Sourcing of Miocene accretionary lapilli on 'Eua, Tonga; atypical dispersal distances and tectonic implications for the central Tonga Ridge.

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Abstract

Volcaniclastics hosting accretionary lapilli on the Tonga Ridge were sourced from the remnant Lau Ridge, prior to Lau back-arc basin opening. For the 'Eua occurrences, an atypical dispersal distance of not less than 70 km is estimated, partly arising from the anomalous easterly position of 'Eua. Dispersal within ocean-surface pyroclastic density currents is supported but strike-slip movement in a fault zone south of 'Eua, post Middle Miocene but pre ridge-splitting, can account for part of the dispersal distance by vertical axis block rotation, a tectonic process common on the southern Tonga-Kermadec-Hikurangi trend. In this model, the volcano which sourced the 'Eua tephra was on a subjacent block, rather than the block which hosts 'Eua. After deposition but prior to the opening of the Lau Basin, the accretionary lapilli on 'Eua became displaced by block rotation c. 40 km towards the Tonga trench and away from source.

Keywords

Accretionary lapilli; Tonga Ridge; dispersal distance; block rotation; pyroclastic density currents.

Introduction

Accretionary lapilli are highly ordered types of ash aggregate typically associated with explosive eruptions, where they may form in the plume itself or in pyroclastic density currents as they interact with the co-ignimbrite ash plume. Dispersal may therefore occur subaerially by expansion of the plume, spreading of any atmospheric umbrella cloud, and/or by pyroclastic density currents. The 'Eua accretionary lapilli contain examples typically 10–15 mm in diameter and are accretionary lapilli *sensu stricto* (Brown et al. 2010, Van Eaton & Wilson 2013), as distinguished from less ordered ash pellets and fragile ash aggregates (Brazier et al. 1982; Carey & Sigurdsson 1982; Wiesner et al. 1995; Brown et al. 2012) which rarely survive in that form but are detected in sieve analysis of grain size. Accretionary lapilli have been reported from

Miocene volcaniclastics which are exposed on the Nomuka group islands (Ballance et al. 2004) and on 'Eua on the Tonga Ridge (Ballance et al. 2004; Cunningham & Beard 2014). The host volcaniclastics were sourced from volcanoes on the Lau Ridge, prior to the splitting of the Lau-Tonga ancestral arc in the latest Late Miocene to form the Lau back-arc basin (Clift et al. 1994, 1995, 1998; Cole et al. 1985; Parson & Wright 1996). Reconstruction of the ancestral ridge places the Nomuka group islands, which are positioned on the west of the Tonga Ridge, at modest dispersal distances from potential source. However, 'Eua is the most easterly of the island exposures along the Tonga Ridge by some margin and this contributes to a dispersal distance from source at the limit of most (but not all) documented occurrences of accretionary lapilli. The resolution of the two problems presented by the anomalous position of 'Eua and the exceptional distance from potential source of the accretionary lapilli found on 'Eua is the focus of this paper. The approach taken to address the two problems is firstly to use data from the Tonga Ridge, the Lau Basin and the Lau Ridge to constrain possible locations for the Middle Miocene source volcano which provided the accretionary lapilli on ‘Eua, to consider how the distance between source and destination may have been impacted by post Middle Miocene tectonics, including block rotation, and to estimate the minimum actual contemporary distance from source. Thereafter, the paper examines constraints on possible maximum dispersal distances for the relatively large accretionary lapilli from ‘Eua. Discussion is then enabled on whether the anomalous position of 'Eua and the unusual dispersal distance of the 'Eua accretionary lapilli from source can be explained by block rotation within the Tonga microplate and/or a dispersal distance enabled by a pyroclastic density current which traversed the ocean surface before depositing the accretionary lapilli on 'Eua.

Regional setting

Located on the northern part of the Hikurangi-Kermadec-Tonga trend, the Tonga and Lau Ridges are dominantly open marine, as delineated by the 2000 meter contour (Fig. 1A). A number of islands occur, some large, but most are barely emergent and exposures are limited. On the Tonga Ridge, the island of ‘Eua is an exception, where an uplifted Eocene basement high and overlying sediments are now exposed subaerially. These sediments include deep marine Middle Miocene volcaniclastics. More is known of the Tonga Ridge (Fig. 1B) than the remnant Lau Ridge. Oil industry activity, including 5 exploration wells on Tongatapu, proved that a deep basin of sediment overlays a presumed volcanic arc basement on the north-central part of the Tonga

Platform (Cunningham & Anscombe 1985). Scientific cruises (Scholl & Vallier 1985, Stevenson et al. 1994) confirmed this frontal arc basin extended south and established that the present Tonga Ridge is broken into a number of fault-delineated blocks (Fig. 1B). On the southern platform, depocentres are identifiable on the west of the basin on isopach A–B (which includes the Miocene), with the sediments thickening generally towards the west. Herzer & Exon (1985) suspected that their alignment along the west side of the basin indicated these sediment "thicks" were fed from volcanic centres “nearby to the west, outside the mapped area”. The Lau Ridge bathymetry is very similar to the Tonga Ridge, broadly outlined by the 2000 meter contour (Fig. 1A), but many more islands with a dominantly volcanic aspect dominate the geology (Woodhall 1985). Basement rocks are not exposed in the islands, the oldest rocks exposed being Middle Miocene, but volcanism extended from 14.0 to <2.5 Ma, so older geology would have been obscured on volcanic islands. Thus the many Lau Islands which have a long-lived volcanic history provide credible candidates for the volcanic centres “nearby to the west, outside the mapped area” of Herzer & Exon (1985). The island arc andesite character of the Lau Volcanic group (14.0–6.0 Ma) and the age range which includes the Middle Miocene, the age of the mafic volcaniclastics on ‘Eua, supports the case. In order to provide a working model for the sourcing of the accretionary lapilli found on the Tonga Ridge, it is now necessary to constrain possible source locations prior to the partition of the ancestral Lau-Tonga Ridge and then consider how the active tectonics in the region may have re-positioned source or settlement site.

The accretionary lapilli and the location of possible volcanic sources

The reported occurrences of accretionary lapilli on the Tonga Ridge are from Miocene volcaniclastics on 'Eua and on two islands in the Nomuka group (Fig. 1B). The 'Eua occurrences (Fig. 2A–C) range up to 20 mm in maximum dimension and typically occur unsorted in grain to grain contact as thin beds up to 20 cm in thickness. The matrix is coarse-grained (>500 µm) or absent. The 'Eua occurrences exhibit characteristics suggesting they settled to pelagic depths (Ballance et al. 2004; Cunningham & Beard 2014) while some of the Nomuka occurrences may have been reworked from the original settlement site (Ballance et al. 2004). The 'Eua host volcaniclastics are typically granulestone/sandstone in grain size, with occasional larger clast sizes, none in excess of 30 mm, and a pelagic planktonic foraminiferal fauna. The fauna are dated at Middle

Miocene, c. 14 Ma, with sparse re-worked slightly earlier fauna (Quinterno 1985; Chaproniere 1994), indicating depths of deposition are not less than 1600 meters. A range of sediment gravity flow types (Ballance et al. 2004) are reflected in the host formation, with rare westwards-dipping cross-beds (Fig. 2D). Tappin & Ballance (1994) reported a WNW verging flame structure. In contrast, the 'Eua beds of accretionary lapilli exhibit a narrow size distribution in that they are large, typically 10-15 mm in diameter, and the matrix is fines-depleted or absent. These features are applied to terminal velocity calculations by Cunningham & Beard (2014) to argue that these beds were the result of settling to pelagic depths and were not delivered by sediment gravity flows or submarine pyroclastic flows. The upper size constraint of volcanogenic clasts in the 'Eua volcaniclastics contrasts with the Nomuka host rocks; on Mango in the Nomuka group of islands, Middle (?) Miocene volcaniclastics contain indications of the proximity of volcanic edifices, such as volcanic boulder-bearing debris flow deposits (Ballance et al. 2004). Further south on the T–E block, the detection of volcanic sources is assisted by the availability of close-spaced oil industry data (Gatliff et al. 1994). With the high rates of sediment supply implicit in island arc environments, the problem of distinguishing reef structures from buried volcanic edifices is important and has been reviewed (Alexander 1985; Herzer & Exon 1985; Pflueger & Havard 1994; Tappin et al. 1994). Only one volcanic edifice was detected along the Tonga Ridge, in the B–C Late Oligocene to Early Miocene interval and on Block D. No ambiguous structures at all were identified on the T–E block within the interval which includes the Middle Miocene (Gatliff et al. 1994) and "No volcanic structures sourcing unit A–B have yet been identified on the Tonga Ridge" (Tappin et al. 1994). Thus the seismostratigraphy reveals no obvious local source on the Tonga Ridge for the accretionary lapilli, either for the Nomuka group or the 'Eua occurrences. The regional setting suggests that sources would be to the west and on the remnant Lau Ridge, where long-lived volcanic islands exist.

Tectonics

The study area of the SW Pacific is a tectonic province with a relatively well-documented geological history, particularly with respect to back-arc extension/basin formation processes (Packham 1978; Tappin 1993; Sager et al. 1994; Tappin et al. 1994; Parson and Wright 1996; Taylor et al. 1996). In the south of the region, on the Tonga-Kermadec-Hikurangi trend, subducting oceanic plate encounters continental crust on South Island, New Zealand (Lamb 2011). Further north, the environment is oceanic. A more sophisticated model for Lau Basin formation (Figs. 3A, 3C) replaced a simple mid-oceanic type spreading centre model with a two-phase model (Parson et al. 1994; Parson & Wright 1996; Taylor et al. 1996). The Lau basin floor geology is asymmetric; patterns of strong positive magnetic intensity are exhibited east of a line running NNW across the Lau Basin at roughly 317^0, reflecting the new oceanic crust being created at the Central and Eastern Lau spreading centres. However, west of that line and east of the 2000 meter isobath on the Lau Ridge, an irregular terrain of north-trending horst/grabens occurs where specific magnetization events were not well delineated, attributed to diffuse spreading to form “extended arc crust”. In broad terms, the ancestral Lau/Tonga Ridge arc crust split and experienced extension to the east of the active arc volcanoes on the remnant Lau Ridge by:

- graben/half-graben faulting accompanied by intrusive activity which mark the location of repeated “failed” spreading centres (creating the “extended arc crust”), before:
- formation of new crust occurred continuously at more typical mid-ocean ridge type spreading centres (the Central Lau Spreading Centre/East Lau Spreading Centre , which were initiated in the north of the Lau Basin and propagated southwards.

During these processes, Lau Ridge and intra-basin volcanism occurred and eventually ceased, before restoration of back-arc volcanism on the currently active Tofua Arc. The net effect is that of an apparent rotation of the Tonga Ridge, the current active arc, some 20^0 clockwise, away from the remnant Lau Ridge segment of the ancestral arc. With no compelling evidence to support a source on the Tonga Ridge, 'Eua appears to be at a considerable distance from a source which must have existed further to the west on the ancestral Lau-Tonga ridge. Using present sea-bed depth contours at 1000 and 2000 meters to estimate the width of the ancestral arc elements, an outline reconstruction (Fig. 3B) is achieved by rotating the Tonga Ridge in the horizontal plane back to the west by the c. 20^0 estimated by Sager et al. (1994). On Block T–E, the distance between the western edge of the Tonga Ridge and 'Eua, where it thins against the proto-‘Eua submergent high is c. 61 km (Fig. 3A), before correction for extension due to post-Middle Miocene faulting. Post-Middle Miocene sub-vertical fault patterns on the Tonga Ridge segment do not suggest this will be material, when compared with pre-Middle Miocene graben/half graben faulting which may be listric at depth. However, the threat of underestimation of extension due to unidentified small faults (Twiss &

Moores 2007), supports the application of a non-trivial provision, say 10%, which would bring the 61 km estimate down to c. 55 km pre-fault extension. The Tonga frontal arc basin segment terminates abruptly on the west with down-to-Tofua faulting (Herzer & Exon 1985). The footprint of any volcanic source on the remnant Lau Ridge segment requires estimation. The profile of the currently active Tofua arc volcanoes provide possible analogues of Lau Ridge volcanic sources. At base, these range up to c. 30 km in width, excluding composite structures which are wider (Chase 1985, Fig. 1). On this basis, 55 plus 15 km = 70 km is indicative of the minimum distance from a source on the eastern edge of the remnant Lau Ridge segment. If the source volcano was originally in what is now the extended arc crust of the western Lau Basin, this figure is increased, but no data is available from the ODP sites in the Lau Basin to constrain this possibility, as none of these reached the Middle Miocene (Fig. 3A). A much higher figure is required if a structure in the position of Ono-i-Lau is considered. In the Lau Basin at the longitude under study, c.105 km of extended arc crust exists and the distance from Ono-i-Lau to the eastern edge of the Lau Ridge is 75 km.

The more local effects of individual block rotation are now considered. During re-processing of oil industry data on the T–E Block, it was noted that a number of physiographic features of the block would be explained if it had rotated 30^0 anticlockwise (Gatliff et al. 1994). One feature is the atypical triangular shape of the Tongatapu-‘Eua block as a whole (Fig. 1B), as reflected at the 1000 m isobath. ‘Eua is closer to the eastern margin of the frontal arc basin than any other basement high, and as an emergent island with an elevation of 912 meters, is much higher. To further explore whether there is seismostratigraphic/geophysical support for the rotation proposition, a number of sources of data were superimposed on Blocks A, B and T–E (Fig. 4). There are clearly a number of departures from the Tonga Ridge NNE-SSW ridge-parallel structural trend, localised to the southern margin of Block T–E. On Block T–E, a trend in total magnetic intensity highs, broadly coincident with basement highs (Gatliff et al. 1994) departs from trend and is deflected east of ‘Eua. Further south, on Blocks A and B, a trend of magnetic intensity anomalies (Stevenson & Childs 1985), coincident with ridge-parallel gravity/basement highs, is abruptly curtailed as the southern margin of the T–E block is encountered. The 'Eua Channel Fault, a major structural feature on the southern Tonga Ridge, disappears north of the Block T–E southern margin, where the Tongatapu/‘Eua Channel depocentre was identified (Herzer and Exon 1985, Gatliff et al. 1994).

The three total magnetic intensity highs immediately east of ‘Eua on the Tongatapu-‘Eua block appear to be displaced by a strike-slip fault c. 40 km to the east of the trend of the magnetic intensity anomalies on Blocks A and B. This would have the effect of anticlockwise rotation *sensu* Gatliff et al. (1994). Further south on the Tonga-Kermadec-Hikurangi trend, Lamb (2011) reviews the tectonics and kinetics of faulting in the leading Australian plate continental crust, which accommodates the effects of non-orthogonal subduction. The distinctive faulting styles described include those which could explain features on the T–E block (Cunningham & Anscombe 1985, Fig. 2) by inverting the rotation effect of strike slip faulting on arcuate faults (Lamb 2011, Fig. 18 a), combined with dextral strike slip faulting on a curved strike slip fault “hinge” (Lamb 2011, Fig. 18 f). Block rotation may be contemporaneous with or post-date block formation. Block formation by ridge-traverse faults may have begun “long before the block geometry became so prominent after Late Miocene time” (Scholl & Herzer 1994). Since the western margin of the T–E block has a down-to-Tofua NNE-SSW fault pattern consistent with the other blocks, any rotation, as noted by Gatliff et al. (1994), must have occurred before the ancestral Lau Tonga arc splitting commenced in the late Late Miocene (5.3 Ma). An event at c. 10 Ma was detected by sediment backstripping analysis on the Tonga Ridge at ODP 841 (Clift et al. 1994) and hence in the early Late Miocene. We now propose a model by which block rotation may have contributed towards the dispersal distance anomaly. The model crucially suggests that, pre-ancestral Lau-Tonga Ridge splitting, a Middle Miocene volcano on what would become subjacent Block A sourced the ‘Eua accretionary lapilli found on what would become Block T–E. Anticlockwise block rotation after deposition, but before Lau Basin opening commenced in the late Late Miocene, affects Block T–E, but not A or N. After rotation of this block, the Nomuka Group islands maintain their distance from source volcano, but ‘Eua has been displaced tectonically 40 km eastwards from the tephra source. The distance between source and resting place for the accretionary lapilli has been increased by 40 km even before ridge splitting in the latest Late Miocene carries 'Eua further east.

Constraining dispersal distances for accretionary lapilli

The evidence for final deposition of the 'Eua accretionary lapilli by settling through a marine column of not less than 1600 meters, as presented in Cunningham & Beard (2014), has been summarised earlier. The processes by which they could have reached the point of settlement will now be reviewed. The present Tofua active volcanic arc

(Fig. 1B) is composed of emergent, barely emergent and submarine volcanic edifices at modest depths and may be a good proxy for the Middle Miocene ancestral active volcanic arc, given the dominantly volcanic insular geology as described earlier for the remnant Lau Ridge. The ash clouds within which ash aggregates form (Brown et al. 2012) are typically associated with subaerial explosive volcanic eruptions, although shallow marine eruptions can also be contenders if they breach water depths (McBirney 1963; Wright & Gamble 1999; White et al. 2003) with the creation of an atmospheric ash cloud. The 'Eua accretionary lapilli may therefore have formed during an explosive volcanic eruption initiated subaerially from an emergent volcanic edifice or at shallow depths. In addition, proximity of the ocean surface permits the possibility of formation of accretionary lapilli in secondary ash-rich steam clouds as pyroclastic density currents enter the sea (Dufek et al. 2007). Dispersal may take place subaerially within the eruption plume/umbrella cloud or as pyroclastic density currents travel across the sea surface (Allen & Cas 2001; Carey et al. 1996; Maeno & Taniguchi 2007).The substantial distances by which less-ordered ash aggregates can be dispersed from source subaerially are well established; ash aggregates dispersed in the eruption plume at Mt St Helens were detected at 200 km from source (Carey & Sigurdsson 1982). In contrast, the dispersal of relatively large and dense accretionary lapilli within the eruption plume must be restricted by their significant mass to more modest dispersal distances from the source volcano, as constrained in tephra dispersal models (Walker et al. 1971; Walker 1981; Carey & Sparks 1986; Pfeiffer et al. 2005; Folch 2012). Accretionary lapilli are technically lapilli, falling within the 2–64 mm range, (Schmid 1981; Fisher & Schmincke 1984). Lapilli-sized tephra can be dense juvenile/country rock clasts, mafic scoria or vesicular silicic pumice clasts. Reported specific gravities of accretionary lapilli, which are dominantly silicic, are in the range of 1200–1500 kg m^{-3} (Sparks et al. 1997). The 'Eua examples are mafic in composition and should therefore be at the upper end of this spectrum or slightly exceed it. Isopleths for 16 mm-sized lapilli for known eruptions show maximum dispersal distance in the range of 20–30 km (Carey & Sparks 1986), for tephra at density of 2500 kg m^{-3} and “larger centrimetric and millimetric fragments typically settle in minutes to few hours at distances of the order of tens of km from the volcano” (Folch 2012). Grain size directly influences terminal velocity of descent of a particle. This varies significantly with height in the atmosphere and departure from sphericity (Dellino et al. 2005). These parameters are accommodated in most tephra transport and dispersal models. Table 1 provides indicative terminal velocities over a range of heights (Pfeiffer et al. 2005) for particles of $\Phi = -4$ (=16 mm), density of 1500 kg m^{-3}, and departure from sphericity. These particles are close to the typical size of the 'Eua accretionary lapilli. The density of 1500 kg m^{-3} is appropriate, as discussed earlier (advanced palagonitisation obscures the original density of the constituent glass particles). These figures would underestimate terminal velocity for the notably spheroidal 'Eua accretionary lapilli. The range of contemporary prevailing wind speeds in the Lesser Antilles range from 5.55 m sec^{-1} in the stratosphere and up to 25 m sec^{-1} in the upper troposphere (Sigurdsson et al.1980). Based on input of the 16 mm clast isopleth for Cotopaxi layer 3, Burden et al. (2011) estimate plume height between 26 km and 32.5 km with a wind speed of 35 m sec^{-1}. If these wind speeds were applicable to the SW Pacific in the Middle Miocene, the effects of wind advection should be modest for tephra the size of the 'Eua accretionary lapilli. Complexity is introduced by the formation of aggregates during plume development, whether in the form of accretionary lapilli or less-ordered ash aggregates, as this is complex to model (Costa et al. 2010); accretionary lapilli often occur in phreatomagmatic eruptions, where phase changes involving latent heat release might increment the upwards convection vector and counter the dominant role, in most models, of the downward terminal ("settling") velocity of descent. Modelling of the phreatomagmatic 25.4 ka Oruanui event (Van Eaton et al. 2012), an ultra-Plinian event, instead of a simple plume/high level umbrella cloud with lower level co-ignimbrite ash clouds, produced "hybrid" ash clouds generated both from the plume and from buoyant co-ignimbrite ash clouds which rise to plume heights. Concentrically layered accretionary lapilli similar to those in 'Eua were dispersed at distances of 120 km from source (Van Eaton & Wilson 2013) in this event. The 25.4 ka Oruanui event is statistically unusual; only 156 (2.3 %) such events are reported from a total of 6736 in the Smithsonian Institute database (Siebert and Simkin 2002–2014). Occurrences from more modest events are reported from dispersal within the Soufriere St Vincent plume at 36 km from source (Brazier et al. 1982) and dispersed within pyroclastic density currents at Mt St Helens at c. 25 km (Fisher et al. 1987), and these are closer to ash pellets as defined (Brown et al 2010; Van Eaton & Wilson 2013), rather than accretionary lapilli. Surface dispersal over the ocean surface is now considered. Pyroclastic density currents can partition into a coarse, dense-clast rich submarine flow and a dilute pyroclastic surface flow running at the surface on entering the sea, as seen with experiments and simulations referred to observed/inferred events and their deposits

(Freundt 2003; Trofimovs et al. 2006; Dufek & Bergantz 2007; Trofimovs et al. 2008; Dufek et al. 2009). Observations of the deposits of the Kos Plateau Tuff (Allen & Cas 2001) supported this model, with the loss of the coarsest vent and conduit-derived lithic clasts over the sea due to sinking, while over land, saltation was considered to have preserved the coarser element in the resulting ignimbrites. Saltation may also occur over water and be accentuated by the occurrence of pumice rafts (Fiske et al. 2001) while, conversely, transport capacity will be influenced by areal dilution, as momentum transfer between large and small particles is diminished (Dufek & Bergantz 2007; Dufek et al. 2009). Such surface flows have travelled for considerable distances (Table 2), carrying bomb and lapilli-sized clasts, in addition to ash and hot gas. In conclusion, for plume/umbrella cloud dispersal within the atmosphere, the "tens of km" metric is supported. For pyroclastic density current-enabled dispersal over land, only a statistically unlikely ultra-Plinian event is capable of providing dispersal via the atmosphere for the minimum 70 km dispersal scenario, (considering the source was close to the eastern edge of the remnant Lau Ridge segment). In contrast, for pyroclastic density current-enabled dispersal across the ocean surface, there is some evidence that relatively modest magnitude events could provide dispersal distances which contribute significantly to the scenario.

Discussion and conclusions

The accretionary lapilli on ‘Eua, Tonga, occur in Middle Miocene pelagic volcaniclastic sediments with no evidence for a proximal volcanic source. A contemporary distance which is unlikely to be less than 70 km, and may be much more, from a source on the Lau segment of the ancestral Lau-Tonga Ridge, is estimated from seismostratigraphic and other data. This is much farther than would be expected for dispersal of these spheroids of significant mass, unless an exceptional ultra-Plinian source is invoked. Tephra fall associated with an ultra-Plinian event on the scale of the Oruanui at 25.4 ka (Van Eaton & Wilson 2013) could, *prima facie*, resolve the dispersal distance problem, since the dispersal distances of accretionary lapilli in the atmosphere by the eruption plume and pyroclastic density currents in that event were substantial. However, there is no field evidence in the area under study for an ultra-Plinian event in the Middle Miocene. At 530 km^3 DRE, the Oruanui event is exceptional and unit 8, which contains the highly dispersed occurrences, exhibits characteristics which suggest that the eruption produced an extremely high mass eruption rate ($\geq 10^9$ kg s^{-1}), with numerical simulations (Van Eaton et al. 2012) implying the potential for transportation of tephra to stratospheric heights. Explosive volcanic events of a much more modest magnitude, but driving pyroclastic density currents over the ocean surface, have dispersed tephra to considerable distances (Table 2), with larger tephra being carried as far as 65 km. The restriction of upper size carried, depending on mass flux during the event, has significance for the Tongan insular Miocene, where the absence of clasts exceeding 30 mm has been attributed to some trapping mechanism elsewhere (Ballance et al. 2004) for clasts of greater size. Delivery by sediment gravity flows is probable for most of the volcaniclastics on the 'Eua high (Tappin & Ballance 1994; Ballance et al. 2004). However, for any component of the 'Eua volcaniclastics delivered by ocean surface pyroclastic density currents, a alternative process by which upper grain size is restricted is suggested. Furthermore, the rare westwards-dipping cross-beds in the 'Eua volcaniclastics (Fig. 2D) may be attributable to sediment overloading on the 'Eua high by periodic ocean surface pyroclastic density currents and consequential westwards backflow.

While delivery by pyroclastic density current over the ocean surface may explain all or part of the dispersal distance issue, it does not explain the anomalous position of the ‘Eua high; 'Eua is positioned much further from the western edge of the Tonga Ridge than any other island. The discontinuities in trends at the southern Block T–E margin, interpreted as block rotation of a particular type, provides a tectonic explanation for this anomaly. The relative thickness of sediment in the Tongatapu/'Eua Channel depocentre (Fig. 4) fits well within this model: with block rotation occurring in the Late Miocene, but pre-splitting, the Tongatapu-‘Eua Channel basin would have been 40 km closer to the source volcanoes to the west for part of the interval 14 – 5.3 Ma, thus only 30 km from source on the minimum 70 km scenario.

For the rotation event to have contributed 40 km to the ‘Eua accretionary lapilli dispersal distance, a number of conditions must apply. Firstly it must pre-date splitting of the ancestral Lau/Tonga Ridge which commenced in latest Late Miocene (5.3 Ma), secondly post-date the deposition of the accretionary lapilli on proto-'Eua at 14 Ma, and thirdly, the accretionary lapilli must have been sourced from a volcano on the ancestral Lau-Tonga Ridge segment which became Block A.

We favour a model where the accretionary lapilli on 'Eua finally settled through a marine column of not less than 1600 meters. Their delivery to the final resting site was most likely achieved by transport within a pyroclastic density current travelling over the ocean surface which, even in the case of those initiated by small/moderate explosive volcanic events, have delivered relatively large tephra considerable distances from source. A dual model, comprising block rotation and dispersal by ocean surface pyroclastic density currents, can explain the anomalies described and accommodate a large range of possible dispersal distances from a source of modest magnitude. The dating of block formation and of subsequent movement is however problematic; ridge-normal faulting is only strongly expressed in displacement of the A–B isopach, implying that it postdated late Late Miocene. Only detailed palaeomagnetic studies of the host Middle Miocene volcaniclastics on ‘Eua could increase precision in this regard; the ubiquity of magnetite in thin hemipelagites which occur in these rocks would make such studies worthwhile.

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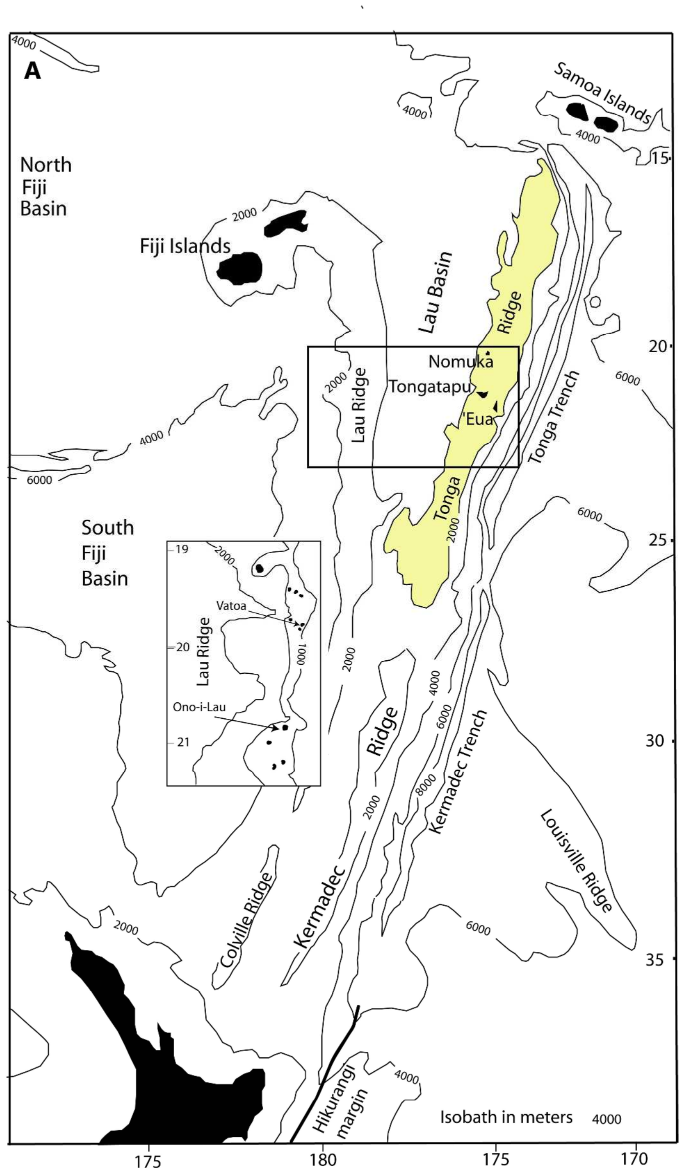

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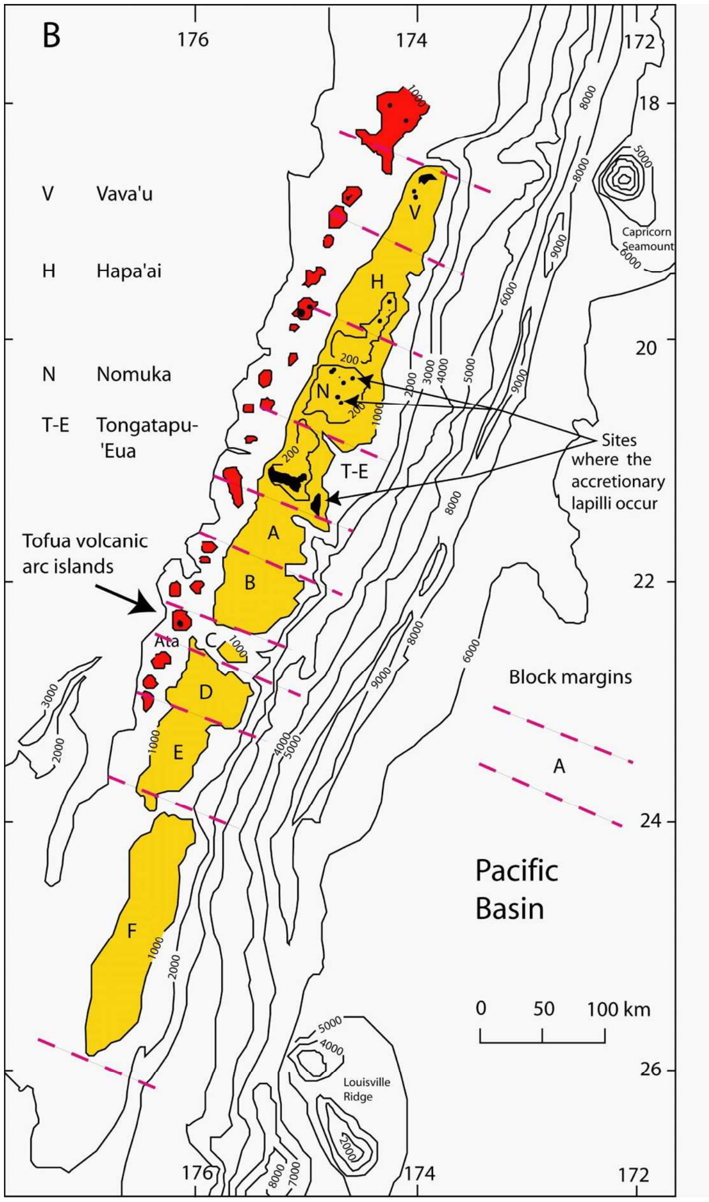

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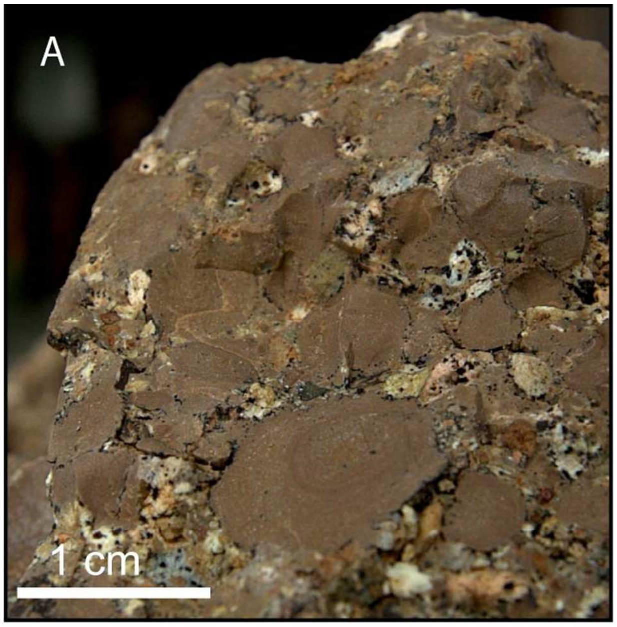

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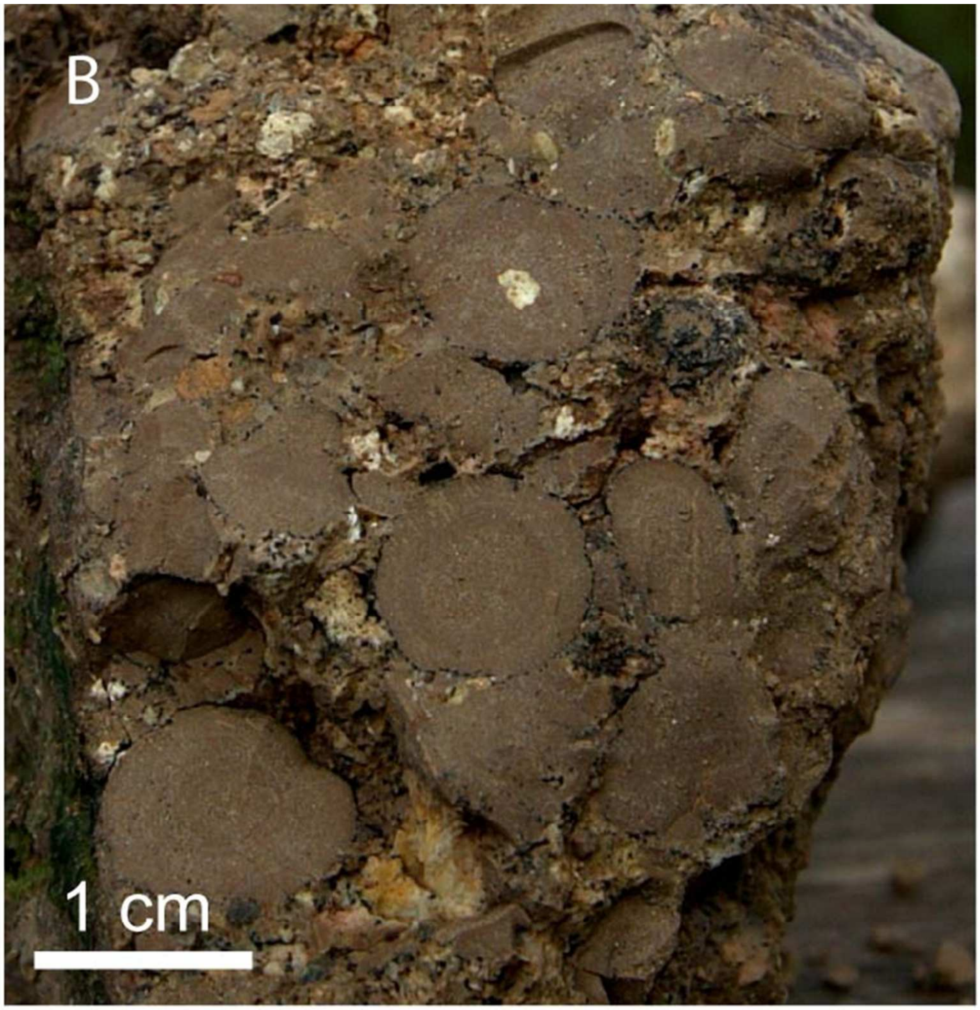

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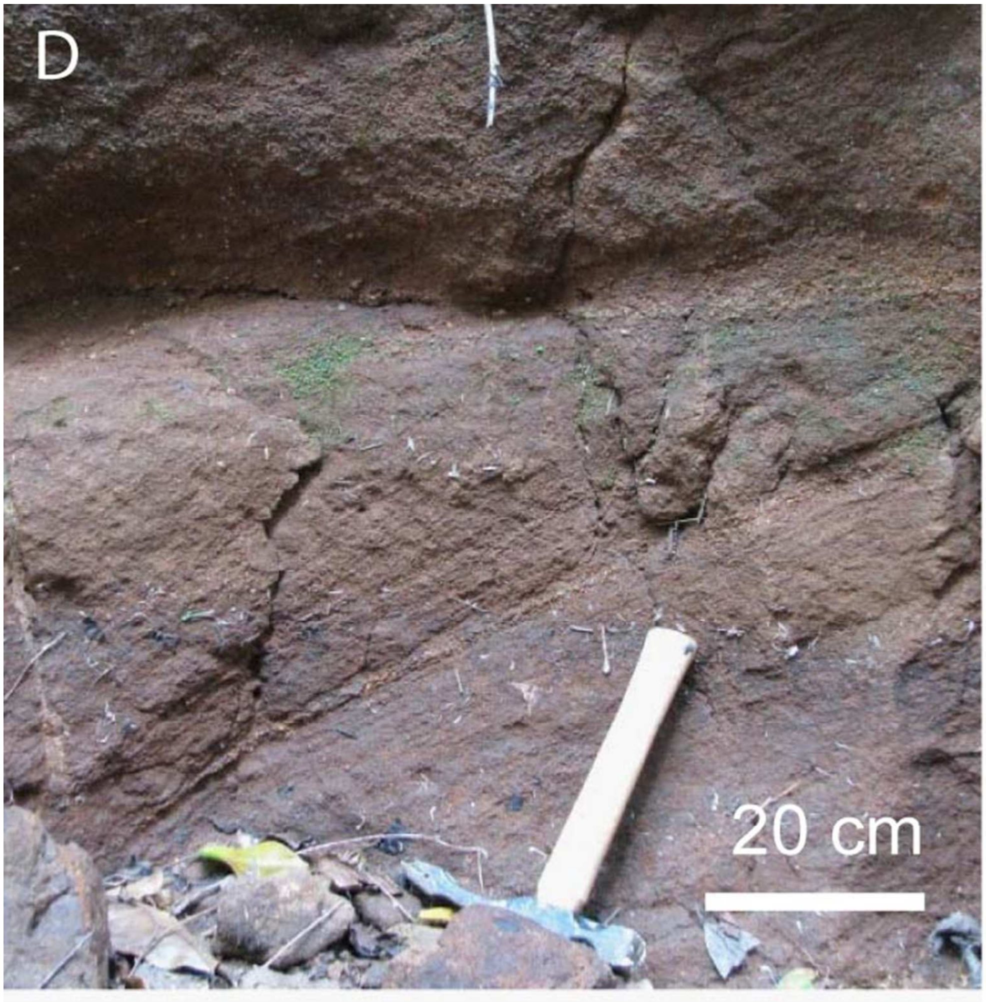

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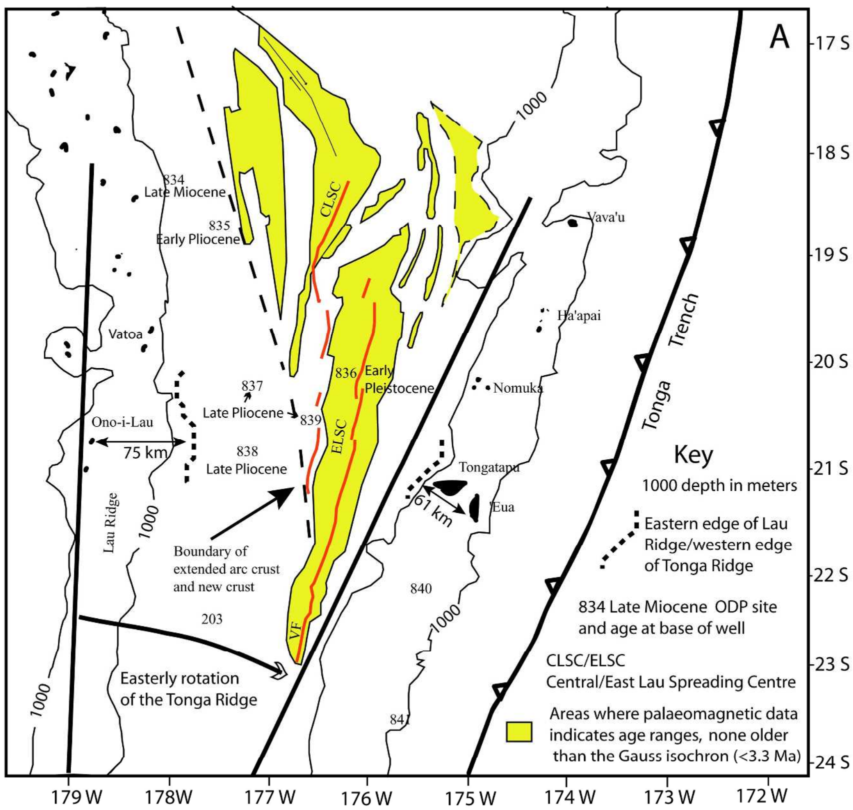

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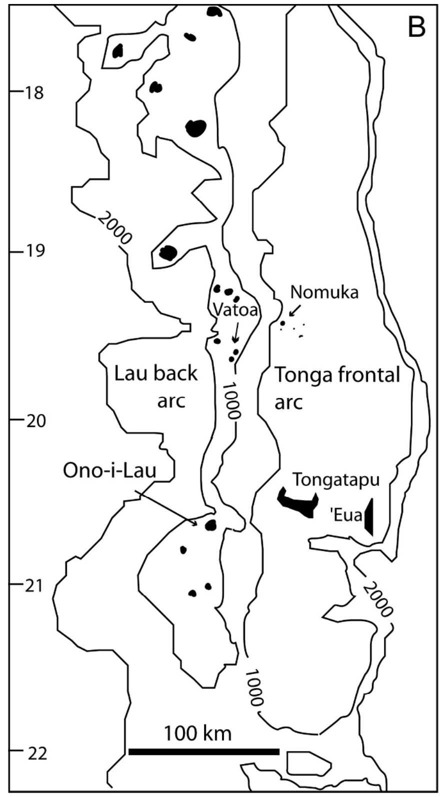

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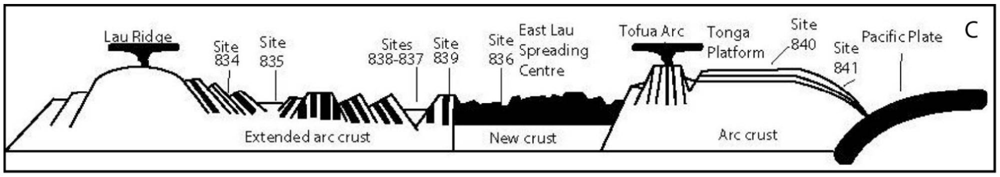

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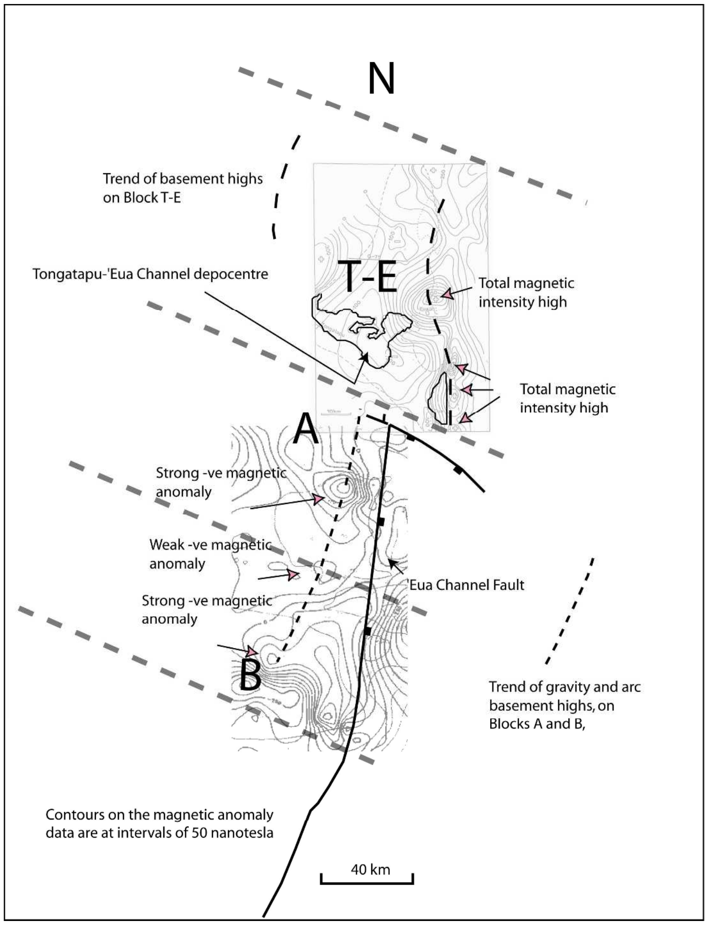

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Height (km)	Sea level	5	15	26
U_t (m sec^{-1})	16	20	50	100

Event	DRE (kg m^{-3})	Larger tephra	Distance from source (km)
Krakatoa	12	pumice stones several centimeters in diameter	65
Kos Plateau Tuff Unit E	30	vent and conduit derived lithic clasts not >200 mm	>60
Kikai Unit D	50	accretionary/armoured lapilli typically 5-9 mm, up to 10 mm	60

~~Sourceing of Middle Miocene accretionary lapilli on 'Eua, Tonga; atypical dispersal distances and their implications.~~

Sourcing of Miocene accretionary lapilli on 'Eua, Tonga; atypical dispersal distances and tectonic implications for the central Tonga Ridge.

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Abstract

Volcaniclastics hosting accretionary lapilli on the Tonga Ridge were sourced from the remnant Lau Ridge, prior to Lau back-arc basin opening. For the 'Eua occurrences, an atypical dispersal distance of not less than 70 km is estimated, partly arising from the anomalous easterly position of 'Eua. Dispersal within ocean-surface pyroclastic density currents is supported but strike-slip movement in a fault zone south of 'Eua, post Middle Miocene but pre ridge-splitting, can account for part of the dispersal distance by vertical axis block rotation, a tectonic process common on the southern Tonga-Kermadec-Hikurangi trend. In this model, the volcano which sourced the 'Eua tephra was on a subjacent block, rather than the block which hosts 'Eua. After deposition but prior to the opening of the Lau Basin, the accretionary lapilli on 'Eua became displaced by block rotation c. 40 km towards the Tonga trench and away from source.

Keywords

Accretionary lapilli; Tonga Ridge; dispersal distance; block rotation; pyroclastic density currents.

Introduction

Accretionary lapilli are highly ordered types of ash aggregate typically associated with explosive eruptions, where they may form in the plume itself or in pyroclastic density currents as they interact with the co-ignimbrite ash plume. Dispersal may therefore occur subaerially by expansion of the plume, spreading of any atmospheric umbrella cloud, and/or by pyroclastic density currents. The 'Eua accretionary lapilli contain examples typically 10–15 mm in diameter and are accretionary lapilli *sensu stricto* (Brown et al. 2010, Van Eaton & Wilson 2013), as distinguished from less ordered ash pellets and fragile ash aggregates (Brazier et al. 1982; Carey & Sigurdsson 1982; Wiesner et al. 1995; Brown et al. 2012) which rarely survive in that form but are detected in sieve analysis of grain size.

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Accretionary lapilli have been reported from Miocene volcaniclastics which are exposed on the Nomuka group islands (Ballance et al. 2004) and on 'Eua on the Tonga Ridge (Ballance et al. 2004; Cunningham & Beard 2014). The host volcaniclastics were sourced from volcanoes on the Lau Ridge, prior to the splitting of the Lau-Tonga ancestral arc in the latest Late Miocene to form the Lau back-arc basin (Clift et al. 1994, 1995, 1998; Cole et al. 1985; Parson & Wright 1996). Reconstruction of the ancestral ridge places the Nomuka group islands, which are positioned on the west of the Tonga Ridge, at modest dispersal distances from potential source. However, 'Eua is the most easterly of the island exposures along the Tonga Ridge by some margin and this contributes to a dispersal distance from source at the limit of most (but not all) documented occurrences of accretionary lapilli. The resolution of the two problems presented by the anomalous position of 'Eua and the exceptional distance from potential source of the accretionary lapilli found on 'Eua is the focus of this paper.

~~While the Tonga Ridge has acted as one microplate during the Lau Basin opening process (Sager et al. 1994), it comprises a number of fault-bounded blocks. These blocks have moved differently *inter se* during tectonic events, revealed by seismostratigraphy (Scholl & Vallier 1985; Stevenson et al. 1994). Rotation of the block hosting 'Eua provides a potential tectonic explanation for the anomalous position of 'Eua and the unusual dispersal distance of the 'Eua accretionary lapilli from source. However the Tonga-Kermadec-Hikurangi trend further south provides evidence for both block rotation *and* unusual dispersal distances for accretionary lapilli (Lamb 2011, Van Eaton & Wilson 2013).~~

The approach taken ~~in this paper~~ to address the two problems is firstly ~~firstly~~ to use data from the Tonga Ridge, the Lau Basin and the Lau Ridge to constrain possible locations for the Middle Miocene source volcano which provided the accretionary lapilli on ‘Eua, to consider how the distance between source and destination may have been impacted by post Middle Miocene tectonics, including block rotation, and to estimate the minimum actual contemporary distance from source. Thereafter, the paper examines constraints on possible maximum dispersal distances for the relatively large accretionary lapilli from ‘Eua. ~~The evidence for block rotation on the central Tonga Ridge is then presented, and the actual relative displacement of 'Eua arising from tectonism alone deduced.~~ Discussion is then enabled on whether the anomalous position of 'Eua and the unusual dispersal distance of the 'Eua accretionary lapilli from source can be explained by block rotation within the Tonga microplate and/or a dispersal distance enabled by a pyroclastic density current which traversed the ocean surface before depositing the accretionary lapilli on 'Eua., or whether a Middle Miocene ultra-Plinian explosive volcanic event on the ancestral Lau-Tonga Ridge must be invoked.

Regional setting

Located on the northern part of the Hikurangi-Kermadec-Tonga trend, the Tonga and Lau Ridges are dominantly open marine, as delineated by the 2000 meter contour (Fig. 1A). A number of islands occur, some large, but most are barely emergent and exposures are limited. On the Tonga Ridge, the island of ‘Eua is an exception, where an uplifted Eocene basement high and overlying sediments are now exposed subaerially. These sediments include deep marine Middle Miocene volcaniclastics. The study area of the SW Pacific (Fig. 1) is a tectonic province with a relatively well-documented geological history, particularly with respect to back-arc extension/basin formation processes (Packham 1978; Tappin 1993; Sager et al. 1994; Tappin et al. 1994; Parson and Wright 1996; Taylor et al. 1996). In the south of the region, on the Tonga-Kermadec-Hikurangi trend, subducting oceanic plate encounters continental crust on South Island, New Zealand (Lamb 2011). Further north, the environment is oceanic.

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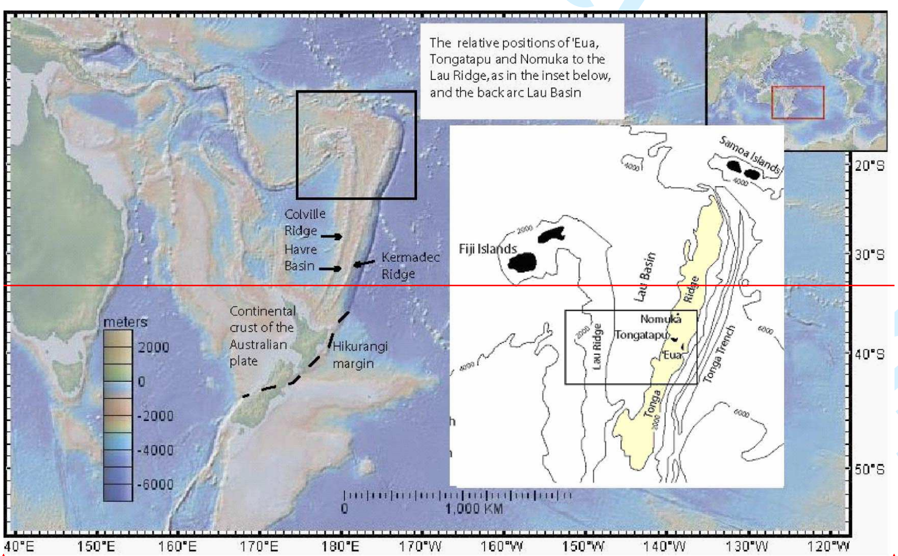

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Figure 1. The position of the Lau Basin on the north end of the Tonga-Kermadec-Hikurangi trend and the study area. The Tonga frontal arc basin sediments (shaded) are broadly coincident with the 2000 meter isobath, after Tappin (1993). Base map from GeoMapApp, http://www.geomapapp.org.

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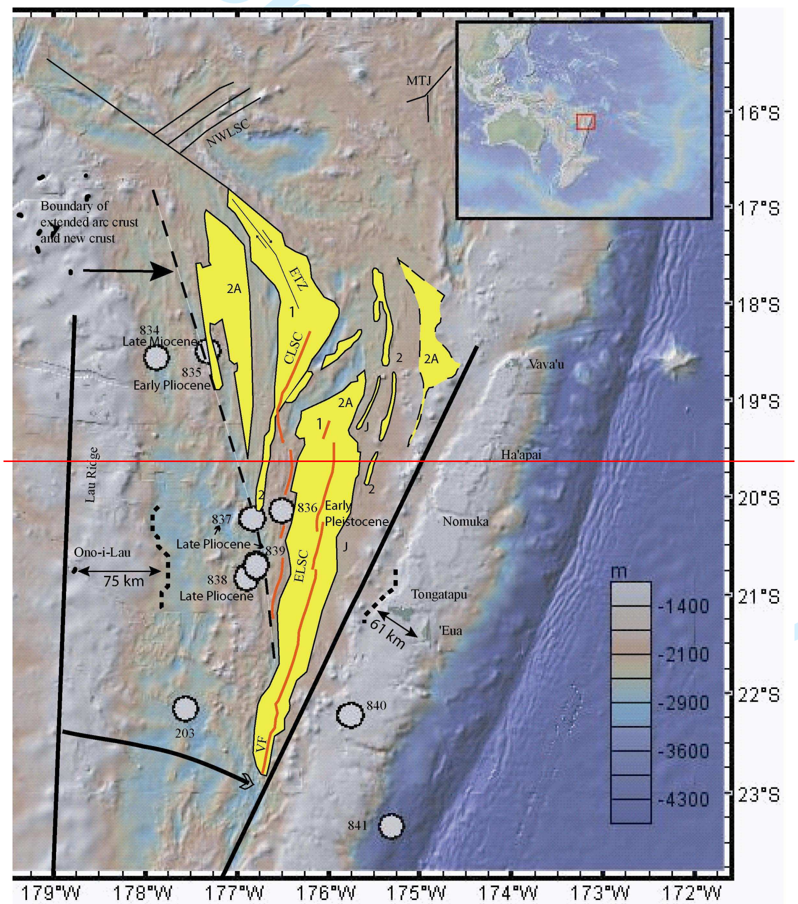
~~A more sophisticated model for Lau Basin formation (Fig. 2–3) replaced a simple mid-oceanic type spreading centre model with a two-phase model (Parson et al. 1994; Parson & Wright 1996; Taylor et al. 1996). The Lau basin floor geology is asymmetric; patterns of strong positive magnetic intensity are exhibited east of a line running NNE across the Lau Basin at roughly 317 degrees, reflecting the new oceanic crust being created at the Central and Eastern Lau spreading centres~~



~~**Figure 2.** Synthesis of data centred on the Lau Basin, after Taylor et al. (1996), with c. 20° easterly rotation of the Tonga Ridge (solid black lines) after Sager et al. (1994), base map from GeoMapApp, http://www.geomapapp.org. Extended legend as follows:~~

~~834 Late Miocene~~	~~ODP site and age at base of well~~
~~Lighter areas (2A)~~	~~Areas where palaeomagnetic data correlates with known age ranges, none older than the Gauss isochron (<3.3 Ma)~~

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1, 2, 2A	Subdivisions of isochrons
J	Jaramillo isochron
CLSC/ELSC	Central Lau Spreading Centre/East Lau Spreading Centre
ETZ/NWSLC/MTJ	Extensional Transform Zone/ NW Lau Spreading Centre/Mangatolo Triple Junction
Dashed line	West of this line, is the "extended ancestral arc crust"
Dotted line	Eastern edge of Lau Ridge/western edge of Tonga Ridge

However west of that line and east of the 2000 meter isobath on the Lau Ridge, an irregular terrain of north-trending horst/grabens occurs where specific magnetization events were not well delineated, attributed to diffuse spreading to form "extended arc crust" (Fig. 3).

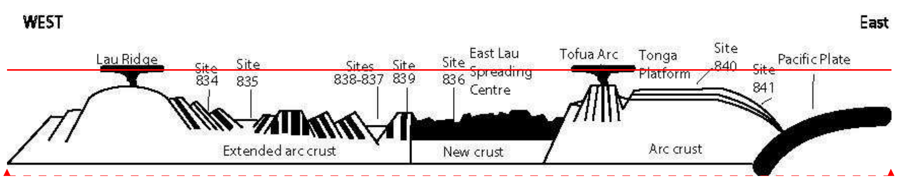


Figure 3. Schematic section of the Lau Ridge, Lau Basin and Tonga Ridge with ODP sites, at c. 1.5–1.0 Ma, after Clift et al. (1995), modified to reflect the work of Parson and Wright (1996).

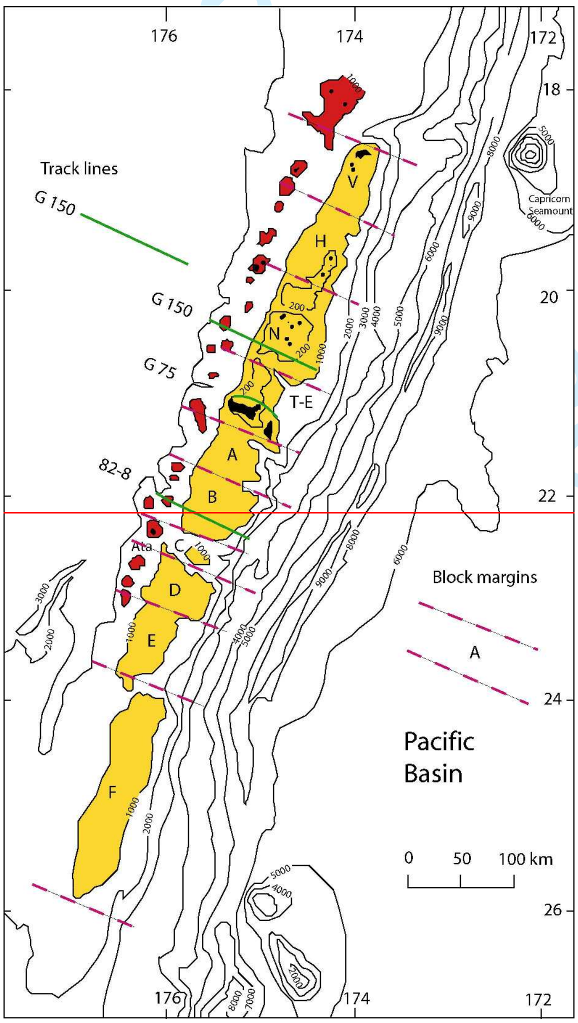
In broad terms, the ancestral Lau/Tonga Ridge arc crust split and experienced extension to the east of the active arc volcanoes on the remnant Lau Ridge by:

- graben/half-graben faulting accompanied by intrusive activity which mark the location of repeated "failed" spreading centres (creating the "extended arc crust"), before:
- formation of new crust occurred continuously at more typical mid-ocean ridge type spreading centres (the Central Lau Spreading Centre/East Lau Spreading Centre (Fig. 2), which were initiated in the north of the Lau Basin and propagated southwards.

During these processes, Lau Ridge and intra-basin volcanism occurred and eventually ceased, before restoration of back-arc volcanism on the currently active Tofua Arc (Fig. 3–4). The net effect is that of an apparent rotation of the Tonga Ridge, the current active arc, some 20^{0} clockwise, away from the remnant Lau Ridge segment of the ancestral arc.

The Tonga Ridge and the remnant Lau Ridge

More is known of the Tonga Ridge (Fig. 1B) than the remnant Lau Ridge. Oil industry activity, including 5 exploration wells on Tongatapu, proved that a deep basin of sediment overlays a presumed volcanic arc basement on the north-central part of the Tonga Platform (Cunningham ~~and~~ & Anscombe 1985). Scientific cruises (Scholl ~~and~~ & Vallier 1985, Stevenson et al. 1994) confirmed this frontal arc basin extended south and established that the present Tonga Ridge is broken into a number of fault-delineated blocks (Fig. 1B~~4~~).



~~**Figure 4.** The Tonga Ridge platform, highlighted by the 1000 meter isobath, with the currently active back-arc Tofua volcanic chain, with block margins and selected track lines, after Tappin et al. (1994), Scholl and Vallier (1985), Austin et al. (1989), Lehner et al. (1983).~~

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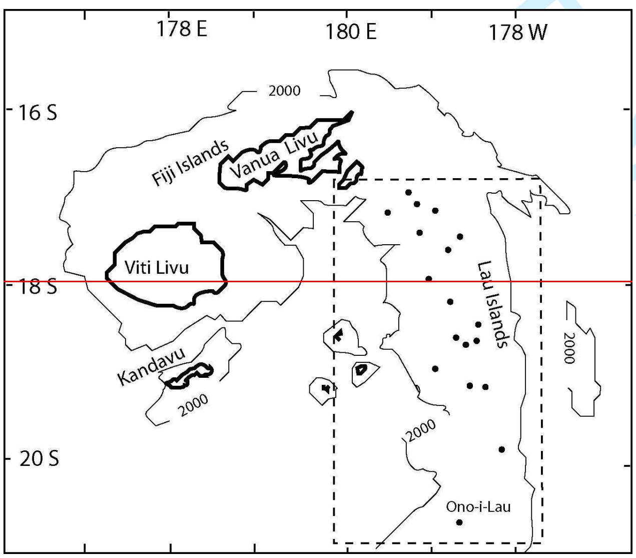
~~Supplementary Information A published online provides a more detailed overview of the seismostratigraphic features and interpreted history of the Tonga Ridge frontal arc basin.~~ On the southern platform, depocentres are identifiable on the west of the basin on isopach A–B (which includes the Miocene), with the sediments thickening generally towards the west. Herzer & Exon (1985) suspected that their alignment along the west side of the basin indicated these sediment "thicks" were fed from volcanic centeres "nearby to the west, outside the mapped area".

The Lau Ridge bathymetry is very similar to the Tonga Ridge, broadly outlined by the 2000 meter contour (Fig. -1A~~5 and Supplementary Information B~~), but many more islands with a dominantly volcanic aspect dominate the geology (Woodhall 1985). Basement rocks are not exposed in the islands, the oldest rocks exposed being Middle Miocene, but volcanism extended from 14.0 to <2.5 Ma, so older geology would have been obscured on volcanic islands.



~~**Figure 5.** Fiji and the Lau islands, after Cole et al. (1985), bathymetric contour interval 2000 meters. The inset box outlines the Lau Islands whose geology was reported by Woodhall (1985), the most southerly of which is Ono-i-Lau.~~

Thus the many Lau Islands which have a long-lived volcanic history provide credible candidates for the volcanic centeres "nearby to the west, outside the mapped area" of Herzer & Exon (1985). The island arc andesite character of the Lau Volcanic group

(14.0–6.0 Ma) and the age range which includes the Middle Miocene, the age of the mafic volcaniclastics on ‘Eua, supports the case. In order to provide a working model for the sourcing of the accretionary lapilli found on the Tonga Ridge, it is now necessary to constrain possible source locations prior to ~~T~~the ~~Tonga Ridge segment~~ partition of the ancestral Lau-Tonga Ridge and then consider how the active tectonics in the region may have re-positioned source or settlement site.~~, hosting a deep sedimentary basin of dominantly volcaniclastic sediment, fed from volcanoes on the remnant Lau Ridge pre-splitting, provides a working model for sourcing of the accretionary lapilli found on the Tonga Ridge.~~

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The accretionary lapilli and the location of possible volcanic sources

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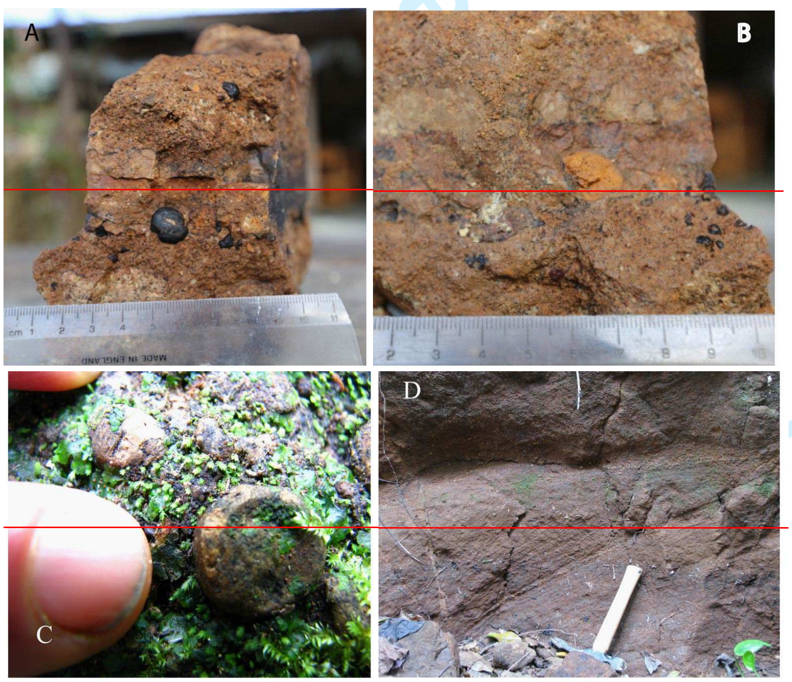

~~**Figure 6.** **A**, 'Eua: Mn-coated accretionary lapillus. **B**, 'Eua: rare large lithic clast (14 mm) in host volcaniclastics. **C**, 'Eua: rimmed accretionary lapillus. **D**, 'Eua, rare cross-bed in host volcaniclastics. Ruler scale is cm/mm.~~

The r~~The r~~eported occurrences of accretionary lapilli on the Tonga Ridge are from Miocene ~~marine~~ volcaniclastics on 'Eua and on ~~from~~ two islands in the Nomuka group

(Fig. 1B). -The 'Eua occurrences (Fig. 2A–C) range up to 20 mm in maximum dimension and typically occur unsorted in grain to grain contact as thin beds up to 20 cm in thickness. The matrix is coarse-grained (>500 µm) or absent. The 'Eua occurrences exhibit characteristics suggesting they settled to pelagic depths (Ballance et al. 2004; Cunningham & Beard 2014) while some of the Nomuka occurrences may have been reworked from the original settlement site (Ballance et al. 2004). The 'Eua host volcaniclastics are typically granulestone/sandstone in grain size, with occasional larger clast sizes, none in excess of 320 mm, and a pelagic planktonic foraminiferal fauna. The fauna are dated at Middle Miocene, c. 14 Ma, with sparse re-worked slightly earlier fauna (Quinterno 1985; Chaproniere 1994), indicating depths of deposition are not less than 1600 meters. A range of sediment gravity flow types (Ballance et al. 2004) are reflected in the host formation, with rare westwards-dippinghading cross-beds (Fig. 26D). Tappin & Ballance (1994) reported a WNW vergingverging flame structure. In contrast, the 'Eua beds of accretionary lapilli exhibit a narrow size distribution in that they are large, typically 10-15 mm in diameter, and the matrix is fines-depleted or absent. These features are applied to terminal velocity calculations by Cunningham & Beard (2014) to argue that these beds were the result of settling to pelagic depths and were not delivered by sediment gravity flows or submarine pyroclastic flows. The upper size constraint of volcanogenic clasts in the 'Eua volcaniclastics contrasts with the Nomuka host rocks; on Mango in the Nomuka group of islands, Middle (?) Miocene volcaniclastics contain indications of the proximity of volcanic edifices, such as volcanic boulder-bearing debris flow deposits (Ballance et al. 2004). Dectecting the Further south on the T–E block, the detection of volcanic sources is assisted by the availability of close-spaced oil industry data (Gatliff et al. 1994). With the high rates of sediment supply implicit in island arc environments, the problem of distinguishing reef structures from buried volcanic edifices is important and has been reviewed (Alexander 1985; Herzer & Exon 1985; Pflueger & Havard 1994; Tappin et al. 1994). Only one volcanic edifice was detected along the Tonga Ridge, in the B–C Late Oligocene to Early Miocene interval and on Block D. No ambiguous structures at all were identified on the T–E block within the interval which includes the Middle Miocene (Gatliff et al. 1994) and “No volcanic structures sourcing unit A–B have yet been identified on the Tonga Ridge” (Tappin et al. 1994). In contrast, some of the host volcaniclastics in the Nomuka group contain evidence of shallow water/proximal volcanic activity, including boulder-sized volcanic clasts. However tThus the seismostratigraphy reveals no obvious

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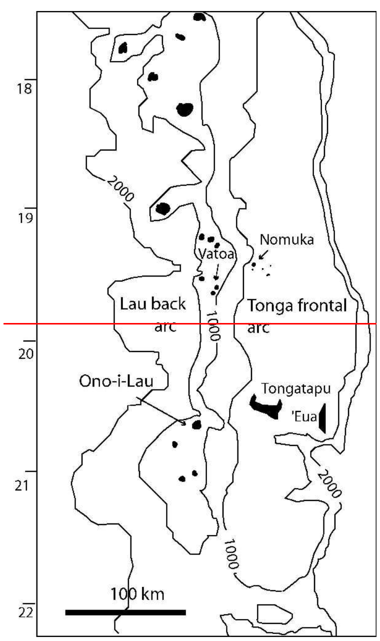
local source on the Tonga Ridge for the accretionary lapilli, either for the Nomuka group or the 'Eua occurrences.

The regional setting suggests that sources would be to the west and on the remnant Lau Ridge, where long-lived volcanic islands exist. ~~The present 1000 meter contour on the Lau Ridge marks commencement of descent to the Lau Basin floor. On the Tonga Ridge, the present 1000 meter contour on the western flank marks commencement of the steep descent to the Tofua Basin floor and steep faults hading westwards appear on most of the seismic lines which cross this contour.~~

~~Using these present sea-bed depth contours at 1000 and 2000 meters to estimate the width of the ancestral arc elements, an outline reconstruction (Fig. 7) is achieved by rotating the Tonga Ridge in the horizontal plane back to the west by the c. 20^0 estimated by Sager et al. (1994).~~



~~**Figure 7.** Outline reconstruction of the ancestral Lau/Tonga ridge, pre-Lau Basin formation, just after splitting commenced.~~

~~In the reconstruction, Ono-i-Lau is closest to 'Eua and Vatoa close to most of the Nomuka group islands. If the gap between the subjacent 1000 meter contours is closed,~~

a potential Lau Ridge source for the ‘Eua Middle Miocene volcaniclastics, located in the region of Ono-i-Lau, would be at a distance of perhaps a little over 90 km from ‘Eua. Even with the high margin of error implicit in the reconstruction, 'Eua appears to be at a considerable distance from a Lau island source. This ignores crustal extension of the ancestral arc elements since the Lau Basin opening, but the Tonga Ridge seismostratigraphy suggests little post-Miocene fault movement on ridge-parallel faults. In contrast, the Nomuka group islands, being on the western edge of the Tonga Ridge, are much closer to the Lau Ridge islands. On Mango in the Nomuka group of islands, Middle (?) Miocene volcaniclastics contain indications of the proximity of volcanic edifices, such as volcanic boulder-bearing debris flow deposits (Ballance et al. 2004). The possibility of the 'Eua source being much nearer, in the western Lau Basin extended arc crust (Fig. 2) or even on the Tonga Ridge itself must be considered. However, evidence of a proximal source in the ancestral Lau-Tonga Ridge segments of the extended arc crust of the western Lau Basin is not available; the ODP sites in the western Lau Basin encountered dates no earlier than Late Miocene at Site 834 and hence possible volcanic edifices, even if identifiable, cannot be dated. In contrast, the data along the Tonga Ridge is rich, and in particular on the T–E block where close-spaced oil industry data is available (Gatliff et al. 1994). With the high rates of sediment supply implicit in island arc environments, the problem of distinguishing reef structures from buried volcanic edifices is important and has been reviewed (Alexander 1985; Herzer & Exon 1985; Pflueger & Havard 1994; Tappin et al. 1994). Only one volcanic edifice was detected along the Tonga Ridge, in the B–C Late Oligocene to Early Miocene interval and on Block D. No ambiguous structures at all were identified on the T–E block within the interval which includes the Middle Miocene (Gatliff et al. 1994). The seismostratigraphy provides sparse vestigial evidence for a Miocene source actually on the Tonga Ridge segment of the ancestral arc; the east-dipping clinoform reflectors within the A–B Middle to Late Miocene interval further south on Block D (see Supplementary Information A) could be interpreted as a volcanic flank structure. But earlier workers would disagree; “No volcanic structures sourcing unit A–B have yet been identified on the Tonga Ridge” (Tappin et al. 1994).

Constraining distance from source for the 'Eua occurrences.

With no compelling evidence to support a source on the Tonga Ridge, 'Eua appears to be at a considerable distance from a source which must have existed further to the west on the ancestral Lau-Tonga ridge. The geological record often preserves only vestigial remnants of any source volcanic edifice. The difficulties of locating the source of tephra for non-historic volcanic events are increased by the high impact of tectonism in this area of the Pacific. However, by using the seismostratigraphic record, we can at least constrain the minimum distance from source of the 'Eua tephra by summing the ancestral arc segments.

The Tonga segment

On Block T–E, the distance between the western edge of the Tonga Ridge and 'Eua, where it thins against the proto-'Eua submergent high is c. 61 km (Fig. 2), before correction for extension due to post-Middle Miocene faulting. Post-Middle Miocene sub-vertical fault patterns on the Tonga Ridge segment do not suggest this will be material, when compared with pre-Middle Miocene graben/half graben faulting which may be listric at depth. However the threat of underestimation of extension due to unidentified small faults (Twiss & Moores 2007), supports the application of a non-trivial provision, say β = 1.1, which would bring the 61 km estimate down to c. 55 km pre-fault extension. The Tonga frontal arc basin segment terminates abruptly on the west with down-to-Tofua faulting (Supplementary Information A). The footprint of any volcanic source on the remnant Lau Ridge segment requires estimation. The profile of the currently active Tofua arc volcanoes provide possible analogues of Lau Ridge volcanic sources. At base, these range up to c. 30 km in width, excluding composite structures which are wider (Chase 1985, Fig. 1). On this basis, 55 plus 15 km = 70 km is indicative of the minimum distance from a source on the eastern edge of the remnant Lau Ridge segment.

The remnant Lau segment

If the source volcano was originally in what is now the extended arc crust of the western Lau Basin and not in the position of Ono-i-Lau on the Lau Ridge (Fig 2), this component could be as low as the 15 km estimate for the source edifice already made above. A much higher figure is required however if a structure in the position of Ono-i-Lau is considered. In the Lau Basin at the longitude under study c.105 km of extended arc crust exists and the distance from Ono-i-Lau to the eastern edge of the Lau Ridge is 75 km (Fig. 2). However a significant number of detectable faults exist on the Lau Ridge (Woodhall 1985) and in the Lau Basin extended arc crust. Adjustment for crustal extension is therefore again required. Faults may be listric at depth and Parson and

Wright (1996) consider arguments for a $\beta = 3$. Applying $\beta = 3$ to the total extended arc and Lau Ridge crust, 60 km remains as the minimal distance from source of the remnant Lau segment.

Combining the two ancestral components on a Ono-i-Lau source scenario provides a minimum 60 km for the Lau Ridge and the extended arc "slivers" in the Lau Basin, plus a post-Middle Miocene extension-adjusted 55 km for the Tonga Ridge segment to give a total of 115 km, which is in range of the estimate of 90 km made on the basis of the outline reconstruction (Fig.7). A minimum of 70 km in total is provided by the scenario where the edifice was close to the eastern edge of the Lau Ridge segment.

Tectonics

The study area of the SW Pacific is a tectonic province with a relatively well-documented geological history, particularly with respect to back-arc extension/basin formation processes (Packham 1978; Tappin 1993; Sager et al. 1994; Tappin et al. 1994; Parson and Wright 1996; Taylor et al. 1996). In the south of the region, on the Tonga-Kermadec-Hikurangi trend, subducting oceanic plate encounters continental crust on South Island, New Zealand (Lamb 2011). Further north, the environment is oceanic. A more sophisticated model for Lau Basin formation (Figs. 3A, 3C) replaced a simple mid-oceanic type spreading centre model with a two-phase model (Parson et al. 1994; Parson & Wright 1996; Taylor et al. 1996). The Lau basin floor geology is asymmetric; patterns of strong positive magnetic intensity are exhibited east of a line running NNW across the Lau Basin at roughly 317^0, reflecting the new oceanic crust being created at the Central and Eastern Lau spreading centres. However, west of that line and east of the 2000 meter isobath on the Lau Ridge, an irregular terrain of north-trending horst/grabens occurs where specific magnetization events were not well delineated, attributed to diffuse spreading to form “extended arc crust”. In broad terms, the ancestral Lau/Tonga Ridge arc crust split and experienced extension to the east of the active arc volcanoes on the remnant Lau Ridge by:

- graben/half-graben faulting accompanied by intrusive activity which mark the location of repeated “failed” spreading centres (creating the “extended arc crust”), before:
- formation of new crust occurred continuously at more typical mid-ocean ridge type spreading centres (the Central Lau Spreading Centre/East Lau Spreading Centre , which were initiated in the north of the Lau Basin and propagated southwards.

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During these processes, Lau Ridge and intra-basin volcanism occurred and eventually ceased, before restoration of back-arc volcanism on the currently active Tofua Arc. The net effect is that of an apparent rotation of the Tonga Ridge, the current active arc, some 20^0 clockwise, away from the remnant Lau Ridge segment of the ancestral arc. With no compelling evidence to support a source on the Tonga Ridge, 'Eua appears to be at a considerable distance from a source which must have existed further to the west on the ancestral Lau-Tonga ridge. Using present sea-bed depth contours at 1000 and 2000 meters to estimate the width of the ancestral arc elements, an outline reconstruction (Fig. 3B) is achieved by rotating the Tonga Ridge in the horizontal plane back to the west by the c. 20^0 estimated by Sager et al. (1994). On Block T–E, the distance between the western edge of the Tonga Ridge and 'Eua, where it thins against the proto-‘Eua submergent high is c. 61 km (Fig. 3A), before correction for extension due to post-Middle Miocene faulting. Post-Middle Miocene sub-vertical fault patterns on the Tonga Ridge segment do not suggest this will be material, when compared with pre-Middle Miocene graben/half graben faulting which may be listric at depth. However, the threat of underestimation of extension due to unidentified small faults (Twiss & Moores 2007), supports the application of a non-trivial provision, say 10%, which would bring the 61 km estimate down to c. 55 km pre-fault extension. The Tonga frontal arc basin segment terminates abruptly on the west with down-to-Tofua faulting (Herzer & Exon 1985). The footprint of any volcanic source on the remnant Lau Ridge segment requires estimation. The profile of the currently active Tofua arc volcanoes provide possible analogues of Lau Ridge volcanic sources. At base, these range up to c. 30 km in width, excluding composite structures which are wider (Chase 1985, Fig. 1). On this basis, 55 plus 15 km = 70 km is indicative of the minimum distance from a source on the eastern edge of the remnant Lau Ridge segment. If the source volcano was originally in what is now the extended arc crust of the western Lau Basin, this figure is increased, but no data is available from the ODP sites in the Lau Basin to constrain this possibility, as none of these reached the Middle Miocene (Fig. 3A). A much higher figure is required if a structure in the position of Ono-i-Lau is considered. In the Lau Basin at the longitude under study, c.105 km of extended arc crust exists and the distance from Ono-i-Lau to the eastern edge of the Lau Ridge is 75 km.

The more local effects of individual block rotation are now considered. During re-processing of oil industry data on the T–E Block, it was noted that a number of physiographic features of the block would be explained if it had rotated 30^0

anticlockwise (Gatliff et al. 1994). One feature is the atypical triangular shape of the Tongatapu-‘Eua block as a whole (Fig. 1B), as reflected at the 1000 m isobath. ‘Eua is closer to the eastern margin of the frontal arc basin than any other basement high, and as an emergent island with an elevation of 912 meters, is much higher. To further explore whether there is seismostratigraphic/geophysical support for the rotation proposition, a number of sources of data were superimposed on Blocks A, B and T–E (Fig. 4). There are clearly a number of departures from the Tonga Ridge NNE-SSW ridge-parallel structural trend, localised to the southern margin of Block T–E. On Block T–E, a trend in total magnetic intensity highs, broadly coincident with basement highs (Gatliff et al. 1994) departs from trend and is deflected east of ‘Eua. Further south, on Blocks A and B, a trend of magnetic intensity anomalies (Stevenson & Childs 1985), coincident with ridge-parallel gravity/basement highs, is abruptly curtailed as the southern margin of the T–E block is encountered. The 'Eua Channel Fault, a major structural feature on the southern Tonga Ridge, disappears north of the Block T–E southern margin, where the Tongatapu/‘Eua Channel depocentre was identified (Herzer and Exon 1985, Gatliff et al. 1994).

The three total magnetic intensity highs immediately east of ‘Eua on the Tongatapu-‘Eua block appear to be displaced by a strike-slip fault c. 40 km to the east of the trend of the magnetic intensity anomalies on Blocks A and B. This would have the effect of anticlockwise rotation *sensu* Gatliff et al. (1994). Further south on the Tonga-Kermadec-Hikurangi trend, Lamb (2011) reviews the tectonics and kinetics of faulting in the leading Australian plate continental crust, which accommodates the effects of non-orthogonal subduction. The distinctive faulting styles described include those which could explain features on the T–E block (Cunningham & Anscombe 1985, Fig. 2) by inverting the rotation effect of strike slip faulting on arcuate faults (Lamb 2011, Fig. 18 a), combined with dextral strike slip faulting on a curved strike slip fault “hinge” (Lamb 2011, Fig. 18 f). Block rotation may be contemporaneous with or post-date block formation. Block formation by ridge-traverse faults may have begun “long before the block geometry became so prominent after Late Miocene time” (Scholl & Herzer 1994). Since the western margin of the T–E block has a down-to-Tofua NNE-SSW fault pattern consistent with the other blocks, any rotation, as noted by Gatliff et al. (1994), must have occurred before the ancestral Lau Tonga arc splitting commenced in the late Late Miocene (5.3 Ma). An event at c. 10 Ma was detected by sediment backstripping analysis on the Tonga Ridge at ODP 841 (Clift et al. 1994) and hence in the early Late

Miocene. We now propose a model by which block rotation may have contributed towards the dispersal distance anomaly. The model crucially suggests that, pre-ancestral Lau-Tonga Ridge splitting, a Middle Miocene volcano on what would become subjacent Block A sourced the 'Eua accretionary lapilli found on what would become Block T–E. Anticlockwise block rotation after deposition, but before Lau Basin opening commenced in the late Late Miocene, affects Block T–E, but not A or N. After rotation of this block, the Nomuka Group islands maintain their distance from source volcano, but 'Eua has been displaced tectonically 40 km eastwards from the tephra source. The distance between source and resting place for the accretionary lapilli has been increased by 40 km even before ridge splitting in the latest Late Miocene carries 'Eua further east.

Constraining dispersal distances for accretionary lapilli

The evidence for final deposition of the 'Eua accretionary lapilli by settling through a marine column of not less than 1600 meters, as presented in Cunningham & Beard (2014), has been summarised earlier. The processes by which they could have reached the point of settlement will now be reviewed. The present Tofua active volcanic arc (Fig. 1B) is composed of emergent, barely emergent and submarine volcanic edifices at modest depths and may be a good proxy for the Middle Miocene ancestral active volcanic arc, given the dominantly volcanic insular geology as described earlier for the remnant Lau Ridge. The ash clouds within which ash aggregates form (Brown et al. 2012) are typically associated with subaerial explosive volcanic eruptions, although shallow marine eruptions can also be contenders if they breach water depths (McBirney 1963; Wright & Gamble 1999; White et al. 2003) with the creation of an atmospheric ash cloud. The 'Eua accretionary lapilli may therefore have formed during an explosive volcanic eruption initiated subaerially from an emergent volcanic edifice or at shallow depths. In addition, proximity of the ocean surface permits the possibility of formation of accretionary lapilli in secondary ash-rich steam clouds as pyroclastic density currents enter the sea (Dufek et al. 2007). Dispersal may take place subaerially within the eruption plume/umbrella cloud or as pyroclastic density currents travel across the sea surface (Allen & Cas 2001; Carey et al. 1996; Maeno & Taniguchi 2007). The 'Eua accretionary lapilli contain examples typically 10–15 mm in diameter and are accretionary lapilli *sensu stricto* (Brown et al. 2010, Van Eaton & Wilson 2013), as distinguished from less ordered ash pellets and fragile ash aggregates (Brazier et al.1982; Carey & Sigurdsson 1982; Wiesner et al.1995; Brown et al. 2012) which rarely

Formatted: Pattern: Clear (White), Tab stops: 2", Left survive in that form but are detected in sieve analysis of grain size. The substantial distances by which -less-ordered ash aggregates can be dispersed from source subaerially are well established; ash aggregates dispersed in the eruption plume at Mt St Helens were detected at 200 km from source (Carey & Sigurdsson 1982). In contrast, the dispersal of relatively large and dense accretionary lapilli within the eruption plume must be restricted by their significant mass to more modest dispersal distances from the source volcano, distances for accretionary lapilli *sensu stricto* of "a few to a few tens of km" of Smellie (1984) accord with the intuition that dispersal of relatively large spheroidal accretionary lapilli through the atmosphere must be restricted by their significant mass to modest dispersal distances from the source volcano. as constrained in tephra dispersal models (Walker et al. 1971; Walker 1981; Carey & Sparks 1986; Pfeiffer et al. 2005; Folch 2012). Accretionary lapilli are technically lapilli, falling within the 2–64 mm range, (Schmid Accretionary lapilli are technically lapilli, falling within the 2–64 mm range of Schmid (1981; Fisher & Schmincke 1984) and "larger centrimetric and millimetric fragments typically settle in minutes to a few hours at distances of the order of tens of km from the volcano" (Folch 2012). . Lapilli-sized tephra can be dense juvenile/country rock clasts, mafic scoria or vesicular silicic pumice clasts. Reported specific gravities of accretionary lapilli, which are dominantly silicic, are in the range of 1200–1500 kg m^{-3} (Sparks et al. 1997). The 'Eua examples are mafic in composition and should therefore be at the upper end of this spectrum or slightly exceed it. Isopleths for 16 mm-sized lapilli for known eruptions show maximum dispersal distance in the range of 20–30 km (Carey & Sparks 1986), for tephra at density of 2500 kg m^{-3},and "larger centrimetric and millimetric fragments typically settle in minutes to few hours at distances of the order of tens of km from the volcano" (Folch 2012). Grain size directly influences terminal velocity of descent of a particle. This varies significantly with height in the atmosphere and departure from sphericity (Dellino et al. 2005). These parameters are accommodated in most tephra transport and dispersal models. Table 1 provides indicative terminal velocities over a range of heights (Pfeiffer et al. 2005) for particles of Φ = -4 (=16 mm), density of 1500 kg m^{-3}, and departure from sphericity. These particles are close to the typical size of the 'Eua accretionary lapilli. The density of 1500 kg m^{-3} is appropriate, as discussed earlier (advanced palagonitisation obscures the original density of the constituent glass particles). These figures would underestimate terminal velocity for the notably spheroidal 'Eua accretionary lapilli. The range of contemporary prevailing wind speeds

Formatted: Not Superscript/ Subscript in the Lesser Antilles range from 5.55 m sec^{-1} in the stratosphere and up to 25 m sec^{-1} in the upper troposphere (Sigurdsson et al.1980). Based on input of the 16 mm clast isopleth for Cotopaxi layer 3, Burden et al. (2011) estimate plume height between 26 km and 32.5 km with a wind speed of 35 m sec^{-1}. If these wind speeds were applicable to the SW Pacific in the Middle Miocene, the effects of wind advection should be modest for tephra the size of the 'Eua accretionary lapilli. Complexity is introduced by the formation of aggregates during plume development, whether in the form of accretionary lapilli or less-ordered ash aggregates, as this is complex to model (Costa et al. 2010); accretionary lapilli often occur in phreatomagmatic eruptions, where phase changes involving latent heat release might increment the upwards convection vector and counter the dominant role, in most models, of the downward terminal ("settling") velocity of descent. Modelling of the phreatomagmatic 25.4 ka Oruanui event (Van Eaton et al. 2012), an ultra-Plinian event, instead of a simple plume/high level umbrella cloud with lower level co-ignimbrite ash clouds, produced "hybrid" ash clouds generated both from the plume and from buoyant co-ignimbrite ash clouds which rise to plume heights. Concentrically layered accretionary lapilli similar to those in 'Eua were dispersed at distances of 120 km from source (Van Eaton & Wilson 2013) in this event. The 25.4 ka Oruanui event is statistically unusual; only 156 (2.3 %) such events are reported from a total of 6736 in the Smithsonian Institute database (Siebert and Simkin 2002–2014). Occurrences from more modest events are reported from dispersal within the Soufriere St Vincent plume at 36 km from source (Brazier et al. 1982) and dispersed within pyroclastic density currents at Mt St Helens at c. 25 km (Fisher et al. 1987), and these are closer to ash pellets as defined (Brown et al 2010; Van Eaton & Wilson 2013), rather than accretionary lapilli. ~~The occurrence of layered accretionary lapilli at 'Eua type are the same type as those dispersed at distances of 120 km from the 26.5 ka ultra-Plinian Oruanui event (Van Eaton & Wilson 2013), are atypical under this view. In contrast, occurrences associated with Soufriere St Vincent at 36 km from source (Brazier et al. 1982) and with Mt St Helens at c. 25 km (Fisher et al. 1987) are potential members of the typical "a few to a few tens of km" class, but these are closer to ash pellets as defined, rather than accretionary lapilli.~~

~~The present Tofua active volcanic arc (Fig. 4) is composed of emergent, barely emergent and submarine volcanic edifices at modest depths and may be a good proxy for the Middle Miocene ancestral active volcanic arc, given the dominantly volcanic insular geology as described earlier for the remnant Lau Ridge. Accretionary lapilli~~

normally form within atmospheric ash clouds associated with subaerial explosive volcanic eruptions (Brown et al. 2012), although shallow marine eruptions can also be contenders if they breach water depths (McBirney 1963; Wright & Gamble 1999; White et al. 2003) with the creation of an atmospheric ash cloud. The 'Eua accretionary lapilli may therefore have formed during an explosive volcanic eruption initiated subaerially from an emergent volcanic edifice or at shallow depths. In addition, proximity of the ocean surface permits the possibility of formation of accretionary lapilli in secondary ash-rich steam clouds as pyroclastic density currents enter the sea (Dufek et al. 2007). Dispersal may therefore occur subaerially by expansion of the eruption plume, spreading of any associated atmospheric umbrella cloud, and/or by associated pyroclastic density currents, but these would rapidly encounter the sea. There is no evidence for dispersal within submarine sediment gravity flows within the 'Eua accretionary lapilli occurrences (Cunningham & Beard 2014); they appear to have settled vertically under gravity. However, for accretionary lapilli dispersed within pyroclastic density currents, sSurface dispersal over the ocean surface is now must be considered. Pyroclastic density currents can partition into a coarse, dense-clast rich submarine flow and a dilute pyroclastic surface flow -running at the surface on entering the sea, as seen with experiments and simulations referred to observed/inferred events and their deposits (Freundt 2003; Trofimovs et al. 2006; ,Dufek & Bergantz 2007;, Trofimovs et al. 2006, Trofimovs et al. 2008;, Dufek et al. 2009). Such surface flows have travelled for considerable distances (Allen & Cas 2001, Carey et al. 1996, Maeno & Tanaguchi 2007) and carrying bombs and lapilli-sized clasts, in addition to ash and hot gas. Observations of the deposits of the Kos Plateau Tuff (Allen & Cas 2001) supported this model, with the loss of the coarsest vent and conduit-derived lithic clasts over the sea due to sinking, while over land, saltation was considered to have preserved the coarser element in the resulting ignimbrites. Saltation may also occur over water and be accentuated by the occurrence of pumice rafts (Fiske et al. 2001) while, conversely, transport capacity will be influenced by areal dilution, as momentum transfer between large and small particles is diminished (Dufek & Bergantz 2007; Dufek et al. 2009). Such surface flows have travelled for considerable distances (Table 2), carrying bomb and lapilli-sized clasts, in addition to ash and hot gas. Pyroclastic flows are more common in silicic eruptions where juvenile volatiles are present, while those associated with basaltic eruptions chiefly arise from phreatomagmatic activity (Yamamoto et al.

2005). The 'Eua tephra is heavily palagonitised, and surviving crystal mineralogy suggests a basaltic andesite composition for the source (Cunningham and Beard 2014).

Insights from tephra dispersal models for explosive volcanic eruptions

Lapilli-sized tephra can be dense juvenile/country rock clasts, mafic scoria or vesicular silicic pumice clasts. Reported specific gravities of accretionary lapilli, which are dominantly silicic, are in the range of 1200–1500 kg m^{-3} (Sparks et al. 1997). The 'Eua examples are mafic in composition and should therefore be at the upper end of this spectrum or slightly exceed it. Tephra dispersal models could provide some insights for dispersal of equivalently-sized/dense accretionary lapilli. Isopleths for 16 mm-sized lapilli for known eruptions show maximum dispersal distance in the range of 20–30 km (Carey & Sparks 1986), for tephra at density of 2500 kg m^{-3}. Such work constrained dispersal within the plume (where the buoyant upwards vector and a downward terminal velocity vector act on ash/tephra to form clast support envelopes, outside of which particles descend vertically), and a lateral vector within the spreading umbrella cloud in a wind-free environment, with any wind advection force further modifying dispersal patterns. A full range of tephra dispersal models is now available (Folch 2012). However not only must the source be modelled and the atmosphere into which the sourced particles are introduced but also, critically for this paper, a transport model incorporated which can accommodate transformations during transport. Costa et al. (2010) noted that "a complete description of ash aggregation in volcanic clouds is a very arduous task and the full coupling of ash ***transport*** (our italics) and ash ***aggregation*** models (our italics) is still computationally prohibitive". Accretionary lapilli and lapilli fundamentally differ in locus of formation; lapilli *sensu stricto* exist at eruption inception, while the transformation represented by the formation of aggregates, whether in the form of accretionary lapilli or the less-ordered ash aggregates referred to earlier, takes place as the eruption cloud develops. Furthermore, early convection-advection models viewed the tephra being dispersed as passive in a dispersal process driven by decompression of magmatic gases. Experimental work has established the key role of vapour, liquid and solid phases of H_2O in the process of formation of accretionary lapilli (Gilbert and Lane 1994, Schumacher and Schmincke 1995, Van Eaton et al. 2012 b). Accretionary lapilli typically occur in phreatomagmatic eruptions, where phase changes involving latent heat release might increment the upwards convection vector and counter the dominant role, in most models, of the downward terminal ("settling") velocity of descent (Pfeiffer et al. 2005, Folch 2012). Hence the initial caution advised in applying such models where wet eruptions are involved (Carey & Sparks 1986). This caution is justified; the ATHAM model, forced with data from the phreatomagmatic 26.5 ka Oruanui event, and run with >= 24% H_2O relative to a MER of 1.1 10^9 kg (Van Eaton et al. 2012 a), instead of a simple plume/high level umbrella cloud with lower level co-ignimbrite ash clouds, produced “hybrid” ash clouds generated both from the plume and by buoyant co-ignimbrite ash clouds which rise to plume heights. This challenges simple distinctions between the plume/umbrella cloud and ash clouds related to pyroclastic density currents, both of which have a potential role in the formation and dispersal of accretionary lapilli.

The 26.5 ka Oruanui event, an ultra-Plinian event, is statistically unusual; only 156 (2.3 %) such events are reported from a total of 6736 in the Smithsonian Institute database (Siebert and Simkin 2002 2014).

Dispersal by pyroclastic density currents travelling over the ocean surface

An experimental approach (Freundt 2003) suggested that, on entering the sea, coarser/denser particles would continue flowing under water, while a dilute ash cloud would flow over the sea surface. Observations of the deposits of the Kos Plateau Tuff (Allen & Cas 2001) supported this model, with the loss of the coarsest vent and conduit-derived lithic clasts over the sea due to sinking, while over land, saltation over the water surface was considered to have preserved the coarser element in the resulting ignimbrites. Saltation may also occur over water and be accentuated by the occurrence of pumice rafts (Fiske et al. 2001) while, conversely, transport capacity will be influenced by dilution, as momentum transfer between large and small particles is diminished (Dufek & Bergantz 2007, Dufek et al. 2009). The actual extent of the contemporary sea surface has been challenged (Pe-Piper et al. 2005) but in the area south of Kos, where dispersal of 39 km and possibly 60 km was reported (Table 1), there is support for the existence of a shallow sea surface (Dufek et al. 2009).

Event	DRE (km^3)	Largest Tephra (mm)	Distance from source (km)	Maximum distance (km)
Krakatoa	12	"small stone"	65	80
Kos Plateau Tuff				
Unit D	10	50	35	>39

Unit E	30	200	35	>60
Koya Tuff	1			>40

In conclusion,

Table 1 Dispersal of larger tephra by pyroclastic density currents travelling over the ocean surface, from Allen & Cas (2001), Carey et al. (1996). DRE = dense rock equivalent. Maximum distance = maximum dispersal distance estimated for the event.

Accretionary lapilli only form when conditions within an ash cloud (whether Plinian or those co-eval with pyroclastic density currents) are favourable and many explosive eruptions do not produce them. No accretionary lapilli have been reported from the Krakatoa 1883 eruption, despite their noted abundance in pyroclastic flow deposits associated with silicic phreatomagmatic activity (Carey et al. 1996). Caution is therefore required; the instances in Table 1 have reported the dispersal of lapilli by pyroclastic density currents over the ocean surface, but not *accretionary* lapilli. The major Krakatoan event delivered lapilli ("small stones") at 65 km and later mud rain over a large area, associated with a climactic increase in magma discharge rate leading to an increase of formation/delivery of pyroclastic flows into and over the sea, rather than a phreatomagmatic phase of eruption initiated at the vent. Instead of magma-water interaction at the vent, a complex, large, co-ignimbrite plume with strong temperature and H_2O gradients is inferred to have been generated during dispersal over land and sea. Increasing distance from source increased the H_2O content but buoyant uplift of the hot core led to cooling and condensation, resulting in distal mud rain. However little evidence was found to support the uptake of seawater in distal flows for the Kos Plateau Tuff (Allen & Cas 2001). Variation in the degree of magma-water interaction at the vent or uptake of H_2O during dispersal may contribute significantly to dispersal distances; the maximum dispersal distance for the Koya Tuff suggests there is no simple relation to the scale of the source eruption, certainly as measured by dense rock equivalent (DRE).

Scaling possible dispersal distances

Other than the size of the accretionary lapilli and knowledge of current wind directions/speeds at elevation, there is no data (e.g. isopleths from which the DRE may be calculated) on the Middle Miocene eruption which supplied the 'Eua accretionary lapilli. Hence no plume modelling of height attained and lateral dispersal within the plume/spreading umbrella cloud is possible, even if the other difficulties discussed

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above could be resolved. Grain size directly influences terminal velocity of descent of a particle. This varies significantly with height in the atmosphere and departure from sphericity (Dellino et al. 2005). These parameters are accommodated in most tephra transport and dispersal models. Table 2 provides indicative terminal velocities over a range of heights (Pfeiffer et al. 2005) for particles of $\Phi = -4$ (=16 mm), density of 1500 kg m^{-3}, and a sphericity measure (F) .

Height (km)	Sea level	10	15	20	26
U_t (m sec^{-1})	17	27	48	50	100

Table 2 Values for U_t , vertical terminal velocity at height, for particles of diameter 16 mm, density of 1500 kg m^{-3} and F (sphericity) = 0.43, from Pfeiffer et al. (2005).

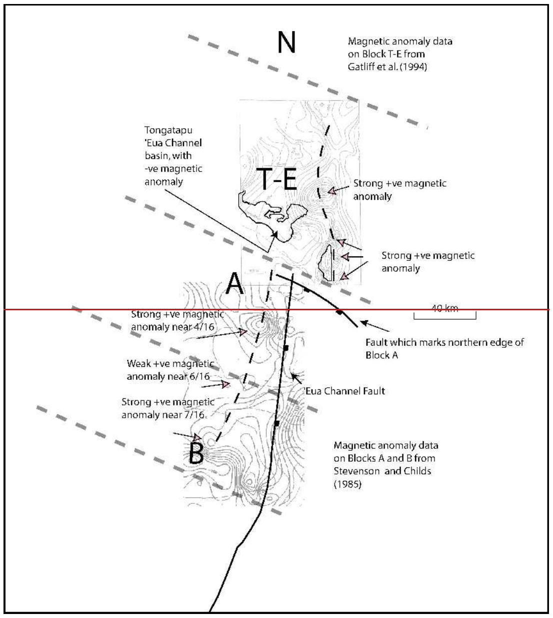
These particles are close to the typical size of the 'Eua accretionary lapilli. The density of 1500 kg m^{-3} is appropriate, as discussed earlier (advanced palagonitisation obscures the original density of the constituent glass particles). These figures would underestimate terminal velocity for the notably spheroidal 'Eua accretionary lapilli. The effect of wind advection can be scaled by reference to these terminal velocity calculations. The range of contemporary prevailing wind speeds in the Lesser Antilles range from 5.55 m sec^{-1} in the stratosphere and up to 25 m sec^{-1} in the upper troposphere (Sigurdsson et al.1980). Based on input of the 16 mm clast isopleth for Cotopaxi layer 3, Burden et al. (2011) estimate plume height between 26 km and 32.5 km with a wind speed of 35 m sec^{-1}. Hence, if these wind speeds are applicable to the SW Pacific, terminal velocity of descent will significantly exceed wind speed. Unless dispersed further laterally in the plume/umbrella cloud, lapilli of significant size (and hence mass) should alight within distances significantly less than the maximum height at which they commence descent. The jetstream could further accentuate dispersal. However 'Eua in the Middle Miocene, pre Lau Basin opening, would still be at c. 20^0 S and hence some

~~distance from the contemporary jetstream path at 30–60^{0} S, where wind speeds are much higher (Bursik et al. 2009).~~

~~F~~for plume/umbrella cloud dispersal within the atmosphere, ~~lateral wind advection should be modest for these particles of significant mass;~~ the "~~few to a few~~ tens of km" metric is supported. ~~intuition seems to have some scientific basis.~~ For pyroclastic density current-enabled dispersal over land, only a statistically unlikely ultra-~~-~~Plinian event is capable of providing dispersal via the atmosphere for the minimum -70 km dispersal scenario, (considering the source was close to the eastern edge of the remnant Lau Ridge segment). In contrast, for pyroclastic density current-enabled dispersal across the ocean surface, there is some evidence that relatively modest magnitude events could provide dispersal distances which contribute significantly to the scenario.~~this figure.~~

~~**Block rotation; the Tongatapu – ‘Eua block**~~

~~During re-processing of oil industry data on the T–E Block, it was noted that a number of physiographic features of the block would be explained if it had rotated 30^{0} anticlockwise (Gatliff et al. 1994). One characteristic is the atypical triangular shape of the Tongatapu–‘Eua block as a whole (Fig. 4), as reflected at the 1000 m isobath. ‘Eua is closer to the eastern margin of the frontal arc basin than any other basement high and as an emergent island with an elevation of 912 meters, is much higher. To further explore whether there is seismostratigraphic/geophysical support for the rotation proposition, a number of sources of data were superimposed on Blocks A, B and T–E (Fig. 8).~~



~~**Figure 8.** Discontinuity of trends across the boundary between tectonic Blocks A, B and T–E.~~

~~There are clearly a number of departures from the Tonga Ridge NNE-SSW ridge-parallel structural trend, localised to the southern margin of Block T–E. The departures are:~~

~~1. On Block T–E, a trend in magnetic intensity anomalies, broadly coincident with gravity/arc basement highs (Gatliff et al. 1994) departs from trend and is deflected east of 'Eua,~~
~~2. Further south, on Blocks A and B, a trend of magnetic intensity anomalies (Stevenson & Childs 1985), coincident with ridge-parallel arc basement highs, is abruptly curtailed as the southern margin of the T–E block is encountered.~~
~~3. The 'Eua Channel Fault, a major structural feature on the southern Tonga Ridge disappears north of the block margin, where a magnetic intensity low centred on Tongatapu/the 'Eua Channel was identified as a sedimentary basin which shallowed to the east and north (Gatliff et al. 1994).~~

The three positive magnetic intensity highs immediately east of ‘Eua on the Tongatapu-‘Eua block appear to be displaced by a strike-slip fault c. 40 km to the east of the trend of the magnetic intensity highs on Blocks A and B. This would have the effect of anticlockwise rotation *sensu* Gatliff et al. (1994). The southern margin of Block T–E is perhaps better considered as a fault zone than localised on one fault. On the T–E block a horst runs NW-SE into Tongatapu (Fig. 9) and this trend is seen onshore on ‘Eua, where faults dominantly trending NW-SE cut the Middle Miocene volcaniclastics and show evidence of lateral movement (Lowe 1987). North of ‘Eua, these trends are restored to ridge-parallel orientation.

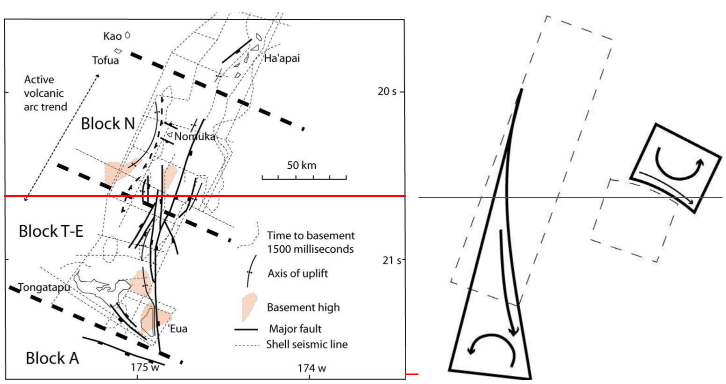


Figure 9. Left: basement trends and faults on Blocks A, T–E and N, after Cunningham & Anscombe (1985). Right: rotation effect of strike-slip faulting on arcuate faults, accommodated by strike-slip faulting on a curved fault “hinge”, after Lamb (2011).

Further south on the Tonga-Kermadec-Hikurangi trend, Lamb (2011) reviews the tectonics and kinetics of block faulting in the leading Australian plate continental crust, which accommodates the effects of non-orthogonal subduction. A number of distinctive block faulting styles are detected, one of which appears to be expressed on the T–E block (Fig. 9) where the anticlockwise rotation effect of sinistral strike slip faulting on arcuate faults is accommodated by dextral strike slip faulting on a curved strike slip fault “hinge”.

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Timing of block formation and rotation

Block rotation may be contemporaneous with or post-date block formation formation. Block formation by ridge-traverse faults may have begun “long before the block

~~geometry became so prominent after Late Miocene time" (Scholl & Herzer 1994 and Supplementary File A). Since the western margin of the T–E block has a down-to-Tofua NNE-SSW fault pattern consistent with the other blocks, any rotation, as noted by Gatliff et al. (1994), must have occurred before the ancestral Lau Tonga arc splitting commenced in the late Late Miocene (5.25 Ma).~~

~~The Tonga Ridge strikes c. N 20^0E. The mean azimuth of slip vectors along the Tonga trench from 35–19^0S ranges from N280^0E' to N285^0E' (Pelletier & Louat 1989). If this applied in the Middle Miocene, prior to the ancestral c. north-trending Lau/Tonga Ridge splitting, non-orthogonal subduction would then have imparted a lateral vector to regional stress patterns, thus providing a similar environment to that associated with block rotation in leading edge continental crust further south on the Tonga-Kermadec-Hikurangi trend. An event at c. 10 Ma was detected by sediment backstripping analysis on the Tonga Ridge at ODP 841 (Clift et al. 1994) and hence in the early Late Miocene. In conclusion, the data provides some support for the provision by block rotation of a right-lateral strike-slip movement of c. 40 km in a fault zone centred on the south of Block T–E and the north of Block A area, after 14 Ma and before splitting of the ancestral Lau/Tonga Ridge commenced in latest Late Miocene. A model is now proposed by which block rotation may have contributed towards the dispersal distance anomaly. The model crucially suggests that , pre-ancestral Lau-Tonga Ridge splitting, a Middle Miocene volcano on what would become subjacent Block A sourced the 'Eua accretionary lapilli found on what would become Block T–E. Anticlockwise block rotation after deposition, but before Lau Basin opening commenced in the late Late Miocene (5.25 Ma), affects Block T–E, but not A or N. After rotation of this block, the Nomuka Group islands maintain their distance from source volcano, but 'Eua has been displaced tectonically 40 km eastwards from the tephra source. The distance between source and resting place for the accretionary lapilli has been increased by 40 km even before ridge splitting in the latest Late Miocene carries 'Eua further east.~~

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Discussion and conclusions

The accretionary lapilli on 'Eua, Tonga, occur in Middle Miocene pelagic volcaniclastic sediments with no ~~compelling~~ evidence for a proximal ~~al~~ volcanic source. A contemporary distance which is unlikely to be less than 70 km, and may be much more, from a source on the Lau segment of the ancestral Lau-Tonga Ridge, is estimated from seismostratigraphic and other data. This ~~distance~~ is much fa~~u~~rther than would be expected for dispersal of these spheroids of significant mass, unless an exceptional ultra-Plinian source is invoked~~. 'Eua is positioned much further from the western edge of the Tonga Ridge than any other island and hence much further from a western Lau-Tonga ancestral arc volcanic source. ~~. Tephra fall associated with ~~A~~an ultra-Plinian event on the scale of the Oruanui at 25.4~~6.5~~ ka (Van Eaton & Wilson 2013) could, *prima facie*, resolve the dispersal distance problem, since the dispersal distances of accretionary lapilli in the atmosphere by the eruption plume and pyroclastic density currents in that event were substantial. ~~; layered accretionary lapilli, the type reported from 'Eua (Cunningham & Beard 2014), with diameters sometimes in excess of 10 mm occur up to 120 km from the virtual source at Lake Taupo.~~ However, ~~-~~ there is no field evidence in the area under study for an ultra-Plinian event in the Middle Miocene. At 530 km^3 DRE, the Oruanui event is exceptional and unit 8, which contains the highly dispersed occurrences, exhibits characteristics which suggest that the eruption produced an extremely high mass eruption rate ($\geq$ ~~>~~10^9 kg s^{-1}), with numerical simulations (Van Eaton et al. 2012~~a~~) implying the potential for transportation of tephra to stratospheric heights. Explosive volcanic events of a much more modest magnitude~~DRE~~, but driving pyroclastic density currents over the ocean surface, have dispersed tephra to considerable distances (Table 2~~1~~), with ~~"small stones"~~larger tephra being carried as far as 65 km. The ~~The transportation of large vent- and conduit-derived clasts (with densities as high as 2500 kg m^{-3}) during transport of the Kos Plateau Tuff across the ocean for considerable distances supports the credibility of dispersal by this process. The~~ restriction of upper size carried, depending on mass flux during the ~~individual~~ event, ~~units, also has local~~has significance for the Tongan insular Miocene, ~~on 'Eua,~~ where the ab~~sse~~sence of clasts exceeding 3~~2~~0 mm has been attributed to some trapping mechanism elsewhere (Ballance et al. 2004) for clasts of greater size. Delivery by sediment gravity flows is probable for most of the volcaniclastics on the 'Eua high (Tappin & Ballance 1994; ~~,~~ Ballance et al. 2004). However, for any component of the 'Eua volcaniclastics delivered by ocean surface pyroclastic density currents, ~~rather than by sediment gravity flows,~~ a~~n~~ alternative ~~alternative~~ process by which upper grain size is restricted is suggested ~~by the Kos Plateau Tuff event~~. Furthermore, the rare westwards-dipping~~hading~~ cross-beds in the 'Eua volcaniclastics (Fig. 2~~6~~D) may be attributable to sediment overloading on the 'Eua high by periodic ocean surface pyroclastic density currents and consequential westwards backflow.

While delivery by pyroclastic density current over the ocean surface may explain all or

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part of the dispersal distance issue, it does not explain the anomalous position of the ‘Eua high; –'Eua is positioned much further from the western edge of the Tonga Ridge than any other island. The discontinuities in trends at the southern Block T–E margin, interpreted as block rotation of a particular type, provides a tectonic explanation for this anomaly. The relative thickness of sediment in the Tongatapu/''Eua Channel depocentre (Fig. 48) fits well within this model: ; with block rotation occurring in the Late Miocene, but pre-splitting, the Tongatapu-—‘Eua Channel basin would have been 40 km closer to the source volcanoes to the west for part of the interval 14 – 5.253 Ma, thus only 30 km from source on the minimum 70 km scenario.

For Tthe rotation event may also to have contributed 40 km to the ‘Eua accretionary lapilli dispersal distance, subject a number of conditions must apply. Firstly it must pre-date splitting of the ancestral Lau/Tonga Ridge which commenced in latest Late Miocene (5.325 Ma), secondly post-date the deposition of the accretionary lapilli on proto-'Eua at 14 Ma, and thirdly, the accretionary lapilli must have been sourced from a volcano on the ancestral Lau-Tonga Ridge segment which became Block A.

We favour a model where Tthe accretionary lapilli on 'Eua finally settled through a marine column of not less than 1600 meters. Their delivery to the final resting settlement site was most likely achieved by transport within a pyroclastic density current travelling over the ocean surface which, even in the case of those initiated by small/moderate explosive volcanic events, have delivered relatively large tephra considerable distances from source. -A dual model, comprising block rotation and dispersal by ocean surface pyroclastic density currents, can explain the anomalies described and accommodate a large range of possible dispersal distances from a source of modest DREmagnitude. The possibility of dispersal within the hybrid ash cloud of an ultra-Plinian event of the Oruanui type is not excluded, but is not supported by any data. TThe dating of block formation and of subsequent movement is however problematic; ridge-normal faulting is only strongly expressed in displacement of the A–B isopach, implying that it occurred mostly ppostdated late Late Miocene. Only detailed palaeomagnetic studies of the host Middle Miocene volcaniclastics on ‘Eua could increase precision in this regard; the ubiquity of magnetite in thin hemipelagites which occur in these rocks would make such studies worthwhile.

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~~**Supplementary information published online**~~

~~Supplementary File 1: A more detailed summary of Tonga Ridge issues relevant to the paper, supported by 7 figures and additional references.~~

~~Supplementary File 2: A more detailed summary on Lau Ridge issues relevant to the paper, supported by a summary figure.~~

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Event		DRE	Largest tephra	Distance from source	Maximum distance
		(km^3)	(mm)	(km)	(km)
Krakatoa		12	"small stone"	65	80
Kos Plateau Tuff					
	Unit D	10	50	35	>39
	Unit E	30	200	35	>60
Koya Tuff		1			>40

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Table 1 Values for U_t , vertical terminal velocity at height, for particles of diameter 16 mm and density of 1500 kg m^{-3}, after Pfeiffer et al. (2005).

Table 21 —Dispersal of larger tephra by pyroclastic density currents travelling over the ocean surface (Carey et al. 1996, , from Allen & Cas (2001), Carey et al. (1996)Maeno & Taniguchi 2007, Ui 1973). . DRE = dense rock equivalent. Maximum distance = maximum dispersal distance estimated for the event.

Height (km)	Sea level	10	15	20	26
U_t (m sec^{-1})	17	27	48	50	100

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Table 2 Values for U_t, vertical terminal velocity at height, for particles of diameter 16 mm, density of 1500 kg m^{-3} and F (sphericity) = 0.43, from Pfeiffer et al. (2005).

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~~**Figure 1.** The position of the Lau Basin on the north end of the Tonga-Kermadec-Hikurangi trend and the study area. The Tonga frontal arc basin sediments (shaded) are broadly coincident with the 2000 meter isobath, after Tappin (1993).~~ **Figure 1** Regional setting. **A**, The position of 'Eua and Nomuka on the Tonga Ridge, and Vatoa and Ono-i-Lau on the Lau Ridge. The Tonga frontal arc basin sediments (shaded) are broadly coincident with the 2000 meter isobath, after Tappin (1993). **B**, The Tonga Ridge platform, highlighted by the 1000 meter isobath, with the currently active back-arc Tofua volcanic chain, with block margins after Tappin et al. (1994), Scholl & Vallier (1985), Austin et al. (1989).

Figure 2 Accretionary lapilli from 'Eua. **A,** Layered accretionary lapilli with coarse ash infill. **B,** Layered accretionary lapilli, some cored, with coarse ash infill. **C**, Rimmed accretionary lapillus. **D**, Rare cross-bed in host volcaniclastics.
~~Base map from GeoMapApp, http://www.geomapapp.org.~~

~~**Figure 2.** Synthesis of data centred on the Lau Basin, after Taylor et al. (1996), with c. 20⁰ easterly rotation of the Tonga Ridge (solid black lines) after Sager et al. (1994),~~ **Figure 3** Lau Basin tectonics. **A,** Synthesis of data centred on the Lau Basin, after Taylor et al. (1996), with c. 20^0 easterly rotation of the Tonga Ridge (solid black lines) after Sager et al. (1994). **B,** Outline reconstruction of the ancestral Lau/Tonga ridge, pre-Lau Basin formation, just after splitting commenced, with bathymetric contours. **C,** Schematic section of the Lau Ridge, Lau Basin and Tonga Ridge with ODP sites, at c. 1.5-1.0 Ma, after Clift et al. (1995), modified to reflect the work of Parson & Wright (1996).

~~base map from GeoMapApp, http://www.geomapapp.org. Extended legend as follows:~~

~~834 Late Miocene~~	~~ODP site and age at base of well~~
~~Lighter areas (2A)~~	~~Areas where palaeomagnetic data correlates with known age ranges, none older than the Gauss isochron (<3.3 Ma)~~
~~1, 2, 2A~~	~~Subdivisions of isochrons~~
~~J~~	~~Jaramillo isochron~~
~~CLSC/ELSC~~	~~Central Lau Spreading Centre/East Lau Spreading Centre~~
~~ETZ/NWSLC/MTJ~~	~~Extensional Transform Zone/ NW Lau Spreading Centre/Mangatolo Triple Junction~~
~~Dashed line~~	~~West of this line, is the "extended ancestral arc crust"~~
~~Dotted line~~	~~Eastern edge of Lau Ridge/western edge of Tonga Ridge~~

~~**Figure 3.** Schematic section of the Lau Ridge, Lau Basin and Tonga Ridge with ODP sites, at c. 1.5-1.0 Ma, after Clift et al. (1995), modified to reflect the work of Parson and Wright (1996).~~

~~**Figure 4.** The Tonga Ridge platform, highlighted by the 1000 meter isobath, with the currently active back-arc Tofua volcanic chain, with block margins and selected track lines, after Tappin et al. (1994), Scholl and Vallier (1985), Austin et al. (1989), Lehner et al. (1983).~~

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Figure 5. Fiji and the Lau islands, after Cole et al. (1985), bathymetric contour interval 2000 meters. The inset box outlines the Lau Islands whose geology was reported by Woodhall (1985), the most southerly of which is Ono-i-Lau.

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Figure 6. **A**, 'Eua: Mn-coated accretionary lapillus. **B**, 'Eua: rare large lithic clast (14 mm) in host volcaniclastics. **C**, 'Eua: rimmed accretionary lapillus. **D**, 'Eua, rare cross-bed in host volcaniclastics. Ruler scale is cm/mm.

Figure 7. Outline reconstruction of the ancestral Lau/Tonga ridge, pre-Lau Basin formation, just after splitting commenced.

Figure 8. Discontinuity of trends across the boundary between Blocks A, B and T-E.

Figure 4. Discontinuity of trends across the boundary between tectonic Blocks A, B and T-E. Trend of gravity and arc basement highs on Blocks A and B is superimposed on residual magnetic anomaly data from Stevenson & Childs (1985), determined by subtracting the 1975 International Geomagnetic Reference Field (IAGA, 1976) from the observed total field measurements. Trend of basement highs on Block T-E is superimposed on total magnetic intensity data from Gatliff et al. (1994).

Figure 9. Left: basement trends and faults on Blocks A, T-E and N, after Cunningham & Anscombe (1985). Right: rotation effect of strike-slip faulting on arcuate faults, accommodated by strike-slip faulting on a curved fault "hinge", after Lamb (2011).