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The Tonga–Kermadec arc and Havre–Lau back-arc system: Their role in the development of tectonic and magmatic models for the western Pacific

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Abstract

The convergent plate boundary marked by the Tonga–Kermadec arc system is one of the clearest examples of an intra-oceanic arc on the modern Earth. Arising from ground breaking research in the 1970's and continuing through the present, the arc has become a testing ground for defining and explaining models for the tectonic and magmatic evolution of intra-oceanic subduction systems. Despite its simple oceanic setting the arc shows significant variations along its length in terms of rock types and structure and because of the lack of involvement of continental crust these allow refinement of the details of or models of how arcs develop and evolve. Of particular importance are the variations in convergence rates and vectors between the major plates and the effect these have on the tectonic evolution of the arc and back-arc. The erupted rocks of the arc have provided the means of testing the contribution of subducted sediment, slab, mantle wedge and overlying crust and most recently tests of P–T–time paths for recycled sediments. Although the arc is dominated by basalts and basaltic andesites, there is increasing evidence for significant proportions of silicic magmas erupted in recent times. Silicic volcanism is also evidenced in the presence of caldera structures revealed by detailed multibeam mapping that have been a feature of research in the last decade. As we enter the 21st century, the Tonga–Kermadec arc continues as an archetypical natural laboratory for the testing of new ideas in subduction zone tectonics and petrology.

Keywords: Tonga–Kermadec arc; Lau Basin; Havre Trough; intra-oceanic arc; back-arc

1. Introduction

In their seminal paper on the correlation between K_2O content and depth to the underlying Wadati–Benioff zone, Dickinson and Hatherton (1967) demonstrated the link between subduction of oceanic lithosphere and the generation of ”orogenic andesites”. With the recognition of the role that subduction plays in the magmatic processes that lead to ”Pacific style” orogenic volcanoes, oceanic arcs became a key to understanding the relative roles of subduction processes and crustal components beneath continental and oceanic crust. The Tonga–Kermadec volcanic arc became recognised as a type example of a volcanic system associated with intra-oceanic subduction (e.g. Oliver and Isacks, 1967; Isacks et al., 1968). When early bathymetry and geophysical data for the Lau Basin were used to develop the concept

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of back-arc basins (Karig, 1970a), the Lau–Tonga–Kermadec system became the basis for generalised tectonic models for the western Pacific region (Karig, 1974). The Tonga–Kermadec arc has come to be regarded as one of the key areas globally where subduction processes can be studied in a well constrained context and many of the geophysical, tectonic, and petrological models for this particular system have provided the basis for our current understanding of the subduction factory.

Since the pioneering work of the late 1960s and early 1970s substantial new information on the Lau Basin and Tonga Ridge has come from a large number of research voyages (e.g. Scholl et al., 1985; Von Stackelberg et al., 1985; Vallier et al., 1985, 1991; Falloon et al., 1987, 1992; Volpe et al., 1988; Collier and Sinha, 1990; Sunkel, 1990; Falloon and Crawford, 1991) culminating in the Ocean Drilling Project (ODP) Leg 135 (Hawkins et al., 1994). During the same period the rocks of the subaerial volcanoes of the Tongan Arc were described and interpreted on a regional scale (Bauer, 1970; Melson et al., 1970; Baker et al., 1971; Ewart et al., 1973, 1977, 1994; Ewart, 1976; Vallier et al., 1985; Ewart and Hawkesworth, 1987). In general the Kermadec segment of the arc system has been poorly documented, partly because, Raoul Island and adjacent Herald Islets, Macaulay Island, Curtis Island and L'Esperance Rock are the only rock outcrops above sea-level. All of these subaerial exposures have been studied intensively (e.g. Brothers and Martin, 1970; Brothers and Searle, 1970, Lloyd and Nathan, 1981; Smith et al., 1988, 2003a,b; Lloyd et al., 1996; Worthington et al., 1999). Apart from the original discovery of submarine volcanic activity in the 1960s (Kibblewhite, 1966) little was known of the largely submarine volcanoes of the Kermadec or Tonga arcs until a resurgence of ship-based science during the late 1980s and 1990s. Spectacular images of submarine volcanoes obtained from recent multibeam mapping together with comprehensive collections of rock samples from associated dredging have refocussed attention on the whole arc system as an important example of intra-oceanic tectonic subduction (e.g. Wright et al., 2002, 2006).

The Tonga–Kermadec subduction system is an intra-oceanic convergent plate margin in the southwestern Pacific that extends for 2550 km between Tonga and New Zealand (Fig. 1). The principal features of the system are subduction of the Pacific Plate and its sediment veneer at the Tonga–Kermadec Trench, arc magmatism along the Tonga–Kermadec Ridge, and crustal extension in the Lau Basin and Havre Trough back-arc. A prominent seamount chain, the Louisville Ridge, intersects the Tonga–Kermadec Trench at 25.6° S separating the Tonga and Kermadec segments of the system. To the north, the Tonga Trench terminates immediately south of Samoa, where the system turns 90° west to intersect both the Fiji Fracture Zone and the inactive Vitiaz Trench. To the south, adjacent to the East Cape of New Zealand's North Island, the Kermadec Trench shallows and becomes the Hikurangi Trough. There, oblique subduction takes place beneath the continental crust of New Zealand, and the resultant magmatism is expressed as the Taupo Volcanic Zone (TVZ) on the North Island.

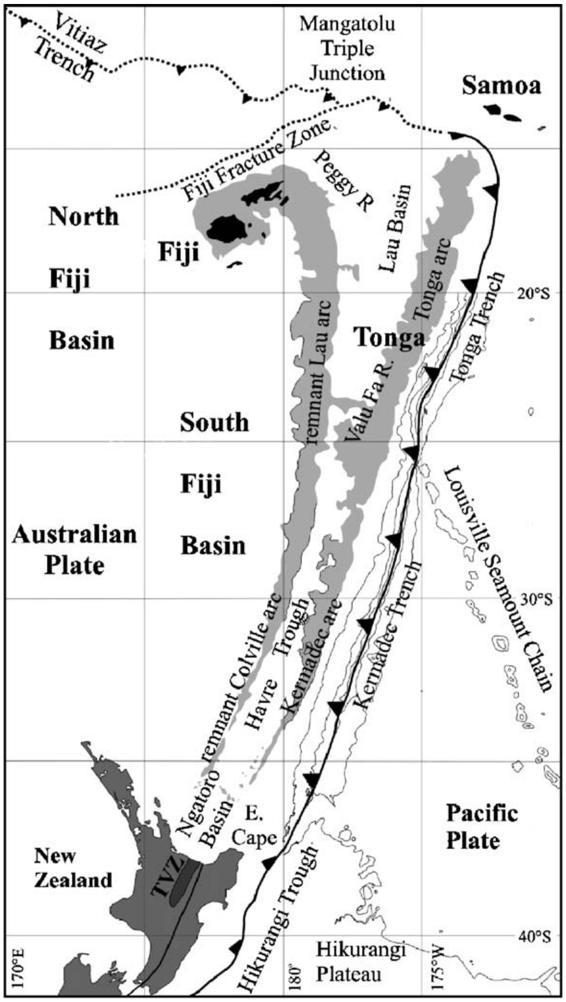


Fig. 1. Southwest Pacific region showing the main features of the Tonga–Kermadec arc–back-arc system.

This paper is a review of the historical development of ideas arising from work on the Tonga–Kermadec system and an introduction to current research that has continued to place the Tonga–Kermadec system at the cutting edge of our understanding of the way that oceanic subduction systems work.

2. Historical development of tectonic models

The general concepts of plate tectonics were well established by the late 1960s (e.g. Vine and Matthews, 1963; Wilson, 1963, 1965; Le Pichon, 1968; Heirtzler et al., 1968; Isacks et al., 1968). At that time, the western Pacific was being interpreted as a complex system of micro-plates, subduction-related volcanic arcs, and back-arcs (e.g. Karig, 1974). Many aspects of these evolving tectonic models were developed and tested in the Tonga–Kermadec arc. Within the earliest tectonic models the interpretation of geochemical and petrographic data for volcanic rocks was significant.

By the early 1970s, the general morphology of the Tonga–Kermadec–Lau system had been established (see chart in Karig, 1970a), as had the pattern of seismicity (Sykes, 1966). A volcanic arc, defined by active basaltic, andesitic, dacitic, and rhyolitic volcanoes extending from Tonga (Baker et al., 1971; Bryan et al., 1972), through the Kermadec Islands (Brothers and Martin, 1970; Brothers and Searle, 1970) and Rumble seamounts (Kibblewhite and Denham, 1967), was recognised, as were the Tonga and Kermadec trenches. The Havre Trough and Lau Basin constituted a system of back-arc basins or a "marginal sea" (Karig, 1970a,b) with inter-basin rifts. All these features were known to be associated with, and overlie, a westward dipping Wadati–Benioff zone (Sykes, 1966). Gill and Gorton's (1973) early reconstruction established the tectonic relationship of the Tongan arc segment to Fiji. Southward along the arc bathymetric information implied a distinction between the northern and southern parts of the system separated by an impinging Louisville Ridge. Volcanic rocks from the islands and sea floor of the back-arc indicated the presence of tholeiitic basalts (e.g. Sclater et al., 1972; Hawkins, 1974; Reay et al., 1974; Gill, 1976). The aseismic Lau–Colville Ridge had been identified and described as a "third arc" and it had been proposed that this feature had been rifted away from the ridge on which the frontal arc is continuing to develop (Karig, 1970a). Gill (1976) supported this interpretation, noting that the basement rocks of the Lau–Colville Ridge are basaltic andesites and dacites that are chemically similar to the volcanic rocks of the islands of the frontal arc.

Estimates of spreading and convergence rates and vectors at the Tonga–Kermadec arc and in the Lau–Havre back-arc have been refined and developed as new magnetic, seismic, and crustal age data and, more recently, global positioning system (GPS) measurements, have become available. An important contribution was that of Malahoff et al. (1982) whose interpretations of magnetic anomaly patterns were influential and locally correct. Sclater et al. (1972) estimated the convergence rate at 11 cm/yr but by the late 1980s it had been demonstrated conclusively that the rates vary with latitude systematically along the arc as the geometry between the convergence vector and the plate boundary changes (e.g. Pelletier and Louat, 1989; 17.8 cm/yr in the north to 7.2 cm/yr in the south; see synopsis in Parson and Wright, 1996). Geodetic observations based on GPS data indicated extremely high convergence rates of around 24 cm/yr at the northern Tonga Trench (Bevis et al., 1995). Taylor et al. (1996) used GPS data to show that spreading rates in the Lau back-arc basin are increasing from ~ 9 cm/yr at 21° S to ~ 13 cm/yr at 18.5° S and ~ 16 cm/yr at 16° S, and this is interpreted to imply a recent increase in opening rates or that significant off-axis extension is occurring.

Throughout the 1970s, much of the research in the region was aimed at obtaining a detailed picture of the tectonics of the back-arc basins and adjacent ridges. More detailed bathymetry became available with consequent better definition of morphology of the back-arc. For example, Peggy Ridge began to appear on charts of the Lau Basin as a well defined linear feature (Barazangi and Isacks, 1971). Heat flow information, sediment distribution data and rock samples confirmed active spreading and magmatism within the back-arc (Sclater et al., 1972; Hawkins, 1974; Lawver et al., 1976) and magnetic data (Sclater et al., 1972; Lawver et al., 1976) provided a basis for estimating spreading rates. Sclater et al. (1972) suggested three alternative tectonic models for the Lau back-arc with the Peggy Ridge being variously interpreted as a ridge, a trench, a transform fault, or an arm of a triple junction. Weissel (1977) proposed that the northern Lau Basin had formed around a ridge–fault–fault triple junction with the Peggy Ridge representing the north-western, strike-slip boundary of one of three small plates.

Estimates of spreading rates within the back-arc system have also been continuously revised as new data have become available. Pelletier and Louat (1989) estimated that spreading rates within the Lau Basin increase from < 1 cm/yr at 33° S to 8 cm/yr at 24° S and Taylor et al. (1996) demonstrated that they have also varied with time over the past 4 Ma with present-day rates being significantly higher than in the past (Bevis et al., 1995). In the southern Havre Trough segment of the back-arc, lithospheric extension is relatively slow (e.g. 1–2 cm/yr in Parson and Wright, 1996).

Recent developments in the tectonic interpretation of the Tonga–Kermadec–Lau system have centred on progressively more detailed geophysics and bathymetry, side-scan and multi-beam swath mapping, and intensive sampling. In particular the swath mapping reported by Parson et al. (1990) was the key breakthrough underlying the focus of the 1990/91 ODP Leg 135 (Hawkins et al., 1994) that was specifically targeted at obtaining a better understanding of the geological history of the Lau Basin and adjacent arc. Eight sites were drilled from the back-arc through the volcanic front to the forearc. Crustal structure across the Tonga Ridge and Lau Basin has now been resolved in some detail (e.g. Crawford et al., 2003).

Tectonic models for the Lau Basin have become more complex and very much more detailed. It was recognised that the spreading axis is segmented into an eastern and central ridge with active magmatism along both segments (Parson et al., 1990; Collier and Sinha, 1992; Parson and Tiffin, 1993; Hawkins et al., 1994). Active magma chambers were identified at the southern end (Valu Fa Ridge) of the eastern ridge (Morton and Sleep, 1985), which was shown to be highly segmented (Wiedicke and Collier, 1993). The central or northern segment was recognised as overlapping the eastern ridge and was demonstrated to be propagating southwards (Parson et al., 1990; Wiedicke and Habler, 1993). Most recent models for the northern Lau Basin interpret the Peggy Ridge as a leaky transform fault with a small triple junction (Kings or Mangatolu triple junction) identified further to the north (Parson et al., 1990; Parson and Tiffin, 1993; Taylor et al., 1996; Hawkins, 1995). Zellmer and Taylor's (2001) three-plate kinematic model for Lau Basin opening provides a modern viable interpretation for the basin. Extension in the Lau Basin is generally attributed to rollback of the subducting plate at the Tonga trench (e.g. Hawkins, 1995).

The application of swath bathymetric mapping, side-scan imagery, and multi-beam methods during the 1980s and early 1990s also resulted in better definition of structure and more robust tectonic models for the southern, Kermadec–Havre Trough part of the system. The volcanic arc was shown to consist of numerous large submarine volcanoes (e.g. Wright, 1994; Gamble and Wright, 1995; Wright et al., 2002, 2006) and, north of 32° S, to lie on the crest of the Kermadec Ridge. Between 35° and 32° S the active volcanic front lies 15–10 km to the west of the ridge crest and it was suggested that this is related to differences in the length of the subducting slab (Pelletier and Dupont, 1990; Wright, 1994) or the effect of Hikurangi Plateau subduction (Davy and Collot, 2000). The transition from the Lau Basin to the Havre Trough was interpreted to mark a shift from true sea floor spreading associated with the creation of new crust to complex rifting with interspersed sediment-filled grabens and magmatically-active rifts separated, in en echelon fashion, by sedimented horsts (Caress, 1991; Parson and Wright, 1996). These features trend obliquely at 20–30° to the adjacent Colville and Kermadec Ridges (Caress, 1991; Gamble and Wright, 1995). A deep (3000 m) rift graben, the Ngatoro Basin, was identified at the southern extremity of the Havre Trough where rifting is propagating into the continental crust of New Zealand's North Island (Cole and Lewis, 1981).

3. Historical development of petrogenetic models

In their 1972 paper Bryan et al. noted that the "South Pacific Ocean is an ideal area in which to test some of the compositional implications of plate tectonic and seafloor spreading". This statement remains true today and over the past three decades petrologists have used the Tonga–Lau–Kermadec system as a testing laboratory in which to examine the processes of magma production, crustal recycling and magmatic and fluid and magma flux rates in subduction systems. The key attributes that have attracted attention are: (a) the assumed absence of a continental crustal input in the northern and central, oceanic parts of the system; (b) the complexity of the back-arc system with the northern section being a region of active seafloor spreading and the southern Havre Trough an extensional rift; (c) the transition from oceanic to continental parts of the system in the south. As more geochemical data have become available and new isotopic systems have been applied, the detailed complexity of the system has been progressively increased but the perception that the Tonga–Kermadec–Lau arc and back-arc is a relatively simple oceanic subduction system with well established convergence rates has persisted and, consequently it has continued to be used as a testing ground for petrological and geochemical concepts and new analytical techniques. Data from the arc have commonly been used as the basis for the development of generalised petrogenetic models for subduction-related magmatic processes (McCulloch and Gamble, 1991; Woodhead et al., 1993, 2001) and included in attempts to calculate elemental flux rates during subduction (e.g. Hawkesworth et al., 1991; Bach et al., 1998). Th–U disequilibrium data for the arc have been used to constrain time scales for magmatic processes taking place in subduction systems (e.g. Turner et al., 1997, 2000; Peate et al., 2001; George et al., 2005).

The earliest petrological work attempted in the Tonga–Kermadec–Lau system was concerned with petrographic attributes and major element chemistry of the rocks in the volcanic front (e.g. Baker et al., 1971; Bryan et al., 1972) but later research focussed progressively towards the submarine parts of the arc and back-arc and, as new analytical techniques emerged and developed, more and more detailed mineralogical, trace element, and isotopic data were integrated into more refined petrological models (e.g. Oversby and Ewart, 1972; Ewart et al., 1973, 1977; Reay et al., 1974; Gill, 1976; Ewart and Hawkesworth, 1987).

The back-arc basins were recognised as sites of active magmatism producing volcanic rocks with geochemical characteristics similar to mid-ocean ridge tholeiitic basalts (Reay et al., 1974; Gill, 1976; Hawkins, 1976). Ewart (1976) concluded that basaltic andesites of Niua Foʻou Island in the northern Tongan back-arc had been generated by processes that were different from those by which the frontal arc lavas originated and in a paper published by Hawkins and Melchior (1985), they went further and used trace element and isotopic data for Lau Basin and Mariana basalts to argue for a new type of back-arc basin basalt that is subtly different from mid-ocean ridge basalts (MORB). They noted that the Lau back-arc basin is zoned in terms of basalt composition and they developed a petrogenetic model for the evolution of a back-arc basin whereby the mantle sources become progressively more depleted and input from subducting lithosphere less obvious with time. Pearce et al. (1995) documented the along-strike variations in Lau Basin basalts which become more “arc like” toward the southern part of the system.

Ewart et al. (1977) compared and contrasted Tonga–Kermadec island arc rocks with those of the Taupo Volcanic Zone in North Island New Zealand. They observed that the volcanic rocks of the oceanic segment of the arc were relatively depleted in large ion lithophile elements such as K, Rb, Cs, and Ba and in some high field strength trace elements including Zr, U, and Th. It was noted that the Tonga–Kermadec arc rocks have Pb and Sr isotopic compositions that are less radiogenic than those found in many volcanic arcs. Ewart et al. (1977) concluded that the primary magmas in the arc are basalts and andesites derived by essentially anhydrous Wadati–Benioff zone melting with magmas subsequently being extensively modified by low-pressure crystal fractionation processes. Tholeiitic rocks were interpreted as the products of low-pressure mantle melting.

Ewart and Hawkesworth (1987) refined these petrogenetic interpretations using an extensive data base of isotopic and trace element data. Their models involved generation from a depleted source of primary arc magmas in the mantle wedge with large ion lithophile elements and some high field strength elements being introduced in fluids migrating from the subducting slab. Changes in trace element chemistry and Sr, Nd, and Pb isotopic compositions laterally along the arc were attributed to variations in the composition of the mantle wedge that are ultimately related to processes in the subducting slab. It was proposed that the mantle sources become progressively less depleted southward along the arc. Trace element data were used to argue that the mantle beneath the arc is depleted during melting that occurs in the back-arc region and this depleted source convects trenchward to underlie the arc.

Gamble et al. (1990, 1993, 1996) also noted that the volcanic rocks of the Kermadec arc show high levels of geochemical variability along and across the arc. They concluded that differences between the basaltic magmas erupted in the back-arc and those emplaced in the volcanic front arise from a combination of slab fluid input and involvement of relatively depleted mantle sources in the generation of the primitive arc magmas. Two seminal papers on transition elements in subduction-related magmatic systems (McCulloch and Gamble, 1991; Woodhead et al., 1993) while not wholly based on the Tonga–Kermadec system were strongly influenced by the data emerging from work on the rocks of the arcs. Subducted sediment was assigned particular significance in influencing the isotopic and trace element heterogeneity of lavas. Macpherson et al. (1998) determined oxygen isotopic compositions for lavas from the southern end of the Tonga–Kermadec system near the transition between the oceanic Kermadec arc and the continental Taupo Volcanic Zone. They concluded that the magnitude of the $^{18}\delta$O enrichments was such that these could not be entirely explained by recycling of subducted material alone; some level of interaction with crust must be involved.

Gamble et al. (1993) also sought to utilise the contrast between the southern (continental) and northern (oceanic) parts of the system to gain an understanding of the involvement of the lithosphere, the role of the slab, and the relative contributions of crust and mantle to magma petrogenesis and they concluded that differences between the two parts of the system could be caused by crustal contamination in the continental part of the system or by differences in the scale and rate of mantle flow beneath New Zealand.

Unusual high-Ca boninite lavas have been recovered from the northern extremity of the arc. These are described in a series of papers by Falloon and Green (1986), Falloon et al. (1987, 1989), Falloon and Crawford (1991), and Danyushevsky et al. (1995). These rocks were argued to have evolved primarily by crystal fractionation but the complexity of the mineral chemistry and large variations in abundances of large ion lithophile elements were interpreted as indications that magma mixing had also been a significant process in their evolution. The isotopic data were used to suggest that the mantle sources were influenced by a regional mantle upwelling of material with ocean island basalt isotopic characteristics.

ODP Leg 135 provided an extensive and detailed set of data for volcanic and intrusive rocks collected at six drill sites across the Lau back-arc basin (eg. Ewart et al., 1994; Hawkins and Allan, 1994; Hergt and Farley, 1994; Hawkins, 1995). The geochemical data confirmed that the magmas parental to the dredged samples were generated from complex sources containing a variably depleted MORB-like source influenced to varying degrees by input from subducting lithosphere. A new discovery was that the isotopic data indicated that the MORB source had progressively changed with time from one with "Pacific" type isotopic characteristics to one reflecting the influence of an "Indian" type mantle. Gamble and Wright (1995) also noted extensive trace element and isotopic heterogeneity in lavas of the southern Havre Trough both along and across the basin and affirmed that the isotopic compositions in this region range from "Pacific" to "Indian". Although available data indicates the presence of two isotopic signatures in the source rocks of the northern part of the Tonga–Kermadec system there are inconsistencies that need to be resolved between the southward propagation of "Indian" mantle suggested by Hergt and Farley (1994) and the Gamble and Wright (1995) requirement that "Indian" mantle was already present beneath the southern Havre Trough during rifting.

The essential elements of the petrological models developed from the 1970s through to the early 1990s have persisted in more modern studies. In most models (eg. Ewart et al., 1998), it is generally proposed that the mantle in the wedge above the subducting slab has been variably depleted by multiple melting events and in some cases these depletion events are argued to have occurred in some segments of the system at spreading ridges in the back-arc basins. Depleted, sub-arc mantle is postulated to be convecting into the corner between the subducting slab and the overlying lithosphere where it is interacting with fluids or melts generated directly or indirectly from the lithosphere of the descending slab. Primitive magmas generated by these processes undergo crystal fractionation and can be further modified by interaction with the mantle and crust as they ascend.

All modern models attempt to explain spatial heterogeneity among the lavas, contrasts between the Lau Basin and Havre Trough, and temporal changes that have taken place during the evolution of the Lau Basin. Geochemical variations in Tonga–Kermadec lavas are commonly postulated to result from differences in the amount and composition of material being added along the arc from the subducting slab and pre-existing heterogeneities in the sub-arc mantle (e.g. Ewart et al., 1998; Haase et al., 2002). An interesting new perspective has been provided by Woodhead et al. (2001) who compared Hf and Nd isotopic data for the Kermadec arc and Havre Trough and concluded that most of the Hf and Nd and also the Pb in western Pacific arc volcanics are very likely to have been transported into the sub-arc region by fluids derived from the subducting slab. An important implication of this interpretation is that there is probably some transfer of almost all elements, not just those conventionally considered to be "mobile", from the slab into the sub-arc mantle.

In the back-arc basins, magmas are considered to have been generated and modified by processes similar to those prevailing at mid-ocean ridges. There are, however, several factors complicating the Lau–Havre back-arc system. Firstly, there is a transition from true, steady state seafloor spreading to rifting and these tectonic changes are reflected in the geochemistry of erupted lavas. Secondly, the lavas show varying slab-fluid input over relatively short distances (15 km) and thirdly, the lateral progression from rifting to true seafloor spreading appears to be associated with a change from "Pacific" to "Indian" type isotopic signatures.

There is strong evidence to support the view that the trace element and isotopic characteristics of some of the magmas erupted in the back-arc region reflect the influence of fluids from the subducting slab. Honda et al. (1993) and Bach and Niedeman (1998) suggested that atmospheric noble gases in volcanic glasses from the southern Lau Basin are derived from slab fluids and Kent et al. (2002) postulated that slab-derived fluids could explain Cl abundance patterns in Lau Basin glasses. Most recently, Sun et al. (2004) used Re data to argue for involvement of slab fluids in the generation of Lau back-arc basaltic glasses. Further work on recycling of volatile elements through subduction systems has been published by Haase et al. (2002) and Wysoczanski et al. (2006).

Despite the intra-oceanic setting, felsic magmatism appears to be common in the Tonga–Kermadec arc. The occurrence of rhyolitic and dacitic rocks on Curtis and Macauley Islands in the Kermadecs has been known for some time (Lloyd and Nathan, 1981; Smith et al., 1988; Lloyd et al., 1996) and rhyolites, rhyolite tuffs, and pumice breccias were reported in drill core from ODP Leg 135 site 841 in the Tongan forearc (Bloomer et al., 1994). More recently, felsic volcanic rocks have also been dredged from several submarine volcanoes in the southern Kermadecs and multibeam mapping has revealed large, submarine caldera structures similar to those associated with large subaerial felsic volcanoes (Gamble et al., 1997; Wright and Gamble, 1999). Smith et al. (2003a,b) postulated that these felsic magmas are generated by partial melting of crust. They developed a model whereby oceanic arcs evolve thermally and geochemically to the point where crust is progressively thickened and heated by underplating of hydrous basaltic and andesitic material to the point where it is hot enough for dehydration melting to begin, with the consequent production of felsic magmas.

In the back-arc region there are clear indications that, even in the case of basaltic magmas, crustal contamination is a factor influencing the geochemistry of the lavas. In a study of the He and Ar isotopic systematics of Lau Basin and Valu Fa glasses, Hilton et al. (1993) concluded that some aspects of the isotopic data could only be explained by assimilation of older oceanic crust. They argued that this process was generally involved in the generation of back-arc and ocean ridge basalts. Macpherson and Mattey (1998) were somewhat more circumspect but their oxygen isotope data for Lau Basin lavas were also consistent with some level of crustal assimilation in some back-arc lavas.

During the last decade there has been a significant focus on the occurrence of high temperature vent fields in both the back-arc and the arc itself. Fouquet et al. (1993) described vents on the Valu Fa Ridge in the southern Lau Basin and the dredging of gold-bearing massive sulphides from the calderas of Rumble II and Brothers volcanoes produced the first direct evidence for submarine hydrothermal systems on the arc (Wright et al., 1998). Towed camera surveys at Brothers volcano returned the first observations of active venting (Stoffers et al., 1999), and a more comprehensive survey of hydrothermal venting along the Kermadec arc is described by de Ronde et al. (2001).

4. The state of the arc — 21st century perspective

After nearly forty years of scientific investigation the Tonga–Kermadec arc remains an archetypical example of an intra-oceanic volcanic arc–back-arc system. Here we provide a synopsis of the system as it is understood at the beginning of the 21st century.

4.1. Tectonic setting

The rate of convergence of the Pacific and Australian plates increases northwards along the plate boundary with increasing distance from the Pacific–Australian (PA–AU) pole of rotation. Subduction rates also increase northwards and are higher than rates of PA–AU convergence; the difference is accommodated by extension along the Lau–Havre–Taupo rift. As the rate of extension also increases northwards from the Taupo Volcanic Zone to the Lau Basin, the wedge of crust between the trench and rift systems is moving independently of both major plates. The independent motion of this wedge has lead to the concept of a Tonga–Kermadec Plate (Pelletier and Louat, 1989), subdivided into Niuafo‘ou, Tonga and Kermadec microplates (Zellmer and Taylor, 2001; Bird, 2003) and which are evident in both seismic activity and digital models of plate motions.

Subduction rates along the Tonga–Kermadec Trench decrease southwards from 24 to 6 cm/yr. For the Tonga section, this decrease reflects a reduction in the extension rate across the Lau Basin. For the Kermadec section, the decrease is primarily a function of distance from the Pacific–Australian Plate pole of rotation at 60.1° S, 181.7° E (De Mets et al., 1994). The velocity vectors that represent convergence of the Pacific and Australian Plates and those representing extension across the Lau Basin and Havre Trough are both oblique to the Tonga–Kermadec Trench, and both become increasingly oblique to the south.

Geodetic data indicate that subduction increases northwards from 164 mm yr^{-1} at Tongatapu in the central Tongan arc to 240 mm yr^{-1} at Niuatoputapu in the northern arc (Bevis et al., 1995). The difference between movement relative to the Pacific Plate at sites in Fiji and on the Lau Ridge and sites in Tonga has been taken as the rate of extension in the Lau Basin between them. This gives extension rates increasing northward from 91 mm yr^{-1} in the central Lau Basin to 159 mm yr^{-1} in the northern Lau Basin. In the Taupo Volcanic Zone at the southern termination of the arc GPS data indicate extension rates of the order of 8±4 mm yr^{-1} (Darby et al., 2000).

Except in northern Tonga Trench and Lau Basin where most of the extension is accommodated by oceanic accretion, the geodetic rates correlate well with estimates based on shallow seismicity in the Kermadec–Havre and Tonga–Lau regions (Pelletier and Louat, 1989). These estimates of subduction rates increase from 72 mm yr^{-1} in the southern Kermadec trench to 164 mm yr^{-1} in the southern Tonga trench and 178 mm yr^{-1} in the northern Tonga trench. Extension rates in the southern Havre Trough are estimated at 8 mm yr^{-1} increasing to 21 mm yr^{-1} in the northern Havre Trough and 80 mm yr^{-1} in the southern Lau Basin. Recent digital modelling by Bird

(2003) gives extension rates of 27 mm yr^{-1} at 33° S in the southern Havre Trough and 55 mm yr^{-1} at 25.5° S in the northernmost Havre Trough.

A band of seismic activity marks the upper surface of the Pacific Plate lithosphere as it subducts beneath the Australian Plate (e.g., Isacks and Barazangi, 1977; Giardini and Woodhouse, 1984; Nothard et al., 1996; England et al., 2004). The subducting slab dips westward at a shallow angle from the trench until it reaches a depth of approximately 50 km; thereafter, its dip increases to 70° by 200 km depth. The volcanoes of the Tonga–Kermadec arc are consistently located 100 km above the slab. A lateral inflection in the slab surface coincides with the separation of the Tonga and Kermadec segments and the slab's behaviour at greater depth differs for each segment. To the west of the Tongan archipelago, it flattens below 300 km although it continues to 670 km. To the west of the Kermadec Trench, the seismic activity terminates at shallower depths and cannot be traced below 350 km south of 32°30′ S. Nevertheless, tomographic images of P-wave velocity variations in the mantle have been interpreted to show the slab subducting to depths greater than 800 km throughout the length of the Tonga–Kermadec margin (Van der Hilst, 1995). In the upper part of the subduction zone the slab dips uniformly at about 50°. It becomes almost horizontal in the transition zone and then sinks into the lower mantle (Hall and Spakman, 2002). Van der Hilst (1995) has proposed that this shape is due to rapid roll back in the northern and slower roll back in the southern part of the system.

Further west, the Lau–Colville Ridge is a remnant arc of Miocene age (Gill, 1976). Crustal extension across the Lau–Colville Ridge commenced at about 6 Ma, and culminated with the separation of the Tonga–Kermadec Ridge (Hawkins, 1995; Ruellan et al., 2003). The southwards-propagating Eastern Lau Spreading Centre (ELSC) became active at 4–5 Ma, and the Central Lau Spreading Centre at 1.5–2 Ma (Hawkins, 1995; Taylor et al., 1996). The latter is propagating southwards at the expense of the ELSC. New oceanic crust is also generated at the Northwestern Lau Spreading Centre and the Mangatolu Triple Junction (Pelletier et al., 1998; Zellmer and Taylor, 2001). The basins and ridges of the western Lau Basin preserve lavas erupted during the pre-spreading phase of rifting, and this style of crustal extension continues to the south of the ELSC and throughout the Havre Trough (Hawkins, 1995; Parson and Wright, 1996).

4.2. Volcanoes of the arc

Superficially, the subaerial volcanoes of the arc appear to form two widely separated groups – the volcanic islands of Tonga and those of the Kermadec Islands – but seafloor mapping increasingly reveals a continuous volcanic chain extending the length of the arc. These Tonga–Kermadec arc volcanoes are mostly confined to a 40-km-wide zone, are irregularly distributed within this zone, and occasionally occur as western and eastern paired edifices. Older volcanic complexes with arc-type geochemical characteristics are recognised to the west of the 40 km wide arc within the Havre Trough. These complexes are severely disrupted by post-volcanic tectonism, partly covered by westward-thickening sediment, and may represent the transient locations of an eastward-migrating volcanic front during the opening of the trough (Wright et al., 1996). Similar degraded volcanic complexes with arc-type geochemical characteristics have been recognised in the western Lau Basin (Hawkins, 1995).

The arc consists of two distinct segments separated at 25.6° S. To the north, the Tonga arc is an almost linear ribbon, curved only near its northern end where it bends westward to follow the trend of the Tonga Trench. To the south, the Kermadec arc is curvilinear in form and is convex towards the Kermadec Trench. The Kermadec arc is offset eastward relative to the extrapolated trend of the Tonga arc and a similar offset occurs between the Tonga and Kermadec Trenches.

A second type of segmentation is defined by changes in the arc–ridge and arc–trench separation (Fig. 2). This style of segmentation primarily reflects changes in the width and structure of the forearc and is distinct from the arc segmentation described above. The majority of the Tonga–Kermadec volcanoes are not built upon the crest of the Tonga–Kermadec Ridge and their relationship to it varies along the arc. Eight arc domains are recognised, within which both the arc–ridge and arc–trench separations are relatively constant, but between which there are significant differences in one or both parameters.

At the northern end of the Tongan Arc the volcanoes rise from a broad relatively deep plateau to form two island clusters; Curacoa, Tafahi and Niuatoputapu toward the north and Fonualei and Toku to the south. Smaller submarine volcanoes occur on a 30-km-wide ridge that links the island groups. Both Curacoa and Fonualei have been active since 1770 (Simkin and Siebert, 1994) but in contrast deeply eroded Toku has an extensive fringing reef and a radiometric age of 3.6 Ma (Gill, cited in Vallier et al., 1985).

In the central part of the Tongan Arc the ridge forms a broad, shallow-water platform capped by numerous reefs and small limestone islands which are the main landmass of the Kingdom of Tonga. The volcanoes are located 55–65 km west of the platform's axis and

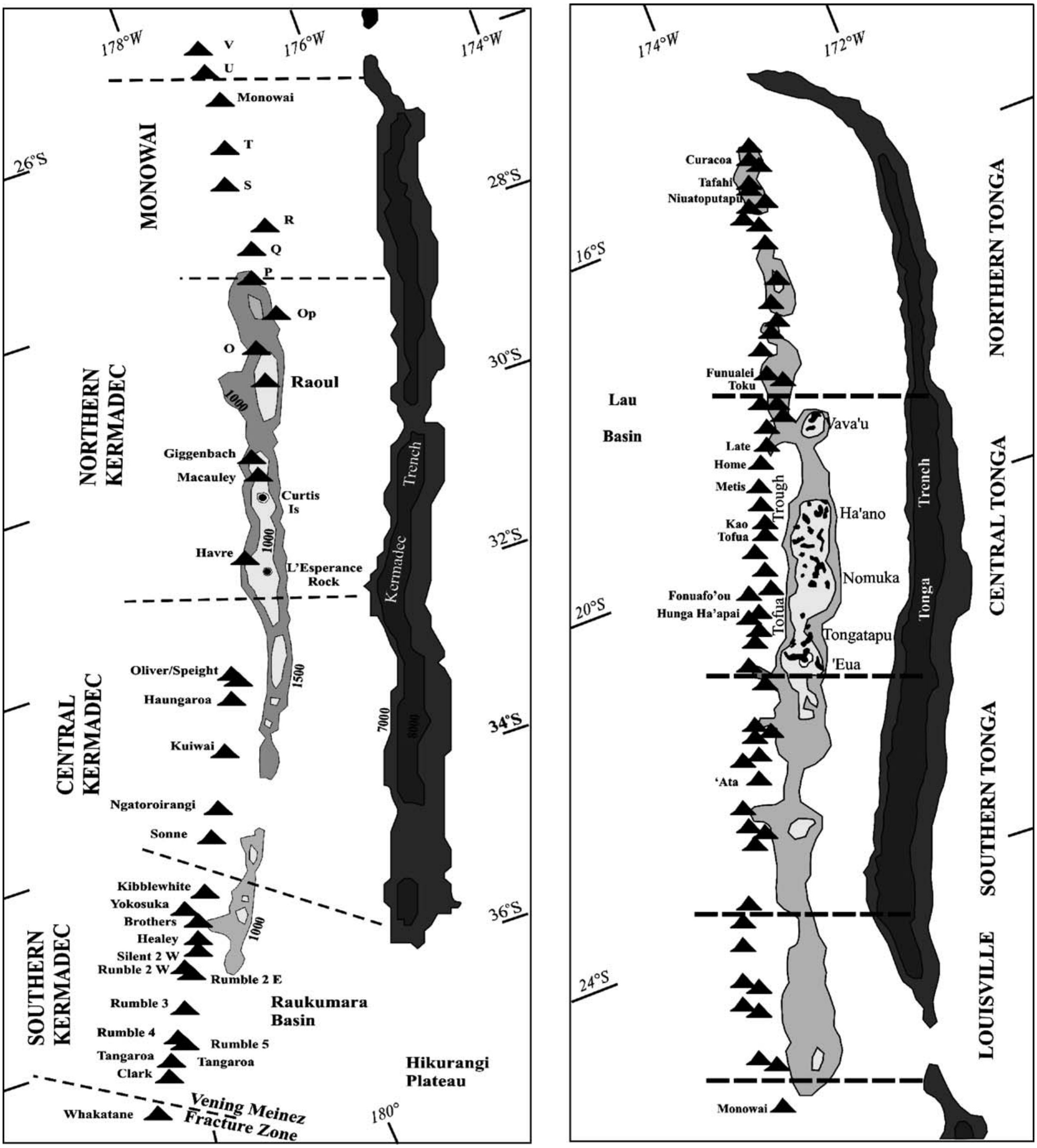


Fig. 2. The Kermadec and Tonga arcs showing segmentation proposed by Worthington (unpublished data). Segmentation of the Kermadec and Tonga Arcs. Volcanoes are shown as conical symbols. The ridge crests are defined by 500, 1000, and 1500 m bathymetric contours and the trench axis by the 8000 and 7000 m bathymetric contours. Bathymetry after NGDC (1996).

separated from it by the 1.8-km-deep Tofua Trough. In contrast to the northern Tonga domain, most of the central Tonga volcanoes are large edifices that rise close to or above sea-level and at least seven of them have erupted since 1770 (Simkin and Siebert, 1994). Since 1770, ephemeral islands built of pyroclastic material have featured in several of the eight eruptive episodes at both Metis and Fonuafo‘ou and some of these islands attained heights of 140 m. Sediments derived from mass wasting on the flanks of Fonuafo‘ou onlap a smaller, apparently older, submarine edifice to the east (Tagudin and Scholl, 1994).

The arc continues southward as a linear feature abutting the western margin of a broader relatively shallow-water platform. Most of the southern Tonga volcanoes are large edifices; however, only 'Ata attains sea-level and only one submarine volcano in the northern part of this domain is known to have erupted since 1770 (Simkin and Siebert, 1994). Seismic surveys across three sets of west–east-paired volcanoes consistently show debris from the western edifices onlapping and partly burying the eastern edifices (Tagudin and Scholl, 1994), although the active submarine volcano near the northern domain boundary is an eastern edifice. 'Ata is also located on the eastern side of the arc but its eroded form suggests a considerable period of inactivity (Johnstone, 1978).

Further south the Tonga Ridge is offset trenchward across a pronounced west–south–west trending fracture at the northern end of this domain and it continues southwards as a broad, relatively deep-water platform. The arc continues as a linear feature, however little is known of the eight conical edifices located 55–65 km west of the ridge. Seismic profiles across a pair of volcanoes near the southern boundary of the domain show the western edifice to be the younger of the two (Tagudin and Scholl, 1994). The two southernmost volcanoes in this arc segment have been designated Volcanoes V and U by the 2004 NZAPLUME III (New Zealand America Plume Mapping Expedition) survey.

The northern boundary of the Monowai domain (Fig. 2) coincides with the separation of the Tonga and Kermadec arc segments. In contrast to the Tonga Ridge, the Kermadec Ridge is narrow and relatively deep. Bathymetric coverage was poor until the detailed surveys of the last 5 years. The active submarine Monowai volcano and four other conical edifices are located 10–30 km west of the ridge. The Kermadec arc and trench are both offset eastward relative to an extrapolation of the Tonga arc and trench and the arc-ridge separation progressively decreases to the south. Volcanoes in this segment mapped by the NZAPLUME III survey have been provisionally designated Volcanoes T to Q.

In the northern segment of the Kermadec arc the ridge continues as a narrow feature and is shallower than to the north. Volcanoes P to O and the volcanic islands of Raoul, Macauley and L'Esperance rise from the ridge crest. Each of these and several other conical edifices are large, low-aspect ratio volcanoes that extend across most of the arc. Raoul consists of a series of coalescing stratocones and the centrally-located Denham Bay caldera has been the site of numerous eruptions since 2.2 ka, including three since 1814 (Worthington et al., 1999). Similarly, Macauley is dominated by a large, centrally-located submarine caldera that formed during a voluminous eruption at 6.3 ka (Lloyd et al., 1996). Curtis Island to the south of Macauley Island is the remnant of a large pyroclastic flow sheet from an unknown centre and in this respect differs from the other Kermadec Islands. L'Esperance has two widely separated summit peaks whose relative ages are unknown; L'Esperance Rock is located on the eastern side of the summit and of the arc, whereas Havre Rock, lying to the west and emergent only at low tide during rough sea conditions, is centrally-located relative to the arc.

In the central segment of the Kermadec arc the ridge is offset 30 km to the east at the northern end of this domain and a similar offset is apparent in the trench. The ridge becomes progressively deeper towards the south. The Star of Bengal Bank near the northern domain boundary has often been assumed to be a volcanic edifice. However, it lies well to the east of the extrapolated position of the arc and samples dredged from its crest include coarse-grained slabs of shallow-water limestone; volcanic clasts are conspicuously absent (Ballance et al., 1999). It is likely that the Star of Bengal bank forms the crest of the Kermadec Ridge and that the arc is located 30 km to the west. There, the ridge has a jagged summit profile more consistent with complex volcanic topography and samples of 1.2–2.0 Ma basalt have been dredged (Ballance et al., 1999). A series of conical submarine edifices can be traced southwards from that site to the better known volcanoes of the southern Kermadec domain (Wright, 1997).

The boundary of central and southern Kermadec segments coincides with both the northern limit of the forearc Raukumara Basin and an increase in the arc-trench separation. The ridge continues to deepen and eventually disappears beneath the sediments of the Raukumara Basin at water depths of 2.4 km. A series of large volcanic edifices are located 20–30 km west of the ridge and evidence of recent volcanic activity is found on the eastern but not the western of two west–east-paired volcanoes (Wright et al., 1996). The only confirmed eruption in historic times was that of Rumble III in 1986 (Wright, 1994); an unpaired but eastern volcano that also has the largest volume of the Tonga–Kermadec volcanoes. The southern boundary of this segment is the Vening Meinesz Fracture Zone marking the transition of the arc from an intra-oceanic to a continental system. This southern segment of the arc contains the widest variety of magma compositions (e.g. Gamble et al.,

1997) possibly reflecting the proximity of the New Zealand continental crust.

In a recent account of new multibeam mapping, Wright et al. (2006) use slightly different criteria to define the segmentation of the southern part of the Kermadec arc. The central segment between 32°20′ S and 34°10′ south is characterised by basement elevations >3200 m water depth and relatively simple stratovolcanoes dominated by low-K basalt and basaltic andesite. The adjoining northern and southern segments have higher basement elevations (typically <2500 m water depth), multi-vent volcanic centres including caldera complexes and erupt sub-equal proportions of dacite and basalt–basaltic andesite. Wright et al. (2006) speculate that the presence of thicker crust creates the conditions necessary for crustal anatexis and the eruption of silicic magmas.

Recent work in the southern part of the Kermadec arc has revealed high levels of active geothermal activity from many of the volcanoes in this segment (Wright et al., 1998; Stoffers et al., 1999; de Ronde et al., 2001, 2003; Massoth et al., 2003; Baker et al., 2003). Geothermal activity in this environment is significantly different from that of the mid-ocean ridges and is providing important clues to the formation of arc-related massive sulphide deposits.

4.3. Rocks of the arc

The petrology of the Tonga–Kermadec arc has been extensively studied by Ewart (1976), Ewart et al. (1977), Ewart and Hawkesworth (1987), Ewart et al. (1994), and Ewart et al. (1998). There is more information available for the Tongan Arc because of the considerably greater extent of subaerial exposure. Tongan Island volcanoes consist mainly of two pyroxene + plagioclase basaltic andesites with minor andesites and dacites. However recent work on both subaerial and submarine Tongan volcanoes suggests that Holocene volcanic activity has been dominated by relatively felsic eruptions of dacite and low-Si rhyolite. Some of these eruptions have been relatively large and have deposited significant lapilli on the main islands of Tonga up to 65 km away (S. Cronin, pers. commun., 2003).

Despite their small size, the Kermadec Islands are more diverse with significant proportions of olivine basalt and plagioclase basalt together with two-pyroxene and plagioclase basaltic andesite, andesite, dacite and low-K rhyolites (Ewart et al., 1998). Felsic rocks occur as pumiceous clasts in pyroclastic flow and fall deposits on Raoul, Macauley and Curtis Islands and as dredged material from the southern volcanoes of the arc. Here as in Tonga there is evidence to suggest that Holocene eruptions from many of the Kermadec volcanoes have been dominated by dacite and low-Si rhyolite (Fig. 3). This has led to the suggestion that the arc may be passing into an adolescent stage of crustal anatexis (Smith et al., 2003a).

4.4. The Lau–Havre back-arc

One of the striking aspects of the Tonga–Kermadec arc system is the complex and varied nature of the back-arc region. Clearly it is the product of an extensional regime that developed during the late Cenozoic as the arc migrated southeastward. In plate tectonic terms this is explained in terms of the southward movement of the pole of rotation that defines the relative movement of the Pacific and Australian plates. In detail this has produced differential extensional rates so that behind the Tongan Arc a magmatically active basin has developed with an opening rate of about 160 mm/yr, which when added to the plate convergence rate of about 80 mm/yr gives a total convergence rate across the arc of 240 mm/yr, the highest yet measured (Bevis et al., 1995). Southward, towards New Zealand, all rates decline, reaching a modest 60 mm/yr in the continental New Zealand segment of the Arc. Behind the Kermadec arc the Havre Trough is best characterised as an extensional graben system separating the active arc from the remnant arc (Colville Arc). In continental New Zealand the extensional regime has produced a wedge-shaped system of grabens (the Taupo Volcanic Zone) that have been interpreted as a back-arc (see discussion in Cole, 1990).

The rocks dredged from the Lau Basin include plagioclase–pyroxene–olivine basalts exhibiting varying

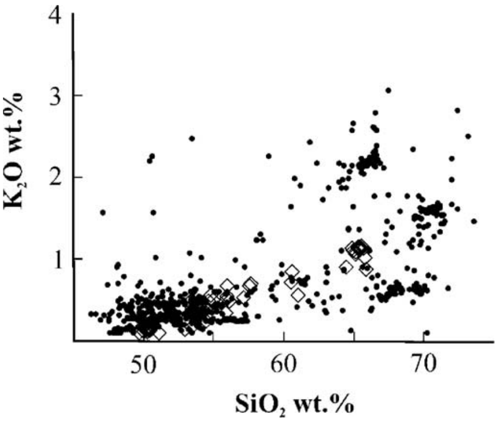
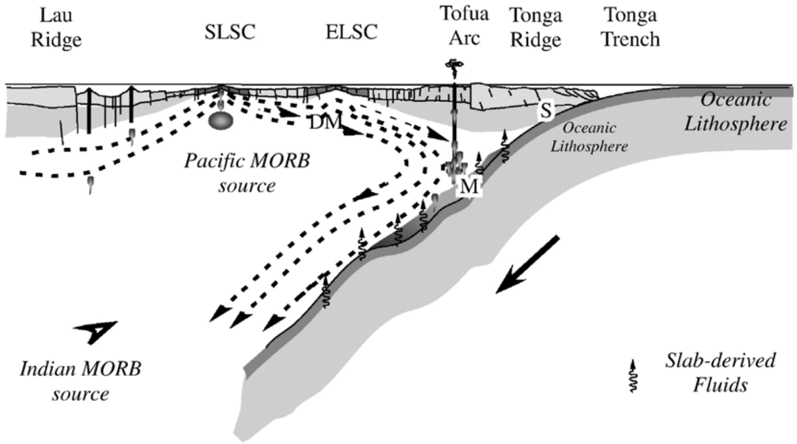
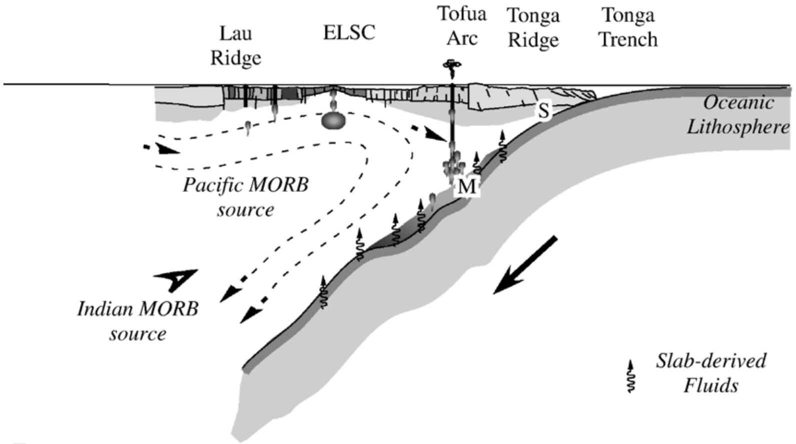


Fig. 3. K_2O vs SiO_2 plot for Kermadec (solid symbols) and Tonga (open symbols) arc lavas. Kermadec data from an unpublished compilation (I Wright pers. commun.), Tonga data from Richard (1962), Bauer (1970), Baker et al. (1971), Ewart et al. (1973, 1977).

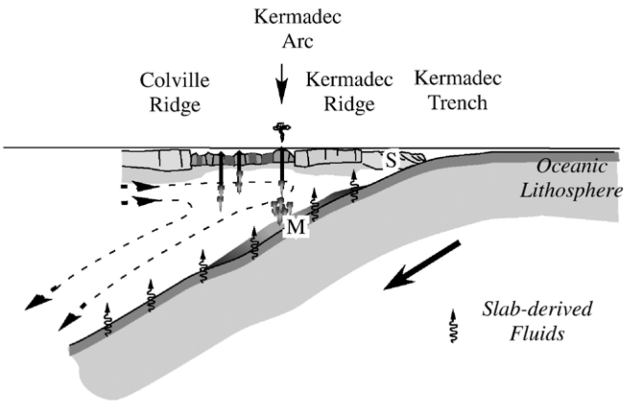
degrees of fractionation and compositions that range from near normal N-MORB to those comparable to modern arc-type volcanics (Ewart et al., 1994). These variations have been interpreted in terms of two competing processes affecting the mantle sources of the magma: mantle depletion processes caused by previous melt



A. Tofua arc and central Lau Basin: seafloor spreading and ridge segmentation in the back arc



B. Tofua arc and southern Lau Basin: initiation of seafloor spreading in the back-arc



C. Kermadec arc and Havre Trough: Rifting in the back-arc extractions linked to back-arc magmatism and enrichment in large ion lithophile elements caused by a subduction contribution (Ewart et al., 1994). The MORB-like characteristics are emphasised northward in the basin.

5. Current research themes

At the beginning of the new millennium the Tonga–Kermadec arc system continues to be regarded as one of the principal locations on the planet where the effects of intra-oceanic plate convergence can be studied within a well-constrained tectonic context (Fig. 4). The region continues to attract considerable international interest. Australian, German, Japanese, New Zealand, and United States funded cruises, with diverse objectives continue to be regularly scheduled to the region and new data are continually being collected on the extensive sample collections held by numerous research institutions across the world. Examples of key research themes currently being pursued include:

1. Studies of crustal structure using swath bathymetric and geophysical information. The objectives of this type of research include more precise definition of the structure of the arc–back-arc system, refinement of parameters such as spreading and convergence rates, and a better understanding of the regional tectonics in oceanic arcs.
2. Submarine topography, geomorphology and physical volcanology of volcanoes of the arc and of the basement on which the volcanoes are built. This activity is based on the spectacular images that have been generated by swath mapping during cruises over the past five years.
3. Determination of the interaction between crust and mantle and the importance of felsic magmatism in subduction systems. (e.g. Gamble et al., 1990, 1993, 1996; Hilton et al., 1993; Smith et al., 2003a,b). This will continue to be a particularly important aspect because the Tonga–Kermadec–Lau system straddles the boundary between the oceanic crust of the SW Pacific and the continental crust of New Zealand.
4. The relationship between tectonic variation along an intra-oceanic subduction system and slab-related fluid flux rates, magma chemistry, hydrothermal flux and chemistry at the sea floor, and mineralization. The Tonga–Kermadec arc is ideal for studying the mobility of elements during subduction because the arc crust is young and thin and crustal contamination effects are minimised. The changes in plate convergence rates along the length of the arc are well documented and should be related to changes in flux rate from the subducting slab. In theory these changes should be manifested in the hydrothermal and magmatic systems associated with subduction.
5. The Lau–Havre back-arc basins continue to be regarded as representative examples of actively spreading oceanic ridge segments and consequently they are targeted as areas in which multi-disciplinary studies of the Earth's active ridge system can be undertaken. Such studies (e.g. "South Pacific Odyssey" programme — US RIDGE 2000; the Australian TELVE cruise programme; the New Zealand NZAPLUME expeditions) are aimed at exploring for active hydrothermal vent systems and attempt to integrate seafloor mapping and bathymetric data with geophysical, petrological, and biological research and information about the thermal and hydrological systematics of the active ridge to obtain holistic models for the ridge component of the Earth system.
6. The use of samples from the Tonga–Kermadec arc and Lau–Havre back-arc system to test the application of new and developing approaches to petrological problems. The relative simplicity of the Tonga–Kermadec intra-oceanic system will continue to provide the basis for its use as a testing ground for the development of new isotopic and other techniques and their application to the understanding of subduction-related petrological processes (e.g. Hilton et al., 1993; Turner et al., 1997; Bach and Niedermann, 1998; Macpherson and Mattey, 1998; Woodhead et al., 2001; Kent et al., 2002; Sun et al., 2004).

Fig. 4. Schematic representations of tectonic and magmatic processes taking place from north to south along the Tonga–Kermadec–Lau convergent plate boundary. Back-arc processes show a transition from rifting and incipient spreading in the south (C) to large-scale seafloor spreading involving overlapping spreading ridges (SLSC = southern Lau spreading centre and ELSC = eastern Lau spreading centre) and ridge segmentation in the north. Models for magma generation in the frontal arc (Tofua and Kermadec arcs) involve interaction of slab derived fluid with the overlying mantle wedge as well as sediment mixing (S). Metasomatised mantle wedge (M) is the source for primary arc magmas. The mantle wedge compositions circulating into the melting zone beneath the frontal arc are depleted (DM = depleted mantle) by magma extraction taking place in the back-arc. It has been postulated (e.g. Hawkins, 1995) that the Lau back-arc mantle has since the Miocene been progressively influenced by lateral flow from the south of an Indian MORB type source which has, over time, displaced Pacific MORB type mantle to the north. The concepts summarised in this figure incorporate ideas from an extensive literature. Most notably from Ewart and Hawkesworth (1987), Hawkins (1995), Gamble et al. (1996), and Parson and Wright (1996). Data relating to depth to Wadati Benioff zone and arc–trench gap along the arc are from England et al. (2004).

The Tonga–Kermadec arc has in the past played a major role in the development of tectonic and petrological models for the development and evolution of convergent plate boundaries and this role as a key testing ground and archetypical natural laboratory is likely to continue for the foreseeable future.

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