CRUSTAL XENOLITHS FROM SOUTHERN AFRICA: CHEMICAL AND AGE VARIATIONS WITHIN THE CONTINENTAL CRUST

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The nature of the lower crust may be inferred from its physical properties, but it may only be sampled at surface exposures of rocks which are thought to have crystallised under suitable P/T conditions, or from xenolith suites included in kimberlites and alkali basalts. Heat flow and heat production studies indicate that the lower crust is relatively depleted in U, Th and K, but whether this is a primary or secondary (i.e. metamorphic) feature remains unresolved. In addition models for the evolution of the continental crust are highly sensitive to whether there are significant age differences between upper and lower crustal rocks in different areas.

REGIONAL GEOLOGY AND P/T ESTIMATES

The geology of southern Africa offers a rare opportunity to study the evolution of the continental lithosphere. The surface outcrop preserves a record of major orogenic and magmatic events ranging in age from 3600-30 Ma. Archaean rocks occur in cratonic nucleii surrounded by mobile belts containing varying proportions of new and reworked crustal material. After the last major orogenic episode and the stabilisation of the crust, both the crust and the underlying sub-continental mantle were sampled by widespread Karoo magmatism from ∿ 190 Ma, as xenoliths in kimberlites emplaced in the Cretaceous, and by mid-Tertiary alkaline volcanism.

Crustal xenoliths have been reported for many of the kimberlite localities in southern Africa. They comprise a cosmopolitan selection of the common rock types exposed on the surface, including a variety of granites, granite gneisses, amphibolites and metasediments, together with basalts and sediments of Karoo age. Of particular interest, however, is a suite of mafic to felsic granulites which preserve temperatures and pressures in the range 550-1000 °C and 4.5-20 kb respectively, and which appear to be restricted to pipes in the younger, Proterozoic belts around the margins of the Archaean[1-3]. To date no comparable high pressure granulite xenoliths have been reported from the cratonic areas, and the highest pressure rocks in our collection from the Kimberley area still record pressures of less than 10 kb. Available P/T data therefore suggest that mineral equilibration in lower crustal xenoliths took place at deeper levels, and also under lower geothermal gradients, in samples from kimberlite pipes off the craton[4].

MAJOR, TRACE ELEMENT AND ISOTOPE VARIATIONS

Amphibolite facies xenoliths from southern Africa are characterised by higher SiO_2, alkalis, and lower Fe and Mg than those of granulite facies. A striking feature of xenolith suites is how few acid to intermediate rock types have been reported with granulite facies mineralogy. The mafic granulite xenoliths have high and variable Sr, Ba and Pb, and REE patterns that range from LREE enriched to LREE depleted, but with no significant HREE depletion and common positive Eu anomalies. Thus plagioclase feldspar, rather than garnet, has influenced their trace element compositions, and the present garnet-bearing assemblages are metamorphic rather than igneous. If follows that the petrogenesis of such granulites should be argued on the basis of normative, rather than modal, mineralogy and they have been successfully modelled as cumulates with varying proportions of plagioclase, clinopyroxene and olivine[5]. Such a model interprets the low average Rb/Sr of 0.017 as a primary feature, and for appropriate U and Pb partition coefficients it predicts slightly low μ values consistent with present day Pb isotope ratios.

Radiogenic isotope studies have been carried out on whole rock xenoliths and a selection of separated minerals from four areas: northern Lesotho and eastern Namaqualand in the marginal Proterozoic mobile belts, and Voorspoed and Kimberley within the Kaapvaal craton. The first concern was the extent to which whole rock xenoliths may have interacted with host kimberlite. A large, gneissic xenolith (30 cm diameter) with a marked alteration rim ∿ 1 cm thick, was sawn into sub-samples ranging from 12 to 100 g. At the time of kimberlite emplacement $^{87}Sr/^{86}Sr$ in the four sub-samples = 0.7292 - 0.7352 and $^{143}Nd/^{144}Nd$ was indistinguishable analytically at 0.51059 ±2 (ε_{Nd} = -38), even though the host kimberlite had values of 0.7038 and 0.51270[6]. Thus entrainment in the kimberlite appears to have leached material from the outer portions of this xenolith without significantly changing the isotope ratios of even the altered rim.

Figure 1 summarises the present day ε_{Sr} and ε_{Nd} values of crustal xenoliths from southern Africa and compares them with those of granulite facies rocks world-wide reported by Ben Othman et al.[7], and the Lewisian[8]. Most of the Lesotho and Namaqualand granulite xenoliths are mafic, they tend to have low Rb/Sr but variable Sm/Nd, and hence now form near vertical ε_{Nd}-ε_{Sr} trends. In this they are similar to the granulites of the Lewisian, albeit not as old (mid-Proterozoic rather than Archaean), and they contrast with many of the granulites analysed by Ben Othman et al. (ibid.) which tend to have relative high ε_{Sr}.

Also illustrated on Figure 1 is a dashed curve linking the present day ε_{Sr}, ε_{Nd} values of crustal material of different ages with average Sm/Nd = 0.178 and Rb/Sr = 0.12 following Weaver and Tarney[9]. It emphasises the relatively low inferred Rb/Sr ratios of the Lewisian and south African granulites consistent with models in which the lower crust is characterised by relatively low alkali and heat producing element abundances. The amphibolite facies xenoliths have high ε_{Sr}, and particularly striking is the difference in ε_{Nd} and ε_{Sr} between the amphibolite and granulite facies xenoliths from Lesotho. The former yield Archaean model Nd ages, whereas the best estimate of the age of the latter is 1.4 ±0.1 Ga[5]

Pb-isotope analyses on selected Lesotho mafic granulites indicate that while many have low Rb/Sr ratios, these are not accompanied by strikingly low U/Pb or Th/Pb. Present day Pb isotope ratios plot just below the Pb-ore growth curve[10] with $^{206}Pb/^{204}Pb$ = 17.3-17.6, implying second stage μ values of ∿ 4.6. Thus although the Lewisian and south African granulites arguably have similar low average Sm/Nd and Rb/Sr ratios, they have significantly different U/Pb and Th/Pb, since the Lewisian is characterised by unusually unradiogenic Pb (inferred μ ∿ 2.6[11]).

AGE IMPLICATIONS

The isotope data reveal no significant differences in whole rock ages between granulite and amphibolite facies xenoliths at the same localities, either within the Archaean craton or in the east Namaqualand mobile melt. At Lesotho, however, which is situated on the craton/mobile belt margin, the granulite facies rocks yield Proterozoic ages whereas those from amphibolite facies rocks are Archaean. Only in very localised areas is there any evidence for whole rock age variations with depth in these segments of the continental crust.

Mineral age data in xenoliths are predictably complex, since they reflect the relationship between temperatures in the xenolith source regions and in the host kimberlite, and the blocking conditions for different decay schemes in different minerals. Amphibolite facies xenoliths tend to preserve Rb-Sr biotite ages similar to, and slightly less than biotite ages from the surface terrains. The two analyses on micas from mafic granulites, by contrast, yield biotite ages of 150-200 Ma: much younger than the probable age of metamorphism, but not totally reset at the time of kimberlite emplacement at ∿ 90 Ma. Nonetheless garnet from a mafic granulite preserves an Sm-Nd age of 770 Ma consistent with cooling after the metamorphic event at 1000-900 Ma recorded in the surface rocks. These preliminary data suggest that integrated mineral age studies on crustal xenolith suites may yield interesting new information on the thermal regimes, particularly after orogenic events, within the continental lithosphere.

DISCUSSION

Perspectives on the nature of the lower crust differ depending on whether they are based on near surface granulites, or on crustal xenolith suites from either kimberlites or alkali basalts. Although most attention is focussed on those aspects of the lower crust which are in some way chemically unusual, the most obvious being low U/Pb and Rb/Sr which with time will generate relatively unradiogenic Pb- and Sr-isotope ratios.

Mafic xenoliths from south Africa and Lewisian gneisses typify granulites which have distinctive trace element features, but generated by primary and secondary processes respectively. Moreover, in each case the trace element features appear to have been mineralogically determined.

Most studies of mafic granulites have concluded that they are of igneous origin[2,4], and the Lesotho rocks have been successfully modelled as liquid compositions and as related cumulates with varying properties of plagioclase, clinopyroxene and olivine[5]. The other way of generating distinctive trace element, and hence isotope ratios in the lower crust is by depletion during granulite facies metamorphism. Heat flow arguments and the many detailed studies on the Lewisian have encouraged speculation that depletion is ubiquitous in the lower crust. However, it is worth noting that most of the granulites analysed by Ben Othman et al. do not appear to have been depleted significantly by metamorphic processes, and the same is true of the granulites in the Indian Archaean[12] and of most mafic granulite xenolith suites[5,13]. Why then does granulite metamorphism sometimes result in the depletion of elements such as Rb, K, and U? The critical reaction appears to be the breakdown of mica in the presence of quartz to form an aluminium silicate, K feldspar and fluid. Rb, Th and U are released into the fluid, whereas K and Ba are partly retained in the K-feldspar, Sr in plagioclase and any amphibole. This is then accentuated for U with the release of more H_2O-rich and of intermediate to acid composition. Basic and/or dry rocks are unlikely to have these trace element ratios changed significantly during granulite facies metamorphism.

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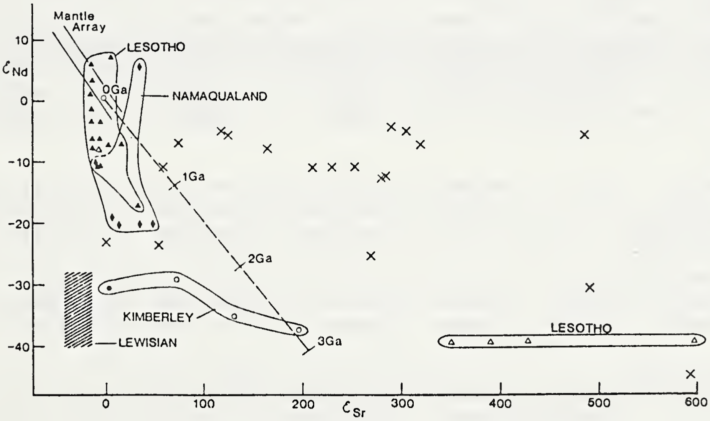

Figure 1 ε_{Nd} vs ε_{Sr} diagram. Crosses are data from Ben Othman et al.[7], the field for the Lewisian is after Hamilton et al.[8], filled symbols are granulite, open symbols are amphibolite facies rocks.