MODELING THE AGE OF THE CAPE RIVA (Y-2) TEPHRA

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ABSTRACT. Tephra from the Cape Riva (Y-2) eruption of Santorini has been found across the eastern Mediterranean. It presents an important link between marine and terrestrial records. A Poisson process (P Sequence) age-depth prior, with model averaging, is used to model individual previously published radiocarbon sequences, cross-linked with an exponential phase model parameter to obtain a robust age. Multiple sequences and ^{14}C determinations from 3 eastern Mediterranean data sets (Seymour et al. 2004; Margari et al. 2009; Müller et al. 2011; Roeser et al. 2012) are used in the model. The modeled age of the Y-2 tephra produced within this study is 22,329–21,088 cal BP at 95.4% probability.

INTRODUCTION

The Cape Riva (also known as Y-2) eruption of the island of Santorini produced a widespread ash horizon that forms an important link between different marine and terrestrial environmental records across the eastern Mediterranean region. It is found in deep-sea sediments from the Black Sea (Kwiecien et al. 2008), Aegean Sea, and the Marmara Sea (Çağatay et al. 2000; Wulf et al. 2002; Aksu et al. 2008); in eastern Mediterranean deep-sea sediments near western Cyprus (Wulf et al. 2002); in terrestrial peat records in Greece (Seymour et al. 2004; Margari et al. 2007; Müller et al. 2011); and in a lake record in Turkey (Roeser et al. 2012). Obtaining an accurate age for this tephra is important because it is frequently used to date and correlate different marine and terrestrial chronologies (e.g. Çağatay et al. 2000; Kwiecien et al. 2008). Indeed, the Cape Riva has been included as part of the European INTIMATE Tephra Framework, representing a key candidate for allowing the precise synchronization of paleorecords (Davies et al. 2012). Despite this, no detailed modeled age range has thus far been developed.

DATING

Tephras can be directly dated using ^{40}Ar/^{39}Ar or indirectly dated using radiocarbon, usually of charred organic material found in the same context. They can also be dated relatively using annual laminations if they were found in varved sequences. Recent developments in ^{40}Ar/^{39}Ar dating have been shown to provide accurate and precise ages of young mafic volcanic rocks, with 1σ uncertainties ranging from 0.5–2% (Lanphere 2000). Dating using the ^{40}Ar/^{39}Ar technique relies on the presence of K-rich minerals (sanidine or anorthoclase) in the form of either phenocrysts (Singer and Pringle 1996) or bulk crystals (Lanphere 2000). These materials are usually found in alkali-rich young tephras, and in coarse-grained, crystal-bearing proximal deposits. Hence, the applicability of the ^{40}Ar/^{39}Ar technique is limited (Blockley et al. 2008a). Unfortunately, the Y-2 tephra does not contain sanidine crystals for ^{40}Ar/^{39}Ar dating, nor has it yet been found in laminated sequences. Instead, ^{14}C was used previously to date the tephra.

The Y-2 tephra has several proposed ^{14}C ages from both marine and terrestrial environments. Interpolation between 2 ^{14}C dates in the marine record from Edremit Bay provided a calibrated age of 21,620 cal BP (Aksu et al. 2008) and another marine record from the Black Sea provided a ^{14}C determination of 19,770 BP (Kwiecien et al. 2008). Charred trees from the lower part of the terres-

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Proceedings of the 21st International Radiocarbon Conference edited by A J T Jull & C Hatté
RADIOCARBON, Vol 55, Nr 2–3, 2013, p 741–747

trial pumice flow have provided ^{14}C determinations of 18,050 ± 340, 18,165 ± 210, and 18,880 ± 230 BP (Pichler and Friedrich 1976). This is supported by Eriksen et al. (1990), who dated charcoal from small trees and branches covered by ignimbrites and provided a ^{14}C determination of 18,150 ± 200 BP. Seymour et al. (2004) also provided ^{14}C determinations of 18,527 ± 145 BP and 18,244 ± 143 BP below the Y-2 tephra layer as part of a tephrochronological record. In addition to the available ^{14}C dates, the Y-2 tephra is found in 3 terrestrial ^{14}C-dated paleoclimatic records from Lesvos Island (Margari et al. 2009) and Tenaghi Philippon (Müller et al. 2011), Greece, and a lake record in Turkey (Roeser et al. 2012).

MODELING

Bayesian analysis is a well-established tool for combining prior information with absolute dates to improve the precision and accuracy of archaeological and paleoenvironmental chronologies. A Bayesian framework is employed to estimate the precise age of the Y-2 tephra. Previous applications of Bayesian techniques in modeling tephra ages can be found in Blockley et al. (2008a,b), where the authors used a mixture of phase models, where related events are grouped together, and age-depth models to test the robustness, as well as enhancing the precision and accuracy, of published tephra ages. Only sequences that have the Y-2 tephra are included in the Bayesian model; the marine ^{14}C dates are not employed due to the uncertain marine reservoir offset.

Bulk sediments and plant macrofossils form the majority of ^{14}C samples for the record from the Megali Limni basin on Lesvos Island (ML01; Margari et al. 2009). The ML01 sequence (10.97 m in length) consists of 9 ^{14}C determinations; 2 of these are outside the limit of ^{14}C and are excluded from the model. The ML01 sequence also has evidence that suggests the presence of a hiatus between the ^{14}C dates in close proximity to the tephra, stratigraphically. Evidence includes an erosion surface at 1.29 m, and also a significant transition to primarily inorganic sediments at 1.5 m (Margari et al. 2009). For these reasons, the ^{14}C determination, SUERC-1287 (1538 ± 28 BP), is also excluded from the model. The rest of the ML01 sequence is still reliable for modeling the age of the Y-2 tephra because it is found at 1.81 m, which is below the erosion surface and the significant transition to inorganic sediments.

The Tenaghi Philippon sequence (14.62 m in length) consists of 20 and 12 ^{14}C determinations, respectively. The sequence was dated with bulk sediments, wood, and carbonates from shells (Müller et al. 2011). The Y-2 tephra is found at 7.61 m in the Tenaghi Philippon sequence (Müller et al. 2011).

Another widespread tephra, the Campanian Ignimbrite (CI), is also found in all of the above peat sequences. In addition to the 2 peat chronologies, ^{14}C determinations on bulk sediments underneath the Y-2 tephra layer are also available from the Philippi peat basin in Macedonia (Seymour et al. 2004). The CI (also known as Y-5) eruption is the largest known eruption of the last 100,000 yr (Barberi et al. 1978). This eruption has been located in the Campi Flegrei region of southern Italy, which is close to the present-day Bay of Naples. The ash horizon of this event is widespread and is recognized in cores across the eastern Mediterranean (Pyle et al. 2006). An extensive study of the age of this tephra yielded a high-precision $^{40}Ar/^{39}Ar$ age of 39,280 ± 100 BP (de Vivo et al. 2001) and this is the age recommended by Pyle et al. (2006) as the accepted geological age of this eruption. It is in good agreement with another $^{40}Ar/^{39}Ar$ age of this tephra (41,100 ± 2100 BP, Ton-That et al. 2001). The age of the Y-5 tephra can be integrated on its own and as a tie-point (point of equal age) into the 2 sequences described above to enhance the precision of the overall chronologies.

The Lake Iznik sequence from Turkey (6.83 m in length) is the only sequence containing ^{14}C determinations from plant material. ^{14}C determinations from other materials (e.g. peat and shells) are also available, but only dates from plant materials are incorporated into the model because they provide the confidence that they relate securely to the context dated, with no reservoir effects. The Y-2 tephra is found at 13.89 m in the Lake Iznik sequence (Roeser et al. 2012).

There are many age-depth modeling programs freely available to researchers (e.g. Buck et al. 1999; Bronk Ramsey 2009; Blaauw and Christen 2011). Bronk Ramsey (2008) introduced a Poisson process (P Sequence) prior for modeling random deposition in primarily sequences with stratigraphic markers or annually laminated sequences. The P Sequence prior relies on the use of a model parameter for step size (k) to define the increment in the model runs, which can be estimated using the variability in distances between the known-age layers. In non-annually laminated sequences with no stratigraphic marker layers, k would have to be estimated using other means, such as the dating information or model agreement with the data (e.g. Blockley et al. 2007). These methods are not satisfactory since there are dangers of circular reasoning. Bronk Ramsey et al. (2010) discussed the use of a model averaging approach to overcome the subjectivity in model selection, and this method is implemented in the most recent OxCal version (Bronk Ramsey and Lee, these proceedings). This modified P Sequence prior is used here to model age-depth sequences.

Age-depth models are constructed for records from Lesvos Island, Tanaghi Philippon, and Lake Iznik using the P Sequence model, for estimating the age of the Y-2 tephra, because it provides the most realistic depiction of sedimentation for this case study, with the complexity (randomness) of the underlying sediment deposition modeled according to a Poisson process. The accelerator mass spectrometry (AMS) ages presented in Seymour et al. (2004) are also incorporated into the model using an exponential distribution as prior information. The exponential Tau Boundary is applied to the ^{14}C dates, as materials just underlying the tephra (Seymour et al. 2004: Figure 3) are most likely to be buried just before the eruption, but with a gradually decreasing probability of being from material deposited substantially earlier than the eruption. This approach had been previously used by Blockley et al. (2008b) to precisely estimate the age of the Neapolitan Yellow Tuff (NYT), with the Boundary parameter as a measure of the abrupt event.

Formal outlier analysis is not employed for this case study due to the good agreement between the ^{14}C likelihoods and the posterior model outputs (as determined by OxCal by agreement indices, A, of >60%; Bronk Ramsey 1995). Tephra dispersal is considered as an abrupt event in terms of the uncertainty associated with absolute age measurements and so the same tephra horizons found in different sequences can be cross-linked to further enhance the precision of chronologies. This method is employed here to model the age of the Y-2 tephra.

RESULTS AND DISCUSSION

The posterior age-depth models for sequences in Lesvos, Tenaghi Philippon, and Lake Iznik are summarized in Table 1 and Figure 1. The modeled k parameters for individual sequences are also shown in Figure 1. Posterior distributions for the exponential model are shown in Figure 2. The model yields a 95.4% age range for the Y-2 tephra of 22,329–21,088 cal BP (Figure 3). This age range, although broad, is in good agreement with the combined ^{14}C ages, which is 22,200–21,411 cal BP at 95.4% (Figure 4), on terrestrial plant material buried by ash for this tephra within their error ranges (Pichler and Friedrich 1976; Eriksen et al. 1990).

Table 1 Calibrated and posterior ages for sequences in Lesvos, Tenaghi Philippon, and Lake Iznik; original data from Margari et al. (2009), Müller et al. (2011), and Roeser et al. (2012), respectively.

Sample	^{14}C age	Depth (m)	Calibrated (BP) 68.2%	Calibrated (BP) 95.4%	Modeled (BP) 68.2%	Modeled (BP) 95.4%
Lesvos						
Y-2		1.81			22,157–21,567	22,329–21,088
R_Date SUERC-5857	19,072 ± 237	1.836	23,208–22,420	23,428–22,247	22,939–22,237	23,410–21,868
R_Date SUERC-5858	21,225 ± 316	2.678	25,845–24,990	26,212–24,501	25,203–24,523	25,624–24,325
R_Date SUERC-5859	20,933 ± 309	3.974	25,385–24,517	25,928–24,281	25,966–25,220	26,619–24,733
R_Date SUERC-5860	27,781 ± 743	5.474	32,921–31,356	34,426–31,091	32,882–31,371	34,121–31,080
R_Date SUERC-3027	32,304 ± 1319	6.677	38,640–35,397	40,595–34,720	38,445–35,675	39,127–35,057
R_Date SUERC-3032	41,384 ± 4128	11.628	48,412–43,106	...–41,814	50,003–46,038	50,003–43,391
Tenaghi Philippon						
R_Date Poz-15890	1950 ± 30	0.76	1933–1869	1986–1825	1933–1869	1984–1826
R_Date Poz-15891	4200 ± 40	1.79	4838–4650	4848–4587	4838–4645	4846–4585
R_Date Poz-15894	5790 ± 40	3.41	6656–6547	6715–6485	6656–6546	6713–6486
R_Date Beta-244646	6350 ± 50	4.2	7412–7179	7417–7171	7415–7246	7419–7175
R_Date Beta-244647	7600 ± 50	4.59	8431–8364	8537–8335	8430–8364	8519–8330
R_Date Beta-244650	8820 ± 50	5.56	10,118–9708	10,156–9687	10,123–9740	10,157–9695
R_Date Beta-244651	9890 ± 60	6.15	11,387–11,226	11,602–11,200	11,389–11,227	11,604–11,201
R_Date Beta-244654	13,570 ± 70	6.98	16,851–16,642	16,933–16,462	16,854–16,648	16,936–16,476
R_Date Beta-244655	16,560 ± 90	7.18	19,857–19,475	20,034–19,442	19,845–19,473	20,020–19,440
Y-2		7.61			22,157–21,567	22,329–21,088
R_Date Beta-244637	20,220 ± 100	8.2	24,307–23,966	24,446–23,846	24,311–23,972	24,447–23,850
R_Date Poz-16295	23,330 ± 150	8.86	28,366–27,971	28,539–27,809	28,345–27,956	28,523–27,799
R_Date Beta-244638	24,310 ± 160	9.3	29,424–28,896	29,504–28,582	29,380–28,854	29,480–28,582
R_Date Beta-244639	25,120 ± 150	9.85	30,215–29,741	30,310–29,545	30,225–29,772	30,315–29,560
R_Date Beta-244640	27,760 ± 190	10.6	32,095–31,518	32,581–31,419	32,057–31,529	32,505–31,420
R_Date Beta-244641	28,680 ± 230	11.25	33,500–32,746	34,400–32,162	33,566–32,823	34,437–32,586
R_Date Beta-244642	32,390 ± 260	11.85	37,145–36,560	37,754–36,387	37,049–36,550	37,545–36,393
R_Date Beta-244643	35,290 ± 350	13.3	41,030–40,088	41,286–39,391	40,931–40,154	41,172–39,618
R_Date Beta-244644	36,520 ± 400	13.83	41,874–41,259	42,201–40,952	41,860–41,286	42,151–41,012
R_Date Beta-244645	39,570 ± 570	14.65	44,156–43,221	44,595–42,801	44,191–43,317	44,596–42,906
R_Date Beta-246628	43,100 ± 1200	15.28	47,684–45,221	49,369–44,735	46,646–45,047	48,037–44,484
Lake Iznik						
R_Date KIA-44582	8230 ± 60	9.28	9294–9091	9403–9026	9282–9038	9400–9023
R_Date KIA-44585	9070 ± 50	9.78	10,251–10,196	10,382–10,170	10,254–10,195	10,390–10,172
R_Date KIA-44588	12,340 ± 130	10.89	14,641–14,030	15,011–13,940	14,506–14,012	14,891–13,886
R_Date KIA-44591	13,450 ± 100	11.69	16,805–16,451	16,893–15,960	16,785–16,401	16,869–15,956
Y-2		13.89			22,157–21,567	22,329–21,088

It is unfortunate that the Y-2 tephra is positioned at the edge of the ML01 sequence, providing little constraint on its age. This is also the reason for its low convergence (<95%). Charred plant materials covered in ignimbrite (Eriksen et al. 1990) suggest that the sample was killed and charred by the volcanic event, which means that their ^{14}C determinations represent the time of the eruption; or that plant material were killed before charring, which means that their ^{14}C determinations represent a time before the eruption. Results from this paper imply that, on currently available dating evidence, the 95.4% probability modeled age range for the Y-2 tephra (22,329–21,088 cal BP) is the best calendar age estimate for the eruption.

The Poisson process model has proved useful in modeling sequences where high-precision chronological resolution is required. The model averaging approach has made a significant contribution to the modeling of the age of the Y-2 tephra in this study. It removes the subjectivity in model selection, and makes the model applicable and easier to use in sequences that are not annually laminated, in this case, peat sequences.

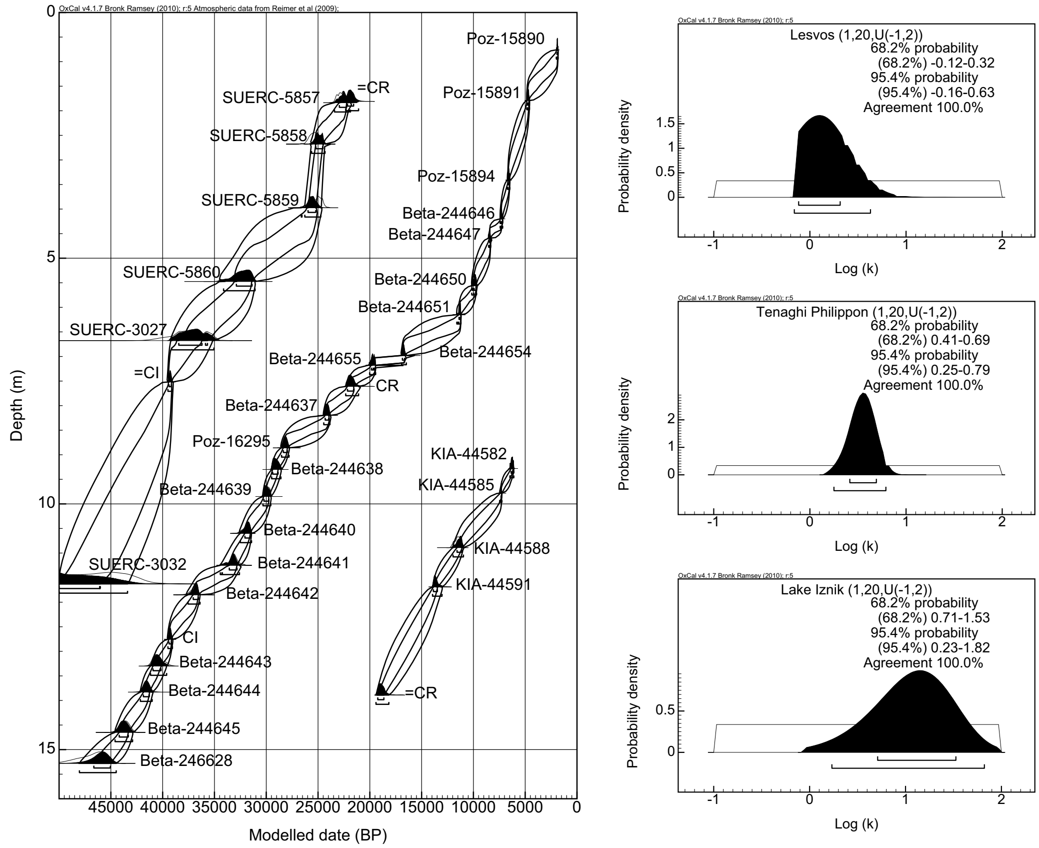

Figure 1 Posterior age-depth models for sequences in Lesvos (left), Tenaghi Philippon (middle), and Lake Iznik (right) and their corresponding modeled *k* values, at 68.2% and 95.4% probability. Original ^{14}C data from Margari et al. (2009), Müller et al. (2011), and Roeser et al. (2012), respectively.

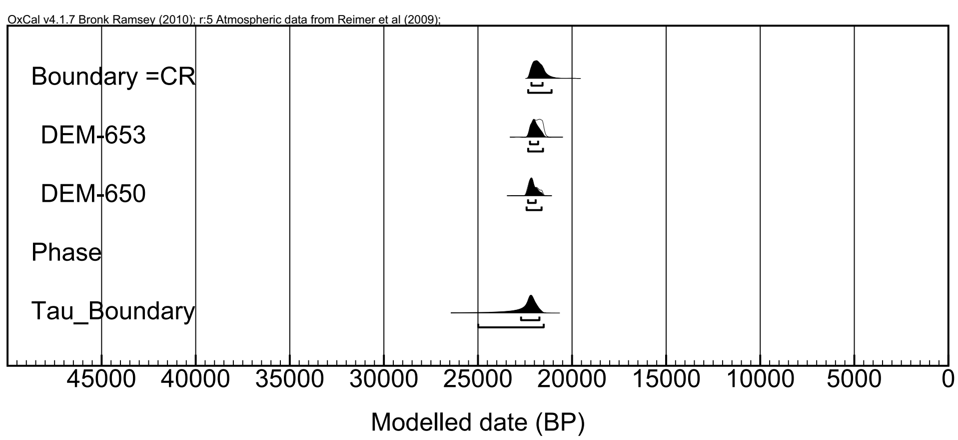

Figure 2 Posterior ages for the exponential phase model for the tephra ages from the Philippi peat basin in Macedonia (Seymour et al. 2004), at 68.2% and 95.4% probability.

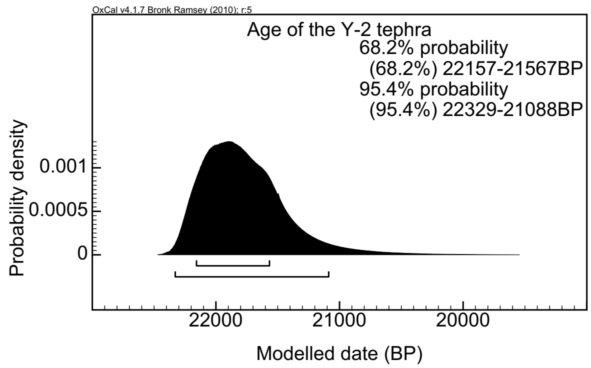

Figure 3 Posterior age of the Y-2 tephra, at 68.2% and 95.4% probability

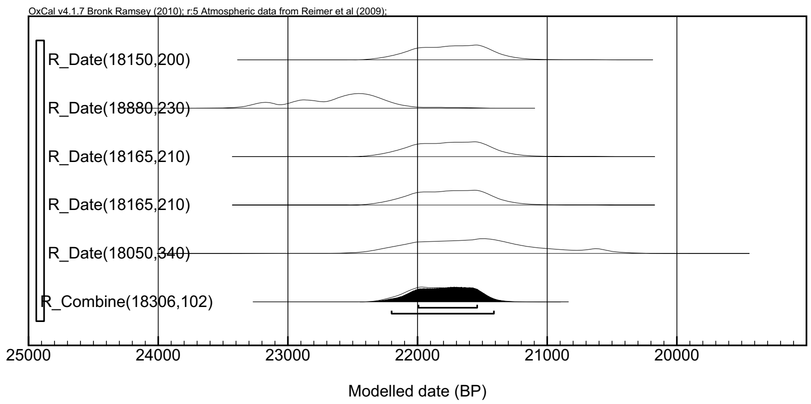

Figure 4 Published proximal ^{14}C ages of the Y-2 tephra from Pichler and Friedrich (1976) and Eriksen et al. (1990) in white and a combination of these ages in black.

Obtaining a robust calendar age for the Y-2 eruption is an important step in allowing the development of more precise absolute chronologies alongside the use of this tephra as an isochronous marker. The calendar age estimate put forward here would suggest the Cape Riva eruption occurred after the onset of GI-2 in the INTIMATE Event Stratigraphy (Blockley et al. 2012).

ACKNOWLEDGMENTS

The authors would like to thank Thomas Higham and Maarten Blaauw for comments. The research behind this paper was conducted in support of a NERC-funded project on Response of Humans to Abrupt Environmental Transitions (NE/E015670/1).

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