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REVIEW

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Evidence at source for the mid-fifteenth century eruption of Kuwae, Vanuatu

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Abstract

The mid-fifteenth century eruption of the Kuwae volcano (Vanuatu), known locally as the Tombuk eruption, is widely but not universally considered responsible for one of the three largest atmospheric sulphate events of the past millennium. Questions remain about its precise magnitude and global signature. This controversy reflects a lack of modern description and characterisation of the eruption at source. Through a comprehensive survey of the published and unpublished literature, we review the available historical, archaeological and volcanological evidence for the Kuwae eruption. All sources suggest an eruption with major impacts regionally. The eruption formed a submarine caldera, collapsing the former landmass of Kuwae and leaving two smaller adjacent islands, Epi and Tongoa. On other islands to the immediate south and north, volcanic impacts were variable, enabling survival of refugees from Kuwae, who later recolonised the remnant islands. This review raises hypotheses and questions to be tested through a new multi-disciplinary field research program that aims to establish the precise date and magnitude of the Tombuk eruption, allowing questions of global impact to be addressed with more confidence.

Keywords Kuwae, Tongoa, Vanuatu, Eruption, Fifteenth century

Introduction

Accurate identification of source volcanoes for large eruptions is a prerequisite for detailed modelling of the role of volcanic forcing in past and future climates (Self 2006; Sigl et al. 2015; Newhall et al. 2018). One of the three largest volcanic climate-forcing events of the past 1000 years (AD 1257) was recently identified as a VEI 7 event at Samalas volcano (Lombok, Indonesia). This identification enabled modelling of the spatial and temporal climate response (Lavigne et al. 2013; Guillet et al. 2017) and detailed reconstruction of the societal and economic impacts of the eruption (Campbell 2017). Tambora, Indonesia, is responsible for the second known forcing event at AD 1815, while one of possibly two events in the AD 1450s has been attributed to Kuwae, Vanuatu (Plummer et al. 2012; Sigl et al. 2013). Of the three, Kuwae remains the most contentious, with a growing secondary literature either accepting the link without question (Gao et al. 2006; Witter and Self 2007), rejecting it as insignificant (Nemeth et al. 2007; Toohey and Sigl 2017; Hartman et al. 2019) or questioning if the event dates earlier or later than the 1450s (Global Volcanism Program 2013; Bauch 2017). This persistent uncertainty reflects the poorly constrained chronology and scale details for the event at source, as well as our limited understanding of its likely regional and global impacts.

The Kuwae volcano was first linked to global signatures for a major eruptive event during the 1990s. Field studies by geologists Monzier, Robin and Eissen suggested the presence of a significant submarine crater between the islands of Epi and Tongoa (Fig. 1), resulting from an eruption which they dated initially to AD ~1425 (Monzier et al. 1994). Emerging evidence for a substantial

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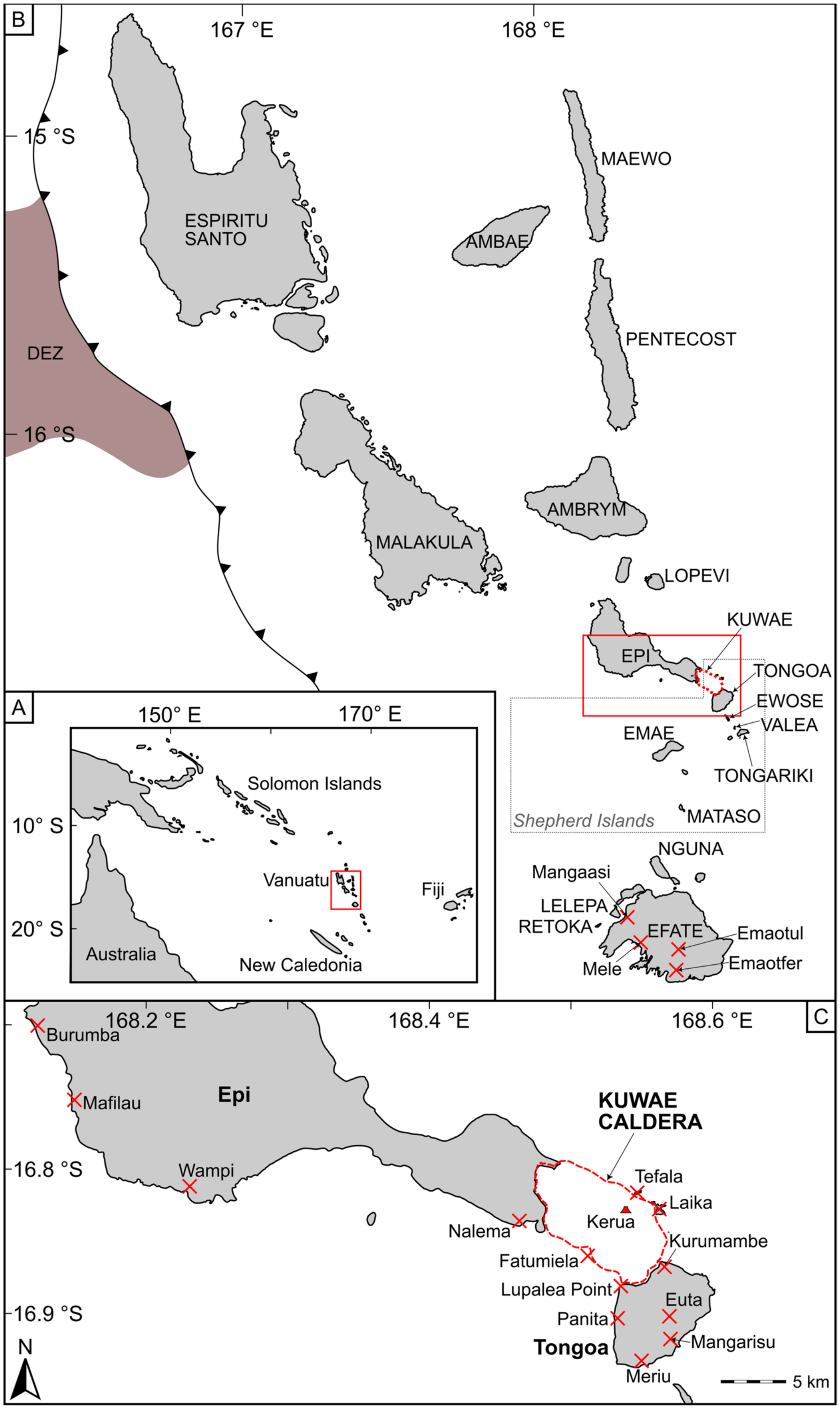

Fig. 1 **A** Location map for Vanuatu in its regional context, showing the location of the regional insert. **B** Regional insert, showing the location of the subduction zone, as well as the modern location of the submarine ridge of the D'Entrecasteaux Zone (DEZ) and the location of the local insert. **C** Local insert, displaying the islands of Epi and Tongoa and the Kuwae caldera

atmospheric sulphate event in Antarctic ice cores, dated to AD 1450 (Delmas et al. 1992), was assumed to correspond to the eruption of Kuwae, and a revised date of AD 1452 for the eruption was adopted (Robin et al. 1994). This link between Kuwae and the global proxy evidence for a major mid-15th century forcing event remains widely accepted, and Kuwae has since been linked to dramatic climate-induced social impacts across the globe (Gill 2000; Atwell 2001; Boucheron 2012; Kužić 2012). Because much of this secondary literature on Kuwae is not informed by an understanding of the nature of the evidence at source, the first step in a critical appraisal of the claims for Kuwae is to review the totality of that evidence and to assess and understand it within its local historical, archaeological and geological contexts.

This paper provides the first comprehensive and critical survey of the available literature on the mid-fifteenth century eruptive event at the Kuwae volcano, known locally as the Tombuk eruption, drawing on published and unpublished sources from a range of disciplines, including anthropology, archaeology, history, linguistics, and geology. This literature is addressed in three sections: 1) the historical evidence for the eruption, which consists largely of local oral traditions that have been documented continuously since the 1890s; 2) the archaeological evidence, deriving mostly from excavations during the 1960s; and 3) the available geological field evidence, gathered since the 1980s. The review concludes with preliminary responses to three questions: What level of confidence can we have in current understandings of the Kuwae event? What are the particular gaps in knowledge that require attention through further research? And how might a multi-disciplinary approach tackle these questions, drawing on contributions from the individual disciplines discussed here?

Historical evidence

Scientific discovery and field exploration of the Tombuk eruption of Kuwae volcano has been guided at every step by exceptional oral historical traditions of local communities throughout the Shepherd Islands of central Vanuatu (Fig. 1). These traditions record a hierarchical system of chiefly titles that extends across the Shepherd Islands and describe the early colonisation of a single large island known as Kuwae. The histories of individual chiefly titles and the lineages of the successive holders of each title remain important today, because they are charters for the distribution of rights to land and resources. Strong connections between knowledge of the eruption and its aftermath, which anchor claims to chiefly titles and land, ensure that multiple narratives continue to be transmitted and closely monitored within communities for accuracy. While the oral traditions cannot provide precise chronological estimates of the date of the eruption, they are considered locally to be accurate in describing sequences of volcanic events, with details that are otherwise inaccessible (Ballard 2021).

Presbyterian missionary Oscar Michelsen, resident on Tongoa Island from 1879 to 1932, was the first to document local narratives of a massive volcanic eruption (Michelsen 1890). More detailed and elaborate versions of these stories have been recorded since by other missionaries, anthropologists, linguists and geologists (Schütz 1972; Rivierre 1996; Ballard 2020). Guided by local communities, missionaries also documented the first archaeological evidence of the eruption, including pottery sherds and shell and stone tools recovered from layers beneath a tephra horizon exposed in cliffs on the south-eastern side of Tongoa (MacLachlan 1940; Miller 1981; Nottage 1988). Colonial official Bernard Hébert recorded Tongoan terms for the pre- and post-eruptive layers, suggesting a local awareness of the relationship between geological processes and the events described in oral traditions (Hébert 1965). Early geological investigations of the Kuwae volcano were also guided by local traditions (Frederick et al. 1893) and ultimately confirmed the presence of a substantial submarine caldera between the islands of Epi and Tongoa (Carney and Macfarlane 1977) (Fig. 1). Hébert and others attempted to estimate the age of the eruption based on a limited understanding of local genealogies, generating dates between the late 16th and mid-17th centuries. A more thorough attempt to document chiefly genealogies found an average of 26 generations of settlement on Kuwae before the eruption and a further 22 generations after the eruption and the recolonisation of Tongoa (Luders 1996).

In the course of interviews in every settlement on Efate and the Shepherd Islands during the 1950s, anthropologist Jean Guiart recorded numerous narratives relating to the Tombuk eruption and its aftermath (Guiart 1973). His work established that the eruption reconfigured the social and linguistic landscape on a regional scale (Clark 1996). Later ethnographic research has confirmed the continuing importance of the eruption in contemporary land disputes and succession of chiefly titles (Sherkin 1999; Calandra 2017). Archaeologist José Garanger further explored Guiart's claims for the historical accuracy of the oral traditions, excavating at numerous sites on Tongoa and the other Shepherd Islands during the 1960s (Garanger 1972) (see below).

The oral traditions suggest that Kuwae was a single landmass, likely encompassing the islands of Epi and Tongoa, as well as the sea between them (Fig. 1C). Active volcanic islands such as Lopevi and Ambrym (Fig. 1B) have eruptions that are regularly visible to the north, but Kuwae's residents were apparently unaware of the presence of an active eruptive centre on the island itself. A narrative, known almost universally in the region, describes the shaming of a young man on Kuwae, named Tombuk or Bae, tricked into sleeping with his mother. Seeking revenge, he visited an uncle on the nearby Lopevi volcano, who supplied him with a magic lizard. Secretly burying the lizard at the base of a tree on Kuwae, Tombuk invited his enemies to a feast at which he burst a series of inflated pig's bladders, triggering increasingly larger earthquakes. Alerted by these earthquakes, many fled the island by canoe, but those who remained were killed when the last bladder burst and the ground erupted beneath them. The last canoes to leave Kuwae were swamped by a tsunami caused by the eruption. Names for the destroyed settlements and canoe landing sites along the former coastline of Kuwae are still recalled[27].

In a second widely told narrative, the only survivors on the remnants of Kuwae to the east of the eruptive centre were an old woman, Tarifekit, who hid in a cave, and a young man, Asingmet, who took refuge in a hollow log drum. They were rescued and adopted by a chief from nearby Makura Island. When Asingmet reached adulthood on Makura, he returned to the southern coast of the new island of Tongoa, which was now habitable. As the initial re-discoverer and settler of Tongoa, he was renamed Matanauretong ('the first on the island of Tongoa'), and later given the formal title Ti Tongoa Liseiriki, as the paramount chief of the new island. His lineage descendants still hold some of the most senior titles on the island today. While these two narratives are the most widely known and recounted in the region, there are many other stories relating to individual chiefly lineages that provide further details of their own experiences of the eruption and their ultimate return to Tongoa. There are also numerous forms of physical evidence in existence today, such as memorial stones set up and specific trees planted on returning to Tongoa, or fragments of the original canoes used in the resettlement of the island (Ballard 2020) (Fig. 2).

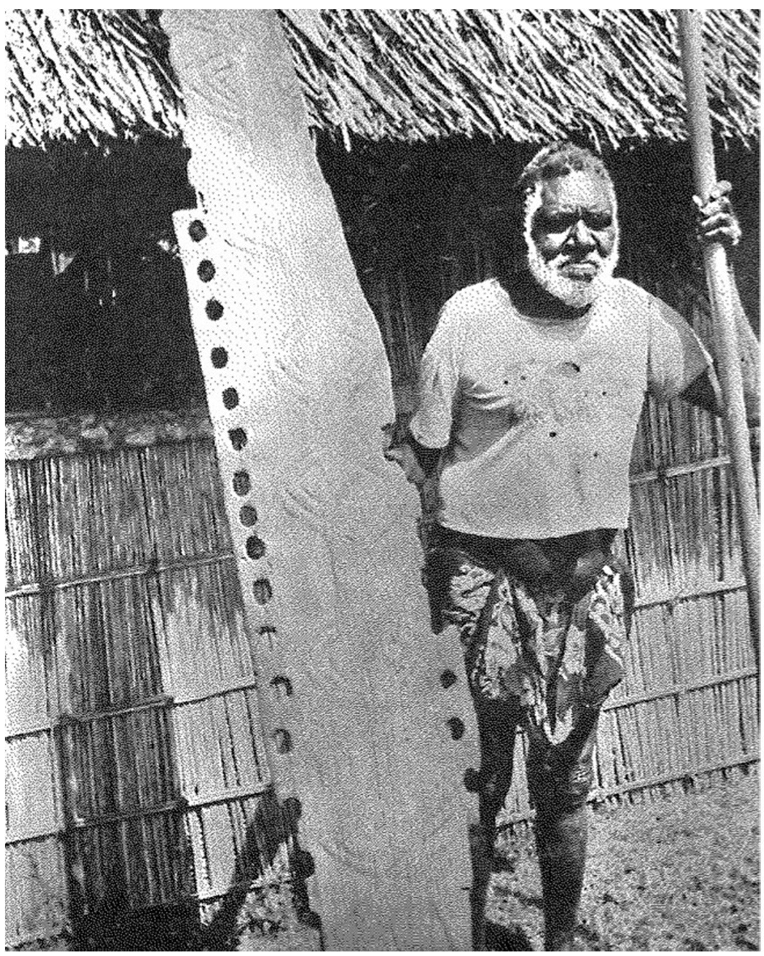

Fig. 2 Heirloom wash strake from a canoe used to recolonise the new island of Tongoa after the Tombuk eruption (Bernard Hébert)(Hébert 1971)

Archaeological evidence

The first archaeological investigations associated with Kuwae were undertaken by José Garanger in 1964. His specific goal was to investigate the oral traditions relating to the Tombuk eruption and its historical links to various prominent chiefs including Ti Tongoa Liseiriki and Roi Mata, a highly influential chief on Efate (Garanger 1972). During 1964 and 1966-1967, Garanger excavated large areas on a number of islands including Efate, the small nearshore islands of Lelepa and Mele, and the communal grave associated with Roi Mata on Retoka Island. In the Shepherd Islands, he focused on Tongoa and Makura. His research remains the only archaeological fieldwork carried out on these two islands.

Garanger established a robust pottery sequence spanning an almost 2500-year period. This sequence demonstrated synchronous changes in style and high levels of interconnectivity across Efate and the Shepherd Islands (Garanger 1972; Bedford 2006). First human settlement in the Kuwae area at ca. 2900 yr BP is now linked to the appearance of Lapita pottery, followed by Erueti pottery from 2800-2200 yr BP, and then by Mangaasi ware from 2200 to ca.1200 yr BP. Pottery production apparently ended on Efate with Mangaasi ware, but continued on Tongoa (then Kuwae) in the form of the distinctive Aknau ware, indicating some degree of cultural divergence during this period. The Tombuk eruption at ca. 500 yr BP (AD ~1450) marked and caused the end of all pottery production in the region (Bedford 2006).

Garanger's investigation of pre-eruption settlement focused on Mangarisu in southeast Tongoa, where archaeological materials were exposed in coastal cliff faces. Eight sites were excavated, often to a depth of almost 3 m (Fig. 3), but many of the excavations were largely sterile of evidence for occupation. The most productive sites were Euta (TO-11), Aknau (TO-22, near Mangarisu) and Lamalake (TO-23, near Mangarisu), which all contained varying quantities of both Early and Late Mangaasi pottery ware, together with the later Aknau ware (Garanger 1972). The pottery-bearing levels on Tongoa were all sealed by coarse pumice-rich deposits associated with the initial stage of the Tombuk eruption, ranging in thickness from 0.5-1 m.

The results from excavations on the island of Makura broadly matched those from Tongoa, with the same pottery sequence identified at a series of sites (Garanger 1972). Unlike Tongoa, distinct eruption deposits were not detected at the sites on Makura, although tsunami deposits were identified, including some just above the Aknau cultural layer. Garanger interpreted the abrupt termination of the Aknau phase as a consequence of the Tombuk eruption. Garanger's pre-eruptive sequence from the Shepherd Islands has been confirmed by subsequent investigations on Efate and elsewhere, demonstrating interconnected settlement across the region associated with either Mangaasi or the later Aknau pottery traditions. No pottery that post-dates the Tombuk eruption has been found anywhere in the Shepherd Islands or Efate (Bedford 2006, 2009).

Garanger attempted to date the Tombuk eruption directly using two charcoal samples extracted from exposed volcanic layers in the cliffs near Meriu village, in south Tongoa (Garanger 1972). These yielded dates of AD 1320±80 and AD 1460±37. The first sample, unidentified 'burnt wood taken from the erupted material of Mweriu', came from 70 cm above the present beach and 8

Fig. 3 Garanger's site TO-27, above Mangarisu cliff, showing the scale and depth of his excavation; Ewose and Valea islands in the distance (José Garanger) (Garanger 1972, Figure 239)

m below the top of the cliff. The other sample he attributed to the geologist Espirat, who had taken it from the same Mweriu deposits, possibly in 1963 (Espirat 1964; Garanger 1972). However, these dates from Garanger's work in the 1960s all lacked the enhanced precision of today's determinations. No attempt was made to identify charcoal to species, in order to understand any in-built age, and the dating of bone at that time was particularly unreliable (Bronk Ramsey 2008). Later dating undertaken by geologists (Monzier et al. 1994; Robin et al. 1994), discussed below, faced similar challenges in relation to accuracy. Charcoal samples were identified to species but inbuilt age may still have been a factor as no details are provided on the exact sections of the samples that were dated. Conventional radiocarbon dating undertaken at the time also gave standard deviations of 50 years or more when calibrated.

The post-eruptive deposits were also extensively examined by Garanger. On Tongoa, he was guided by local communities to a series of former settlement sites, including ceremonial and burial areas. Many sites are linked to named individuals associated with the initial re-settlement of the island (Garanger 1972). Several of the sites featured visible standing stones, stone platforms and stone alignments. Three sites were also productive in terms of subsurface remains, including burials at Mangarisu (TO-28 and TO-29) and Panita (TO-51). Five mortuary sites were discovered, with 22 burial features and skeletal remains of more than 31 adults, six of whom were associated with named individuals (Garanger 1972; Valentin et al. 2011). The only dating for any of these sites was on a collagen sample from the individual thought to have been Ti Tongoa Liseiriki, which returned a date of AD 1475±85, post-dating the eruption by an interval that would allow for the recolonisation of Tongoa. However, as noted above, none of the dates can now be considered reliable, and the stratigraphy of several of the post-eruption sites investigated by Garanger on Tongoa suggests that the chronology of resettlement may not be as straightforward as implied by the date from the Liseiriki burial. The very extensive sites at Mangarisu comprised a series of stone structures and burial features said to be associated with some of the first returnees, but they clearly date to a period after substantial soil development or accumulation on top of the Tombuk eruptive deposits. All the graves from these sites appear to be dug either into the upper soil, or through it into lower deposits.

On the island of Makura, post-eruptive evidence of settlement was found in the interior of the island, at an area known as Tavia, where two test pits were dug to a depth of 80 cm. There is no mention of volcanic deposits but, at the base of both test pits, cooking features were dated to AD 1690±80 (Garanger 1972).

Beyond Tongoa and the Shepherd Islands

To the south of the Shepherd Islands, on Efate and its offshore islands, archaeological evidence for either the Tombuk or other Kuwae volcanic deposits is absent, despite previous claims (Bedford 2006; Bedford et al. 2006). Following extensive excavations at the Mangaasi site on the west coast of Efate in 1967, Garanger interpreted a unit as a tsunami deposit related to the Tombuk eruption (Garanger 1972). This mention was repeated in a later interpretation of the site's stratigraphy, along with an earlier tsunami deposit thought to represent the major Ambrym caldera event of ca. 2000 yr BP (Spriggs 1997). Later excavations at the same site, in an area further inland, also interpreted tephra-rich layers to be related to the eruptions at Ambrym and Kuwae (Bedford et al. 1998). However, subsequent chemical analyses have associated the earlier tephra-rich deposit with an eruption of nearby Nguna at ca. 2200 yr BP (Bedford 2006; Bedford et al. 2006), while the more recent deposits are now interpreted as landslide debris sourced from the nearby cliffs containing ~1 Ma pumice from the Efate volcanics. Mangaasi-style pottery is found on the ground surface across Nguna Island, some 25 km closer to Tongoa than Efate, indicating very low terrestrial tephra accumulation following the end of pottery production on the island at ca. 1200 yr BP.

To the north and west of Kuwae caldera, Epi Island has seen only limited archaeological investigation, although Malakula and its nearshore islands to the northwest have had more intensive excavation (Bedford 2006; Hoffmann 2006; Valentin et al. 2011). On Epi, two coastal sites were investigated on the central west coast, one at Mafilau and the other at Burumba, some 36 km from the Kuwae caldera. Both Epi sites may show evidence of the Tombuk eruption (Stuart Bedford, unpublished data), although there is limited chronology information and no chemical analyses have been undertaken (Bedford and Spriggs 2008). These possible volcanic deposits may also record eruptions of Lopevi or other small volcanic centres on Epi. Many excavations on Malakula and its nearshore islands show tephra deposits from nearby active volcanoes (Ambrym, Lopevi) (Bedford 2003), with no evidence yet for Kuwae tephra (Stuart Bedford, unpublished data).

Garanger's research in the Shepherd Islands confirmed the cataclysmic Tombuk eruption known from oral tradition and revealed archaeological evidence of both pre- and post-eruptive settlement. The pre-eruptive cultural deposits on both Tongoa and Makura can be correlated with the chronologies established for Efate, but the post-eruptive chronology remains poorly defined. The archaeological record suggests that the Tombuk eruption was massively destructive in the proximal environment, but that its impacts were less catastrophic on islands to the immediate south and north, which provided refugia for fleeing populations.

Geological evidence

Tectonic setting and volcanoes of Vanuatu

Volcanism in Vanuatu is generated by subduction of the Australian Plate beneath the oceanic crust of the Pacific plate since 10 Ma(Meffre and Crawford 2001; Schellart et al. 2006). Convergence rates are lowest in the central block of the Vanuatu arc (14-17°S), caused by the arrival of the thicker and more buoyant crust of the D'Entrecasteaux Zone (2-3 Ma; Fig. 1A) and the West Torres Massif (0.7 Ma) (Taylor 1995; Meffre and Crawford 2001; Schellart et al. 2002; Bergeot et al. 2009). The largest volcanic events (VEI 6+) in the Vanuatu arc are associated with explosive, caldera-forming eruptions of intermediate to felsic magmas from north of Efate Island (~1 Ma (Stewart et al. 2010)), Yenkahe (<40 ka, Tanna Island (Firth et al. 2015)), and Tombuk (~mid-fifteenth century; Kuwae Island (Monzier et al. 1994)). The most recent of these eruptions (Tombuk) lies near the southern boundary of the central arc block, where the subducted slab is estimated to be ~225 km deep (Hayes et al. 2012).

Morphology of the Kuwae caldera

Initial geological studies in the central islands of Vanuatu described extensive pumice-rich deposits from a large explosive eruption and postulated the source of this (and the site of the collapsed Kuwae Island) as a caldera between the present islands of Tongoa, Ewose and Tongariki (Gorton 1977). Subsequent regional bathymetric studies re-located the Kuwae caldera northward as a ~12x6 km, NW-SE-oriented basin between Epi and Tongoa islands (Carney and Macfarlane 1977). Based on studies of pyroclastic deposits on Tongoa and nearby islands, the Kuwae caldera was postulated as the source of a major eruption of VEI 6-7 (Monzier et al. 1994; Robin et al. 1994). The islets of Laika, Tefala, Tefalakiki and Fatumiela lie near the caldera rim, and an active submarine volcano, Kerua (also known as Karua), has formed in the eastern half of the caldera (Exon and Cronan 1983). The available bathymetry is not detailed enough, nor is there sufficient geophysical evidence to confirm caldera ring faults, or any compound or nested structures. Kerua has breached the surface during eruptions at least six times since the 1870s (Gorton 1977) (Fig. 4), most recently in 1974. Active hydrothermal alteration is widespread on the ocean floor, with discoloured water indicating ongoing activity (Exon and Cronan 1983; Crawford et al. 1988).

Based on 1992 bathymetry, the seafloor within the Kuwae caldera indicates two sub-zones, a SE part at ~250 m and a deeper portion at ~450 m in the NW[16]. It is not clear if these are structurally different, or the result of differential post-caldera volcanic infill. The floor is underlain by well-layered and flat-lying deposits ~225 m-thick[60], which are interpreted as pyroclastic deposits from the Kuwae eruption (Monzier et al. 1994). (Monzier et al. 1994) postulated a pre-existing topography and geology for Kuwae that was similar to the current surfaces of Epi and Tongoa[11], with an average elevation of 500-600 m asl,

Fig. 4 Eruption of the Kerua vent in the submarine crater between Tongoa and Epi islands, 1897 (Oscar Michelsen) (Michelsen 1897)

implying an overall collapse depth of between 650-950 m (Monzier et al. 1994). Assuming that the Kuwae caldera was ~45 km^2 in area, an overall collapse volume of ~32-39 km^3 was calculated, suggesting that an equivalent volume of magma was erupted (Monzier et al. 1994).

Geology of caldera margins

Western Epi comprises an uplifted sequence of andesitic, submarine lava flows, pyroclastic deposits and volcaniclastic sediments of Pleistocene age (Gorton 1977). Eastern Epi, bordering the Kuwae caldera, is dominated by uniform basaltic lavas and pyroclastic deposits (Gorton 1977). Tongoa, on the southern Kuwae caldera margin, consists mainly of a basaltic sequence of stacked lava flows and pyroclastic deposits associated with scoria and tuff cones (up to 250 m high) (Warden et al. 1972; Gorton 1977; Nemeth et al. 2007). Overlying the basaltic sequence (and a distinctive paleosol) on both Tongoa and eastern Epi are andesitic-dacitic pumice-dominated pyroclastic deposits, attributed to the mid-15th century Tombuk eruption from the Kuwae caldera (Monzier et al. 1994; Robin et al. 1994).

Proximal evidence of the very explosive Tombuk eruption includes complex pyroclastic deposit sequences of up to 150 m-thick observed in outcrops at Lupalea Point, Meriu and Mangarisu on Tongoa, and also Laika Island (Monzier et al. 1994; Robin et al. 1994) (see Fig. 1). They include a lower, mafic series (>30 m) of tuffs and lavas exposed at Lupalea Point, and an upper (120 m-thick) felsic series of pyroclastic deposits with a range of texture, grain size and bedding characteristics, described in several outcrops on Tongoa and Laika (Monzier et al. 1994; Robin et al. 1994). The mafic series is only exposed in the lower parts at Lupalea Point and includes tuff and lapilli tuff deposits, interpreted as results of phreatomagmatic volcanism, intercalated with ash and lapilli fall layers from scoria cones (Monzier et al. 1994; Robin et al. 1994). The upper parts of the cliff section at Lupalea Point comprise two ignimbrites, pumice-rich breccias and lapilli-tuffs. Overall, the Lupalea Point succession is ~70 m thick (Monzier et al. 1994; Robin et al. 1994). At sites on the eastern and southeastern coasts of Tongoa (Mangarisu and Meriu, respectively), cliffs and exposures 20-30 m high comprise similar, massive ignimbrite/pumice-rich breccias as the upper Lupalea point unit. This upper ignimbrite unit was correlated to the lower parts of 90 m-high outcrops of coarse pumice breccia and lapilli tuff deposits on Laika Island (Monzier et al. 1994; Robin et al. 1994).

A re-visit to the caldera margin sequences by (Nemeth et al. 2007) interpreted the mafic series as pre-Tombuk era deposits, i.e., older Tongoa volcanic deposits that form the caldera wall (Carney and Macfarlane 1977). (Nemeth et al. 2007) described a great diversity in textures, geometry and bedding of the felsic pyroclastic deposits linked to the Tombuk eruption. The deposits were also shown to thin rapidly on Tongoa, from >90 m to ~3 m-thick in a few kilometres, with strong depositional control by topography. Similar to earlier studies, they also noted that the eruption sequence involved a long sequence of different volcanic processes, including tephra fall, pyroclastic surges and pyroclastic flows, along with evidence for time breaks between some units. Based on the complex stratigraphy and noting clasts of older welded ignimbrites within the fifteenth-century units, (Nemeth et al. 2007) suggested that the caldera could also be a composite feature, with the fifteenth-century Tombuk event as the most recent in a series of large eruptions.

Evidence of Tombuk pyroclastic deposits on other islands

There has been no systematic search for Tombuk pyroclastic deposits on islands further away from the Kuwae caldera. In the late 1960s, pyroclastic deposits similar in texture and appearance to those on Epi and Tongoa were described and correlated from islands farther to the south and southwest, including Tongariki and Ewose (Gorton 1977), and have also been recognised in ongoing archaeological studies, especially on Emae Island (Stuart Bedford, unpublished data). Further afield, tephras with the Kuwae composition have not been noted, except for a lake-sediment sequence at Lake Emaotul (Strandberg et al. 2023) on southern Efate, along with chemically similar deposits in the nearby Emaotfer swamp (Wirrmann et al. 2011). In both cases, the tephra is dispersed over 5-10 cm as individual ash particles within peat and lake muds sites and is absent or weathered in soil sequences.

Timing and correlation of the event

Six samples dated in geological studies estimate the Tombuk eruption between AD 1420 and 1430 (Monzier et al. 1994; Robin et al. 1994), broadly confirming the archaeological determinations (Garanger 1972). On the basis of this age, the event was correlated with aerosol spikes in ice core records (Mosley-Thompson et al. 1982), and then specifically to an AD 1453 sulphur spike (Pang 1993). The ~30-year disparity in age estimates was interpreted to reflect inbuilt age of the charcoal ^{14}C determinations from the Tombuk event, and/or large error ranges associated with small sample size (Monzier et al. 1994; Robin et al. 1994). Following this correlation, Kuwae was widely accepted as the source, and AD 1453 fixed as the date of the Tombuk event (Cole-Dai et al. 2000; Stenni et al. 2002; Baroni et al. 2008; Ren et al. 2010). With increasing dating accuracy, the sulphur spike has been redated to AD 1458 (Palmer et al. 2001;

Budner and Cole-Dai 2003; Castellano et al. 2005), while other studies have identified two separate events, most commonly in AD 1453 and 1458 (Fisher et al. 1995; Ferris et al. 2011; Plummer et al. 2012; Sigl et al. 2013). Both of these events appear in ice cores in both hemispheres, but the AD 1453 event is more pronounced in Greenland ice cores, while the AD 1458 event is more pronounced in Antarctic ice cores (Plummer et al. 2012; Sigl et al. 2013). This has led to a hypothesis of two separate volcanic sources for these spikes: an AD 1453 event in the Northern Hemisphere, and an event at AD 1458 in the Southern Hemisphere, close to the equator (Plummer et al. 2012; Sigl et al. 2013).

To test whether the Tombuk event had potential for global atmospheric reach, (Witter and Self 2007) re-analysed a subset of samples collected earlier from Lupalea Point, Tongoa. They identified a wider range of compositions than earlier studies (Robin et al. 1994), with Tombuk pyroclastic deposits dominantly in the dacitic field (Fig. 5). By analysing the concentrations of volatile elements (especially sulphur), and comparing matrix glass to melt inclusions and assuming a total eruptive volume of 30-60 km^3, (Witter and Self 2007) estimated a sudden release of >100 Tg H_2SO_4 for the Tombuk eruption. This atmospheric sulphur injection was thus similar in scale to the 1815 Tambora eruption (Gao et al. 2006; Sigl et al. 2013).

Summary and research targets

A review of all available published and unpublished literature provides the grounds for a more detailed and balanced assessment of the evidence at source for the nature, magnitude, timing, and local impacts of the mid-fifteenth century Tombuk eruption of the Kuwae volcano. Historical, archaeological and geological evidence suggest an extremely large eruption event (VEI 6-7) that either created or enlarged a caldera between the current islands of Epi and Tongoa. The eruption profoundly reconfigured the physical, social, cultural and linguistic landscapes of central Vanuatu. The present distribution of the population of this area and its languages can be attributed directly to the historical processes of recolonisation of the Shepherd Islands in the aftermath of the eruption. Current evidence shows

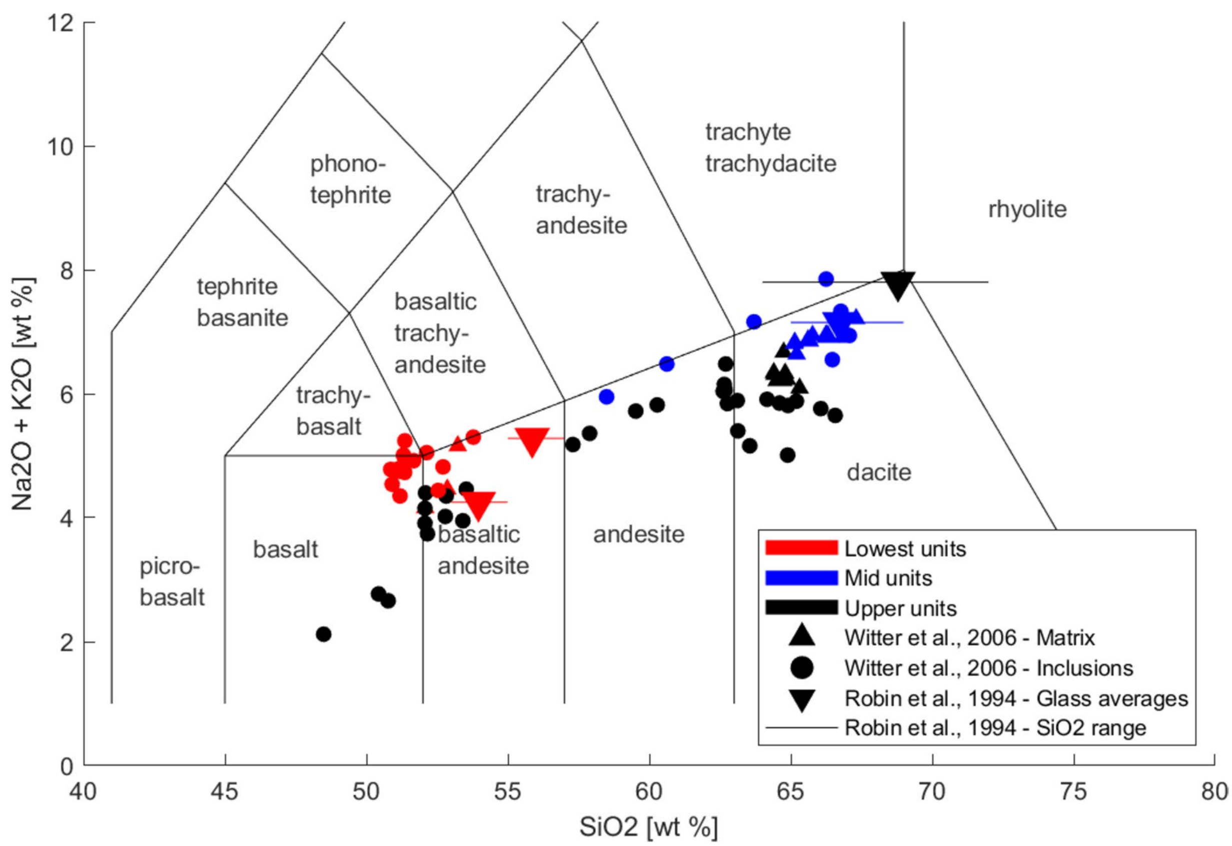

Fig. 5 Total alkali vs. silica (TAS) diagram for samples from Robin et al. (1994)(Robin et al. 1994) and Witter and Self (2007)(Witter and Self 2007). Data by Witter and Self (2007)(Witter and Self 2007) are for individual samples. Data by Robin et al. (1994)(Robin et al. 1994) are averaged data for multiple samples from each stratigraphic unit

that widespread environmental devastation followed the eruption, suggesting almost no chance of survival on southern Kuwae Island (now Tongoa) and central Kuwae (now southern Epi). The far western and northern parts of Kuwae (now Epi) and other islands nearby may have served as refuges, as linguistic data and oral traditions suggest (Hoffmann 2006). While the timing and nature of resettlement remain ill-defined, at the time of first European contact in the early nineteenth century, Epi and Tongoa were densely populated (Thurston 1871).

The Tombuk event remains a strong candidate for one of the mid-fifteenth century sulphur signals, specifically the AD 1458 event according to Antarctic ice core studies (Gao et al. 2006; Esper et al. 2013; Sigl et al. 2015). This is, in part, because few alternative eruptions of comparable scale are confidently identified elsewhere in the world for this period. Currently, the weakest links in this proposed correlation are: (1) the absence of robust chemical comparison of distal tephra and sulphur spikes in ice cores against a complete proximal database; (2) the poor resolution of proximal age determinations for the Tombuk eruption and/or other events from Kuwae caldera; and (3) the limited understanding of the eruption magnitude, including factors such as the climactic column height and the eruption duration. Moreover, more robust local stratigraphic and chemical reconstruction of the eruption is needed to identify possible eruptive phases and timing of climactic events, including the possibility of more than one climactic event.

A multi-disciplinary approach is essential in reconstructing the history of the discovery of the Tombuk eruption. The development of protocols for collaboration between disciplines with such different methods of enquiry and forms of evidence, and the maintenance of independent lines of argument for each discipline, will be essential in avoiding the earlier pitfalls of circular confirmation, such as the speculative identification of Tombuk with the initial ice core evidence and dates. Whether or not Kuwae is confirmed as the source of one of the mid-fifteenth century sulphate signals and its associated global climatic effects, this contribution should provide a template for similar enquiry elsewhere.

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
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Competing interests
The authors declare no competing interests.

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References
Atwell WS (2001) Volcanism and short-term climatic change in East Asian and World history, c. 1200–1699. J World Hist 12:29–98. https://doi.org/10.1353/jwh.2001.0002
Ballard C (2020) The lizard in the volcano: narratives of the Kuwae eruption. Contemp Pac 32:98–123. https://doi.org/10.1353/cp.2020.0005
Ballard C (2021) Transmission's end? Cataclysm and chronology in Indigenous oral tradition. In: The Routledge Companion to Global Indigenous History, 1st edn. Routledge, London, p 571–602
Baroni M, Savarino J, Cole-Dai J et al (2008) Anomalous sulfur isotope compositions of volcanic sulfate over the last millennium in Antarctic ice cores. J Geophys Res 113:1–12. https://doi.org/10.1029/2008JD010185
Bauch M (2017) The day the sun turned blue: A volcanic eruption in the early 1460s and its possible climatic Impact—A natural disaster perceived globally in the late Middle Ages? In: Schenk GJ (ed) Historical disaster experiences - towards a comparative and transcultural history of disasters across Asia and Europe. Springer, Cham, pp 107–138
Bedford S (2006) Pieces of the Vanuatu Puzzle: Archaeology of the North, South and Centre. ANU Press, Canberra
Bedford S (2009) Les traditions potières Erueti et Mangaasi du Vanuatu central: réévaluation et comparaison quarante ans après leur identification initiale. J Société Océan 128:25–38. https://doi.org/10.4000/jso.5800
Bedford S, Spriggs M (2008) Northern Vanuatu as a Pacific Crossroads: The Archaeology of Discovery, Interaction, and the Emergence of the "Ethnographic Present." Asian Perspect 47:95–120
Bedford S, Spriggs M, Wilson M, Regenvanu R (1998) The Australian National University—National Museum of Vanuatu Archaeology Project: A preliminary report on the establishment of cultural sequences and rock art research. Asian Perspect 37:165–193
Bedford S, Spriggs M, Regenvanu R (2006) The Teouma Lapita site and the early human settlement of the Pacific Islands. Antiquity 80:812–828. https://doi.org/10.1017/S0003598X00094448
Bedford S (2003) The timing and nature of Lapita colonisation in Vanuatu: the haze begins to clear. In: Sand C (ed) Pacific Archaeology: assessments and prospects. Les Cahiers de l'archeologie en Nouvelle-Caledonie 15, Noumea, p 147–158
Bergeot N, Bouin MN, Diament M et al (2009) Horizontal and vertical interseismic velocity fields in the Vanuatu subduction zone from GPS measurements: Evidence for a central Vanuatu locked zone. J Geophys Res 114:B06405. https://doi.org/10.1029/2007JB005249
Boucheron P (2012) Introduction: Les boucles du monde: contours du XVe siècle. In: Histoire du monde au XVe siècle. Hachette

Bronk Ramsey C (2008) Radiocarbon dating: revolutions in understanding. Archaeometry 50:249–275. https://doi.org/10.1111/j.1475-4754.2008.00394.x
Budner D, Cole-Dai J (2003) The number and magnitude of large explosive volcanic eruptions between 904 and 1865 A.D.: Quantitative evidence from a new South Pole ice core. In: Volcanism and the Earth's Atmosphere, Geophysical Monograph. American Geophysical Union, Washington DC, p 165–176
Calandra M (2017) Jardins de Terre, Jardins de mer à Tongoa (Vanuatu). Une anthropologie de la nature domestique dans un milieu affecté par la catastrophe. PhD Thesis, Paris, EHESS
Campbell BMS (2017) Global climates, the 1257 mega-eruption of Samalas volcano, Indonesia, and the english food crisis of 1258. Trans R Hist Soc 27:87–121. https://doi.org/10.1017/S0080440117000056
Carney JN, Macfarlane A (1977) Submarine geology, Epi-Tongoa. In: Macfarlane A (ed) Annual report of the Geological Survery for the year 1975. New Hebrides Geological Survey, Port Vila, pp 11–13
Castellano E, Becagli S, Hansson M et al (2005) Holocene volcanic history as recorded in the sulfate stratigraphy of the European Project for Ice Coring in Antarctica Dome C (EDC96) ice core. J Geophys Res 110:1–12. https://doi.org/10.1029/2004JD005259
Clark R (1996) Linguistic consequences of the Kuwae eruption. In: Davidson J, Irwin G, Leach F, et al. (eds) Oceanic Culture History: Essays in Honour of Roger Green. N Zealand J Archaeol Dunedin, pp 275–285
Cole-Dai J, Mosley-Thompson E, Wight SP, Thompson LG (2000) A 4100-year record of explosive volcanism from an East Antarctica ice core. J Geophys Res Atmospheres 105:24431–24441. https://doi.org/10.1029/2000JD900254
Crawford AJ, Greene HG, Exon NF (1988) Geology and offshore resources of pacific island Arcs – Vanuatu region. In: Greene HG, Wong FL (eds) Circum-Pacific Council for Energy and Mineral Resources Earth Sciences Series. Circum-Pacific Council for Energy and Mineral Resources, Houston, Texas
Delmas RJ, Kirchner S, Palais JM, Petit J-R (1992) 1000 years of explosive volcanism recorded at the South Pole. Tellus 44B:335–350. https://doi.org/10.1034/j.1600-0889.1992.00011.x
Esper J, Schneider L, Krusic PJ, et al (2013) European summer temperature response to annually dated volcanic eruptions over the past nine centuries. Bull Volcanol 75:. https://doi.org/10.1007/s00445-013-0736-z
Espirat JJ (1964) Etude géologique de l'île Tongariki et observations sur la géologie des îles Shepherd. Rapp Bur Rech Géologiques Minières Nouméa 41:
Exon NF, Cronan DS (1983) Hydrothermal iron deposits and associated sediments from submarine volcanoes off Vanuatu, southwest Pacific. Mar Geol 52:M43–M52. https://doi.org/10.1016/0025-3227(83)90052-X
Ferris DG, Cole-Dai J, Reyes AR, Budner DM (2011) South Pole ice core record of explosive volcanic eruptions in the first and second millennia A.D. and evidence of a large eruption in the tropics around 535 A.D. J Geophys Res 116:1–11. https://doi.org/10.1029/2011JD015916
Firth CW, Cronin SJ, Turner SP et al (2015) Dynamics and pre-eruptive conditions of catastrophic, ignimbrite-producing eruptions from the Yenkahe Caldera, Vanuatu. J Volcanol Geotherm Res 308:39–60. https://doi.org/10.1016/j.jvolgeores.2015.10.012
Fisher DA, Koerner RM, Reeh N (1995) Holocene climatic records from Agassiz ice cap, Ellesmere Island, NWT, Canada. The Holocene 5:19–24. https://doi.org/10.1177/095968369500500103
Frederick GC, Hinde GJ, Teall JJH (1893) Geological notes on certain islands in the New Hebrides. Q J Geol Soc 49:227–232. https://doi.org/10.1144/GSL.JGS.1893.049.01-04.38
Gao C, Robock A, Self S et al (2006) The 1452 or 1453 A.D. Kuwae eruption signal derived from multiple ice core records: Greatest volcanic sulfate event of the past 700 years. J Geophys Res 111:1–11. https://doi.org/10.1029/2005JD006710
Garanger J (1972) Archéologie des Nouvelles-Hébrides. Société des Océanistes, Paris
Gill RB (2000) The Great Maya Droughts: Water, Life, and Death. UNM Press, Albuquerue
Global Volcanism Program (2013) Kuwae (257070). In: Volcanoes World. https://volcano.si.edu/volcano.cfm?vn=257070. Accessed 28 Feb 2023
Gorton MP (1977) The geochemistry and origin of quaternary volcanism in the New Hebrides. Geochim Cosmochim Acta 41:1257–1270. https://doi.org/10.1016/0016-7037(77)90071-0
Guiart J (1973) Le dossier rassemblé. In: Espirat J-J, Guiart J, Lagrange M-S, Renaud M (eds) Système des titres électifs ou héréditaires dans les Nouvelles-Hébrides centrales d'Efaté aux îles Shepherd. Institut d'ethnologie, Musée de l'Homme, Paris
Guillet S, Corona C, Stoffel M et al (2017) Climate response to the Samalas volcanic eruption in 1257 revealed by proxy records. Nat Geosci 10:123–128. https://doi.org/10.1038/ngeo2875
Hartman LH, Kurbatov AV, Winski DA, et al (2019) Volcanic glass properties from 1459 C.E. volcanic event in South Pole ice core dismiss Kuwae caldera as a potential source. Sci Rep 9:14437. https://doi.org/10.1038/s41598-019-50939-x
Hayes GP, Wald DJ, Johnson RL (2012) Slab1.0: A three-dimensional model of global subduction zone geometries. J Geophys Res Solid Earth 117. https://doi.org/10.1029/2011JB008524
Hébert B (1965) Contribution à l'étude archéologique de l'île Efate et des îles avoisinantes. Études Mélanésiennes 18–20:71–98
Hébert B (1971) Note sur les grandes pirogues à voile de la région de l'île Efaté et des îles avoisinantes. Études Mélanésiennes 21–25:55–71
Hoffmann A (2006) Looking to Epi: Further consequences of the Kuwae eruption, Central Vanuatu, AD 1452. Bull Indo-Pac Prehistory Assoc 26:62–71. https://doi.org/10.7152/bippa.v26i0.11994
Kužić K (2012) The impact of the eruption of the Kuwae volcano of 1452/1453 on Croatian lands. Zb Hist 30:109–121
Lavigne F, Degeai J-P, Komorowski J-C et al (2013) Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani volcanic complex Indonesia. Proc Natl Acad Sci 110:16742–16747. https://doi.org/10.1073/pnas.1307520110
Luders D (1996) Legend and history: did the Vanuatu-Tonga Kava trade cease in A.D. 1447? J Polyn Soc 105:287–310
MacLachlan RRC (1940) Three pot sherds from the New Hebrides. J Polyn Soc 49:172
Meffre S, Crawford AJ (2001) Collision tectonics in the New Hebrides arc (Vanuatu). Isl Arc 10:33–50. https://doi.org/10.1046/j.1440-1738.2001.00292.x
Michelsen O (1890) Cannibals won for Christ: A Story of Missionary Perils and Triumphs in Tongoa. Morgan and Scott, London
Michelsen O (1897) Volcanic eruption off Tongoa. Presbyterian Research Centre Archive, Dunedin, New Zealand, P-A11.37-105. Accessed from Pacific Manuscripts Bureau, Photo 88-105.
Miller JG (1981) Book II: The Growth of the Church to 1880. General Assembly of the Presbyterian Church of Australia, Sydney
Monzier M, Robin C, Eissen J-P (1994) Kuwae (≈1425 A.D.): the forgotten caldera. J Volcanol Geotherm Res 59:207–218. https://doi.org/10.1016/0377-0273(94)90091-4
Mosley-Thompson E, Thompson LG, South S, Station P (1982) Nine centuries of microparticle deposition at the South Pole. Quat Res 17:1–13. https://doi.org/10.1016/0033-5894(82)90041-2
Nemeth K, Cronin SJ, White JDLL et al (2007) Kuwae caldera and climate confusion. Open Geol J 1:7–11. https://doi.org/10.2174/1874262900701010007
Newhall C, Self S, Robock A (2018) Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts. Geosphere 14:572–603. https://doi.org/10.1130/GES01513.1
Nottage B (1988) Break of Day Islands: The New Hebrides Diary of Basil Nottage, 1932-1939. Presbyterian Church of New Zealand, Dunedin
Palmer AS, van Ommen TD, Curran MAJ et al (2001) High-precision dating of volcanic events (A.D. 1301–1995) using ice cores from Law Dome. Antarctica. J Geophys Res Atmospheres 106:28089–28095. https://doi.org/10.1029/2001JD000330
Pang KD (1993) Climatic impact of the mid-fifteenth century Kuwae caldera formation, as reconstructed from historical and proxy data, Abstract [A11D-12] presented at 1993 Fall Meeting, AGU, San Francisco, CA, 6-10 Dec.
Plummer CT, Curran MAJ, van Ommen TD et al (2012) An independently dated 2000-yr volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the 1450s CE eruption of Kuwae, Vanuatu. Clim Past 8:1929–1940. https://doi.org/10.5194/cp-8-1929-2012

Ren J, Li C, Hou S et al (2010) A 2680 year volcanic record from the DT-401 East Antarctic ice core. J Geophys Res 115:D11301. https://doi.org/10.1029/2009JD012892
Rivierre J-C (1996) Mythistoire et archéologie dans le Centre-Vanuatu. In: Julien M, Orliac M, Orliac C et al (eds) Mémoire de pierre, mémoire d'homme: tradition et archéologie en Océanie. Publications de la Sorbonne, Paris, pp 431–463
Robin C, Monzier M, Eissen J (1994) Formation of the mid-fifteenth century Kuwae caldera (Vanuatu) by an initial hydroclastic and subsequent ignimbritic eruption. Bull Volcanol 56:170–183. https://doi.org/10.1007/BF00279602
Schellart WP, Lister GS, Jessell MW (2002) Analogue modeling of arc and backarc deformation in the New Hebrides arc and North Fiji Basin. Geology 30:311–314. https://doi.org/10.1130/0091-7613(2002)030%3c0311:AMOAAB%3e2.0.CO;2
Schellart WP, Lister GS, Toy VG (2006) A Late Cretaceous and Cenozoic reconstruction of the Southwest Pacific region: Tectonics controlled by subduction and slab rollback processes. Earth-Sci Rev 76:191–233. https://doi.org/10.1016/j.earscirev.2006.01.002
Schütz AJ (1972) Nguna Texts: A Collection of Traditional and Modern Narratives from the Central New Hebrides. University of Hawai'i Press, Honolulu
Self S (2006) The effects and consequences of very large explosive volcanic eruptions. Philos Trans R Soc Math Phys Eng Sci 364:2073–2097. https://doi.org/10.1098/rsta.2006.1814
Sherkin SG (1999) Forever united: identity-construction across the rural-urban divide. PhD Thesis, The University of Adelaide, Adelaide
Sigl M, McConnell JR, Layman L et al (2013) A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years. J Geophys Res Atmospheres 118:1151–1169. https://doi.org/10.1029/2012JD018603
Sigl M, Winstrup M, McConnell JR et al (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature 523:543–549. https://doi.org/10.1038/nature14565
Spriggs M (1997) The Island Melanesians, 1st edn. Blackwell, Cambridge
Stenni B, Proposito M, Gragnani R, et al (2002) Eight centuries of volcanic signal and climate change at Talos Dome (East Antarctica). J Geophys Res Atmospheres 107. https://doi.org/10.1029/2000JD000317
Stewart RB, Németh K, Cronin SJ (2010) Is Efate (Vanuatu, SW Pacific) a result of subaerial or submarine eruption? An alternative model for the 1 ma Efate pumice formation. Cent Eur J Geosci 2:306–320. https://doi.org/10.2478/v10085-010-0020-9
Strandberg NA, Sear DA, Langdon PG, et al (2023) Island ecosystem responses to the Kuwae eruption and precipitation change over the last 1600 years, Efate, Vanuatu. Front Ecol Evol 11:. https://doi.org/10.3389/fevo.2023.1087577
Taylor FW (1995) Geodetic measurements of convergence at the New Hebrides island arc indicate arc fragmentation caused by an impinging aseismic ridge. Geology 23:1011–1014. https://doi.org/10.1130/0091-7613(1995)023%3c1011:GMOCAT%3e2.3.CO;2
Thurston JB (1871) Journal of a Voyage from Ovalau, Fiji, to the New Hebrides in Search of Voluntary Emigrants. National Archives of Fiji, Ms, Perrins Papers
Toohey M, Sigl M (2017) Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. Earth Syst Sci Data 9:809–831. https://doi.org/10.5194/essd-9-809-2017
Valentin F, Spriggs M, Bedford S, Buckley H (2011) Vanuatu mortuary practices over three millennia: Lapita to the early European contact period. J Pac Archaeol 2:49–65
Warden AJ, Curtis R, Mitchell AHG, Espirat J-J (1972) Geology of the Central Islands, 1:100,000 mapsheet. New Hebrides Geological Survey, Port Vila
Wirrmann D, Eagar SH, Harper MA et al (2011) First insights into mid-Holocene environmental change in central Vanuatu inferred from a terrestrial record from Emaotfer Swamp, Efaté Island. Quat Sci Rev 30:3908–3924. https://doi.org/10.1016/j.quascirev.2011.10.003
Witter JB, Self S (2007) The Kuwae (Vanuatu) eruption of AD 1452: potential magnitude and volatile release. Bull Volcanol 69:301–318. https://doi.org/10.1007/s00445-006-0075-4

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