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Assessing the effects of volcanic disasters on human settlement in the Willaumez Peninsula, Papua New Guinea: a Bayesian approach to radiocarbon calibration

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Abstract: Bayesian statistical approaches to calibrating radiocarbon determinations can make a significant contribution to disaster studies by adding precision to the dating of both the environmental forcing agent and the consequent human responses. An archaeological case study in the Willaumez Peninsula region of New Britain, Papua New Guinea uses radiocarbon dating to examine the chronology of five major volcanic events and the timing and nature of recolonization. The results demonstrate the general applicability of Bayesian-based approaches for building a sound tephrochronology and for evaluating the impacts of volcanic hazards on human history.

Key words: Volcanic disasters, tephrochronology, archaeology, radiocarbon, Bayesian calibration, Papua New Guinea, Holocene, human–environment interaction.

Introduction

Archaeologists and other scholars have often turned to natural disasters, particularly volcanic eruptions, to explain cultural change and societal collapse (e.g., Sheets 1983; Sheets and McKee 1994; Oliver-Smith and Hoffman, 1999; Bawden and Reycraft, 2000; McCoy and Heiken, 2000; McGuire et al., 2000; Hoffman and Oliver-Smith, 2002; Torrence and Grattan, 2002a). However, few claims for volcanically forced change have been based on solid empirical evidence (Torrence and Grattan, 2002b: 7–9). In most cases, the possibility of coincidence versus actual causation has not been adequately addressed, usually because either the volcanic event or the human response is not precisely dated. Buck et al. (2003) have demonstrated the value of Bayesian-based calibration methods for refining the dating of a single volcanic tephra, and urged ‘tephrochronologists to seek fastidiously both high-quality radiocarbon data and reliable stratigraphic sequences’ (Buck et al., 2003: 639) that could benefit from these techniques. We follow their suggestion by applying Bayesian calibration techniques to the dating of a well-characterized sequence of five tephras using 115 radiocarbon determinations. The accurate dating of these eruptions enables a comparative historical study of how multiple Holocene volcanic disasters have impacted on two different human populations.

Ongoing interdisciplinary research on the Willaumez Peninsula of New Britain Island, Papua New Guinea (Figure 1), is investigating the impact of volcanic eruptions on human history. Pyroclastic flows and deep falls of airborne tephra emanating from five Holocene eruptions, each with a volcanic explosive index (VEI) rating of 5–6, devastated large regions (Machida et al., 1996; Boyd et al., 1999). These volcanic events would have had wide-scale, disastrous effects on marine and terrestrial ecosystems and, by implication, on the human societies who depended on them. Prehistoric societies could not have sustained themselves immediately after these events because the natural and cultivated vegetation would have been destroyed and the dusty ash would have been a serious health risk for some years afterward (cf. Blong, 1984; Machida et al., 1996; Torrence, 2002a; Neall et al., 2008). Archaeologists have proposed that these disasters caused profound changes in the cultural history of the region, as represented by changes in artefact types, exchange systems and land use patterns (Torrence et al., 2000; Torrence, 2002a, b, 2004; Lilley, 2004a, b; Torrence and...
Doelman, 2007). It has also been suggested that human populations adopted particular patterns of behaviour that enabled them to mitigate some effects of the disasters (Torrence et al., 2000; Torrence and Doelman, 2007). We use Bayesian modelling of a new suite of radiocarbon dates to test these hypotheses.

The Bayesian statistical paradigm of posterior probability, clearly described by Buck et al. (1996, 2003), has been increasingly applied to radiocarbon dating (reviewed in Buck et al., 1991, 1992, 1994, 1996; Buck, 2001). In the case of archaeological deposits dated by radiocarbon determinations, it is assumed that if an a priori relationship exists between events or deposits that are being dated, then it is statistically valid to combine subjective stratigraphic information and probabilistic radiocarbon data in order to produce testable analytical models (Buck et al., 1996; Buck, 2001). Furthermore, in complex situations where there are large numbers of radiocarbon determinations, it is desirable to minimize the range of the radiocarbon probability likelihoods for those dates in order to secure the most precise ranges (cf. Buck et al., 2003: 646).

A Bayesian-based approach to calibration is ideal in our case because we can incorporate prior knowledge from a regional tephrochronology. The quality of the radiocarbon information also permits us to create a Bayesian analytical model that incorporates all of the radiocarbon dates relating to the entire volcanic/occupation sequence. A complex Bayesian model has been designed to achieve two aims. First, precise dating of the event is necessary in order to detect whether a volcanic eruption was directly contemporary with changes in cultural behaviour. Second, changes in the length of abandonment after each eruption are calculated as a way of comparing the ability of populations to survive and recolonize. Abandonment is measured by examining the difference between the date for each eruptive event and the earliest date derived from archaeological material following that event.

**Background**

Stratigraphic studies combined with physical and geochemical analyses have established a regional tephrochronology (Lowe and Hunt, 2001) in West New Britain Province, Papua New Guinea (Machida et al., 1996; Torrence et al., 2000; McKee et al., 2005). The sequence consists of five distinctive tephras, four of which are from the Witori volcano (W-K1, W-K2, W-K3, W-K4) and the fifth from the Dakataua volcano (Dk) (Figure 1) together with soils bearing traces of human occupation formed on each tephra. The resulting tephrochronological sequence is an important relative dating tool for reconstructing the human and environmental history of West New Britain (eg, Specht et al., 1991; Pavlides, 1993, 2004, 2006; Pavlides and Gosden, 1994; Torrence et al., 2000; Boyd et al., 2005; Lentfer and Torrence, 2007; Torrence and Doelman, 2007; Neall et al., 2008).

An ongoing programme of collaborative field research on the Willaumez Peninsula in West New Britain province, Papua New Guinea coordinated by Torrence aims to characterize and accurately date these eruptions and trace human behaviour across the landscapes preserved under each tephra. To achieve this, extensive excavations at several sites on Garua Island have been augmented by 136 test pits measuring 1 m² in two study areas: 69 on Garua Island and 67 in a study region at the southern end of the peninsula.
peninsula itself (hereafter termed the 'Isthmus') (Figures 2 and 3). The test pits were located to adequately sample environmental variability (Torrence and Stevenson, 2000: 327; Torrence, 2002b; Torrence and Doelman, 2007). Detailed maps of the test pits and descriptions of the excavations are presented in Torrence (2002a, b, 2008), Torrence and Stevenson (2000), Specht and Torrence (2007a) and Torrence and Doelman (2007). Assignment of tephra layers to a specific volcanic event is primarily based on stratigraphic context and physical characteristics, as described in Machida et al. (1996), backed up by geochemical characterization using SEM EDAX of at least one full sequence in each study area (Torrence et al., 2000; Hugh Davies, personal communication, 2006).

Since the depth of the tephra layers diminishes with distance from the source volcano (e.g., Machida et al., 1996), the tephra stratigraphy and cultural phasing varies slightly between the two regions (Figures 4 and 5). All the tephras are evident in the Isthmus region, although Dk is patchy in occurrence and very thin where preserved (Figure 4). Owing to wide-scale redeposition shortly after it was emplaced, W-K1 is also sporadically preserved in situ in the Isthmus region. In contrast, on Garua Island (Figure 5) only the W-K2 and Dk tephras are well preserved, whereas the thin W-K3 tephra is identifiable only infrequently. W-K1 is only found in redeposited contexts and W-K4 has not yet been positively identified on Garua Island (contra Torrence et al., 2000). The utility of the Numundo and W-H series tephras shown in Figure 4 is limited because they are either restricted in their spatial extent and/or are thin and patchy in occurrence (Machida et al., 1996; McKee et al., 2005). They are not included in this analysis.

Calendar ages for W-K1, W-K4 and Dk were previously estimated using calibrated radiocarbon determinations obtained from carbonized material preserved within in situ deposits of airfall tephras (Machida et al., 1996). As a proxy for eruptions not directly dated (W-K2 and W-K3), Torrence et al. (2000) used the youngest of the radiocarbon dates from archaeological layers underneath the tephras. The length of time the Willaumez Peninsula had been abandoned following each eruption was calculated as the interval between the estimated eruption date and the earliest radiocarbon determination from material recovered above the tephra (Torrence et al., 2000; Torrence, 2002a). The results, summarized in Table 1, indicated that following a volcanic disaster, the region was recolonized more quickly through time. This pattern was ascribed to a reduction in the severity of the volcanic forcing mechanism, combined with changes in social processes, subsistence and settlement systems, cultural conceptions about landscape and population size (Torrence et al., 2000; Torrence, 2002b).

These approaches have limitations. For example, using the youngest date beneath a tephra to date the eruption assumes that the plant ceased metabolizing immediately before or at the time of the volcanic event. It also places emphasis on single radiocarbon determinations, which may be problematic if they are not representative of the earliest reoccupation. Given a twofold increase in radiocarbon dates from archaeological contexts following fieldwork in the Isthmus study region, together with additional determinations from Garua taken to test the findings of the previous
study, it is timely to reconsider the relationships between volcanic activity and human history. In addition, the enlarged data set enables a comparison of the impact of each eruption on two human populations located at different distances from the eruptive centres and situated in the contrasting mainland (Isthmus) and offshore island (Garua) settings.

**Materials**

Our analysis uses 115 radiocarbon determinations, mainly derived from archaeological test pits, 61 of which are previously unpublished. Their provenance and analytical details are provided in Tables 2–4, where they have been ordered, first, by their placement in the stratigraphy of the specific excavation, second, according to the regional tephrochronology and, third, by their radiocarbon ages. Eighteen samples collected either from within volcanic tephra or from sites in neighbouring parts of New Britain (Machida et al., 1996; Torrence et al., 2000; McKee et al., 2005; McKee, Torrence and Neall, unpublished data, 2007) were also included (Table 4). Sample selection aimed to achieve widespread spatial coverage across the study regions and to adequately represent deposits immediately above and below each tephra layer, thereby providing the best chance for precise dating of both eruptions and reoccupation. Given the extent of the sampling, we have assumed the radiocarbon determinations accurately reflect the history of human occupation in each region.

The majority of the samples that represent human activity are short-lived nutshell and should therefore provide precise absolute dates (Tables 2 and 3). Given that these nuts were a source of food and found in context with cultural artefacts, we assume they ceased metabolizing as a result of human agency. In contrast, all but one of the determinations from other areas of New Britain were derived from unidentified charcoal samples so it is not possible to assess whether they represent long-lived species (Table 4).

In an initial search for outliers, we noted that two dates did not correspond to the tephrochronology. Sample SUA 2991 (1530 ± 70; Machida et al., 1996: 71) is a conventional date made on a sample from a whole log embedded within the W-K4 tephra. Several dates on nutshell from beneath this tephra were younger than SUA 2991, suggesting that the log sample was old wood, so it has been omitted from this analysis. Dk tephra has been recently identified in the Isthmus region as stratified directly below W-K4, (McKee et al., 2005), which has a date of 1320 ± 60 (Beta 29254 Machida et al., 1996: 71). The previous date of 1150 ± 69 (ARL 263) for the Dk eruption, noted by Machida et al. (1996: 71) as from uncertain context, is therefore far too young and was removed from the study. More recent fieldwork in the same region has yielded samples from well-stratified Dk contexts which are included here instead (McKee, Torrence and Neall, unpublished data, 2007). Given the consistency of the remaining dates with the tephrastratigraphy, no other formal outlier detection was necessary.

**Methods**

The application of the Bayesian statistical paradigm to radiocarbon calibration has been aided by the accessibility of programs such as *OxCal* (Bronk Ramsey, 1995, 2001, 2005, 2007) and *BCal* (Buck et al., 2001). Both incorporate options for building Bayesian-based calibration models that make it possible to increase the precision of radiocarbon results through the incorporation of relevant stratigraphic information; *OxCal* is used exclusively here. *OxCal* Bayesian calibration models make use of the stratigraphic relationships between samples to calculate a posterior distribution for each radiocarbon date, and a highest posterior density region (hereafter HPD), which represents the posterior probability distribution at two standard deviations (2 sigma 95%). In addition, we have used *OxCal* to calculate posterior distributions and HPD regions for otherwise undated volcanic eruptions that took place between dated occupation deposits and to measure the gap between eruptions and the beginning of subsequent human occupation.

Our Bayesian calibration model incorporates the Boundary, Phase, R_combine, TPQ and Interval model building functions of *OxCal* (Bronk Ramsey, 2005, 2007). For the purposes of our *OxCal* model, all dates derived from archaeological and geological contexts on New Britain that fall between any two eruptions are viewed as belonging to a particular occupation phase. When
Table 2  Radiocarbon determinations from excavations in the mainland Isthmus region. The stratigraphic position of each eruption is shown. The calibration and modelling was carried out using OxCal version 4.0.5 (Bronk Ramsey, 2007)

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*a1, Not previously published.*
Table 3  Radiocarbon determinations from excavations on Garua Island. The stratigraphic position of each eruption is shown. The W-K4 tephra has not been identified within the excavations on Garua Island (cf. Figure 5). The calibration and modelling was carried out using OxCal version 4.0.5 (Bronk Ramsey, 2007)

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(Continued)
characterizing a set of stratified dates that belong to one such phase, distinct Boundary and Phase constraints are used to fulfil the requirements of the Bayesian formulae used by OxCal (Bronk Ramsey, 2005, 2007). This ensures that an analysis is tightly constrained by the probability distributions of the radiocarbon determinations themselves (Bronk Ramsey, 2000; Steier and Rom, 2000). Dates from contemporaneous occupation phases on Garua, the Isthmus and neighbouring regions have been grouped within separate sets of Boundary and Phase constraints, which reflect the established tephras stratigraphy (Tables 2–4). Incorporating all available dates, but isolating groups of dates within separate constraints, ensures that all samples are used to calculate the dates of eruptions, but isolates determinations from the two study regions so that we can compare lengths of abandonment through time and across space.

Dates from elsewhere on New Britain help refine the dating of the eruptions (Table 4), but do not affect the analysis of reoccupation on Garua and the Isthmus. This was achieved by using OxCal’s terminus post quem or TPQ function. In the model these dates can only fall after the earliest date in that group and therefore do not affect the calculation of the dates for recolonization.

Only two of the volcanic events can be dated directly with radiocarbon determinations: Dk and W-K4. There are two compatible determinations from within the Dk tephra (Torrence and Neall, 2004; McKee et al., 2005; McKee, Torrence and Neall, unpublished data, 2007). The R.Combine function in OxCal was used to combine the posterior distributions for the two determinations and produce a single refined date range for the Dk event (Table 4). The single date from the W-K4 tephra was input directly into the model. In the absence of specific determinations for the other eruptions, additional Boundary constraints were added to the model to act as proxy dates. The probability distribution calculated for each Boundary provides a posterior distribution for the relevant eruption. Since Buck et al. (2003: 644, table 5) have argued cogently that the mode or modes represent the ‘most likely dates’ within a posterior distribution and a HPD region, they were also calculated.

As with dating the eruptions, both the HPD region and the mode(s) were used to calculate the length of abandonment in the two regions after each eruption. First, we used OxCal’s Interval function (Bronk Ramsey, 2007) to calculate the length of time between an eruption and the earliest subsequent dates. Since the Interval considers all dates within a posterior distribution to be likely, the calculation is not dramatically affected by localized wiggles in the calibration curve. On the other hand, the Interval calculation might give too much weight to the tail ends of the posterior distribution, which have a lower probability. We also compare the modal date(s) for the eruption with those for the calculated boundary date for the earliest evidence of human occupation in each region. This method for determining length of abandonment produces fewer alternatives, but has the disadvantage of seeming more precise than may be warranted because it does not consider the full 2 sigma probability range and may be overly sensitive to variations in the calibration curve. Since each approach has advantages and drawbacks, we made calculations using both the full HPD interval and the modes.

### Results

An OxCal output chart of the entire model can be downloaded at [http://www.arch.cam.ac.uk/~cap59/](http://www.arch.cam.ac.uk/~cap59/). OxCal generated accuracy scores of between 106.2 and 108.0 for ten runs of the model, suggesting that it is highly robust and therefore likely to produce reliable results. The results are summarized in Tables 5–7. Figures 6–9 display graphic representations of the calculated
Table 4  Radiocarbon determinations from excavations on New Britain that are outside the study areas. The stratigraphic position of each eruption is shown. The calibration and modelling was carried out using OxCal version 4.0.5 (Bronk Ramsey, 2007).

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W-K1 Eruption

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Dk Eruption

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W-K4 Eruption

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* 2, Torrence et al. (2000); 4, Machida et al. (1996); 5, McKee et al. (2008); 6, Specht and Gosden (1997).
**Table 5** Highest posterior distribution (HPD) and its modal date based samples within volcanic tephra or as derived from the Bayesian model

<table>
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<th>Modal date(s) (cal. BP)</th>
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<td>3315</td>
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<td>W-K3 Eruption (est)</td>
<td>1740–1540</td>
<td>1615</td>
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<tr>
<td>Dk Eruption (date)</td>
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<tr>
<td>W-K4 Eruption (date)</td>
<td>1310–1170</td>
<td>1280</td>
</tr>
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**Table 6** Calendar age estimates for the boundary delimiting the earliest re-occupation after each eruption in each region. The major modal dates are shown in **bold**, and minor modes, if present, are in plain font

<table>
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<th>Reoccupation</th>
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<th>Garua</th>
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<td>Modal date(s) (cal. BP)</td>
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<td>After W-K2</td>
<td>3330–3040</td>
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<tr>
<td>After W-K3</td>
<td>1650–1520</td>
<td><strong>1560</strong></td>
</tr>
<tr>
<td>After Dk</td>
<td>1270–1080</td>
<td><strong>1175</strong></td>
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</table>

**Table 7** Estimates for length of abandonment following volcanic events based on Bayesian modelling using both *Interval* and mode based calculations. The major mode is shown in **bold** and minor modes, if present, are in plain font

<table>
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<th>Abandonment</th>
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<th>Garua</th>
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<td>Interval 95% HPD</td>
<td>Mode calculation(s)</td>
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<td>Post W-K1 (with NZA 1570)</td>
<td>1360–2000</td>
<td><strong>1710 years</strong></td>
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<td>Post W-K2</td>
<td>0–310</td>
<td><strong>155 years</strong></td>
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<tr>
<td>Post W-K3</td>
<td>0–160</td>
<td><strong>55 years</strong></td>
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<td>Post Dk</td>
<td>0–170</td>
<td><strong>105 years</strong></td>
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<tr>
<td>Post W-K4</td>
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**Figure 6** Bayesian calibration plots produced using OxCal v.4.0.5 (Bronk Ramsey, 2007) showing the HPD for the W-K1 eruption boundary (shown in dark grey) and those for the boundaries that delineate the earliest reoccupation on the Isthmus (shown in grey) and Garua (shown in white)
posterior distribution for each eruption and the posterior boundary distributions for the earliest dates after each eruption in each region.

**Discussion**

**Dating the eruptions**

Bayesian analysis of the enlarged data set produced eruption dates that differ in key respects from previous estimations by Machida et al. (1996) and Torrence et al. (2000) (Tables 1 and 5, Figures 6–9). Unsurprisingly, the tightest probability ranges are for the two eruptions where radiocarbon dates were collected from within the tephra: Dk and W-K4. The summed HPD of two dates for the Dk eruption (1350–1270 cal. BP) is smaller than the calibrated range of either of the dates. Within the 80-yr span, the modal date is 1300 cal. BP. In contrast, the HPD for the W-K4 eruption (1310–1170 cal. BP) is broader than for the summed Dk date because the single date has a larger standard deviation than either of the Dk dates. Similarity between the Dk and W-K4 modes is due to the overlap in the posterior distributions for the two eruptions and the shape of the calibration curve at this point. The high likelihood that these
two events occurred close together is supported by the tephra-stratigraphy, because W-K4 lies directly on Dk with no soil development between the two layers (McKee et al., 2005) (Figure 4).

The HPDs generated by Oxcal for the W-K1 (6160–5750 cal. BP), W-K2 (3480–3150 cal. BP) and W-K3 (1740–1540 cal. BP) eruptions (Table 5; Figures 6–8) are estimates controlled by the posterior distributions of the samples taken from within soils located directly above and below in situ airfall tephra. They are thus less precise than the dates from the Dk and W-K4 tephras. The modal dates for W-K1 (5920 cal. BP) and W-K3 (1615 cal. BP) are close to those previously proposed, perhaps because very few new radiocarbon determinations were used in the Bayesian analysis. The modal date for W-K2 (3315 cal. BP) however, represents a major difference from previous estimates.

In terms of making a contribution to our understanding of the prehistory of the region, the new dates for the W-K2 eruption are the most significant. Currently, the most important controversy in Pacific prehistory surrounds the origin of pottery, which is marked by a distinctly decorated style called Lapita (Kirch, 1997). Debate surrounds whether Lapita pottery was introduced from outside Papua New Guinea or was invented locally (Spriggs, 1997). In contrast to previous dates (Table 1), both the interval and modal dates for W-K2 now put this event remarkably close to the earliest dates for Lapita pottery (c. 3400–3200 cal. BP) (Kirch, 2001), some of which come from Garua Island itself (cf. Specht and Torrence, 2007a, 2007b). The possible contemporaneity between W-K2, the loss of obsidian stemmed tools (Araho et al., 2002; Specht, 2005) and the beginning of Lapita pottery in the Willaumez Peninsula raises the issue of whether this natural disaster was responsible for the wide-scale extinction of particular cultural groups. The catastrophe might have facilitated the arrival of immigrants bearing a new ceramic style and possibly a different language (Lilley, 2004a). Another possibility is that the human disaster caused by W-K2 was the catalyst for the local adoption of Lapita pottery. Since the close correlation of the dates is so provocative, more research is required to evaluate the possibility that W-K2 had a major role to play in the origin and spread of Lapita style pottery.

Based on previous dating, Lilley (2004b: 93–94) hypothesized a correlation between the W-K3 eruption and major changes in the Vitiaz Strait region to the west of our study area. He proposed that the arrival of refugees from the disaster stimulated the reappearance of pottery after a 1000 yr gap in production and eventually led to the growth of a regional exchange system. The Bayesian-derived date for W-K3 still supports Lilley’s proposals, but additional research is required to substantiate a causal link between the abandonment of the Willaumez Peninsula following W-K3 and cultural changes elsewhere.

**Length of abandonment**

One way to assess the impact of a volcanic event on human groups is to examine the length of time the region was abandoned following a volcanic disaster (cf. Sheets et al., 1991; Torrence, 2002a). A comparison of the HPDs for the Witori and Dakatana eruptions (Table 5; Figures 6–9) and those for the earliest subsequent reoccupations (Table 6; Figures 6–9) shows that in each case, the probability distributions at two standard deviations are not substantially distinct and may actually overlap. This implies that there is some statistical possibility that there is no gap in human occupation between each volcanic event and resettlement in one or other region. Although the uncalibrated radiocarbon ages for any two determinations might be significantly separated in time, when calibrated to 2 standard deviations, the posterior distribution for a determination with a small standard deviation of ±25 will have a range in the order of 100 years, depending on the shape of the calibration curve. This means it can be statistically difficult to differentiate the dates of two events that occurred close together in time. Furthermore, with the ranges being close to one another, in terms of statistical probability there may have been little or no gap between the eruption and the reoccupation (Table 7).

There are, however, theoretical grounds for putting less emphasis on the extremities of the distributions. Following deep falls of airfall tephra, it is unlikely that human populations would be able to maintain themselves in place both because forests and gardens would have been totally destroyed and since the dust derived from fresh tephra would pose a major health hazard, as exemplified by the 1994 Pinatubo eruption which was of equivalent scale (Blong, 1984; Newhall and Punongbayan, 1996; Boyd et al., 1999; cf. Neall et al., 2008). For this reason we assume that the area of the posterior distributions with greatest probability for length of abandonment together with values calculated on the basis of comparing modal dates (Table 6) are most relevant for comparing the impact of these large eruptions.

Torrence et al. (2000; Torrence, 2002a) proposed the null hypothesis that the length of abandonment should be closely correlated with the severity of the volcanic forcing mechanism (Torrence and Grattan, 2002b: 7) as measured by the VEI of the events and, more importantly, by the local depth of airfall tephra. Recent fieldwork has shown that contrary to initial predictions based on a small number of observations (Machida et al., 1996), the Isthmus was initially more fully impacted by airfall tephra following W-K1 owing to the particular direction of the wind, than after the supposedly larger W-K2 eruption (Neall et al., 2008). In situ falls of W-K1 tephra, however, are only preserved in patches in the Isthmus and redeposited W-K1 tephras are commonly found in low-lying contexts (Torrence, field notes, 2000, 2001, 2002). Similarly, the presence of waterlain deposits of W-K1 tephra in stream sections on Garua Island together with its total absence in the excavations suggest it was washed away shortly after it was emplaced, probably during the wet season (Torrence et al., 2000: 231). Based primarily on tephra depths, the predicted impacts of the volcanic events listed in decreasing order are as follows: Isthmus W-K1, W-K2, W-K3, W-K4, Dk; Garua Island Dk, W-K2, W-K1, W-K3.

Overall, the history of abandonment resulting from the Bayesian analysis is markedly different from previous estimates (cf. Tables 1 and 7). The progressive increase in the speed of recolonization observed by Torrence et al. (2000) is not supported by the new dating. On the other hand, the original null hypothesis is negated in several cases and so the role of cultural factors in mitigating the effects of the eruptions, as proposed by Torrence et al. (2000; cf. Torrence and Doelman, 2007; Torrence, 2008), is still relevant.

Beginning with W-K1, the period of abandonment on Garua has been significantly reduced from the previous estimate by Torrence et al. (2000), primarily due to the inclusion of additional dates from deposits deeper than those previously dated. In comparison, the length of abandonment in the Isthmus is estimated to be remarkably long. Based on historical studies of forest regeneration in other tropical regions (eg, Thornton, 1996; Torrence, 2002a), after W-K1 vegetation should have recovered many centuries before there is evidence for people returning to the Isthmus. It is of course possible that our sample of dates is too small to detect the first colonizers. We have very few samples of organic material from layers dated to this phase by the tephrochronology because of poor preservation of organic material from open settings in a region with extremely high rainfall. Regardless of these difficulties, however, it seems likely that even if people had returned more quickly than we have monitored, the population size of the colonizers would have been very small.

Given the apparent devastating impact of the W-K1 eruption on the human population of the Isthmus, the persistence after this disaster of distinctive retouched obsidian artefacts called stemmed tools is quite surprising. The largest class of this tool form may have
functioned as valuables and was possibly associated with a particular social status (Araho et al., 2002; Specht, 2005). Their reappearance after the W-K1 event indicates that the use of these artefacts as well as the associated beliefs and practices may have been maintained outside the area, perhaps on Garua Island, for as much as 1000 years, and then re-imported to the Isthmus. Whether the actual function of stemmed tools or just their form was preserved over this long period is an important question for future research.

Turning to the W-K2 eruption, recolonization was probably slower on Garua than following W-K1, which makes sense given that a substantial depth of tephra (c. 0.5 m) was preserved over the island (Torrence, 2002a: 296) (Table 7). Conforming to the null hypothesis, it took slightly longer to return to the mainland where tephra depths were nearly twice the depth as on Garua. It is also interesting that, as noted above, the large, distinctive stemmed tools did not survive the W-K2 eruption in either region and a new innovation, Lapita pottery, was introduced. Lapita pottery does not occur above the W-K3 tephra in either area, but it is not clear if it had already been abandoned by the time of the eruptions or was a casualty of this disaster (Specht and Torrence, 2007a, b).

Unlike previous events, the pattern of recolonization after W-K3 negates the null hypothesis because it appears to have been swifter on the Isthmus, where relatively thick depths of tephra have been preserved, than it was on Garua. In addition, the surprisingly long interval and modal length of abandonment on Garua Island is followed by only one date for occupation before the subsequent Dk eruption. Since W-K3 is only a thin indistinct layer on Garua, if preserved at all (e.g., Lentfer and Torrence 2007), it is difficult to understand how the apparently minimal environmental impact of the eruption could have seriously disrupted the island’s population.

Torrence and Stevenson (2000: 337–39) have proposed that the abandonment of Garua after W-K3 was not related to the eruption, but was simply the consequence of shifting cultivation with a small population moving periodically between different regions. Their proposal helps explain another puzzling feature revealed by the Bayesian modelling. Beginning at least 150 years before W-K3, between 1930 and 1620 cal. BP, there is a surprising gap in occupation on the Isthmus, at a time when there is evidence for occupation on both Garua and inland New Britain (see Pavlides, 2006) (see Tables 6 and 7). It is plausible that the nature of the subsistence system, rather than the volcanic event itself also has an important role to play in the history of settlement in the region.

Bayesian calculations for the post W-K4 reoccupation have produced the most novel results for archaeology, probably because this period is poorly researched in Papua New Guinea as a whole. In terms of the model, abandonment on the mainland was much longer than expected given the relatively shallow depth of
the tephra (Figure 4). What we may be witnessing, however, is the combined effects of two nearly simultaneous events: Dk and W-K4. Although both produced small amounts of tephra on the Isthmus, the hazard emanated from opposite directions (Dakataua to the north and Witori to the south, Figure 1), thereby seriously restricting places available for refuge. Possibly the previous Dk eruption had already brought refugees from the north where Garua and its environs had experienced the deepest falls of tephra during the Holocene. When the Isthmus was impacted again by W-K4, local resources and social alliances already strained to their limits may have simply collapsed.

One of the major findings of the Bayesian modelling is that the Dakataua eruption had a much more profound affect on the settlement of Garua Island than had previously been detected. The Interval calculation indicates that the island may have been unoccupied for up to 260 years afterwards and the mode at 235 years favours the high end of this distribution. Given the devastation that would have been associated with the substantial depth of Dk tephra (c. 0.75 m), the long period of abandonment makes more sense than the previous low estimation by Torrence et al. (2000) (Table 1).

In summary, results obtained from the Bayesian analyses are unable to negate the hypothesis that the physical damage of each volcanic disaster as measured by the depth of airfall tephra preserved in situ is directly correlated with its impacts on the cultural history of the Willaumez Peninsula, particularly in terms of the history of settlement. The predicted order for severity of volcanic disaster for both the Isthmus and Garua Island is reflected in the varying lengths of abandonment, with the exception of W-K4 in the Isthmus, owing to the combined effects of the closely timed Dk and W-K4 impacts. There are, however, indications that cultural processes had a role to play in mitigating or exacerbating the consequences of volcanic activity. This is particularly suggested in the major differences between W-K1, which was followed by long abandonment and little cultural change, and W-K2, which is correlated with relatively rapid recolonization but major changes in cultural assemblages.

**Pattern of recolonization**

A further way to understand how populations recover from disasters is to compare the rate and character of recolonization for areas impacted by massive volcanic events. Given the relatively large number of dates for each tephras stratigraphic layer, we make the working assumption that the number of contemporary dates provides an adequate measure of the intensity of land use at any one time. We can therefore monitor changes in where and when people were present in the landscape by tracking radiocarbon dates, as shown in Figures 10 and 11 where they are placed in order along an x-axis with the age of the determination plotted on the y-axis.

As shown in Figures 10 and 11, the contrast in patterns of recolonization in the two regions is most marked following the W-K1 event. On Garua Island (Figure 11), there is an irregular build up of dates with large gaps between them until after 4100 BP when there is a consistent increase. This pattern suggests that recolonization was a relatively slow and erratic process by a small and highly mobile population. It also seems likely that the rapid first return to the region failed and was followed by a second period of abandonment before successful recolonization was achieved. In contrast, the mainland Isthmus (Figure 10) appears to have been essentially abandoned for c. 1700 years and then repopulated in a single burst just before the population increase on Garua: c. 4100 BP. Although tephra depths were greater on the Isthmus, it is difficult to explain the apparently protracted absence of occupation unless the early colonizers were highly focused on marine rather than terrestrial resources. The recovery of artefacts from many inland settings dating to this period, however, does not support that hypothesis (Torrence and Doelman, 2007). Since the pattern may also be a product of poor preservation of samples and/or shallow excavations into this lowest stratigraphic unit, further efforts should be made to obtain additional dates for this period.

Recolonization following the W-K2 event has a totally different pattern and indicates a relatively rapid resettlement of both Garua and the Isthmus. It is notable, however, that the process may have begun earlier on the offshore island than on the mainland (Table 7), perhaps because of the cultural attraction of the obsidian sources on Garua, as demonstrated by their exchange outside the region (Torrence, 2004; Summerhayes, 2007). In addition, the occurrence of numerous contemporary dates immediately following the event suggests that the earliest recolonization in both areas was fuelled by sizeable groups, but whether these were new immigrants introducing Lapita pottery to the region or people returning to their homeland remains an important question.

Recolonization after W-K3 is difficult to trace because of the brevity of the period before the subsequent Dk eruption. Since there is a large cluster of dates immediately following the eruption in the Isthmus region, large areas of the peninsular were probably reoccupied more or less simultaneously, possibly indicating a sizeable group of immigrants. There is only one date from Garua for the same period, which may be a product of sampling, but implies low population density as discussed previously.

Following the major Dk event it seems likely that people fled the northern, heavily impacted end of the Willaumez Peninsula and moved south to find refuge where there was significantly less impact. Although the period of abandonment following W-K4 is surprisingly long, it is notable that in the Isthmus region the cultural layers on top of W-K4 are very widespread and generally quite thick across the sampled region, suggesting once the area was recolonized, it was populated by relatively large numbers of people probably with a fairly intensive system of land use.

**Future studies**

Bayesian modelling has identified a number of possible weaknesses in the current set of radiocarbon determinations that could be addressed by increasing the number of samples with material at hand and through further fieldwork. The dating of the Dk event seems quite secure, but very little is known about the more recent history of the Dakataua volcano and how it affected prehistory in the region, although a preliminary sequence has been reported by Machida et al. (1996) and partially confirmed by recent fieldwork (Torrence and Neall, 2004). Since airfall tephras postdating the Dk event have been observed on Garua Island, further research aimed at assessing their impacts should be worthwhile.

Dating the Witori events on the basis of archaeological dates has probably progressed about as far as is possible. This approach is limited because it is biased by the history of settlement in the region, which may not always correlate with volcanic activity. Improvements require samples obtained from within well-characterized volcanic tephra (cf. Buck et al., 2003), although a recent attempt to revisit locations described by Machida et al. (1996) was unsuccessful (C.O. McKee, personal communication, 2002). Advances in this realm are probably dependent on consistent searching and good luck.

The addition of multiple dates from archaeological contexts would greatly increase confidence in our estimations for the length of abandonment and also help flesh out the pattern of recolonization after each event. It would be particularly important to increase the sample of dates from contexts following the W-K1 and W-K4 eruptions on the Isthmus and those bracketing the W-K3 eruption in both areas. A program focusing on the latter time period would also help track the relationships between volcanic activity and the cessation of Lapita pottery in this region.
Conclusions

The dates derived from Bayesian modelling have enabled a careful analysis of how a series of Holocene eruptions impacted human populations on the Willaumez Peninsula. The results demonstrate that not all volcanic events, even those with great magnitude, necessarily lead to cultural change. In some cases, such as with stemmed tools after the W-K1 disaster, cultural practices were persistent. In contrast, the potential correlation between the introduction and cessation of Lapita pottery and the W-K2 and W-K3 events, respectively, is tantalisingly close, much more so than anticipated previously, but a clear theoretical perspective is still needed to link these environmental disasters with the specific cultural responses. Data generated from the Bayesian analyses show that within the Willaumez Peninsula the impact of the eruptions largely reflected the intensity of the volcanic hazard, with the possible exception of W-K4 in the Isthmus, perhaps because of the combined effects of Dk and W-K4. Although W-K1 produced a major cultural disaster by depopulating a large region for a long period of time, viewed from a different perspective, it caused little if any cultural change.

Our study emphasizes the point made by Torrence and Grattan (2002b: 3) that detailed analyses of human responses reveal the ‘flexibility and adaptability’ of societies when facing disasters. Although we found no evidence to show that societies became better at coping with volcanic disasters through time, as predicted by Torrence et al. (2000), it is important to note that cultural groups did recolonize the region relatively quickly after most eruptions and that overall they persisted in this highly risky environment with remarkably little change. To understand this long-term adaptation to adversity, we may need to look further back into their history, as people had been coping with relatively frequent volcanic events since they first colonized the region c. 40 000 years ago (Torrence et al., 2004; Neall et al. 2008).

The new eruption dates obtained from Bayesian modelling will play a critical role in archaeological and environmental research in West New Britain because the paucity of well-preserved organic material means there is a high dependence on tephrochronology. This more secure dating of the chronological markers will also greatly assist in making comparisons in human history between New Britain and surrounding areas. If preserved in other regions, such as the Papua New Guinea mainland, these well-characterized and now firmly dated tephras could also serve as useful chronological markers.

Finally, our case study shows that Bayesian statistical techniques have an important role to play in debates about the impacts of natural disasters on human history. The use of Bayesian-based approaches to obtain precise estimates for volcanic events and to track how humans responded in terms of abandonment and recolonization in the Willaumez Peninsula well illustrates the potential role of these methods. The Bayesian calibrations for five major volcanic disasters in Papua New Guinea improves the estimates for both the date of the eruptions and the length of time the region was subsequently abandoned. The case study also demonstrates the value of Bayesian modelling for increasing the accuracy of relative dating provided by tephrochronology. As we have shown, the potential for enhancement is especially large where there is a long stratigraphy with multiple tephras, because the strength of the Bayesian approach is that it utilizes the prior knowledge embedded in the ordering of the layers.

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