THE PETROGENESIS OF METASOMATISED SUB-OCEANIC MANTLE BENEATH SANTIAGO: CAPE VERDE ISLANDS.

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The Cape Verde Islands are the surface manifestation of a large oceanic plateau and are situated approximately 500 km west of the Senegalese coast of Africa. All nine major islands include highly undersaturated volcanic rocks including larnite normative melililites. Carbonatites are reported from 6 islands, including Santiago. The islands are situated near the pole of rotation of the African plate which has resulted in semi-continuous volcanism since the early Tertiary. Ultramafic xenoliths are common in volcanics on several Cape Verde Islands. This study is confined to Santiago where abundant xenoliths, up to 30 cm across, occur in Cenozoic olivine nephelinite, basanite and olivine basalt. The xenoliths comprise three lithological groups; 1) spinel lherzolite; 2) dunite; 3) wehrlite. The spinel lherzolite suite has allotriomorphic-granular textures. Olivine (Fo88-91) and orthopyroxene (Wo 0.5 En 91.4 Fs 8.1 to Wo 3.4 En 85.0 Fs 11.6) are anhedral deformed grains (up to 1 cm). Clinopyroxene (Wo 39.8 En 53.1 Fs 7.1 - Wo 48.5 En 46.7 Fs 4.8) up to 3 mm, is anhedral chrome-diopside and contains exsolved spinel blebs and orthopyroxene. Intergranular domains consisting of glass and euhedral to subhedral fine-grained olivine (0.4 mm), diopside and chrome spinel are relatively common. In addition some glassy zones which contain phlogopite and carbonate are interpreted as local partial melts probably formed by decompression.

The dunite suite has allotriomorphic-granular textures with anhedral and deformed olivine grains. Olivines have more Fe-rich compositions than the lherzolite-harzburgite suite (Fo 84-89). Wehrlites typically possess igneous textures with poikilitic clinopyroxene enclosing olivine and spinel. Deformed olivine has similar composition to the dunite suite. Clinopyroxene compositions are more iron-rich than those of the dunitic and harzburgite-lherzolite suites.

The Cape Verde lherzolite xenoliths show little petrological or chemical evidence of secondary alteration ($H_2O<1\%$). The lherzolites define an inverse relationship between CaO, Al_2O_3, TiO_2 and Na_2O with MgO content comparable to trends defined by other xenolith assemblages (e.g., Maaloe and Aoki, 1977). These chemical variations are accompanied by systematic changes in mineral compositions (e.g. Fo in olivine). Therefore, despite petrological evidence of metasomatism the lherzolites retain chemical evidence of melt extraction. Several trace elements (Co, Cr, V, Ni, Sc) show systematic variations as a function of MgO. By utilizing the known partitioning of Fe/Mg and Ni between peridotite residuals and melts it is possible to calculate the degree of melt extracted from a peridotite. The least metasomatized lherzolites require the extraction of between 15 and 28% melt. Calculated melt compositions are comparable to picritic compositions proposed as primary MORB compositions (e.g., Elthon, 1979).

The lherzolite xenoliths that have undergone the greatest apparent metasomatism have lower MgO and higher CaO and Na_2O . Notably there appears little increase in Al_2O_3 content with modal metasomatism which implies that either the fluid had low Al_2O_3, or that no Al_2O_3 bearing phases were produced. The presence of metasomatic amphibole, phlogopite, spinel and carbonate, indicates that the metasomatic fluid was highly silica undersaturated possibly melilititic or carbonatitic in composition. The dunite and wehrlite xenoliths have suffered minor metasomatism. Compared to the lherzolites xenoliths the dunites have higher Cr, FeO, Co and TiO_2 and lower Ni, Al_2O_3, Sc and V contents consistent with a cumulate origin. The major and trace element variations of the dunite-wehrlite suite establish they represent the cumulate products of a fractionating magma involving the precipitation of spinel, olivine and clinopyroxene.

The dunites have low REE contents, $(Yb)_n = 0.5$, that are characterized by slight LREE enrichment $(Ce/Yb)_n=4$. The wehrlites have higher REE abundances than the dunites (Yb_n 1-3). Wehrlite REE patterns are characteristic of many other pyroxene-rich xenoliths (Irving, 1980) being characterized by MREE enrichment with a maximum at Nd and relative depletion in La and Ce. This REE distribution is compatible with precipitation of a clinopyroxene-rich cumulate from LREE enriched magma (e.g., Irving, 1980). Using published REE partition coefficients it is possible to calculate the REE content of the magma parental to the pryroxenites. These calculations indicate $(Ce/Yb)_n$ ratios of parental magmas between 8 and 12 comparable to the least undersaturated Cape Verde magmas.

The lherzolite xenoliths have highly variable REE abundances $(Yb)_n$ 0.8-2, $(Ce)_n$ 0.9-19. Xenoliths depleted in terms of their major element abundances have the lowest HREE contents and are characterized by MREE depletion. Despite the major and trace element evidence for a residual origin the LREE are markedly enriched, $(Ce/Sm)_n$ 3.5-7.3 defining a "v" shaped pattern. In contrast the four xenoliths that show petrographic evidence for the greatest metasomatism have relatively simple LREE enriched patterns. As with the wehrlite samples, La and Ce enrichment is less marked than expected from the slope of the middle REE. The "v" shaped REE patterns of the lherzolites requires the involvement of two processes in their petrogenesis. HREE depletion and lower MREE abundances implies that the xenoliths originated as residues following partial melting. Subsequent LREE enrichment was superimposed on a LREE depleted pattern. Assuming that the lherzolite xenoliths were initially LREE depleted comparable to a MORB-like source it is possible to calculate the approximate REE composition of the material added to each xenolith. The calculated fluids have $(Ce/Yb)_n$ ratios greater than 50. This extremely high degree of LREE enrichment is only found in the most undersaturated melilitites and carbonatites among the Cape Verde volcanics. Xenoliths that have suffered the greatest degree of metasomatism record increased HREE abundances. If we again assume derivation from a MORB-like source, it is possible to estimate the nature of the metasomatic fluid. In contrast to the "depleted" lherzolite, the addition of melilitites or carbonatites would result in greater LREE enrichment than observed . Approximately 10% basanite addition is required to explain the REE patterns. The metasomatic fluids are less LREE enriched than those that produced the "depleted" xenoliths.

In order to fully evaluate the petrogenesis of Santiago ultramafic xenoliths the isotopic variations of the host volcanism must be known (see Davies et al. (1989) plus refs therein). Sr-Nd isotope ratios of the northern islands are less depleted than Atlantic MORB (0.7029-0.7032; 0.5130-0.5129) and on a Sr-Nd isotope diagram plot below the "mantle array" between MORB and HIMU islands. On a Sr-Nd isotope diagram the southern islands define a slope that is steeper than the "mantle array" extending from the field of the northern islands (0.7032-0.7039; 0.5129-0.5126). Rocks from Santiago have significant Sr-Nd isotope heterogeneity and encompass almost the entire range defined by the southern islands. Pb isotope ratios also form two geographically controlled groups. The northern islands define arrays that plot on the NHRL on both $^{207}Pb/^{204}Pb$ v $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ v $^{206}Pb/^{204}Pb$ diagrams with $^{206}Pb/^{204}Pb$ between 19.14 and 19.77. The youngest volcanism in the northern islands generally has the most depleted Sr-Nd-Pb isotope ratios. The southern islands have generally less radiogenic Pb isotope ratios ($^{206}Pb/^{204}Pb$ 19.44 to 18.74) and are characterized by relatively high ^{207}Pb and ^{208}Pb such that they plot above the NHRL. Although less extreme, the southern islands are characterized by Sr, Nd and Pb isotope ratios similar to Hawaii and Walvis Ridge (EMI) .

The Cape Verde xenolith suite records significant Sr-Nd isotope variation. On a Sr-Nd covariation diagram samples plot below the 'mantle array' with Nd isotope values ranging from close to Bulk Earth to almost MORB, 0.51269-0.5130. These data plot within the field defined by Cape Verde volcanism. The Santiago xenoliths most depleted in terms of major elements plot within the field of the northern Cape Verde Islands. The xenoliths have significant Pb isotope variation ($^{206}Pb/^{204}Pb$, 18.7-19.3) that extends to $^{206}Pb/^{204}Pb$ values less radiogenic than Cape Verde volcanism. In terms of a $^{207}Pb/^{204}Pb$ v $^{206}Pb/^{204}Pb$ diagram there is considerable overlap with the field defined by the southern islands. However, on a $^{208}Pb/^{204}Pb$ v $^{206}Pb/^{204}Pb$ diagram only the four xenoliths that have the greatest trace element enrichment plot in the field of the southern islands. The two "depleted" samples with the most extreme "V" shaped REE patterns plot on the NHRL with values close to or within the field defined by the northern islands.

An important conclusion to be made from the Sr-Nd-Pb isotope ratios of the xenoliths is that they are different to the Santiago volcanics proving that the xenoliths are not simply the product of, or the source to the volcanism. Mixing relationships on Sr-Nd-Pb diagrams establish that at least three isotopically distinct components are involved in the petrogenesis of the xenoliths; components from the northern and southern islands and a MORB-like component. Sr-Pb and Nd-Pb isotope variation diagrams show that over half of the xenoliths have isotope systematics distinct from the host lavas of Santiago. The two wehrlite xenoliths have Sr-Nd-Pb isotope systematics compatible with formation from the lavas of Santiago. Coupled with the major and trace element relationships, these isotope relationships prove that the wehrlites are products of Santiago volcanism. Lherzolite xenoliths with the greatest trace element enrichment (28,27) also have Sr-Nd-Pb systematics that are indistinguishable from Santiago volcanism suggesting that the trace elements of the lherzolites dominated by a metasomatic component derived from Santiago volcanism. Four xenoliths (29,42,41 and 34) represent mixtures between a MORB residue and Santiago volcanism. The mixing relationships on Pb-Pb and Pb-Sr isotope diagrams imply that both the precursor MORB source and the metasomatic component are isotopically heterogeneous such that no single mixing lines are evident. Two "depleted" xenoliths with the most LREE enrichment (30,39) appear to represent mixtures between MORB-like and northern island components. The extreme LREE enrichment and relatively high CaO imply that the metasomatic fluid was a carbonatite. No isotope data are available for carbonatites from the southern island. However, we expect that all Cape Verde carbonatites come from a similar source and hence have isotope systematics comparable to the northern Cape Verde islands.

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