

## 30. PROTON-MICROPROBE TRACE ELEMENT STUDY OF SELECTED LEG 135 CORE SAMPLES<sup>1</sup>

A. Ewart<sup>2</sup> and W.L. Griffin<sup>3</sup>

### ABSTRACT

In-situ proton-microprobe analyses are presented for glasses, plagioclases, pyroxenes, olivines, and spinels in eleven samples from Sites 834–836, 839, and 841 (vitrophyric rhyolite), plus a Tongan dacite. Elements analyzed are Mn, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Pb, and Sn (in spinels only). The data are used to calculate two sets of partition coefficients, one set based on the ratio of element in mineral/element in coexisting glass. The second set of coefficients, thought to be more robust, is corrected by application of the Rayleigh fractionation equations, which requires additional use of modal data. Data are presented for phenocryst core-rim phases and microphenocryst-groundmass phases from a few samples.

Comparison with published coefficients reveals an overall consistency with those presented here, but with some notable anomalies. Examples are relatively high Zr values for pyroxenes and abnormally low Mn values in olivines and clinopyroxenes from Site 839 lavas. Some anomalies may reflect kinetic effects, but interpretation of the coefficients is complicated, especially in olivines from Sites 836 and 839, by possible crystal-liquid disequilibrium resulting from mixing processes.

### INTRODUCTION

The primary aim of this contribution is to provide a set of partition coefficients for plagioclase, pyroxenes, olivines, and spinels, determined on 11 samples selected from the Ocean Drilling Program (ODP) Leg 135 cores. Such partition coefficients are an essential part of the data base required for the petrogenetic modeling of such processes as fractional crystallization and melting. Surprisingly, the available published data are very erratic in their availability. Partition coefficients for the rare-earth elements (REE), Mn, Cu, Ni, Co, Sc, Cr, V, Sr, Ba, and Ga have been determined for plagioclases, pyroxenes, and magnetites from various basaltic andesites, andesites and dacites from the modern axial Tongan volcanoes (Ewart et al., 1973; Ewart and Hawkesworth, 1987). These coefficients are based on analyses, by spark source mass spectrography, optical spectrography, and X-ray fluorescence methods, of mineral separates. Although by far the majority of natural partition coefficients are determined on physically separated minerals (and coexisting glass), usually from volcanic rocks, inherent problems include the difficulty of attaining high purity separates (an essential requirement) and the particularly difficult problem of small mineral inclusions, especially phases such as apatite. The very low P<sub>2</sub>O<sub>5</sub> and Zr concentrations of the Tongan mafic lavas, however, generally precludes the presence of apatite and zircon as inclusions within this volcanic suite. It is clearly advantageous to apply an in-situ technique for trace element analyses of coexisting mineral and glass phases in appropriate volcanic rocks for determining the partitioning behavior of trace elements between minerals, and mineral-glass phases. One such technique is proton-microprobe analysis, described below.

### METHODS

Proton-microprobe analyses were carried out at the CSIRO Heavy Ion Analytical Facility, using methods described by Griffin et al. (1988, 1989). A beam of 3 MeV protons is focused on to a target by an electrostatic lens (Sie and Ryan, 1985), forming a spot approxi-

mately 20 µm in diameter. The X-radiation produced is collected by a Si (Li) detector, and the data processed as described by Ryan et al. (1990). During the analyses reported here, the major element spectra were attenuated by a 200-µm filter to allow use of higher beam currents (6–12 nA) and the attainment of relatively low detection levels within analysis times of approximately 5–10 min. Such a filter, however, limits analyzed elements to those with Z > Fe. Where possible, at least three spots were analyzed per mineral, and the spectra of individual spots summed to produce a composite spectrum and therefore enhance counting statistics. Quoted uncertainties are 1 standard deviation (SD), based on the counting statistics. The analytical methods employed are in principle independent of standards (Ryan et al., 1990). However, analytical data are normalized to electron microprobe analyses for Fe to correct for bias caused by possible accumulated charge measurement problems; these corrections are usually within 10%–15%, except where beam penetration has occurred through a mineral. The accuracy of the technique is estimated to be on the order of 5% relative, at concentration levels greater than 2–3 times mean detection levels (Ryan et al., 1990).

Electron microprobe analyses were carried out at the University of Queensland, Centre for Microscopy and Microanalysis using a newly installed, fully automatic JEOL superprobe. Glass analyses used an enlarged beam of approximately 15 µm diameter.

### SAMPLES AND PROCEDURES

Eleven Leg 135 samples were chosen, based on a range of whole rock compositions, relatively abundant phenocrysts, and the presence of preserved interstitial glass. Seven of the samples are olivine ± clinopyroxene ± plagioclase basalts, three are clinopyroxene-orthopyroxene-plagioclase basaltic andesites, and one is a vitrophyric low-K<sub>2</sub>O rhyolite from Site 841. The additional sample is a two-pyroxene-plagioclase dacite from Fonualei Island, Tonga (Sample F32/69; see Ewart et al., 1973, for details). Modal analyses and details of the site and core locations are presented in Table 1.

Calculated partition coefficients (= D) are presented for the elements Mn, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Ba, and Pb (Tables 2–6). Additional elements that are capable of routine analysis by proton microprobe include Ge, Nb, Mo, Th, U, La, Ce, Nd, As, Sb, Br, Hf, and Sn. The very depleted geochemistry of the Lau-Tonga magmas (e.g., see Ewart et al., this volume), however, precluded the routine detection of these elements in the constituent minerals within the lavas, although Sn was detected in the spinels. The analytical data for

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

<sup>2</sup> Department of Earth Sciences, University of Queensland, St. Lucia, Queensland 4072, Australia.

<sup>3</sup> Division of Exploration Geoscience, CSIRO, North Ryde, New South Wales, 2113, Australia.

glasses and minerals are presented in Tables 7–11, whereas electron microprobe analyses of the glasses are presented in Table 12. All glasses analyzed were found to be homogeneous.

Partition coefficients are calculated in two ways. The simplest, and most commonly used, is the ratio of the concentration of element in mineral/concentration of element in coexisting glass (= liquid; apparent partition coefficients). Korrington and Noble (1971) pointed out, however, that most phenocryst minerals are zoned both with respect to major and trace elements, and as only the surfaces of such zoned crystals are likely to be in equilibrium with the surrounding liquid during crystallization, the simple bulk crystal/liquid ratio calculation will thus potentially yield erroneous coefficients. The extent of this error will depend on the percentage of each phenocryst, the percentages of coprecipitating phenocrysts, and how close ideal fractional crystallization was approached. To minimize the error, Korrington and Noble (1971) applied and adapted the Rayleigh distillation equations to calculate partition coefficients. The necessary data required are (1) concentration of each element in groundmass glass; (2) weight fractions of the groundmass and the phenocryst phases (determined from modes; Table 1); and (3) the average concentrations of elements in each of the various phenocryst phases. In principle, the coefficients can be calculated from some combination of groundmass, whole-rock, and phenocryst trace element data (eqs. 3–5 in Korrington and Noble, 1971). In this report, only groundmass and phenocryst data are used (thus using eqs. 5, 7, and 8 of Korrington and Noble, 1971). The results of this method of calculation are shown in Tables 2–6, where they can be compared with the simpler ratio method of calculation. Ewart et al. (1973) showed that for the Tongan volcanic rocks, in which partition coefficients were based on analyses of separated mineral concentrations, the Rayleigh corrected data resulted in more robust coefficients. This is especially important for element-mineral combinations with high partition coefficients, such as Ni in olivine. Nevertheless, implicit in these calculations is the assumption that throughout phenocryst precipitation, the phenocryst phases maintained the same relative proportions in which they are now observed in each rock. The proximity of most of the samples to the relevant cotectic curves (e.g., Ewart et al., this volume) suggests that this assumption probably is reasonable. The Rayleigh correction procedure is also considered to provide a more realistic upper limit for those partition coefficients based on element abundances that are below their detection limits. Therefore, these are shown in Tables 2–6 where appropriate. In these tables, the 1 standard deviation (SD) of uncertainty given for the Rayleigh calculated coefficients are based on the  $\pm 1$  SD errors given for each element analyzed (Tables 7–11), with coefficients calculated for the  $\pm$  extremes of values; these yield values that are equivalent to the method used by Green et al. (1989).

The relatively large spot size of the proton-microprobe beam (approximately 20  $\mu\text{m}$  in diameter) precluded detailed study of zoning within phenocryst and microphenocryst phases, ideally required to test the applicability of the Rayleigh correction procedure. Nevertheless, in a number of samples, phenocryst/microphenocryst cores and rims (or associated groundmass phases) were analyzed. Comparison of the data for these pairs, together with comparisons of the numerically higher partition coefficients calculated by both calculation methods, suggest that the Rayleigh corrected data provide increased consistency, and thus provide more reliable coefficients. For most of the numerically smaller partition coefficients, however, differences between the two sets of coefficients are relatively insignificant.

In Tables 2–6, comparisons of the new data are made with previous data (Rayleigh corrected) for basaltic andesites, andesites, and dacites for Tonga (Ewart et al., 1973), and also with data from a partition coefficient data base, created from published partition coefficients determined for naturally occurring phenocryst-groundmass data from volcanic rocks. The data set includes some 900 sets of mineral-liquid pairs, with about 4000 individual coefficients. Examples of its application are given in Ewart et al. (1988) and Ewart and Chappell (1989).

## DISCUSSION

### Plagioclase

Only Sr and Ga are strongly partitioned into plagioclase, for those elements analyzed (Table 2). Apart from anomalously high Rb and Ba coefficients in Sample 135-836A-3H-CC, 0–9 cm, and the Sr coefficient in Sample 135-835B-4R-1, 131–141 cm, the determined coefficients are consistent with the range of relevant coefficients determined for the Tongan lavas and the more general basaltic and basaltic andesite coefficients in the literature. Zr, however, exhibits what are effectively bimodal coefficients, lying either between 0.024 and  $<0.12$ , or between 0.22 and 0.38. The lower set of values are within the range reported in the literature, but the second set appear anomalous. It is interesting to note, however, that these higher Zr coefficients all occur in samples from Sites 835 and 839, those lavas having strongly developed “arc-like” affinities (e.g., Ewart et al., this volume), whereas the Fonualei dacite (active Tongan arc) also exhibits a relatively high plagioclase Zr coefficient ( $D = 0.36$ ). Zircon has not been observed in these samples (noting their rather low Zr abundances), and thus the presence of small zircon inclusions is precluded as an explanation. Similarly, the possible presence of glass inclusions within the plagioclases (caused, for example, by quench crystallization) is also an unlikely explanation, as if should they enhance the apparent Zr concentrations in the plagioclases, they would also result in abnormally high coefficients for Zn and Cu. These were not observed, however. The possibility that the explanation lies in kinetic effects accompanying rapid high-temperature crystallization is feasible, but as yet impossible to evaluate.

The Sr coefficients are similar to the basaltic plagioclase megacryst value of  $1.61 \pm 0.67$  given by Phinney and Morrison (1990), and with two exceptions, within the range of literature values (Table 2). The exceptions are Samples 135-835B-4R-1, 134–141 cm (high Sr) and 135-839B-38R-1, 8–12 cm (low Sr); although the possibility of disequilibrium plagioclase exists in these two examples (e.g., Ewart et al., this volume), this could also apply to other samples in which the Sr coefficients lie within the normal range. The Rb coefficients are variable, but consistent with published values, whereas Ba is below detection levels in most samples. Published Ba partition coefficients are mostly  $<1$  (see also Phinney and Morrison, 1990), consistent with the Leg 135 data set, with the exception of two anomalous values, one of which is a quenched plagioclase rim in Sample 135-839B-23R-1, 0–6 cm. The Pb coefficients are also variable, but significantly, the higher D values all have relatively high analytical uncertainties and thus need to be treated with caution. The preferred D values, based on the present data set, are between approximately 0.5 to 0.6.

The Tongan plagioclase data (Ewart et al., 1973) exhibit increasing partition coefficients from basaltic andesites through to dacites, especially evident for Sr and Ga. Such trends are not so clearly defined in the present data set, although the Zn coefficients are relatively high in the rhyolitic and dacitic plagioclases, whereas Ga and Sr are relatively high in the rhyolitic plagioclase. In two of the samples (135-839B-23R-1, 0–6 cm, and -35R-1, 7–11 cm), comparative core and rim compositions are available. The only two elements that exhibit systematic and significant differences are Sr and Ga, the partition coefficients decreasing at the plagioclase rims of both samples. For other elements, differences are within analytical uncertainties.

### Clinopyroxene

This phase is notable for relatively strong partitioning of Mn, Ni, Cu, Zn, Ga, Y, and, in some samples, even Sr into its lattice. The coefficients, with the notable exception of Sr, are within the ranges of published values for basaltic and basaltic andesite clinopyroxenes, although few data for Y and Ga are available for natural clinopyroxenes. Experimental data of Green et al. (1989) and Kuehner et al.

(1989) indicate basaltic clinopyroxene  $D_Y$  values of 0.1 and 0.3–0.53, respectively, compared with values of 0.58–0.89 in this study. The Mn coefficients for the mafic lavas are slightly lower than determined in the Tonga lavas (although the  $D_{Mn}$  value for the Fonualei dacite is similar), but are mostly comparable to the lower range reported in the literature (including the experimental data of Dunn, 1987), with the values in the samples from Site 839 being noticeably lower than those in the clinopyroxenes from Sites 834 and 835. The Ni coefficients are puzzlingly variable, although the Rayleigh corrected data are more coherent; it is suggested that the variability is most likely to reflect the relative stages of clinopyroxene and olivine precipitation, and their effects on the Ni-MgO contents of the coexisting liquid.

The Sr coefficients are mostly higher than normally reported, with  $D_{Sr}$  of 0.13 being the upper limit (see also experimental data of Green et al. [1989] and Kuehner et al. [1989]). The Zr coefficients tend to be bimodal, either low (<0.09) or between 0.13 and 0.31. Published values on natural clinopyroxenes are also erratic (undoubtedly reflecting included zircon in some cases), whereas experimentally determined values range from 0.1 (Green et al., 1989) to 0.27–0.44 (Kuehner et al., 1989) to 0.05–0.45 (Dunn and McCallum, 1982). The latter authors attribute the observed variability of their Zr data to Al in the pyroxenes and melt.

A trend toward increasing partition coefficients is apparent for Mn (most strongly developed in the rhyolite), Zn, and Y (in the rhyolite). For Sample 135-839B-23R-1, 0–6 cm, comparative analyses are presented for microphenocrystal and groundmass clinopyroxene. The results indicate significant increased partitioning of Mn, Ni, Cu, Zn, and Sr in the groundmass phase, which at least in part may be kinetically controlled.

### Orthopyroxene

Data are available only from Site 839 basaltic andesites (Unit 9) and the Fonualei dacite. The strong partitioning of Mn and especially Ni are evident. Although the partition coefficients (Table 4) are generally consistent with the very limited published values for natural orthopyroxenes, data are scarce for Zr, Ga, Rb, Sr, Y, Zr, Ba, and Pb. The experimental data of Green et al. (1989) give partition coefficients for Sr, Zr, and Y of 0.04, 0.18, and 0.18, respectively. The measured Leg 135 data are higher for Sr and Y, ranging from 0.07 to 0.19 (Sr), and from 0.19 to 0.32 (Y). Measured Zr coefficients are variable, ranging between <0.03 and 0.14 (with a single groundmass value of 0.59).

The Zn and Mn coefficients increase markedly in the dacitic orthopyroxene, consistent with transition element behavior in the Tongan pyroxenes in general (Ewart et al., 1973). Comparative coefficients are presented for microphenocrystal and groundmass orthopyroxene in Sample 135-839B-29R-1, 134–136 cm. Significant increases in the coefficients of Cu, Zn, Ga, and Zr, and a decrease in Y, occur in the groundmass phase.

### Olivine

The elements Mn, Ni, and Zn exhibit the strongest partitioning (predictably) into olivine. Coefficients for Mn range from 1.18 to 1.81 for samples from Sites 834 and 835 (similar to the experimental values determined by Dunn [1987]), but are notably lower in samples from Sites 836 and 839 (0.83–0.96). Coefficients for Ni and Zn (in part) behave similarly, suggesting olivine-liquid disequilibrium in the lavas from Sites 836 and 839. Hart and Davis (1978) found that olivine<sub>Ni</sub>/liquid<sub>Ni</sub> (=  $D$ ) partitioning is strongly correlated with melt MgO, but it is independent of liquid Ni concentrations, with only weak temperature dependence. These authors expressed the compositional dependence as  $D = (124/MgO) - 0.9$ . Predicted MgO (liquid) values, using this equation with the Rayleigh corrected coefficients, are shown in Table 5, and are compared with MgO abundances in coexisting glasses and the whole rocks. The predicted MgO values are consis-

tently low in the basalts from Sites 834–836, indicating that the Ni-partition coefficients are higher than are predicted by the equation. Magma mixing within the Site 834–836 magmas is a possible explanation, as discussed elsewhere in this volume (Hergt and Nilsson; Bryan et al.), although Mg-Fe partitioning data suggest only minimal effects in the Site 834 samples analyzed here (Ewart et al., this volume). In the case of the two Site 839 samples, the predicted MgO (liquid) values are actually higher than observed. In these examples, incorporation of highly magnesian olivines into more evolved melt is indicated by additional Mg-Fe crystal-liquid exchange data (Allan, this volume; Ewart et al., this volume).

Notwithstanding the evidence pointing toward disequilibrium olivine in many of the Leg 135 samples, the calculated partition coefficients are within the ranges reported in the literature for basalts and basaltic andesites, with the exception of two anomalously high Pb values, and the relatively high Zr coefficients in the two Site 839 olivines, noted above. Comparative core and rim compositions are available for Sample 135-834B-35R-1, 58–60 cm. These indicate significant decreases in the coefficients for Mn and Ni, and increases in Zn and Sr, in the slightly more Fe-rich rim zones.

### Spinel

The Cr-spinels exhibit strong partitioning of Mn, Ni, Zn, and Ga, and Sn is detected in two analyses. Comparison of core and rim compositions from Sample 135-839B-22R-1, 6–9 cm, show that the Zn coefficient changes significantly, decreasing in the rim zone, which is thought to be temperature controlled.

Two titaniferous magnetites have been analyzed: (1) from the Site 841 vitrophyric rhyolite and (2) from the Fonualei dacite. Again, Mn, Zn, and Ga are strongly partitioned into the spinel, with the coefficients increasing markedly in the rhyolitic magnetite; this latter phase also shows high  $D_Y$ . Few magnetite data are available for comparison from equivalent dacites and low- $K_2O$  rhyolites. Recent data of Francalanci (1989) for magnetite in a potassic andesite, however, are relevant, in that they report partition coefficients for Sr, Zr, and Y of 0.15, 0.45, and 1.7, respectively. These are very similar to the values determined in this work.

### SUMMARY

Based on in-situ proton-microprobe analyses of phenocrystal, microphenocrystal, and some groundmass mineral phases and coexisting glasses, partition coefficients are presented for Mn, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Ba, and Pb. Mineral phases include plagioclase, clinopyroxenes, orthopyroxene, olivine, Cr-spinel, and titaniferous magnetite. Eleven samples have been analyzed from Leg 135 drill sites comprising basalts from Sites 834–836 and 839; basaltic andesites from Site 839; and low- $K_2O$  rhyolite from Site 841. An additional dacite from Fonualei Island (modern Tongan Arc) is included. Data for additional elements were not obtained because of the generally depleted trace element geochemistry of the Lau Basin and Tongan lavas.

The partition coefficients are presented first as ratios of element concentration in mineral/concentration of element in glass (apparent partition coefficients), and second as coefficients corrected using the Rayleigh distillation model (also requiring modal data). We consider that the Rayleigh corrected data provide a more robust data set, especially for the larger partition coefficients.

Comparison with published partition coefficients, including a set determined specifically on modern Tongan lavas, reveals an overall consistency with the data determined in this work, but with some notable anomalies. Examples are some relatively high-Zr coefficients in plagioclases, relatively high-Sr coefficients in pyroxenes, and low-Mn coefficients in clinopyroxenes and olivines from Site 839 lavas. We suggest that some of the anomalies could be kinetically controlled, this receiving some support from comparisons of limited data for phenocryst core-rim and microphenocryst-groundmass pairs

from the same samples. Interpretation of the overall partition coefficient data is, however, complicated by possible crystal-liquid disequilibrium resulting from mixing processes, thought to show most obviously in the olivines from lavas of Sites 836 and 839. Calculated coefficients for some elements increase markedly in the dacite and rhyolite (relative to mineral phases in the mafic lavas). Examples are Zr, Ga, and Sr in plagioclase; Mn, Ga, and Y in clinopyroxene; Mn and Zn in orthopyroxene; and Zn, Ga, and Y in the rhyolite titaniferous magnetite.

**ACKNOWLEDGMENTS**

Special thanks are owed to Tin Tin Win of the CSIRO, HIAF Laboratory for invaluable help with data processing, and to Dr. C.J. Stephens (University of Queensland) for much help in processing electron microprobe data. Reviews by T.H. Green and R.C. Price greatly improved the manuscript presentation.

**REFERENCES\***

Dunn, T., 1987. Partitioning of Hf, Lu, Ti, and Mn between olivine, clinopyroxene and basaltic liquid. *Contrib. Mineral. Petrol.*, 96:476-484.  
 Dunn, T., and McCallum, I.S., 1982. The partitioning of Zr and Nb between diopside and melts in the system diopside-albite-anorthite. *Geochim. Cosmochim. Acta*, 46:623-629.  
 Ewart, A., Bryan, W.B., and Gill, J., 1973. Mineralogy and geochemistry of the younger volcanic islands of Tonga, southwest Pacific. *J. Petrol.*, 14:429-465.  
 Ewart, A., and Chappell, B.W., 1989. East Australian petrology and geochemistry: trace element geochemistry. In Johnson R.W. (Ed.), *Intraplate Volcanism in Eastern Australia and New Zealand*: Cambridge (Cambridge Univ. Press), 219-235.  
 Ewart, A., Chappell, B.W., and Menzies, M.A., 1988. An overview of the geochemical and isotopic characteristics of the eastern Australia Cainozoic volcanic provinces. In Menzies, M.A. (Ed.), *Oceanic and Continental Lithosphere: Similarities and Differences*. *J. Petrol., Spec. Publ.*, 225-274.  
 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.

Francalanci, L., 1989. Trace element partition coefficients for minerals in shoshonitic and calc-alkaline rocks from Stromboli Island (Aeolian Arc). *Neues Jahrb. Mineral. Abh.*, 160:229-247.  
 Green, T.H., Sie, S.H., Ryan, C.G., and Cousens, D.R., 1989. Proton microprobe-determined partitioning of Nb, Ta, Zr, Sr and Y between garnet, clinopyroxene and basaltic magmas at high pressure and temperature. *Chem. Geol.*, 74:201-216.  
 Griffin, W.L., Jaques, A.L., Sie, S.H., Ryan, C.G., Cousens, D.R., and Suter, G.F., 1988. Conditions of diamond growth: a proton microprobe study of inclusions in West Australian diamonds. *Contrib. Mineral. Petrol.*, 99:143-152.  
 Griffin, W.L., Smith, D., Boyd, F.R., Cousens, D.R., Ryan, C.G., Sie, S.H., and Suter, G.F., 1989. Trace element zoning in garnets from sheared mantle xenoliths. *Geochim. Cosmochim. Acta*, 53:561-567.  
 Hart, S.R., and Davis, K.E., 1978. Nickel partitioning between olivine and silicate melt. *Earth Planet. Sci. Lett.*, 40:203-219.  
 Korrington, M.K., and Noble, D.C., 1971. Distribution of Sr and Ba between natural feldspar and igneous melt. *Earth Planet. Sci. Lett.*, 11:147-151.  
 Kuehner, S.M., Laughlin, J.R., Grossman, L., Johnson, M.L., and Burnett, D.C., 1989. Determination of trace element mineral/liquid partition coefficients in melilite and diopside by ion and electron microprobe techniques. *Geochim. Cosmochim. Acta*, 53:3115-3130.  
 Phinney, W.C., and Morrison, D.A., 1990. Partition coefficients for calcic plagioclase: implications for Archean anorthosites. *Geochim. Cosmochim. Acta*, 54:1639-1654.  
 Ryan, C.G., Cousens, D.R., Sie, S.H., Griffin, W.L., and Clayton, E.J., 1990. Quantitative PIXE microanalysis in the geosciences. *Nucl. Instrum. Methods Phys. Res., Sect. B*, 47:55-71.  
 Sie, S.H., and Ryan, C.G., 1985. An electrostatic "Russian" quadruplet microprobe lens. *Nucl. Instrum. Methods, Phys. Res., Sect. B*, 15:664-670.

\* 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).

**Date of initial receipt: 29 June 1992**  
**Date of acceptance: 3 April 1993**  
**Ms 135SR-146**

**Table 1. Modal analyses (volume percent) of samples analyzed by proton microprobe.**

Hole	834B	834B	835B	836A	836A	839B	839B	839B	839B	839B	841B
Core, section	35R-1	57R-1	4R-1	3H-CC	4H-CC	22R-1	23R-1	29R-1	35R-1	38R-1	50R-1
Interval (cm)	58-60	126-128	134-141		0-13	6-9	0-6	134-136	7-11	8-12	5-9
Unit	8	13	1	3	3	3	3	9	9	9	2B
<b>Phenocrysts</b>											
Plagioclase	8.0	9.0	10.7	8.1	13.7	-	-	11.5	14.8	9.3	Plagioclase 14.1
Clinopyroxene	5.0	2.8	6.9	-	-	1.2	1.1	0.2	0.1	0.4	Quartz 6.8
Olivine	1.5	0.9	1.7	2.4	3.5	16.8	16.2	-	-	-	Clinopyroxene 1.1
Orthopyroxene	-	-	-	-	-	-	-	0.5	0.7	0.3	Orthopyroxene 0.5
Chromite	-	-	-	-	<<0.1	0.3	0.2	-	-	-	Magnetite 0.8
Total Phenocrysts	14.5	12.7	19.3	10.5	17.2	18.3	17.5	12.2	15.5	10.0	Hornblende <0.1
											Total 23.3
<b>Vesicles</b>											
Vesicles	18.0	15.7	4.7	1.2	-	31.1	34.1	15.9	17.7	4.8	Vesicles 8.7
<b>Groundmass</b>											
Plagioclase	2.2	1.5	1.0	1.8	-	-	<0.1	21.6	11.5	12.5	Groundmass 76.7
Clinopyroxene	0.2	0.5	0.5	-	-	10.3	19.6	14.2	-	2.9	(glass)
Olivine	0.1	-	0.1	-	-	1.7	0.8	-	-	-	N 1799
Opacues	-	-	-	-	-	-	-	0.8	-	-	
Mesostasis (glass)	-	-	-	-	82.8	-	-	51.1	17.0	-	
Mesostasis (composite)*	82.9	85.3	79.0	87.7	-	56.2	57.8	-	53.2	71.0	
Segregation vesicle glass	-	-	-	-	-	2.2	1.2	-	2.8	3.6	
Segregation vesicle infilling (devitrified)	-	-	-	-	-	-	11.3	3.0	-	-	
N	1447	1613	1360	1205	1721	1827	2066	1214	1332	1315	

Notes: Data are recalculated vesicle-free. N = number of points counted.

\* Includes devitrified ± glassy mesostasis.

**Table 2. Calculated partition coefficients for plagioclase phases analyzed by proton microprobe.**

Hole	834B	834B	835B	836A	836A	839B	839B
Core, section	35R-1	57R-1	4R-1	3H-CC	4H-CC	23R-1	23R-1
Interval (cm)	58-60	126-128	134-141	0-9	0-13	0-6	0-6
Type	Phen	Phen	Phen	Phen	Phen	Mphen core	Mphen rim
Mn (1)	-	-	-	-	-	-	-
(2)	<0.035	<0.048	<0.068	<0.083	<0.029	<0.068	<0.074
Ni (1)	-	-	-	-	-	-	-
(2)	<0.15	<0.26	<0.22	<0.23	<0.36	<0.73	<0.73
Cu (1)	0.11	0.15	-	-	0.045	0.072	0.084
(2)	0.13 (0.01)	0.17 (0.01)	<0.064	<0.11	0.049 (0.004)	0.082 (0.022)	0.095 (0.015)
Zn (1)	0.070	0.13	0.028	0.20	0.042	0.095	0.091
(2)	0.075 (0.01)	0.14 (0.01)	0.031 (0.015)	0.21 (0.02)	0.045 (0.006)	0.096 (0.014)	0.092 (0.014)
Ga (1)	1.26	1.18	1.84	0.99	0.96	1.74	1.46
(2)	1.28 (0.10)	1.18 (0.01)	1.83 (0.03)	1.00 (0.08)	0.98 (0.04)	1.94 (0.02)	1.64 (0.03)
Rb (1)	-	-	0.37	3.2	-	-	-
(2)	<0.75	<0.21	0.41 (0.10)	2.9 (0.07)	<0.78	<0.49	<0.58
Sr (1)	1.53	1.45	4.11	1.57	1.01	1.68	1.49
(2)	1.53 (0.01)	1.43 (0.01)	3.63 (0.02)	1.55 (0.01)	1.03 (0.01)	1.92 (0.02)	1.69 (0.03)
Y (1)	-	-	-	-	0.084	-	-
(2)	<0.076	<0.12	<0.19	<0.12	0.092 (0.026)	<0.29	<0.31
Zr (1)	0.024	0.022	0.34	-	-	-	0.22
(2)	0.026 (0.020)	0.024 (0.023)	0.38 (0.04)	<0.13	<0.029	<0.12	0.24 (0.12)
Ba (1)	-	-	-	5.24	-	-	2.0
(2)	<0.84	<0.92	<1.15	4.39 (1.0)	<0.86	<1.87	2.2 (0.3)
Pb (1)	3.5	0.59	-	2.10	0.96	-	-
(2)	2.95 (0.86)	0.61 (0.04)	<0.51	2.00 (0.43)	0.98 (0.22)	<1.21	<1.3
An%(mol.)	75-77	78-83	71-86	76-86	80-90	85-88	84-85

**Table 2 (continued).**

Hole	839B	839B	839B	839B	841B	Fonualei	Tonga*	Tonga*	Literature +
Core, section	29R-1	35R-1	35R-1	38R-1	50R-1	F32/69	basaltic	andesites	basalts and
Interval (cm)	134-136	7-11	7-11	8-12	5-9		andesites	and dacites	basaltic
Type	Phen	Phen core	Phen rim	Phen	Phen	Phen			andesites
Mn (1)	-	-	-	0.032	-	0.047			0.016-0.07
(2)	<0.029	<0.045	<0.046	0.030 (0.007)	<0.079	0.045 (0.004)			
Ni (1)	-	-	-	-	-	-			0.05-0.22
(2)	<0.44	<0.94	<0.94	<0.51	<0.63	<0.52			
Cu (1)	0.054	-	-	0.028	-	0.23			0.004-0.7
(2)	0.073 (0.01)	<0.075	<0.075	0.033 (0.004)	<0.60	0.24 (0.02)	0.07-0.24	0.08-0.32	
Zn (1)	0.043	0.058	0.072	0.037	0.18	0.141			0.04-0.19
(2)	0.055 (0.01)	0.067 (0.023)	0.084 (0.015)	0.043 (0.006)	0.15 (0.01)	0.142 (0.01)			
Ga (1)	1.43	1.73	1.36	1.30	1.59	1.03			
(2)	1.37 (0.07)	1.57 (0.01)	1.30 (0.01)	1.26 (0.07)	1.54 (0.04)	1.03 (0.01)	0.88-1.1	1.1-1.7	
Rb (1)	-	0.27	0.36	-	-	0.25			0.026-0.36
(2)	<0.11	0.30 (0.08)	0.40 (0.08)	<0.11	<0.087	0.25 (0.01)			
Sr (1)	2.27	1.48	1.35	0.93	4.06	1.37			1.04-2.22
(2)	1.90 (0.02)	1.39 (0.01)	1.30 (0.01)	0.94 (0.01)	3.44 (0.05)	1.37 (0.01)	1.4-1.7	1.8-2.6	
Y (1)	-	-	-	-	-	-			0.05-0.13
(2)	<0.10	<0.24	<0.28	<0.073	<0.023	<0.072			
Zr (1)	0.17	0.24	0.20	-	-	0.36			0.01-0.05
(2)	0.24 (0.02)	0.28 (0.01)	0.22 (0.05)	<0.030	<0.008	0.36 (0.01)			
Ba (1)	0.39	-	-	-	0.28	0.29			0.054-1.05
(2)	0.48 (0.08)	<0.71	<0.73	<0.45	0.32 (0.04)	0.29 (0.04)	0.15-0.19	0.11-0.17	
Pb (1)	1.15	-	-	0.48	-	-			0.1-5.4
(2)	1.13 (0.26)	<0.64	<0.70	0.51 (0.02)	<0.74	<0.60			
An%(mol.)	82-89	88-91	74-83	87-95	40-48	88.9			

Notes: (1) = calculated as  $C_{solid}/C_{liquid}$ , and (2) calculated assuming Rayleigh fractionation. Phen = phenocrysts, and Mphen = microphenocrysts. Figures in parentheses are 1 SD based on the 1 SD proton-microprobe uncertainties.

\* After Ewart et al. (1973) based on mineral separates.

+ See text.

Table 3. Calculated partition coefficients for clinopyroxene phases analyzed by proton microprobe.

Hole	834B	834B	835B	839B	839B	839B	841B	Fonualei	Tonga*	Tonga*	Literature+
Core, section	35R-1	57R-1	4R-1	23R-1	23R-1	38R-1	50R-1	F32/69	basaltic	andesites	basalts and
Interval (cm)	58-60	126-128	134-141	0-6	0-6	8-12	5-9		andesites	and dacites	basaltic
Type	Mphen	Mphen	Phen	Mphen	Gmss	Phen	Phen	Phen			andesites
Mn (1)	0.89	0.70	0.95	0.55	0.61	0.68	14.4	2.25			0.81-1.5
(2)	0.90 (0.01)	0.69 (0.01)	0.99 (0.02)	0.56 (0.02)	0.62 (0.02)	0.65 (0.02)	12.1 (0.2)	2.16 (0.01)	1.2-1.5	1.8-4.2	
Ni (1)	4.60	0.44	5.82	1.85	4.67	-	-	-			0.26-8.4
(2)	2.82 (0.13)	0.40 (0.04)	3.70 (0.12)	0.26 (0.01)	0.66 (0.01)	<0.51	<2.5	<2.1	5.6-8.4		
Cu (1)	0.52	0.55		0.28	0.60	0.51	-	-			0.07-0.7
(2)	0.57 (0.02)	0.59 (0.01)	<0.056	0.31 (0.02)	0.67 (0.02)	0.59 (0.01)	<1.94	<0.27	0.12-0.69	0.25-0.87	
Zn (1)	0.43	0.77	0.27	0.53	0.71	0.58	2.63	1.08			0.33-0.74
(2)	0.46 (0.01)	0.81 (0.02)	0.29 (0.01)	0.53 (0.01)	0.72 (0.01)	0.67 (0.01)	2.06 (0.02)	1.09 (0.01)			
Ga (1)	0.55	0.56	0.30	0.35	0.40	1.15	-	0.28			0.35
(2)	0.56 (0.03)	0.56 (0.02)	0.30 (0.02)	0.39 (0.03)	0.44 (0.08)	1.11 (0.01)	<0.29	0.28 (0.01)			
Rb (1)	-	-	-	-	-	0.30	-	-			0.001-0.08
(2)	<0.64	<0.21	<0.15	<0.39	<0.41	0.34 (0.07)	<0.21	<0.12			
Sr (1)	0.44	0.52	0.070	0.43	0.60	0.83	0.10	0.10			0.07-0.13
(2)	0.44 (0.01)	0.52 (0.01)	0.062 (0.01)	0.49 (0.01)	0.68 (0.01)	0.85 (0.01)	0.086 (0.014)	0.10 (0.01)			
Y (1)	0.68	0.54	0.62	0.79	0.69	0.56	1.92	0.76			0.42
(2)	0.73 (0.02)	0.58 (0.01)	0.68 (0.02)	0.89 (0.05)	0.78 (0.08)	0.64 (0.08)	2.14 (0.01)	0.79 (0.03)			
Zr (1)	0.23	-	0.12	-	-	-	0.076	0.30			0.14-1.24
(2)	0.25 (0.01)	<0.025	0.13 (0.01)	<0.081	<0.086	<0.049	0.088 (0.011)	0.31 (0.03)			
Ba (1)	-	-	-	-	-	-	-	0.15			0.001-0.05
(2)	<0.56	<0.74	<0.55	<1.15	<1.25	<0.69	<0.22	0.16 (0.06)			
Pb (1)	-	0.65	-	-	-	1.34	-	-			0.15-1.0
(2)	<0.71	0.67 (0.02)	<0.40	<1.0	<1.1	1.42 (0.70)	<2.1	<1.7			
Ca (atomic %)	39.8	41.8	41.5	42.3	42.3	39.6	39.7	36.6			
Mg	51.5	49.3	48.8	49.0	47.5	47.6	33.2	37.8			
Fe+Mn	8.8	9.0	9.8	8.7	10.3	12.8	27.2	25.6			

Notes: (1) = calculated as  $C_{solid}/C_{liquid}$ , and (2) calculated assuming Rayleigh fractionation. Mphen = microphenocrysts, Gmss = groundmass, and Phen = phenocrysts. Figures in parentheses are 1 SD based on the 1 SD proton-microprobe uncertainties.

\* After Ewart et al. (1973) based on mineral separates.

+ See text.

Table 4. Calculated partition coefficients for orthopyroxene phases analyzed by proton microprobe.

Hole	839B	839B	839B	839B	Fonualei	Tonga*	Tonga*	Literature+
Core, section	29R-1	29R-1	35R-1	38R-1	F32/69	basaltic	andesites-	basaltic
Interval (cm)	134-136	134-136	7-11	8-12		andesites	dacites	andesites
Type	Mphen	Gmss	Phen	Phen	Phen			
Mn (1)	1.55	1.49	2.28	2.01	3.0			1.8-2.2
(2)	1.85 (0.30)	1.80 (0.25)	1.36 (0.02)	1.92 (0.17)	2.88 (0.05)	1.8-2.2	2.4-6.4	
Ni (1)	8.22	7.67	15.2	21.4	-			5.2-14.8
(2)	6.85 (0.15)	6.53 (0.27)	16.2 (0.1)	22.7 (0.4)	-	7.3-11.0	-	
Cu (1)	0.15	0.53	0.10	0.11	-			0.16-0.92
(2)	0.21 (0.01)	0.69 (0.02)	0.12 (0.01)	0.12 (0.06)	<0.12	0.17-0.92	0.34-1.2	
Zn (1)	0.90	1.0	1.01	1.10	1.67			-
(2)	1.16 (0.05)	1.28 (0.05)	1.18 (0.02)	1.27 (0.01)	1.68 (0.02)			
Ga (1)	0.20	0.38	0.25	0.25	0.27			-
(2)	0.20 (0.02)	0.36 (0.04)	0.23 (0.02)	0.24 (0.04)	0.27 (0.03)			
Rb (1)	-	-	-	-	-			0.029
(2)	<0.08	<0.2	<0.09	<0.12	<0.08			
Sr (1)	0.23	0.22	0.074	0.11	0.079			0.01
(2)	0.19 (0.01)	0.18 (0.07)	0.069 (0.003)	0.12 (0.01)	0.079 (0.006)			
Y (1)	0.24	0.14	0.23	0.22	0.24			-
(2)	0.32 (0.02)	0.19 (0.05)	0.26 (0.02)	0.25 (0.02)	0.24 (0.02)			
Zr (1)	-	0.44	0.12	0.076	0.20			-
(2)	<0.03	0.59 (0.01)	0.14 (0.02)	0.089 (0.013)	0.21 (0.01)			
Ba (1)	-	-	-	-	0.17			0.01
(2)	<0.17	<0.34	<0.18	<0.28	0.17 (0.03)			
Pb (1)	-	-	0.43	-	-			-
(2)	<0.45	<0.45	0.46 (0.09)	<0.46	<1.0			
Ca (atomic %)	3.9	4.7	4.2	4.2	4.4			
Mg	72.8	68.2	73.7	73.0	53.3			
Fe+Mn	23.2	27.1	22.2	22.8	42.3			

Notes: (1) = calculated as  $C_{solid}/C_{liquid}$ , and (2) calculated assuming Rayleigh fractionation. Mphen = microphenocrysts, Gmss = groundmass, and Phen = phenocrysts. Figures in parentheses are 1 SD based on the 1 SD proton-microprobe uncertainties.

\* After Ewart et al. (1973) based on mineral separates.

+ See text.

**Table 5. Calculated partition coefficients for olivine phases analyzed by proton microprobe.**

Hole	834B	834B	834B	835B	836A	836A	839B	839B	Literature <sup>+</sup>
Core, section	35R-1	35R-1	57R-1	4R-1	3H-CC	4H-CC	22R-1	23R-1	basalts- basaltic andesites
Interval (cm)	58-60	58-60	126-128	134-141	0-6	0-13	6-9	0-6	
Type	Phen core	Phen rim	Phen	Phen	Phen	Phen	Phen	Phen	andesites
Mn (1)	1.36	1.19	1.82	1.15	1.0	0.91	0.83	0.79	0.8-2.6
(2)	1.38 (0.03)	1.21 (0.01)	1.81 (0.06)	1.18 (0.01)	0.96 (0.01)	0.88 (0.10)	0.83 (0.02)	0.80 (0.08)	
Ni (1)	62.6	45.3	30.0	40.7	23.3	25.3	131	94.9	4.5-21.7
(2)	38.4 (2.0)	30.6 (1.6)	27.0 (2.5)	25.9 (1.3)	18.0 (0.8)	17.4 (0.5)	13.8 (1.1)	13.5 (0.5)	
Cu (1)	-	-	0.54	-	0.29	-	0.079	0.059	0.02-4.3
(2)	<0.12	<0.13	0.57 (0.01)	<0.06	0.31 (0.05)	<0.07	0.090 (0.01)	0.066 (0.017)	
Zn (1)	1.11	1.18	1.22	0.96	0.77	1.04	0.86	0.85	0.67-3.0
(2)	1.19 (0.01)	1.27 (0.02)	1.29 (0.02)	1.07 (0.02)	0.80 (0.01)	1.12 (0.02)	0.87 (0.012)	0.86 (0.01)	
Ga (1)	-	-	-	-	-	-	-	-	0.04-0.05
(2)	<0.34	<0.35	<0.42	<0.22	<0.61	<0.41	<0.17	<0.23	
Rb (1)	1.63	-	-	-	-	2.1	0.77	-	0.0002-0.19
(2)	1.69 (0.7)	<1.7	<0.20	<0.17	<0.33	2.1 (0.9)	0.80 (0.01)	<0.26	
Sr (1)	0.023	0.083	0.26	-	-	-	-	0.011	0.002-0.12
(2)	0.023 (0.02)	0.083 (0.01)	0.26 (0.02)	<0.014	<0.035	<0.020	<0.009	0.012 (0.005)	
Y (1)	-	-	0.73	-	-	-	-	-	-
(2)	<0.14	<0.15	0.78 (0.01)	<0.12	<0.17	<0.11	<0.13	-	
Zr (1)	0.11	0.062	-	0.11	-	0.11	0.38	0.18	0.04
(2)	0.13 (0.05)	0.068 (0.033)	<0.041	0.12 (0.02)	<0.068	0.12 (0.04)	0.42 (0.09)	0.20 (0.03)	
Pb (1)	-	-	-	0.60	-	-	0.79	-	-
(2)	<1.7	<1.7	<0.41	0.64 (0.06)	<0.67	<0.15	0.81 (0.09)	<0.68	
Fo (mol%)	84-87	83-85	83-86	81-85	86-87	87-88	88-92	88-92	
MgO predicted liquid	3.16	3.94	4.44	4.63	6.56	6.78	8.44	8.61	
MgO glass	6.12	6.12	6.43	6.37	8.26	8.17	6.89	6.94	
MgO whole rock	7.02	7.02	7.24	7.66	-	9.09	-	14.83	

Notes: (1) = calculated as  $C_{solid}/C_{liquid}$ , and (2) calculated assuming Rayleigh fractionation. Phen = phenocrysts. Figures in parentheses are 1 SD based on the 1 SD proton-microprobe uncertainties.

<sup>+</sup> See text.

**Table 6. Calculated partition coefficients for oxide phases analyzed by proton microprobe.**

Chromites				Magnetites			Literature <sup>+</sup>
Hole	839B	839B	839B	841B	Fonualei	Tonga*	
Core, section	22R-1	23R-1	23R-1	50R-1	F32/69	andesites- dacites	basaltic andesites, andesites
Interval (cm)	6-9	0-6	0-6	5-9			
Type	Mphen	Mphen (cores)	Mphen (rims)	Mphen	Mphen		
Mn (1)	6.72	5.28	4.77	14.8	2.18		1.4-3.2
(2)	6.80 (1.25)	5.39 (0.88)	4.87 (1.20)	12.4 (0.4)	2.09 (0.29)	1.4-2.9	
Ni (1)	75.4	62.1	53.8				4-19
(2)	7.96 (0.59)	8.80 (0.23)	7.63 (1.47)	<2.1	-	19	
Cu (1)	0.086	0.060					1.3-6.7
(2)	0.098 (0.017)	0.068 (0.025)	<0.15	<3.0	-	1.3-2.3	
Zn (1)	4.91	3.90	4.78	45.7	6.23		5.4-12.7
(2)	4.96 (0.16)	3.96 (0.09)	4.85 (0.12)	35.9 (0.2)	6.27 (0.09)		
Ga (1)	2.06	2.28	2.64	4.49	2.90		-
(2)	2.34 (0.40)	2.56 (0.14)	2.96 (0.14)	4.37 (0.06)	2.90 (0.28)		
Rb (1)							-
(2)	<1.1	<0.42	<0.79	<0.12	-		
Sr (1)				0.81	0.21		-
(2)	<0.020	<0.018	<0.033	0.69 (0.05)	0.21 (0.03)		
Y (1)				1.69	-		-
(2)	<0.24	<0.19	<0.36	1.88 (0.05)	-		
Zr (1)				0.27	0.39		-
(2)	<0.21	<0.075	<0.14	0.32 (0.02)	0.40 (0.05)		
Pb (1)							-
(2)	<1.4	<1.1	<2.3	<2.4	-		

Notes: (1)= calculated as  $C_{solid}/C_{liquid}$ , and (2) calculated assuming Rayleigh fractionation. Mphen = microphenocrysts. Figures in parentheses are 1 SD based on the 1 SD proton-microprobe uncertainties.

\* After Ewart et al. (1973) based on mineral separates.

<sup>+</sup> See text.

**Table 7. Proton-microprobe analyses of Lau-Tonga glasses.**

Hole	834B	834B	835B	836A	836A	839B	839B	839B	839B	839B	839B	839B	839B	841B	Fonualei 32/69
Core, section	35R-1	57R-1	4R-1	3H-CC	4H-CC	22R-1	22R-1	22R-1	23R-1	29R-1	35R-1	35R-1	38R-1	50R-1	
Interval (cm)	58-60	126-128	134-141	0-7	0-13	6-9	6-9	6-9	0-6	134-136	7-11	7-11	8-12	5-9	
Glass type	Rind	Rind	Inter-stitial	Gmss	Gmss	Rind"A"	Rind"B"	Segregation vesicle glass	Rind	Inter-stitial	Inter-stitial	Segregation vesicle glass	Inter-stitial	Gmss	Gmss
Trace elements (ppm):															
Mn	944±63	933±55	978±79	947±70	875±36	855±47	870±32	945±65	1090±56	1580±317	1100±47	1070±57	1140±76	293±23	1740±49
Fe(%)	6.54±0.04	6.75±0.05	7.27±0.06	6.41±0.04	6.56±0.03	6.34±0.04	6.34±0.04	6.85±0.04	6.16±0.03	10.7±1.7	8.15±0.06	8.74±0.07	9.05±0.06	1.66±0.007	6.1±0.04
Ni	17.4±1.8	20.5±2.5	22.5±2.0	46±3.6	57±2.9	15.1±2.3	21.5±2.1	<6.1	19.5±2.4	<9	<11	<8	<8	<5	<5.8
Cu	63±2.0	76±3.5	89±4.1	79±2	110±2.8	96±1.6	99±2.1	134±2.5	109±3.1	156±13	124±4.2	98±3	177±4.4	<3.5	26.7±1.3
Zn	66±2.4	74.5±2.6	83±2.6	120±3	55±2.2	65±2.3	63±1.9	99±1.7	78±2.4	121±9	107±3.5	113±2	105±2.3	51±1.0	124±1.5
Ga	12.1±1.5	12±1.1	11.5±1.1	9.1±1.1	9.2±0.9	12.4±1.0	9.8±1.0	12.9±0.6	10.6±0.7	13.2±1.4	12.9±1.1	12.9±0.9	10.9±1.1	13.8±0.9	17.7±0.8
Ge	<2.5	<3	<1.8	<2.2	<1.8	<2.8	<2.4	<2.4	<1.9	<3	<3	<2.2	<2.2	<1.6	1.2±0.4
Rb	<1.9	12.1±1.5	13.2±1.2	5.5±1.0	<1.4	<1.8	2.6±0.8	2.5±0.8	6.8±0.8	22±2	16.2±1.8	13.1±1.1	14.3±1.4	14.7±0.8	21±0.9
Sr	155±2	163±3	133±2	140±2	148±2	172±2.4	169±2.0	204±2.0	168±1.8	155±4	209±5	185±3	218±2	53±1.4	347±3
Y	24±1.2	25±2	20.6±1.2	17.1±1.0	19.0±0.7	13.8±0.8	14.0±0.9	13.9±0.9	15.2±0.8	26.3±1.7	19.9±1.5	22.8±1.2	25±1.1	64±1.3	22.9±1.2
Zr	79±2.2	134±5	120±2.8	78±4	50±3	11.9±2	19.7±2.1	18.3±1.9	40±2.5	75±5	94±4	77±2.5	71±2.5	202±3	76±2.4
Ba	68±24	<104	92±30	<68	<7	<55	<50	55±20	66±20	243±36	232±48	179±38	134±28	256±32	284±25
Pb	<4.3	15±2.6	12.6±2.4	10±3	4.5±1.4	4.3±1.7	4.2±1.9	6.6±1.6	6.0±1.5	7.4±3.8	15.1±2.8	9.2±2.0	7.1±3.0	<3.5	<3.7
Nb	<3	<4.8	<3.7	<3.4	<2.3	<3.6	<2.3	<2.6	<2.5	<3.8	<4.8	<3.3	<3.4	<2.7	1.9±0.53
Mo	<3.5	<5	<2.6	<3.3	<2.4	<3.9	<3.5	<3.7	-	<3.8	-	<3.2	-	-	-
U	<3.6	<5.7	<4.5	<4.1	<2.8	<4.8	<3.1	<3.3	<3.2	<6.0	<4.1	<4.3	<2.9	-	-
N	3	3	6	5	6	4	5	5	5	3	3	5	6	4	5

Notes: Values in ppm except where noted otherwise. Gmss = groundmass. Figures with ± sign are the 1 SD uncertainties. N = number of discrete spot analyses.

**Table 8. Proton-microprobe analyses of Lau-Tonga plagioclase.**

Hole	834B	834B	835B	836A	836A	839B	839B	839B	839B	839B	839B	839B	841B	Fonualei 32/69
Core, section	35R-1	57R-1	4R-1	3H-CC	4H-CC	23R-1	23R-1	29R-1	35R-1	35R-1	35R-1	38R-1	50R-1	
Interval (cm)	58-60	126-128	134-141	0-7	0-13	0-6	0-6	134-136	58-60	58-60	8-12	5-9		
Type	Phen	Phen	Phen	Phen	Phen	Mphen	Mphen	Phen	Phen	Phen	Phen	Phen	Phen	Phen
	Averaged	Averaged	Averaged	Averaged	Averaged	Core	Rim	Averaged	Core	Rim	Averaged	Averaged	Averaged	Averaged
Trace elements (ppm):														
Mn	<33	<47	<67	<99	<26	<73	<79	<39	<83	<85	36±11	<28		82±10
Fe(%)	0.47±0.003	0.40±0.003	0.46±0.004	0.34±0.005	0.39±0.002	0.71±0.005	0.65±0.005	0.58±0.004	0.56±0.005	0.56±0.003	0.53±0.003	0.23±0.01		0.75±0.004
Ni	<4.3	<6	<8	<14	<3	<10	<10	<5	<11	<11	<4	<3		<3
Cu	6.6±0.7	12.1±1.2	<5	<8	4.9±0.5	7.9±2.3	9.2±1.7	8.4±1.0	<8	<8	5±0.7	<2		6.2±0.7
Zn	4.6±0.5	9.7±0.9	2.3±1.2	23.5±2.9	2.3±0.4	7.4±1.3	7.1±1.3	5.2±0.7	6.2±2.3	7.7±1.5	3.9±0.6	9.4±0.6		17.5±0.6
Ga	15.3±0.6	14.1±1.4	21.2±1.7	9.0±1.8	8.8±0.4	18.4±1.3	15.5±1.3	18.9±0.7	22.3±2.1	17.5±1.6	14.2±0.6	21.9±0.7		18.2±0.6
Ge	<1.8	<3	<1.7	<1.8	<3.9	<4.0	<2.0	<4.3	<4.7	<2.2	<1.6			-
Rb	<1.4	<2.4	4.9±1.6	17.7±2.7	<1.1	<3.0	<3.6	<1.7	4.3±1.7	5.8±1.8	<1.4	<1.1		5.2±0.4
Sr	237±2	236±3	547±5	220±5	149±1.4	283±6	250±7	352±3	310±5	283±5	203±2	215±2		475±4
Y	<1.7	<2.8	<3.5	<1.9	1.6±0.5	<3.9	<4.2	<2.1	<4.2	<4.9	<1.6	<1.3		1.6±0.5
Zr	1.9±1.5	2.9±2.9	41±4.1	-	<1.3	<4.4	8.7±4.9	13±2	23±5.2	18.5±5	<1.8	<1.4		27±1.1
Ba	<55	<94	<103	356±97	<39	<109	131±52	95±30	<156	<162	<55	71±17		81±18
Pb	3.5±1.3	8.8±2.3	<6	21±5	4.3±1.1	<7	<7.4	8.5±2.1	<9	<10	3.4±1.5	<2.5		<2.2
N	4	3	2	2	4	1	1	5	1	1	4	4		6

Notes: Values in ppm except where noted otherwise. Phen = phenocrysts, and Mphen = microphenocrysts. Figures with ± sign are the 1 SD uncertainties. N = number of discrete spot analyses.

**Table 9. Proton-microprobe analyses of Lau-Tonga pyroxene.**

Clinopyroxenes									Orthopyroxenes				
Hole	834B	834B	835B	839B	839B	839B	841B	Fonualei	Fonualei	839B	839B	839B	839B
Core, section	35R-1	57R-1	4R-1	23R-1	23R-1	38R-1	50R-1	32/69	32/69	29R-1	29R-1	35R-1	38R-1
Interval (cm)	58-60	126-128	134-141	0-6	0-6	8-12	5-9			134-136	134-136	7-11	8-12
Pyroxene type	Mphen	Phen	Phen	Mphen	Gmss	Phen	Phen	Phen	Phen	Mphen	Gmss	Phen	Phen
Trace elements (ppm):													
Cr	1010±250	<320	1110±250	444±180	<469	<330	<616	-	-	<184	<656	<255	276±178
Mn	838±51	649±46	933±58	599±55	666±65	775±60	4230±151	3910±114	5220±79	2450±47	2360±107	2510±97	2290±46
Fe(%)	4.28±0.02	4.32±0.04	4.59±0.02	4.2±0.02	5.29±0.03	5.73±0.05	12.0±0.07	12.0±0.07	19.5±0.12	11.3±0.06	13.5±0.06	11.4±0.09	10.6±0.06
Ni	80±1.7	9±1.8	131±3.5	36±3.0	91±5	<8.4	<12	<12	<6	74±2.4	69±4.2	167±3	171±3
Cu	33±2	42±1.9	<4.4	30±2.6	64.5±3.3	90±2.0	<6.5	<7	<3	24±1.2	82±4	12.6±1.1	19±1.3
Zn	28.5±1.2	57±1.5	22±1.3	41±1.8	55±1.9	61±2.1	134±3.8	134±2.5	207±6	109±2.9	121±4	108±2.5	116±2
Ga	6.7±0.5	6.7±0.8	3.5±0.6	<3.7	4.2±1.0	12.5±1.3	<4.1	5.0±1.1	4.7±0.6	2.7±0.5	<5.0	3.2±0.6	2.7±0.6
Ge	<1.7	<3	<2.2	<4	<4	<2.7	<4.1	4.2±0.8	1.8±0.4	<1.7	<3.7	1.4±0.4	1.5±0.4
Rb	<1.2	<2.4	<1.8	<2.4	<2.5	4.3±1.2	<2.7	<2.4	<1.7	<1.3	<3.2	<1.3	<1.3
Sr	68±1	85±2.1	9.3±1.0	73±2.3	100±3.1	182±2.9	5.4±1.0	35±1	27.5±2.1	35±1.0	34±2	15.4±0.9	25±0.7
Y	16.2±0.6	13.5±1.2	12.7±1.0	12±1.2	10.5±1.6	14±1.1	123±3	17.5±1.5	5.4±0.6	6.2±0.7	3.7±1.2	4.5±0.6	5.5±0.5
Zr	18±1	<3.1	13.9±1.6	<2.9	<3.1	<3	15.3±2.1	23±2.3	15.4±1.0	<1.8	33±2.2	11.5±1.2	5.4±1.0
Ba	<37	<76	<49	<67	<73	<85	<50	43±20	48±13	<32	<67	<40	<35
Pb	<3.0	9.7±1.7	<47	<6	<6.5	9.5±2.4	<7	<6.2	<3.8	<3.4	<7.9	6.5±2.2	<3.1
N	5	2	3	1	1	3	1	2	4	8	1	8	7

Notes: Values in ppm except where noted otherwise. Mphen = microphenocrysts, Phen = phenocrysts, and Gmss = groundmass. Figures with ± sign are the 1 SD uncertainties. N = number of discrete spot analyses.

**Table 10. Proton-microprobe analyses of Lau-Tonga olivine.**

Hole	834B	834B	834B	835B	836B	836A	839B	839B
Core, section	35R-1	35R-1	57R-1	4R-1	3H-CC	4H-CC	22R-1	23R-1
Interval (cm)	58-60	58-60	126-128	134-141	0-7	0-13	6-9	0-6
Type	Phen							
	Core	Rim	Averaged	Averaged	Averaged		Averaged	Averaged
Trace elements (ppm):								
Mn	1280±109	1120±67	1700±143	1120±83	945±74	793±109	712±54	857±138
Fe(%)	10.5±0.05	11.7±0.05	11.4±0.07	11.4±0.06	9.64±0.05	9.15±0.03	7.66±0.03	7.11±0.03
Ni	1090±22	789±21	615±10	915±11	1070±18	1440±14	2390±27	1850±18
Cu	<7.8	<7.8	41±2.6	<4.6	23±4.3	<7.3	7.7±1.1	6.4±1.8
Zn	73±2	78±4	91±2	80±1	92±2	57±3	55±1	66±1.8
Ga	<4.1	<4.2	<5.0	<2.5	<5.5	<3.7	<1.7	<2.2
Ge	<3.4	<3.6	<2.3	<2.0	<2.6	<3.2	<1.7	<1.9
Rb	3.1±1.3	<3.1	-	<2.0	-	3.0±1.3	2.0±0.6	<1.6
Sr	3.6±1.2	12.9±1.6	42±2	<2.1	-	<2.9	<1.3	1.8±0.7
Y	<3.1	<3.4	18.3±1.6	<2.2	<4.9	<3.0	<1.4	<1.8
Zr	9.0±3.4	4.9±2.5	-	13±3.2	-	5.4±2.0	6.0±1.1	7.2±1.5
Pb	<7.2	<7.4	-	7.5±2.0	-	<6.9	3.4±2.1	<3.9
N	1	1	4	4	3	1	5	3

Notes: Values in ppm except where noted otherwise. Phen = phenocrysts. Figures with ± sign are the 1 SD uncertainties. N = number of discrete spot analyses.

Table 11. Proton-microprobe analyses of Lau-Tonga chromite magnetite.

Chromites				Magnetites	
Hole	839B	839B	839	841B	32/69
Core, section	22R-1	23R-1	23R-1	50R-1	
Interval (cm)	6-9	0-6	5-9		
Type	Mphen Averaged	Mphen Cores	Mphen Rim	Mphen Averaged	Mphen
Trace elements (ppm):					
Mn(%)	0.58±0.14	0.575±0.13	0.52±0.16	0.433±0.017	0.38±0.06
Fe(%)	13.0±0.03	12.9±0.02	15.5±0.04	58.90±0.51	62.3±0.51
Ni	1380±20	1210±20	1050±23	<10	-
Cu	8.4±1.7	6.5±2.6	<14.6	<10	-
Zn	314±4	304±2.5	373±7	2330±32	772±23
Ga	22.9±0.9	24.2±1.0	28±2.2	62±3	51.3±7.2
Ge	<2.8	<3.0	<6.6	<3	-
Rb	<2.9	<2.6	<4.9	<1.5	-
Sr	<2.9	<2.6	<4.9	43±4	73±12
Y	<2.9	<2.6	<4.9	108±5	-
Zr	<3.0	<2.7	<5.1	55±3	30±4.7
Nb	<3.5	<2.7	<5.4	<4	-
Pb	<5.7	<6.2	<13	<8	-
Sn	21±4	<11	30±8	30±4	26±7.8
Mo	<4	<3	<6	<7	-
As				-	16.7±3.5
N	4	4	1	3	1

Notes: Values in ppm except where noted otherwise. Mphen = microphenocrysts. Figures with ± sign are the 1 SD uncertainties. N = number of discrete spot analyses.

Table 12. Electron microprobe analyses of glasses analyzed by proton microprobe.

Hole	834B	834B	835B	836A	836A	839B	839B	839B	839B	839B	839B	841B
Core, section	35R-1	57R-1	4R-1	3H-CC	4H-CC	22R-1	22R-1	23R-1	35R-1	35R-1	38R-1	50R-1
Interval (cm)	58-60	126-128	134-141	0-6	0-13	6-9	6-9	0-6	7-11	7-11	8-12	5-9
Type	Rind	Rind	Interstitial	Gmss	Gmss	Rind	Segregation	Rind	Interstitial	Segregation	Interstitial	Gmss*
Major elements (wt.%)												
SiO <sub>2</sub>	52.82	52.07	52.69	50.46	49.87	53.18	54.48	52.83	58.00	55.92	52.35	77.44
TiO <sub>2</sub>	1.28	1.31	1.07	0.87	0.86	0.64	0.68	0.68	1.19	1.04	0.89	0.25
Al <sub>2</sub> O <sub>3</sub>	15.61	15.66	15.23	15.26	15.16	15.55	17.08	15.21	14.14	14.18	13.79	12.19
FeO*	8.52	8.79	9.52	8.35	8.54	8.25	9.21	8.31	10.80	11.94	11.79	2.10
MnO	0.14	0.16	0.16	0.17	0.15	0.18	0.16	0.16	0.18	0.16	0.15	0.07
MgO	6.12	6.43	6.37	8.26	8.17	6.89	4.62	6.94	2.83	3.95	7.10	0.25
CaO	10.75	11.26	11.13	13.11	13.22	11.98	9.87	12.14	7.73	8.21	9.60	1.81
Na <sub>2</sub> O	2.75	2.53	2.42	2.00	1.96	1.87	1.86	1.95	1.67	1.54	1.88	4.46
K <sub>2</sub> O	0.11	0.12	0.19	0.05	0.06	0.28	0.33	0.28	0.42	0.44	0.64	1.44
Total	98.10	98.33	98.78	98.53	97.99	98.82	98.29	98.50	96.96	97.38	98.19	100.01

Notes: The asterisk (\*) represents shipboard data, recalculated to 100% anhydrous. Gmss = groundmass.