A revised age of AD 667-699 for the latest major eruption at Rabaul

McKee, C. O., Baillie, M. G., & Reimer, P. J. (2015). A revised age of AD 667-699 for the latest major eruption at Rabaul. Bulletin of volcanology, 77, [65]. DOI: 10.1007/s00445-015-0954-7

Bulletin of Volcanology

A revised age of AD 667-699 for the latest major eruption at Rabaul.

--Manuscript Draft--

Manuscript Number:	BUVO-D-15-00040R2
Full Title:	A revised age of AD 667-699 for the latest major eruption at Rabaul.
Article Type:	Research Article
Corresponding Author:	Chris McKee Port Moresby Geophysical Observatory Port Moresby, NCD PAPUA NEW GUINEA
Corresponding Author Secondary Information:	
Order of Authors:	Chris McKee
	Michael Baillie
	Paula Reimer
Funding Information:	
Abstract:	The most recent major eruption at Rabaul was one of the largest known events at this complex system, having a VEI rating of 6. The eruption generated widespread airfall pumice lapilli and ash deposits and ignimbrites of different types. The total volume of pyroclastic material produced in the eruption exceeded 11 km3 and led to a new phase of collapse within Rabaul Caldera. Initial 14C dating of the eruptive products yielded an age of about 1400 yrs BP, and the eruption became known as the "1400 BP" eruption. Previous analyses of the timing of the eruption have linked it to events in AD 536 and AD 639. However, we have re-evaluated the age of the eruption using the Bayesian wiggle-match radiocarbon dating method, and the eruption is now thought to have occurred in the interval AD 667-699. The only significant equatorial eruptions recorded in both Greenland and Antarctic ice during this interval are at AD 681 and AD 684, dates that coincide with frost rings in bristlecone pines of western USA in the same years. Definitively linking the Rabaul eruption to this narrow age range will require identification of Rabaul tephra in the ice records. However, it is proposed that a new working hypothesis for the timing of the most recent major eruption at Rabaul is that it occurred in the interval AD 681-684.
Response to Reviewers:	See attachment

A Revised Age of AD667-699

for the Latest Major Eruption at Rabaul

Chris O. McKee[1]
Michael G. Baillie[2]
Paula J. Reimer[2]

1. Port Moresby Geophysical Observatory, Port Moresby, NCD, Papua New Guinea
2. School of Geography, Archaeology and Palaeoecology, Queen’s University Belfast, Belfast, Northern Ireland, UK

ABSTRACT

The most recent major eruption at Rabaul was one of the largest known volcanic events at this complex system, having a VEI rating of 6. The eruption generated widespread pumice lapilli and ash fall deposits and ignimbrites of different types. The total volume of pyroclastic material produced in the eruption exceeded 11 km^3 and led to a new phase of collapse within Rabaul Caldera. Initial ^{14}C dating of the event yielded an age of about 1400 yrs BP, and the eruption became known as the “1400 BP” eruption. Previous analyses of the timing of the eruption have sought to link it to events in AD 536 and AD 639. However, we have re-evaluated the age of the eruption using the Bayesian wiggle-match radiocarbon dating method, and the eruption is now thought to have occurred in the interval AD 667-699. The only significant equatorial eruptions recorded in both Greenland and Antarctic ice during this interval are at AD 681 and AD 684, dates that coincide with frost rings in bristlecone pines of western USA in the same years. Definitively linking the Rabaul eruption to this narrow date range will require identification of Rabaul tephra in the ice records. However, it is proposed that a new working hypothesis for the timing of the most recent major eruption at Rabaul is that it occurred in the interval AD 681–684.

1. INTRODUCTION

The latest major eruption from Rabaul Volcano, New Britain Island, Papua New Guinea, is well documented in many respects. The initial description of the deposits of the eruption formed part of a series of studies of the geology and petrology of Rabaul Caldera (Heming 1974; Heming and Carmichael 1973; Peterman and Heming 1974; Heming 1977). This work was followed by a considerably more detailed examination of the deposits and their eruption mechanisms (Walker et al. 1981). However, the timing of the eruption has not been determined precisely and analyses of available ^{14}C dates have produced different and confusing results.

The timing of the eruption was initially determined to be approximately 1400 yrs BP (Heming 1974) from a small number of ^{14}C dates. Additional ^{14}C and thermoluminescence dates (Nairn et al. 1989, 1995) supported this timing. Thus, the event became popularly known as the “1400 BP” eruption. However, different analyses of the ^{14}C data have arrived at different conclusions on the calendar year age of the eruption, linking the event variously to severe atmospheric effects that began in AD 536 (Stothers and Rampino 1983; Stothers 1984), and to ice core high acidity levels at AD 639–640 (McKee et al. 2011).

This study reviews the published ^{14}C dates and the previous analyses of the timing of the latest major eruption at Rabaul, and presents new high precision^{14}C results from Bayesian “wiggle match” core-rim dating of a section of a large charcoalized log hosted by a component of the pyroclastic flow deposits of the eruption. The new results indicate an age in the range AD 667–699.

2. THE LATEST MAJOR ERUPTION FROM RABAUL VOLCANO

Heming (1974) identified widespread dacitic pumice lapilli and ash fall deposits and overlying pyroclastic flow deposits that form a surficial blanket over a large area around Rabaul as the products of the latest major activity from vents within Rabaul Caldera. The bedded fall deposits were reported to be over 15 m thick at one location near the northwestern rim of the caldera, while the pyroclastic flow deposits attain thicknesses as great as 30 m. Deposit thickness measurements and the areal extent of the deposits, at least 650 km^2, allowed Heming (1974) to estimate the volume of erupted pyroclastic products to be 24 km^3. Petrological details of the eruptive products were presented by Heming (1974) and a high magmatic quench temperature was determined by Heming and Carmichael (1973).

Walker et al. (1981) carried out extensive measurements including granulometric studies on samples from more than 80 sites located as much as 25 km from the caldera to characterize the deposits of the eruption. The fall deposits were identified as the products of a plinian eruption and the broad dispersal indicative of a high eruption column. Collapse of the plinian eruption column led to the development of pyroclastic flows. These flows consist of a thin and extensive landscape-blanketing ignimbrite veneer deposit, and normal, ponded valley-fill type ignimbrite. Sedimentation of mainly lithic fragments from the ignimbrite led to the formation of a ground layer which underlies the main part of the ignimbrite. A variant of the ignimbrite found nearer to source is depleted in fine-grained fragments and contains complete charcoalized logs, but these are not abundant. The ignimbrite is mostly non-welded and is a type-example of “low-aspect-ratio” ignimbrite (Walker et al. 1980). The volume of the pyroclastic deposits generated by the eruption was calculated to be not less than 11 km^3 (Walker et al. 1981). The eruption has been assigned a VEI rating of 6 (Newhall and Self 1982).

In later accounts of the detailed geological mapping of Rabaul Caldera and surrounding area (Nairn et al. 1989, 1995) and of the related petrological and geochemical studies (Wood et al. 1995), the products of the latest major eruption were referred to as the Rabaul Pyroclastics

Formation. Two members of the formation were identified – the Rabaul Ignimbrite and the Rabaul Plinian Fall, both after Walker et al. (1981).

3. SINGLE-SAMPLE RADIOCARBON DATING

Summary of published ^{14}C dates

A total of four single-sample ^{14}C dates from charcoal fragments contained within the deposits of the Rabaul Pyroclastics Formation was obtained by Heming (1974). One additional date was obtained from the palaeosol beneath these deposits. Nairn et al. (1989) obtained one new date from charcoal within the ignimbrite and two new dates from the palaeosol beneath the plinian fall deposits. All of these results are shown in Table 1. Greater consistency is evident in the dates from charcoal.

Weighted mean ^{14}C date

Following the method of Long and Rippeteau (1974), a chi-squared test was used to determine that the five ^{14}C dates from charcoal within the Rabaul Pyroclastics were statistically indistinguishable ($T'=3.91$, $X_i^2(.05)=9.49$) and the weighted mean was calculated to be 1380 ± 34 yrs BP. This result was reported previously (McKee et al. 2011) together with weighted mean ages for major eruptions at the volcanoes Dakataua and Witori, also located on New Britain Island.

Calendar year calibration

Calendar year calibrations with 1 σ and 2 σ ranges derived from OxCal v 3.10 (Bronk Ramsey, 2005) and using the northern hemisphere calibration curve, IntCal09 (Reimer et al., 2009), were also reported by McKee et al (2011), and are re-calibrated here with IntCal13 (Reimer et al., 2013) as shown in Table 2. The calibration results indicate 7th Century AD timing for the Rabaul Pyroclastics eruption. Calendar year ages were also reported by Heming (1974) but those results were not calibrated and represent simple arithmetic differences between the ^{14}C dates and AD 1950 (see below).

Remarks

The process of calculating the weighted mean of a set of ^{14}C dates assigns greater significance to the more precise dates i.e. those with smaller uncertainties. This process may be justified statistically as it addresses analytical quality. However, it does not take into account the history of the dated material, particularly whether that material was alive and part of the carbon cycle at the time of the charcoalizing event.

There will be a natural spread of the radiocarbon dates of the charcoal fragments produced when a forest, including mature trees several decades to more than a century old, is overwhelmed by a hot pyroclastic flow. Many of the charcoal fragments will be from older growth parts of shattered trees and the dates obtained from them will be older than the age of the charcoalizing event. The spread of ^{14}C dates from charcoal within the Rabaul Pyroclastics deposits (Table 1) appears to reflect this situation, being skewed to somewhat older dates. Thus, many of the dates will be less reliable indicators of the timing of the charcoalizing event. It follows that use of these data in averaging processes will also produce less reliable results.

More accurate timing of volcanic eruptions using the single-sample radiocarbon method may be achieved by the dating of younger growth parts of vegetation such as bark and twigs. Greater accuracy in timing will also result from use of the wiggle-match radiocarbon dating technique as long as the tree sample is complete to the outer growth rings.

4. BAYESIAN WIGGLE-MATCH RADIOCARBON DATING

High precision core-rim ^{14}C dating

Bayesian wiggle-match dating uses multiple high precision ^{14}C dates from a sequence with known calendar year spacing between samples, such as tree-rings, and then finds the best match for the sequence of dates against the ^{14}C-calendar year calibration curve. In dating a charcoalized log, if we assume that the log was a living tree at the time of the charcoalizing event, in this case passage of a hot pyroclastic flow, the outermost section of the log will yield a ^{14}C date close to the time of the charcoalizing event, and the inner parts of the log, progressively from rim to core, will yield successively earlier ^{14}C dates.

For the purpose of wiggle-match dating we collected a section of a large charcoalized log from the fines-depleted ignimbrite of the Rabaul Pyroclastics deposits at a location near the southern rim of the caldera. The charcoalized log had a diameter of about 35 cm, indicating that the tree had been growing for a considerable period of time prior to the time of the eruption. There were 230 rings with a continuous outer ring which ran to the underbark surface (Fig. 1). The tree was of a conifer species (Dr J. Pilcher, pers. comm.) with clear ring boundaries and no sign of problem rings. Samples were cut in twenty year blocks starting from the outer ring (Table 3).

The samples were pretreated using the % acid-alkali-acid method (4% HCl at 80°C for 2 hrs, 2% NaOH at 80°C for 2 hr, 4%HCl at 80°C for 2 hrs and rinsed to neutral after each step). The samples were then dried, combusted in a flow of oxygen, converted to benzene and analysed by liquid scintillation counting in the Queen's University Belfast Radiocarbon Laboratory in 1994. The radiocarbon ages were normalized for $\delta^{13}C$ fractionation and calculated according to Stuiver and Polach (1977). The results of the high precision ^{14}C dating from the inner wood to the rim of the log are shown in Table 3.

The set of dates in Table 3 has a range similar to that of the dates obtained from single-sample radiocarbon dating (Table 1). The succession of dates from the inner wood to the rim is systematic except for one date in the middle of the sequence: sample UB-3806 yielded a date of 1435 ± 21 yr BP, which is older than the date for the inner-most part of the log analyzed, and hence may be an outlier. However, the calibration curve does contain numerous reversals that could satisfactorily explain the apparently anomalous date for UB-3806.

Calendar year calibration

Calendar year calibration is complicated by uncertainty over the use of either northern hemisphere or southern hemisphere calibration curves. For a near-equatorial location such as Rabaul the choice is equivocal. However, Papua New Guinea lies very close to the January inter-tropical convergence zone so the site most likely was influenced by northern hemisphere air masses. In addition the southern hemisphere calibration curve SHCal13 (Hogg et al. 2013) is dominated by tree rings from New Zealand which would be strongly influenced by upwelling in the Southern Ocean (McCormac et al. 1998).

The radiocarbon dates were modelled using a D_Sequence (wiggle-match) in OxCal v4.1 (Bronk Ramsey et al. 2001; Bronk Ramsey 2009a) with the northern hemisphere calibration curve (IntCal13). A gap of 20 years was included between each sample mid-point and 10 years between the outermost sample mid-point and the last ring. The SSimple outlier model (Bronk Ramsey 2009b) was used with a prior probability of 5% for each sample being an outlier. To account for a possible laboratory offset the Delta_R function was used. An offset of -20 ± 20 was selected based on the documented difference between the Waikato and Belfast laboratories of −3.9 ± 2.5 for tree-rings from the period AD 955–1945 (McCormac et al. 2002). The sample UB-3806 had a posterior outlier probability of 12% and all other samples were below 6%. The succession of 5 wiggle-match dates gave a modelled age of AD 667–699 for the last ring at 95.4% confidence levels (Fig. 2a). Taking UB-3806 out of the model gives a wider age range of AD 672-719 (Fig.

2b), however, as there is no good reason to discard UB-3806, for the purposes of this paper, we will use AD 667–699 as the most probable timing of the Rabaul Pyroclastics eruption. It is possible that this suggested age dating can be further refined using evidence of volcanic activity from other chronologies such as ice cores and tree rings.

5. CALIBRATED AGES AND OTHER CHRONOLOGIES

Large explosive volcanic eruptions inject massive quantities of ash and aerosol-forming gases into the stratosphere often forming “dry fogs”. The aerosols are predominantly sulphurous and are produced when volcanic SO_2 and water vapour combine to form sulphuric acid droplets. Other common volcanic gases that comprise the aerosols may include compounds of chlorine and fluorine. Solar radiation, absorbed and back-scattered by the volcanic clouds, produces haziness and lowers the atmospheric and surface temperatures, hence the term “volcanic winter” for this phenomenon. Reports of the atmospheric veiling and optical effects such as unusual twilights, mock suns and Bishop’s rings induced by dry fogs may be the only immediate evidence in some cases of major eruptions which were not observed directly (Lamb 1970; Stothers and Rampino 1983). Short-term climatic cooling associated with some large eruptions may be recorded by frost rings in trees at high latitudes (e.g. LaMarche and Hirschboeck 1984; Briffa et al. 1990; Salzer and Hughes, 2007). Also, the precipitation of volcanic aerosols on glacial ice of the Greenland and Antarctic Ice Sheets may be preserved as high acidity levels in the ice sheets (e.g. Zielinski et al. 1994; Hammer et al. 1997). Although tree rings can be resolved to specific calendar years, ice core dates can be offset by a few years (Larsen et al. 2008) and it has been robustly suggested that in the 6th and 7th centuries the European ice dates (GICC05) may be too old by about seven years (Baillie 2008; Baillie and McAneney 2015).

Using this revised timescale, a search of available ice core records for the period covered by the wiggle-match dating, AD 667 to 699, revealed two high acidity horizons in both Greenland (Sigl et al. 2013) and Antarctic ice cores (Sigl et al. 2013; Plummer et al. 2012) consistent with frost rings in bristlecone pines in western USA at AD 681 and 684 (Baillie and McAneney 2015). The presence of acid in both ice sheets is indicative of probable equatorial eruptions (Baillie and McAneney 2015). Whether the Rabaul eruption can be definitively linked to this environmental evidence of volcanic activity, and so refine the timing of the eruption, is dependent on ultimate identification of Rabaul tephra in the ice records (e.g. Coulter et al. 2012).

6. DISCUSSION

Comparison of wiggle-match and single-sample ^{14}C dating

The main advantage of wiggle-match dating over single-sample ^{14}C dating is that it reduces the calibrated age ranges. This combined with careful selection of the material to be dated yields more reliable results on the timing of the charcoalizing event. The incorporation of abundant large charcoalized logs in pyroclastic deposits is commonly a good indication that the logs originated from a landscape that was vegetated until the time of the passage of the pyroclastic flow. Determination of a sequence of dates from the core to the rim of a charcoalized log not only ensures that the youngest part of the tree is dated but also that the sequence of dates can be compared more confidently with the calendar year calibration curve.

For single-sample ^{14}C dating, when only scattered fragments of charcoal are present, there is no way of knowing which part of a tree is represented by an individual fragment. Also, some charcoal fragments may be exotic and may predate the charcoalizing event. Consequently, the date obtained from a fragment of charcoal will carry an uncertainty relating to sampling that is difficult to quantify. Individual dates from multiple samples will produce a range of ages that tend to be older than the age of the charcoalizing event and calculation of weighted means will merely provide a statistical average of these “older than” dates.

The weighted mean age of the previously published ^{14}C dates on charcoal from the Rabaul Pyroclastics was 1380 ± 34 yrs BP, almost one hundred radiocarbon years older than the date for the outermost part of the log analysed by the wiggle-match technique. It is likely that the weighted mean age is too old by about one hundred years, which in turn would make the calibrated age too old by a significant time period. Thus, correlation of the previously calibrated age with ice core acidity peaks at AD 639 and AD 640 (McKee et al. 2011) can be taken to be erroneous.

Mystery cloud of AD 536

The mystery cloud of AD 536 was the densest and most persistent dry fog on record (Stothers 1984). Observed in Europe and the Middle East in AD 536–537, it caused severe dimming of the sun resulting in cold conditions and poor harvests of crops. High acidity levels in ice cores from Greenland at AD 540 ± 10 and at AD 533–534 ± 2 (Hammer et al. 1980; Larsen et al. 2008), and from Antarctica at AD 542 ± 17 (Larsen et al. 2008) have been suggested to be associated with this dry fog.

An eruption at Rabaul was tentatively inferred to be responsible for the mystery cloud (Stothers and Rampino 1983; Stothers 1984). However, with the revision of the age of the Rabaul Pyroclastics eruption to AD 667–699, any suggested link between the mystery cloud of AD 536 and a major eruption at Rabaul can now be dismissed. Additionally, the original basis for the claimed association can be seen to be erroneous. The ^{14}C age used as the basis for the link was the average of two dates from Heming (1974): 1430 ± 90 yrs BP and 1390 ± 90 yrs BP, which were arithmetically converted to calendar year dates of AD 520 and AD 560. However, they are not calibrated ages. Calibration of the two original ^{14}C dates would have resulted in calendar year ages about one century later than the mystery cloud of AD 536 and the ice core acidity peaks of AD 533–542, eliminating any possibility of a link between the Rabaul Pyroclastics eruption and the observed and recorded atmospheric and surface effects of the mystery cloud.

7. CONCLUSIONS

The results of new high precision Bayesian wiggle-match dating from the inner wood to the rim of a large charcoalized log hosted by pyroclastic deposits from Rabaul Volcano have led to revision of the age of the latest major eruption at Rabaul to AD 667–699 at 95.4 % confidence levels.

Evidence from other chronologies, including acidity peaks in Greenland and Antarctic ice that can be linked to frost rings in bristlecone pines of western USA, indicates two major volcanic eruptions from equatorial sources within the revised age range for the Rabaul Pyroclastics eruption, at AD 681and AD 684.

Further investigation, involving identification of Rabaul tephra in the ice records, is required to definitively refine the timing of the Rabaul eruption, but based on the evidence presented here we propose that a new working hypothesis for the date of this volcanic event is AD 681–684.

ACKNOWLEDGEMENTS

We thank Professor Hugh Davies of the Geology Department, University of Papua New Guinea, for providing reviews of several versions of the manuscript, and Marissa Sari Egara of the Port Moresby Geophysical Observatory for word processing of the manuscript. We also thank Dr Alan Hogg, Waikato University, and Dr Manuel Nathenson, U.S. Geological Survey, for constructive reviews. COM publishes with the permission of the Secretary, Department of Mineral Policy and Geohazards Management, Papua New Guinea.

FIGURES

1. The sampled charcoalized log in situ hosted by ignimbrite of the Rabaul Pyroclastics Formation. The log is complete to the underbark. Photo courtesy of Rabaul Volcano Observatory.

2. Wiggle-matched calibration using the northern hemisphere calibration curve with a) the five radiocarbon dates giving an age range of AD 667–699 at 95.4% confidence levels for the timing of the Rabaul Pyroclastics eruption, and b) with UB-3806 removed which gives an age range of AD 672–719. Probability distributions for calibration of individual samples are shown in light gray and the modelled probability is shown in dark gray.

TABLES

1. Radiocarbon dates relevant to the Rabaul Pyroclastics Formation.

2. Weighted mean age and calibrated age ranges for charcoal from the Rabaul Pyroclastics Formation.

3. Radiocarbon ages for blocks of rings from a charcoalized tree hosted by ignimbrite at a location near the southern rim of Rabaul Caldera and used for wiggle-match dating of the Rabaul Pyroclastics Formation.

REFERENCES

Baillie MGL (2008) Proposed re-dating of the European ice core chronology by seven years prior to the 7th century AD. Geophysical Research Letters 35 L15813, doi.org/10.1029/2008GL034755

Baillie MGL, McAneney J (2015) Tree ring effects and ice core acidities clarify the volcanic record of the first millenium. Climate of the Past 11:105-114.doi.org/10.5194/cp-11-105-2015

Briffa KR, Bartholin TS, Eckstein D, Jones PD, Karlen W, Schweingrube FH, Zetterberg PA (1990) 1,400-year tree-ring record of summer temperatures in Fennoscandia. Nature 346:434-439.

Bronk Ramsey C (2005) OxCal version 3.10

Bronk Ramsey C, van der Plicht J, Weninger B (2001) 'Wiggle matching' radiocarbon dates. Radiocarbon 43 2A:381-389

Bronk Ramsey C (2009a) Bayesian analysis of radiocarbon dates. Radiocarbon 55 1:337-360

Bronk Ramsey C (2009b) Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51 3:1023-1045

Coulter SE, Pilcher JR, Plunkett G, Baillie M, Hall VA, Steffensen JP, Vinther BM, Clausen HB, Johnson SJ (2012) Holocene tephras highlight complexity of volcanic signals in Greenland ice cores. Journal of Geophysical Research 117 D21303 doi:10.1029/2012JD017698

Hammer CU, Clausen HB, Dansgaard W (1980) Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. Nature 288:230-235

Hammer CU, Clausen HB, Langway CCJr (1997) 50,000 Years of Recorded Global Volcanism. Climatic Change 35:1-15

Heming RF (1974) Geology and Petrology of Rabaul Caldera, Papua New Guinea. Geological Society of America Bulletin 85 8:1253-1264

Heming RF (1977) Mineralogy and proposed P-T paths of basaltic lavas from Rabaul Caldera, Papua New Guinea. Contributions to Mineralogy and Petrology 61:15-33

Heming RF, Carmichael ISE (1973) High temperature pumice flows from the Rabaul Caldera, Papua New Guinea. Contributions to Mineralogy and Petrology 38:1-20

Hogg AG, Hua Q, Blackwell PG, Niu M, Buck CE, Guilderson TP, Heaton TJ, Palmer JG, Reimer PJ, Reimer RW, Turney CSM, Zimmerman SRH (2013) SHCal13 Southern Hemisphere Calibration, 0-50,000 Years cal BP. Radiocarbon 55 4:1889-1903

LaMarche VC Jr, Hirshboeck KK (1984) Frost rings in trees as records of major volcanic eruptions. Nature 307:121-126

Lamb HM (1970) Volcanic dust in the atmosphere; with its chronology and assessment of its meteorological significance. Philosophical Transactions of the Royal Society London 266:425-533

Larsen LB, Vinther BM, Briffa KR, Melvin TM, Clausen HB, Jones PD, Siggaard-Andersen M-L, Hammer CU, Eronne M, Grudd H, Gunnarson BE, Hantemirov RM, Naurzbaev MM, Nicolussi K (2008) New ice core evidence for a volcanic cause of the A.D. 536 dust veil. Geophysical Research Letters 35 L04708 doi: 10.1029/2007GL032450

Long A, Rippeteau B (1974) Testing contemporaneity and averaging radiocarbon dates. American Antiquity 39:205-215

McCormac FG, Hogg AG, Higham TFG, Lynch P, Stieglitz J, Broecker WS, Baillie MGL, Palmer JG, Xiong LM, Pilcher JR, Brown D, Hoper ST (!998) Temporal variation in the inter-hemispheric ^{14}C offset. Geophysical Research Letters 25(9):1321-1324

McCormac FG, Reimer PJ, Hogg AG, Higham TFG, Baillie MGL, Palmer J, Stuiver M (2002) Calibration of the radiocarbon time scale for the southern hemisphere: AD 1850-950. Radiocarbon 44(3):641-651

McKee CO, Neall VE, Torrence R (2011) A remarkable pulse of large scale volcanism on New Britain Island, Papua New Guinea. Bulletin of Volcanology 73:27-37

Nairn IA, Talai B, Wood CP, McKee CO (1989) Rabaul Caldera, Papua New Guinea 1: 25,000 reconnaissance geological map and eruption history. New Zealand Geological Survey, Department of Scientific and Industrial Research

Nairn IA, McKee CO, Talai B, Wood CP (1995) Geology and eruptive history of the Rabaul Caldera area, Papua New Guinea. Journal of Volcanology and Geothermal Research 69:255-284

Newhall CG, Self S (1982) The Volcanic Explosivity Index (VEI): An Estimate of Explosive Magnitude for Historical Volcanism. Journal of Geophysical Research (Oceans & Atmospheres) 87:1231-1238

Peterman ZE, Heming RF (1974) Sr^{87}/Sr^{86} Ratios of Calc-Alkalic Lavas from the Rabaul Caldera, Papua New Guinea. Geological Society of America Bulletin 85 8:1265-1268

Plummer CT, Curran MAJ, Van Ommen TD, Rasmussen SO, Moy AD, Vance TR, Clausen HB, Vinther BM, Mayewski PA (2012) An independently dated 2000 year volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the 1450s CE eruption of Kuwae, Vanuatu. Climate of the Past 8:1929-1940

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0 - 50,000 years cal BP. Radiocarbon 51 4:1111-1150

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, van der Plicht J (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon 55 4:1869-1887

Salzer MW, Hughes MK (2007) Bristlecone pine tree rings and volcanic eruptions over the last 5000 years. Quaternary Research 67:57-68

Sigl M, McConnell JR, Layman L, Maseli O, McGwire K, Pasteris D, Dahl-Jensen D, Steffensen JP, Vinther BM, Edwards R, Mulvaney R, Kipfstuhl S (2013) A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years. Journal of Geophysical Research 118:1151-1169

Stothers RB (1984) Mystery cloud of AD 536. Nature 307:344-345

Stothers RB, Rampino MR (1983) Volcanic eruptions in the Mediterranean before AD 630 from written and archaeological sources. Journal of Geophysical Research 88 B8:6357-6371

Stuiver M, Polach HA (1977) Reporting of C-14 data – Discussion. Radiocarbon 19 3:355-363

Walker GPL, Heming RF, Wilson CJN (1980) Low aspect ratio ignimbrites. Nature 283:286-287

Walker GPL, Heming RF, Sprod TJ, Walker HR (1981) Latest major eruptions of Rabaul Volcano. In: Johnson RW (ed) Cooke-Ravian Volume of Volcanological Papers, Geological Survey of Papua New Guinea Memoir 10:181-193

Wood CP, Nairn IA, McKee CO, Talai B (1995) Petrology of Rabaul Caldera, Papua New Guinea. Journal of Volcanology and Geothermal Research 69:289-306

Zielinski GA, Mayewski PA, Meeker ID, Whitlow S, Twickler MS, Morrison M, Meese D, Alley RB, Gow AJ (1994) Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system. Science 264:948-952

Table 1. Radiocarbon dates relevant to the Rabaul Pyroclastics Formation

Deposit dated	Sample No.	^{14}C date (yrs BP)	Source
Rabaul Pyroclastics	1001 B *	1280 ± 81	Heming (1974)
	155 *	1360 ± 55	Nairn et al. (1989)
	8032 †	1390 ± 90	Heming (1974)
	8033 †	1430 ± 90	Heming (1974)
	7030 †	1505 ± 90	Heming (1974)
Palaeosol under R.P.	91006M1 #	830 ± 70	Nairn et al. (1995)
	P1344 *	1450 ± 60	Heming (1974)
	92009M1 #	1600 ± 70	Nairn et al. (1995)

* Dated by N.Z.D.S.I.R., Lower Hutt, New Zealand

† Dated at GEOCHRON Laboratories, Cambridge, Massachusetts, USA

Dated at Beta Analytic Inc., Miami, Florida, USA

Table 2

Table 2. Weighted mean age and calibrated age ranges for charcoal from the Rabaul Pyroclastics Formation.

Deposit dated	Weighted Mean Age (yrs BP)	Calibrated Age (AD)	
Rabaul Pyroclastics	1380 ± 34	634-670	(68.2%)
		600-687	(95.4%)

Table 3

Table 3. **Radiocarbon ages for blocks of rings from a charcoalized tree hosted by ignimbrite at a location near the southern rim of Rabaul Caldera and used for wiggle-match dating of the Rabaul Pyroclastics Formation**

Laboratory number	Relative position	Ring numbers	^{14}C BP (1σ)	$\delta^{13}C_{VPDB}$ (‰)
UB-3804	1 - outermost to bark	230-211	1288 ± 21	-26.7
UB-3805	2	210-191	1294 ± 23	-26.3
UB-3806	3	190-181	1435 ± 21	-26.4
UB-3807	4	170-151	1405 ± 21	-26.5
UB-3808	5 - innermost to core	150-130	1412 ± 21	-26.6

Ages from Queen’s University Belfast Radiocarbon Laboratory

Figure 1

Figure 2a

Click here to download Figure: RevRevAgeRabaulFig2a.png

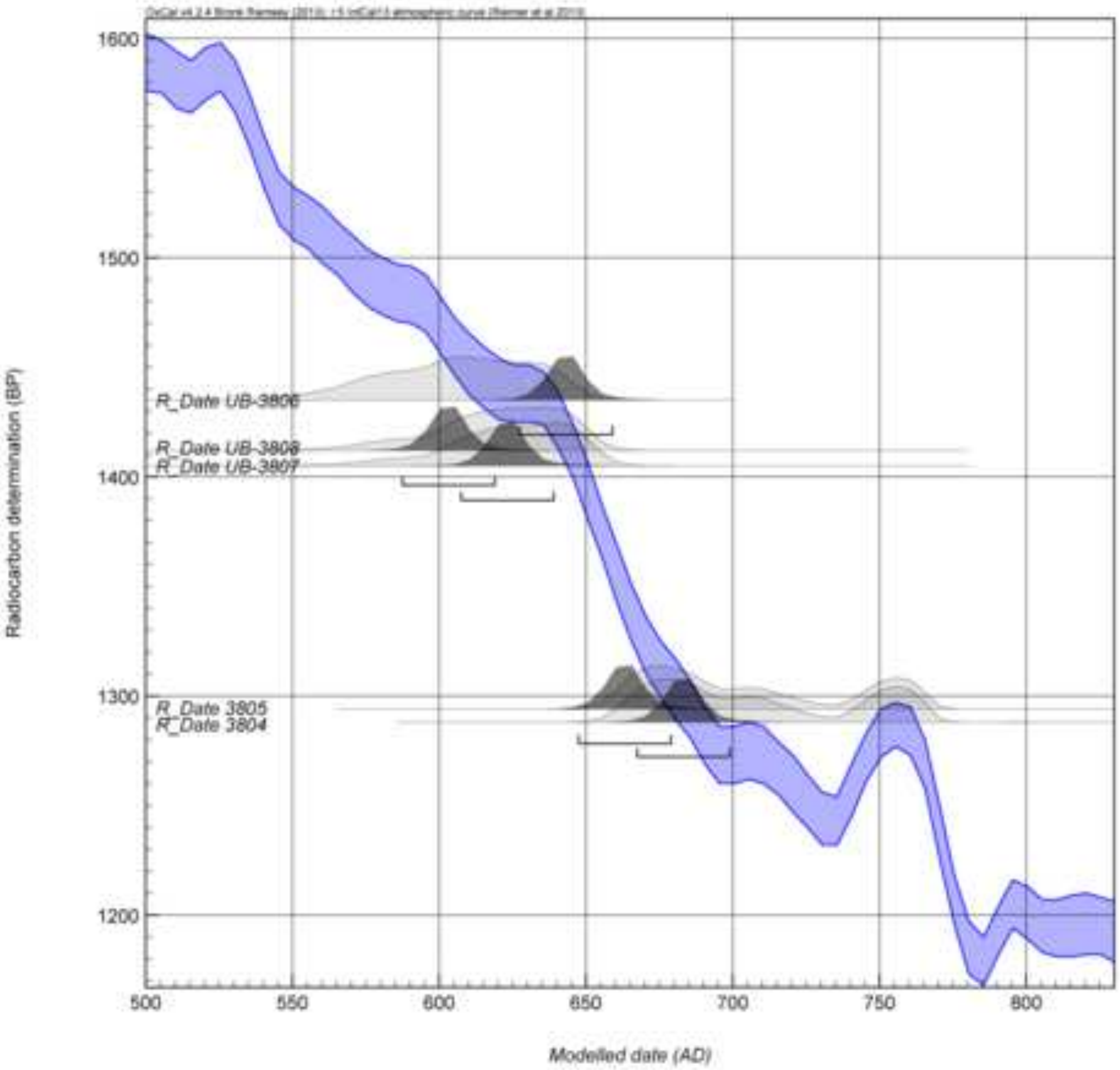
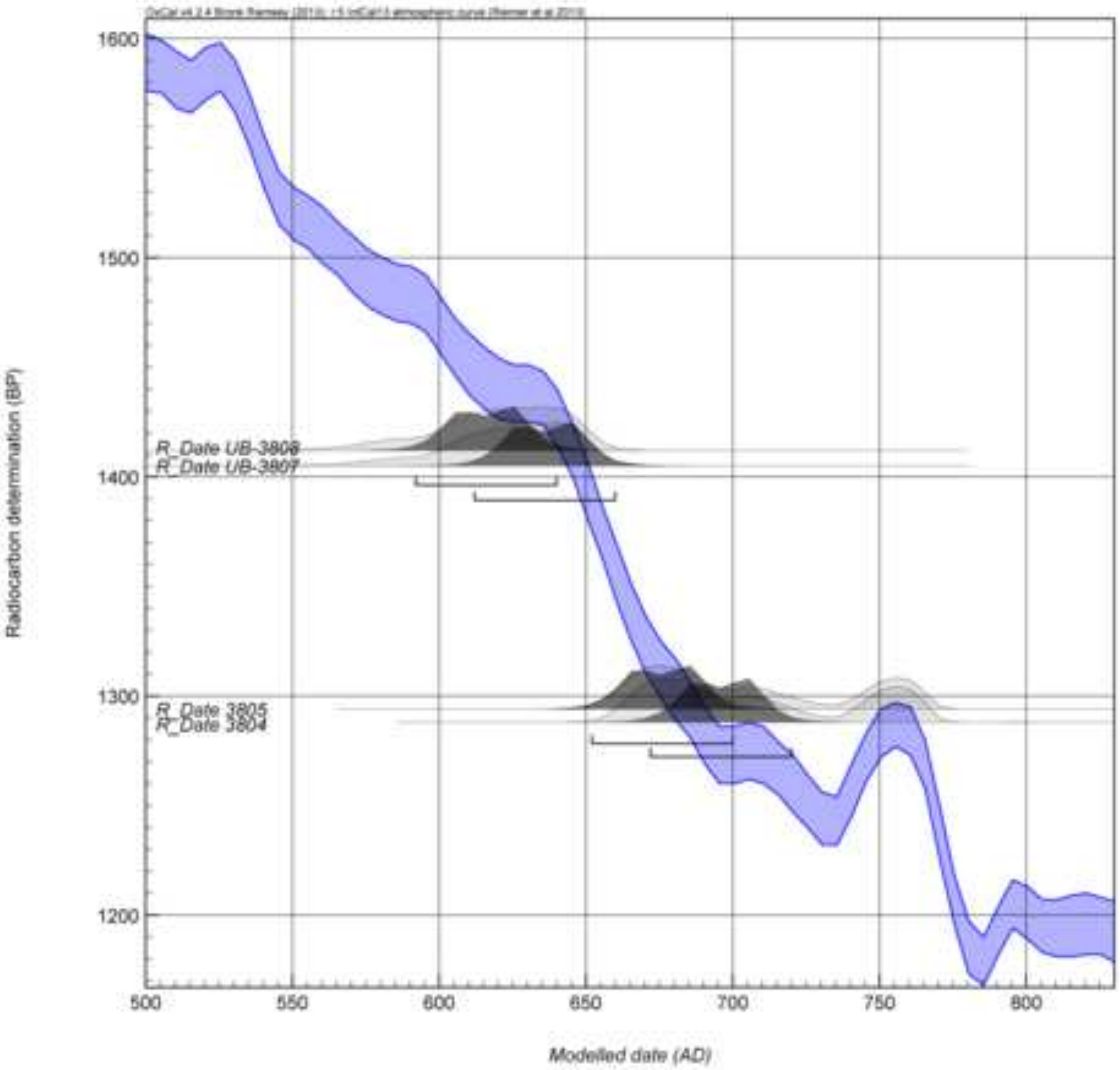


Figure 2b

Click here to download Figure: RevRevAgeRabaulFig2b.png



A revised age of the AD 700-760 for the latest major eruption at Rabaul.
McKee, Baillie, Reimer

Review. Alan G. Hogg.
Date: 17/04/15

The paper is well written and makes a useful contribution in assigning a calendar age range to the last major eruption at Rabaul volcano. It utilises ^{14}C wiggle matching of five new ^{14}C dates obtained at equal spacing through a log carbonised by the eruption to obtain an accurate calendar age range for the event. The paper should be published but is missing some critical information, required to better understand the methodology utilised for this work. The wiggle matching could also be improved in my opinion – see more detailed comments below.

1. line 123. It would be useful to add the student t-test associated with the weighted mean age i.e. X= 1381 ± 34 (t=3.9; 5% 9.5).
   Done.
2. line 155. "Greater accuracy in timing will also result from use of the wiggle-match radiocarbon dating technique", as long as the tree has been preserved to bark edge and is not missing a significant percentage of rings.
   Added
3. Line 164.'assume' not 'ssume'
   Corrected.
4. Line 169.

   The authors state that a carbonised log ~35cm in diameter was collected from the eruption deposits but they do not discuss some critical aspects of the log:
   a. species? Is this species prone to missing rings?
      The tree was of a conifer species with clear ring boundaries and no evidence of problem rings.
   b. Was bark present? If not the outer rings may be missing and the date will be too old. If bark was not present, why do the authors think the result will be reliable?
      The log was complete with continuous rings to the underbark. A photo of the log in situ and showing the underbark has been added.
   c. Table 3 shows that 5 samples were analysed – what were the ring numbers? Were the samples decadal?
      Ring numbers given in Table 3. Samples were bidecadal which is now stated in the text.
   d. How were the samples pretreated? ABA? Multiple base extractions or 1 only?
      Sample pretreatment described. It was ABA with only 1 base extraction.

5. Line 179. UB-3806 should not have been discarded simply because it was not systematic. The calibration curves are full of non-uniform sequences

and UB-3806 may have been showing a real feature in the curve. When the model agreement index is low, the best approach is to utilise theoutlier analysis tool to quantify the degree of variance. When outlier analysis is applied (e.g. Outlier_Model("SSimple",N(0,2),0,"s");), UB-3806 is indeed identified as an outlier (Prior=5; Posterior=20-33 depending upon the curve used) and its removal for further analysis can then be justified. The possibility of a laboratory offset can also be mitigated by addition of a delta_R line (e.g. Delta_R("",0,20);) – and this further improves the agreement index, even though the modelled delta_R is low (~0 to -6 yrdepending upon the curve used). In addition, the eruption age needs to have additional years added to the modelled D_Sequence result. If the outermost (youngest) sample was decadal, an additional 5 years needs to be added as the modelled D_Sequence result is the average of 10 rings (or however many were present in the outer sample).In my opinion, the wiggle matching should be redone and should at the very least use the latest calibration curves (IntCal13 and SHCal13).
Wiggle matching was redone using IntCal13 and Outlier analysis added as suggested. Delta_Rfunction of Delta_R("",-20,20) was used since previous work showed there was a small negative offset between the Belfast and Waikato lab. A ten year gap to the last ring was included. Results both with and without the sample UB-3806 are given.

6. Line 202. The choice of calibration curve for PNG is indeed equivocal as the authors say but my choice every time for locations like this would be IntCal, as PNG lies very close to the January ITCZ. And apart from this, SHCal for this time period is dominated by measurements from New Zealand which lies some 5,500 km further south and is more likely to be influenced by the Southern Ocean than sites much further north.
We agree and have used the IntCal13 curve and stated why.

7. Lines 338-339. I think it would be better to utilise the 95% confidence interval derived from the wiggle match as the 'new working hypothesis' for this eruption. Links to high acidity levels in the ice cores are always tentative, and the wiggle match results will be more reliable (*e.g*. the New Zealand Taupo eruption, determined at AD 232 ± 15 by extensive wiggle matching, but "identified" in the ice cores at AD 181 ± 2 and by historic records at ~AD 186).
This section was rewritten stating the need to identify Rabaul tephra in the ice records in order to definitively refine the timing of the Rabaul eruption.

8. Line 468, Table 1. This table should include the laboratory numbers where they are known.
Laboratory numbers are not known as they were not included in the papers used to source the ^{14}C dates. Details of the relevant dating laboratories have been added to Table 1.

9. Line 493, Table 3. It is essential that this table shows the ring numbers.
Ring numbers have been added to Table 3.

Reviewer #2: Review of Chris McKee, Michael Baillie, and Paula Reimer, A revised age of AD 700-760 for the latest major eruption at Rabaul, Bulletin of Volcanology

The paper reviews existing radiocarbon ages for the latest major eruption of Rabaul and proposes a new age based on a wiggle match to a set of rings from a single tree. Such a wiggle match should, but is not guaranteed, to provide a better age. The manuscript is in general in good shape, but there are some issues that should be addressed.

Lines 129-134 Just because McKee, Neall, and Torrance (2011) used IntCal09 does not mean that you should carry through using it in your calibration. If you want to give the IntCal09 calibrated age, you should also use IntCal13 and report its results. See below discussion of your wiggle match.

We have now used IntCal13 to recalibrate the weighted mean age and also for the wiggle match.

Lines 138-155 Although your discussion is true, the weighted mean age and its calibrated result are valid. The radiocarbon ages have large uncertainties, most around 90 years. The 95.4 %-calibrated age of 590-690 AD is in reasonable agreement with the Northern hemisphere calibrated age 698-730 AD. One skews younger and the other skews older, but they don't disagree. My only point here is that I think you are a bit more negative about the weighted mean age than is necessary.

The re-calibrated weighted mean date is skewed older than the wiggle-match date but we agree that it is still in reasonable agreement.

Line 174 d13C should be delta13C with the 13 as a superscript.
Done

Lines 190-200 You use the Southern hemisphere calibration curve SHCal04 from 2004 and Northern Hemisphere curve IntCal09 from 2009. But it is not clear that the 2004 curve for the Southern Hemisphere was created in a way that it is consistent with Northern hemisphere curve created in 2009. OxCal has IntCal13 and SHCal13 that were both created in 2013 with the Southern Hemisphere curve closely tied to the Northern Hemisphere curve. I really think that you should be doing your calibrations using those curves. Just because McKee, Neall, and Torrance (2011) used IntCal09 doesn't mean that you should continue using it for your new data. It really is better to use the most recent calibrations and not continue using older ones.

Agreed. IntCal13 is used for the wiggle match.

Lines 230-235 Castellano et al. (2005, JGR, v. 110, D06114) found volcanic events at AD 699 and AD 765 from ice core in Antarctica. Given the location of Rabaul just south of the equator, ash could go either north or south. You might want to mention these events as they offer additional correlations with your ages. They are not much out of your age range of AD 700-760.

We restricted consideration of ice core ages to those that satisfy the following conditions:

1. Be within the revised age range of AD 667-699
2. Have bipolar representation
3. Correlate with dendrological data - frost rings in this instance

The only dates that meet all criteria are AD 681 and 684

Figure 1 caption. The existing figure caption is simply an inadequate explanation for a reader who has not done an OxCal wiggle match recently. I hadn't done one in a couple years, and I had to go back to my notes to understand the figure. Here is a suggested rewrite.

1. Calibration curves for radiocarbon ages to calendar years for the southern hemisphere (blue, SHCal04) and for northern hemisphere atmospheric data (green, InCal09). Probability density for calibration of individual ages for each ring are shown as light lines. Probability density for the age of the outer layer from a wiggle match using the D_Sequence routines from OxCal(Bronk Ramsey, 2005) for the southern hemisphere calibration curve is shown in a darker color shifted by the number of rings with the individual age calibrations. Age range of AD 700-760 at 95.4% confidence levels for the timing of the RabaulPyroclastics eruption combines the ranges for the southern and northern hemisphere calibrations.

The figure caption has been re-written.

Table 3 lacks the ring count from the tree for each individual age. From Figure 1, I deduce that the rings are at 0, 20, 40, 60, and 80 (though the first dated ring may actually be a count of 10 with all the others 10 higher). However this information should appear in Table 3 so that some person in the future can rerun the wiggle match with improved calibration curves that come out every few years.

Tree-ring counts have been added to Table 3.

The caption to Table 3 is incorrect. Please revise to something like "Radiocarbon ages for individual rings in a tree (supply location information) used for wiggle-matching dating for the RabaulPyroclastics Formation. Ages from Queen's University Belfast Radiocarbon Laboratory." In the table, d13C should be delta13C with the 13 as a superscript.
Done.

Manuel Nathenson
U.S. Geological Survey