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# Pumice rafting and faunal dispersion during 2001–2002 in the Southwest Pacific: record of a dacitic submarine explosive eruption from Tonga

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## Abstract

A new influx of sea-rafted pumice reached the eastern coast of Australia in October 2002, approximately 1 year after a felsic, shallow-marine explosive eruption at a previously unknown volcano (0403-091) along the Tofua volcanic arc (Tonga). The eruption produced floating pumice rafts that first became stranded in Fiji in November 2001, approximately 1 month after the eruption. Strandings of sea-rafted pumice along shorelines have been the only record of products from this submarine explosive eruption at the remote, submerged volcano.

Computed drift trajectories of the sea-rafted pumice using numerical models of southwest Pacific surface wind fields and ocean currents indicate two cyclonic systems disturbed the drift of pumice to eastern Australia, as well as the importance of the combined wave and direct wind effect on pumice trajectory. Pumice became stranded along at least two-thirds (>2000 km) of the coastline of eastern Australia, being deposited on beaches during a sustained period of fresh onshore winds. Typical amounts of pumice initially stranded on beaches were 500–4000 individual clasts per $m^2$, and a minimum volume estimate of pumice that arrived to eastern Australia is $1.25\times10^5$ $m^3$. Pumice was beached below maximum tidal/storm surge levels and was quickly reworked back into the ocean, such that the concentration of beached pumice rapidly dissipated within weeks of the initial stranding, and little record of this stranding event now exists.

Most stranded pumice clasts ranged in size from 2 to 5 cm in diameter; the largest measured clasts were 10 cm in Australia and 20 cm in Fiji. The pumice has a low phenocryst content (<5% modal), containing the assemblage of calcic plagioclase ($An_{88-74}$), augite ($En_{35}Fs_{29}Wo_{36}$), pigeonite ($En_{45}Fs_{46}Wo_{9}$), and titanomagnetite. Examined pumice clasts are

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compositionally homogenous, although there is considerable variation in clast vesicularity, both within and between clasts. The pumice composition is low-K dacite (65–68 wt.% $SiO_2$) and similar to other pumice-forming eruptions from the Tonga region.

Most clasts stranded along eastern Australia were fouled by a variety of organisms, whereas pumice stranded on beaches in Fiji ~1 month after the eruption was free of binding organisms. The dominant rafted organisms in order of abundance were algae, goose barnacles (*Lepas* sp.), serpulid worms, calcareous algae, bryozoans, corals (*Pocillopora* sp., *Porites* sp., *Cyphastrea* sp.), oysters (*Saccostrea* sp.), and gastropods (*Janthina* sp.). The size of some rafted corals implied growth of at least 12 months in viable water. The abundance and variety of fouling taxa, coupled with the long dispersal trajectory (>3500 km) and period of pumice floatation (≥1 year), confirm the importance of sea-rafted pumice as a long-distance dispersal mechanism for marine organisms including marine pests and harmful invasive species. Billions of individual rafting pumice clasts can be generated in a single small-volume eruption, such as observed here, and the geological implications for the transport of sessile taxa over large distances are significant. An avenue for future research is to examine whether speciation events and volcanicity are linked; the periodic development of globalism for some taxa (e.g., corals, gastropods, bryozoa) may correlate in time and/or space with voluminous silicic igneous events capable of producing $>10^6$ $km^3$ of silicic pumice-rich pyroclastic material and emplaced into ocean basins.


*Keywords:* pumice; dacite; Tonga; Southwest Pacific; submarine explosive eruption; long-distance rafting; invasive species; trajectory analysis; surface currents

## 1. Introduction

A conspicuous feature of many coastlines along the nonvolcanic passive margins of the southern hemisphere continents is the considerable abundance of stranded pumice sourced from numerous but often very distant Holocene eruptions (e.g., [1–3]). Following the eruption of Krakatau in 1883, it became widely appreciated that silicic pumice (with densities $<1.0$ g $cm^{-3}$) could remain buoyant in water and drift across oceans for periods of months to years [4,5]. Large drifts of pumice can develop by direct fallout from buoyant subaerial eruption columns into the oceans, subaerial pyroclastic density currents entering the sea, and potentially from shallow-marine, silicic explosive eruptions [6–8]. Floating pumice rafts may travel over 20,000 km [9,10], and the resultant sea-rafted dispersal of pumice far exceeds that achievable from buoyant plinian eruption columns and pyroclastic density currents.

New arrivals of sea-rafted pumices at shorelines may be the only record of submarine explosive eruptions from submerged volcanoes in remote areas where direct observations are difficult. An example of this was the strandings of pumice from Tonga and Fiji to the Great Barrier Reef (northeast Australia) in 1964 and 1965 [11,12]. The pumice strandings could not be related to a subaerial explosive eruption from any island volcano in the Tonga region, and the pumice was alternatively inferred to be sourced from a submarine explosive eruption [7]. Submerged silicic calderas are being increasingly recognised as integral features of modern oceanic arcs (e.g., [8,13]), and their existence provides important clues on the volcanotectonic (extensional) setting of oceanic arcs (e.g., [14]). Recent investigations of oceanic arcs have revealed many submerged volcanoes are blanketed by pumice [8,15], suggesting that silicic pumice (and ash) can be an important contributor to sedimentation along island arcs and in neighbouring back-arc basins [16,17].

The southwest Pacific Ocean (Fig. 1) is an ideal area to examine the characteristics and dispersal of sea-rafted pumice as it is bounded to the east by an area of active (both emergent and submerged) island arc volcanism including silicic, explosive, pumice-producing eruptions (Tonga–Kermadec volcanic arc; the source region) with many volcanic products shed into the ocean. It is faced on the other side, >3000 km distant, by the nonvolcanic margin of eastern Australia with extensive sand beaches that serve as excellent repositories of sea-rafted volcanic, natural, and other artificial material. Furthermore, oceanic currents (South Equatorial Current) and winds (South East trades) in the region transport flotsam directly toward the eastern Australian coastline. Volcanic

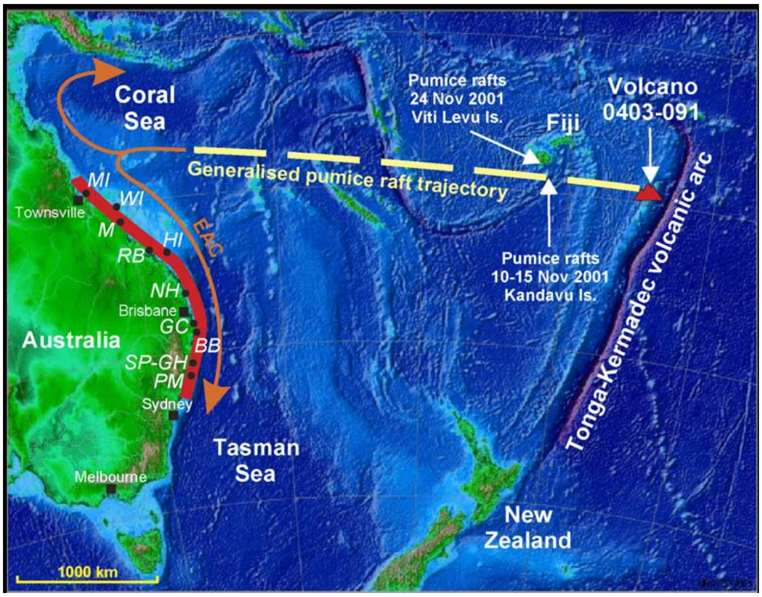


Fig. 1. Map of the southwest Pacific showing location of the unnamed volcano (0403-091) in the Tofua volcanic arc that erupted in September–October 2001 producing the pumice rafts. The general dispersal trajectory of the sea-rafted pumice is shown by the dashed line, with sea-rafted pumice reaching the eastern Australian coastline ~1 year after the eruption after entering the East Australian Current (EAC). Extent of pumice beaching shown by the red line. Sample and observation site abbreviations (in italics): MI, Magnetic Island; WI, Whitsunday Island; M, Mackay; RB, Rosslyn Bay; HI, Heron Island (southern Great Barrier Reef); NH, Noosa Heads; GC, Gold Coast; BB, Byron Bay; SP-GH, Stuarts Point-Grassy Head; PM, Port Macquarie.

products from the Tonga–Kermadec arc are well-characterised through several studies over the last 30–40 years (e.g., [18–21]), such that distinct regional differences aid in constraining the source region or volcanoes for the sea-rafted pumice.

Several pumice stranding events recorded along the shorelines of eastern Australia have corresponded to eruptions in the Tonga region [3,7,11]. Older Holocene deposits of beached pumice occur in elevated backshore regions remote from storm surges and maximum sea levels, or buried in dune deposits (e.g., [3,22]). Observations of the drift and arrival of pumice from eruptions at Curacoa Reef (Tonga, July 1973), Metis Shoals (April–May 1979), and Late Iki/Home Reef (Tonga, March 1984) indicate arrival times along eastern Australian shorelines at least 7–8 months after each eruption [3,23,24]. In the absence of direct observations, the petrography and chemical composition of many stranded pumice deposits indicate they were sourced from volcanoes along the Tonga–Kermadec volcanic arc (e.g., [2,3,7,22]). One advantage of studying any new stranding event of sea-rafted pumice is that it overcomes the problems for old stranded or buried pumice deposits that probably reflect the cumulative effect of multiple stranding events and subsequent reworking [2,25].

We report on a new sea-rafted pumice stranding event in October 2002 along at least two-thirds of the coastline of eastern Australia (>2000 km length). The source of pumice was a shallow-marine explosive eruption in September 2001 from an unnamed volcano (0403-091) along the Tofua volcanic arc. This stranding event shows many similarities to the 1964–1965 pumice strandings in Fiji and eastern Australia, which also had no known subaerial source eruption, leading to the inference of a submarine silicic explosive eruption as the source of the sea-rafted pumice [7]. The 2001–2002 pumice is similar in composition to pumice of previous stranding events and reinforces the Tonga region as a prime source area for stranded pumice deposits along eastern Australia. The pumice was significant for having an abundance and a variety of fouling organisms, such as corals, barnacles, bryozoa, mollusca, and algae, confirming previous observations that sea-rafted pumice is an important mechanism for the long-range dispersal of coral and other organisms [26–28]. We document here for the first time a range of species that have utilised this long-range transport mechanism to eastern Australia. Computed drift trajectories for the sea-rafted pumice are made using numerical models of southwest Pacific surface wind fields and ocean currents to (1) model the derivation of pumice strandings in Fiji and Australia from the same source eruption; (2) reproduce the observed arrival times; and (3) evaluate the relative importance of surface trade winds and ocean currents in the dispersal of pumice.

## 2. Source pumice-producing eruption

Several volcanic eruptions occurred in the southwest Pacific region during the period 2001 to October 2002 but were small volume basaltic lava and ash eruptions from the island volcanoes of Vanuatu and the Solomon Islands (see [29]). The products of these eruptions were compositionally distinct from the sea-rafted pumice in eastern Australia, and the eruptions were also non-pumice-producing. However, a shallow marine explosive eruption from a previously unrecognised submarine volcano along the Tofua arc (Fig. 2) occurred during September and October 2001 and was first detected by seismic activity at night during September 27–28 [30]. There were few direct observations of the eruption. No details are available on the form or structure of this submarine volcano, although bathymetry indicates the volcanic summit is probably within 200–300 m of the surface [31]. Initial reports were of an ash-rich column and island forming on September 27–28, 2001, and subsequent large areas of water discolouration (up to 15 km$^2$) in the region were reported from October 1–26 [31,32]. From the seismic waves recorded during the eruption, it appears the explosive phase of the eruption continued for ~26 h from the first explosions, whereas fumarolic activity may have produced gases and sublimates until at least late October 2001 [31]. It was not until early November 2001 that substantial pumice rafts (100–150 m diameter) were first observed being stranded on the islands of Kandavu and Viti Levu in Fiji (Fig. 2; [30]). The early report of an island forming was concluded by Taylor [31] to essentially be a floating pumice raft, and the ash-rich eruption column reflected volcanic gases, steam, and pyroclastic material breaking the surface. Post-eruptive depth of the volcano is unknown, and no shoal or island was observed during visits to the site of activity in October 2001 [31].

## 3. October 2002 pumice beaching

Beaching of considerable volumes of pumice along the shorelines of Queensland and New South Wales began in late September–October 2002 during a sustained period of moderate to fresh, southeast to northeast onshore winds generated from relatively persistent high-pressure ridges over the northern Tasman and Coral Seas [33–35]. Stranded pumice extended for over 2000 km along the eastern coast of Australia from north of Townsville to Sydney (Fig. 1). Typical amounts of pumice initially stranded were 500–4000 individual clasts per m$^2$, and a minimum volume estimate of pumice is $1.25\times10^5$ m$^3$ (~$3.6\times10^4$ m$^3$ DRE). These volume estimates, however, substantially underrepresent the true eruptive volume because (1) a considerable volume of pumice will also have been stranded on islands (e.g., Fiji) along the trajectory path to Australia (e.g., [7,30]); (2) hot juvenile particles quickly absorb water and sink such that small pumiceous particles (ca. <0.5 mm) will sink almost immediately [36,37], and a large proportion of pumice may have cooled and sank immediately near the vent; and (3) organism overloading may have induced sinking of pumice clasts in transit to Australia. Recent observations from oceanographic cruises of submerged arc volcanoes indicate extensive 'pumice blankets' over many submarine volcanic edifices (e.g., [8,13,15]), indicating that significant volumes of pumice are deposited near vent. Nevertheless, the number of pumice clasts estimated to have been beached along the eastern Australian coast was $>8\times10^9$; this is of prime significance as even a small volume pumice-producing eruption can produce innumerable transporting opportunities for sessile organisms (see below).

Most stranded pumice clasts ranged in size from 2 to 5 cm in diameter, although numerous clasts up to 10 cm also occurred. Maximum pumice size from stranded deposits in Fiji was 20-cm diameter. Some

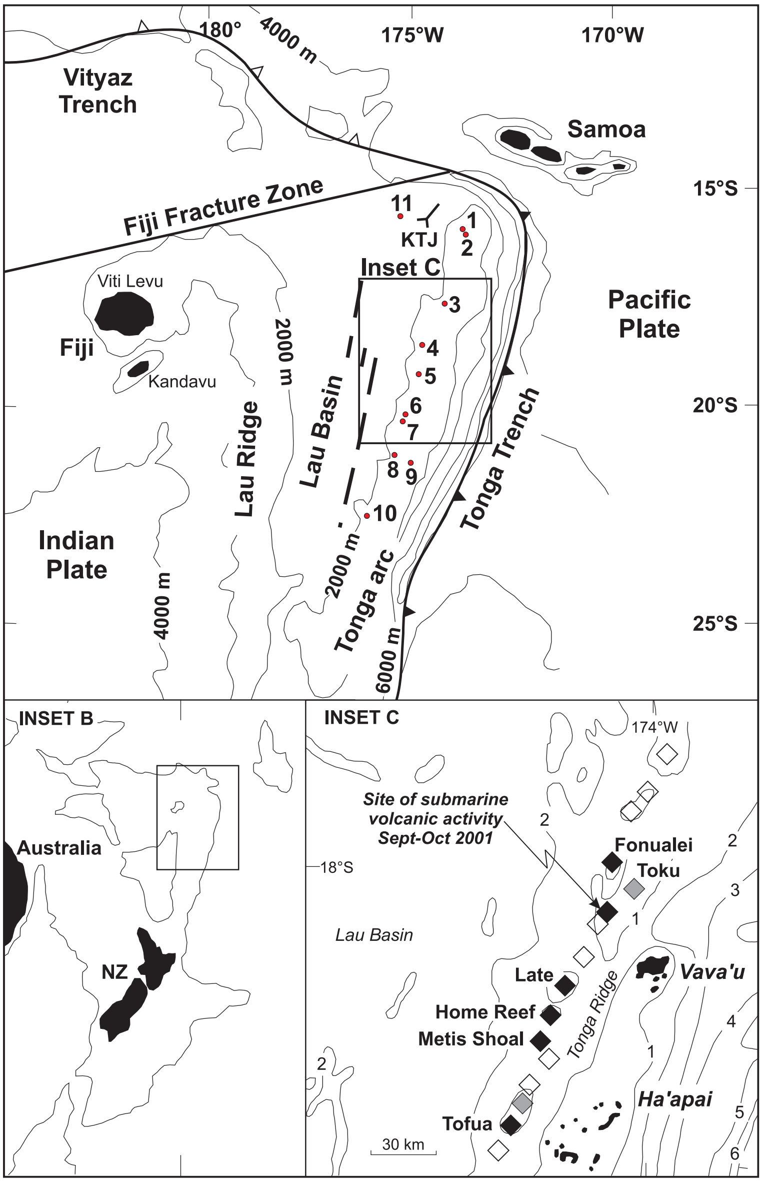


Fig. 2. Tonga arc showing major regional tectonic features, with volcanic islands numbered: 1, Tafahi; 2, Niuatoputapu; 3, Fonualei; 4, Late; 5, Metis; 6, Kao; 7, Tofua; 8, Hunga Ha'apai and Hunga Tonga; 9, Eua; 10, Ata; 11, Niua fo'ou. Other abbreviation: KTJ, Kings Triple Junction. Dashed lines in Lau Basin are, from left to right, the central, intermediate, and east Lau Spreading Centres. Modified from Ewart et al. [20]. Inset B, location of Tonga arc in the southwest Pacific. Inset C, locality map of the Tofua arc showing the site of submarine explosive volcanic activity in September–October 2001, the source of pumice rafts. Black diamonds denote volcanoes with historic activity, grey diamonds are inactive centres, and hollow diamonds are probable submarine volcanic centres. Bathymetric contours in kilometres. The Home Reef eruption of 1984 also produced sea-rafted pumice that reached eastern Australia [23,24]; modified after Taylor [31].

reduction in pumice clast size may have occurred during transport, such as by clast breakup and abrasion in littoral zones. Considerable variation in clast vesicularity exists within the collected specimens. Several pumice clasts, particularly those collected from rafts in Fiji, possess dark glassy and poorly vesicular margins/rinds, and more vesiculated interiors. Vesicularity textures are heterogeneous even within the same clast, with both massive micro-vesiculated and tubed or fibrous vesicle domains occurring. Tubed pumice was a minor but distinctive pumice clast-type stranded in eastern Australia.

### 3.1. Beach deposition

Pumice initially formed laterally extensive tidal strand lines and was associated with other flotsam, such as hydroids ('by-the-wind sailor', *Valella*) and bottles. As the pumice was not deposited during a storm event and therefore at higher shoreline elevations, pumice was reworked in to the surf zone by the tidal cycles, and the initial stranded pumice concentrations quickly dissipated. Within weeks of the initial stranding event, many exposed beaches had little to no record of the pumice stranding; what pumice remained was that blown into backshore regions and/or partly buried by aeolian sand deposits. Since the first arrival, the stranding of pumice on beaches has progressively increased southwards as material was transported by the East Australian Current. The more substantial preservation of pumice on beaches several months after the first stranding occurred on sheltered beaches/coves. This suggests that not all pumice stranding events may be preserved, and particular conditions (e.g., storm surges, protected beaches, and backshore regions) are required for any significant long-term deposit stability. This stranding event contrasts with that suggested for the 1964–1965 event in Fiji and on the Great Barrier Reef, which was inferred to be associated with storm events [7,11].

Much of the pumice preserved on the beaches in backshore regions had been significantly modified within 2 months after the initial stranding event by (1) showing substantial clast rounding; and (2) lacking organisms with soft-tissue (algae, goose barnacles; compare Fig. 3A and B). Only the coral, serpulid, and oyster skeletons, and some algae (*Lobophora*) had persisted on pumice clasts to accumulate in beach deposits long after molluscs, crustaceans, and other fleshy organisms had decomposed or been scavenged [27]. Littoral abrasive processes thus may have important implications for preserving evidence in the

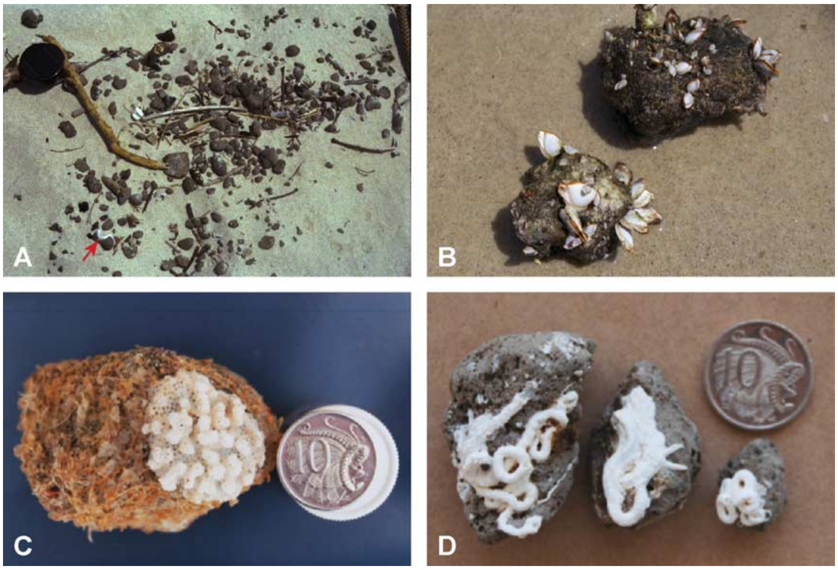


Fig. 3. (A) Abraded pumice strand deposit, Byron Bay. Note the rounded pumice morphology and lack of attached biota. A serpulid skeleton attached to one pumice clast is indicated by the arrow. Lens cap is 5-cm diameter. (B) Newly stranded pumice clasts at Byron Bay with abundant goose barnacles (*Lepas*) and algal coverings. Note several mature goose barnacles attached to end of pumice clast at bottom centre. (C) Approximately 1-year-old colonial coral *P. damicornis* attached to an algal-covered pumice clast, collected from Mackay harbour in April 2003. Coin is 2.3-cm diameter. (D) Serpulid colony skeletons on pumice clasts. Note the attachment and growth to mature colonies have occurred independent of pumice clast size. Coin is 2.3-cm diameter.

geological record of the introduction of species to new areas by pumice rafting.

## 4. Rafted taxa

Almost all the newly arrived pumice clasts to eastern Australia were fouled by attached biota, with dark algal coverings common to all clasts, concealing the primary character of the pumice. Goose barnacles (*Lepas*) were the most common of the attached marine invertebrates, often occurring in groups attached to single pumice clasts (Fig. 3B). Goose barnacles were observed still attached and growing on pumice clasts that had remained in ocean water at least four months after the initial strandings. It was also observed that many stranded pumice clasts were encrusted with barnacles of the genus *Lepas* up to about 1 cm in length, almost 1 year after the 1984 Home Reef eruption [38]. The distribution of the goose barnacles on pumice clasts is also noteworthy. As previously observed by Donovan [39], peduncles for mature individuals tended to be sited within vesicular hollows, and we commonly observed the more mature individuals to be sited within small surface depressions of the pumice clast, where protection for initial attachment and barnacle growth was provided. Some algal species also preferentially occurred within protected embayments of the pumice clast surface. Although some pumice clasts had fouling organisms restricted to one side (i.e., forming a keel), mature goose barnacle individuals were often preferentially attached at the ends of pumice clasts forming fan arrangements, allowing the barnacles to remain immersed but also in direct sunlight. Commonly, the largest individuals often were found attached to the ends of pumice clasts (Fig. 3B). Goose barnacles never remained attached to the pumice clasts after any significant period where the clasts remained stranded on beaches.

Stranded pumice specimens examined in more detail from three localities (Table 1) had a variety of other attached epibionts and associated biota: bryozoans (indeterminate fouling cheilostome), colonial corals (*Pocillopora damicornis*; Fig. 3C; *Porites* sp. and *Cyphastrea* sp.), several varieties of algae, of which *Lobophora variegata* was the most common species remaining attached to pumice after stranding, and calcareous worms (Serpulidae). The serpulids often occurred in colonies (some having >30 individuals), leaving rigid carbonate tubes attached to pumice clasts that usually survived littoral abrasion processes (Fig. 3D). Less commonly attached to pumice clasts were oysters (*Saccostrea*) and a gastropod (*Janthina* sp.); these are not included in the tabulated sample group of Table 1 due to their rarity.

Given the wide range of many of the epibiontic taxonomic groups and the limited sample size, precise constraints on their growth parameters or origin have been difficult. Bryozoa and algae were near ubiquitous (like the goose barnacles) and suggest immersion for periods of weeks to months. Some *Pocillopora* colonies had branches 2–5 mm high with colony diameters up to 30 mm wide, suggesting approximately 1 year in the water prior to their collection. The 1-year growth implies initial attachment was outside the Great Barrier Reef area, and colonisation occurred during pumice transit across the tropical southwest Pacific (e.g., [26]).

A single attached oyster, collected from Port Macquarie, was 3 cm wide and suggests a number of months of immersion prior to stranding. Oyster spawning can result from a number of events, including freshwater input from river or rain, but generally is associated with warmer months (R. Ablard, personal communication, 2004). The oyster

Table 1
Summary of attached biota observed on stranded pumice clasts along the eastern Australian coast

| Location (lat/long) $n$=sample size | Coral | *Lobophora* | Fouling cheilostome | *Saccostrea* | Calcareous algal complex | Serpulid |
|---|---|---|---|---|---|---|
| Grassy Head, NSW (30°47′ S, 153°0′ E) $n$=35 | 1 | 28 | 9 | 0 | 11 | 16 |
| Port Macquarie, NSW (31°31′ S, 152°52′ E) $n$=7 | 0 | 3 | 3 | 1 | 6 | 1 |
| Rosslyn Bay, QLD (23°10′ S, 150°46′ E) $n$=8 | 4 | 7 | 6 | 1 | 4 | 4 |

Goose barnacles are not included in the species tabulation as they did not remain attached to pumice clasts. Note that corals were more abundant on pumice collected within the tropics.

size is consistent with months rather than weeks of immersion of the pumice clast. The presence of the planktonic gastropod *Janthina* sp. may be just fortuitous. Its pelagic habit would not benefit from attachment to pumice.

It is clear that transport times allowed for colonisation for 1 year. Pumice clasts therefore were fouled within a few months of the eruption, but after the rafts had reached Fiji in November 2001 where the pumice was free of attached organisms. Attached shelled organisms were also reported from beached pumice clasts within 6 months of the 1984 Home Reef eruption [40]. These observations imply that many organisms attached to pumice originated outside the immediate eastern Australian zone and were then transported down the eastern coast of Australia.

## 5. Pumice chemistry

Frequent eruptions have been recorded from the Tonga–Kermadec arc over the last 80 years that produced pumice rafts (Falcon Island, 1927–36; Curacoa Reef, 1973; Metis Shoal, 1979; Home Reef, 1984; Submarine Volcano III, 1999; [29,31]). However, little geochemical data on these eruptive products are available, and consequently, geochemical comparisons to previous pumice raft-forming eruptions are limited. We present here the first complete trace element and rare earth element data set for a sea-rafted pumice suite from this region. Several chemical analyses of individual pumice clasts were undertaken to (1) characterise the eruptive products and magma chemistry as the pumice rafts have provided the only assessable record of the eruption; and (2) confirm via chemical similarity that the pumice material beached along eastern Australia in October 2002 was the same as the pumice rafts observed at Fiji in November 2001. Description of the analytical techniques is given in Appendix A.

### *5.1. Phenocryst compositions*

Pumice clasts contain, in order of relative abundance, microphenocrysts of bytownite ($An_{88-74}$), augite ($En_{35}Fs_{29}Wo_{36}$), pigeonite ($En_{45}Fs_{46}Wo_{9}$), and titanomagnetite that usually occur in small glomerocrystic aggregates. This assemblage is the same for basaltic andesite lavas from the Tongan islands, with magnetite appearing in the more silicic lavas [19]. The calcic plagioclase compositions are similar to those of drift pumice from a similar eruption in the Tonga region in 1964 (Fig. 4A; [7]). Both normal and reversely zoned plagioclase phenocrysts are present, with core and rim compositions varying by up to 10 mol% anorthite content. Orthopyroxene exhibits a relatively narrow compositional range (Fig. 4B), being moderately Fe-rich and classifying as pigeonite. This contrasts with other sea-rafted pumice deposits, in which the orthopyroxene phase is hypersthene [2,7,22]. Greater compositional variation is present in the coexisting augite, varying primarily in the wollastonite end member component ($Wo_{31–38}$). The calcic augites are similar in composition to those of the Eua Island sea-rafted pumice [7], but more Fe-rich than the 1967 dacite eruption of Metis Shoal [21]. Neither pyroxene phase, however, shows significant compositional zonation (<5%), although apparently abrupt compositional changes occur at phenocryst rims where augites are rimmed by pigeonite, and less commonly, pigeonite rimmed by augite. Similar shifts are also observed in the basaltic andesite lavas from the Tongan islands [19]. The presence of two coexisting pyroxenes permits magmatic temperatures to be estimated using the two-pyroxene thermometer of Lindsley [41]. The pyroxene compositions indicate preeruptive magmatic temperatures of ~1000 °C (Fig. 4B). Magma temperatures have also been estimated from the coexisting pyroxenes using the QUILF program of Anderson et al. [42]. The thermometer is most sensitive to variations in CaO content in the orthopyroxene, which shows little variation compared with the coexisting augite phenocrysts (Fig. 4B). Averaged phenocryst compositions yield a temperature estimate of 984 ± 55 °C, whereas the pairing of the most calcic and Fe-rich rim compositions indicate temperatures of 893 ± 178 °C and 976 ± 63 °C, respectively. All values have been calculated at 1 kbar; however, there is insignificant variation in the thermometer with pressure. Iron-rich magnetite microphenocrysts show little compositional variation, with a narrow range in ulvöspinel solid solution ($Usp_{28–30}$).

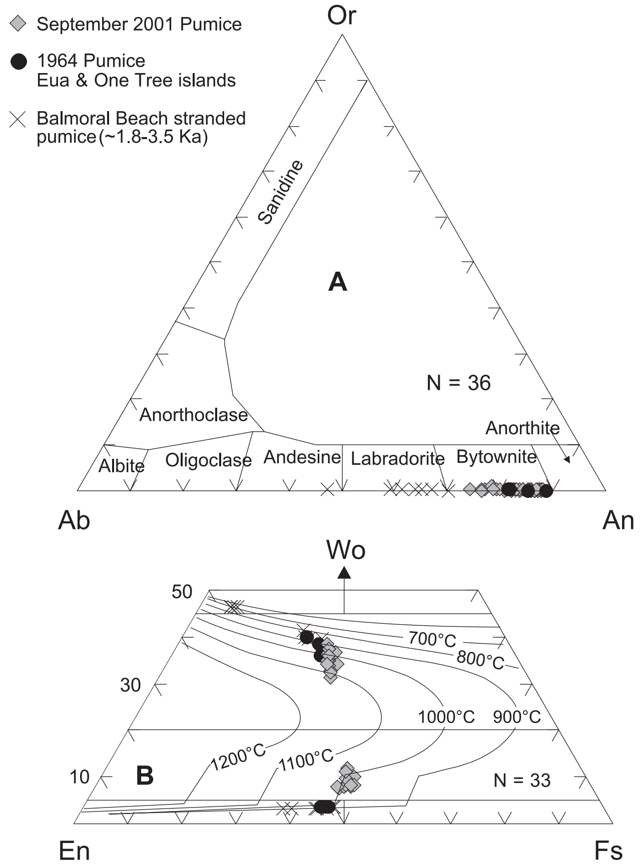


Fig. 4. Phenocryst compositions of pumice clasts stranded on Queensland beaches from the September 2001 eruption of Volcano 0403-091. The data are compared with phenocryst compositions of stranded pumice from (1) Eua Island (Tonga) and Herald Cay Island (Great Barrier Reef) following a similar shallow submarine eruption in the Tonga region in 1964 [7], and (2) palaeopumice strand deposits (>1800–3500 ybp) from Balmoral Beach, New South Wales [22]. (A) Feldspar phenocryst compositions. Abbreviations: Ab, albite; An, anorthite; Or, orthoclase; *N* is number of analyses. (B) Pyroxene phenocryst compositions expressed in terms of the three-component system: wollastonite (Wo), enstatite (En), and ferrosillite (Fs), with field boundaries after Morimoto [43]. Temperature contours (0.1 MPa) after Lindsley [41]. *N* is number of analyses.

### *5.2. Pumice composition*

Whole-clast and pumice glass compositions are given in Tables 2 and 3, respectively. Pumice clasts are low-K dacites with $SiO_2$ contents in the range ~65–68 wt.% (recalculated to 100% on a volatile-free basis), although one clast collected from Heron Island on the Great Barrier Reef is more rhyodacitic in composition (Table 2). Coupled with subtle variations in other major elements ($TiO_2$, $Al_2O_3$, $Fe_2O_3T$, CaO), this suggests some primary compositional variation to the magma tapped by the submarine explosive eruption. Glass compositions are only slightly more silicic than the whole pumice dacite compositions (Fig. 5A, B). Overall, pumice clasts are similar in composition to previously stranded pumice on the Great Barrier Reef in having low alkalis, high iron, and a silicic composition (Fig. 5); these are characteristic of volcanic products from the Tonga region of the Tonga–Kermadec arc [7,11].

The extended trace and rare earth element data set illustrate very similar MORB-normalised patterns for analysed pumice clasts collected from rafts in Fiji (November 2001) and those stranded on eastern Australian beaches from October 2002 (Fig. 6). Variation between clasts primarily exists in the magnitude of the characteristic Nb and Ta depletions for subduction-related arc volcanics, and the more

Table 2
Major and trace element compositions of individual pumice clasts collected from Fiji and eastern Australia

| Sample | Fiji1 | Fiji2 | PM1 | RB1 | SP1 | GC1 | HI1 |
|---|---|---|---|---|---|---|---|
| Location | Fiji | Fiji | Pt Macquarie | Rosslyn Bay | Stuarts Pt | Gold Coast | Heron Is. |
| *Major elements (wt.%)* | | | | | | | |
| $SiO_2$ | 65.44 | 65.56 | 66.73 | 67.71 | 66.18 | 65.90 | 71.30 |
| $TiO_2$ | 0.55 | 0.55 | 0.55 | 0.58 | 0.62 | 0.58 | 0.36 |
| $Al_2O_3$ | 12.65 | 12.78 | 12.41 | 11.81 | 11.99 | 12.31 | 12.80 |
| $Fe_2O_3$ | 9.63 | 9.69 | 9.53 | 9.03 | 9.66 | 9.88 | 5.50 |
| MnO | 0.18 | 0.18 | 0.18 | 0.17 | 0.17 | 0.18 | 0.10 |
| MgO | 1.36 | 1.34 | 1.29 | 1.31 | 1.38 | 1.43 | 1.07 |
| CaO | 5.74 | 5.85 | 5.76 | 5.99 | 5.60 | 5.77 | 4.34 |
| $Na_2O$ | 3.41 | 3.12 | 2.64 | 2.56 | 3.54 | 3.20 | 3.45 |
| $K_2O$ | 0.72 | 0.78 | 0.75 | 0.69 | 0.71 | 0.60 | 0.90 |
| $P_2O_5$ | 0.32 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.18 |
| LOI | 0.88 | 0.53 | 0.23 | 0.85 | 1.28 | 1.87 | 0.92 |
| Raw Total | 100.60 | 98.45 | 99.00 | 100.52 | 99.72 | 99.50 | 99.80 |
| *Trace elements (ppm)* | | | | | | | |
| Li | 8.40 | 8.58 | 8.70 | 8.54 | 8.54 | 8.71 | 9.75 |
| Be | 0.33 | 0.34 | 0.33 | 0.34 | 0.32 | 0.34 | 0.48 |
| Sc | 35.22 | 32.60 | 33.35 | 31.83 | 34.13 | 30.26 | 19.76 |
| Ti | 3238.47 | 3239.03 | 3201.63 | 3309.66 | 3423.36 | 2961.97 | 2184.38 |
| V | 88.16 | 80.88 | 95.17 | 86.77 | 92.98 | 53.74 | 82.52 |
| Cr | 0.27 | 0.22 | 1.30 | 1.86 | 0.76 | 1.42 | 5.04 |
| Co | 18.24 | 17.19 | 18.12 | 17.69 | 18.39 | 15.10 | 10.54 |
| Ni | 0.91 | 0.89 | 1.44 | 1.70 | 1.26 | 1.62 | 2.22 |
| Cu | 38.38 | 35.60 | 33.10 | 33.34 | 34.84 | 40.13 | 48.18 |
| Zn | 99.33 | 99.09 | 97.84 | 96.47 | 104.52 | 96.29 | 58.74 |
| Ga | 13.16 | 13.24 | 12.81 | 12.33 | 12.89 | 12.62 | 11.22 |
| Rb | 7.38 | 7.57 | 7.64 | 8.89 | 7.58 | 7.80 | 12.40 |
| Sr | 224.00 | 226.10 | 220.04 | 235.39 | 222.47 | 221.38 | 171.90 |
| Y | 19.19 | 19.52 | 18.33 | 18.54 | 19.07 | 19.87 | 16.82 |
| Zr | 31.21 | 32.14 | 41.76 | 32.96 | 31.52 | 37.70 | 44.47 |
| Nb | 0.35 | 0.37 | 0.46 | 0.90 | 0.61 | 0.38 | 2.49 |
| Mo | 2.34 | 2.38 | 2.19 | 2.24 | 2.32 | 2.44 | 2.11 |
| Cd | 0.05 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| Sn | 1.87 | 0.97 | 0.44 | 0.48 | 0.48 | 3.03 | 0.60 |
| Sb | 0.11 | 0.11 | 0.11 | 0.12 | 0.13 | 0.12 | 0.13 |
| Cs | 0.47 | 0.49 | 0.49 | 0.53 | 0.48 | 0.50 | 0.47 |
| Ba | 148.98 | 153.33 | 141.46 | 152.48 | 148.97 | 156.84 | 184.42 |
| La | 2.22 | 2.30 | 2.52 | 2.78 | 3.41 | 2.39 | 4.33 |
| Ce | 5.93 | 6.10 | 6.33 | 6.85 | 6.16 | 6.27 | 9.11 |
| Pr | 1.01 | 1.03 | 1.05 | 1.11 | 1.04 | 1.06 | 1.29 |
| Nd | 5.33 | 5.46 | 5.33 | 5.56 | 5.42 | 5.57 | 5.91 |
| Sm | 1.86 | 1.89 | 1.82 | 1.85 | 1.86 | 1.94 | 1.77 |
| Eu | 0.65 | 0.66 | 0.63 | 0.65 | 0.65 | 0.67 | 0.54 |
| Tb | 0.48 | 0.48 | 0.45 | 0.46 | 0.48 | 0.49 | 0.42 |
| Gd | 2.60 | 2.65 | 2.52 | 2.55 | 2.60 | 2.70 | 2.32 |
| Dy | 3.25 | 3.29 | 3.10 | 3.13 | 3.23 | 3.33 | 2.78 |
| Ho | 0.75 | 0.76 | 0.72 | 0.73 | 0.75 | 0.78 | 0.64 |
| Er | 2.27 | 2.31 | 2.16 | 2.16 | 2.26 | 2.35 | 1.96 |
| Tm | 0.36 | 0.36 | 0.34 | 0.34 | 0.35 | 0.37 | 0.31 |
| Yb | 2.39 | 2.42 | 2.28 | 2.29 | 2.38 | 2.46 | 2.07 |
| Lu | 0.37 | 0.38 | 0.36 | 0.35 | 0.37 | 0.38 | 0.32 |
| Hf | 1.07 | 1.10 | 1.28 | 1.09 | 1.08 | 1.24 | 1.39 |

Table 2 (*continued*)

| Sample | Fiji1 | Fiji2 | PM1 | RB1 | SP1 | GC1 | HI1 |
|---|---|---|---|---|---|---|---|
| Location | Fiji | Fiji | Pt Macquarie | Rosslyn Bay | Stuarts Pt | Gold Coast | Heron Is. |
| *Trace elements (ppm)* | | | | | | | |
| Ta | 0.02 | 0.02 | 0.03 | 0.05 | 0.04 | 0.02 | 0.11 |
| W | 0.12 | 0.13 | 0.13 | 0.19 | 0.16 | 0.14 | 0.28 |
| Tl | 0.08 | 0.08 | 0.07 | 0.08 | 0.08 | 0.09 | 0.12 |
| Pb | 2.87 | 2.93 | 2.80 | 3.09 | 3.13 | 3.23 | 3.68 |
| Th | 0.20 | 0.20 | 0.30 | 0.37 | 0.24 | 0.22 | 0.74 |
| U | 0.23 | 0.23 | 0.28 | 0.27 | 0.25 | 0.26 | 0.46 |

compatible elements Cr and Ni at the right of the diagram. The rhyodacitic pumice clast from Heron Island exhibits only slightly higher large ion lithophile element abundances in comparison to the volumetrically dominant dacite pumice. Overall, the dacite pumice exhibits similar normalised patterns to basaltic andesite lavas erupted from neighbouring volcanoes along the Tofua arc (Figs. 5C and 6).

## 6. Pumice trajectory analysis

A trajectory analysis has been undertaken to map the dispersal of pumice from the September 27–28 eruption of Volcano 0403-091 across the southwest Pacific Ocean to eastern Australia. Knowledge of the trajectory taken by pumice on its journey to the Australian coast provides insight into raft dispersal as well as possible island and reef encounters, which may have aided the rafting of biological material. The trajectory taken by the pumice is a combination of surface currents, wave motions, and direct wind drag. Various atmospheric and oceanic data sources are combined here to provide a best estimate of their effects and the resultant trajectory of the pumice over the deep ocean. We first briefly outline the methodology for deriving the surface velocity field from which the behaviour of floating pumice can be modelled.

Table 3
Electron microprobe analyses of pumice glass collected from eastern Australia

| Sample | Pumice1 | Pumice1 | Pumice1 | Pumice2 | Pumice2 | Pumice2 |
|---|---|---|---|---|---|---|
| No. | 1 | 2 | 3 | 4 | 5 | 6 |
| $SiO_2$ | 66.69 | 67.62 | 66.21 | 67.30 | 68.55 | 66.14 |
| $TiO_2$ | 0.52 | 0.54 | 0.48 | 0.46 | 0.53 | 0.52 |
| $Al_2O_3$ | 12.30 | 12.53 | 12.04 | 11.99 | 12.25 | 12.25 |
| FeO | 7.79 | 8.30 | 8.08 | 8.09 | 8.04 | 8.00 |
| MnO | 0.20 | 0.17 | 0.12 | 0.14 | 0.13 | 0.17 |
| MgO | 0.94 | 0.92 | 0.92 | 0.96 | 0.86 | 0.95 |
| CaO | 5.33 | 5.45 | 5.42 | 5.12 | 5.19 | 5.37 |
| $Na_2O$ | 2.87 | 2.86 | 2.41 | 2.76 | 2.91 | 2.73 |
| $K_2O$ | 0.76 | 0.70 | 0.67 | 0.71 | 0.75 | 0.71 |
| $P_2O_5$ | 0.22 | 0.16 | 0.16 | 0.21 | 0.20 | 0.19 |
| BaO | 0.06 | 0.00 | 0.02 | 0.07 | 0.03 | 0.07 |
| SrO | 0.15 | 0.16 | 0.19 | 0.15 | 0.17 | 0.15 |
| Total | 97.81 | 99.41 | 96.73 | 97.97 | 99.60 | 97.25 |

### 6.1. Methodology

The surface currents are derived using the methodology of Bonjean and Lagerloef [48]. In this method, the surface currents are a combination of wind-driven Ekman currents, $V_{Ek}$, and currents induced by changes in the sea surface height (SSH) and the Coriolis force, $V_{Geo}$, along with a small sea surface temperature correction, $V_{\varphi}$. Due to limitations of the geostrophic assumption and tidal influences, velocity vectors can only be calculated for deep water where bottom drag is not important on surface current dynamics.

Atmospheric data were extracted from global tropospheric analyses performed at the National Center for Environmental Prediction. The final global data assimilation (FNL) run of the Global Forecast System is archived at the National Center for Atmospheric Research. The FNL is run at a high horizontal resolution of T254 (~55 km) with 64 levels in the vertical. Many observations are assimilated into the run including data from the SeaWinds sensor on the QuikSCAT satellite. These data are used to calculate a surface wind stress field using the methodology of Large and Pond [49]. The data set therefore provides a 'best guess' surface wind stress field on a regular $1^{\circ}\times1^{\circ}$ grid every 6 h.

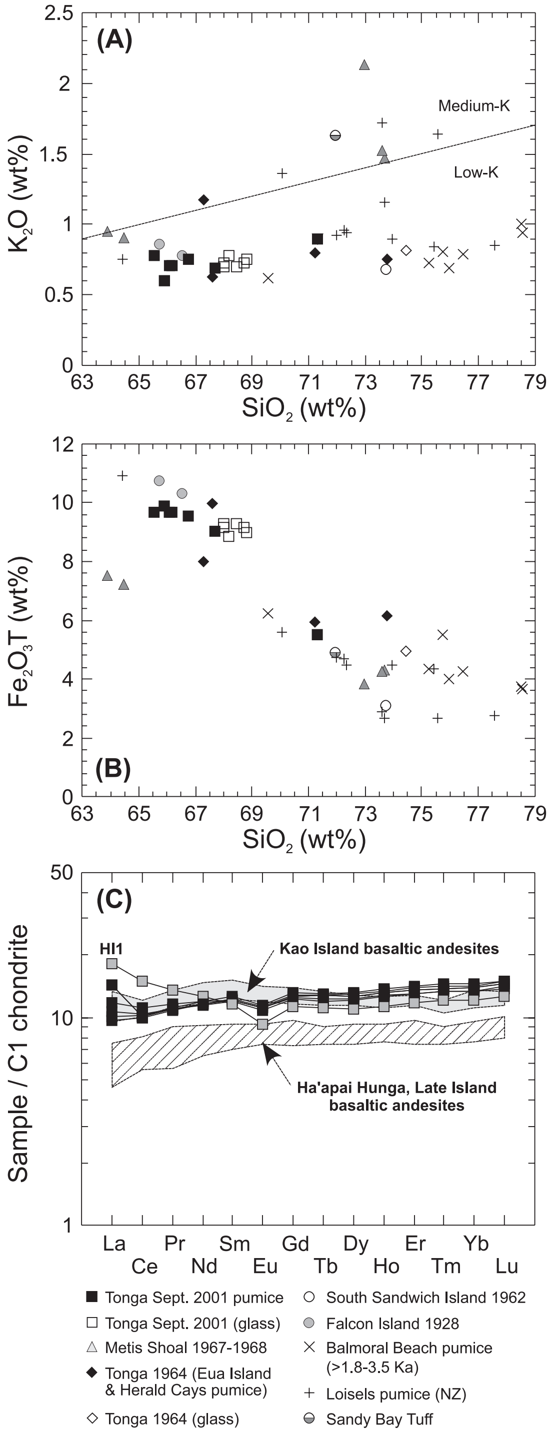


Fig. 5. Compositions of whole pumice clasts and glass from the September 2001 eruption of Volcano 0403-091, compared with other examples of sea-rafted pumice (data sources: [2,7,21,22,44]). Whole pumice data LOI-free normalised to 100 wt.%; microprobe data have been normalised to 100%. (A) $K_2O$ versus $SiO_2$ plot illustrating the low-K character of the sea-rafted pumice. Low- and medium-K boundary from Le Maitre et al. [45]. (B) $Fe_2O_3T$ versus $SiO_2$ plot illustrating the Fe-rich compositions of the September 2001 sea-rafted pumice that is also similar in major element composition to sea-rafted pumice from the 1964 eruption [7] and the 1928 Falcon Island eruption from the Tonga region. (C) Chondrite-normalised [46] rare earth element diagram. The more rhyolitic composition pumice clast collected from Heron Island (HI1; Great Barrier Reef) shows a slightly more pronounced light rare earth enrichment and Eu depletion. Overall, pumice from the September 2001 eruption shows compositional affinity to the less-depleted basaltic andesite lavas erupted from Kao Island (data from Ewart et al. [20]).

The SSH was calculated by combining the mean dynamic height of the sea surface relative to 1000-m depth level [50], with SSH deviations measured by several satellites to generate a single high-precision altimetry data set (compiled at the Centre National d'Etudes Spatiales, France). Deviations between the measured surface and the geopotential surface were then used to calculate ocean surface gradients, from which the strength of the ocean currents is inferred by using the assumption of geostrophy, where there is a balance between Coriolis forces and pressure gradients.

Once the surface current has been established using the data sets and methodology outlined above, further account must be taken of the influence of Stokes drift produced by wave motion and the direct effect of wind on the pumice protruding from the surface of the water. Recent theoretical and modelling studies have attempted to quantify the impact of waves on surface currents [51,52]. They show a significant modification of surface currents towards the downwind direction, compared to the Ekman layer currents $V_{Ek}$, which are at 45° to the left of the direction of the wind in the southern hemisphere. Studies of the motion of oil spills [53,54] and ice drift [55,56] in oceans also demonstrate that real trajectories are a compromise between the surface current (unaffected by waves) and the surface wind stress. Due to the number of unknowns involved, an empirical method is employed to determine the final pumice trajectory. Here, the surface velocity field $\boldsymbol{V}_S$

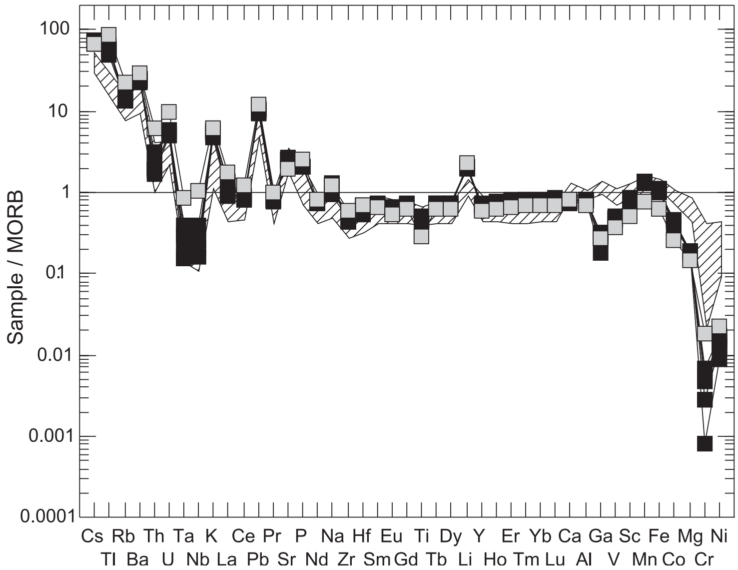


Fig. 6. Pumice clast element abundances normalised to MORB values using the extended element set and order of Pearce and Parkinson [47]. The rhyolitic pumice clast sampled from Heron Island is distinguished (grey squares), which shows slightly elevated abundances of the large ion lithophile elements, whereas all pumice clasts show strong depletions in the compatible elements, particularly Cr and Ni. Hatched field is basaltic andesite compositions from Tonga (data from Ewart et al. [20]).

is estimated as the vector combination of the surface currents and the surface wind stress modified by a constant, $\alpha$, i.e.

$$\boldsymbol{V}_{\mathrm{S}} = V_{\mathrm{Ek}} + V_{\mathrm{Geo}} + V_{\varphi} + \alpha\tau \qquad (1)$$

where $V_{\mathrm{Ek}}$, $V_{\mathrm{Geo}}$, and $V_{\varphi}$ are the surface velocity components from the wind-driven Ekman layer, the geostrophic currents driven by SSH anomalies, and the small sea surface temperature correction, respectively; $\tau$ is the surface wind stress field, and $\alpha$, a constant of units $m^2$.

Given the location and time of the generation of the pumice raft (i.e., the volcanic eruption) and the observational constraint at Kandavu Island (Fiji) ~45 days later, an optimal value of $\alpha$ is calculated that produces a trajectory from the origin to Fiji in the required time. Using this value for $\alpha$, the entire pumice trajectory can be calculated. Because the Fiji observations provide a range in location and time of the pumice observations, multiple (2112) values for $\alpha$ and the associated trajectories are calculated. Each trajectory is calculated using a fourth-order Runga–Kutta advection scheme with the velocity field interpolated bilinearly in space and linearly in time. It should be noted that given the spatial resolution of the data ($1° \times 1°$), the effects of small Pacific islands on the trajectories have been ignored.

### *6.2. Trajectory model*

The optimized values of $\alpha$, which give trajectories that best reproduce the observations of pumice from the eruption site to the Fijian islands, have a mean of 1.282 $m^2$ and a standard deviation of 0.142 $m^2$. This value produces a combined wave and direct wind effect on the pumice whose magnitude is 60% greater than the surface currents due to $V_{\mathrm{Ek}}$, $V_{\mathrm{Geo}}$, and $V_{\varphi}$. This combined effect compares to an increase of around 40% produced by waves only as found by Perrie et al. [51]. A pertinent example of the important influence that prevailing winds have on pumice raft dispersal was observations made of the floating pumice lapilli blanket following the 23 September 1952 eruption at Myojinsho volcano, Japan [57]. The pumice raft drifted in the direction of the prevailing winds (southeastward), whereas a mass of tephra suspended in the water column, being transported by the ocean currents only, separated from the pumice and extended southwestward [57].

Fig. 7 presents the modelled pumice trajectories and allows us to track the dispersal of pumice from Volcano 0403-091 to eastern Australia. Clearly, all the trajectories pass to the south of the main Fijian island of Viti Levu but toward the island of Kandavu where the pumice was first observed. No trajectories pass to the north of Viti Levu (through the Koro Sea) despite some observations of pumice rafts being made in this region [30]. These occurrences are likely however, because some of the pumice trajectories were deviated due to interaction with the Fijian islands themselves. Given the constraints of data resolution, this interaction cannot be resolved in the current study.

The pumice headed almost due west at first, passing south of the main Fijian islands before a rapid change to a southward course in late January 2002. This southward deflection was due to a persistent low-pressure system located southwest of New Caledonia. The pumice then continued to drift on a WNW course passing between Vanuatu and New Caledonia, eventually reaching the Coral Sea and Australian continental shelf off northern Queensland. Throughout the course of the pumice raft journey, the trajectories dispersed continuously except for a period in the first half of February 2002. During this time, Cyclone Claudia, a category 1 cyclone, formed to the west of New Caledonia, in front of the modelled lead pumice rafts. The effect was to blow the pumice back toward the ESE causing the trajectories to temporarily converge, thus briefly reversing dispersion of the pumice raft. This is a somewhat counterintuitive effect as a cyclone would be expected to dramatically disrupt the integrity of the pumice raft(s). The nature and intensity of the cyclonic effects, however, are dependent on the relative positions of the cyclone and pumice raft.

The trajectory analysis predicts arrival of the pumice raft into the Coral Sea within 8–9 months after the eruption (Fig. 7). Due to a lack of ocean–current data, trajectory analysis for the final stages of pumice dispersal cannot be resolved for shelfal regions along the eastern Australian coast. Oceanographically, the eastern coast of Australia is influenced by a southward-flowing, warm-water,

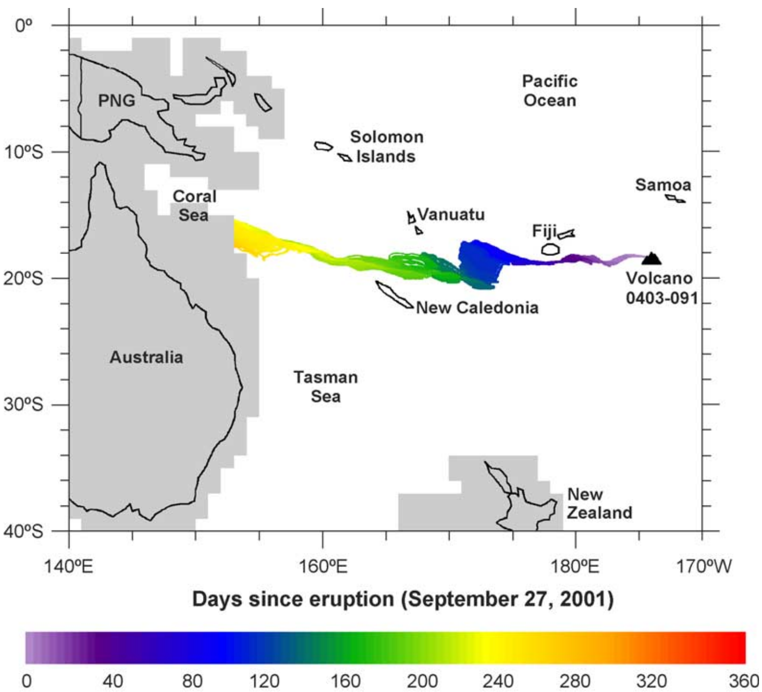


Fig. 7. Trajectories of pumice from an integration of the surface velocity field with values of $\alpha$ in the range of $1.282\pm0.142$ $m^2$. The grey area represents continental shelves of <1000 m depth, where geostrophic ocean currents were not calculated. PNG, Papua New Guinea.

western boundary current, the East Australian Current (EAC; Fig. 1) system [58,59]. The southwards movement of pumice from the western Coral Sea along the eastern Australian coast was accomplished by the EAC. According to the trajectories of Fig. 7, the pumice arrived in the source region for the EAC during winter, when the EAC is weakest. Given the time and location of sightings of pumice strandings on the east Australian coast, pumice needed to move south with the EAC at an average velocity of ~20 cm $s^{-1}$, which is comparable to the weak winter EAC surface velocities (e.g., [58]). Beaching of the pumice was further facilitated by the easterly trade winds at this time [33–35], driving the surface Ekman flux and pumice rafts shoreward.

## 7. Discussion

### *7.1. Significance of sea-rafted pumice*

Sea-rafted pumice is significant for several reasons. (1) It can provide a record of submarine silicic explosive volcanism that may not be otherwise recorded [7]. For example, most of the volcanic centres in the Tofua volcanic arc are quite isolated and not visited on a regular basis, so small-scale activity may go unobserved and hence unreported (P.W. Taylor, personal communication, 2003). Furthermore, the main phase for the eruption from Volcano 0403-091 was at night based on timing of associated seismic activity [30]. (2) Sea-rafted pumice can be used as natural "drift bottle" experiments to constrain large-scale oceanic and integrated surface wind–ocean circulation patterns and transport rates (e.g., [9,10], this study). (3) Pumice rafts are an important mechanism for the long-range dispersal of coral [26,27] and other attached biota. The important implication for those organisms with short larval or planktic egg stages is that pumice rafts may act as vectors for otherwise restricted benthic or relatively sendentary taxa. For example, the potential for dispersal of archaeogastropods, which lack planktonic and planktotrophic larval stages (they possess short-lived planktonic egg stages only) is increased by pumice rafting. (4) Masses of floating pumice may be thick and coherent enough to transport larger objects and materials, leading to important anthropological implications. Intriguing observations of pumice rafts from the 1883 Krakatau eruption reported in Simkin and Fiske [5] include the transport of bones of eruption victims >6000 km to east Africa in 10 months; other pumice masses transporting trees (and possibly seeds) to Micronesia; and some floating masses were so thick as to support standing men. (5) Stranded pumice deposits have been used to date and correlate Holocene beach deposits including archeological sites [3,22], assuming an instantaneous and widespread stranding of pumice for beach deposit correlations. (6) Strandings of sea-rafted pumice represent the only substantial mechanism of contributing nutrients or chemical elements, especially the micronutrients of Si, Fe, Mn, Zn, Cu, and Mo necessary for plant growth to the soils of coral cay islands that are otherwise strongly impoverished [60]. Drift pumice has been crushed and added as a fertiliser to cultivated atoll soils [61]. (7) Pumice rafts can pose a volcanic hazard and be disruptive to shipping or be a visual pollutant to tourist beaches and waters [6,23,31,40]. (8) Sea-rafted pumice can also have harmful biological effects. Observations of the Home Reef eruption in 1984 indicated that a large kill of deep-sea fish followed the arrival of pumice rafts in the Lau Island Group [40], while the pumice rafts asphyxiated marine life when stranded in shallow water, and large fish jumping onto the pumice were apparently unable to penetrate through it and back to safety [23]. The pumice rafts also have the potential to introduce harmful invasive species to pristine areas and circumvent quarantine measures.

### *7.2. Pumice floatation*

The generation and longevity of large volumes of floating pumice rafts, such as observed following the September 2001 eruption from Volcano 0403-091, raise two important questions. First, how is hot pumice erupted from submarine vents and then transferred through the water column to form accumulations of cooled, yet buoyant pumice rafts at the ocean surface? There are few published data concerning the details of subaqueous eruptive processes [62], particularly for submarine silicic explosive eruptions. Second, for how long can the sea-rafted pumice material remain buoyant? The very low density enables pumice to float on water for long periods of time and travel thousands of kilometres, but studies have shown that cold pumice will slowly absorb water into vesicles and eventually sink [36,37].

Although when first erupted, pumice is highly buoyant because of high-temperature magmatic gases that have inflated vesicles, it can have very different settling and hydrodynamic behaviours depending on the environment in which it cools [8]. Two pyroxene geothermometry indicate preeruptive magmatic temperatures were ~1000 °C for the eruption from Volcano 0403-091 (Fig. 4B). Experimental studies have indicated that hot pumice (>150 °C) often sinks immediately when put in water as hot dry air inside is rapidly cooled and contracts in volume, sucking water into most vesicles [36]. The generation of pumice rafts from submarine explosive eruptions is somewhat counterintuitive in light of these experimental results, as the hot pumice and tephra ejected into the water column should rapidly ingest seawater into vesicle pore spaces and sink. However, it remains unclear how applicable the dry air-filled pumice experiments are to subaqueous eruptions, where pumice vesicles will be filled with high-temperature, water-dominated magmatic gases.

One mechanism to generate the pumice rafts is for eruption columns to breach the sea surface, ejecting tephra into the air, which then have the opportunity to cool by ingesting air and become ‘floaters’ when the tephra falls back into the sea [8]. However, of the few observations made for the September–October 2001 eruption from Volcano 0403-091, there were no indications of a substantial eruption column breaching the sea surface (cf., 1984 Home Reef eruption [40]), but the eruption may have been capable of piercing the water column to produce a low tephra fountain, with water largely excluded from the core of the eruption column. Direct contact between the erupting tephra and water therefore may not have been ubiquitous during the potentially entirely submarine eruption from Volcano 0403-091. Based on interpretations for the 1963 Surtla eruption, a steam cupola or sheath (i.e., water exclusion zone, where particles are transported in part through steam) may have developed during relatively high and sustained discharge phases of the eruption [63,64]. Water exclusion zones would have shielded much of the erupting tephra from the ambient water, and limited rapid ingestion of seawater into the pumice clasts, waterlogging and sinking. Thermal convection of ambient water, the rise of the steam cupola, and gas-supported jets of tephra exiting the vent will promote the rise of hot pumice clasts towards the sea surface, where vapour films developed around clasts may further prevent saturation until clast surfaces cool below boiling [17,65].

On contact with water, cold pumice clasts initially, rapidly absorb water by the flooding of large vesicles connected directly to the exterior, followed by a phase of slow, steady absorption over periods of up to many years [36,37,66]. BET nitrogen absorption and Hg-porisometry studies indicate that nearly all pore space in pumice is interconnected, thus facilitating exchange of air for water, such that all pumice should eventually sink when immersed in water [36]. Experimental studies on the duration of pumice floatation have dealt mostly with pumice material <2 cm in diameter that remained afloat for weeks to months [37], whereas cobble-sized rhyolitic pumice has been observed to remain afloat for ~2 years [10]. Pumice raft material from the 2001 eruption of Volcano 0403-091 stranded along eastern Australian coastlines comprised pumice almost entirely >2 cm in diameter, with the finer size fractions of pumice expected to have been removed during dispersal via waterlogging and sinking to contribute to shelfal and deep-sea sedimentation along the raft trajectory.

Several factors may operate to maintain pumice floatation and permit pumice rafts to survive for years. Large pumice may float with significant freeboard, so that the effective surface area across which water can penetrate is lower, and the larger clasts will also have a lower proportion of vesicles opening directly to the clast surface, thereby reducing its effective permeability [37]. Pore space in the pumice clasts may not all be interconnected, preventing gas escape and replacement by water (i.e., hydraulic conductivity). Although available BET nitrogen absorption and Hg-porisometry data indicate that nearly all pore space is interconnected [36], it is increasingly recognised that pumice from silicic explosive eruptions do show variations in vesicle-population size distributions, shapes, clast permeabilities, and vesicle connectivity (e.g., [67–69]). It was observed in this study that many individual clasts from the pumice rafts were heterogeneous in terms of vesicle textures and population size distributions suggesting that pumice saturation will not be uniform at individual clast scales and particularly so for the larger clasts. Experimental studies have also not considered that fouling of clast surfaces (e.g., by algae; Fig. 3B, D) may aid in reducing pumice saturation and its effective permeability with time by blocking direct connections of vesicles to the exterior. Growth of organisms however may ultimately overload the pumice and result in sinking of the clast. Water-logging of pumice can also be reduced and reversed when pumice is stranded on beaches for significant periods before being reentrained into the oceans by storm and wave activity.

### 7.3. Ecological impacts

Knowledge of dispersal mechanisms, dispersal routes, and dispersal range is vital to our understanding of biogeography and evolution [27,28]. The transport of marine fouling agents and flotsam and shipping vectors for biological interchange have been addressed by many authors. Some studies have indicated the importance of geological rafts (pumice) as a modern dispersal agent, particularly in the Pacific, and by inference, rafting is a process that occurred in the geological past [26,27,39,70]. Despite the small-volume explosive eruption from Volcano 0403-091, more than $10^{10}$ individual pumice clasts or rafts were produced, and for the 1984 Home Reef eruption, $>10^{14}$ individual clasts forming the pumice rafts were estimated [26]. Thus, innumerable rafting opportunities occur for opportunistic organisms following such pumice-producing explosive eruptions, as well as a transport mechanism that can survive for years and travel many thousands of kilometres.

The potential of pumice to remain afloat for years and drift thousands of kilometres fundamentally changes the dispersal range or limitations for many marine organisms, especially those with short planktonic larval stages. Although floating pumice has been shown to be an important long-distance rafting mechanism for corals [26–28,70], the coincidence of pumice rafts and coral spawning events must also be a critical factor. It is noteworthy that the eruption and generation of the pumice rafts in this instance, just preceded late Spring coral spawning events in the southwest Pacific. It is clear from the size and nature of the attached biota to the pumice clasts that transport times allowed colonisation for up to a year or more. This implies many organisms attached to pumice outside the immediate eastern Australian zone and were subsequently transported down the eastern coast of Australia. The trajectory analysis (Fig. 7) indicates the New Caledonia–Vanuatu region as a probable source area for attached biota. Furthermore, it has been noted that some coral colonies can grow to reproductive size while still attached to the pumice [26]. The several months of transportation time provides the opportunity for biogeographic exchange, and it may be a mechanism by which biogeographic mixing in the marine realm occurs naturally.

Of potential importance is that whilst concentrated efforts on biosecurity are made with respect to shipping, contents of ballast and the use of antifouling mechanisms on shipping (e.g., [71]), pumice rafting may be a vector that circumvents these quarantine precautions. An example of this are the serpulids observed fouling the pumice clasts. The fouling serpulid *Hydroides elegans* [72] is a designated marine pest in Australia [73], and the biological and economic impact of very large settlements of this species elsewhere have previously been substantial [74].

In conclusion, there are significant geological implications for the transport of sessile taxa over large distances by pumice rafts. Some outstanding questions are the following: do elevated periods of major silicic explosive volcanicity result in loss of endemism? Are speciation events and volcanicity linked by the availability of this transport vector for some benthic taxa? Speciation events and volcanicity may be linked such that the periodic development of globalism for some taxa (e.g., corals, gastropods, bryozoa) may correlate in time and/or space with particular igneous events. It is clear that silicic explosive volcanism is necessary to firstly, produce the geologic (pumice) raft material; secondly, have significant extent (e.g., continent-scale) and volume to have global significance and impact; and thirdly, be proximal to ocean basins for the pumiceous material to be deposited. Silicic explosive eruptions have produced some of the largest volume deposits ever known (e.g., [75]), and it is being increasingly recognised that there are continental-scale (>1500 km long), , and long-lived silicic igneous provinces capable of producing $>10^6$ $km^3$ of silicic pumice-rich pyroclastic material [76] that can be emplaced into ocean basins. Such provinces may thus be an unrecognised trigger for the loss of endemism for some opportunistic species via large-scale pumice rafting processes.

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## Appendix A

Major element analyses were performed on ignited rock powders. Approximately 1 g of powder was dried at 110 °C overnight and reweighed before being heated in a furnace oven to 1000 °C for approximately 2 h. After cooling, the samples were reweighed to determine loss-on-ignition. Samples were analysed for all 10 major oxides at the Department of Earth Sciences, University of Queensland. Major elements were determined using a lithium metaborate fusion method of ignited powders at a flux to sample ratio of 4:1. The fusion beads were completely dissolved in 1 M nitric acid. The resultant solutions were run on a PE3300 DV ICP-OES by calibrating the response against that of JGS reference materials JA2 and JB2 using 5 ppm Lutetium as an internal standard. Iron is determined as total ferric iron and expressed as $Fe_2O_3T$ (Table 2).

To remove sea salt, approximately 1 g of the powdered samples was placed in a tube with 12 ml of MQ, shook, and then left standing briefly before being centrifuged. The water was then decanted, and this process was repeated two more times before the washed powders were dried in fused silica crucibles in an oven, and finally left to cool to reach ambient temperature. Trace and rare earth elements were analysed by inductively coupled plasma-mass spectrometry (ICP-MS) at the ACQUIRE Laboratory of the University of Queensland.

Polished and carbon-coated thin sections were analysed by electron microprobe to determine mineral and glass chemistry at the Centre for Microscopy and Microanalysis, University of Queensland, using a JEOL 8800-L (wavelength dispersive) electron microprobe. Analyses were performed with an accelerating voltage of 15 kV and with a probe current of 15 nA. Data were corrected online using the ZAF correction procedure. Pyroxene and magnetite were analysed with a 1-μm probe diameter, whereas plagioclase and glass were analysed using a probe diameter of 10 μm to avoid volatilisation of alkali elements. During glass analyses, the stage was moved slowly and continuously to also reduce the effects of alkali migration from the probe target volume [77]. Precision and accuracy for each analytical run were checked by comparing results of a suite of geological and oxide standards of known composition, analysed at the start and end of each analytical run.

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