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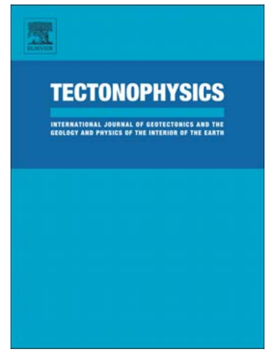

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Cretaceous fore-arc basalts from the Tonga arc: geochemistry and implications for the tectonic history of the SW Pacific.

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ABSTRACT

The Tonga fore arc preserves a complex history of subduction initiation, back-arc basin formation and arc volcanism which has extended from the Cretaceous to the present. In this paper, we discuss the geochemistry of a Cretaceous basalt/dolerite/gabbro suite recovered in two dredges from the Tonga fore-arc at ~19°S. The geochemistry of the Tonga fore-arc suite is unlike that of the uniformly depleted MORB basalts of the subducting Pacific plate and therefore is unlikely to be accreted Pacific Cretaceous crust. The ~102Ma age obtained for one Tongan fore-arc dolerite is contemporaneous with a major phase of Cretaceous subduction-related volcanism, recorded both in detrital zircon age populations and associated volcanics from New Caledonia and New Zealand. We believe the Tonga fore-arc basalts are a remnant of a hypothesized, once extensive Cretaceous back-arc basin, called the East New Caledonia Basin, which we propose existed from ~102 - 50 Ma. The allochthonous Poya terrane of New Caledonia is geochemically very similar to the Tonga fore arc basalts and represents a younger (~84 – 55 Ma) remnant of the same basin. Subduction-related Cretaceous volcanics from the SW Pacific, representing both arc and back-arc settings, all appear to have similar Zr/Nb values, suggesting a common mantle component in their petrogenesis. The Tonga fore arc basalts are also similar to fore arc basalts recovered from the the Izu-Bonin-Mariana fore arc, but unlike these basalts they are not associated with subduction intiation.

1. Introduction

Basement terranes exposed in modern fore-arcs have the potential to preserve the tectono-magmatic record of long-lived subduction systems (Meffre et al., 2012; Stern et al., 2012). Modern fore-arcs are widely believed to be modern analogues of many ophiolite rock assemblages, thus a better understanding of fore arc geology and tectonic history will contribute to a better understanding of not only ophiolite formation and their tectonic significance but also the overall global tectonic cycle (Stern et al., 2012). The SW Pacific is characterized by continental ridges, back arc basins and remnant volcanic arcs formed by Mesozoic subduction, Cretaceous rifting and Cenozoic subduction (Crawford et al., 2003; Sdrolias et al., 2003; Schellart et al., 2006; Bache et al., 2012). The Tonga fore-arc, therefore, may preserve aspects of this complex evolutionary history. Indeed, Meffre et al (2012) demonstrate via U-Pb dating of zircons that the Tonga fore arc is composed of a number of different components ranging in age from Cretaceous to the Pliocene. A significant aspect of the data set presented by Meffre et al (2012) is a mid-Cretaceous age (~102Ma) from a dolerite recovered from the fore arc at ~19°S and ~6000m water depth. In this paper, we present the geochemistry of rocks recovered along with this dolerite sample. We suggest that the geochemistry of these rocks reveals that they represent a coherent tholeiitic back-arc basin association similar to the Cretaceous aged allochthonous Poya terrane of New Caledonia. We propose that both the Tonga fore-arc and Poya terrane tholeiitic rocks are possible remnants of a hypothesized once extensive Cretaceous back arc basin referred to as the East New Caledonia Basin (Eissen et al., 1998).

2. Geological Setting

Tonga is recognised as a type example of an extension-dominanted non-accretionary convergent margin (Lonsdale, 1986; Tappin, 1994; Tappin et al., 1994; MacLeod, 1994; Clift et al., 1998; Clift and MacLeod, 1999; Wright et al., 2000; Figure 1). The Tonga fore arc from 14° to 26° S may be subdivided latitudinally into three major blocks, based on morphology, structure, and sediment geometry(Tappin, 1994; Wright et al., 2000):

(i) a northern block (north of ~18° 30'S, Figure 1) lies in the deepest water, and includes small islands formed by Tofua volcanic arc volcanoes that penetrate a relatively thin sedimentary section with no preferential regional dip;

(ii) a central block (~18° 30' to 22° S, Figure 1) is composed of numerous small islands with a sedimentary section dipping mainly towards the east, and the Tofua volcanic arc lying on the western margin of this part of the fore arc;

(iii) and a southern block (~22° to 26° S, Figure 1) is entirely submarine with shallow water depths, a sedimentary section dipping westward towards the Lau Basin, and the Tofua volcanic arc against the western margin of the forearc.

During the 1996 voyage of the RV Melville rock samples were recovered by dredging of the Tonga forearc at ~19°S, located within the central block (Figure 2; Table 1). In this area, the fore-arc displays a typical 'equilibrium' bathymetric profile and morphology resulting from tectonic erosion (Raitt et al., 1955; Lonsdale, 1986; Wright et al., 2000). A new seamount collision is developing north of the dredge locations as the Capricorn seamount enters the trench (Figure 2). Lonsdale (1986) and Clift et al. (1998) have suggested that in contrast to the rest of the trench which is dominanted by tectonic erosion, a small accretionary prism exists west of the Capricorn seamount. The trench axis here comprises a series of en echelon basins, developed as grabens on the subducting plate as it enters the trench. Locally, what is morphologically the trench axis is structurally the axis of a graben in the Pacific Plate, and the plate boundary is actually within the landward slope (Hilde, 1983; Bloomer and Fisher, 1987; Lonsdale, 1986).

The landward trench slopes in this area are steep, with prominent structural highs in the middle and lower landward slopes. These structural highs commonly define the trench slope break at about 4000 m water depth and appear to be fault blocks (Wright et al., 2000). The fore-arc in this area is dominated by strong normal faulting, as evidenced by the many large, trench-parallel scarps, most of which must have accommodated large-scale subsidence of the fore arc and a gradual, regional tilt of fault blocks toward the trench axis (Wright et al., 2000).

During the Boomerang Leg 8 cruise of the RV Melville (May to June 1996), four dredges were conducted on the Tonga fore arc at ~19°S (Figure 2, Table 1). The dredges 99 and 100 recovered basalts, dolerites and gabbros from ~6000-7000m water depth. The basalts include aphyric to sparsely porphyritic glassy pillow fragments as well as more massive interior parts of pillow lavas. Glass has been completely replaced by secondary minerals due to seafloor weathering; however plagioclase and clinopyroxene microphenocrysts remain relatively unaltered. Olivine when present is mostly completely altered. The dolerites are relatively fresh compared to the altered lavas. The gabbroic rocks are relatively fresh, mostly isotropic equigranular gabbros with minor amounts of orthopyroxene. A dolerite from dredge 100 (sample 100-1-40, Table 2) was found to contain interstitial zircons which gave a U-Pb crystallization age of 102.4 ± 4.5Ma (Meffre et al., 2012). Although it was only possible to date this single sample, we consider that the rocks recovered from dredges 99 and 100 are all most likely sampled from the same basement unit, both due to the close proximity of the two dredges and the geochemical coherence of the rocks taken as a group (as discussed below).

3. Methods and Results

Major, trace and isotope geochemistry for basalts, dolerites and gabbros recovered by dredges 99 and 100 are presented in Table 2. Major elements and some trace elements were determined by xrf at the University of Tasmania while trace elements of selected samples were also determined by solution-ICP-Ms at the University of Tasmania using methods outlined in Falloon et al. (2007). Sr, Nd and Pb isotopes were determined at the Helmholtz Centre for Ocean Research, Keil using the methods outlined in Hoernle et al. (2011). Although we present geochemical data for gabbros in dredge 99, this paper will focus on the geochemistry of the basalts and dolerites as they represent magmatic compositions as opposed to the cumulate gabbros.

The loss of ignition (LOI) values for the analysed basalts and dolerites range from ~1-4 wt% (Table 2, Figure 3) and reflect their relatively fresh to slightly altered nature consistent with petrographic evidence for seafloor alteration. The rocks all have relatively high MgO contents (mostly >6 wt%, Figure 4) and there is no correlation between elements susceptible to sea-floor alteration and LOI values (e.g., K_2O, Figure 3). Therefore ,geochemistry mostly likely reflects original magmatic compositions.

The basalts and dolerites together are relatively primitive low-K tholeiitic magmas with MgO varying from 4-10 wt% (Figures 4-6; Table 2). Zr contents as determined by xrf vary from 32 to138 ppm in the dolerites and basalts from dredges 99 amd 100 and correlate well with Zr contents determined by solution-ICP-Ms (Table 2). However a couple of dolerite samples (99-2-8 and 100-1-40, Table 2) have slightly lower Zr contents determined by solution-ICP-Ms and this could be due to incomplete dissolution of micro-zircons in these samples. Because of this potential problem we only use Zr contents determined by xrf in this paper. Dolerites from dredge 99 are in general more depleted in incompatible elements compared to dolerites and basalts from dredge 100. Dredge 99 dolerites have slightly lower $(La/Sm)_N$ values (0.54-0.56 versus 0.66-1.12) and Nb values (1.2-1.3 ppm versus 1.3-7.5 ppm, as determined by xrf, Table 2). As Zr contents in dredge 99 dolerites are similar dredge 100 dolerites, this results in significantly higher Zr/Nb values in the dredge 99 dolerites (86-94 versus 13-28). One of the analysed dolerites from dredge 99 is problematic. Sample 99-2-8, compared to other dolerites from dredges 99 and 100, has significantly higher SiO_2, CaO and lower MgO and Na_2O contents (Figure 4). It also has high Sr contents (375 ppm as determined by solution-ICP-Ms, Table 2) high Sr/Nd values (Figure 5f) and $^{87}Sr/^{86}Sr$ isotopic values (0.704404, Table 2, Figure 9a). These features could potentially be explained by modification by post-magmatic alteration or alternatively they simply reflect a more evolved magma composition with a significant subduction related enrichment in Sr and $^{87}Sr/^{86}Sr$ values. A subduction influence would also be consistent with the more depleted Nb contents and $(La/Sm)_N$ values. As the LOI values and petrography for sample 99-2-8 are not anomalous, we believe that the geochemistry of this sample has not been significantly modified from its original magmatic composition.

An important geochemical feature of the dredge 99 and 100 rocks is that, although in general they have depleted light Rare Earth Element (LREE) patterns ($(La/Sm)_N$ <1, Figure 5), they show an almost continuous range in $(La/Sm)_N$ values from 0.54-1.12 (Figures 5, 6). This feature is very similar to basalts reported from the Izu-Bonin-Mariana (IBM) fore-arc by Reagan et al. (2010), who referred to these distinctive basalts as fore-arc basalts (FAB). The IBM FAB are believed to be the result of mixing between melts derived from fertile and depleted mantle sources during the initial stages of subduction (Reagan et al., 2010). Figures 4-6 show a close correspondence between the dredge 99 and 100 compositions and the IBM FAB. Although the IBM FAB extend to more depleted

LREE compositions (Figure 6) and lower Ti/V values (Figure 7), the average IBM FAB composition closely matches the depleted compositions from dredge 100 when compared on a normalised abundance plot (Figure 8). Furthermore, the most enriched IBM FAB pattern is a close match to the enriched samples from dredge 100 (Figure 8). The fact that there is not a complete overlap in compositions, we believe is mostly due to sampling bias in both the Tonga and IBM fore arcs.

We believe these similarities in geochemistry have petrogenetic significance and henceforth, in this paper, we refer to the basalts and dolerites recovered from dredges 99 and 100 as a Tongan FAB suite.

4. Discussion

4.1. Cretaceous Pacific MORB

A key question which needs to be addressed before further discussion on the tectonic significance of the recovered mid-Cretaceous Tonga FAB suite is whether it is possible that they represent accreted Pacific oceanic crust. This possibility is supported by the very similar major element chemistry of the Tonga FAB and Cretaceous Pacific crust, as both suites have low-K tholeiitic magma compositions (Figure 4). In particular dolerites from dredge 99 have very similar $(La/Sm)_N$ values and Nb contents to the the Cretaceous Pacific Crust (Figure 5b, c). However, we consider this possibility to be highly unlikely due (a) to the significant differences in geochemistry between the Tonga FAB suite and basaltic lavas of the subducting mid-Cretaceous Pacific crust in trace element and isotopic compositions and, (b) because of the nature of tectonic processes occurring at the non-accretionary Tonga Trench. These points are discussed further below.

Pacific crust currently being subducted at the Tonga Trench is of mid-Cretaceous age (95-110 Ma; Seton et al., 2009). It was formed at the paleo spreading centre now represented by the Osbourn Trough, which was active between ~118 Ma to ~86 Ma (Figure 1, Billen and Stock, 2000; Worthington et al., 2006; Castillo et al., 2009; Zhang et al., 2012). Newly formed oceanic crust created at the Osbourn Trough spreading centre initially split the ancestral Manihiki/Hikurangi Plateau and subsequently separated the Manihiki and Hikurangi Plateaus. Spreading at the Osbourn

Trough is believed to have ceased when the Hikurangi Plateau collided with the Chatham Rise paleo subduction system (Mortimer et al., 2006).

The geochemical nature of the mid-Cretaceous Pacific basaltic crust currently being subducted at the Tonga trench has been determined from a) dredged rocks recovered from the seaward slopes of the Tonga trench (Bloomer & Fisher, 1987) as well as along the seaward side (east) of the Tonga trench from prominent fault scarps near the top of the oceanic outer slope (Castillo et al., 2009) and b) from rocks recovered by dredging of the Osbourn Trough (Worthington et al., 2006) and drilling into crust created by the Osbourn Trough paleo-spreading centre (Zhang et al., 2012). Together the geochemical data from these different localities gives a consistent picture of a relatively uniform N-MORB Pacific oceanic crust similar to that being created at the modern day East Pacific Rise spreading centres (Worthington et al., 2006; Zhang et al., 2012).

Of particular significance for the purposes of this study is the observation of Castillo et al. (2009) that there appears to be a latitudinal variation in geochemical composition of the subducting Pacific crust. This variation can be explained by the history of spreading and melt generation at the Osbourn Trough paleo-spreading centre (Castillo et al., 2009). Initially, mantle-derived melts at the paleo-spreading centre were influenced by the relatively enriched mantle sources responsible for the creation of the ancestral Manihiki/Hikurangi plateau. As spreading progressed, the influence of this source diminished and mantle melts were predominantly derived from depleted asthenospheric mantle (Castillo et al., 2009). However, despite the possible influence of the enriched mantle sources during the initial stages of spreading, most crust generated at the Osbourn Trough paleo-spreading centre is typical of that expected from melting of depleted MORB mantle sources (Worthington et al., 2006; Castillo et al., 2009; Zhang et al., 2012). For example, between 16° and 24°S the basalts recovered by Castillo et al. (2009) have $(La/Sm)_N$ values of between 0.45-0.63, which is similar to the range in values displayed by lavas recovered by drilling at IOPD site U1356 (0.40-0.72, Zhang et al., 2012). These two general features, overall depleted MORB geochemistry and latitudinal variation, allows us to demonstrate that several geochemical features of the Tonga Cretaceous FAB suite are distinctly different from the subducting depleted MORB of the mid-Cretaceous Pacific crust, and in particular, are very different compared to Pacific crust sampled at the same 'relative' latitude (~19°S, see Figure 7 and 9).

For example, compared to the dated Tonga fore arc dolerite 100-1-40, the dredged Cretaceous Pacific crust lavas recovered close to Dr 100 at 19°S have lower $(La/Sm)_N$ values (0.62 vs 1.13, Figure 5, 6), and higher Ti/V values (39 vs 33, Figure 7) values. Isotopic values are also very different, with the Pacific Cretaceous lavas having higher $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$ and lower $^{208}Pb/^{204}Pb$ values (Figure 9). As well, the Tonga FAB suite shows a significant range in Zr/Nb values not present in basalts sampled from the mid-Cretaceous Pacific crust. As can be seen from Figure 5d, mid-Cretaceous Pacific crust has relatively uniform Zr/Nb values (26-74 overall but more restricted range of 40-60 in basalts from hole U1365E, Figure 5d). In contrast the dolerites and basalts from dredge 100 have uniformly lower Zr/Nb values (18-25, Figure 5d), whereas the dolerites from dredge 99 have significantly higher Zr/Nb values (86-94, Figure 5d) compared to basalts sampled from the mid-Cretaceous Pacific crust (Figure 5d). Although we have not sampled intermediate compositions, we believe that the range in Zr/Nb values of the Tonga FAB suite is a continuous range which, as will be discussed below, has petrogenetic significance.

As noted above, the Tonga Trench is regarded as an end-member example of a subduction system undergoing rapid convergence, slab roll-back and vigorous tectonic erosion (Lonsdale, 1986; Wright et al., 2000). Tectonic accretion, therefore, is a very unlikely process for this subduction system. Tectonic accretion, if it occurs, is believed to be a short-lived phenomenon due to seamount subduction and normal steady-state subduction processes. As the Tonga FAB suite does not have OIB geochemistry, it is unlikely for them to have formed within intra-plate volcanoes accreted during seamount subduction. During steady state subduction processes, the Pacific crust undergoes extension as it approaches the Tonga trench, developing well defined horst and graben structures (Lonsdale, 1986; Wright et al., 2000; Crawford et al., 2003). During the process of subduction, these horst and graben structures form the floor of the Tonga trench, creating a narrow 'axial gorge'. As a result, it is possible for a graben structure, which is entirely contained within the underthrusting Pacific crust to temporally form both the landward and seaward sides of the trench graben structure at depths below the principal thrust plane (Lonsdale, 1986). At the latitude of ~19-20°S, this mechanism is the likely explanation for the recovery of N-MORB like basalts from depths >9000m (Bloomer & Fisher, 1987). As the Tonga FAB suite was recovered at mid-slope depths of ~6000m, it is very unlikely that they are the result of either accretion of seamounts or the subducting Pacific basaltic crust itself. This conclusion is consistent with the strong geochemical differences between the Tonga FAB and the subducting Pacific crust as noted above.

4.2. Implications for SW Pacific tectonic evolution

Having established that the Tongan FAB recovered by dredges 99 and 100 represent a basement suite of mid-Cretaceous –age, we proceed to discuss the tectonic significance of this suite. Two aspects of the Tongan FAB suite which are critical for its tectonic significance are: (a) the mid-Cretaceous age of 102.5±4.5Ma (Meffre et al., 2012), and (b) its geochemistry compared to other Cretaceous volcanic rocks from the SW Pacific.

Both New Caledonia and New Zealand contain fragments of east Gondwana crust of Cretaceous age (Cluzel et al., 1994; 2011, 2012; Tulloch et al., 2009). In New Caledonia, major Late Cretaceous volcano-sedimentary units unconformably overlies older Permian-Mesozoic accreted basement terranes (“Formation a Charbon”; Cluzel et al., 2010, 2011, 2012). Cluzel et al. (2011) demonstrate that detrital zircons from this sedimentary unit are of local provenance and record a history of Cretaceous magmatism between ~70-140Ma (Cluzel et al., 2011). Similar rocks with similar aged detrital zircons have also been reported from the West Norfolk Ridge to the north west of New Zealand (Mortimer et al., 2010) indicating a regional magmatic source.

Figure 10 shows that the detrital zircons populations have a prominent peak at ~102Ma, exactly coincident with the age of Tongan FAB suite. This suggests that the Tongan FAB suite was potentially associated with the most active phase of Cretaceous magmatism along the east Gondwana margin. Support for this relationship comes from the presence of Cretaceous arc volcanics of the same age from the Noumea Basin of New Caledonia (~103Ma, Nicholson et al., 2011) which are a typical calc-alkaline continental volcanic arc suite (Nicholson et al., 2011). This age was obtained from only one rhyolite flow unit and although Nicholson et al. (2011) were careful in only analysing zircons from fresh rhyolite flow units, as stated by Nicholson et al . (2011), there is still the potential that the age obtained was from an inherited zircon (Nicholson et al 2011). However we consider the similarities in geochemistry between the Mt Camel Terrane (see below) and the Noumea Basin lavas as significant and supportive of the age obtained by Nicholson et al. (2011).

Compared to the Tonga FAB suite, the Noumea Basin suite is more evolved (< 5 wt% MgO), has higher K_2O (Figure 4), is significantly more enriched in incompatible high field strength elements such as Zr, Nb, P and Th (Figure 5) and shows LREE enriched REE patterns (Figure 6). The Noumea Basin lavas are also of the same age as Cretaceous lavas from the Mount Camel Terrane in Northland, New Zealand (~101-102Ma, Nicholson et al., 2008; Tulloch et al., 2009), which are remarkably similar to those from the Noumea Basin (Figures 4-6) and to continental volcanic arc subduction-related magmatic suites (Nicholson et al., 2008).

In summary, therefore, we have evidence from the age of detrital zircon populations and the age of volcanics from New Caledonia to New Zealand of a wide-spread, robust, Cretaceous magmatic arc at ~102Ma associated with the Tonga FAB suite. Most of the magmatic rocks in the south western Pacific of this age show the influence of subduction, however the absence of large well-defined andesitic volcanic and volcaniclastic sequences has hindered Cretaceous tectonic reconstructions. Despite these uncertainties the evidence presented in this study for a Cretaceous Tongan FAB suite representing a Cretaceous marginal basin related to the Cretaceous volcanic arc contrasts with the tectonic interpretations for the IBM Eocene FAB formed during subduction initiation. Interestingly the IBM fore arc also contains Mesozoic FAB-type tholeiitic basalts. These were first thought to be accreted seamounts (Johnston et al., 1991) but were subsequently re-interpreted as part of a pre-existing marginal basin on their age and geochemistry (Ishizuka et al., 2011). These are older than those from Tonga (159 Ma, Ishizuka et al., 2011) and have Indian rather than Pacific isotopic affinities similar to other Mesozoic Basalts in the Philippine Sea Plate. We believe that the geochemical similiarities between the Tonga FAB and IBM FAB suites suggests that both suites were formed in a similar tectonic environment – that being a back-arc setting. Our results therefore support the arguments presented in Meffre et al. (2012) that FAB suites are most likely pre-existing back-arc basin crust unrelated to subduction initiation.

In support of a Cretaceous back-arc basin origin for the Tonga FAB suite is its very similar geochemistry compared to the Cretaceous Poya Terrane of New Caledonia. The Poya Terrane of New Caledonia is an allochthonous marginal basin tholeiitic suite occurring as isolated fault bounded wedges beneath the New Caledonia Ophiolitic Nappe (Eissen et al., 1998; Cluzel et al., 2001). The oldest reliable ages for the Poya Terrane come from associated radiolarian fauna, which give Upper Cretaceous ages of ~ 84 Ma (Cluzel et al., 2001). The geochemistry of the Poya Terrane basalts is consistent with eruption in a back-arc basin setting (Eissen et al., 1998; Cluzel et al., 2001). Tholeiites of the Poya Terrane range in composition from ‘depleted’ to ‘enriched’ end-members (Cluzel et al., 2001). Cluzel et al. (2001) referred to these end-members as BABB-type and P-MORB respectively. As can be seen from Figures 4-9, there is a pronounced overlap in composition between the Tongan FAB suite and the Poya Terrrane tholeiites. Primitive mantle normalised element diagrams (Figure 8) show that the dated dolerite (100-1-40) from dredge 100 is a very close match to the undepleted MORB-type (Figure 8a), whereas more depleted tholeiites from dredge 100 (100-1-8, 100-1-20) closely match the BABB-type end-member (Figure 8b). Both the Poya Terrane and the Tonga FAB suite are very similar to the IBM FAB suite, which also varies from depleted to more enriched compositions (Reagan et al., 2010). In terms of isotopic compositions the Poya Terrane tholeiites compared to the Tonga FAB extend to lower $^{143}Nd/^{144}Nd$ and higher $^{87}Sr/^{86}Sr$ values (Figure 9a). This observation could be due either to the limited sampling of the Tongan FAB, or alternatively more enriched mantle sources were present at the time of Poya Terrane magmatism . These observations suggest that the Tonga FAB suite and the Poya Terrane are remnants of the same Cretaceous back-arc basin which must have been active from at least 102-84Ma. The older parts of this basin have evidently not been preserved during obduction of the Poya Terrane in Eocene times (Cluzel et al., 2001). An additional important observation concerning all the Cretacous volcanics from the SW Pacific is that they all share the same low Zr/Nb values (Figure 5d). The more depleted end-members from both the Poya and Tonga FAB extend to higher Zr/Nb, but the undepleted MORB-type lavas, which comprise the majority of lavas present in the Poya Terrane (Cluzel et al., 2001), have the same low Zr/Nb values as volcanic arc front lavas from the Noumea Basin and the Mt Camel Terrane. This suggests that there was a common 'asthenospheric' mantle source component involved in both the arc and back-arc magmas during the middle Cretaceous.

Our preferred tectonic scenario to explain the close geochemical relationships between the Poya Terrane and the Tonga FAB, their impressively overlapping ages, and potentially mantle sources, with ~102Ma volcanic arc lavas is based on that proposed by Eissen et al., (1998) for the Poya Terrane. In the tectonic scenario proposed by Eissen et al., (1998), the Poya Terrane represents the western edge of a marginal basin called the East New Caledonia Basin (ENCB), which existed along the entire East Gondwana margin from at least 85Ma to 50Ma (Figure 11). The results of this study suggest that the ENCB is as old as 102Ma and indeed extended to at least the position of the Tonga FAB suite (present day position ~19°S, Figure 2). The fact that a potential remnant of the ENCB is present in the Tonga fore-arc suggests that subduction erosion since ~50Ma along the current active subduction system may have mostly destroyed the evidence for the presence of the ENCB and arc crust. As suggested by Eissen et al., (1998), remnants of the ENCB may be also be present in the basement of the Western Belt of the Vanuatu island arc and of Fiji. The presence of the ENCB crust in the Tonga fore arc leads us to speculate that a significant amount of 'oceanic' crust present within back-arc basins formed post ~50Ma (South Fiji and Lau Basins) may potentially be remnants of the ENCB.

5. Conclusions

Dredged tholeiitic rocks from the Tonga forearc at ~19°S and ~6000m water depths have recovered a mid-Cretaceous aged (102Ma) fore arc basalt suite similar in composition to that reported from the IBM fore arc. The Tongan FAB suite is a remnant of a back-arc basin associated with a continental volcanic arc of the same age, which potentially existed along the entire East Gondwana margin in Upper Albian times. The Tonga FAB is geochemically almost identical to the allohcthonous Poya Terrane in New Caledonia. The Poya Terrane has been proposed to represent oceanic crust of the

East New Caledonia Basin and our results suggest that this basin was present from 102-50Ma, before being 'destroyed' during tectonic processes associated with plate reorganizations in the Tertiary. This study demonstrates that the Tonga fore arc not only preserves the history of subduction initiation (Meffre et al., 2012), but also a diverse range of basement terranes of differing ages from the entire history of the East Gondwana convergent margin in the SW Pacific.

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Figure Captions

(web & print) **Fig.1.** Regional bathymetry of the SW Pacific showing the location of the Tonga fore arc and trench (bathymetry created using geomapapp; Ryan et al., 2008, http://www.geomapapp.org). Yellow square outlines the area of Figure 2. Red polygons numbered 1 to 3 refer to the distinct structural blocks of the Tonga fore arc and trench as defined by Wright et al. (2000) (see text for discussion). Bold text show the relative positons of geographical entities mentioned in the text as follows: NFB = Northern Lau Basin; VA = Vanuatu Arc; FJ = Fiji; HR = Hunter Ridge; NC (PT, NB) = New Caledonia and the Poya Terrane and Noumea Basin (for more detailed location of the Poya Terrane and Noumea Basin, the reader is referred to Nicholson et al., 2011); NR = Norfolk Ridge; SFB = South Fiji Basin; LR = Lau Ridge; LB = Lau Basin; TR = Tonga Ridge: NI (MtC) = Northland, North Island New Zealand and the Mount Carmel Terrane (for more detailed location of the Mt Camel Terrane the reader is referred to Nicholson et al., 2008); HP = Hikurangi Plateau; CR = Chatham Rise; LR = Loisville Ridge; OT = Osbourn Trough; MP = Manihiki Plateau(web & print)

Fig.2. Bathymetric map (200-m contour interval) of the Tonga Trench and forearc, showing the location of dredges at ~19°S. Map was created from a 200-m Sea Beam 2000 grid (Boomerang 8), with portions of the trench axis filled in by Sea Beam data from Marathon 6 (Wright et al., 2000). Map projection is Mercator. (web & print)

(web & print) **Fig.3.** Loss of Ignition (LOI) and K_2O versus MgO for basalts and dolerites recovered by dredges 99 and 100.

(web) **Fig.4.** Major elements (a) SiO_2, (b) TiO_2, (c) Al_2O_3, (d) FeO^T, total iron as FeO, (e) CaO, (f) Na_2O, (g) K_2O,and (h) P_2O_5 wt% versus MgO wt% for dredged volcanic rocks from the Tonga fore arc at ~19°S. All analyses have been resumed to 100 wt% on an anhydrous basis. Plotted symbols are as follows: dredge 100, blue circles; dredge 99 blue inverted triangle; black circles, IBM FAB (Reagan et al., 2010); orange inverted triangles, Poya terrane BABB-like compositions, orange right pointing triangles, Poya terrane undepleted MORB-like compositions (Cameron, 1989; Eissen et al., 1998; Cluzel et al., 2001); red triangles, Osbourn Trough lavas (Zhang et al., 2012); red circles, Pacific Cretaceous crust (Castillo et al., 2009); forest green inverted triangle, Mount Camel terrane volcanics (Nicholson et al., 2008); green triangles, Noumea Basin volcanics (Nicholson et al., 2011).

(print) **Fig.4.** Major elements (a) SiO_2, (b) TiO_2, (c) Al_2O_3, (d) FeO^T, total iron as FeO, (e) CaO, (f) Na_2O, (g) K_2O,and (h) P_2O_5 wt% versus MgO wt% for dredged volcanic rocks from the Tonga fore arc at ~19°S. All analyses have been resumed to 100 wt% on an anhydrous basis. Plotted symbols are as follows: dredge 100, dark grey circles; dredge 99 dark grey inverted triangle; black circles, IBM FAB (Reagan et al., 2010); light grey inverted triangles, Poya terrane babb-like compositions, light grey right pointing triangles, Poya terrane undepleted morb-like compositions (Cameron, 1989; Eissen et al., 1998; Cluzel et al., 2001); open triangles, Osbourn Trough lavas (Zhang et al., 2012); open circles, Pacific Cretaceous crust (Castillo et al., 2009); black inverted triangle, Mount Camel terrane volcanics (Nicholson et al., 2008); black triangles, Noumea Basin volcanics (Nicholson et al., 2011).

(web) **Fig.5.** Trace elements a) Zr ppm, c) Nb ppm, e) Y ppm, h) P_2O_5 wt% and trace element ratios values b) $(La/Sm)_N$, d) Zr/Nb, f) Sr/Nd and g) Th/Nd x 100 versus TiO_2 wt%. Symbols as for Fig.4. except in a), c) and d) red squares are altered lavas dredged from the Osbourn Trough (Worthington et al., 2006).

(print) **Fig.5.** Trace elements a) Zr ppm, c) Nb ppm, e) Y ppm, h) P_2O_5 wt% and trace element ratios values b) $(La/Sm)_N$, d) Zr/Nb, f) Sr/Nd and g) Th/Nd x 100 versus TiO_2 wt%. Symbols as for Fig.4. except in a), c) and d) open squares are altered lavas dredged from the Osbourn Trough (Worthington et al., 2006).

(web & print) **Fig.6.** Chondrite-normalized REE patterns for the Tonga FAB suite compared to a) Noumea Basin lavas, b) Mount Carmel Terrane lavas, c) Poya terrane undepleted MORB like lavas, d) Poya terrane BABB-like lavas, e) Pacific Cretaceous crust and f) IBM FAB suite. Symbols and data sources as for Fig.4. Chondrite normalization values are from Taylor and Gorton (1977).

(web & print) **Fig.7.** Ti/V values versus Zr ppm. Symbols as for Fig.4 and Fig.5. ‘19°S’ is placed next to the composition of Pacific crust dredged at this latitude (Castillo et al., 2009).

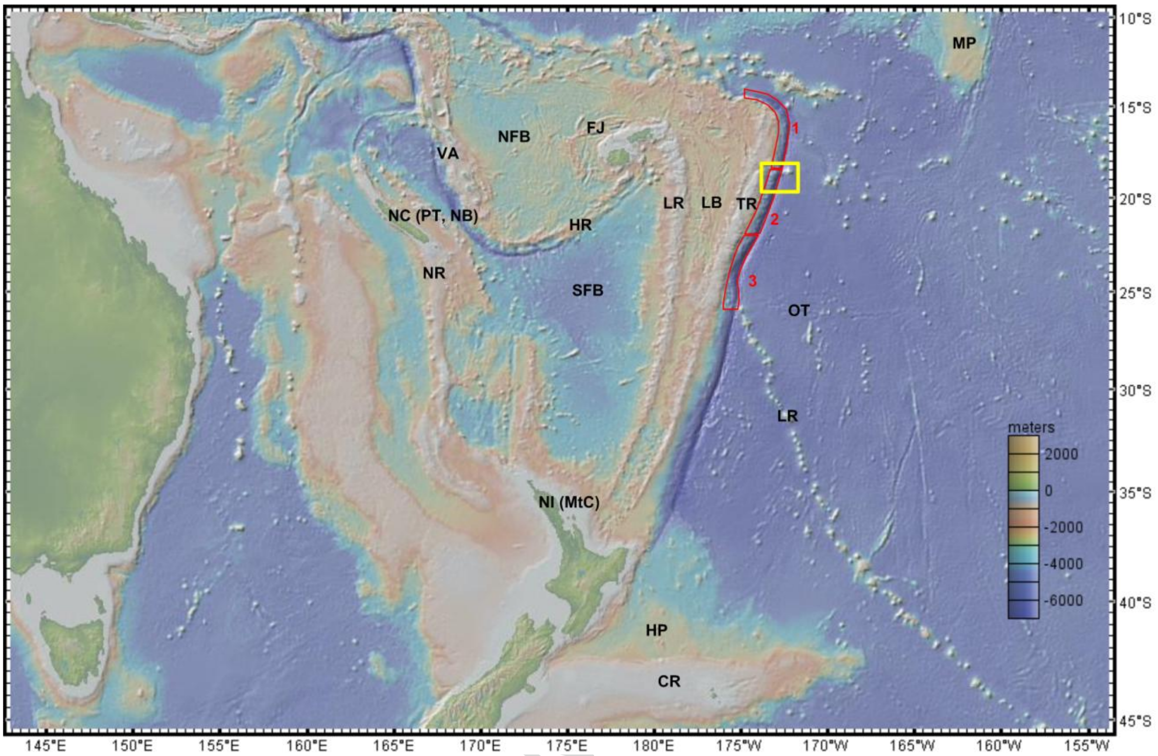
(web) **Fig.8.** Primitive mantle normalized trace element abundance patterns of the Tonga FAB suite (blue circles) compared to: a) the Poya terrane undepleted MORB-like lavas (thin black lines, Cluzel et al., 2001), and the most fertile IBM FAB composition (black circle, sample 975-R22, Reagan et al., 2010); b) the Poya terrane BABB-like lavas (thin black lines, Cluzel et al., 2001), and the average IBM FAB composition (inverted black triangle, Reagan et al., 2010). Primitive mantle normalizing values from Sun and McDonough (1989).

(print) **Fig.8.** Primitive mantle normalized trace element abundance patterns of the Tonga FAB suite (grey circles) compared to: a) the Poya terrane undepleted MORB-like lavas (thin black lines, Cluzel et al., 2001), and the most fertile IBM FAB composition (black circle, sample 975-R22, Reagan et al., 2010); b) the Poya terrane BABB-like lavas (thin black lines, Cluzel et al., 2001), and the average IBM FAB composition (inverted black triangle, Reagan et al., 2010). Primitive mantle normalizing values from Sun and McDonough (1989).(web & print)

Fig.9. The $^{143}Nd/^{144}Nd$ versus a) $^{87}Sr/^{86}Sr$ and b) $^{206}Pb/^{204}Pb$ isotopic compositions of the Tonga FAB compared to relevant magmatic suites. Small black circles Pacific MORB glasses and gray circles Indian MORB glasses (Petrological Database of the Ocean Floor, www.petdb.org). Symbols as for Fig.4 and 5. '19°S' is placed next to the composition of Pacific crust dredged at this latitude (Castillo et al., 2009).

(web & print) **Fig.10.** Probability density diagram for the age of detrital zircons from the Late Cretaceous sandstones of New Caledonia restricted to the 70–140Ma (modified from Figure 4 of Cluzel et al., 2011). Vertical shaded bar is the age of and standard error on the U-Pb ziron age for dolerite sample 100-1-40 from dredge 100 on the Tonga fore arc (Meffre et al., 2012).

(web & print) **Fig.11.** Schematic geodynamic reconstruction of New Caledonia and the SW Pacific around ~70 Ma (modified from Figure 5, Eissen et al., 1998). A = Australia; ENCB = East New Caledonia Basin; LHR = Lord Howe Rise;NC = New Caledonia; NCB = New Caledonia Basin; NLB; NR = Norfolk Ridge.



10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
145°E
150°E
155°E
160°E
165°E
170°E
175°E
180°E
175°W
170°W
165°W
160°W
155°W
MP
VA
NFB
FJ
NC (PT, NB)
HR
LR
LB
TR
1
2
3
NR
SFB
OT
LR
NI (MtC)
HP
CR
meters
2000
0
-2000
-4000
-6000

Figure 1

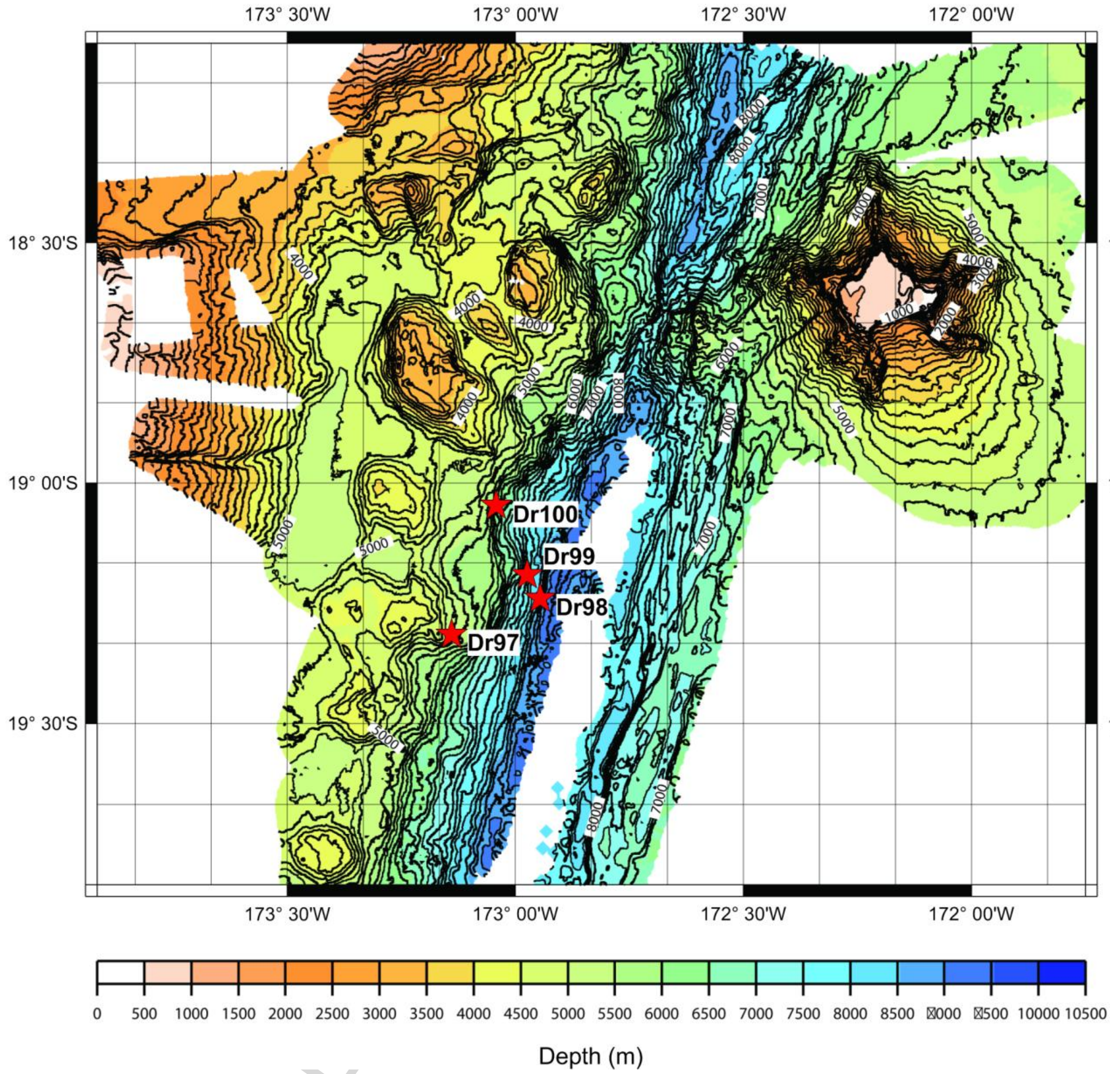
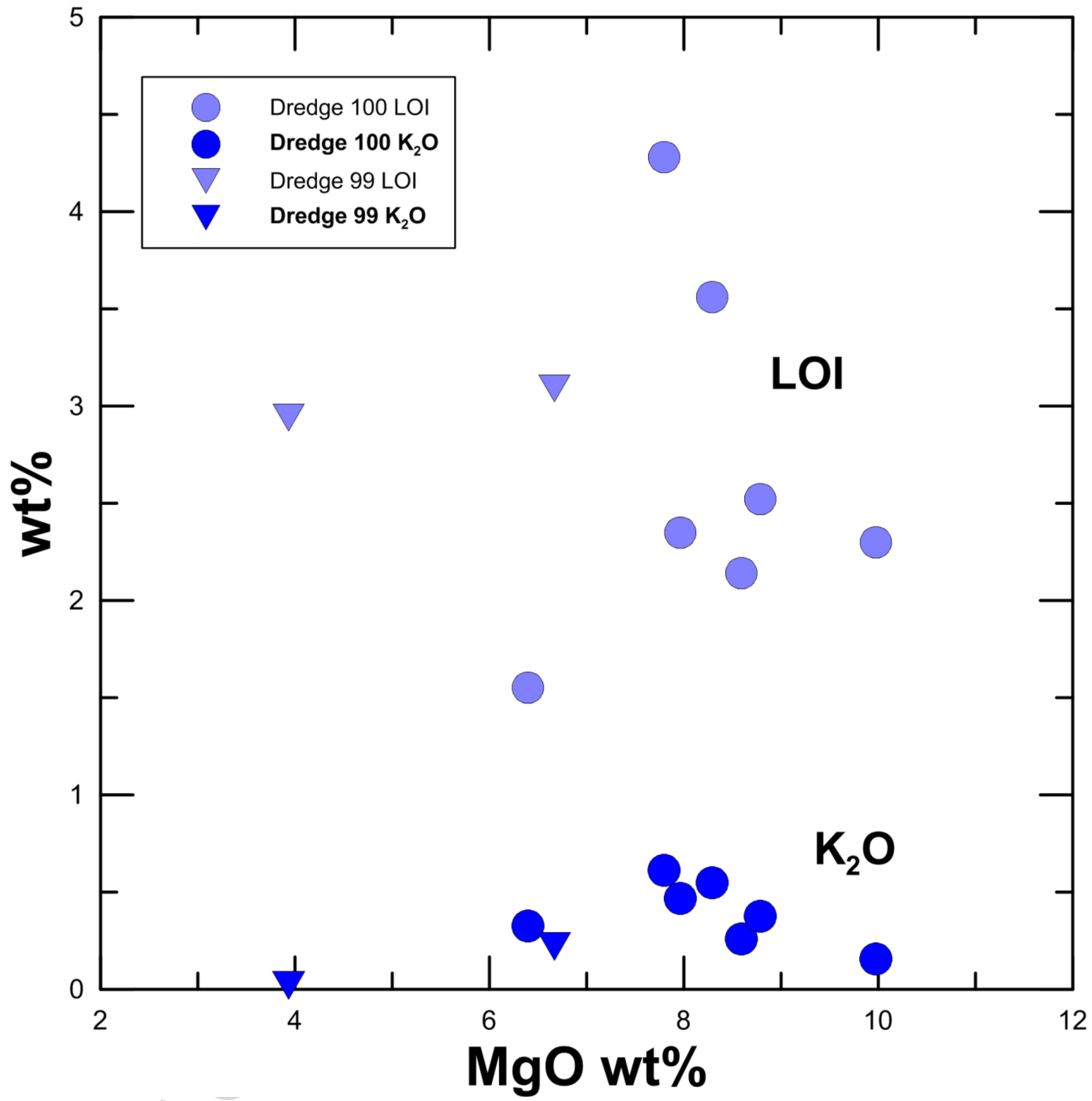

173° 30'W
173° 00'W
172° 30'W
172° 00'W
18° 30'S
19° 00'S
19° 30'S
Dr100
Dr99
Dr98
Dr97
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
10000
10500
Depth (m)

Figure 2



Dredge 100 LOI
Dredge 100 K2O
Dredge 99 LOI
Dredge 99 K2O
LOI
K2O
wt%
MgO wt%
0
1
2
3
4
5
2
4
6
8
10
12

Figure 3

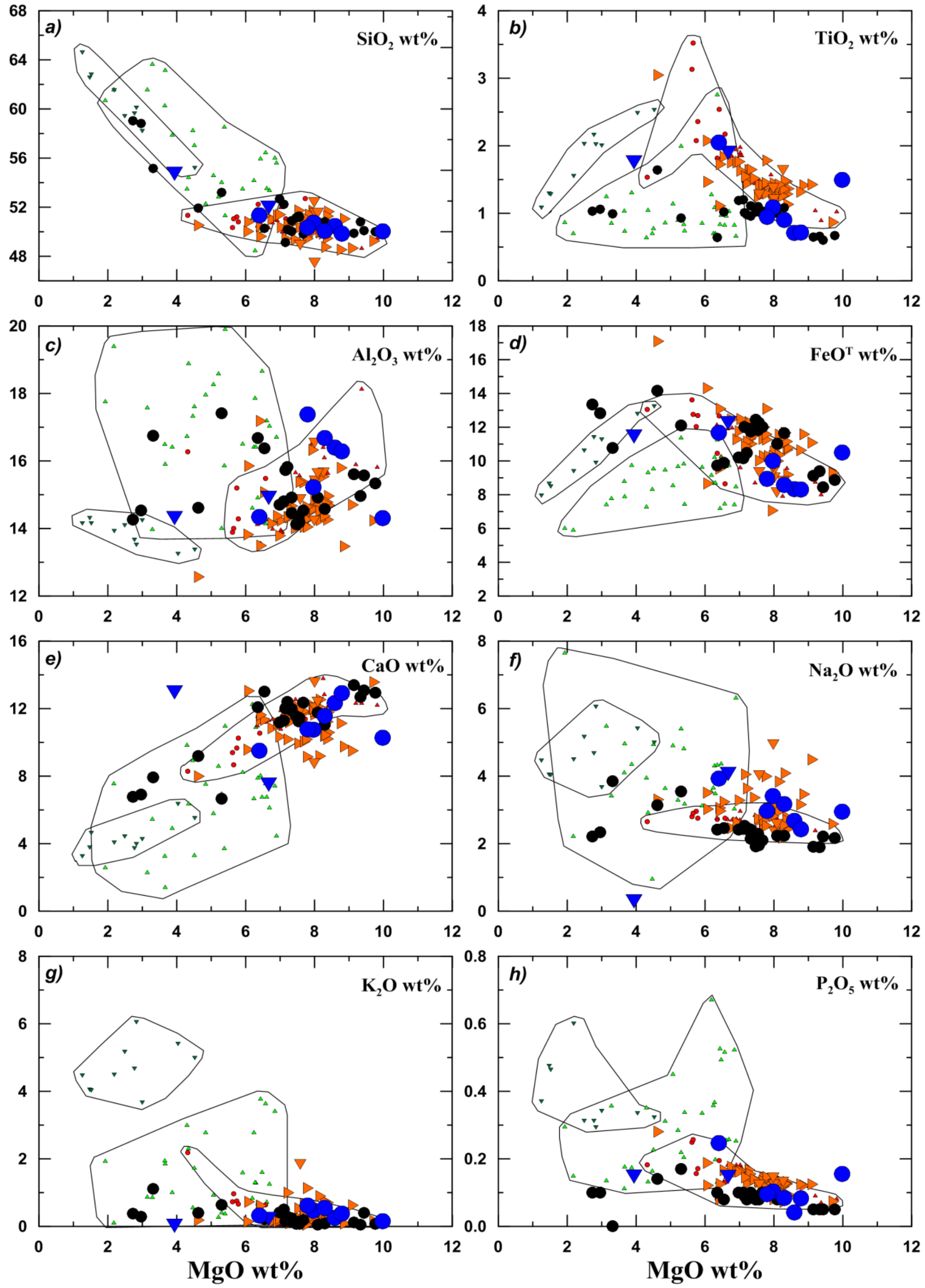

a)
SiO2 wt%
b)
TiO2 wt%
c)
Al2O3 wt%
d)
FeOT wt%
e)
CaO wt%
f)
Na2O wt%
g)
K2O wt%
h)
P2O5 wt%
MgO wt%
MgO wt%

Figure 4

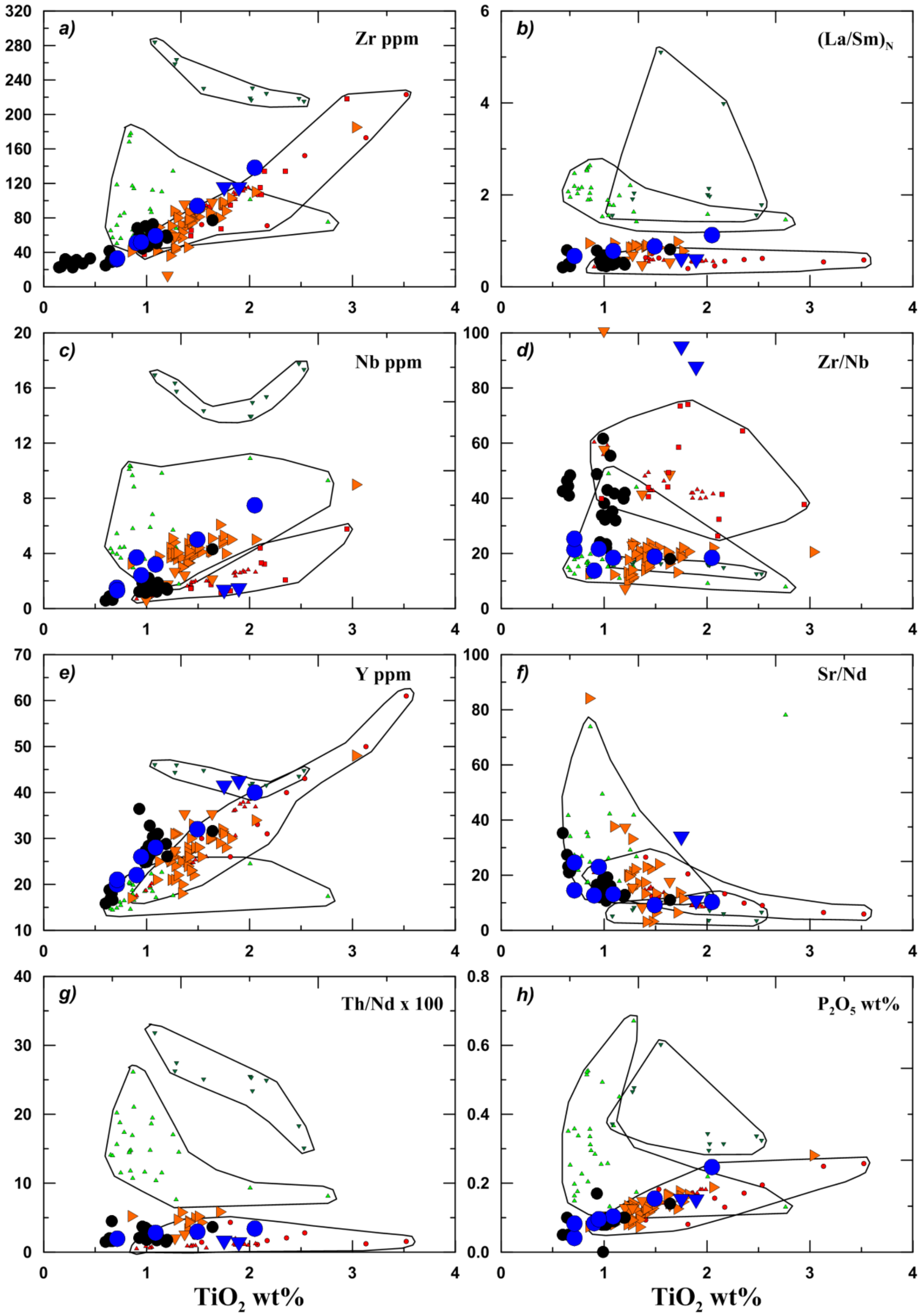
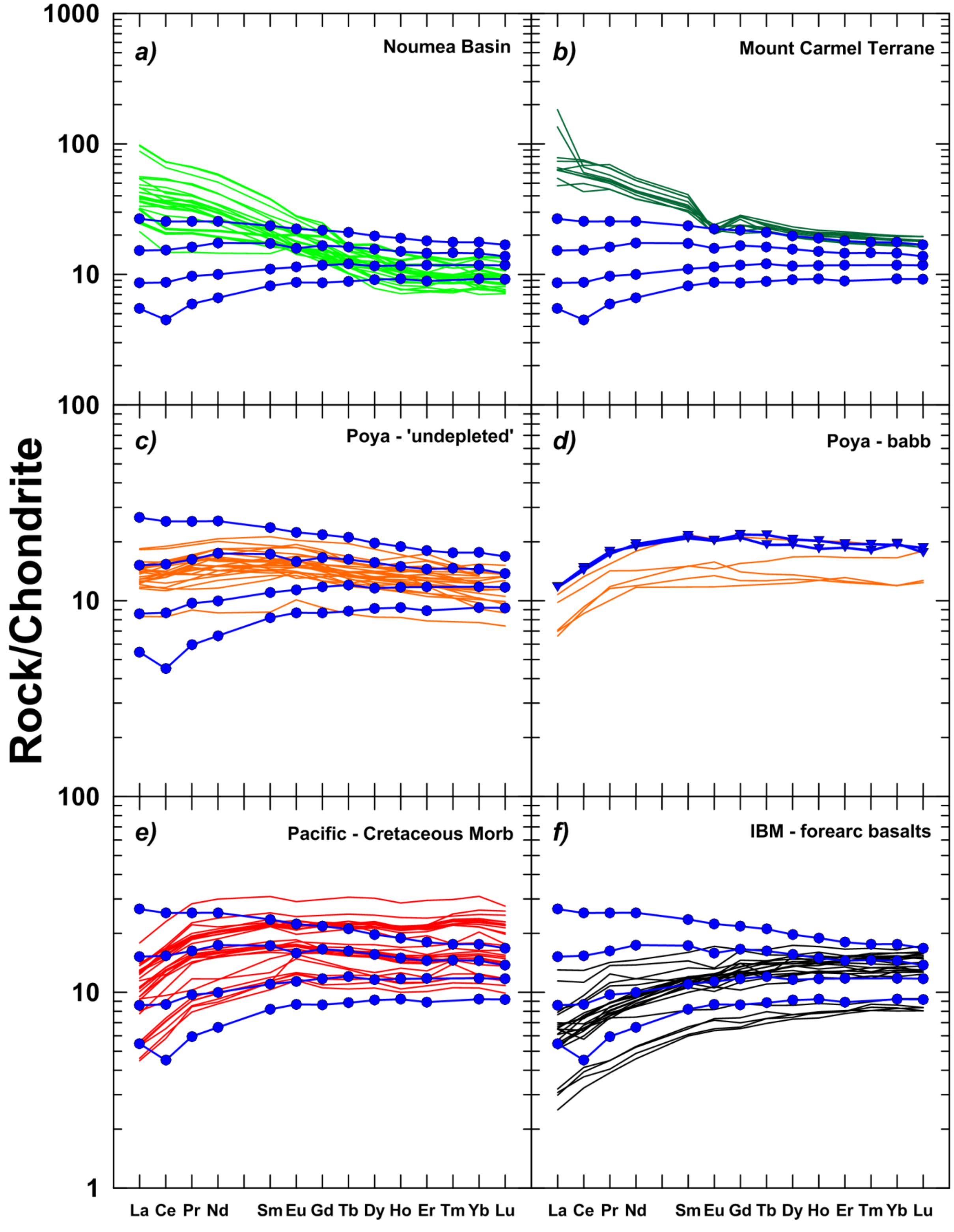
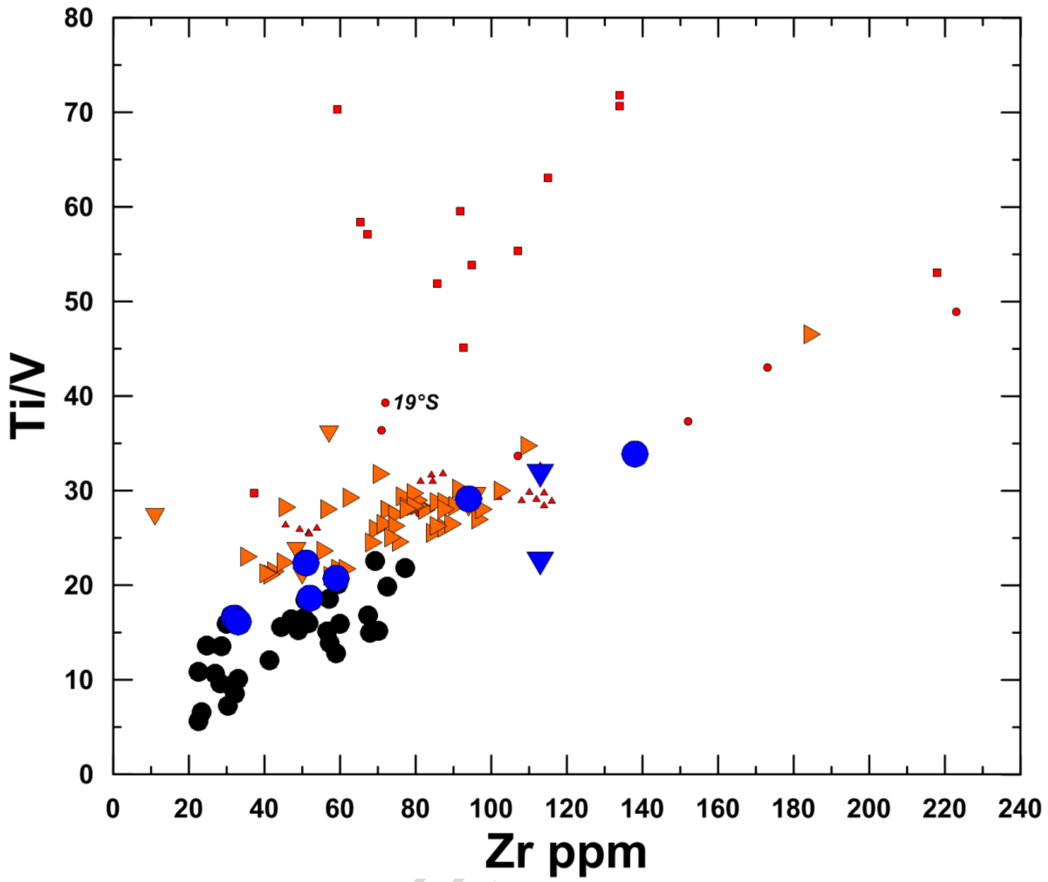

a)
Zr ppm
b)
(La/Sm)N
c)
Nb ppm
d)
Zr/Nb
e)
Y ppm
f)
Sr/Nd
g)
Th/Nd x 100
h)
P2O5 wt%
TiO2 wt%
TiO2 wt%

Figure 5



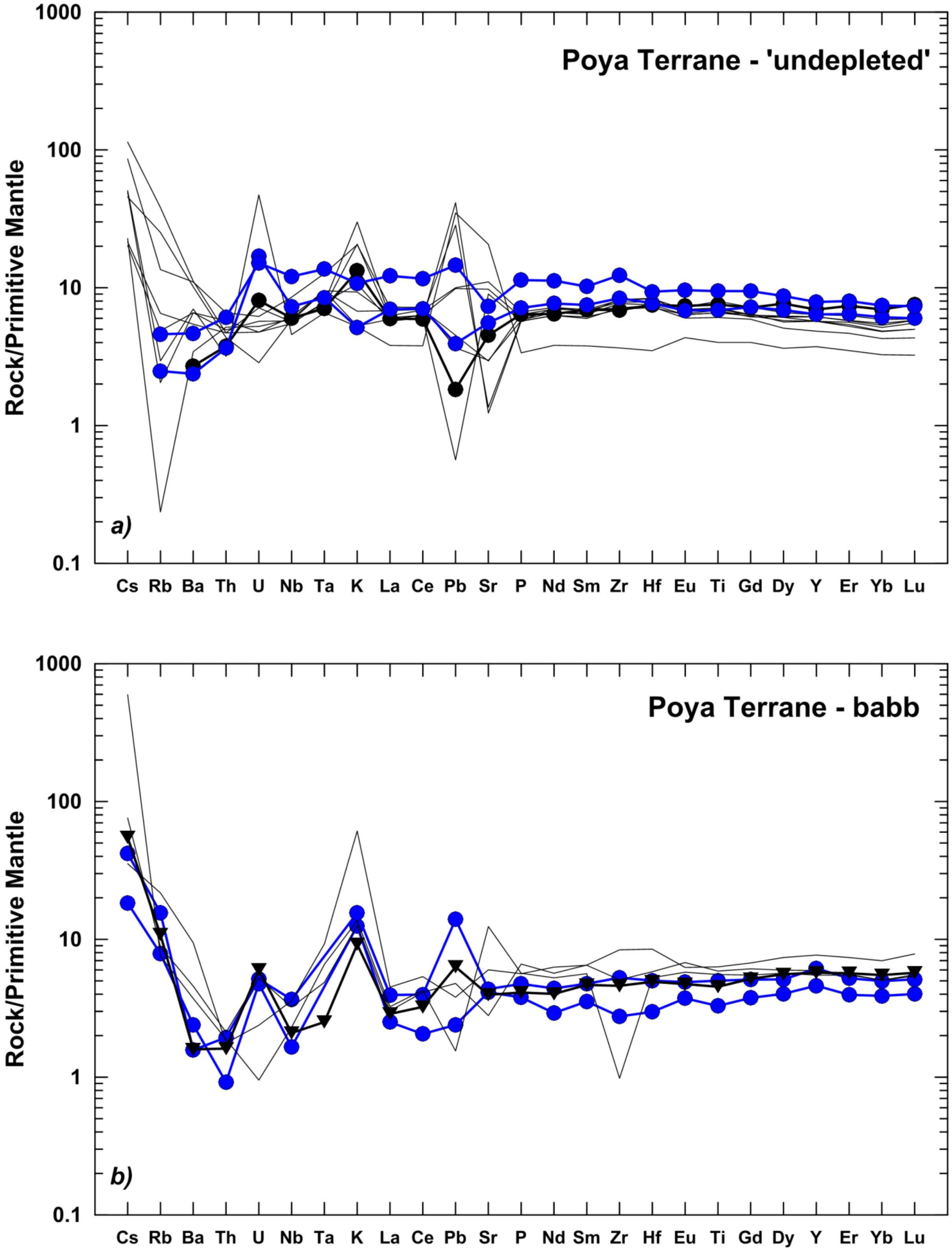
Rock/Chondrite
1000
100
10
1
a)
Noumea Basin
b)
Mount Carmel Terrane
c)
Poya - 'undepleted'
d)
Poya - babb
e)
Pacific - Cretaceous Morb
f)
IBM - forearc basalts
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Figure 6



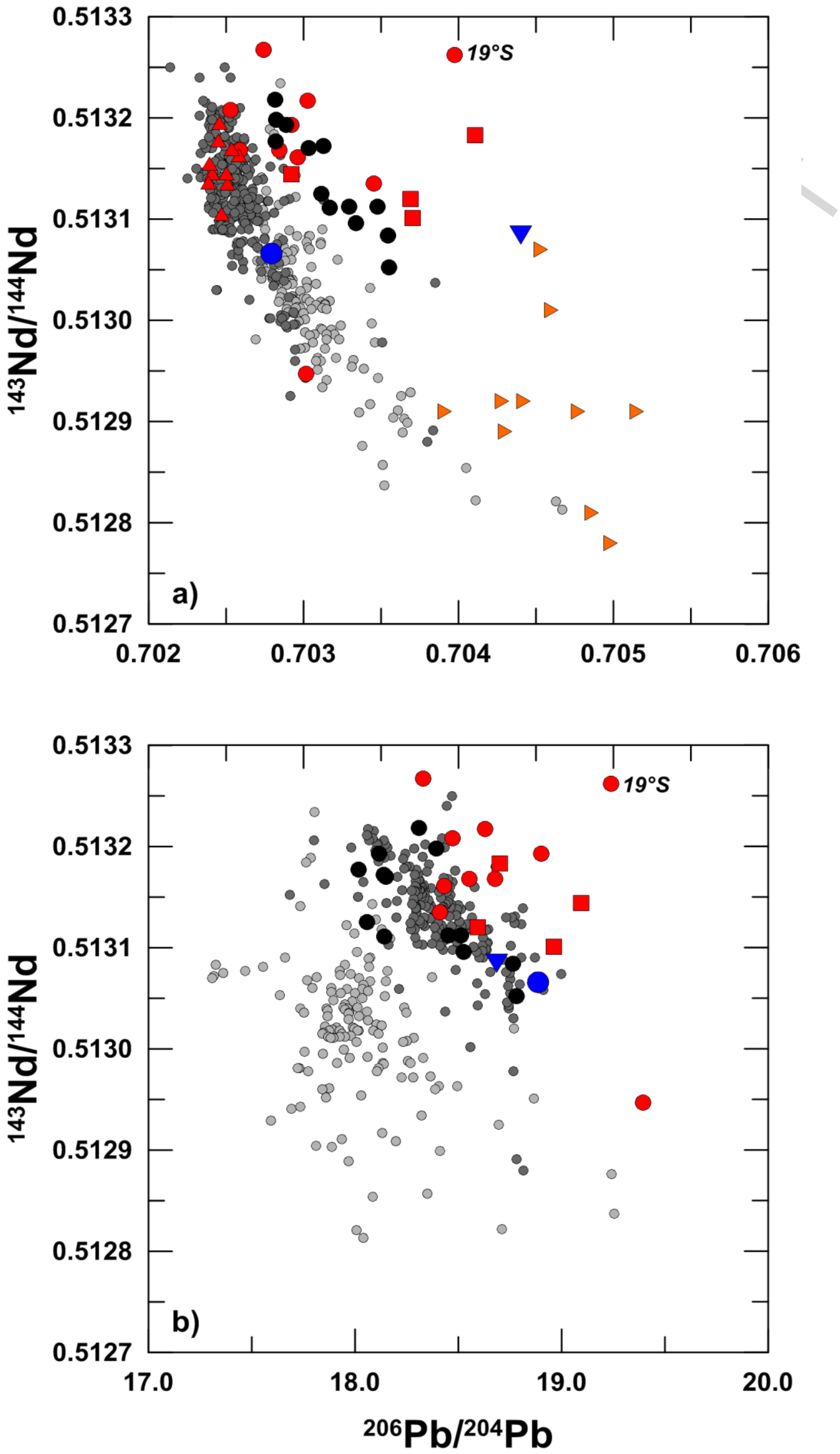
80
70
60
50
40
30
20
10
0
Ti/V
19°S
0
20
40
60
80
100
120
140
160
180
200
220
240
Zr ppm

Figure 7



Poya Terrane - 'undepleted'
Rock/Primitive Mantle
1000
100
10
1
0.1
a)
Cs Rb Ba Th U Nb Ta K La Ce Pb Sr P Nd Sm Zr Hf Eu Ti Gd Dy Y Er Yb Lu
Poya Terrane - babb
b)

Figure 8



0.5133
0.5132
0.5131
0.5130
0.5129
0.5128
0.5127
$^{143}Nd/^{144}Nd$
19°S
a)
0.702
0.703
0.704
0.705
0.706
b)
17.0
18.0
19.0
20.0
$^{206}Pb/^{204}Pb$

Figure 9

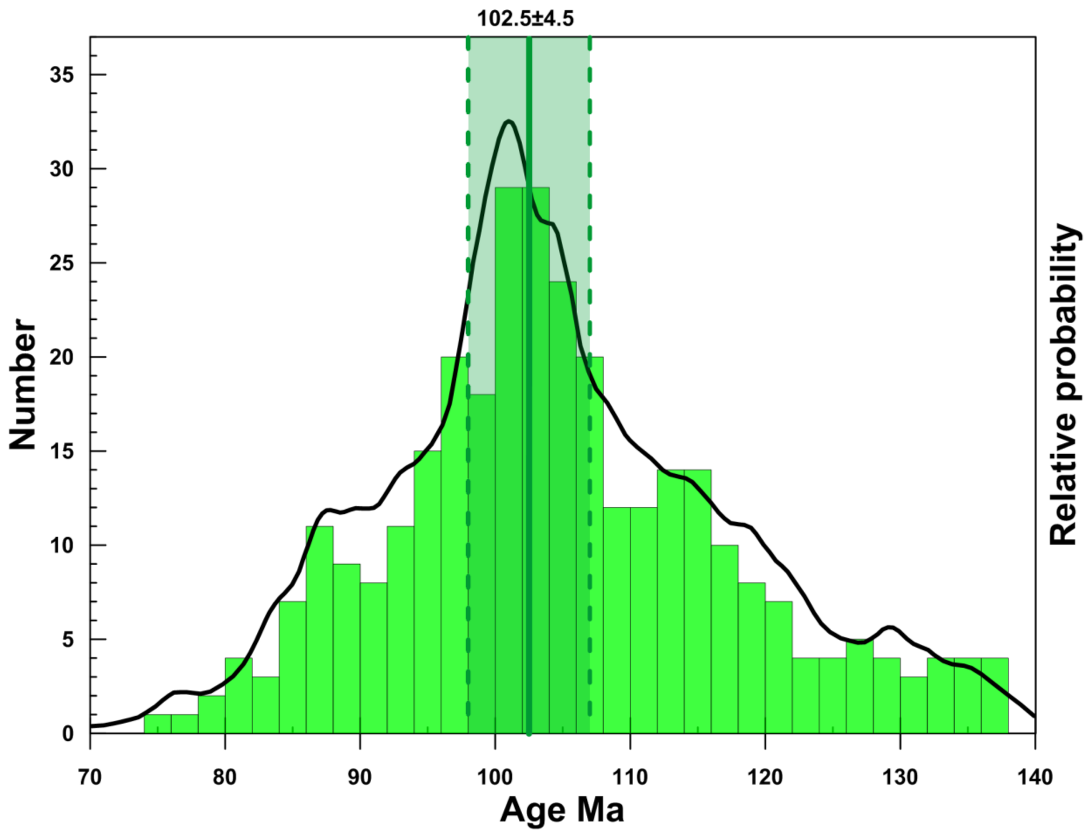

102.5±4.5
Number
Relative probability
Age Ma
0
5
10
15
20
25
30
35
70
80
90
100
110
120
130
140

Figure 10

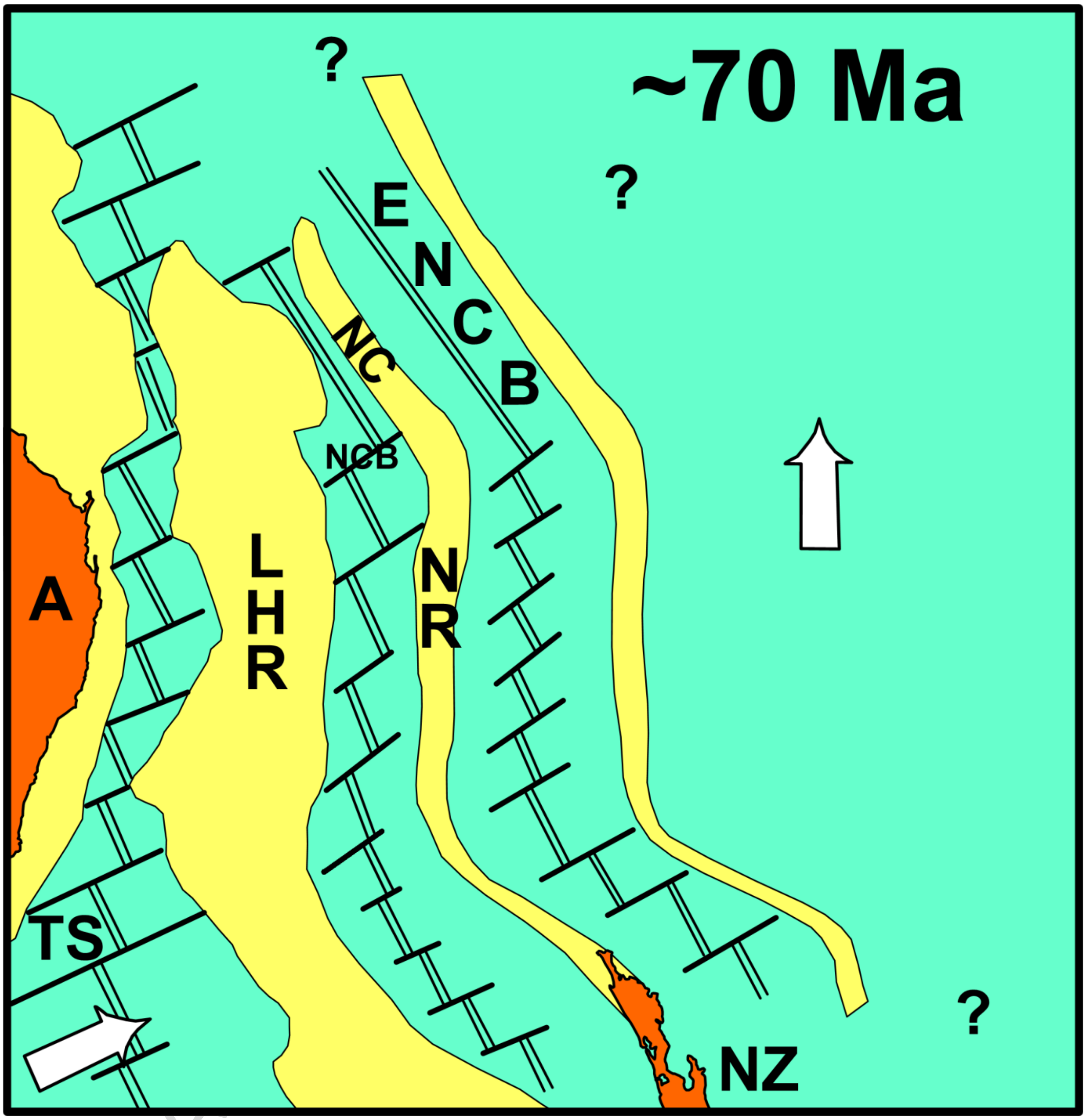


Figure 11

Table 1
Dredge locations located at ~19°S which recovered rocks from the Tonga fore arc during the 1996 voyage of the RV Melville

Dredge	Latitude (°S)	Longitude (°W)	Depth range (m)	Recovery/deck log
D97	19°19.69 - 19° 19.7	173° 09.21 - 173° 09.2	5016 - 4965	~50-60 kg of volcaniclastic sandstones, siltstones, and sedimentary breccias
D98	19° 15.19 - 19° 15.02	172° 56.29 – 172° 57.34	9371 - 8194	~80-90 kg of serpentinized ultramafics and relatively fresh dunite
D99	19° 11.01 - 19° 11.28	172° 58.51 - 172° 59.64	7531 - 6820	~250-300 kg of gabbro, volcanic rocks and sediments
D100	19° 03.61 - 19° 03.67	173° 02.50 - 173° 03.42	6345 - 5695	~ 150 kg of altered volcanics and sediments

Table 2
Major (wt%) trace element (ppm) and Sr-Nd-Pb isotope compositions of igneous rocks recovered by dredging of the Tonga fore arc.

Sample no.	99-2-8	99-2-10	99-1-3	99-1-4	99-1-6	99-1-26	99-1-33	99-2-1	100-1-19	100-1-20	100-1-8	100-1-21	100-1-32	100-1-39	100-1-40
Type[a]	D	D	G	G	G	G	G	G	B	B	B	B	B	D	D
SiO_2	54.71	51.95	50.54	48.63	47.59	50.75	51.04	50.31	50.47	49.83	50.75	50.05	50.35	50.01	51.34
TiO_2	1.75	1.90	0.35	0.26	0.25	0.35	0.28	0.23	0.71	0.71	1.09	0.90	0.95	1.49	2.05
Al_2O_3	14.31	14.91	16.91	17.60	14.42	17.63	17.11	20.10	16.40	16.29	15.22	16.68	17.38	14.31	14.35
FeO[b]	11.44	12.24	4.66	5.78	7.60	4.41	6.09	5.05	8.34	8.31	10.00	8.57	8.94	10.49	11.68
MnO	0.42	0.41	0.10	0.12	0.15	0.10	0.14	0.10	0.20	0.27	0.26	0.15	0.14	0.19	0.20
MgO	3.93	6.67	9.56	11.18	15.57	8.73	9.57	8.40	8.59	8.79	7.96	8.29	7.79	9.98	6.40
CaO	12.97	7.50	16.15	14.67	13.24	16.15	13.91	13.39	12.32	12.92	10.74	11.56	10.77	10.28	9.50
Na_2O	0.29	4.06	1.70	1.66	1.17	1.84	1.80	2.28	2.67	2.43	3.41	3.17	2.96	2.94	3.92
K_2O	0.02	0.22	0.02	0.09	0.01	0.03	0.05	0.16	0.26	0.38	0.47	0.55	0.61	0.16	0.32
P_2O_5	0.15	0.15	0.01	0.01	0.01	0.01	0.01	0.00	0.04	0.08	0.10	0.08	0.09	0.16	0.25
LOI[c]	2.94	3.09	1.09	3.36	4.25	1.19	1.06	3.75	2.14	2.52	2.35	3.56	4.28	2.30	1.55
Total[d]	99.51	99.94	99.1	99.6	99.85	99.98	99.09	100.4	100.03	100.26	100.10	99.86	100.03	99.98	99.90
xrf															
Rb	<1	<1	1	1	1	1	1	1	4.2	5	9.9	10.3	5.8	1.1	3.3
Ba	<4	13	4	4	4	4	4	<4	19	18	12	9	27	20	35
Nb	1.2	1.3	1	1	1	1	1	<1	1.5	1.3	3.2	3.7	2.4	5	7.5
La	5	5	4	2	3	2	2	<2	4	3	4	3	3	6	10
Ce	10	14	4	4	4	4	4	<4	<4	4	10	8	4	12	22
Sr	319	114	106	132	74	116	133	190	98	87	92	114	115	120	154
Nd	11	12	4	2	2	2	2	<2	4	6	7	9	5	13	15
Zr	113	113	7	5	5	6	4	4	32	33	59	51	52	94	138
Y	41	42	9.3	6.9	6.2	9	7	5	20	21	28	22	26	32	40
V	471	360	193	143	129	186	160	127	258	265	314	242	306	307	363
Sc	34	39	50	35	34	49	45	36	42	44	48	39	46	35	42
Cr	6	24	171	868	1039	164	72	92	487	486	375	463	516	378	8
Ni	16	30	97	213	386	91	52	79	100	102	96	142	124	202	27

Sample no.	99-2-8	99-2-10	99-1-3	99-1-4	99-1-6	99-1-26	99-1-33	99-2-1	100-1-19	100-1-20	100-1-8	100-1-21	100-1-32	100-1-39	100-1-40
Type[a]	D	D	G	G	G	G	G	G	B	B	B	B	B	D	D

icp-ms															
La	3.70	3.69					0.17			1.72	2.71			4.79	8.38
Ce	11.98	11.62					0.57			3.65	7.06			12.50	20.67
Pr	2.07	2.01					0.14			0.69	1.13			1.89	2.95
Nd	11.32	11.63					0.95			3.95	5.97			10.41	15.23
Sm	4.00	4.12					0.48			1.57	2.12			3.32	4.53
Eu	1.46	1.47					0.31			0.63	0.82			1.15	1.61
Gd	5.44	5.64					0.84			2.24	3.04			4.31	5.63
Tb	0.95	1.06					0.17			0.43	0.59			0.80	1.03
Dy	6.28	6.68					1.14			2.97	3.77			5.09	6.42
Ho	1.34	1.48					0.25			0.67	0.86			1.09	1.38
Er	3.98	4.16					0.73			1.90	2.50			3.09	3.84
Tm	0.58	0.63					0.11							0.47	0.57
Yb	4.08	4.01					0.67			1.92	2.46			3.02	3.67
Lu	0.57	0.60					0.10			0.30	0.38			0.44	0.54
Sc	32	40					51							38	45
V	470	387					161							297	361
Cr	5	22					66							363	9
Co	22	40					39							56	46
Ni	11	28					53							184	25
Cu	9	19					11							68	46
Zn	122	194					32							87	113
Rb	0.21	2.17					0.54							1.58	2.92
Sr	375	116					133							118	155
Y	37.4	39.0					6.1							29.2	35.9
Zr	91.8	106.9					3.9			30.9	56.7			92.8	117.4
Nb	1.24	1.46					0.01			1.18	2.61			5.21	8.61
Cs	0.002						<0.01			0.145	0.332				
Ba	3	16					1			17	11			17	33
Hf	2.71	2.82					0.19			0.92	1.55			2.38	2.89
Ta	0.16	0.12					0.00							0.35	0.56
Pb	1.50	0.55					<0.05			0.17	0.99			0.28	1.03
Th	0.15	0.13					<0.01			0.08	0.17			0.31	0.52
Sample no.	99-2-8	99-2-10	99-1-3	99-1-4	99-1-6	99-1-26	99-1-33	99-2-1	100-1-19	100-1-20	100-1-8	100-1-21	100-1-32	100-1-39	100-1-40
Type[a]	D	D	G	G	G	G	G	G	B	B	B	B	B	D	D
U	0.09	0.0					<0.			0.10	0.1			0.35	0.32

		8	00	1	
$^{87}Sr/^{86}Sr$	0.704404				0.702794
$^{143}Nd/^{144}Nd$	0.513084				0.513066
$^{206}Pb/^{204}Pb$	18.685				18.886
$^{207}Pb/^{204}Pb$	15.520				15.538
$^{208}Pb/^{204}Pb$	38.209				38.351

a igneous rock type: G, gabbro; D, dolerite; B, basalt
b total iron calculated as FeO
c LOI, loss on ignition
d total refers to original analysis sum; major elements have been recalculated to a total of 100% on an anhydrous basis

Highlights

- The geochemistry of a Cretaceous Tongan fore-arc basalt (FAB) suite is reported
- The Tonga FAB suite is very similar to the Poya Terrane basalts of New Caledonia
- Similar geochemistry to IBM FAB but not associated with subducution initiation
- Possibly a remnant of the hypothesized back-arc East New Caledonia Basin