

Radio cycling of subducted sediments into the Samoan mantle plume

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ABSTRACT

Harzburgite xenoliths from the Samoan hotspot carry extraordinarily enriched Sr-Nd-Pb isotopic ratios previously attributed to metasomatism by a carbonatitic fluid derived from recycled sediments. I describe here the gas composition and microthermometric properties of fluid inclusions that have trapped this unusual agent. The inclusions are dominantly pure CO₂ and were apparently formed at the base of the crust. They have high ³He/⁴He ratios (12 times the atmospheric ratio), inconsistent with the radiogenic values expected for recycled sediments. Furthermore, inclusion C/³He ratios of ~3 × 10⁹ are indistinguishable from typical mantle values and are far lower than those in sediments (>10¹¹). These striking observations imply that little of the helium and carbon in the metasomatic fluid was derived from the recycled source required by the Sr-Nd-Pb isotopes. The metasomatic fluid is probably a product of mixing within the Samoan hot spot of a volatile-rich high ³He/⁴He plume melt and recycled sediments. The retention of high ³He/⁴He ratios in such a mixture requires very rapid cycling of the sedimentary component through the mantle (probably <10⁷ yr), rather than the billions of years often envisaged. This time scale indicates involvement of material recently returned to the mantle at the nearby Tonga Trench, and pelagic sediments near the trench have approximately the requisite geochemical signature. The unique isotopic characteristics of the Samoan plume likely arise from its unusual tectonic setting at the northern terminus of subduction in the Tonga Trench.

INTRODUCTION

The subduction of sediments and altered oceanic crust is probably a major source of mantle chemical heterogeneity (e.g., Hofmann and White, 1982; Zindler and Hart, 1986). Deeply subducted material, as identified by distinctive isotopic characteristics, may be recycled into mantle-derived rocks, particularly those erupted at certain oceanic hotspots (White and Hofmann, 1982). Such islands provide important data on mantle processes, but the relations among crustal recycling, plume volcanism, and the geochemical structure and evolution of the mantle remain controversial. Basalts from the Samoan Islands carry particularly strong evidence for a recycled sedimentary component in their source (White and Hofmann, 1982; Wright and White, 1986). Their radiogenic isotope systematics form a compositional extreme defining the high ⁸⁷Sr/⁸⁶Sr, intermediate ¹⁴³Nd/¹⁴⁴Nd mantle end member termed EM2 by Zindler and Hart (1986). Paradoxically, Samoan rocks also have among the highest known ³He/⁴He ratios, a signature that cannot result from subduction and is instead most compatible with derivation from an undegassed reservoir (Farley et al., 1992). These high ³He/⁴He ratios are apparently unique to the Samoan variety of EM2.

I report here new compositional and microthermometric data on fluid inclusions that have apparently trapped a metasomatic agent with the EM2 signature. The diversity

of data now available on these xenoliths places important limits on the composition and origin of the Samoan EM2 component.

SAMPLES AND PREVIOUS WORK

The Samoan xenoliths have now been studied in great detail (Wright, 1987; Poreda and Farley, 1992; Hauri et al., 1993; Farley et al., 1994). They are hosted by young silica-undersaturated lavas erupted along a linear rift zone extending for several hundred kilometres along the strike of the Samoan chain (Fig. 1). Harzburgites are the dominant lithology; there are rare dunites and wehrlites. Metasomatized harzburgites from Savai'i have extremely high ⁸⁷Sr/⁸⁶Sr (0.7128) Dupal Pb (high ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb for a given ²⁰⁶Pb/²⁰⁴Pb; Hart, 1984), and unusually enriched trace element patterns. These characteristics led Hauri et al. (1993) to propose that the Samoan mantle had undergone infiltration of a carbonatitic fluid composed of carbon and lithophile species derived from subducted sediments. The xenoliths also have abundant fluid inclusions, and as indicated by their radiogenic Sr (to 0.7123), these inclusions host the metasomatic agent. Samoan basalts have similar but less-extreme isotopic systematics (Wright and White, 1986), suggesting that the metasomatic agent is also involved in basalt petrogenesis.

Savai'i xenoliths have high and uniform ³He/⁴He ratios of 11.5 ± 0.5 times the atmospheric value (R_A, 1.39 × 10⁻⁶) com-

pared with ~8 R_A in mid-ocean ridge basalts (Poreda and Farley, 1992). The presence of high ³He/⁴He ratios in fluids bearing a "recycled" lithophile signature is difficult to understand and was the primary motivation for this study.

This work focuses on two harzburgites from a cinder cone on the northeastern side of Savai'i (Fig. 1). Although they are chemically similar, the two xenoliths differ dramatically in their degree of deformation and in their fluid-inclusion abundances (Farley et al., 1994). Major element compositions are indistinguishable from those reported by Hauri et al. (1993). Both samples have magnesian olivines (Fe_{0.2}) and pyroxenes (Mg/[Mg + Fe] between 0.92 and 0.95) and siliceous melt inclusions (SiO₂ 56–70 wt%). In the mildly porphyroclastic harzburgite SAV 1-7, randomly oriented arcuate healed fractures are decorated with both melt and fluid inclusions, which range from elongate vermicular to spherical and are 10–50 μm in maximum dimension. Vermicular inclusions (frequently with trapped melt) are most common in orthopyroxene and only infrequently cross grain boundaries. In contrast, SAV 26X is intensely deformed, with ubiquitous subparallel fractures dissecting the entire xenolith. Where healed, the fractures host an enormous number of spherical fluid inclusions, generally larger than those of

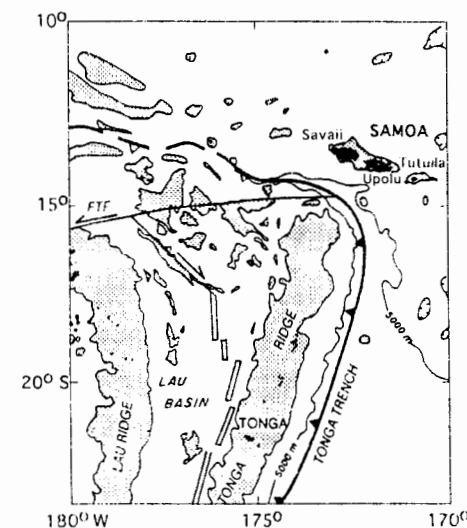


Figure 1. Map of Samoan Archipelago and its relation to Tonga Trench. FTF denotes Fiji transform fault. This figure is modified after Tiffin (1993).

TABLE 1. HELIUM AND CARBON IN SAVAI'I XENOLITHS

Sample	Description	^3He (10^{-15} mol/g)	$^3\text{He}/^4\text{He}$ (R_A)	Manometric CO_2 (ppm)	FTIR CO_2 (ppm)	$\text{C}/^3\text{He}$ ($\times 10^9$)
SAV 26X	Severely sheared harzburgite	4.2 ± 0.4	12.0 ± 0.5	433 ± 7	OL 189 - 419 OPX 442 - 625	2.4
SAV 1-7 OL	Porphyroclastic harzburgite	0.13 ± 0.01	11.3 ± 0.5	21 ± 2	<4 - 52	3.6
SAV 1-7 OPX	Porphyroclastic harzburgite	0.10 ± 0.01	11.9 ± 0.5	N.A.	33 - 94	24
Xenoliths from Hawaii and Reunion	Lherzolites, harzburgites, dunitites and wehrlites [†]	0.002 - 2.82	8.1 - 24	<0.4 - 960	N.A.	2.2 - 31
MORB	Glasses [‡]	N.A.	~8	63 - 595	N.A.	1.2 - 6.6

Note: Helium data are average values from Farley et al. (1994). Bulk analyses of SAV 26X were performed on whole rock because the phases are intimately intergrown. CO_2 was determined both by manometry of gas released by crushing of bulk samples, and by Fourier transform infrared (FTIR) spectroscopy of ~1-mm-wide regions of doubly polished thick sections computed using the extinction coefficient of Fine and Stolper (1985). $\text{C}/^3\text{He}$ ratios were determined by combining concentrations from independent bulk splits (except for SAV 1-7 opx, where the average FTIR CO_2 value was used). N.A. indicates data are not available.

[†] Trull et. al (1993).
[‡] Marty and Jambon (1987).

SAV 1-7 (up to 200 μm in diameter). Most of the largest inclusions have decrepitated and are now simply voids. Orthopyroxenes in this xenolith are intensely turbid as a consequence of many tiny (<3 μm) fluid inclusions.

To complement previous noble gas measurements, these two samples were analyzed for CO_2 content by manometry of bulk samples and by thick-section Fourier-transform infrared (FTIR) spectroscopy. In addition, fluid-inclusion microthermometry was performed to determine the composition and filling pressures of the inclusions.

RESULTS

All analyzed phases from both xenoliths have $^3\text{He}/^4\text{He}$ ratios of ~11.7 R_A (Table 1), identical to ratios found in five other xenoliths from this locality and comparable to the lowest values found in Samoan basalts (Poreda and Farley, 1992; Farley et al., 1992). Helium concentrations are also high, especially in SAV 26X (250 pmol/g); this highly deformed xenolith is enriched in helium by a factor of 25 relative to SAV 1-7. Bulk CO_2 concentrations range from 21 to 440 ppm, again with the highest concentrations in SAV 26X. The $\text{C}/^3\text{He}$ ratios in the olivines of SAV 1-7 and in the SAV 26X bulk rock are both $\sim 3 \times 10^9$, whereas the ratio in the orthopyroxene of SAV 1-7 is 10 times higher.

FTIR spectroscopy reveals substantial spatial variations in CO_2 content, reflecting a heterogeneous distribution of fluid inclusions over the millimetre scale. In both xenoliths, orthopyroxene hosts about two to three times more CO_2 than coexisting olivine. The intensely turbid (metasomatized?) orthopyroxenes in SAV 26X are particularly CO_2 rich, up to 625 ppm. No other IR active species (in particular H_2O , SO_2 , H_2S , CH_4 , NH_3) could be conclusively identified.

After FTIR analysis the sections were

subjected to fluid-inclusion microthermometry. The melting behavior of fluid inclusions reflects the composition of the inclusion fluid (Roedder, 1983). In SAV 26X and the olivines of SAV 1-7, the majority of inclusions exhibit a final melting temperature (T_m) of -56.6°C ; the triple point of pure CO_2 (Fig. 2A). In contrast, inclusions in the SAV 1-7 orthopyroxenes have a much greater T_m range, from -56.6 to -58.2°C ; a frequency maximum is at -57.5°C . The lowest melting points are found exclusively in the vermicular inclusions, and the distinctive T_m distribution in SAV 1-7 orthopyroxenes is a consequence of the presence of such inclusions almost exclusively in this phase.

These results indicate that most of the in-

clusions in both xenoliths are essentially pure CO_2 (>99.5 mol%). However, T_m values as low as -58.2°C require that a subpopulation of inclusions, especially the vermicular variety, carry up to ~5 mol% of an additional constituent(s). The IR active species listed above should have been detectable at this level, so this additional component cannot be IR active. It has previously been suggested that noble gases may be responsible for T_m reduction in mantle fluid inclusions (e.g., Andersen et al., 1984). As shown in Table 1, noble gases compose a very small fraction of the total fluid in the inclusions, certainly <0.1 mol%, and therefore can be ruled out. Cl/Ar ratios of ~1000 have been measured in some mantle fluids (Ozima et al., 1989); if such fluids are

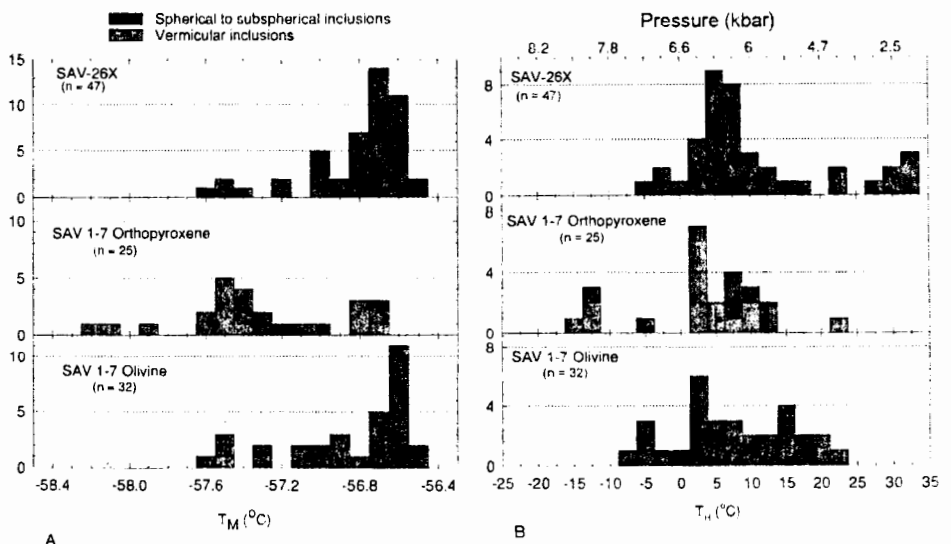


Figure 2. Distribution of temperatures (T) of (A) final melting (T_m) and (B) homogenization (T_h) temperatures in two Samoan xenoliths. Microthermometry was performed on doubly polished 100- μm -thick sections with Fluid Inc. stage (accuracy $\pm 0.1^\circ\text{C}$). Very turbid mineral grains prevented identification of mineral phases within SAV 26X. Top axis in B indicates pressure of last equilibration implied for CO_2 inclusion at 1200°C . Note that pressure uncertainties resulting from impurities in inclusions are comparatively small, at most few percent. Four inclusions in SAV 26X homogenized into gas phase (not shown); all others homogenized into liquid phase.

(Farley et al., 1994) suggest Cl concentrations of nearly 10 mol%. Cl therefore is a likely source of the T_m reduction observed in some inclusions.

The temperature at which two-phase fluid inclusions (liquid + vapor) homogenize can be used to estimate the depth of inclusion entrapment. In SAV 1-7 the inclusion fluids homogenize exclusively into the liquid phase, over a range of temperatures from -15 to 25 °C; there is a sharp peak at ~5 °C. SAV 26X exhibits a similar peak, but with a substantial tail to higher homogenization temperatures, up to 31 °C. In addition, a few very large inclusions in SAV 26X homogenize into the gas phase. By assuming that the inclusions were trapped at a typical mantle temperature of 1200 °C, these homogenization temperatures can be related to the pressure at which the inclusions last equilibrated (Roedder, 1983). Such values represent a minimum estimate of the pressure of inclusion formation, because physical reequilibration during ascent (e.g., partial decrepitation) can lead to lower values. The Samoan fluid inclusions record pressures up to ~8 kbar; distribution peaked strongly at ~6 kbar (Fig. 2B). The tail toward lower pressures indicates partial decrepitation of some inclusions, particularly the largest inclusions in SAV 26X. Note that the sharp peak in all three distributions at ~6 kbar is not likely to reflect a maximum tensile strength beyond which the inclusions will decrepitate, because other studies record much greater pressures (up to 12 kbar) for inclusions of similar size in similar minerals from other localities (e.g., Andersen et al., 1984; Hansteen et al., 1991). If it is assumed that the 6 kbar figure reflects a purely lithostatic load, this pressure corresponds to a depth of about 18 km, coinciding roughly with the base of the crust in a hotspot environment.

DISCUSSION

Petrographic and geochemical evidence documents extensive interaction of the Samoan xenoliths with a metasomatic fluid now carried within the fluid inclusions. The fluid has a high $^3\text{He}/^4\text{He}$ ratio (~12 R_A), very radiogenic Sr (>0.712), Dupal Pb, and a distinctive enriched (carbonatitic) trace element pattern (Hauri et al., 1993). The Sr, Nd, and Pb isotopic signatures in the fluid are similar to those of oceanic sediments (e.g., Ben-Othman et al., 1989). Most inclusions are pure CO_2 , but some also contain up to a few mol% of an IR-inactive species (Cl?). Fluid-inclusion geobarometry suggests that this unusual fluid is trapped at the top of the mantle, where the crust may act as a barrier to fluid migration.

Farley et al. (1994) proposed that this metasomatic fluid arises by the separation of a volatile-rich phase from a subducted sedimentary protolith; the high volatile content is attributed to penetration of crustal carbon through the subduction-zone filter. Because sediments are enriched in ^4He -producing U and Th, and are depleted in ^3He relative to the mantle, recycled sediments should be characterized by very low $^3\text{He}/^4\text{He}$ ratios (certainly <8 R_A , the ratio in pristine oceanic crust). Nevertheless, despite the strong isotopic evidence for a recycled component in the fluid inclusions, they do not have a low $^3\text{He}/^4\text{He}$ ratio. This same paradox was noted in Samoan basalts (Farley et al., 1992). It seems inescapable that helium in the metasomatic fluid (and in Samoan basalts) has a source independent of the recycled component.

This observation requires the addition of mantle helium (rich in ^3He) to the recycled material or its derivative fluid. This possibility can be evaluated through consideration of the relative C and ^3He abundances in the xenoliths. Previous workers have shown that $\text{C}/^3\text{He}$ ratios are fairly uniform in mantle samples, despite large variations in He concentration and isotopic ratio (Trull et al., 1993; Marty and Jambon, 1987). The $\text{C}/^3\text{He}$ ratio varies only over a factor of 30 ($1\text{--}30 \times 10^9$) in mid-ocean ridge basalts and ocean-island xenoliths (Table 1). This restricted range exists despite the tendency for mantle samples to lose He by diffusion during eruption (Farley et al., 1994). A characteristic $\text{C}/^3\text{He}$ ratio of $\sim 5 \times 10^9$ apparently tags a "normal" mantle provenance of both C and ^3He in mantle fluids.

$\text{C}/^3\text{He}$ ratios of $2.4\text{--}24 \times 10^9$ in the Samoan xenoliths lie completely within the characteristic mantle range (Table 1). The SAV 1-7 orthopyroxene has a higher $\text{C}/^3\text{He}$ ratio than coexisting olivine by a factor of seven, but this high value is a consequence of preferential He loss from the orthopyroxene (Farley et al., 1994). Therefore, the best estimate for the $\text{C}/^3\text{He}$ ratio of the inclusion fluid is $\sim 3 \times 10^9$. In comparison, the lowest $\text{C}/^3\text{He}$ ratios in sedimentary materials are at least several orders of magnitude higher. For example, even the most slowly accumulating pelagic clays (which are rich in extraterrestrial ^3He and poor in C compared to other subducting material) have $\text{C}/^3\text{He}$ ratios $> 2 \times 10^{11}$ (Farley, unpublished). Diffusive loss of ^3He from the down-going sediments (e.g., Hiyagon, 1994) can only raise this ratio.

That the metasomatic fluid carries the characteristic mantle $\text{C}/^3\text{He}$ ratio suggests that both ^3He and carbon are derived from the same source as most other oceanic volcanic rocks; otherwise, a completely fortu-

itous mixture of recycled carbon (with very high $\text{C}/^3\text{He}$) and mantle He (somehow separated from its associated carbon) would be required. These data make it difficult to accept the idea that the metasomatic agent is composed of predominantly recycled carbon (Hauri et al., 1993). It is more likely that CO_2 and helium are derived from the Samoan plume source; Samoan shield lavas with $^3\text{He}/^4\text{He}$ ratios up to 24 R_A confirm that the Samoan plume has the appropriate composition (Farley et al., 1992). In contrast, the isotopically enriched lithophile elements must arise from incorporation of a large fraction of volatile-poor recycled sediment.

If the trapped metasomatic fluid is in fact a mixture of plume and recycled components, then He-Sr isotope systematics place a tight limit on the mantle residence time (t_{res}) of the recycled component. The high U and Th abundances of the metasomatic fluid (about 80 and 320 ppm, respectively; Hauri et al., 1993) rapidly yield large quantities of radiogenic ^4He . As a consequence, as t_{res} increases, the recycled component becomes increasingly effective at reducing the $^3\text{He}/^4\text{He}$ ratio in the mixture. The curvature of two component mixing arrays between plume and recycled components is governed by the parameter

$$r = \frac{\text{He}_p}{\text{He}_r(t_{\text{res}})} \times \frac{\text{Sr}_r}{\text{Sr}_p}$$

where He and Sr are concentrations in the plume and recycled sources and He_r is a function of t_{res} . The xenolith data provide an estimate of r , from which t_{res} can be computed using reasonable values of Sr_r , Sr_p , and He_p . As shown in Figure 3, t_{res} recorded by the xenoliths must be very short, between about 3 and 20 m.y. Uncertainties in the composition of the end members probably introduce an uncertainty of a factor of a few to this calculation, but previous estimates of several billion years residence times (e.g., Hofmann and White, 1982) clearly cannot apply to the Samoan EM2 component. Although the particulars presented here are model dependent, the short residence time is a robust conclusion arising from the high radioelement concentrations and high $^3\text{He}/^4\text{He}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the metasomatic fluid. A short t_{res} may also explain why the Samoan metasomatic fluid is so isotopically extreme relative to other oceanic rocks—the recycled materials have had little time to be diluted into the ambient mantle.

A mantle residence time of ~10 m.y. requires the involvement of actively subducting material, possibly associated with the downgoing slab in the nearby Tonga Trench (Fig. 1). The proximity of Savai'i to the

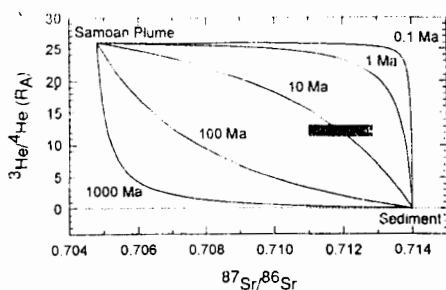


Figure 3. He-Sr mixing curves between plume and recycled end members as function of mantle residence time of recycled component, t_{res} . Filled box shows compositional range of Samoan xenoliths (Farley et al., 1994; Hauri et al., 1993). Best-fit curve indicates that t_{res} must be very short, probably ~10 m.y. Plume source is taken to have isotopic characteristics of highest $^3\text{He}/^4\text{He}$ Samoan basalts (Farley et al., 1992), 20 ppm Sr, and lower mantle He concentration (Allegre et al., 1986). Recycled source is assumed to have $^{87}\text{Sr}/^{86}\text{Sr}$ as high as is commonly observed in oceanic sediments (Ben-Othman et al., 1989), typical deep-sea sediment Sr content (240 ppm), and U and Th abundances inferred by Hauri et al. (1993). Model assumes no fractionation of He from Sr, U, and Th, because all are highly incompatible elements, and that helium is completely degassed upon subduction.

trench (<50 km) and the parallelism between the strike of the posterosional vents and the trench have been noted previously, and suggest structural control on the distribution of volcanic centers (Natland, 1980). The results presented here also suggest a chemical link. Geophysical surveys show little evidence for sediment offscraping in the northern Tonga Trench, indicating that sediments are entering the mantle in this area (Hill and Tiffin, 1993). Although poorly characterized, the pelagic sediments near the trench are isotopically similar to Samoan rocks, with high $^{87}\text{Sr}/^{86}\text{Sr}$, intermediate Nd, and Dupal Pb (Ben-Othman et al., 1989; Peucker-Ehrinbrink et al., 1994). They are also very poor in C and ^4He (Farley, unpublished), so there is little difficulty in maintaining a high $^3\text{He}/^4\text{He}$ ratio and a mantle $\text{C}/^3\text{He}$ ratio in mixtures with this component.

The Samoan Islands do not lie directly above the subducting slab, but to the north, on the Pacific plate (Fig. 1). The westward bend of the trench south of Savai'i marks the northern terminus of subduction and the appearance of the southwest-trending Fiji transform fault. Thus, the lateral edge of the slab lies within 50 km of Savai'i. Although a mechanism cannot be specified at present, it seems at least plausible that plume and sediment components may be interacting in this complex region. If this hypothesis is correct, Samoan geochemistry may offer a means to

assess shallow mantle flow near the slab. In this regard it is interesting that posterosional lavas from Savai'i and Upolu (which lie closest to the trench) carry a much stronger EM2 signature (Wright and White, 1986) than do comparable lavas on Tutuila (located 75 km farther east, i.e., away from the trench).

The involvement of a recently subducted component accounts well for the observed isotopic systematics of Samoan rocks and links the unique characteristics of the Samoan variety of EM2 with the unusual tectonic setting of the archipelago. Other ocean islands with EM2 isotopic characteristics do not have comparably high $^3\text{He}/^4\text{He}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and so need not be cycled so quickly. Further characterization of the composition of the down-going package in the Tonga Trench and its likely physical and chemical behavior in the shallow subduction environment is necessary to explore this hypothesis more quantitatively.

ACKNOWLEDGMENTS

Supported by National Science Foundation grants EAR-93-04267 and EAR-92-04822. I thank J. Natland, R. Poreda, E. Stolper, G. Rossman, and J. Eiler for various contributions to this effort. The manuscript benefited from reviews by W. M. White and A. Cohen.

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Manuscript received October 28, 1994

Revised manuscript received February 9, 1995

Manuscript accepted February 27, 1995