Arc-backarc systems of northern Kermadec-Tonga

R.J. Arculus

Department of Earth and Marine Sciences, Australian National University, Canberra, ACT 0200, Australia

Abstract

Over the past seven years, a combination of New Zealand-, Australian-, and German-led research voyages using the research vessels *Tangaroa*, *Southern Surveyor*, and *Sonne* respectively, have revolutionised our understanding of the Kermadec-Tonga arc-backarc systems. This convergent margin is the most seismically-active subduction zone system on Earth with convergence rates steadily increasing northwards from the Hikurangi Trench to ~250 mm/year at northern Tonga. In combination with the intra-oceanic setting, factors potentially producing magmatic, tectonic, and hydrothermal variability in this system include an increase in potentially subductable sediment northwards along-strike, intersection of the Louisville Ridge (hot-spot chain) and Osbourn Trough (paleo-spreading centre) with the arc at ~ 25^{o}S, and the possibility of Samoan (hot-spot) plume ingression in the northern Lau Basin. The bulk of the magmatism is submarine; whereas only a few emergent (some transient) volcanic islands exist, about 80 submarine volcanic centres of significant size (>1000 m above surrounding sea floor) are present between White Island in the south to north of Tafahi in Tonga. About 35% of these centres are hydrothermally active. Important petrogenetic features of the volcanic rocks along this arc system are the abundance of rhyolite (some quartz-amphibole-bearing), and the outcrop of primitive olivine-clinopyroxene-phyric basalts in satellite cones of the major edifices. Many of the edifices consist of complex caldera systems. Eruptions from and degradation of these edifices were probably tsunamigenic. Many of the hydrothermal systems developed within the edifices are likely destroyed during the sector collapses which are the characteristic edifice degradation mode. There are three backarc spreading systems along this margin: the Havre Trough, Valu Fa-Eastern Lau Spreading Centre, and the nascent Fonualei Rifts. The latter are particularly notable in having captured the entire suprasubduction zone magmatic flux for a distance of about 150 km, shutting down the adjacent volcanic front arc volcanoes.

Introduction

The 2,500 km-long, intra-oceanic Tonga-Kermadec arc system (Fig. 1) has been the focus of intensive study for many years including seminal papers on subduction zone seismicity during the development of the plate tectonic paradigm (Oliver & Isacks, 1967), the formation of remnant arcs (Karig, 1972), recognition of the extremely refractory nature of the mantle wedge overlying the subducting Pacific Plate (Ewart & Hawkesworth, 1987), and history of the opening of the Lau Basin based on ODP Leg 135 results (Hawkins, 1994). More recently, the complexities of the opening/spreading history of the Lau Basin have been described by Zellmer & Taylor (2001), and the Tonga-Kermadec system has been a prime focus of studies utilising U-Th disequilibria concerned with rates of fluid transport from the subducted plate to the surface (Turner, 2002).

During the 1970s, a major development occurred in the way bathymetry and acoustic backscatter of the sea floor could be obtained with multibeam sonar swath mapping. Following deployment of civilian 30 kHz systems capable of fairly high resolution, complete coverage surveys in water depths d”3500m in the Tonga-Kermadec arc-backarc systems began about 7 years ago,

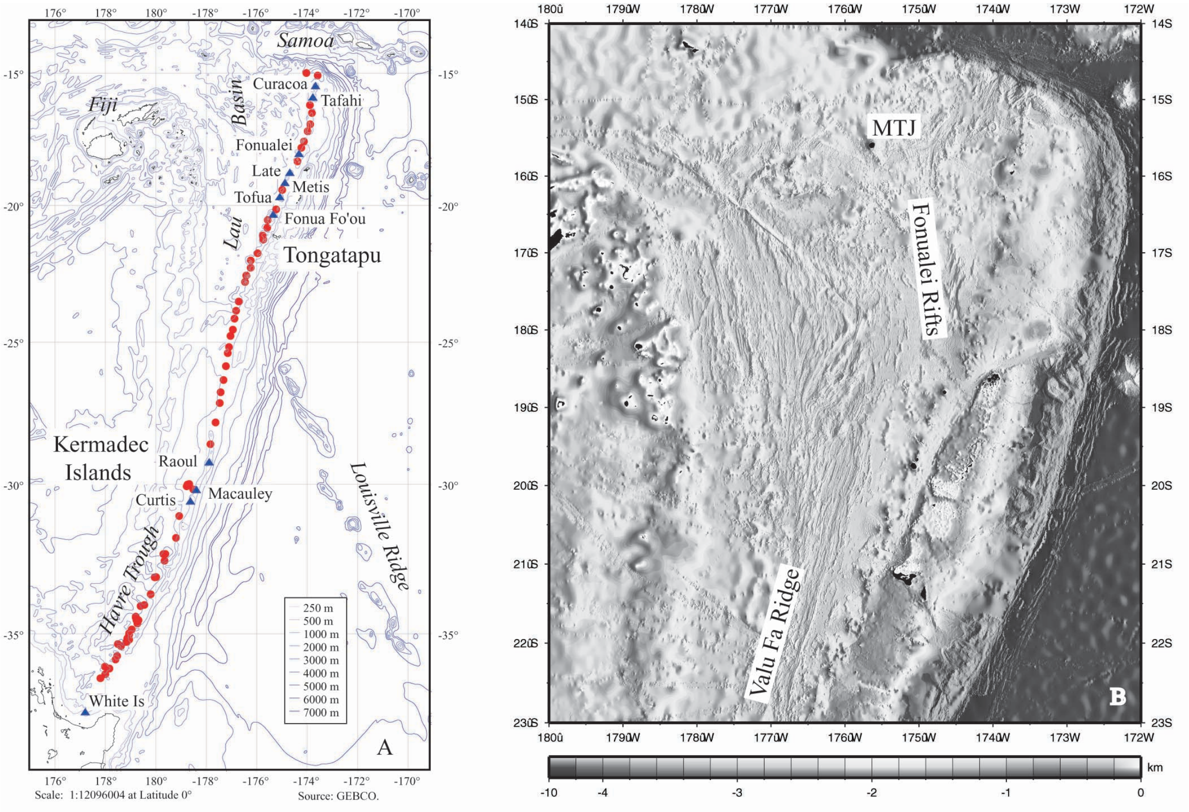

Figure 1. A. Location map of subaerial (triangles) and newly-discovered submarine (dots) volcanoes in the Tonga-Kermadec Arc; B. Bathymetric compilation from Zellmer & Taylor (2001) of Tonga-Lau region showing location of the Valu Fa Ridge, Fonualei Rifts, and Mangatolu Triple Junction.

and has revolutionised the way we can study the morphology, structure, and tectonics of and recover samples from the seafloor. In addition, we can now explore the water column in detail over distinctive topographic features for hydrothermal plume activity.

In the last few years, discoveries in the Tonga-Kermadec system during several research voyages (NZAPLUME I to III, Sonne 135 and 167, TELVE and NoToVE) include about 80 new major volcanic edifices, most with basal diameters >10 km, spaced approximately 30 km apart along the length of the Arc. About 35% of these are hydrothermally active (de Ronde et al., 2001). To contrast these recent advances in understanding of the level of volcanic-hydrothermal activity in the Arc, it is appropriate to cite a representative statement of the scientific community's views presented in the NSF (USA) Margins Program 2004 Science Plans, that addressed the choice of convergent margin in the western Pacific for detailed study: "Tonga has the fastest convergence rate in the world and is a natural end-member for investigating convergence rate as the forcing function that drives the (subduction) factory. Confusingly, however, volcanic activity here is apparently rather low." The fact is the Tonga Arc-Backarc systems are highly active but mostly in the submarine domain.

There are a number of reasons for selecting the Tonga-Kermadec Arc-Backarc systems as a primary target for convergent margin studies, including: 1. a progressive change in convergence rate from a few mm per year at the southern end of the Hikurangi Trench to about 250 mm per year at the northern end of the Tonga Trench; 2. the amount of potentially subductable sediment also increases northwards from the Hikurangi Trench, except for the extra thickness of volcaniclastic apron in the vicinity of the Louisville Ridge at ~25°S; 3. Subduction of the Louisville Ridge (hot-spot volcano chain) and Osbourn Trough (paleo-spreading centre) at ~25°S; 4. potential ingress of Samoan plume-modified mantle at the northern end of the Lau Basin due to the retreating hinge of the Tonga Trench; 5. development of three, arc-proximal, backarc rifting zones (Havre Trough; Valu Fa-Eastern Lau Spreading Centre; Fonualei Rifts); 6. overall well-constrained opening histories for the Havre Trough and Lau Basin.

In this contribution, some of the major results in the northern Kermadec-Tonga section of the arc (north of 25°S) are summarised from research voyage reports, extended abstracts, and recent publications (Stoffers et al., 2003; Arculus, 2003; Worthington et al., 2003; Massoth et al., 2003; Arculus, 2004; Baker et al., 2005). The companion paper in this volume by de Ronde addresses the Kermadec section to the south of this latitude.

The Tonga arc-backarcs

Arc

The locations of newly identified submarine volcanoes forming the volcanic front of the Tonga Arc are listed in Table 1 and Figure 1. The edifices comprise stratovolcanoes of variable complexity, and steep-walled calderas with diameters <12 km. Large-scale sector collapses occur on many of these structures, and concentric ridges on the outer flanks of some calderas appear to be mega-bedforms associated with mass flows and edifice failures. Topographic rims of many calderas are capped by numerous conical vents; cones are also present within many calderas. Some examples are shown in Figure 2.

Table 1. Locations of Tonga Arc submarine volcanoes*

Volcano	lat. (°S)	long. (°W)	Hydro-thermally-active?
P	15.120	173.550	
O	15.367	174.000	√
L	16.250	173.860	
K	16.550	173.780	
J2	16.980	173.850	
J1	17.240	173.950	√?
I	17.630	174.100	
H	17.870	174.200	
F	18.380	174.350	
E	19.450	174.960	√
C	20.180	175.200	√
B	20.570	175.530	
A	20.860	175.550	√
1	21.150	175.733	√
2	21.300	175.700	
3	21.800	175.933	
4	22.067	176.208	√?
7	22.617	176.383	
8	22.850	176.433	√
14	23.567	176.683	√
15	23.900	176.783	
16	24.183	176.850	√
18	24.583	176.917	√
19	24.808	177.008	√

*official names awaiting Kingdom of Tonga decision

The compositional range of lavas in the Tonga arc is from high-Mg basalt to rhyolite (some quartz-amphibole-bearing). In fact, rhyolitic pumice blankets the entire structures of many of the larger volcanoes while in contrast, a number of the satellite cones have erupted primitive, glass-rich olivine-clinopyroxene-phyric basalts; these latter magma types are not found on the subaerial islands. For most of the submarine as well as the subaerial volcanoes, the lavas are characterized by flat or weakly light rare earth element (LREE)-depleted abundance patterns relative to chondrites, reflecting a refractory nature of the volumetrically most significant magma

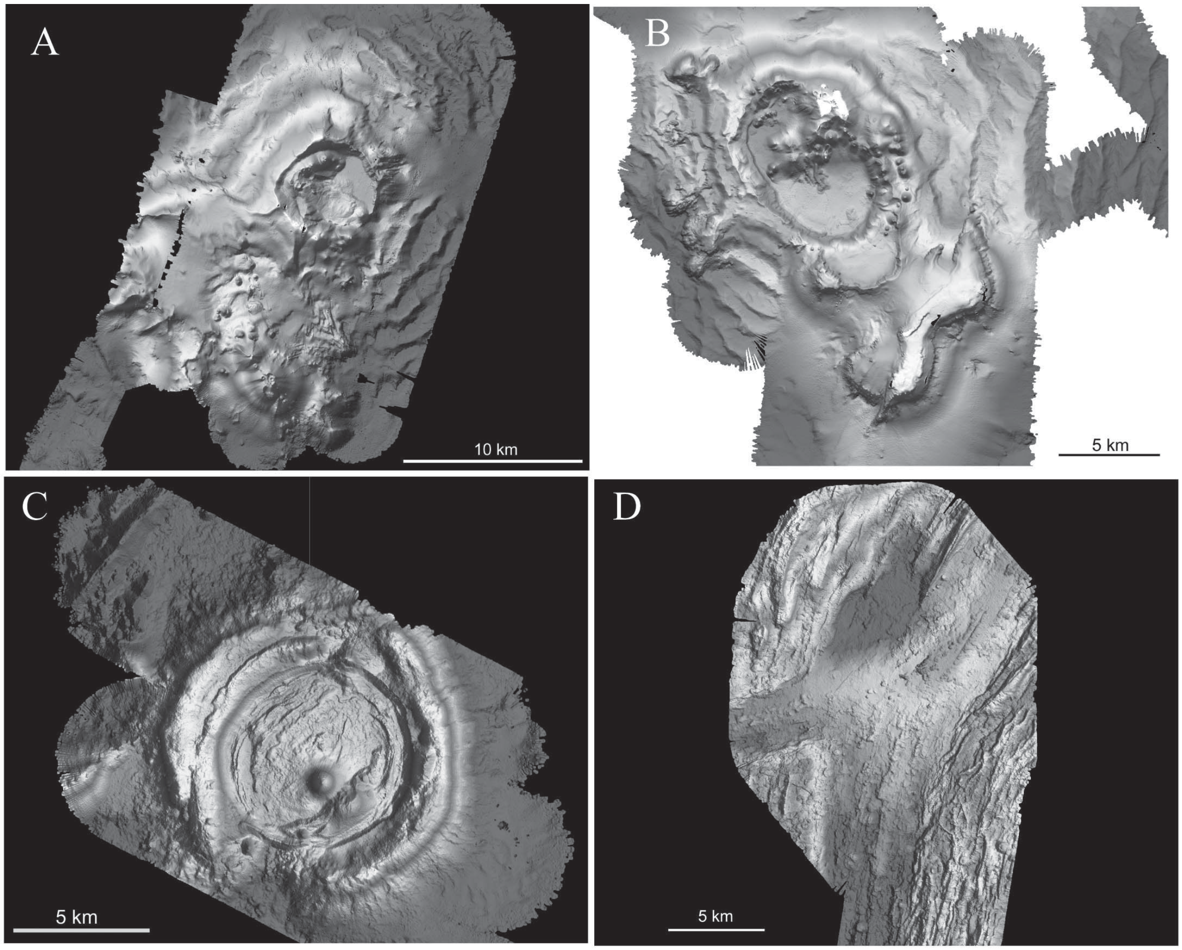

Figure 2. Selected kHz swathmap images of volcanoes in the northern Tonga Arc and the Magatolu Triple Junction (for locations, see Fig. 1 and Table 1): A. Volcano D; B. Volcano F; C. Volcano O; D. Mangatolu Triple Junction.

source in the mantle wedge. However, in the region of the subaerial edifice of Ata (22.3^{o}S) and in line with the subducted projection of the Louisville Ridge, the lavas are LREE-enriched (Worthington et al., 2003), possibly reflecting a greater proportion of subducted plume-related material in the petrogenesis of the arc lavas. About 35% of these volcanoes are associated with hydrothermal plumes (Table 1). Sites of hydrothermal venting are commonly located at summit or intracaldera cones, and also near the base of caldera walls.

Overall relationships exist along the Tonga-Kermadec ~~A~~rc between depth of basement, nature of volcanic structures, and magma composition; more felsic (dacite to rhyolite) lavas are associated with higher basement elevation, multi-vent stratovolcanoes, and caldera complexes, but the exact relationship between formerly contiguous arc-remnant arc basement prior to formation of the Havre Trough-Lau Basin and establishment of the current arc edifices is complex. The predominant mode of formation of felsic magma-dominated calderas is interpreted to be mass pyrocl~~lcl~~astic discharge with syn-eruptive caldera collapse in water depths <1000 m. Other types of edifice failure are: sector collapses extending for full volcano flank heights that feed debris fields, and in some cases expose radial fissure dikes; mega-bedforms comprising a series of ridges striking parallel to adjacent projected caldera margins. Close to the caldera, these ridges have relative relief of about 150m decreasing to <10 m at distances >20 km from the caldera. All of these collapse styles were likely tsunamigenic. Terrain between many adjacent submarine volcanic edifices is blanketed by degraded and subdued equivalents of these mega-bedforms. Overall, these debris flows constitute a significant mode of arc crustal formation. Localised failure of caldera walls may be related to rock alteration by hydrothermal activity.

Backarcs

The southernmost 100 km of the actively spreading ridge in the eastern Lau Basin is divided into several linear segments comprising the Valu Fa Ridge, striking more northerly than the trend of the adjacent Tonga Arc so that the Ridge-Arc distance increases northwards from ~ 40 to ~120 km concurrent with an increase in spreading rate (40 to 90 mm per year)(Martinez & Taylor, 2003). Rocks recovered from these segments span a complete range from basalt to rhyolite with flat or weakly LREE-depleted abundance patterns relative to chondrites, and overall trace element abundance patterns very similar to those of the adjacent Tonga Arc (Goddard et al., 2004). A continuous "tow-yo" hydrothermal plume survey of the Valu Fa found fields (Hine Hina; Vai Lili) that had been strongly active in the 1980s (Fouquet et al., 1991) had waned considerably (Baker et al., 2005). Two new major fields (Mariner and TELVE) are located in the vicinity of segment overlaps coincident with along-axis maxima in ridge axis inflation.

In the northeast of the Lau Basin are the Fonualei Rifts, extending south of the Mangatolu Triple Junction (Figs. 1 and 2). A complete 30 kHz swathmap of these Rifts was obtained during the SS11/2004 (NoToVE) voyage. Except for the northernmost segment, spreading in the Rifts is not as well organized as in the Valu Fa Ridge with numerous small and overlapping rifts, some of which are distinctly curvilinear. Numerous particulate plumes were identified with vertical hydrocasts above a number of the rift axes, indicative of some major hydrothermal plume sources, and possible net contributors to the very large, ^{3}He-rich hydrothermal plume identified at 1700m depth in the Lau Basin (Lupton et al., 2003). The striking feature of the Fonualei Rifts is the capture of the entire suprasubduction zone magmatic flux for a distance of about 150 km, shutting down the adjacent Tonga Arc volcanoes which are carbonate covered and degraded with no evidence of recent volcanic activity (Arculus, 2004). Preliminary analyses of the samples recovered from the Fonualei Rifts show them to be arc-like basalts and andesites with flat or weakly LREE-depleted/enriched abundance patterns relative to chondrites. The lavas are also extremely depleted in Na probably reflecting both a highly refractory mantle source and relatively large percentages of melting of this source.

For both the Valu Fa Ridge and Fonualei Rifts, analysis of FeO (by wet chemical titration) and thus calculation of $Fe_2O_3/(Fe_2O_3 + FeO)$ with reasonable assumptions of temperatures of eruption indicate redox states for the majority of glass samples 2 $\log_{10}$ orders more oxidized than the synthetic fayalite-magnetite-quartz buffer.

Acknowledgements

Results summarized here are based on the efforts of numerous shipboard and shore-based scientists associated with the research voyages cited in the text; some of the papers emerging from these voyages are listed below. I thank in particular Nicole Keller and Nicole Mikkelson for their analytical efforts with the Valu Fa and Fonualei Rifts glasses. I am also grateful to Cornel de Ronde and Ian Wright for the invitation to participate in NZAPLUME III, and the Australian Government for use of the Marine National Facility.

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Author

Richard Arculus is an igneous petrologist, and currently the Professor of Geology and Head of the Department of Earth & Marines Sciences at the Australian National University. He has been involved in studies of volcanic island arcs and backarc basins since his doctoral studies at the University of Durham (UK) in the early 1970s. Richard has taught at universities in the USA (Rice University & University of Michigan), and Australia (University of New England and the ANU). He was actively involved with the international Ocean Drilling Program's efforts in the arcs of the western Pacific, and since moving back to the ANU in the mid-1990's, has been a participant or led several research voyages with Australia's Marine National Facility (RV *Franklin* and RV *Southern Surveyor*) and the RV *Tangaroa* in waters of Papua New Guinea, Solomon Islands, Vanuatu, Tonga, and Kermadecs.