29. MAJOR ELEMENT, TRACE ELEMENT, AND ISOTOPE (Pb, Sr, AND Nd) GEOCHEMISTRY OF SITE 839 BASALTS AND BASALTIC ANDESITES: IMPLICATIONS FOR ARC VOLCANISM¹

A. Ewart,² J.M. Hergt,³ and J.W. Hawkins⁴

ABSTRACT

Four petrographic lava types occur, ranging from aphyric to moderately phyric clinopyroxene-olivine tholeiitic basalts (Unit 1); olivine-clinopyroxene picritic basalts, sparsely to strongly olivine-phyric (Unit 3-type); olivine-clinopyroxene basalts (clinopyroxene dominant) (Unit 4); and moderately to strongly phyric two-pyroxene-plagioclase basaltic andesites (Unit 9-type). The olivine phyric lavas contain forsteritic olivines (extending to Fo_{92}), and very magnesian Cr-rich spinels similar to those occurring in boninitic lavas. The basaltic andesites are mineralogically and petrographically indistinguishable from the modern Tofua Arc basaltic andesites, one notable feature being the highly calcic cores in plagioclase phenocrysts (up to An_{95}). The forsteritic olivines, the Cr-spinels, and the calcic plagioclases are unlikely to have been precipitated in the lava compositions in which they occur, and are thought to have been incorporated from highly primitive melts by way of mixing processes (as advocated by Allan, this volume). Notwithstanding the evidence for mixing, the major element chemistries of the Unit 1- and Unit 9-type lavas are shown to be consistent with the derivation of the Unit 9-type basaltic andesites by means of fractional crystallization, through magmas of similar chemistry to Unit 1. Some trace element discrepancies in the modeling, and the relative volcanic stratigraphy of Site 839, however, preclude a direct liquid line of descent between the actual recovered units.

Trace element data as well as TiO₂ and Na₂O data clearly illustrate the arc-like affinities of the magmas, with strong high-field-strength element depletion and large-ion-lithophile element enrichment. The abundance patterns are very close to those of the Tofua and Kermadec arc magmas, and also Valu Fa.

Pb-, Sr-, and Nd-isotopic compositions indicate closest affinities with a "Pacific" MORB source, apparently characteristic of the western, older part of the Lau Basin. A subduction-related isotopic contribution is, however, inferred. The sources of the Site 839 magmas are thus inferred to be similar to, but less depleted geochemically, than those of the modern Tofua Arc magmas. The Site 839 sequence is interpreted as an older remnant of a volcanic construct of the "proto-Tofua arc," originally developed adjacent to the Tonga Ridge. Opening of the eastern Lau Basin, because of southward migrating propagators, has split and isolated the sequence, leaving it stranded within the modern Lau Basin.

INTRODUCTION

Site 839 lies approximately 55 km west of the East Lau Spreading Center (ELSC); it is situated very close to, but just west of, the boundary between the western older Lau Basin (with "basin and range" style topography) and the younger eastern basin, the latter formed by the southward movement of the propagator systems forming the ELSC and Valu Fa Ridge (Parson, Hawkins, Allan, et al., 1992; see Fig. 1).

Nine volcanic units were recovered (Parson, Hawkins, Allan, et al., 1992). The sediment occurring above Unit 2 in Hole 839A is latest Pliocene (Subzone CN13b) in age, whereas the sediment immediately overlying Unit 2 in Core 135-839B-18R is of late Pliocene age (Subzone CN12d). These dates imply a minimum age of volcanism of approximately 1.5 Ma. Magnetic polarity measurements on the deepest basaltic andesites recovered at Hole 839B suggest an age of either the Réunion Subchron (2.01–2.14 Ma) or the Gauss Chron (2.48–2.92 Ma; Parson, Hawkins, Allan, et al., 1992). The following notes summarize the essential petrographic features of the nine units recovered:

Unit 9, the lowermost unit, comprises a series of flows of moderately to highly phyric clinopyroxene-orthopyroxene-plagioclase basaltic andesites, with strong petrographic similarities to the modern Tofua Arc lavas. The unit is at least 135 m thick, but a small chemical change occurs at 410 meters below seafloor (approximately 47 m below top of unit), also seen as a discontinuity in the downhole logs. Phenocryst contents range between 3 to 16 modal %, dominated by calcic plagioclase (3.5 to 14.8 modal %), which occurs as both single crystals, but more commonly as monomineralic glomerocrysts. Oscillatory zoning and cores and zones with abundant melt inclusions are common. The lavas of Unit 9 are conspicuously vesicular (10 to 20 modal %), and segregation vesicles and pipe vesicles are common.

Unit 8 comprises only a single piece of moderately to highly phyric clinopyroxene-olivine basalt, petrographically equivalent to Units 3 and 6. The fragment may thus represent a downhole-displaced fragment from these higher units.

Unit 7 is similarly represented by only two pieces of two-pyroxene-plagioclase basaltic andesite, petrographically identical to Units 2, 5, and 9. These fragments may therefore represent downhole-displaced fragments.

Unit 6 comprises a highly vesicular, moderately phyric clinopyroxeneolivine basalt, represented by two fragments, petrographically identical to Unit 3, which again may represent downhole-displaced fragments.

Unit 5 is a vesicular and moderately phyric orthopyroxene-clinopyroxene-plagioclase basaltic andesite, comprising only three fragments which are petrographically identical to the upper part of Unit 9, as well as to Units 2 and 7. The possibility exists that these fragments may also represent downhole displacement from Unit 2.

Unit 4 is a phyric olivine-clinopyroxene basalt, with maximum thickness of 19 m although the lower contact was not recovered. It appears to comprise a series of thin flows or pillow lavas. Although true phenocryst-sized (>0.5 mm) olivines and clinopyroxenes are sparse, this unit is seriate textured and characterized by abundant microphenocrysts (0.1–0.5 mm) of dominantly clinopyroxene with minor olivine. The clinopyroxenes are notable for the development of curved cleavages and pronounced shadowy extinction, indicative of rapid crystal growth. Cr-spinel inclusions occur in olivines of all sizes. Unit 4 thus differs from the overlying Unit 3 in the absence of large olivine phenocrysts, the strong development of microphenocrysts, and

¹ Hawkins, J., Parson, L., Allan, J., et al., 1994. Proc. ODP, Sci. Results, 135: College Station, TX (Ocean Drilling Program).

 ² Department of Earth Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia.
 ³ Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes,

⁶ Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom (present address: School of Earth Sciences, The University of Melbourne, Parkville, Victoria, 3052, Australia).

⁴ Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, U.S.A.



Figure 1. Location map of the Lau Basin showing bathymetry (km), location of Lau and Tonga ridges, and drill-hole sites (Leg 135 and DSDP Site 203). CLSC, ILSC, and ELSC are the Central, Intermediate, and Eastern Lau spreading centers, respectively; KTJ = King's Triple Junction, NF = Niuafo'ou, Taf = Tafahi, T = Tongatapu, E = 'Eua, A = 'Ata, U = Upolu, and V = Vava'u. Also shown (dashed line) is the approximate boundary between the older western and eastern Lau Basin crustal provinces (Parson and Hawkins, this volume).

the dominance of clinopyroxene over olivine. Vesicle content is high, ranging from 5 to 30 modal %. Groundmass phases include clinopyroxene, plagioclase, olivine, and rare magnetite.

Unit 3 varies from sparsely to strongly phyric clinopyroxene-olivine basalts (perhaps more appropriately termed picritic basalts), with a total thickness of 58.3 m, and comprising numerous thin flows or pillow lavas. Petrographically, the unit is notable for the dominance of olivine (often containing small (up to 0.05 mm) Cr-spinel inclusions; see also Allan, this volume) ranging from large phenocrysts (4 mm) to microphenocrysts, and varying in abundance from <2 to 28 modal %. Phenocryst contents show an overall increase in abundance and size downward, but vary widely within individual core sections. There is therefore no evidence for the systematic settling of olivine within the individual cooling units. Clinopyroxene occurs as phenocrysts to microphenocrysts, as isolated crystals and glomeroporphyritic intergrowths. Cr-spinel also occurs as discrete euhedra, up to 3 mm diameter. Plagioclase only occurs as rare microphenocrysts, but is present as a ubiquitous groundmass quench phase. This unit is vesicular (10 to 30 modal %), and dark segregation vesicles are common.

Unit 2 is a dark, moderately phyric orthopyroxene-clinopyroxeneplagioclase basaltic andesite, representing a series of thinly bedded flows, with a total thickness of nearly 10 m. It is strongly vesicular and petrographically similar to Unit 9.

Unit 1 comprises an aphyric to moderately phyric clinopyroxeneolivine basalt, holocrystalline, with a diabasic and strongly seriate texture. It appears to represent either a more massive eruptive unit, or consists possibly of a small number of relatively thick (>5 m) flows, with a total thickness of nearly 43 m. The unit is mostly aphyric, but it becomes moderately phyric at the base and is strongly vesicular (10-30 modal%). Phenocrysts comprise plagioclase, olivine, clinopyroxene, and rare glomerocrysts of Cr-spinel, but the marked seriate texture makes distinction between phenocrysts and groundmass arbitrary. Coarse groundmass phases comprise olivine, clinopyroxene, plagioclase, and titaniferous magnetite with orthopyroxene common in the central parts of the unit, but sparse in the upper and lower parts. Of particular interest is the occurrence of orthopyroxene and pigeonite rimming olivine. A fine grained mesostasis constitutes 20-50 modal% of the unit, with well-developed quench textures. The unit has suffered slight to moderate alteration, mainly the development of Fe-oxyhydroxides, and secondary zeolite in vesicles and local replacement of mesostasis.

From a petrographic viewpoint, it is clear that four distinct types occur: Unit 1; Units 2, 5, 7 and 9 (referred to as Unit 9-type); Units 3, 6, and 8 (referred to as Unit 3-type); and Unit 4. In this report, the various units will be treated within these four petrographic groupings.

Chemical and modal data utilized in the following presentations are based on the Leg 135 *Initial Reports* volume (Parson, Hawkins, Allan, et al., 1992), new modal, major, and trace element data presented in Ewart et al. (this volume), and Table 1.

MINERALOGY

Plagioclase

The plagioclase compositions in all Site 839 units are notably calcic, more so than found in most lavas from sites 834 through 838 (Ewart et al., this volume). Within the Unit 9-type basaltic andesites, in which plagioclase is the dominant phenocryst phase, compositions range from An₈₅ to An₉₅ (most between An₈₇₋₉₁), with the narrow sodic rims of most phenocrysts lying in the range from An₇₄ to An₈₂. Groundmass microlite compositions range from An₆₃ to An₈₀. These compositions are thus very similar to those of the phenocrystal plagioclases occurring within the modern Tofua Arc basaltic andesites (Fig. 2). The phenocrystal and coarse groundmass plagioclases in the diabasic Unit 1 are almost as calcic, between An₈₇ and An₉₀ with rims to An76, and more sodic finer grained groundmass plagioclase. The rare microphenocrysts occurring in Unit 3-type picritic basalts lie between An₈₄ and An₈₉, with groundmass microlites of An₆₈₋₇₉. Groundmass plagioclase in Unit 4 lavas lies between An73 to An87. As a general observation for the Site 839 lavas, apart from the occurrence of narrow, relatively sodic quench rims, zoning within plagioclase phenocrysts is limited to within 5% An, although intricate zoning patterns exist (Bryan and Pearce, this volume). Zones and cores containing abundant melt (glass) inclusions are also conspicuous in some phenocrysts from Unit 9-type lavas, again a common feature in plagioclases in modern Tofua Arc lavas.

Olivine

The distribution of olivine compositions within the Site 839 units is shown in Figure 3. The conspicuous phenocrystal to microphenocrystal olivine occurring in the Unit 3-type lavas is relatively magnesian, with compositions varying from Fo₈₇ to Fo₉₂, the slightly less magnesian compositions occurring within the microphenocrysts. Compositions across individual phenocrysts are relatively constant, commonly lying between Fo₉₀ to Fo_{91.5}. However, narrow rims with compositions from Fo₈₆ to Fo₈₈ are normally present. Olivines within Unit 4, occurring as phenocrystal to microphenocrystal sizes, range from Fo₈₂ to Fo₉₀, slightly less magnesian than found in Unit 3-type. Within Unit 1, olivine is a less common phenocrystal and groundmass



Figure 2. Histograms showing the distribution of phenocrystal and groundmass plagioclase compositions in Site 839 volcanic units, together with comparative data from basaltic andesites of the modern Tofua Arc (islands of Tafahi, Late, and Hunga Ha'apai; after Ewart, 1976, and Ewart et al., 1973), and the northern Tonga boninitic lavas from Stations 21 and 23 (after Falloon et al., 1989; Falloon and Crawford, 1991). Site 839 specimens used for this, and accompanying mineralogical plots are as follows: Unit 1 = 135-839B-12R-2, 14–19 cm; -13R-2, 25–30 cm; and -15R-4, 113–118 cm. Unit 2 = 135-839B-18R-1, 6–9 cm, and -18R-1, 18–23 cm. Unit 3 = 135-839B-20R-1, 29–33 cm; -22R-1, 6–9 cm; -23R-1, 0–6 cm; -25R-1, 33–38 cm; and -25R-1, 38–41 cm. Unit 4 = 135-835B-25R-1, 48–53 cm. Unit 9 = 135-839B-29R-1, 134–136 cm; -30R-1, 79–84 cm; -31R-1, 7–12 cm; -35R-1, 7–11 cm; -35R-1, 57–59 cm; -38R-1, 8–12 cm; and -41R-1, 15–18 cm.

phase, exhibiting compositions from Fo_{81} to Fo_{87} . Allan (this volume) records slightly more magnesian olivine phenocrysts occurring within the finest-grained upper portion of Unit 1.

The occurrence of such magnesian olivines is of interest in the context of the Lau Basin–Tonga region. Forsteritic olivines are recorded from the modern Tofua Arc lavas at Tofua (near Fo₉₀; Bauer, 1970), Metis Shoal (Fo₉₃; Melson et al., 1970), and more extensively in the northern Tonga boninites, in which compositions ranging from Fo₇₈ to Fo₉₄ are recorded (Falloon et al., 1989; Falloon and Crawford,



Figure 3. Histograms showing the distributions of phenocrystal and microphenocrystal olivine compositions in Site 839 volcanic units, together with compositional ranges reported from the northern Tonga boninitic lavas from Stations 21, 23, and 24 (references as in caption to Fig. 2).

1991). Within the modern Lau Basin spreading centers, Sunkel (1990) records compositions extending from $Fo_{88.8}$ to $Fo_{91.3}$ in ELSC lavas, and from $Fo_{68.2}$ to $Fo_{90.6}$ in some Valu Fa lavas. In the Central Lau Spreading Center (CLSC), the Peggy Ridge, and at Sites 834 through 836, olivine compositions extend to $Fo_{89.9}$ (e.g., Frenzel et al., 1990; Hawkins and Melchior, 1985; Ewart et al., this volume; Hawkins and Allan, this volume). These compositions plausibly reflect the extent of how refractory the magma sources are within these different subregions of the Lau-Tonga system, the most magnesian compositions reflecting the most refractory sources (e.g., Duncan and Green, 1987). The occurrence, therefore, of highly magnesian olivines in the Unit 3-type lavas of Site 839 is considered petrogenetically significant, the site itself lying well within the Lau Basin.

Pyroxenes

Pyroxene compositions are illustrated in Figure 4 for Units 1 to 4, and 9. The pyroxenes of Units 3 and 4, comprising phenocrysts and microphenocrysts, lie predominantly in the diopsidic augite and magnesian augite fields, extending to subcalcic augite compositions. No Ca-poor compositions, however, were found. The subcalcic compositions, in some grains in Unit 4 also exhibiting limited Fe-enrichment, occur most characteristically either as microphenocryst rims or in smaller microphenocrystal grains. The overall compositional ranges of the pyroxenes of Units 3 and 4 are similar to those documented by Duncan and Green (1987) in some of the Troodos picritic lavas.

Pyroxenes in the Unit 1 diabasic tholeiite, and the basaltic andesite of Units 2 and 9 are quite distinct from those in Units 3 and 4, most notably in the occurrence of orthopyroxenes, the development of a complete range of subcalcic to low-Ca groundmass compositions, and the occurrence of relatively Fe-enriched compositions in some of the finer grained groundmass grains. For comparison, Figure 4 plots the compositions of phenocrystal and groundmass pyroxenes from the northern Tongan boninitic suite, and modern Tofua Arc basaltic andesites. It is evident that these Tofua basaltic andesite pyroxenes show similar compositional ranges to the Unit 2 and Unit 9 pyroxenes,



Figure 4. Plots of groundmass and phenocrystal pyroxene compositions, expressed in terms of Ca, Mg, and Fe + Mn (atomic%), in Site 839 volcanic units. Comparative data are also presented for the northern Tonga boninitic lavas of Stations 23 to 25 (references as in caption to Fig. 2), and the basaltic andesites of the modern Tofua Arc (islands of Tafahi, Late, and Hunga Ha'apai; after Ewart, 1976). Where both solid circles and crosses are shown, the solid circles = phenocrysts and the crosses = groundmass pyroxenes.

although the groundmass pyroxenes extend to more Fe-enriched compositions. The northern Tonga boninitic lavas differ with respect to their more magnesian orthopyroxene and diopsidic augite phenocrysts.

Cr-spinels

Allan (this volume) has given a detailed description of the occurrence and chemistry of Cr-spinels occurring in lavas from Sites 834, 836, and 839. In Site 839, Cr-spinel occurs in Units 1, 3, and 4. In Unit 1, it occurs as embayed and rounded megacrysts (up to 1.1 mm diameter) and glomerocrysts, and as small euhedral inclusions within phenocrystal olivine. The groundmass spinel is titaniferous magnetite. Within Unit 3, Cr-spinel occurs as euhedral crystals in the groundmass, with the largest crystals between 2- and 3-mm diameter; as inclusions within olivine phenocrysts and microphenocrysts; and as rare inclusions in phenocrystal clinopyroxene. Cr-spinels in Unit 4 occur only as sparse, small inclusions in olivine phenocrysts and microphenocrysts.

Allan (this volume) has shown that the spinels have high Cr/(Cr + Al + Fe³⁺) ratios, varying from 0.52 to 0.76, and Mg/(Mg + Fe²⁺ ratios from 0.27 (rims) to 0.75 (cores). Within the main body of Unit 1, however, the Mg/(Mg + Fe²⁺) ratios of the Cr-spinels range between 0.45 to 0.64, and do not possess such magnesian cores as found in spinels in the uppermost zone. From spinel-melt Mg-Fe²⁺ exchange equilibria, Allan (this volume) estimates the core compositions to have been in equilibrium with highly primitive melts with Mg/(Mg + Fe²⁺) of 0.75 to 0.8, and further suggests that the zoning implies magma mixing between these primitive spinel-bearing melts and more evolved spinel-barren lavas [Mg/(Mg + Fe²⁺) < 0.6] shortly before eruption.

Summary

Mineralogically, the Site 839 lavas fall into three groupings; the picritic basalts of the Unit 3-type and Unit 4; the basaltic andesites of Unit 9-type; and Unit 1, which in many respects is intermediate

between the previous two types. The basaltic andesites are shown to be very similar in both phenocrystal and groundmass mineralogy to the modern Tofua Arc basaltic andesites. A particularly characteristic feature is the occurrence of anorthitic core areas in plagioclase phenocrysts. Such highly calcic compositions are unlikely to represent compositions in equilibrium with the basaltic andesite melts, and are thus thought to represent inherited compositions from more primitive melts, which themselves must have been characterized by very low Na/Ca ratios (Falloon et al., 1989).

The Unit 3-type picritic basalts are characterized by forsteritic olivine phenocrysts, and Cr-rich Cr-spinels with highly magnesian cores. Allan (this volume) has shown that these Cr-spinels core compositions cannot have precipitated from the lava compositions in which they are found, and this similarly applies to the olivine phenocrysts (see also Ewart et al., this volume). Allan (this volume) notes the similarity of the Site 839 Cr-spinels to those in boninitic melts, and the implication that the inferred highly primitive melts from which the Site 839 Cr-spinels and olivines have precipitated were derived from highly depleted lherzolite or harzburgite source(s). A similar interpretation also seems to apply to Unit 4 lavas.

Unit 1 contains similar Cr-spinels, and at least in the uppermost, finest-grained zone, forsteritic olivines (Allan, this volume), also suggesting inherited compositions from a more primitive precursor. Such extreme compositions have not yet been found, however, in the main body of this unit. Unit 1 is clearly tholeitic, as shown by the partially resorbed and rounded olivines with overgrowths of pigeonite and/or orthopyroxene, and the extensive development of subcalcic pyroxene compositions. As noted, therefore, this unit is considered to be mineralogically intermediate between the picritic basalts and basaltic andesite units.

CHEMISTRY

Interunit Variations

Data sources utilized in the following section are from Table 1; Ewart et al. (this volume); shipboard data (Parson, Hawkins, Allan,



Figure 5. Compositions of whole-rock and glass chemistries from Site 839 plotted in terms of olivine (Oliv), silica (Qtz), and clinopyroxene (Cpx), as projected from plagioclase. Data subdivided according to phenocryst assemblage. The solid curved lines are the 1-atm. cotectics and reaction curves (after Grove and Bryan, 1983), whereas the dotted curves are the inferred cotectics at $PH_2O = 1000$ bar (Grove et al., 1982). Projection scheme also after Grove et al. (1982). The tie-line joins a whole-rock-matrix pair from Unit 3. Also shown are the two-pyroxene-plagioclase basaltic andesites and andesites from Sites 836 to 838, which plot in the same region at the Unit 9-type lavas of Site 839. The general fields of the Unit 1-, 3-, 4-, and 9-type lavas are labeled.

et al., 1992); and K. Nilsson (unpubl. glass microprobe analyses, 1992). Major element compositions are shown (Fig. 5) projected from plagioclase on to the olivine(Oliv)-clinopyroxene(Cpx)-silica(Qtz) plane. Also plotted are glasses from Units 3, 4, and 9, together with the two-pyroxene-plagioclase lavas from Sites 836 through 838. The data are subdivided according to phenocryst assemblage. The four petrographic groupings of the lavas within Site 839 are clearly separated on this plot; the Unit 3-type compositions project within the olivine field, whereas the single Unit 4 analysis projects very close to the olivine-augite boundary curve, consistent with the petrography of this lava. A control on the possible effects of crystal-liquid fractionation is provided by the separated matrix-whole rock pair from Unit 3 (Samples 135-839B-25R-1, 27-32 cm (matrix) and 33-41 cm; see table 4 in Ewart et al., this volume). Of particular significance is the projected position of the matrix (joined by tie-line to rock composition in Fig. 5), which lies within the compositional field of Unit 1, suggesting a possible crystal-liquid lineage between the Unit 1- and Unit 3-type lavas.

The two-pyroxene-plagioclase basaltic andesites, and their coexisting glasses, plot appropriately within the low-Ca pyroxene fields (Fig. 5), consistent with their mineralogy, and coincident with the mineralogically equivalent lavas (basaltic andesites and andesites) from Sites 836 to 838. Unit 1 compositions project below the twopyroxene fields, lying on the inferred 1 Kb PH₂O boundary curve (Grove et al., 1982). This also suggests a possible liquid-crystal relationship between the Unit 1 and Unit 9-type magmas; furthermore, the fact that the Unit 9-type, Unit 1, and Unit 3 matrix compositions all project on to the 1-Kbar water pressure curves implies significant partial water pressures during their crystallization; the strongly vesicular character of these lavas is significant in this context. Bryan et al. (this volume) present further experimental phase equilibria relevant to the extent of hydrous crystallization of these magmas.



Figure 6. Variation diagrams for Site 839 lavas showing variations of FeO^{*}, Na₂O, TiO₂, Sr, Zr, and Ni vs. MgO. The tie-lines join the whole rock-matrix pair from Unit 3.

Although the Unit 1 lavas and the Unit 3 matrix compositions project on to the 1-Kbar olivine-augite boundary curve, the analyzed Unit 3 and 4 glasses, in fact, project on to the 1-bar boundary curve (Fig. 5). The reason for this discrepancy between the rock and glass data is unknown, but it could represent analytical bias in the different techniques used for the two groups of data. Alternately, the glass may represent low pressure compositions, reflecting continued microphenocryst-liquid fractionation during magma emplacement and eruption.

To evaluate the relationships between the units further, a series of variation diagrams are presented (Fig. 6), in which FeO^{*} (= total Fe as FeO), TiO₂, Sr, Na₂O, Ni, and Zr are plotted vs. MgO. It is noted that the trace elements are omitted in the case of the glasses, as the major and trace elements for these were not measured on the identical aliquots of samples. In each plot, a series of reasonably coherent and continuous trends are present, consistent with crystal-liquid fractionation involving early removal of olivine \pm clinopyroxene. This results in enrichments of TiO₂, Sr, Zr, Na₂O, and at a more advanced stage, also FeO^{*}. In this context, it is relevant to note the strong enrichments of FeO^{*}, TiO₂, and Na₂O in the Unit 2 and 9 glasses, reflecting the absence of phenocrystal Fe-Ti oxides, and the highly calcic plagio-clase phenocryst compositions, respectively.

Superimposed on the overall element variation trends are the distinct, often cross-cutting element variation trends of the individual units, being especially pronounced in the FeO* and Na₂O vs. MgO plots for Unit 1 and the Unit 3-types. Although secondary mobility of Na₂O could perhaps account for the within-unit Na₂O variations, it is thought more likely that these trends are real and relate to local fractionation processes within each unit. These could, for example, result from fractionation within the eruptive conduit systems, localized within-flow crystal fractionation, or magma mixing processes within the pre-eruptive magma systems (e.g., Allan, this volume).

Table 1. Trace element and isotopic data for Hole 839B lavas.

Core, section:	12R-2 84-87	13R-2 100-104	18R-1 0-6	19R-1 0-5	19R-1 15-19	19R-1 38-41	21R-1 53-56	23R-1 32-35	25R-1 48-53	27R-1 7-11	27R-1	29R-1 39-43	29R-1	36R-1 32-37	37R-1	42R-1
Unit:	1	1	2	2	3	3	3	3	40-55	5	6	9	9	9	9	9
Major elements ((wt%):					30.450										
SiO ₂		-	55.87	-	53.25	52.71	52.81	52.97			53.03		-			55.72
TiO ₂			1.07		0.66	0.61	0.68	0.68			0.65				÷===)	1.02
$Al_2\tilde{O}_3$	_	1000	14.76		16.31	17.08	16.05	15.78			16.40	-				14.64
FeO	—	7777	11.65		8.69	8.36	9.26	8.82		_	8.63		_	_		11.92
MnO	-		0.17		0.18	0.07	0.14	0.14	-		0.16	—	-		-	0.20
MgO	_		4.39		6.76	6.37	6.77	6.90			6.79					4.26
CaO	_		8.91	_	11.85	12.40	12.05	12.51			11.88		\rightarrow			9.11
Na ₂ O	—		2.57		1.91	1.95	1.89	1.84			1.98		-	(<u> </u>	_	2.50
K ₂ O	_		0.47	—	0.32	0.30	0.30	0.30	-	-	0.33		_	_		0.48
P_2O_5	_		0.14	-	0.07	0.14	0.06	0.07	_	-	0.15	_	—	_	-	0.15
Trace elements ()	ppm):															
Rb	3.49	4.96	6.64	8.30	4.39	4.28	3.85	4.66	2.73	10.42	4.63	10.59	10.43	7.25	5.73	5.79
Sr	150	154	195	209	153	151	139	156	131	230	150	240	247	204	193	229
Y	15.1	15.4	23.6	23.7	14.6	14.5	13.3	15.0	15.2	21.2	14.1	20.8	21.6	21.4	19.7	21.2
Zr	21.2	22.1	39.0	40.4	25.6	25.9	23.9	26.2	20.4	42.5	25.3	42.1	42.5	35.9	33.2	38.7
Nb	0.24	0.26	0.39	0.51	0.37	0.34	0.33	0.30	0.18	0.51	0.29	0.54	0.54	0.33	0.28	0.40
Cs	0.11	0.16	0.15	0.15	0.09	0.11	0.11	0.12	0.07	0.18	0.12	0.17	0.15	0.14	0.12	0.11
Ba	45.1	44.4	73.6	72.2	48.4	47.8	45.6	48.5	38.2	106.9	49.6	107.0	105.0	73.9	71.1	76.1
La	1.48	1.52	3.01	2.99	2.03	1.89	1.90	2.01	1.12	3.27	1.93	3.21	3.24	2.02	1.87	2.60
Ce	4.26	4.27	7.86	8.13	5.25	5.22	4.79	5.40	3.23	8.70	5.56	8.57	8.51	5.67	5.44	7.25
Pr	0.71	0.67	1.29	1.26	0.85	0.86	0.79	0.82	0.57	1.36	0.78	1.31	1.25	1.00	0.88	1.20
Nd	4.17	4.04	7.60	7.46	4.84	4.59	4.33	4.73	3.43	7.73	4.97	7.48	7.40	5.71	5.59	6.49
Sm	1.47	1.64	2.64	2.56	1.49	1.70	1.52	1.72	1.41	2.41	1.59	2.35	2.39	2.15	2.11	2.43
Eu	0.62	0.59	1.01	0.91	0.63	0.61	0.62	0.58	0.55	0.87	0.68	0.85	0.86	0.82	0.77	1.00
Gd	2.17	2.23	3.66	3.36	2.21	2.09	2.07	2.12	1.97	3.27	2.00	3.14	3.13	2.76	2.94	3.06
Tb	0.38	0.36	0.51	0.60	0.29	0.30	0.30	0.34	0.31	0.57	0.31	0.51	0.54	0.48	0.53	0.47
Dy	2.57	2.49	3.85	3.73	2.42	2.37	2.16	2.24	2.37	3.42	2.32	3.32	3.35	3.14	3.10	3.22
Ho	0.59	0.56	0.85	0.83	0.47	0.47	0.51	0.55	0.54	0.74	0.50	0.67	0.66	0.71	0.64	0.82
Er	1.61	1.64	2.35	2.44	1.42	1.32	1.33	1.47	1.48	2.22	1.26	2.16	2.10	2.12	1.99	2.12
Im	0.22	0.23	0.40	0.38	0.22	0.19	0.20	0.23	0.23	0.33	0.24	0.34	0.34	0.32	0.31	0.28
YD	1.40	1.46	2.25	2.19	1.38	1.37	1.35	1.45	1.31	2.08	1.55	1.90	1.93	1.86	1.89	1.99
Lu	0.25	0.29	0.42	0.46	0.23	0.20	0.21	0.22	0.23	0.58	0.20	0.39	0.55	0.41	0.36	0.31
HI	0.71	0.81	1.45	1.30	0.80	0.84	0.79	0.78	0.72	1.34	0.82	1.27	1.33	1.11	1.04	1.13
la	0.03	0.02	0.04	0.05	0.08	0.45	0.06	0.38	0.05	0.05	0.05	0.07	0.08	0.02	0.06	0.05
W	0.02	0.02	0.09	0.05	0.09	0.05	0.04	0.05	0.04	0.04	0.00	0.05	0.05	0.05	0.04	0.05
11 Db	0.05	0.05	1.12	0.10	0.12	0.15	0.12	0.15	0.09	0.15	0.10	0.28	0.09	0.05	0.06	0.06
PD	0.45	0.55	1.12	1.15	0.08	0.14	0.08	0.81	0.02	0.25	2.01	1.38	2.33	1.20	1.12	1.29
In	0.14	0.15	0.27	0.50	0.18	0.18	0.17	0.17	0.10	0.33	0.18	0.32	0.57	0.17	0.10	0.25
0	0.08	0.08	0.15	0.10	0.08	0.08	0.09	0.07	0.05	0.19	0.06	0.54	0.10	0.09	0.08	0.10
Isotope analyses:																
200Pb/204Pb	18.684	18.710	18.674	18.689	18.659	18.654	18.659	18.676	18.664	18.712	18.667	18.712	18.692	18.663	18.659	18.669
207 Pb/204 Pb	15.539	15.548	15.519	15.536	15.518	15.514	15.519	15.535	15.536	15.545	15.523	15.540	15.522	15.537	15.530	15.515
208Pb/204Pb	38.261	38.293	38.192	38.247	38.182	38.168	38.170	38.222	38.198	38.280	38.193	38.264	38.209	38.219	38.193	38.176
Sr/80Sr	_	0.703201		0.703081	N Starson	0.703040			0.703093	0.703175	0.703043	0.703173	0.703159	0.703407	0.703116	
Nd/144Nd			0.513062	0.513059	0.513074	0.513074	0.513089	0.513084	0.513092	0.513082	0.513079	0.513084	0.513056	0.513094	0.513096	0.51308

Notes: Major element data based on electron microprobe analyses of glass (K. Nilsson). Trace elements by ICP-MS (University of Durham; J. Hergt). Isotopic analyses at Open University (J. Hergt). Total Fe expressed as FeO.



Figure 7. N-MORB normalized (Sun and McDonough, 1989) element abundance plots for the four main petrographic types of Site 839. The shaded zones represent the envelope of dominant compositions. Open circle represents outlying data point. Plots based on XRF and ICP-MS data.

Trace Element Abundance Patterns

N-MORB-normalized trace element abundance patterns, and chondrite normalized REE patterns, are illustrated (Figs. 7–8) for the samples representing the main petrographic groupings within Site 839. One feature that is immediately apparent is the clear "arc-like" trace element patterns, these being present within each unit. These "arc" signatures are seen in the very strong Nb and Ta depletions; in the low levels of REEs, Zr, Hf, Ti, and Yb; and especially in the relative enrichments of Cs, Rb, and Ba, and, to a lesser extent, K, U, Pb, and



Figure 8. Chondrite-normalized (Sun and McDonough, 1989) plots of the REEs for lava samples from Site 839, based on ICP-MS data.

Sr. The patterns compare very closely with those of the Valu Fa and the Tofua and Kermadec arc lavas presented in Ewart et al. (this volume), and are distinct from the other lavas recovered at Sites 834–838. A similar conclusion can be reached from the REE data (Fig. 8), illustrating the relatively low REE abundances and the LREE depletions. In these aspects, the Site 839 data are again very closely comparable with the modern Tofua Arc lavas (Ewart et al., this volume).

To evaluate the tectonomagmatic relationships further between the Site 839 lavas, the modern Lau Basin spreading centers, and modern Tonga-Kermadec arc lavas, La/Nb vs. Ba/Nb (using only ICP-MS data for Nb for Leg 135 data) is presented (Fig. 9). The similarities between the Site 839, the Valu Fa, and the Tonga-Kermadec arc lavas are apparent, entirely consistent with the previously presented mineralogical data. The second aspect shown by the plot is the general pattern of change from N-MORB-like in lavas from Sites 834 and 836, and the Central and Eastern Lau spreading centers (CLSC and ELSC), toward more arc-like compositions. As previously shown (Ewart et al., this volume), these plots clearly emphasize the distinctive character of the Site 839 magmas relative to those recovered from Sites 834 to 838.

Discussion: Possible Roles of Crystal Fractionation and Mixing Processes

In the previously presented mineralogy, it was shown that the highly forsteritic olivines within the picritic lavas of Unit 3-type and Unit 4, and the highly calcic plagioclase phenocryst cores in the Unit 9-type lavas, are unlikely to represent compositions in equilibrium with those of the erupted melts. By implication, these olivines and plagioclases would represent phases inherited from more primitive precursor melts. Allan (this volume) has reinforced these observations by showing, quantitatively, that the zoning in the large Cr-spinels in Units 3, 4 and 1 (at least in part) require that these phases precipitated from primitive, highly magnesian melts, again implying that the erupted lavas are hybrid. Allan has thus warned against use of whole rock, and even glass data, of the Site 839 lavas in simple petrogenetic interpretations. Interestingly, however, the Site 839 isotopic data (see following sections) do not obviously display mixing arrays (c.f. data for Site 834; Hergt and Nilsson, this volume), but in fact define relatively restricted compositional fields in the Pb-Sr-Nd isotopic compositional space. This implies either remarkably efficient mixing, or isotopically homogeneous magma source(s) for all Site 839 eruptive units. In the case of Unit 1 and the picritic Unit 3, Allan (this volume) suggests that one explanation is infusion of new, evolved magma from a separate magma batch into the lower crystal-rich,

Table 2. Results of numerical modelin	g of selected	parent-derivative combinations	within Hole 839B lavas.
---------------------------------------	---------------	--------------------------------	-------------------------

	Parent	Derivative		Parent	Derivative		Parent	Derivative			Parent	Derivative	
Hole: Core, section: Interval (cm): Unit: Type:	839B 25R-1 33-41 3 Rock	839B 25R-1 27–32 3 (matrix) Actual	Estimated	839B Average 3 Rock	839B Average 1 Actual	Estimated	839B 13R-2 25-30 1 Rock	839B 35R-1 7–11 9 Actual	Estimated	Estimated	839B 13R-2 25–30 1 Rock	839B 38R-1 8–12 9 Actual	Estimated
											-		
$\frac{\Sigma R^2}{F}$	1 1	_	0.34 0.647	-		0.13 0.751		-	0.084 0.751	0.078 0.729	_	_	0.080 0.745
Minerals: Oliv%	_	_	81.5		-	56.2		-	22.9	17.8	-	_	23.2
Cpx%	_	_	(Fogg) 18.5	_		(Fo86) 30.3			(Fo ₈₆) 53.5	(Fo ₈₆) 48.7	-	-	(Fo ₈₆) 51.4
Plag% Opx%		-	_	_	=	13.5	_	_	23.6	25.9 7.6	_	_	25.5
Major element	s (wt%):												
TiO ₂ Al ₂ O ₃ FeO* MnO MgO	0.52 10.69 9.18 0.16 20.13	0.70 16.27 8.86 0.16 7.97	0.77 16.20 8.98 0.15 7.86	0.58 12.63 9.14 0.17 14.74	0.62 15.00 9.02 0.17 9.28	0.74 14.94 9.09 0.17 9.22	0.68 15.33 8.73 0.16 8.81	0.86 17.02 9.53 0.17 4.98	0.84 17.13 9.60 0.17 5.09	0.87 17.11 9.63 0.17 5.07	0.68 15.33 8.73 0.16 8.81	0.85 16.96 9.52 0.17 5.00	0.85 17.00 9.65 0.17 5.03
Na ₂ O K ₂ O P ₂ O ₅	1.32 0.21 0.05	1.73 0.34 0.08	2.03 0.32 0.08	1.24 0.29 0.07	1.35 0.25 0.07	1.58 0.38 0.09	1.68 0.27 0.08	2.03 0.50 0.08	2.11 0.36 0.11	2.16 0.37 0.11	1.68 0.27 0.08	10.34 1.93 0.46 0.08	2.12 0.36 0.11
Trace elements	s (ppm):	4.0	57	5.0	0.0		10	67	12.0	12.0	10	62	12.2
Ba Sr Zr Y Ni La Ce Nd Sm Eu Gd Yb Lu	32.2 106 25.6 11.2 604 0.23 1.55 4.05 3.71 1.33 0.46 1.59 1.07 0.16	$\begin{array}{c} 4.9.8\\ 4.9.8\\ 166\\ 35.0\\ 15.4\\ 92\\ 0.38\\ 2.53\\ 6.14\\ 5.68\\ 2.01\\ 0.70\\ 2.41\\ 1.54\\ 0.23\end{array}$	$\begin{array}{c} 49.3\\ 163\\ 37.9\\ 15.9\\ 7.3\\ 0.35\\ 2.36\\ 6.15\\ 5.57\\ 1.99\\ 0.68\\ 2.35\\ 1.58\\ 0.24\end{array}$	$\begin{array}{c} 39.6\\ 130\\ 32\\ 14\\ 308\\ 0.30\\ 1.75\\ 4.62\\ 4.18\\ 1.48\\ 1.48\\ 1.82\\ 1.23\\ 0.18\end{array}$	$\begin{array}{c} 9 \\ 49 \\ 140 \\ 30 \\ 13 \\ 137 \\ 0.39 \\ 1.97 \\ 5.18 \\ 4.74 \\ 1.74 \\ 1.74 \\ 0.69 \\ 2.34 \\ 1.70 \\ 0.32 \end{array}$	$\begin{array}{c} 5.3\\ 52\\ 161\\ 41.5\\ 17.2\\ 41\\ 0.40\\ 2.28\\ 5.99\\ 5.37\\ 1.89\\ 0.67\\ 2.30\\ 1.56\\ 0.23\\ \end{array}$	$\begin{array}{c} 100\\ 51.6\\ 137\\ 30.7\\ 13.4\\ 125\\ 0.39\\ 1.97\\ 5.18\\ 4.74\\ 1.74\\ 0.69\\ 2.34\\ 1.70\\ 0.32 \end{array}$	$\begin{array}{c} 3.7.6\\ 169\\ 40.7\\ 18.1\\ 20\\ 0.30\\ 2.44\\ 5.47\\ 5.24\\ 2.00\\ 0.72\\ 2.48\\ 1.81\\ 0.27\end{array}$	$\begin{array}{c} 67.2\\ 161\\ 39.9\\ 15.7\\ 51\\ 0.51\\ 2.52\\ 6.59\\ 5.93\\ 2.16\\ 0.83\\ 2.84\\ 2.07\\ 0.39\end{array}$	69.1 162 44.1 16.0 51 0.53 2.58 6.72 6.08 2.21 0.85 2.91 2.12 0.40	$\begin{array}{c} 51.6\\ 137\\ 30.7\\ 13.4\\ 125\\ 0.39\\ 1.97\\ 5.18\\ 4.74\\ 1.74\\ 0.69\\ 2.34\\ 1.70\\ 0.32 \end{array}$	76.6 169 41.7 19.2 21 0.28 2.22 6.08 5.93 2.28 0.83 2.81 1.90 0.28	$\begin{array}{c} 67.7\\ 161\\ 40.2\\ 15.8\\ 50\\ 0.52\\ 2.54\\ 6.64\\ 5.98\\ 2.18\\ 0.84\\ 2.87\\ 2.09\\ 0.39\end{array}$

 Table 3. Partition coefficients used in the compilation of Table 2.

Element	Olivine	Clinopyroxene	Plagioclase	Orthopyroxene
Rb	0.00018	0.11	0.10	0.0006
Ba	0.00086	0.077	0.15	0.014
Sr	0.00019	0.10	1.60	0.07
Zr	0.10	0.10	0.037	0.08
Y	0.068	0.80	0.05	0.25
Ni	13.2	2.0	0.05	6.5
Nb	0.01	0.05	0.01	0.02
La	0.0018	0.158	0.22	0.238
Ce	0.0018	0.223	0.169	0.301
Nd	0.0018	0.360	0.114	0.144
Sm	0.0019	0.424	0.091	0.141
Eu	0.0019	0.487	0.333	0.133
Gd	0.0020	0.569	0.073	0.131
Yb	0.0094	0.563	0.021	0.257
Lu	0.0118	0.550	0.0156	0.280

Notes: Based on data in Ewart and Hawkesworth (1987) and an unpublished data base compiled by A. Ewart and A.R. Duncan (see also Ewart and Griffin, this volume).

cumulate portion of a primitive magma body, with subsequent rapid eruption. Alternately, Allan suggests the possibility of self-mixing within a strongly zoned magma chamber.

In the following discussion, the possibility of crystal fractionation within, and linking the Site 839 units is explored through least-squares modeling, some results of which are shown in Table 2. These are based on the best least-squares fits of major element compositions (measured by ΣR^2 , the sum of squares of residuals), for given mineral phase assemblages (based on microprobe analyses); these least-squares solutions are then used to calculate trace element abundances in the derivative liquids, assuming Rayleigh fractionation. The parental, actual, and estimated derivative compositions are shown in Table 2, with a selection of trace element data. The partition coefficients used are given in Table 3.

To test the applicability of the partition coefficients, the results for the Unit 3 matrix–whole-rock pair are shown, based on olivineclinopyroxene fractionation. The agreement between the calculated and analyzed major and trace element data are considered satisfactory. The latter agree to within 6% (relative) for the REE data; except for Ni and Cr, other elements mostly fit to within 10%–15% of the analyzed values. The marked Cr discrepancy can be attributed to the difficulty of accurately modeling Cr-spinel fractionation. The Ni discrepancies are notable. The K_D^{Ni-ol} used (13.2) is based on measured values by proton microprobe (Ewart and Griffin, this volume), whereas backcalculating the K_D^{Ni-ol} , using the whole rock-matrix data, indicates a bulk K_D^{Ni} value of 5.3. As the larger olivines are probably xenocrystal, the measured K_D^{Ni-ol} is, therefore, unlikely to represent a true "equilibrium" value (see previous mineralogical discussion). The calculations for the other elements, however, suggest that the remaining partition coefficients used are appropriate to the magma systems being modeled.

The remaining models illustrated in Table 2 involve potential or idealized fractionation of Unit 1 from Unit 3, and two sets of solutions linking (by model crystal-liquid fractionation) Units 3 and 9. The Unit 1 to Unit 3 solutions are based on averaged values for each unit, on account of the wide variability of the Unit 3 compositions, a procedure not ideal for such calculations. Nevertheless, trace element fits are predominantly within 10%–20% of the average measured values; Ni and Cr are again notable exceptions, whereas Rb, Zr, and Y show 30% relative discrepancies between observed and calculated abundances.



Figure 9. Ba/Nb vs. La/Nb ratios comparing Site 834 through 839 lavas, and the forearc Site 841 dike/sill complexes. Also shown are the generalized fields for the Tonga-Kermadec arc lavas, the northern Tonga boninites, and the lavas of Valu Fa, King's Triple Junction, CLSC, ILSC, and ELSC.

The results do suggest, however, that the derivation of Unit 1-type magma from a parent with Unit 3-type chemistry is a plausible process, involving removal of olivine (Fo₈₆), minor clinopyroxene, and minor plagioclase (An₈₉).

Least-squares solutions linking Unit 1 and Unit 9-type magmas give exceptional fits to major element data, involving removal of olivine (Fo₈₆), plagioclase (An₈₉), clinopyroxene, with and without orthopyroxene. The latter phase is permitted in some, but not all, solutions. Comparison of calculated trace element data in the third model indicates agreement to within 5%–15% (no orthopyroxene), and to within 5%–20% (including orthopyroxene). Again, however, discrepancies for Ni, Cr, Rb, Lu, and Nb are apparent. The fourth model shows particularly good agreement, which for most trace elements is better than 10% (relative). Exceptions include Rb (and Cs), which are inferred to have undergone mild disturbance in Unit 1 (see Parson, Hawkins, Allan, et al., 1992), Ni, Cr, Lu, and Nb. The latter element (and Ta), are "excessively" depleted in the Unit 9 basaltic andesites compared with the Unit 1 basalts (i.e., the Unit 9-type magmas are depleted with respect to Nb, Rb, and Lu relative to Unit 1).

The purpose of the previous calculations has been to evaluate the plausibility of fractional crystallization processes interlinking the chemistry of the major unit-types at Site 839, using analyzed mineral phases from these units as the model fractionating phases. The fits of the major element data are remarkably good, and many of the trace elements give acceptable agreement between observed and calculated abundances. Consistent discrepancies occur, however, for Ni, Cr, Rb (and Cs), Lu, and Nb (and Ta) between the models linking Unit 1 and Unit 9-type lavas, and Ni, Cr, Rb, Zr, and Y between Unit 1 and Unit 3-type lavas. Nevertheless, the results are interpreted as supporting the plausibility of the fractional crystallization derivation of Unit 9-type lavas.

The relative dominance of basaltic andesites in the Tofua Arc is well documented (e.g., Ewart et al., 1977), and these have previously been interpreted as derivative magmas from primitive low-Al₂O₃ arc melts (Ewart and Hawkesworth, 1987). The mineralogical and chemical similarities between the Unit 9-type basaltic andesites and those of the Tofua Arc have already been emphasized. In addition, however, to the trace element discrepancies noted above, the relative stratigraphy of the Site 839 units also argues against a *direct* liquid line of descent linking the magmas of Unit 1, Unit 3-type, and Unit 9-type. It is, nevertheless, suggested that a melt with a bulk chemistry similar to Unit 1 constituted an early phase of the inferred liquid line of descent leading to the basaltic andesites (Unit 9-type). It is also relevant to recall here that the compositions of the matrix sample separated



Figure 10. Pb-isotopic compositions of Site 839 lavas (solid circles) in the context of the regional MORBs, modern Lau Basin spreading center (MLB), Valu Fa (VF), Site 834 (open squares), regional sediments, and the modern Tofua Arc lavas; the latter field excludes the single data point for 'Ata (shaded squares) and the northernmost Tongan volcanoes of Niuatoputapu and Tafahi shown separately. Also shown are data from 'Eua (solid squares) and the data field of Site 841.

from Unit 3 (Sample 135-839B-25R-1, 27-33 cm), and the Unit 3 glasses, converge toward Unit 1 (e.g., Figs. 5-6).

As shown by the phenocrystal olivine and Cr-spinel cores in Unit 3 and the topmost part of Unit 1, together with the highly calcic plagioclase cores in Unit 9-type lavas, there existed within the Site 839 volcanic construct an even more primitive melt, which Allan (this volume) suggests had a Mg/(Mg + Fe²⁺) ratio of 0.75 to 0.8.

ISOTOPE GEOCHEMISTRY

Ewart et al. (this volume) have interpreted the changing geochemical patterns across the Lau Basin, and into and along the Tofua arc, in terms of changing mantle peridotite source characteristics. Specifically, two dominating processes are inferred (cf. Ewart and Hawkesworth, 1987): one being progressive source depletion, whereas the second involves selective LILE-source metasomatism (addition) related to dehydration and metamorphism of the subducting slab. The increasingly arc-like geochemical characteristics are specifically correlated with increasingly depleted mantle sources, while the depletion processes are directly correlated with the melt extraction processes accompanying Lau Basin extension and magmatism.

It is, therefore, relevant to view the isotopic composition of the Site 839 lavas in the context of the whole Lau-Tonga system. Site 839 isotope data are presented in Table 1. Other data sources used are Boespflug et al. (1990), Cole et al. (1990), Ewart and Hawkesworth (1987), Falloon and Crawford (1991), Falloon et al. (1989), Hawkins and Melchior (1985), Jenner et al. (1987), Loock et al. (1990), Oversby and Ewart (1972), Vallier et al. (1991), Volpe et al. (1988), and Hergt and Hawkesworth (this volume).

Pb-isotope data are plotted in Figures 10 and 11, the latter plot providing a more detailed view of the Lau-Tonga data fields. The first



Figure 11. Enlarged Pb-isotope plot illustrating the compositional affinities and possible correlations between lavas of Site 839 (larger solid circles), Valu Fa, Tonga (southern and central volcanoes, excluding 'Ata), 'Ata, the northern Tongan volcanoes of Niuatoputapu and Tafahi, and 'Eua (solid squares).

point to note is the relatively small data field of Site 839 lavas when considered in terms of the range of compositions present in the possible mantle and sediment components that could, in principle, have contributed to the source region(s) of the Site 839 lavas. This implies a relatively well-mixed, or homogenized, source in spite of the range of lava compositions represented. Source homogeneity is also a feature noted by Oversby and Ewart (1972) for the central and southern-central Tongan volcanoes (noting the deviation of the single available analysis from the southernmost volcano of 'Ata, described below).

Hergt and Hawkesworth (this volume) describe two well defined mixing trends in Pb-Pb isotope space, based on the combined available data from the Lau Basin and the Tofua Arc. These trends extend from two separate MORB compositions (i.e. "Pacific" and "Indian" MORB-like compositions) and converge toward isotopic compositions presumed to reflect the components released from the subducting plate beneath Tonga. These authors argue that the original Lau-Tonga Arc (i.e., before backarc basin formation) was underlain by mantle that was isotopically similar to that giving rise to Pacific MORB, further implying that early arc volcanic magmas represent mixtures between this "Pacific" mantle and a slab-derived flux. The only available Pb-isotopic data for these earliest lavas are from 'Eua and Site 841 (Bloomer et al., this volume), and these exhibit relatively high ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb ratios (Figs. 10–11).

During the initial horst-and-graben stages of Lau backarc basin opening, this same "Pacific" asthenospheric mantle source has been tapped, from which magmas ranging from N-MORB to compositions intermediate between N-MORB and arc-type have been erupted (Hergt and Nilsson, this volume; Ewart et al., this volume). The continued opening of the Lau Basin, notably the later phase associated with the onset of true backarc seafloor spreading (propagator driven), coincided with the influx and tapping of asthenospheric mantle with isotopic characteristics typical of "Indian" MORB, specifically into



Figure 12. ¹⁴³Nd/¹⁴⁴Nd vs. ⁸⁷Sr/⁸⁶Sr for the Site 839 lavas (solid circles) compared to the regional MORB data fields, Site 834 (open squares), the modern Lau Basin spreading centers (MLB, excluding Valu Fa), Valu Fa, the Lau Volcanic Group (LVG), Site 841, the Tofua Arc lavas (excluding 'Ata), 'Ata (shaded square), and 'Eua (solid square).

the sub-arc wedge beneath the eastern Lau Basin. Hergt and Hawkesworth (this volume) consequently suggest that island arc lavas erupted after the adjacent propagator-driven sea-floor spreading had been established are mixtures of "Indian" MORB mantle and a slabderived flux. This has resulted in lower ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb ratios in the modern Tofua Arc lavas relative to the older magmas noted above. The two Pb-isotopic trends are therefore explained as reflecting the change from "Pacific" to "Indian" mantle beneath the backarc region with continued opening, rather than by differences in the composition of the inferred slab-derived trace element flux into the mantle wedge.

Two apparent exceptions to this model are noted. The first are the northernmost Tongan volcanoes of Tafahi and Niuatoputapu, both inferred to represent erupted melts from strongly depleted mantle source. This mantle appears not to have been replenished by an "Indian" MORB source and, in fact, the isotopic compositions of the lavas are thought to provide the closest approach to those of the slab-derived component (e.g., Ewart and Hawkesworth, 1987). The second exception is recognized at 'Ata, the southernmost Tongan volcanic island located immediately east of the Valu Fa Ridge, the site at which the southward moving propagator is only now becoming established. Hergt and Hawkesworth (this volume) suggest that 'Ata has retained the original Pacific mantle composition in its source, whereas the Valu Fa magmas are just beginning to show the input of the "Indian" MORB source (i.e. are slightly displaced from the "Pacific" MORB-subduction flux trend toward the "Indian" MORB trend).

The Pb-isotopic compositions of the Site 839 lavas lie along the "Pacific" MORB mixing trend, whereas Pb-, Sr-, and Nd-isotopic compositions lie closer to the lavas from the older arc mantle (e.g., Eua, Site 841, and also 'Ata; Figs. 10–12), compared with the modern Tofua Arc lavas (except for 'Ata). The Site 839 magmas are consequently interpreted here as mixtures between "Pacific" MORB mantle and the inferred slab-derived component. This explains their relatively high ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb ratios, and also clarifies why the Sr- and Nd-isotopic ratios of the Site 839 lavas are displaced toward the "Pacific" MORB field relative to most of the Tofua Arc magmas.

Figure 11 emphasizes the very similar Pb-isotopic compositions existing between the Site 839 lavas and the single analysis from 'Ata, and further suggests that a mixing trend may exist linking the above compositions with 'Eua, and extrapolating further toward the sediment compositions. The limited 'Eua and 'Ata data makes this interpretation highly tentative. Nevertheless, the isotopic similarities between Site 839 and 'Ata are considered important here and are used, together with other geochemical features of the Site 839 lavas, to argue that Site 839



Figure 13. ⁸⁷Sr/⁸⁶Sr vs. Zr/Ba comparing the Site 834 through 839 lavas with those of the Tofua Arc and north Tongan boninitic (Station 21) lavas, together with the generalized fields for the other main volcanic groups within the region. LVG and KVG are the Lau and Korobasaga volcanic groups, respectively, of the Lau Ridge. The mixing curves, calculated between N-MORB source, depleted N-MORB source, and a subduction component, are from Ewart and Hawkesworth (1987). Data for Samoa after Newson et al. (1986), Palacz and Saunders (1986), and Wright and White (1987).

represents an abandoned arc construct (similar to 'Ata today) that has been isolated from the early arc during the seafloor spreading phase of the Lau Basin opening.

Sr- and Nd-Isotope/Trace Element Relationships

In the previous discussion, the influence of a radiogenic "slabderived component" has been inferred, together with prior mantle source depletion processes. Ewart and Hawkesworth (1987) explained the Sr- and Nd-isotopic variations within the Tongan lavas in terms of variable contributions from, and mixing between three source components: namely, N-MORB source, depleted N-MORB source, and a subduction "flux." The balance between source depletion and the addition of a subduction component to the source was inferred through Zr/Ba and Sr/Nd ratios (see also Ewart et al., this volume).

Figure 13 illustrates the Sr-isotope vs. Zr/Ba fields for various Lau-Tonga-Kermadec subregions, including Sites 834 through 839. To minimize the effects of fractionation on the trace element data, only samples with >4% MgO are included. Superimposed on the plot are the unmodified mixing curves of Ewart and Hawkesworth (1987), and interestingly, the enlarged data set presented here are broadly consistent with these previously calculated mixing curves. Nevertheless, considerable variability of compositions exists. A companion plot (not shown) of Nd-isotope vs. Zr/Ba ratios reveals a similar pattern of variation.

The Site 839 data fall within the same compositional space as the Kermadec–Tonga–Lau Ridge arc magmas, and are clearly distinct from the lavas of Sites 834 through 836 (Fig. 13). Moreover, the trends and relative compositions of the Site 839 lavas are consistent with the addition of a subduction component (having isotopic and trace element parameters consistent with those defined by Ewart and Hawkesworth [1987]) into their magma source(s); the latter, however, are not as depleted as the sources of the Tongan magmas, as implied by the Zr/Ba ratios. This inference is also consistent with other aspects of the trace element chemistries of Site 839 and the Tongan lavas, as shown by the data presented in Ewart et al. (this volume).



Figure 14. ⁸⁷Sr/⁸⁶Sr vs. Sr/Nd, comparing the Site 834 through 839 lavas with those of the other Lau-Tonga-Kermadec volcanic groups. Also included are the data from Volpe et al. (1988) for the CLSC and King's Triple Junction (KTJ). Other symbols as in key in Figure 13.

A second feature illustrated by Figure 13 is the existence of two data trends in the higher Zr/Ba ratio region of the data plots. One group is clearly defined by Site 834 and some Site 835 lavas, whereas the second trend, characterized by more radiogenic Sr (and less radiogenic Nd), occurs within the CLSC, ELSC, and some Site 836 lavas. These two trends are correlated with the "Indian" and "Pacific" MORB trends shown in Figure 10. The two trends converge in the compositional space defined by the Valu Fa magmas.

The above picture is complicated further, however, by the data of Volpe et al. (1988), which is not included on Figure 13 because of the lack of Zr/Ba data. These data are included, however, in the plot of 87Sr/86Sr vs. Sr/Nd (Fig. 14). This particular data set provides additional Sr- and Nd-isotopic compositions for the CLSC, the Peggy Ridge, and the region of the King's Triple Junction, in the northeast Lau Basin. The data indicate a greater complexity in the isotopic chemistry of the CLSC, with most data lying within the main CLSC-ELSC-Valu Fa "trend," but with some samples deviating toward more radiogenic compositions (the E-type MORB of Volpe et al. [1988]), although at least one sample seems to lie between the main CLSC data field and the Site 834 data field. The Peggy Ridge data (not illustrated in Fig. 14) show significant variation, some lying within the CLSC field, whereas other samples have even more radiogenic Sr (and unradiogenic Nd) compositions. The occurrence of such radiogenic Sr compositions is significant in the context of the northernmost Lau Province, which is characterized by a mantle significantly more radiogenic in Sr, and less radiogenic in Nd, than the bulk of the central and southern Lau lavas, and most of Tonga and the Lau Ridge lavas (cf. Volpe et al., 1988). This is well exemplified by the King's Triple Junction lavas, the compositions of which clearly overlap those of Niuafo'ou; similar isotopic trends are also evident in the isotopic compositions of some of the boninites in northernmost Tonga (Falloon and Crawford, 1991; Falloon et al., 1989). As pointed out by Volpe et al. (1988), a strong indication exists for the addition of an oceanic-island basalt component into the northernmost Lau Basin mantle, most plausibly emanating from the long-lived Samoan thermal plume. This signature may have spread as far as the Peggy Ridge. It is also consistent with the geophysical data determined by Giardini and Woodhouse (1986), indicating that deeper mantle material is being displaced to the south beneath the northern Lau Basin region.

The most important aspect relevant to Site 839 shown by Figure 14, is again the relatively coherent trend linking the Sr-isotopic–Sr/Nd data among Sites 834, 835, 839, and some of the Site 836 lavas. This trend seems to reflect the western, older Lau Basin province, equated here with the "Pacific" MORB-type mantle source. Significantly, the Site 839 lavas lie at the higher Sr/Nd ratio and thus more radiogenic termination of this trend, consistent with their enhanced "arc-like" geochemical signatures. The northern Tongan volcano of Tafahi defines the high Sr/Nd ratio and the most radiogenic Sr termination of the data trend, consistent with the previous suggestions that these magmas exhibit the closest approach, isotopically, to the slab-derived component.

SUMMARY

The Site 839 lavas define four petrographic groupings: clinopyroxene-olivine tholeiitic basalts (Unit 1); clinopyroxene-olivine picritic basalts, sparsely to strongly olivine phyric (Unit 3-type); a sparsely phyric olivine-clinopyroxene picritic basalt, notable for dominance of clinopyroxene over olivine (Unit 4); and two-pyroxene plagioclase basaltic andesites (Unit 9-type). The Unit 3-type carries phenocrystal olivines with cores in the range from Fo₉₀ to Fo₉₂, and Cr-rich spinels similar to those found within boninitic sequences. The Unit 9-type basaltic andesites contain coexisting augite and orthopyroxene phenocrysts and carry a range of low-Ca and subcalcic groundmass pyroxenes; highly calcic phenocrystal plagioclase is the dominant phenocryst phase; these lavas are petrographically and mineralogically indistinguishable from the modern basaltic andesites of the Tofua Arc.

The highly calcic plagioclase core areas in the Unit 9-type basaltic andesites, and the forsteritic olivine and highly magnesian Cr-spinel megacryst cores that occur in Unit 3-type, Unit 4, and the uppermost part of Unit 1, cannot have precipitated in the lavas in which they occur. Allan (this volume) interprets the Cr-spinels as showing mixing between a highly primitive melt [Mg/(Mg + Fe²⁺) = 0.75–0.8] and a more evolved, spinel-barren melt.

Notwithstanding the evidence for mixing, the major element chemistries of Unit 1 and Unit 9-type lavas are shown to be consistent with the derivation of the basaltic andesites of Unit 9-type, by fractional crystallization, through or from melts of equivalent or similar chemistry to Unit 1. This is also supported by most, but not all, available trace element data. The convergence of the matrix and glass compositions from Unit 3-type lavas toward Unit 1 chemistry is also noted. Nevertheless, the relative stratigraphy of the Site 839 units, and some trace element modeling discrepancies (Ni, Cr, Rb, Lu, and Nb) indicate that the units in question were not themselves directly limited through fractionation processes.

Trace element and TiO_2 and Na_2O data clearly illustrate the arclike affinities of Site 839 magmas. This is seen, for example, in the strong HFSE depletions (relative to N-MORB) and relative enrichments of LILEs. The element abundance patterns are thus very close to those of the Tonga and Kermadec arc lavas, and also Valu Fa, but quite distinct from Site 834, CLSC, and ELSC lavas.

The Pb-isotope data reveal the Site 839 lavas to be compositionally similar to Valu Fa and 'Ata, and slightly further displaced from the compositional field of the southern-central Tongan lavas. A similar relationship is found in the Sr-Nd isotopic composition space. Significantly, the Site 839 magma sources seem to exhibit clear affinities with the "Pacific MORB-type" source, as also illustrated by the Sites 834 and 835 magmas. This is thought to be a source characteristic of the western, older Lau Basin, and apparently isotopically distinct from the source of the younger, eastern, propagator-controlled segment of the Lau Basin.



Figure 15. Two highly schematic maps to illustrate the inferred tectonic evolution, and isolation from the evolving Tofua Arc, of the Site 839 volcanic construct. Solid circles are inferred proto-Tofua Arc, and open circles are newly developing volcanic constructs within the Tofua Arc. Solid triangles represent (schematically) contemporaneous volcanic centers on the Lau Ridge.

When integrated with trace element data, the isotopic data do suggest the addition of a "subduction component"; this, however, is variable in its intensity among Site 839, the Tongan arc magmas, and the older Lau Ridge arc magmas. The differences are attributed, at least in part, to the geochemical effect of a variably depleted mantle source from which the respective magma sequences are inferred to have been derived. Reference to Figures 13 and 14 suggest that the source(s) of the Site 839 lavas (and the Lau Ridge arc lavas) were not as depleted as those of the modern Tongan arc lavas. In fact, the source depletion appears to increase northward along the Tongan arc, correlated with the northward increase in the degree of opening of the Lau Basin (Ewart et al. this volume).

The Site 839 lavas are interpreted as an older remnant of a volcanic construct of a "proto-Tofua Arc," originally developed adjacent to the western margin of the Tonga Ridge. It is suggested that this construct has subsequently been separated from the Tonga Ridge by the influence of the ELSC and Valu Fa propagator, which has effectively severed the Site 839 lavas from near the Tongan Ridge, and left them "stranded" within the Lau Basin, very close to the margin of the western and eastern Lau Basin provinces. A possible scenario is illustrated schematically in Figure 15.

ACKNOWLEDGMENTS

We thank the staff and crew of the *JOIDES Resolution* and Ocean Drilling Program for their enthusiastic and skilled work during the Leg 135 drilling. Analytical work on which this project is based were conducted at the Departments of Earth Sciences at the University of Durham, Open University, Monash University, The University of Queensland and Australian National University. Thanks are owed to staff in these departments for extensive assistance. Thanks are also owed to C.J. Stephens, Centre for Microscopy and Microanalysis, The University of Queensland, for extensive assistance during microprobe analyses, especially in data reduction. The manuscript was greatly improved by comments from J. Allan, J.W. Cole, S.H. Bloomer, and ODP editorial staff. Figures were drafted by Mrs. E. Burdin, The University of Queensland.

REFERENCES*

Bauer, G.R., 1970. The geology of Tofua Island, Tonga. Pac. Sci., 24:333-350.

^{*} Abbreviations for names of organizations and publication titles in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

- Boespflug, X., Dosso, L., Bougault, H., and Joron, J.L., 1990. Trace element and isotopic (Sr and Nd) geochemistry of volcanic rocks from the Lau Basin. In von Stackelberg, U., and von Rad, U. (Eds.), Geological Evolution and Hydrothermal Activity in the Lau and North Fiji Basins, Southwest Pacific Ocean (Results of SONNE Cruise SO-35). Geol. Jahrb., 92:503–516.
- Cole, J.W., Graham, I.J., and Gibson, I.L., 1990. Magmatic evolution of Late Cenozoic volcanic rocks of the Lau Ridge, Fiji. *Contrib. Mineral. Petrol.*, 104:540–554.
- Duncan, R.A., and Green, D.H., 1987. The genesis of refractory melts in the formation of oceanic crust. *Contrib. Mineral. Petrol.*, 96:326–342.
- Ewart, A., 1976. A petrological study of the younger Tongan andesites and dacites and olivine tholeiites of Niuafo'ou Island, S.W. Pacific. *Contrib. Mineral. Petrol.*, 58:1–21.
- Ewart, A., Brothers, R.N., and Mateen, A., 1977. An outline of the geology and geochemistry, and the possible petrogenetic evolution of the volcanic rocks of the Tonga–Kermadec–New Zealand island arc. J. Volcanol. Geotherm. Res., 2:205–250.
- Ewart, A., Bryan, W.B., and Gill, J.B., 1973. Mineralogy and geochemistry of the younger volcanic islands of Tonga, southwest Pacific. J. Petrol., 14:429–465.
- Ewart, A., and Hawkesworth, C.J., 1987. The Pleistocene-Recent Tonga-Kermadec arc lavas: interpretation of new isotopic and rare earth data in terms of a depleted mantle source model. J. Petrol., 28:495–530.
- Falloon, T.J., and Crawford, A.J., 1991. The petrogenesis of high-calcium boninite lavas dredged from the northern Tonga Ridge. *Earth Planet. Sci. Lett.*, 102:375–394.
- Falloon, T.J., Green, D.H., McCulloch, M.T., 1989. Petrogenesis of high-Mg and associated lavas from the north Tonga Trench. In Crawford, A.J. (Ed.), Bonites and Related Rocks: London (Unwin Hyman), 357–395.
- Frenzel, G., Mühe, R., and Stoffers, P., 1990. Petrology of volcanic rocks from the Lau Basin, Southwest Pacific. Geol. Jahrb., Riehe D, 92:395–479.
- Giardini, D., and Woodhouse, J.H., 1986. Horizontal shear flow in the mantle beneath the Tonga Arc. *Nature*, 319:551–555.
- Grove, T.L., and Bryan, W.B., 1983. Fractionation of pyroxene-phyric MORB at low pressure: an experimental study. *Contrib. Mineral. Petrol.*, 84:293– 309.
- Grove, T.L., Gerlach, D.C., and Sando, T.W., 1982. Origin of calc-alkaline series lavas at Medicine Lake Volcano by fractionation, assimilation and mixing. *Contrib. Mineral. Petrol.*, 80:160–182.
- Hawkins, J.W., and Melchior, J.T., 1985. Petrology of Mariana Trough and Lau Basin basalts. J. Geophys. Res., 90:11431–11468.
- Jenner, G.A., Cawood, P.A., Rautenschlein, M., and White, W.M., 1987. Composition of backarc basin volcanics, Valu Fa Ridge, Lau Basin:

evidence for a slab-derived component in their mantle source. J. Volcanol. Geotherm. Res., 32:209–222.

- Loock, G., McDonough, W.F., Goldstein, S.L., and Hofmann, A.W., 1990. Isotopic compositions of volcanic glasses from the Lau Basin. *Mar. Min.*, 9:235–245.
- Melson, W.G., Jarosewich, E., and Lundquist, C.A., 1970. Volcanic eruption at Metis Shoal, Tonga, 1967–1968. Description and petrology. *Smithson. Contrib. Earth Sci.*, 4.
- Newsom, H.E., White, W.M., Jochum, K.P., and Hofmann, A.W., 1986. Siderophile and chalcophile element abundances in oceanic basalts, Pb isotope evolution and growth of the Earth's core. *Earth Planet. Sci. Lett.*, 80:299–313.
- Oversby, V.M., and Ewart, A., 1972. Lead isotopic compositions of Tonga-Kermadec volcanics and their petrogenetic significance. *Contrib. Mineral. Petrol.*, 37:181–210.
- Palacz, Z.A., and Saunders, A.D., 1986. Coupled trace element and isotope enrichment in the Cook-Austral-Samoa islands, southwest Pacific. *Earth Planet, Sci. Lett.*, 79:270–280.
- Parson, L., Hawkins, J., Allan, J., et al., 1992. Proc. ODP, Init. Repts., 135: College Station, TX (Ocean Drilling Program).
- Sun, S.-S., and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Saunders, A.D., and Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*. Geol. Soc. Spec. Publ. London, 42:313–345.
- Sunkel, G., 1990. Origin of petrological and geochemical variations of Lau Basin lavas (SW Pacific). Mar. Min., 9:205-234.
- Vallier, T.L., Jenner, G.A., Frey, F.A., Gill, J.B., Davis, A.S., Volpe, A.M., Hawkins, J.W., Morris, J.D., Cawood, P.A., Morton, J.L., Scholl, D.W., Rautenschlein, M., White, W.M., Williams, R.W., Stevenson, A.J., and White, L.D., 1991. Subalkaline andesite from Valu Fa Ridge, a backarc spreading center in southern Lau Basin: petrogenesis, comparative chemistry, and tectonic implication. *Chem. Geol.*, 91:227–256.
- Volpe, A.M., Macdougall, J.D., and Hawkins, J.W., 1988. Lau basin basalts (LBB): trace element and Sr-Nd isotopic evidence for heterogeneity in backarc basin mantle. *Earth Planet. Sci. Lett.*, 90:174–186.
- Wright, E., and White, W.M., 1987. The origin of Samoa: new evidence from Sr, Nd, and Pb isotopes. *Earth Planet. Sci. Lett.*, 81:151–162.

Date of initial receipt: 29 June 1993 Date of acceptance: 26 July 1993 Ms 135SR-161