crust than occurs in Post-Archean time[3]. The data are consistent with an upper crust derived from the bimodal basaltic - felsic Archean igneous suites. The bulk composition of the Archean crust appears to be only slightly more basic than the upper crust. There is only minor evidence of intracrustal melting and the production of K-rich granites with Eu depletion must comprise less than 10% of the exposed upper crust, from the sedimentary REE data, which only very rarely show Eu depletion in contrast to Post-Archean shales. On the model adopted here, the bulk of the crust has grown by 2.5 Ae and hence the bulk compositions may reflect that of the Archean bimodal basaltic - (tonalite-trondhjemite) suite. This is not very different in composition to that of the "andesite" model, except that it contains more Ni and Cr.

The composition of the lower crust, which comprises 60-80% of the continental crust, remains a major unknown factor for models of terrestrial crustal evolution. For the lower crust, we lack those large scale natural sampling processes (such as production of clastic sediments or loess) which have simplified the task of arriving at upper crustal compositions. Lower crustal samples are either random (as xenoliths in volcanic pipes) or from restricted outcrop areas of granulite terrains. The lower crust is almost certainly heterogeneous in detail, and may be further complicated by the presence of imbricate thrust sheets. One constraint is that the granodioritic (S.L.) rocks of the upper crust originated by partial melting within the crust, at depths of less than 40 km[4,5]. The lower crust must accordingly include many regions from which granitic melts (S.L.) have been extracted. If we recognize such material in the scattered samples available it will provide valuable limitations on the bulk composition of the crust.

Various approaches are possible. One is to model the bulk crust and calculate residual compositions following the extraction of granitic melts.

In Table 1 (cols. D,E), such calculations are presented for the extraction of a minimum granitic melt from proposed total crustal compositions allowing for 10 and 20% extraction of melt. A slightly different approach is to extract the known upper crustal composition (Col. A) from the model total crust, assuming that the upper crust forms 33% (Col. F) and 20% (Col. G) of the total. These four compositions indicate that the lower crust should contain compositions high in Al_2O_3, CaO, low in K_2O, with positive Eu anomalies ($Eu/Eu^* > 1$) and Nd_N/Sm_N ratios approaching chondritic values. Figs. 1 and 2 show the upper crustal REE patterns, and the predicted REE patterns for the lower crust.

A second approach is to examine the composition of dry granulite samples, formed at lower crustal temperatures and pressures to see whether they match the model calculations. Fyfe[5] has pointed out the importance of removal of H_2O and minimum granitic melts at the upper amphibolite grade of metamorphism, allowing the development of the anhydrous mineralogy typical of the granulite facies. Granulite facies rocks can be expected to show wide variations in composition due to several processes:
(A) Development of granulite facies mineralogy in dry source rocks from which a granitic melt has been extracted during amphibolite facies metamorphism[5].
(B) Dehydration of source rocks with loss of an hydrous fluid phase, resulting in granulites depleted in alkalies and U[6].
(C) Dehydration without partial melting or loss of trace elements (eg Jequie complex, Brazil)[7].
(D) Dehydration accompanied by loss of CO_2 (eg Southern India)[8]
(E) Subsequent retrograde metamorphism to produce amphibolite facies mineralogy in which any or all of the above processes have operated.

Accordingly, much complexity is expected, and shown by the random examples of lower crustal compositions available. In Table 1, Cols. H to Q, data are given for a suite of Lewisian[9] and Scourian granulites[10], granulite xenoliths from Lesotho[11,12] Bournac, France[13] and eclogites from Sauviat-sur-Vige, France[14]. These compositions are typified by high Al_2O_3, and CaO, low K_2O and positive europium anomalies. Fig. 4 shows the REE patterns. Figure 5 shows similar REE patterns in granulite xenoliths from alkali basalts from Central Hoggar, Algeria[15]. All these patterns display Eu enrichment, which accordingly is not uncommon in lower crustal material, although it is rare in upper crustal rocks. The major and trace element compositions tend to show much variation, as noted by Griffin et al[11] in their study of the Lesotho xenoliths. In this example, minerals such as garnet show Eu enrichment and the development of the bulk rock REE pattern, with positive Eu anomalies, clearly predates the granulite facies metamorphism. Accordingly, the extraction of granitic melts prior to granulite facies metamorphism will change the bulk rock composition, including development of the Eu enrichment (since the granitic melts are typified by Eu depletion). It should be noted that Nd/Sm ratios (Table 1) are lower than either upper crust or total crustal estimates, placing important constraints on isotopic models of the lower crust.

Condie et al[16] report REE patterns with strong Eu enrichment from Archean tonalitic gneisses in Southern India. Minor amounts of granitic gneisses and tonalites have probably developed from the tonalites. The origin of the Eu enrichment in the tonalites is ascribed to partial melting of a mafic source enriched in Eu. An alternative hypothesis, presented here, is that the present tonalite chemistry is residual and that the Eu enrichment has been generated by extraction of an Eu depleted granodioritic melt. Fig. 6 shows that a mixture of upper crust and the Southern Indian tonalites generates REE patterns which resemble normal Archean tonalites, with no Eu anomaly. The other trace element data are also consistent with the proposal that the Southern Indian tonalites are residual from earlier tonalitic parents. The REE patterns show a close resemblance to the Scourian data. The well studied Scourian succession has been the subject of varying interpretations. Pride and Muecke[10] note the following arguments in favour of extraction of partial melts (a) anhydrous nature of the complex (b) incompatible element depletion (c) narrow range of mineral compositions (d) major element trends unlike those of upper crustal igneous rock sequences (e) REE abundances are lower than those typical of upper crustal rocks, with enrichment of europium. Accordingly, there is much evidence for europium enrichment in lower crustal samples. Whether this is caused by melt extraction leaving Eu in residual plagioclase remains to be fully tested.

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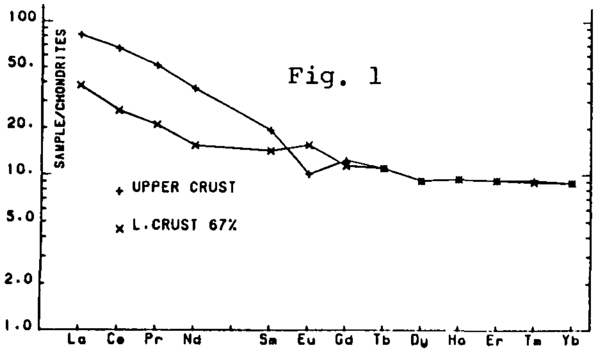


Fig. 1

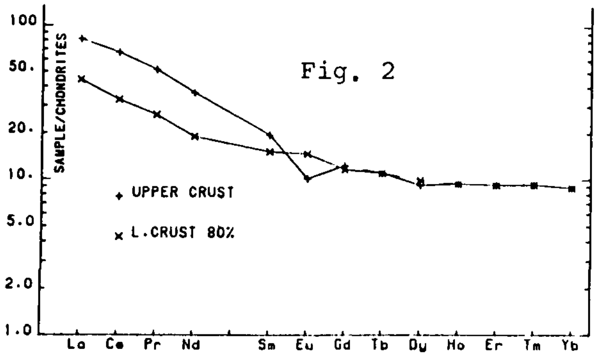


Fig. 2

Table 1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
SiO_2	66.0	58.0	76.5	53.4	55.9	54.0	56.0	61.3	50.6	52.2	52.6	57.5	66.5	65.3	49.5	48.5	41.9
TiO_2	0.6	0.8	0.1	1.0	0.9	0.9	0.9	0.56	0.77	1.3	1.2	0.96	0.54	0.51	0.70	0.55	0.23
Al_2O_3	16.0	18.0	12.9	19.3	18.6	19.0	18.5	18.1	17.9	19.5	24.5	19.5	16.5	16.2	18.5	19.7	18.0
FeO_T	4.5	7.5	1.1	9.1	8.2	9.0	8.3	5.4	8.8	9.2	5.9	5.7	4.0	4.2	6.6	5.5	13.3
MgO	2.3	3.5	0.1	4.4	3.9	4.1	3.8	2.4	8.2	5.9	2.0	2.8	2.0	2.3	8.3	8.7	27.6
CaO	3.5	7.5	0.7	9.2	8.3	9.5	8.5	5.1	9.4	8.7	7.9	6.6	5.4	5.3	14.5	14.8	5.3
Na_2O	3.8	3.5	3.8	3.4	3.5	3.4	3.4	4.9	3.3	2.7	4.0	4.9	4.1	4.3	1.6	2.0	0.65
K_2O	3.3	1.5	4.7	0.7	1.1	0.6	1.1	2.4	1.0	0.55	1.7	0.9	0.8	0.9	0.4	0.26	-
Eu/Eu*	0.64	1.0	0.45	1.35	1.12	1.22	1.10	1.97	2.4	1.46	3.14	1.69	1.29	1.34	1.31	1.50	1.70
Nd_N/Sm_N	1.88	1.41	1.72	1.14	1.29	1.09	1.26	1.79	1.24	-	-	-	-	-	1.29	1.26	1.24

A Upper Crust[1] B Total Crust[1] C Minimum melt composition[17] D Residue following 20% melt extraction from total crust

E Residue following 10% melt extraction F Predicted lower crust composition after extracting 33% upper crust Col. 1 from Col. 2 G Predicted lower crust composition following extraction of 20% upper crust.

H Lewisian granulites, Ave of 8[9] I Lesotho garnet granulites PHN 1670, 2533, 2852 and L.13[11] [12]

J Granulite xenolith, Bournac 3199[13] K Granulite xenolith, Bournac 3197[13] L Scourian granulite 65-16[10]

M Ibid, 67-34[10] N Ibid, 67-41[10] O Sauviat-Sur-Vige metagabbro 4736[14] P Ibid 4737 eclogite[14]

Q Ibid 4739 garnet peridotite[14]

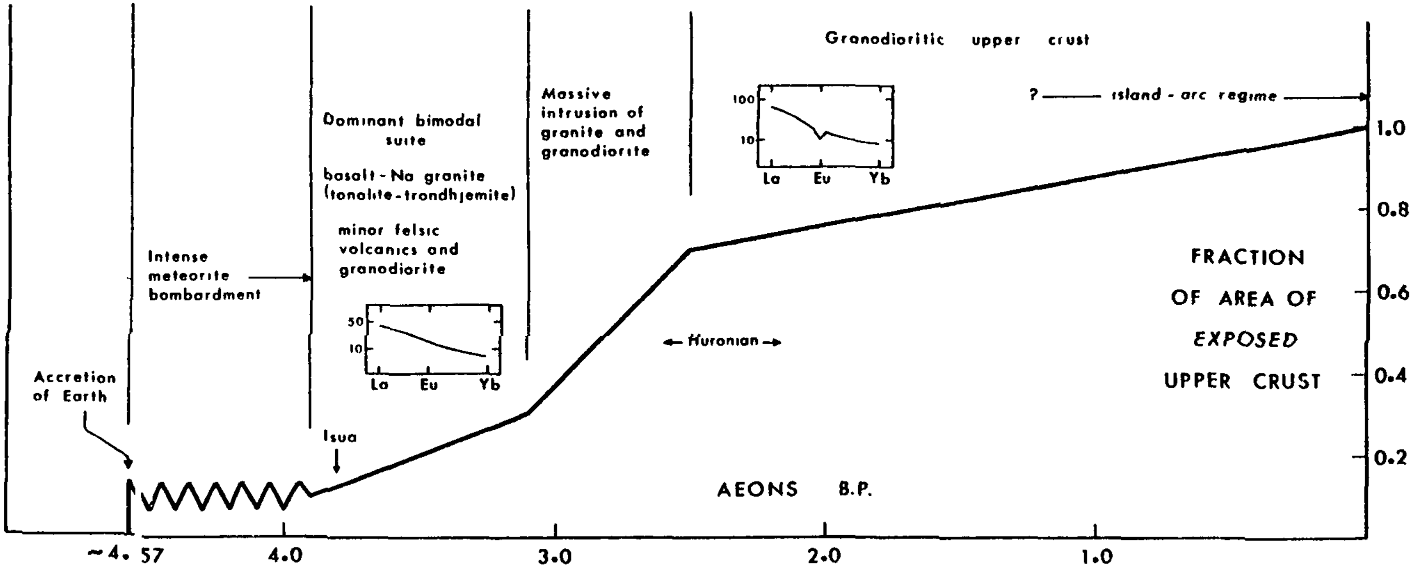
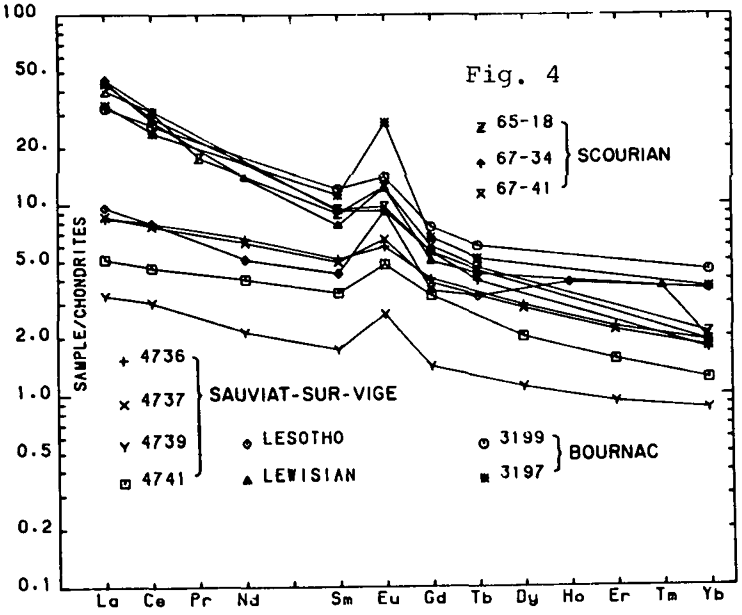


Fig. 3



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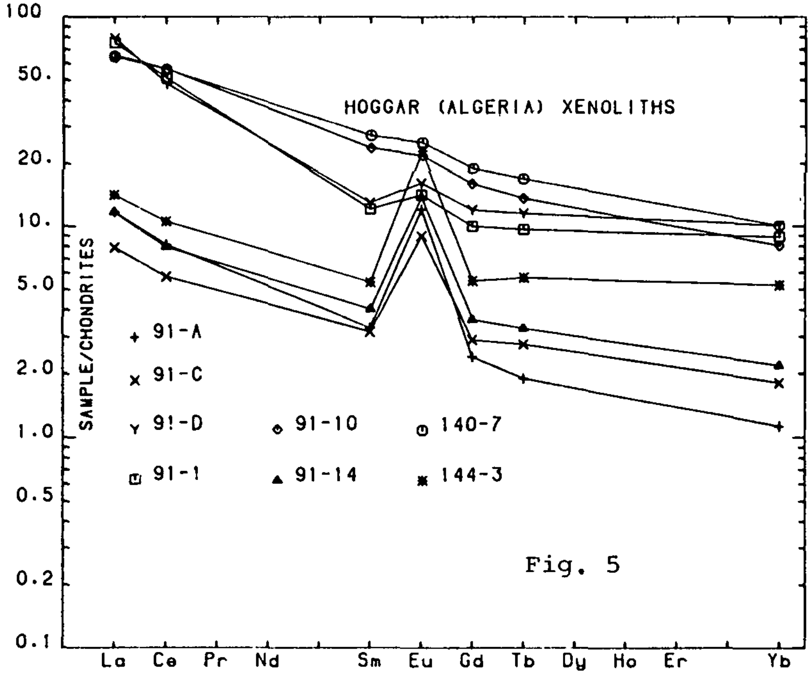

Fig. 5

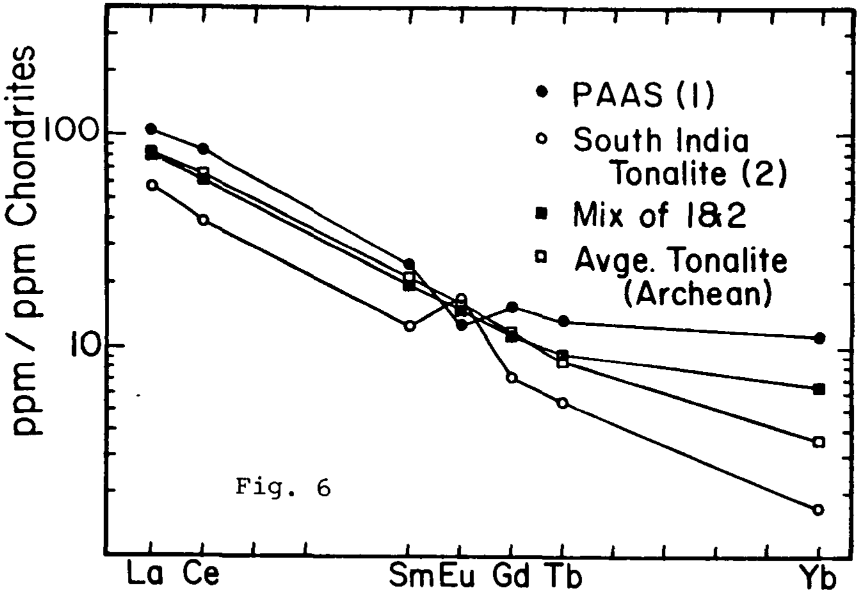

Fig. 6