NATURE AND EVOLUTION OF THE SUBCONTINENTAL MANTLE LITHOSPHERE BELOW SOUTHERN SOUTH AMERICA AND IMPLICATIONS FOR ANDEAN MAGMA GENESIS

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ABSTRACT

Ultramafic xenoliths found in the Pleistocene Pali-Aike alkali basalts, the southernmost outcropping of the Patagonian Plateau lavas of southern South America, include both garnet-bearing and garnet-free lherzolites, harzburgites, and orthopyroxenites. Mineral geothermometry and geobarometry indicate that these inclusions are derived from the subcontinental mantle lithosphere. The conditions of equilibration of the various types of inclusions indicate that infertile Mg-rich harzburgite is dominant at depths shallower than about 50 kilometers while at greater depths fertile garnet-lherzolites occur along with infertile harzburgites, and in the deepest portion of the subcontinental mantle lithosphere represented by the inclusions, between 70-80 kilometers depth, fertile garnet-lherzolites are dominant and infertile Mg-rich harzburgites are absent.

The Sr and Nd isotopic compositions of the inclusions are similar to oceanic basalts, with the isotopic compositions of the fertile garnet-lherzolites being similar to MORB. The lack of any phases with Sr and Nd isotopic compositions implying ancient enrichment event, such as have been reported from xenoliths derived from below the Precambrian cratonic regions of Africa, suggests that the accretion of the lithospheric mantle below southern South America was a relatively recent event, consistent with the Phanerozoic age of the crustal rocks in this region. The isotopic similarity of the Pali-Aike xenoliths with oceanic basalt indicates that prior to being removed from large scale convective overturn and stablized below the continental crust, this mantle material was evolving along with the current suboceanic mantle system. The main lithologic diversity observed in the Pali-Aike xenoliths probably formed during this pre-accretionary stage by heterogeneous removal of magma below an oceanic spreading center leaving increased proportions of infertile harzburgites in the shallower parts of the mantle. Fe-rich garnet-orthopyroxenites found as segregations within lherzolites and harzburgites may be recrystallized cumulates formed in magma conduits during this event. An even earlier event, at least 2-3 billion years ago, must have depleted the Pali-Aike garnet-lherzolites in Rb relative to Sr, and Nd relative to Sm, to allow the development of the MORB-like isotopic compositions observed in these xenoliths.

The subcontinental mantle lithosphere below southern South America has experienced a relatively recent enrichment in large-ion-lithophile elements by both a nonmodal "mantle metasomatic" event and by the introduction of phlogopite veins. The Sr and Nd isotopic composition of the phlogopite is within the field of mixtures of subducted oceanic basalts and sediments, suggesting that the phlogopite was formed from fluids derived by the dehydration of subducted oceanic crust. The isotopic compositions of the Pali-Aike alkali basalts lie along a mixing curve between the garnet-lherzolites and the phlogopite, suggesting that modal metasomatism of the subjacent mantle may have been the precursor for the generation of the basalts.

The deepest portions of the subcontinental lithosphere below southern South America may be considered as a "plum-pudding" type mantle, with plums of garnet-lherzolite + phlogopite, which together may yield an oceanic island type alkali basalt, in a pudding of MORB-source type garnet-lherzolite. A similar plum-pudding type mantle asthenosphere is proposed to be a suitable source for Andean orogenic magmas. The plums in this asthenosphere may be formed from primitive undifferentiated lower mantle, from subducted oceanic lithosphere not completely re-equilibrated within the upper mantle, or by the local delamination of the deepest portions of the subcontinental mantle lithosphere.

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RESUMEN

Los xenolitos ultramáficos, incluidos en los basaltos pleistocénicos de Pali-Aike, que constituyen los afloramientos más australes de las lavas patagónicas del sur de Sudamérica, corresponden tanto a lherzolitas con y sin granates, a harzburgitas, como a ortopiroxenitas. Estudios de geotermometría y geobarometría, basados en los análisis químicos de minerales, indican que estas inclusiones derivaron del manto litosférico subcontinental. Las condiciones de equilibrio de los distintos tipos de xenolitos indican que las harzburgitas magnésicas estériles son dominantes a profundidades inferiores a 50 km, mientras que a profundidades mayores coexisten lherzolitas fértiles de granate junto a harzburgitas estériles. En las partes más profundas del manto litosférico subcontinental, representadas por las inclusiones, entre 70-80 km de profundidad, las lherzolitas fértiles de granate son dominantes y las harzburgitas estériles están ausentes.

Las composiciones isotópicas de Sr y Nd de las inclusiones ultramáficas son similares a las de los basaltos oceánicos y, en particular, las composiciones de las lherzolitas fértiles de granate son similares a las de los basaltos de dorsales oceánicas. La ausencia de fases con composiciones isotópicas de Sr y Nd, indicativas de un antiguo episodio de enriquecimiento en elementos litófilos de gran radio iónico, como los que se han documentado en los xenolitos derivados de las regiones bajo los cratones precámbricos de Africa, sugieren que la acreción del manto litosférico bajo el extremo sur de Sudamérica fue un evento relativamente reciente, consistente con la edad fanerozoica de las rocas corticales de esta región. La similitud isotópica de los xenolitos de Pali-Aike con la de los basaltos oceánicos sugiere que, antes de ser removidos del flujo convectivo de gran escala y estabilizados bajo la corteza continental, este material del manto se encontraba evolucionando junto con el manto suboceánico actual. La mayor parte de las diversas litologías de los xenolitos de Pali-Aike, probablemente, se formaron durante la etapa preacrecionaria, por extracción heterogénea de magma bajo un centro de extensión oceánica, dejando proporciones crecientes de harzburgitas estériles en las zonas más superficiales del manto. Ortopiroxenitas ricas en fierro, que se encuentran como segregaciones dentro de harzburgitas y lherzolitas, posiblemente representen cúmulos recristalizados, formados en conductos magmáticos, durante este evento. Un episodio aún más antiguo, de hace por lo menos 2-3 mil millones de años, empobreció las lherzolitas de granate de Pali-Aike, en Rb con respecto a Sr y en Nd con respecto al Sm, para permitir el desarrollo de la composición isotópica similar a los basaltos de dorsales oceánicos observadas en los xenolitos.

El manto litosférico bajo el sur de Sudamérica ha experimentado un enriquecimiento relativamente reciente en elementos litófilos de gran radio iónico, por medio de un metasomatismo del manto no modal, y también, por medio de la introducción de venas de flogopitas. La composición isotópica de Sr y Nd de la flogopita está dentro del campo de mezclas entre los basaltos oceánicos y sedimentos subductados, lo que sugiere que la flogopita se formó de fluidos derivados de la deshidratación de la corteza oceánica subductada. La composición isotópica de los basaltos alcalinos de Pali-Aike cae a lo largo de la curva de mezcla entre lherzolitas de granate y flogopita, sugiriendo un metasomatismo modal del manto subyacente, probablemente precursor de la generación de los basaltos.

Las partes más profundas de la litósfera, bajo el extremo sur de Sudamérica, pueden ser consideradas como un manto tipo "plum-pudding", con "plums" de lherzolitas de granate + flogopita, las que, en conjunto, pueden producir un basalto alcalino tipo oceánico, en una masa (pudding) de lherzolitas de granate, capaz de generar basaltos como el de las dorsales oceánicas. Un manto astenosférico similar se propone como una fuente apropiada para los magmas orogénicos de los Andes. Los "plums" en esta astenósfera se pueden formar a partir del manto inferior primitivo, no diferenciado, desde litósfera oceánica subductada, no completamente reequilibrada en el manto superior, o por descamaciones de las partes más profundas del manto litosférico subcontinental.

INTRODUCTION

Mafic magmas are derived from the upper mantle, and "the origin and evolution of intermediate and silicic magmas depend upon mantle-derived basalts" (Hildreth, 1981). Clearly our understanding of the magmatic, as well as the tectonic evolution of the Andean Cordillera, or any part of the earth's crust depends, to a large extent, on our understanding of the upper mantle. An important source of information concerning the nature of the upper mantle are peridotite xenoliths transported to the surface in alkali basalts and kimberlites. This paper reviews the petrochemical characteristics, and their implication for upper mantle magmatic processes, of peridotite xenoliths found in late Cenozoic alkali basalts of Patagonia; in particular a suite of xenoliths from the Pali-Aike volcanic field which is the southernmost outcropping of the Patagonian plateau lavas (Figure 1; Skewes and Stern, 1979; Stern *et al.*, 1985).

The theory of plate tectonics has clarified many

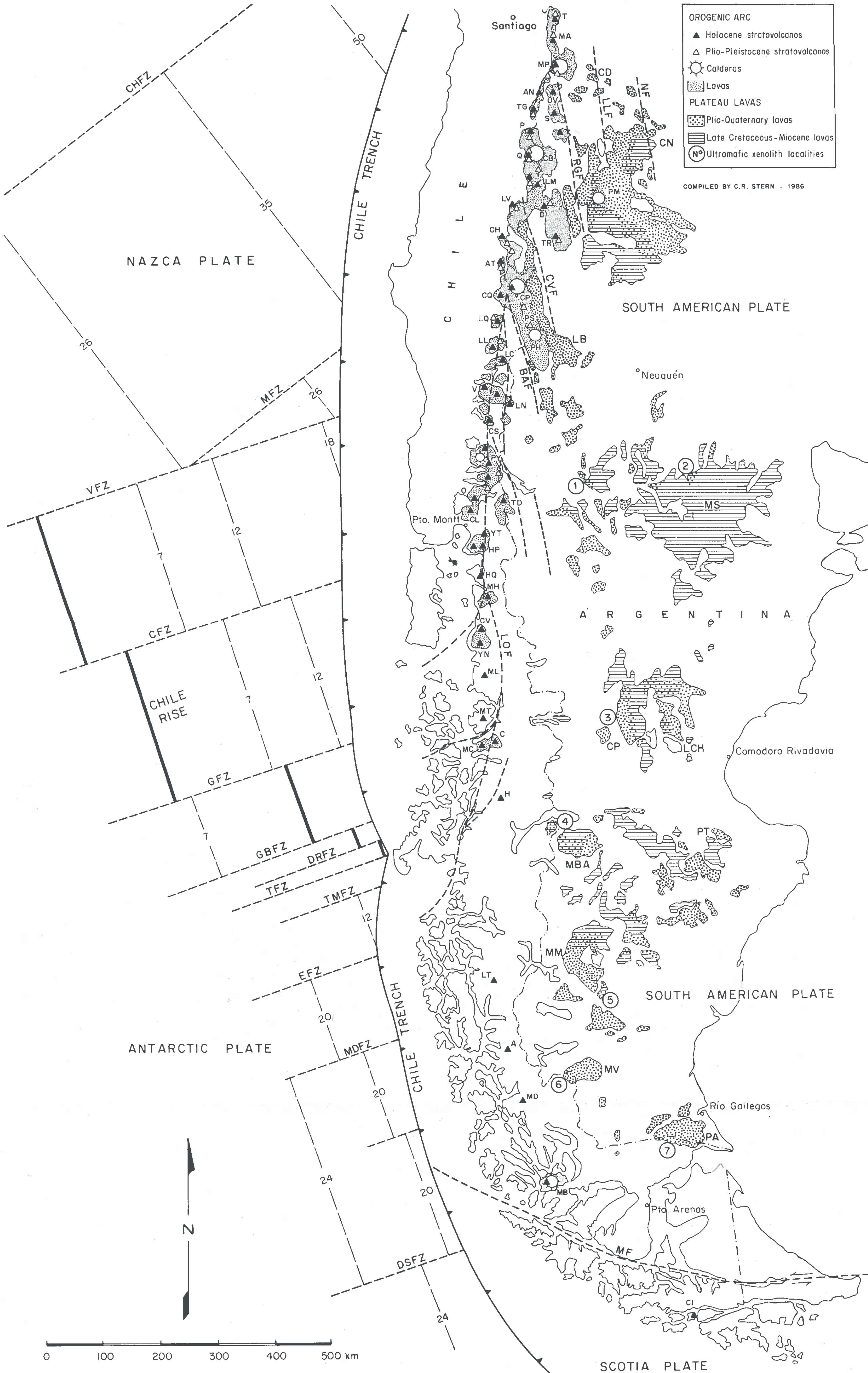

FIG. 1. Outcrop of Plio-Pleistocene as well as older units of the Patagonian plateau lavas in southern America, and the localities at which ultramafic xenoliths have been found within this volcanic province (Ramos *et al.*, 1982). The xenoliths discussed in the text are from locality No. 7 in the PA = Pali-Aike volcanic field. The figure also shows the location of the Plio-Pleistocene Andean orogenic arc and the major plates, plate boundaries, and continental megafaults along the southern margin of South America.

aspects of the structure and evolution of the upper mantle as well as of the crust. An important implication of plate tectonics is the distinction between relatively hot asthenosphere in which convective circulation may result in a general homogenization, and the relatively cool lithosphere in which small scale heterogeneities resulting from magmatic and tectonic events may be preserved in the mantle as they are in the crust. Also important is the distinction between oceanic lithosphere which is created from the asthenosphere at oceanic spreading centers and in general returns to the asthenosphere by subduction after a geologically relatively short time, and the continental lithosphere which, as is indicated by the record of crustal rocks, has a more complicated and extended evolution and once formed may persist for a geologically long time. Studies of ultramafic xenoliths have confirmed that the subcontinental mantle lithosphere, like the continental crust, is lithologically and chemically, in particular isotopically, very heterogeneous and differs in important respects from the suboceanic asthenosphere source of oceanic basalts (see for reviews, Harte, 1983; Menzies, 1983; Cohen *et al.*, 1984). Distinctive aspects of Andean magmas, and in general any magmas erupted in continental rather than oceanic regions, may be due either to the generation of melts within, or the interaction of asthenosphere derived melts with, not only the continental crust but the heterogeneous subcontinental mantle lithosphere as well.

The ultramafic xenoliths found in the Pali-Aike basalts are of more than merely regional interest because they include garnet-bearing peridotites which are only rarely found in alkali basalts. Garnet-peridotites are common in kimberlites, but kimberlites typically occur in tectonically inactive cratonic regions of Precambrian continental crust. In contrast, the Pali-Aike basalts are located in a region interpreted as a Phanerozoic accretionary terrain (de Wit, 1977) which is currently an area of back-arc magmatic activity. Also, kimberlites are usually of Cretaceous age or older while the Pali-Aike basalts were erupted less than 1 Ma ago so that some of the characteristics of the peridotite xenoliths they contain may be understood in terms of the neotectonics of the region. As described below, the ultramafic xenoliths found in the Pali-Aike volcanic field preserve evidence of a sequence, dating from early earth history to recent times, of mantle processes relevant to the understanding of Andean magmatism and the evolution of the continental lithosphere of southern South America.

PETROCHEMISTRY OF THE XENOLITHS

GENERAL PETROLOGY

In general, most of the xenoliths found in the Pali-Aike basalts are remarkably devoid of any effects of their transport, in the host basalt, from depths of as much as 80 kilometers to the surface, despite the fact that it was very likely that they were heated to over 1,200°C in the minimun of 5-20 hours that this must have taken. The xenoliths found within the Pali-Aike basalts include mafic granulites (Selverstone and Stern, 1983) and pyroxenites with Fe-Ti-rich augites which are similar to what are termed Type II xenoliths found in alkali basalts in other parts of the world (Wilshire and Shervais, 1975), but by far the most common xenoliths encountered in the Pali-Aike basalts, and the main focus of this review, are peridotites with Cr-rich diopsides similar to what are termed Type I xenoliths. The Pali-Aike Type I peridotites include (Figure 2) true lherzolites as well as harzburgites and minor dunites and pyroxenites, particularly orthopyroxenites. The orthopyroxene in the Type I orthopyroxenites, which occur both as small isolated xenoliths and as segregations, generally with poorly defined margins, within harzburgites and lherzolites, are more Mg-rich than orthopyroxenes in the Type II pyroxenites.

All the Type I peridotite xenoliths encountered in the Pali-Aike basalts have coarse granular textures. Some of the xenoliths exhibit a distinct fabric, but none are similar to the deformed porphyroclastic and mosaic-porhyroclastic types described from kimberlites. Mineralogically the peridotite xenoliths from Pali-Aike fall into two simply distinguishable groups; garnet-bearing and garnet-free. Garnet in the garnet-bearing peridotites varies from 1-25 modal percent in the lherzolites and harzburgites and from 1-60 modal percent in the orthopyroxenites. Spinel occurs in both garnet-bearing and garnet-free peridotites; it typically constitutes less than 5 modal percent of the xenoliths. Amphibole, which ranges from 0-5 modal percent, oc-

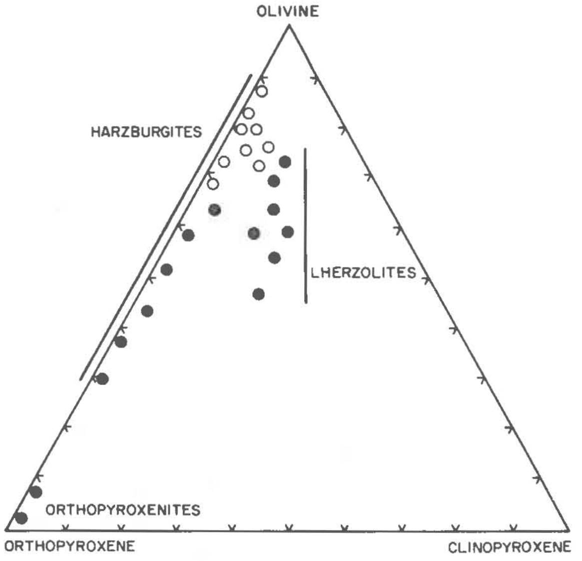

FIG. 2. Modal mineralogy of 15 garnet-bearing (solid circles) and 9 garnet-free (empty circles) Type I peridotite xenoliths from Pali-Aike for which mineral chemistry was also determined. The figure is not considered to be an accurate representation of the relative proportion of different peridotite types found at Pali-Aike, and olivine-rich xenoliths are certainly more abundant than indicated in the figure.

curs as disseminated grains similar in dimension to the other minerals in the xenoliths. Phlogopite occassionally occurs as very pale in color, isolated grains, but typically is observed as vein-like concentrations, with relatively sharp planar boundaries, of strongly pleochroic orange to golden color grains. Phlogopite has been observed in both garnet-free and garnet-bearing peridotites, but only in those xenoliths which mineral geothermometry indicate equilibrated at temperatures greater than 900°C. Ilmenite has been observed associated with the strongly colored vein phlogopite.

MINERAL CHEMISTRY

Olivines in the Pali-Aike peridotites vary from Fo_{92} to Fo_{85} (Figure 3), although this range does not include any analysis of olivine in dunites. Olivines in garnet-free harzburgites are more magnesian than in either lherzolites or garnet-harzburgites. Based on their olivine composition, the garnet-free harzburgites would be classified as Mg-rich while the garnet-harzburgites would be classified as Fe-rich (Harte, 1983).

Orthopyroxenes vary from En_{90} to En_{81} with the more Fe-rich orthopyroxenes being found in the orthopyroxenites. As with olivines, the garnet-free harzburgites contain more magnesian orthopyroxenes than the garnet-harzburgites. Orthopyroxenes in compound xenoliths of orthopyroxenite and lherzolite or harzburgites are always similar in composition in both parts of the xenolith. Al_2O_3 in orthopyroxenes in the Pali-Aike Type I peridotites ranges from 2.5-4.5 weight percent, consistent with the high pressure origin of these xenoliths.

Clinopyroxenes in the Pali-Aike Type I peridotites are Cr-rich diopsides with Cr_2O_3 between 0.8-1.7 weight percent, Al_2O_3 between 3.4-5.8 weight percent, and Na_2O between 0.8-2.2 weight percent. Garnets are Cr-pyrope with between 0.3-2.2 weight percent Cr_2O_3. Iron contents are higher and chrome contents lower in garnet in garnet-orthopyroxenites compared to garnet-lherzolites and garnet-harzburgites, but as with orthopyroxenes, garnets in different parts of orthopyroxenite-peridotite compound xenoliths are similar in composition.

As noted above, spinels occur in both garnet-bearing and garnet-free peridotites. Spinels in garnet-free peridotites include both high-alumina/low-chrome types as well as low-alumina/high-chrome types better referred to as chromites (Figure 4). Spinels coexisting with garnets are exclusively the latter low-Al/high-Cr type, and spinels in the garnet-free parts of garnet-free and garnet-bearing compound xenoliths are also always the low-Al/high-Cr

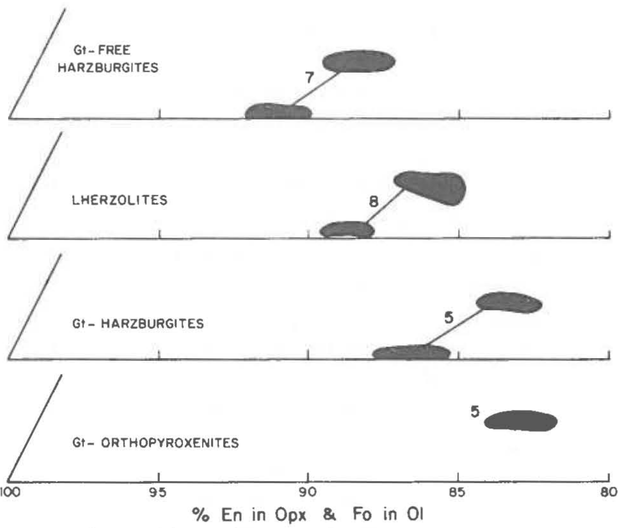

FIG. 3. Compositions of olivines and orthopyroxenes in various types of Type I peridotite xenoliths from Pali-Aike, plotted in the lower left Mg-rich corner of an enstatite (or forsterite)-wollastonite-ferrosilite (or fayalite) ternary diagram. Numbers next to tie-lines indicate the number of different samples analyzed for each rock type.

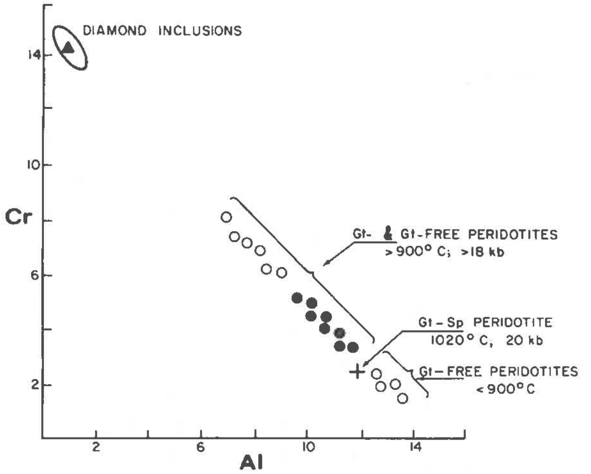

FIG. 4. Alumina *versus* chrome cation content of spinels in garnet-free (open circles) and garnet-bearing (filled circles) peridotites from Pali-Aike. The solid triangle is the composition of spinel inclusions within diamonds (Haggerty, 1979) and the cross (+) is the composition of spinels coexisting with garnet at 1020° and 20 kilobars in lherzolites from Australia (Ferguson *et al.*, 1977). Note that all the Pali-Aike garnet-free xenoliths that plot at higher Al contents than this point equilibrated at less than 900°C, while those that plot at higher Cr contents equilibrated at higher T and P as do the garnet-bearing xenoliths.

type. Mineral geothermometry and geobarometry suggest that the garnet-free peridotites which contain low-Al/high-Cr chromites equilibrated at greater depths than those with high-Al/low-Cr spinels (Figure 4).

Amphiboles are pargasites with K_2O between 0.9-1.4 weight percent, TiO_2 between 1.8-2.4 weight percent, and Cr_2O_3 between 1.4-1.7 weight percent. Pale disseminated phlogopite has relatively high MgO between 24.0-25.6 weight percent and Cr_2O_3 between 2.1-2.3 weight percent and relatively low FeO between 2.5-4.0 weight percent and TiO_2 between 0.6-0.7 weight percent. Strongly colored phlogopite associated with veins occasionally containing ilmenite have lower MgO between 20.8-22.2 weight percent and Cr_2O_3 between 0.5-1.2 weight percent and higher FeO between 5.0-6.1 weight percent and much higher TiO_2 between 5.3-7.0 weight percent. The strong color and pleochroism of these phlogopites is clearly due to the high TiO_2 content.

MAJOR ELEMENT CHEMISTRY

Garnet-lherzolites average $SiO_2 = 44.9$; $TiO_2 = 0.2$; $Al_2O_3 = 3.9$; $FeO = 8.3$; $Mg = 37.2$; $CaO = 3.1$; $Na_2O = 0.25$; and $Cr_2O_3 = 0.4$ weight percent. This average is similar, with respect to these element, to estimates of the primitive mantle, termed pyrolite, made by Ringwood (1967). The high calcium, alumina, and sodium content of these garnet-lherzolites is consistent with the high modal abundance of garnet and clinopyroxene that they contain. These garnet-lherzolites are certainly fertile with respect to basaltic component, but the amount of basalt that they could yield would be limited by the amount of TiO_2 and Na_2O that they contain. Also K_2O content in all the garnet-lherzolites is very low, below 0.1 weight percent.

The garnet-free peridotites have higher MgO and lower FeO, Al_2O_3, CaO, Na_2O and TiO_2 contents, consistent with their lower modal abundance of clinopyroxene and lack of garnet. The garnet-free peridotites as a group are infertile with respect to basaltic component, and in this respect resemble

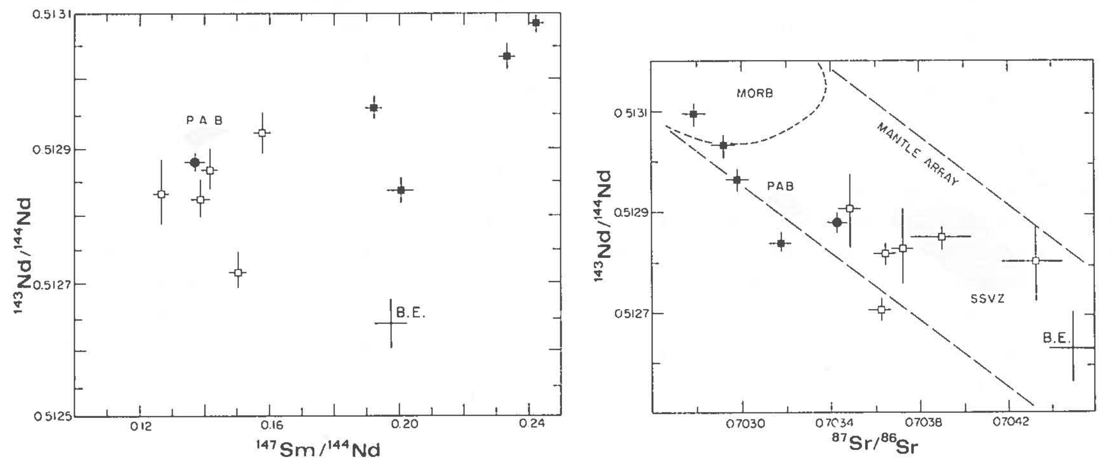

FIG. 5. $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ *versus* $^{147}Sm/^{144}Nd$ for garnet-lherzolites (solid squares), garnet-free peridotites (empty squares) and vein phlogopite (solid circle) from Pali-Aike. The figures also show the fields for the Pali-Aike basalts (PAB) and high-Al basalts (SSVZ) from central-south Chilean Andean volcanos (Hickey *et al.*, 1986), as well as the isotopic compositions of the Bulk Earth, MORB, and the mantle array of all oceanic basalts.

coarse granular Mg-rich xenoliths from other parts of the world.

ISOTOPE AND TRACE ELEMENT CHEMISTRY

Garnet-lherzolites have higher concentrations of Rb, Sr, Nd, Sm, and Zr than garnet-free peridotites, as well as higher Sm/Nd and $^{143}Nd/^{144}Nd$ and lower Rb/Sr and $^{87}Sr/^{86}Sr$ (Figure 5). The isotopic compositions of all the Pali-Aike xenoliths indicate time-intergrated depletion of Nd relative to Sm and Rb relative to Sr. The Sm/Nd and $^{143}Nd/^{144}Nd$ values of the fertile garnet-lherzolites from Pali-Aike are higher than most previously analyzed garnet-lherzolites from other localities in the world (Hawkesworth *et al.*, 1983). The isotopic compositions of these fertile garnet-lherzolites vary from values similar to mid-ocean ridge basalts to values with low $^{87}Sr/^{86}Sr$ compared to the mantle array defined by all oceanic basalts. The total range of isotopic compositions of all the inclusions encompasses the isotopic compositions of the Pali-Aike alkali basalts as well as of high-Al olivine basalt from orogenic volcanic centers in the southern Andes of central-south Chile (Figure 5). The samples as a group do not define an isochron.

Vein phlogopite has low $^{87}Sr/^{86}Sr$ despite having high Rb/Sr = 2, and the isotopic composition of this phlogopite lies on the low $^{87}Sr/^{86}Sr$ of the mantle array.

DISCUSSION AND CONCLUSIONS

STRUCTURE OF THE SUBCONTINENTAL LITHOSPHERE

The most obvious implication of the petrochemistry of the peridotite xenoliths found in the Pali-Aike basalts is that the mantle below southern South America is very heterogeneous mineralogically and chemically, consisting of various proportions of garnet-bearing and garnet-free lherzolites, harzburgites, and orthopyroxenites, all transected on occasion by phlogopite veins. These various lithologies are not in isotopic equilibrium.

Estimates of the depth of equilibration of the xenoliths in the mantle, prior to their transport to the surface, are provided by temperatures and pressures determined using mineral geothermometers and geobarometers. Temperatures determined using the two-pyroxene geothermometer described by Wells (1977) range from 830-1,080°C for garnet-free peridotites and from 900-1,150°C for the garnet-bearing xenoliths. With these temperatures, pressures determined for the garnet-bearing xenoliths on the basis of the Al_2O_3 content of orthopyroxenes (Akella, 1976) range from 23-31 kilobars, while a more recent geobarometer which accounts for the effects of Cr (Nickel and Green, 1985), yield pressures which range from 18-24 kilobars.

These estimates of the temperatures and pressures at which they equilibrated, combined with the coarse granular textures of the xenoliths, indicate that they represent samples of the subcontinental lithosphere down to a depth of approximately 80 kilometers. The estimated temperatures and pressures of equilibration of the xenoliths determine a geothermal gradient of about 10°C/km between 60-80 kilometers depth and a temperature of 1,150°C at a depth of 80 kilometers. This geothermal gradient and the temperature at 80 kilometers depth are both more similar to estimates of suboceanic thermal conditions than to those believed to exit below continental cratons with low heat flow, and are considered appropriate for the tectonically active area of back-arc magmatic activity in which the Pali-Aike basalts occur.

Figure 6 presents a schematic cross-section through the continental lithosphere below southern South America based on the xenoliths found in the Pali-Aike basalts. A significant feature of this cross-section reflects the observation that some of the infertile garnet-free xenoliths have equilibrated at similar or higher temperatures than some of the garnet-bearing xenoliths. Since temperature is expected to increase with depth, this indicates that the distribution of the two groups of xenoliths is not strictly related to depth in the mantle. No garnet-peridotites from Pali-Aike yield temperatures of equilibration less than 900°C. indicating that garnet does not occur in the upper part of the subcontinental mantle, consistent with the experimentally well documented pressure-induced transition from Al-Cr-spinel-peridotite at relatively shallow depths in the mantle to garnet-peridotite at greater depths. However, garnet-free peridotites do apparently occur within the lower subcontinental mantle lithosphere at depths below the Al-Cr-spinel-peridotite to garnet-peridotite transition. This is confirmed by direct observation of compound gar-

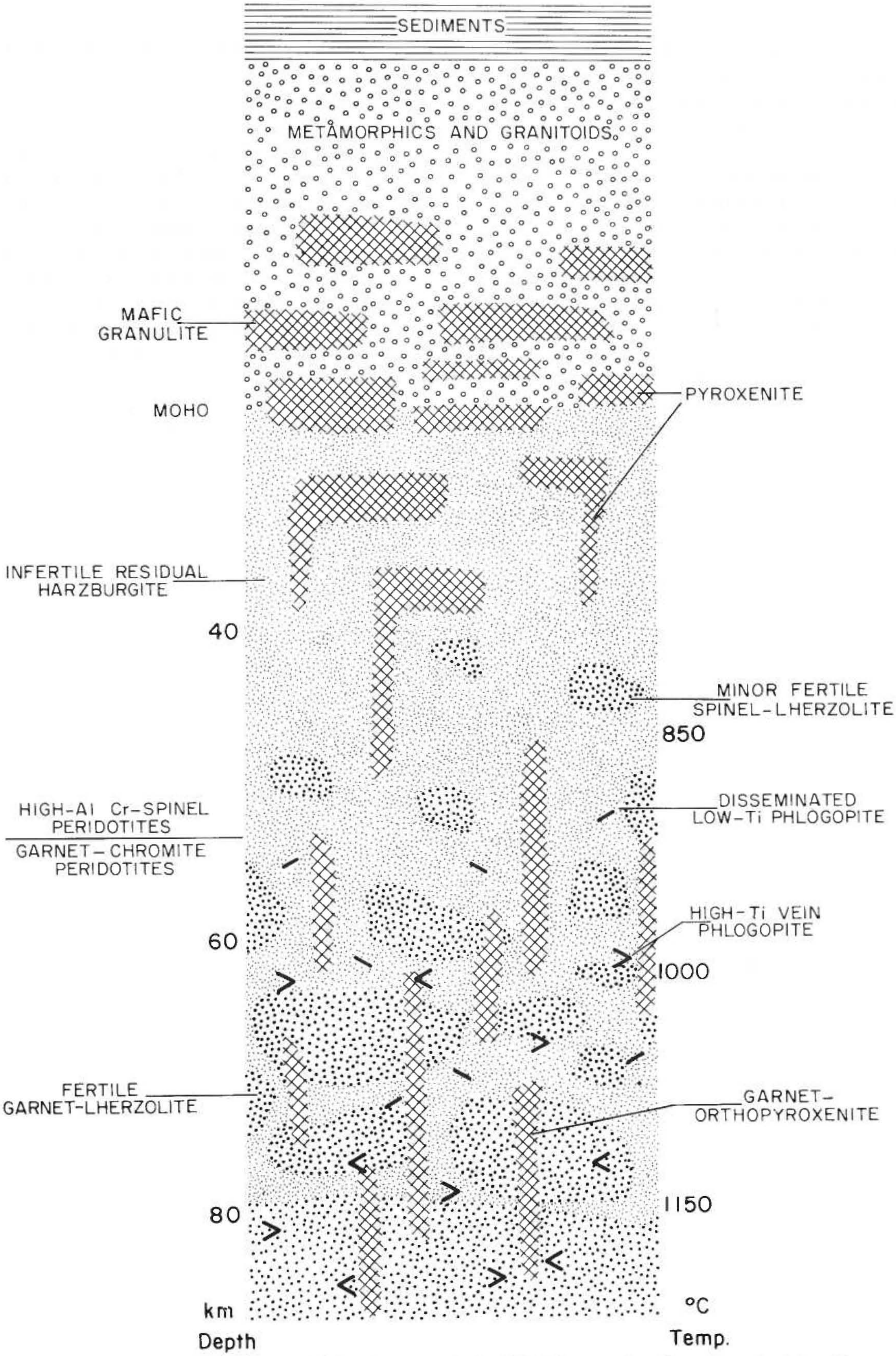

FIG. 6. Cross-section of the continental lithosphere to a depth of 80 kilometers based on observed relationships among the xenoliths in the Pali-Aike basalts as outlined in the text.

net-free and garnet-bearing peridotite xenoliths. Spinels in both garnet-free and garnet-bearing peridotites that have equilibrated at depths greater than the Al-Cr-spinel-peridotite to garnet-peridotite transition are always chromites (Figure 4, 6). No infertile Mg-rich garnet-free xenoliths with temperatures of equilibration greater than 1,080°C have been encountered among the Pali-Aike peridotites which suggests that the proportion of fertile garnet-lherzolites increases in the deeper portions of the subcontinental mantle lithosphere.

Mafic granulite xenoliths found in the Pali-Aike basalts crystallized within the lower continental crust (Selverstone and Stern, 1983). Type II pyroxenites may have formed at similar or greater depths. No xenoliths have been found at Pali-Aike that are unequivocally derived from the lowest part of the lower continental crust or upper parts of the subcontinental mantle between 20-40 kilometers depth. The presence of Type II pyroxenites and infertile harzburgites in this portion of the lithospheric cross-section (Figure 6) is inferred from cross-sections constructed on the basis of xenolith suites from other parts of the world. The deeper part of the lithosphere cross-section contains infertile garnet-orthopyroxenites and garnet-harzburgites as well as garnet-free-harzburgites and garnet-lherzolites. Also, both vein and disseminated phlogopite occur in the deepest part of the subcontinental mantle lithosphere, being encountered only in xenoliths that equilibrated at temperatures above 900°C.

EVOLUTION OF THE CONTINENTAL LITHOSPHERE

Lithologic and chemical variations observed in mantle xenoliths from other parts of the world have been explained by multiple depletion and enrichment events (see for reviews, Harte, 1983; Menzies, 1983). The fact that the xenoliths from Pali-Aike do not define an isochron suggests that the lithologic and isotopic heterogeneities inferred for the subcontinental mantle lithosphere below southern South America developed by a sequence of such events. These events may have occurred in part prior to and in part after this section of the mantle was stabilized below the continental crust and thus isolated from large scale convective overturn. The lack of any phases with Sr and Nd isotopic compositions suggesting the preservation of heterogeneities resulting from ancient enrichment events (Figure 7), such as have been reported from ultramafic xenoliths derived from the subcontinental lithosphere below the Precambrian craton of Africa (Cohen *et al.*, 1984), indicates that the accretion of the continental lithosphere below southern South America was a relatively recent event. This is consistent with the Phanerozoic age of the crustal rocks in this region. The isotopic similarity between the Pali-Aike xenoliths and oceanic basalts suggests that prior to being stabilized below the continental crust, this mantle material must have been evolving along with the current suboceanic mantle system.

The Pali-Aike garnet-lherzolites clearly resemble the type of mantle material from which mid-ocean

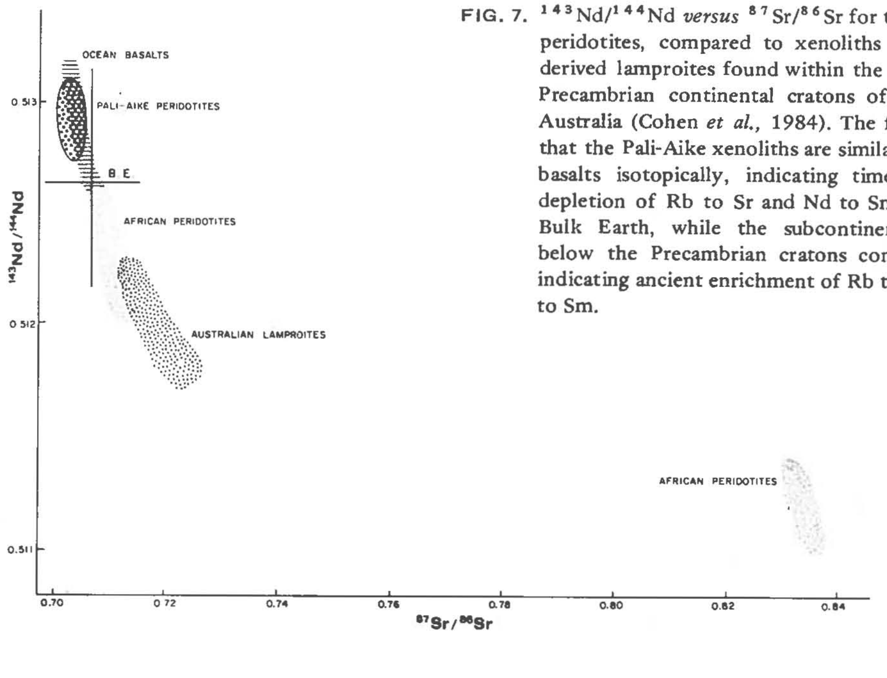

FIG. 7. $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$ for the Pali-Aike peridotites, compared to xenoliths and mantle derived lamproites found within the limits of the Precambrian continental cratons of Africa and Australia (Cohen *et al.*, 1984). The figure shows that the Pali-Aike xenoliths are similar to oceanic basalts isotopically, indicating time integrated depletion of Rb to Sr and Nd to Sm relative to Bulk Earth, while the subcontinental mantle below the Precambrian cratons contain phases indicating ancient enrichment of Rb to Sr and Nd to Sm.

ridge basalts are derived; fertile with respect to basaltic component but with MORB isotopic compositions indicative of time-intergrated depletion of large-ion-lithophile elements. Just like MORB-source mantle, the garnet-lherzolites from Pali-Aike must have experienced an event, at least 2-3 billion years ago, that depleted them in Rb relative to Sr and Nd relative to Sm. This event might have involved 1) extraction from the primitive undifferentiated mantle of a liquid resembling kimberlite formed by a small degree of partial melting (Wood, 1979; Menzies, 1983); 2) gradual removal of large-ion-lithophile elements out of the mantle into the crust by melting of mantle-derived oceanic basalts being subducted below Archean continental margins in much the way the upper mantle/continental crust system is currently evolving (see for review, O'Nions *et al.*, 1979); or 3) removal of melt from a garnet- and clinopyroxene-rich cumulate derived from an early terrestrial magma ocean formed by 15-20 percent partial melting of the whole mantle in association with the accretion of the earth or formation of the earth's core (Anderson, 1981).

The main lithologic variations observed in the Pali-Aike xenoliths probably formed by heterogeneous removal of basaltic magma resulting in infertile Mg-rich residual harzburgites being intermixed with unmelted, still fertile, garnet-lherzolites. Fe-

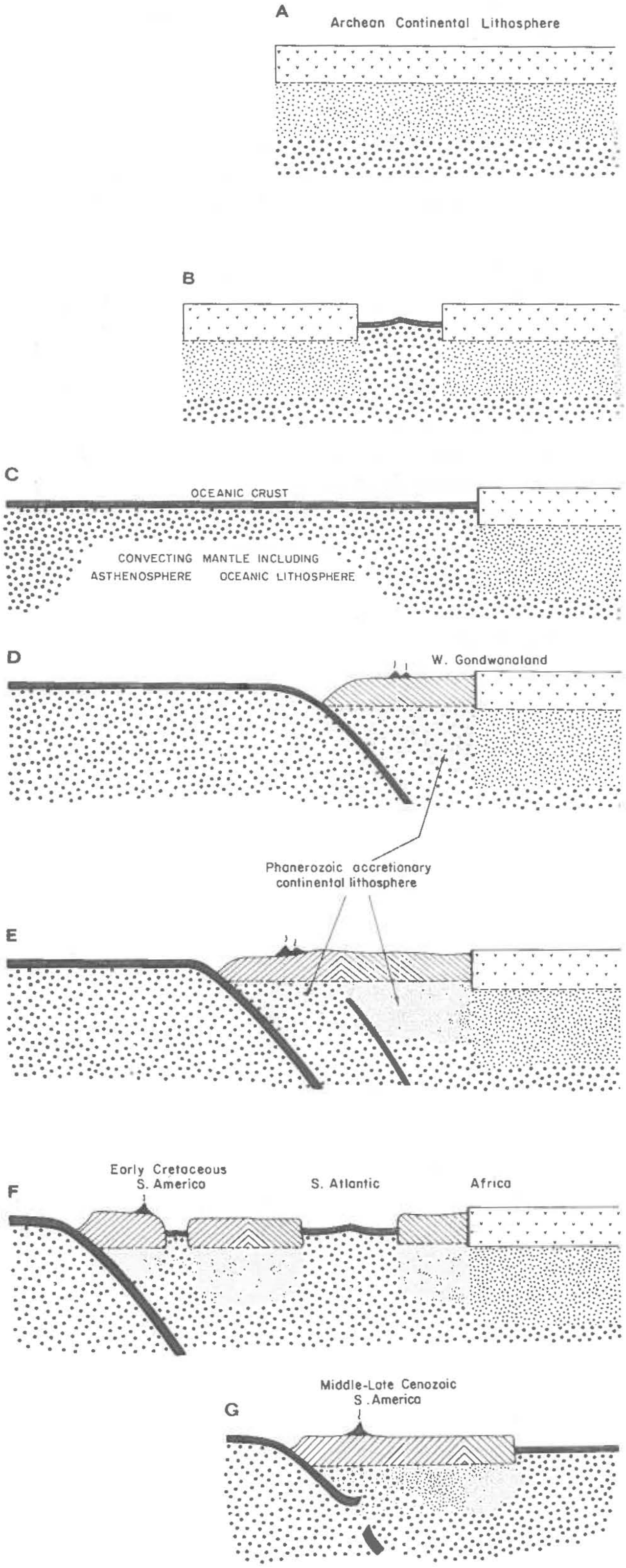

FIG. 8. Schematic cartoon illustrating possible events of significance for the evolution of the southern South American continental lithosphere. An Atlantic type continental margin along the margin of the Archean continental craton (A, B, C) changed to a Pacific type margin in the late Precambrian, and the continental crust of southern South America formed by accretion in arc-trench terrains along the western margin of this Gondwanaland craton during the Paleozoic (D,E; de Wit, 1977). The subcontinental mantle lithosphere may have been isolated from large scale convective overturn during this period thus preserving lithologic heterogeneities inherited from its creation at an oceanic spreading center. Alternatively, remobilization of the Paleozoic subcontinental lithosphere during either 1) the Mesozoic breakup of Gondwanaland (F), which was associated with rifting, back-arc basin development, and widespread bi-modal volcanism in southern South America (de Wit, 1977); or 2) the subduction of the Chile Rise below southernmost South America in the late Cenozoic, may have resulted in the formation of a new subcontinental mantle lithosphere with lithologic heterogeneities related to the heterogeneous extraction of basaltic melt during these events.

rich but infertile garnet-orthopyroxenites may represent recrystallized cumulate phases formed in magma conduits associated with this event, and Fe-rich garnet-hazburgites could represent a more advanced stage of recrystallization and reequilibration between such cumulates and residual garnet-free harzburgite. High temperatures must have been required for this event to produce the large percentage of melt extracted as indicated by the refractory mineralogy and mineral chemistry of residual harzburgites and dunites. This event may have occurred below an oceanic spreading center when the mantle now stabilized below southern South America was still involved in large scale upper mantle convective overturn. The isolation of the subcontinental lithosphere from active convective overturn in the mantle which then preserved these heterogeneities may have occurred in the Paleozoic in association with the accretion of the arc-trench gap materials, which now form the crustal rocks of southernmost South America (de Wit, 1977), to the western margin of Gondwanaland (Figure 8). This scenario is supported by isotopic studies of the Patagonian plateau lavas which have yielded pseudo-isochrons of 500-600 million years favoring the Paleozoic as the age of isotopic equilibration of the mantle source regions of these basalts which may be the deepest parts of the subcontinental lithosphere (Hawkesworth *et al.,* 1979; Stern *et al.,* 1983). Alternatively, the extraction of large volumes of basaltic melt from the subcontinental mantle below southern South America may have occurred in the Mesozoic when rifting of South America from Africa was associated with widespread bimodal basaltic and silicic volcanism (Figure 8). The formation of the mafic granulite xenoliths found in the Pali-Aike basalts has been attributed to this event (Selverstone and Stern, 1983).

A feature of the xenoliths that developed after this material was stabilized below the continental crust is the observed decoupling of trace element compositions and isotopic ratios such that the xenoliths have Sm/Nd similar to or less than Bulk Earth but isotopic compositions implying time-integrated depletion of Nd relative to Sm (Figure 5). This effect has been observed in many suites of xenoliths from other parts of the world and has been explained by "mantle metasomatism" which introduces large-ion-lithophile element enriched fluids into the mantle without modifying its mineralogy (see for review, Menzies, 1983). The timing of this mantle enrichment event is uncertain, but the high Rb/Sr and low $^{87}Sr/^{86}Sr$ of vein phlogopite indicates that the modal metasomatic event responsible for the emplacement of these veins occurred relatively shortly before the xenoliths were transported to the surface in the Pali-Aike basalts. The "mantle metasomatism" responsible for the decoupling of trace element and isotopic compositions may have occurred by the recrystallization and gradual dispersal of earlier generations of such phlogopite veins, the evidence for which is now preserved as disseminated low-Ti phlogopite grains.

The veins phlogopite, and by implication the fluids that they were deposited from, are isotopically distinct from the Pali-Aike basalts and perhaps not derived directly from the magmas that developed into the basalts. The isotopic composition of the phlogopite lies on the low $^{87}Sr/^{86}Sr$ side of the mantle array as do mixtures of oceanic sediments and mid-ocean ridge basalts (Hickey *et al.,* 1986). The fluids from which the phlogopite was deposited may have been derived from the dehydration of such mixtures subducted below the western continental margin of South America. Such fluids may pass through the asthenosphere wedge without precipitating mineral phases until they enter the cooler lithosphere (Figure 9) or may only be introduced into the lithosphere, particularly lithosphere well east of the oceanic trench such as below the region of Pali-Aike, during periods of very low angle subduction such as may have occurred below southern South America just after the subduction of the southern extension of the Chile Rise during the mid-late Cenozoic.

IMPLICATIONS FOR ANDEAN MAGMA GENERATION

Hickey *et al.* (1986) have given persuasive arguments for the importance of oceanic island basalt type source mantle in the generation of recent Andean orogenic magmas, particularly those from central-south Chilean stratovolcanos. The alkali basalts from Pali-Aike are compositionally similar to oceanic island alkali basalts and Futa and Stern (in press) have shown that Andean orogenic magmas may be formed from a mantle with geochemical characteristics similar to the source region of the Pali-Aike basalts. The Pali-Aike basalts clearly formed at greater depths than the mantle section that they sampled on route to the surface. This is confirmed by the temperatures of equilibration of

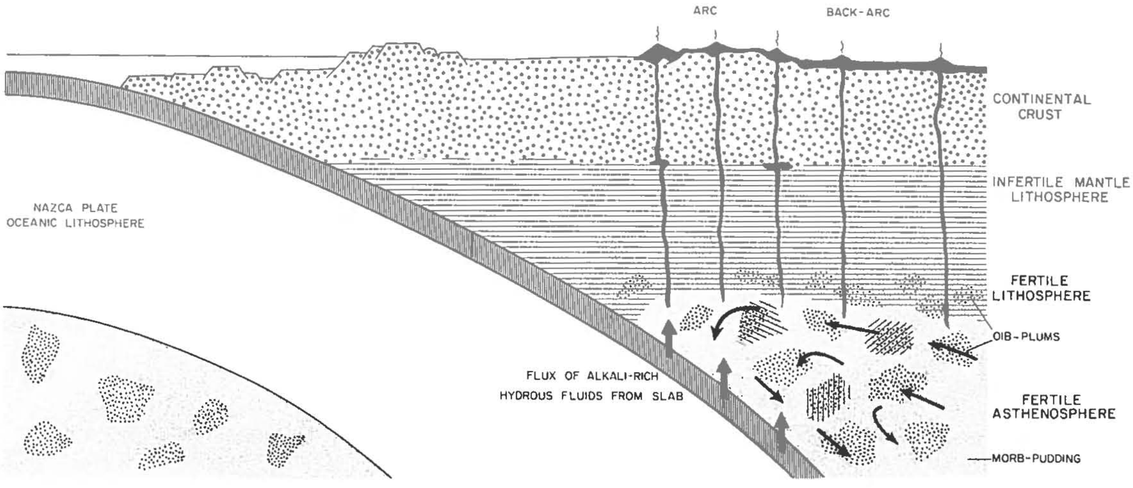

FIG. 9. Schematic cross-section through the western margin of southern South America based on the lithosphere cross-section shown in figure 6, and the suggestion that both the Pali-Aike alkali and orogenic high-Al basalts form from a plum-pudding mantle containing plums of oceanic island basalt type source material in a pudding of mid-ocean ridge basalt type source material. Flow in the asthenosphere in response to subduction maintains a renewable supply of fertile plum-pudding mantle. The plums may be derived from primitive undifferentiated lower mantle, from older unequilibrated subducted oceanic lithosphere, or from delamination of the lower portion of the continental lithosphere which contains plums of garnet-lherzolite + phlogopite veins capable of yielding the Pali-Aike basalts. Orogenic volcanism depends on dehydration of the subducted slab producing alkali-rich fluids (Hickey *et al.*, 1986; Futa and Stern, in press) and similar fluids derived from deeper levels of the subducted slab may have produced the phlogopite observed in the Pali-Aike xenoliths.

the Pali-Aike peridotite inclusions which are well below the liquidus temperatures of the basalts. However, the source regions of the Pali-Aike basalts certainly had some features in common with the lower portions of the subcontinental mantle lithosphere, probably consisting of fertile garnet-lherzolite which has experienced time integrated depletion of large-ion-lithophile elements and a relatively recent enrichment in these elements (Figure 5).

It has recently been proposed that the source region of some ocean island basalts may be "plums", derived either from primitive lower mantle or from subducted oceanic lithosphere not completely re-equilibrated within the upper mantle, in a "pudding" of MORB-source mantle (Morris and Hart, 1983; Zindler *et al.*, 1984). The lower subcontinental mantle lithosphere below southern South America is such a "plum-pudding" mantle, with a pudding of fertile garnet-lherzolite isotopically similar to MORB-source type mantle, and plums of garnet-lherzolite cut by phlogopite veins which together could yield basalts with Sr and Nd isotopic compositions similar to the Pali-Aike basalt (Figure 5). The OIB-source type plum that melted to produce the Pali-Aike basalts may have been derived from incorporation of the deepest portions of the subcontinental lithosphere into the asthenosphere (Figure 9). Such a processes, involving delamination of the lower portions of the continental lithosphere, has previously been suggested (McKenzie and O'Nions, 1983) as a viable mechanism for introducing oceanic island basalt type source plums into the asthenosphere.

Hickey *et al.* (1986) placed the OIB-source type mantle involved in the generation of Andean orogenic magmas in the subcontinental mantle lithosphere. Futa and Stern (in press) suggested that the subcontinental mantle lithosphere would not be a renewable source of fertile mantle material as required by the long history of Andean magmatic activity. They placed the OIB-source type mantle for Andean orogenic volcanics in plums in a plum-pudding asthenosphere in which flow above the subducted oceanic lithosphere could be expected to provide a renewable source of fertile material (Figure 9). Nevertheless, some of the plums in this asthenosphere may be derived by local delamination of the subcontinental mantle lithosphere. The extent to which OIB-source type plums contributing to the formation of Andean orogenic magmas are derived from the lower portions of the continental lithosphere, from subducted oceanic lithosphere, or from primitive undifferentiated lower mantle will have to be evaluated with Pb and rare-gas isotopic analysis in conjuntion with the available Sr and Nd isotopic data.

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REFERENCES

AKELLA, J. 1976. Garnet-pyroxene equilibria in the system $CaSiO_3$-Al_2O_3-$MgSiO_3$ and in natural mixtures. Am. Mineral., Vol. 61, p. 589-598.

ANDERSON, D. L. 1981. Hotspots, basalts, and the evolution of the mantle, Science, Vol. 213, p. 82-89.

BRUHN, R. L.; STERN, C. R.; DE WIT, M. J. 1978. The bearing of new field and geochemical data on the origin and development of a volcanic-tectonic rift zone and back-arc basin in southernmost South America. Earth Planet Sci. Lett., Vol. 41, p. 32-46.

COHEN, R. S.; O'NIONS, R. K.; DAWSON, J. B. 1984. Isotope geochemistry of xenoliths from East Africa: implications for the development of mantle reservoirs and their interaction. Earth. Planet. Sci. Lett., Vol. 68, p. 209-220.

DE WIT, M. J. 1977. The evolution of the Scotia arc as a key to the reconstruction of Gondwanaland. Tectonophysics, Vol. 37, p. 53-81.

FERGUSON, J.; ELLIS, D. J.; ENGLAND, R. M. 1977. Unique spinel-garnet lherzolite inclusions in kimberlites from Australia. Geology, Vol. 5, p. 278-280.

FUTA, K.; STERN, C. R. (in press) Sr and Nd isotopic and trace element compositions of recent volcanic centers of the southern Andes: implications for petrogenesis of orogenic magmas along a continental margin. Earth Planet. Sci. Lett.

HAGGERTY, S. E. 1979. Spinels in high pressure regimes. *In* The mantle sample: inclusions in kimberlites and other volcanics (Boyd, F. R.; Meyer, H. O. A.; eds.). Am. Geophys. Union Press, p. 183-196, Washington D. C.

HARTE, B. 1983. Mantle peridotites and processes - the kimberlite sample. *In* Continental basalts and mantle xenoliths(Hawkesworth C. J.; Norry, M. J.; eds.). Shiva Geol. Ser., Shiva Press, p. 46-91. Cheshire, England.

HAWKESWORTH, C. J.; NORRY, M. J.; RODDICK, J. C.; BAKER, P. E.; FRANCIS, P. W.; THORPE, R. S. 1979. $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$ and incompatible trace element variations in calc-alkaline andesitic and plateau lavas from South America. Earth Planet. Sci. Lett., Vol. 42, p. 45-57.

HAWKESWORTH, C. J.; ERLANK, A. J.; MARSH, J. S.; MENZIES, M. A.; VAN CALSTEREN, P. 1983. Evolution of the continental lithosphere: evidence from volcanics and xenoliths in southern Africa. *In* Continental basalts and mantle xenoliths (Hawkesworth. C. J.; Norry, M. J.; eds.). Shiva Geol. Ser., Shiva Press, p. 111-138. Cheshire, England.

HICKEY, R. L.; FREY, F. A.; GERLACH, D. C.; LOPEZ-ESCOBAR, L. 1986. Multiple sources for basaltic arc rocks from the southern volcanic zone of the Andes (34-41°S): trace element and isotopic evidences for the contributions from subducted oceanic crust, mantle and continental crust. J. Geophys. Res., Vol. 91, p. 5963-5983.

HILDRETH, W. 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. J. Geophys. Res., Vol 86, p. 10153-10192.

McKENZIE, D. P.; O'NIONS, R. K. 1983. Mantle reservoirs and ocean island basalts. Nature, Vol. 301, p. 229-231.

MENZIES, M. 1983. Mantle ultramafic xenoliths in alkaline magmas: evidence for mantle heterogeneity modified by magmatic activity. *In* Continental basalts and mantle xenoliths (Hawkesworth, C. J.; Norry, M. J.; eds.). Shiva Geol. Ser., Shiva Press, p. 92-110. Cheshire, England.

MORRIS, J. D.; HART, S. R. 1983. Isotopic and incompatible element constraints on the genesis of island arc volcanics, Cold Bay and Amak Island, Aleutians. Geochim. Cosmochim. Acta, Vol. 47, p. 2015-2030.

NICKEL, K. G.; GREEN, D. H. 1985. Empirical geothermobarometry for garnet peridotites and implications for the nature of the lithosphere, kimberlites and diamonds. Earth Planet. Sci. Lett., Vol. 73, p. 158-170.

O'NIONS, R. K.; EVENSON, N. M.; HAMILTON, P. J. 1979. Geochemical modeling of mantle differentiation and crustal growth. J. Geophys. Res., Vol. 84, p. 6091-6101.

RAMOS, V. A.; NIEMEYER, H.; SKARMETA, J.; MUÑOZ, J. 1982. Magmatic evolution of the austral Patagonian Andes. Earth Sci. Rev., Vol. 18, p. 411-443.

RINGWOOD, A. E. 1967. The chemical composition and origin of the earth, *In* Advances in earth sciences (Hurley, P. M.; ed.). M.I.T. Press, p. 287-356. Cambridge, Mass, U.S.A.

SELVERSTONE, J. E.; STERN, C. R. 1979. Petrology and petrogenesis of mafic granulite xenoliths from the Pali-Aike volcanic field, South America. Am. Mineral., Vol. 68, p. 1102-1112.

SKEWES, M. A.; STERN, C. R. 1979. Petrology and geochemistry of alkali basalts and ultramafic inclusions from the Pali-Aike basalts in southern South America and the origin of the Patagonian plateau lavas. J. Volcan. Geotherm. Res., Vol. 6, p. 3-25.

STERN, C. R.; FUTA, K.; ZICHING, P. 1983. Pb, Sr and Nd isotopic compositions of alkali basalts of the Patagonian plateau lavas, South America. Geol. Soc. Am., Abstr. Progr., Vol. 15, p. 465.

STERN, C. R.; FUTA, K.; SAUL, S.; SKEWES, M. A. 1985. Ultramafic xenoliths found in the Pali-Aike alkali basalts: their implications for the nature of the mantle below southern South America. *In* Congr. Geol. Chileno, No. 4, Actas, Vol. 3, p. 531-548. Antofagasta.

STERN, C. R.; MUÑOZ, J.; BERMUDEZ, A.; DELPINO, D. (in press). Plio-Quaternary units of the Patagonian plateau lavas: Late Cenozoic arc, intra-arc, and back-arc magmatism in southern South America. *In* The geotectonic evolution of South America (Cordani, U.; ed.). G.S.A. Press.

WELLS, P. R. A. 1977. Pyroxene thermometry in simple and complex systems. Contr. Min. Pet., Vol. 62, p. 129-139.

WILSHIRE, H. G.; SHERVAIS, J. W. 1975. Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks from the western United States. Phys. Chem. Earth, Vol. 9, p. 257-272.

WOOD, D. A. 1979. A variably veined sub-oceanic upper mantle-genetic significance for mid-oceanic ridge basalts from geochemical evidence. Geology, Vol. 7, p. 499-503.

ZINDLER, A.; STAUDIGEL, H.; BATIZA, R. 1984. Isotopic and trace element geochemistry of young Pacific seamounts; implications for the scale of upper mantle heterogeneity. Earth Planet. Sci. Lett., Vol. 70, p. 175-195.

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