EARLY TO MIDDLE HOLOCENE COASTAL DUNE AND ESTUARINE DEPOSITION, SANTA MARIA VALLEY, CALIFORNIA

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Abstract: Late Quaternary deposition in many terrestrial basins along the California coast consists of interbedded fluvial, estuarine, and dune facies deposited in response to relative sea level changes. Radiocarbon dating of sediments retrieved from boreholes drilled through the Guadalupe dune sheet at the mouth of the Santa Maria River, where uplift rates are zero or less, indicate that estuarine deposition began locally around 9–11 ka in response to rising sea level. The estuarine deposits were then buried by dune sands around 3.5–4.3 ka, perhaps in response to sea-level regression during mid-Holocene (~4.5 ka) glaciation and not the earlier glacial periods, as previously inferred by others. [Key words: coastal dunes, sea-level change, Santa Maria River, Holocene, California.]

INTRODUCTION

River basins along the California coast are typically filled by late Quaternary stratigraphic sequences of interbedded coarse fluvial gravels, estuarine silts and fine sands, and eolian sands (Worts, 1951; Dupré, 1991). These variations in lithology and depositional environment are often correlated with relative sea level rising and falling in response to climate change (Dupré et al., 1980; Dupré, 1991; Muhs, 1992). For example, the shift from fluvial gravel to estuarine deposits is often related to rising sea level as climate changes from glacial to interglacial conditions (Dupré et al., 1980; Dupré, 1991). Coastal dune sands, which are useful indicators of sea-level change, accumulate most extensively during marine regressions, even during short-duration glacial interludes, and thus are useful surrogates of climatic changes.

Evidence for the Last Glacial Maximum (>20 ka), when sea level was at least 85 m lower than present, is found in marine and non-marine records throughout California (Fig. 1; Muhs, 1992; Behl and Kennett, 1996; Clark and Gillespie, 1996; Owen et al., 2003; Wells et al., 2003). Evidence for the terminal Pleistocene cold interlude, the Younger Dryas Stade (11.6–12.9 ka), is found in the San Bernardino Mountains, Mojave Desert, and Santa Barbara Channel (Behl and Kennett, 1996; Owen et al., 2003; Wells et al., 2003). Evidence for mid-Holocene (~4.5 ka) cooling trend is also reflected in the San Bernardino Mountains, Sierra Nevada, Mojave

Physical Geography, 2006, **27**, 2, pp. 127–136.

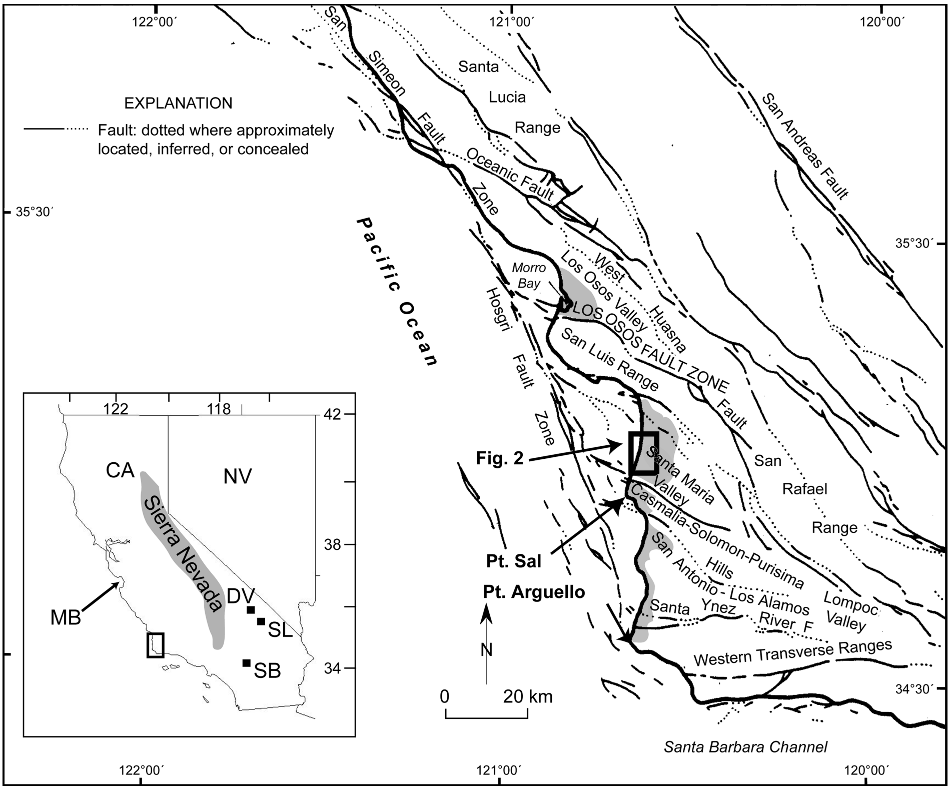

Fig. 1. The central California coast showing (shaded) extent of coastal dune complexes at Morro Bay, the mouth of the Santa Maria River, and Point Sal to Point Arguello (after Lettis and Hall, 1994; Cooper, 1967). Inset map shows Monterrey Bay (MB), San Bernardino Mountains (SB), Silver Lake (SL), and Death Valley (DV) relative to the study area.

Desert, and Santa Barbara Channel (Enzel et al., 1989; Anderson and Smith, 1994; Friddell et al., 2003; Owen et al., 2003).

Located in the middle latitudes, California's surrogate climate records are important indicators of regional barometric pressure patterns and climatic conditions (Smith, 1991). However, surrogate records, as recorded by coastal dune sheets, that might record climatically induced sea-level changes are complicated by tectonics and sparse age control, especially for the larger deposits. In northern California, at least 10 fluvial-estuarine-dune sequences are found in river valleys emptying into Monterey Bay (Dupré et al., 1980). The uppermost sequence is thought to have been deposited after 18 ka (after the Last Glacial Maximum; Dupré, 1991). This is consistent with Cooper's (1967) estimated ~11 ka age of the uppermost dune deposits inland from Monterey Bay.

In southern California, late Pleistocene dune deposits correlative with the Last Glacial Maximum are found at San Miguel Island (20–18 ka; Johnson, 1977), San Nicholas Island (~27–14 ka; Muhs, 1992) and Point Sal (23 ka; Orme, 1992). In addition, dunes with radiocarbon ages of 4160 yrs B.P. and 6 ka ages are found at

Morro Bay (Fig. 1) and in Baja California (Orme and Tchakerian, 1986; Orme, 1992). Unfortunately, the age control for these Holocene dune deposits is sparse and the relative sea level is influenced by both tectonic uplift and eustatic sea level changes (Dupré et al., 1980; Page et al., 1998).

In this paper, we present radiocarbon ages of sediments underlying and within the Guadalupe dune sheet. This dune sheet is one of the larger dune complexes on the California coast (Cooper, 1967), and tectonic uplift rates in the Santa Maria River valley are zero or less (Lettis and Hall, 1994). Based on these conditions, we hypothesize that facies changes in river valley sediments here are influenced by climatically induced eustatic sea level changes only, and should yield a reliable proxy for paleoclimate. From these radiocarbon ages, we bracket inception of the Guadalupe dune sheet between 3530 ± 70 (Beta 167955) and 4360 ± 70 yrs. B.P. (Beta 120500), which correlates with the sea-level recession inferred for the mid-Holocene. The base of the estuarine upper alluvium of Worts (1951) is dated at 9–11 ka and is correlated with a relative sea level inferred at the end of the Younger Dryas Stade (11.6 ka).

GEOLOGIC SETTING

The Santa Maria River valley is located between the San Luis Range and the Casmalia Hills (Fig. 1). Like many alluvial valleys along the California coast, the Santa Maria River valley has assumed its present form in response to late Cenozoic uplift of the Coast Ranges (Page et al., 1998). Lettis and Hall (1994) estimated that the late Pleistocene to present tectonic subsidence rate at the mouth of the Santa Maria River is zero.

Worts (1951) divided the late Pleistocene to Holocene alluvial deposits beneath the Santa Maria valley into two informal members: lower alluvium and upper alluvium. The lower alluvium consists of gravel to sand with sparse lenses of silt, and has an estimated thickness of 35 m. The upper alluvium is composed of interbedded sand, silt, and some clay that thins from ~30 m thick near the coast to zero 12 km inland (Worts, 1951). Numerous borings drilled in the Santa Maria valley (as both water production and water monitoring wells) found over 190 m of fluvial deposits beneath the lower alluvium in the Santa Maria valley (Department of Water Resources, 1970).

The age of the upper alluvium–lower alluvium contact has been correlated with climatically induced, sea-level changes at 30–40 ka B.P. (Payne et al., 1979), 18 ka B.P. (Dupré, 1991), and 11 ka B.P. (PS Associates, 1987); however, we are unaware of previous specific age data on the lower or upper alluvium. Offshore, the lower alluvium–upper alluvium contact is detected in seismic reflection surveys along the continental shelf (Cummings and Johnson, 1994).

At the mouth of the Santa Maria River, the Guadalupe dune sheet overlies the upper alluvium and mantles the coastline between the San Luis Range and the Casmalia Hills (Fig. 1; Cooper, 1967). This study focuses on that part of the dunes located just north of the mouth of the Santa Maria River (Fig. 2). Here, Orme and Tchakerian (1986) subdivided the Holocene dunes of the Guadalupe field into two main groups: older parabolic and younger transverse dunes. In general, the

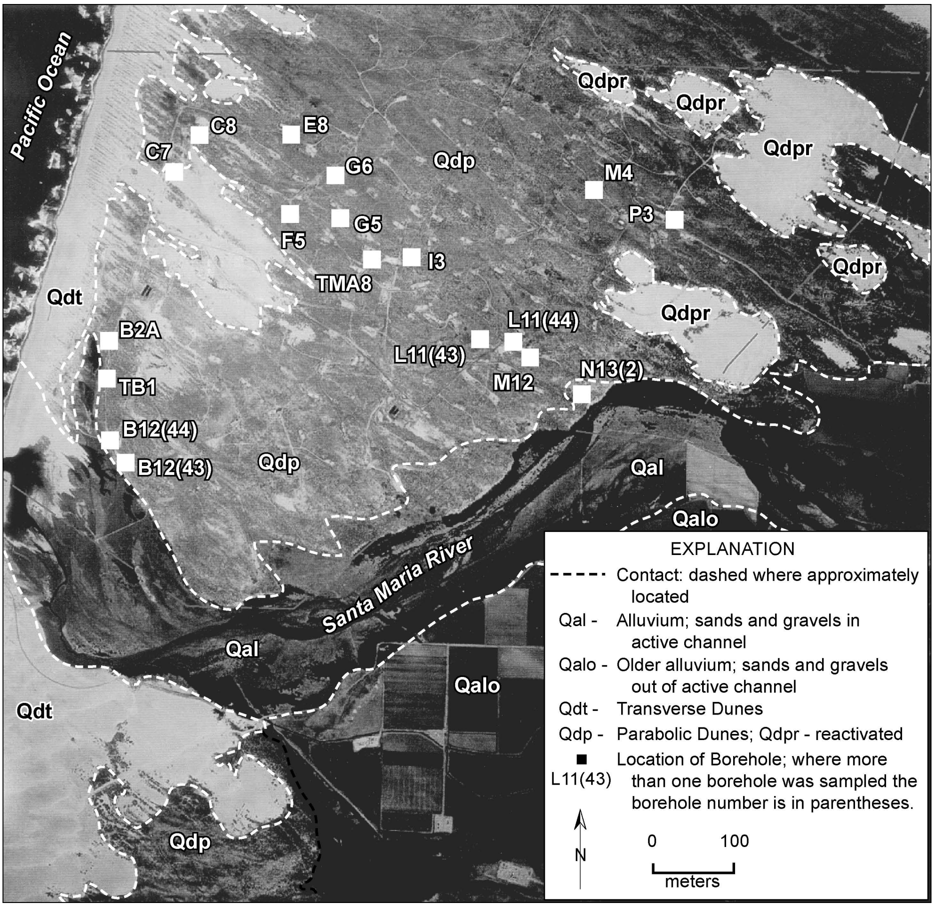

Fig. 2. Surficial geology of the Guadalupe dune sheet and the mouth of the Santa Maria River. *Source:* Based on July 6, 1989, vertical aerial photograph.

vegetated older parabolic dunes correlate with morphologically similar deposits found from Oregon to Baja California (Cooper, 1967; Orme and Tchakerian, 1986; Orme, 1992). The younger transverse dunes are less vegetated and found mainly along the shoreline. Both Holocene dune groups overlie reddish late Pleistocene paleodunes, elsewhere (Orme, 1992). Portions of the parabolic dunes are remobilized inland (Fig. 2).

INVESTIGATION

Boreholes were drilled through the Guadalupe dune sheet and into the underlying upper alluvium and locally into the coarse-grained lower alluvium. Two cores (I3 and P3) were drilled completely through the upper alluvium, showing the thickness of the upper alluvium to be 27–31 m. In Core I3, which is 2 km from the shoreline, the base of the upper alluvium is 22 m below sea level. In each borehole when

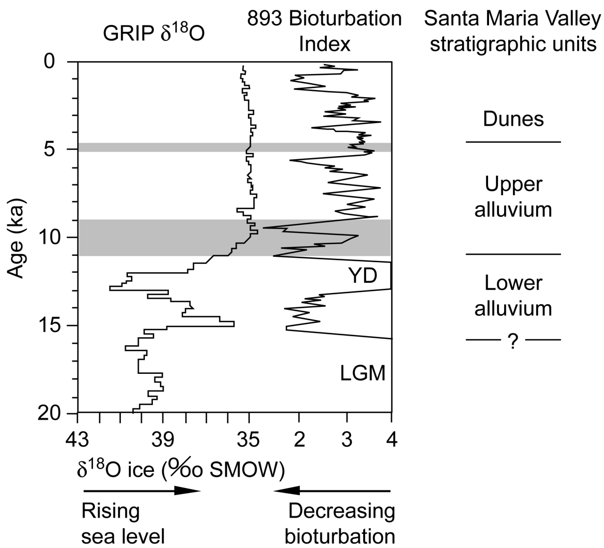

Fig. 3. $\delta^{18}O$ from Greenland Ice-Core Project (GRIP), bioturbation index from the 893 drill core from the Santa Barbara Channel, and the Santa Maria Valley stratigraphic units. Grey bands show the age of the top and bottom of the upper alluvium determined in this study. YD is Younger Dryas; LGM is last glacial maximum; SMOW is standard mean ocean water (in part after Cannariato et al., 1999).

the top of the upper alluvium was found, a sample was collected for ^{14}C analysis. I3, P3, and other boring cores were visually examined and samples with observable organic carbon were selected for ^{14}C dating. A sample of wood recovered from a borehole 0.75 m above the upper alluvium was also collected and analyzed.

Samples were submitted to Beta Analytic Laboratory for ^{14}C analysis, either by accelerator mass spectrometry or radiometric counting, depending on sample condition (Table 1). The samples were bulk organic sediments except for two wood samples. In Table 1, the location (e.g., B2A) corresponds with the abandoned oil well facilities where the borehole was drilled. Samples were pretreated with an HCl wash to remove any carbonates present. Half-lives were calculated using the Libby ^{14}C half-life of 5568 years. Dissolved inorganic carbon in groundwater is insignificant.

RESULTS AND DISCUSSION

A total of 31 ^{14}C ages were obtained on bulk organic sediments and wood from the upper alluvium that underlies the Guadalupe dune sheet (Table 1). Radiocarbon ages for the upper alluvium range from 4360 ± 70 (Beta 120500) to 17,150 ± 220 (Beta 120544) yr B.P. A radiocarbon age from a piece of wood at the base of the dune sheet is 3530 ± 70 yr B.P. (Beta 167955).

In 11 cores, samples were collected at multiple depths. In 5 of these cores, the ages were in the correct vertical sequence (younger over older); however, in 6 cores, the ages were inverted. The largest difference in inverted ages was about

Table 1. Results of ^{14}C Analysis from Upper Alluvium Beneath the Guadalupe Dune Sheet

Location and borehole	Elevation (m msl[a])	Depth (m bgs[b])	Material	^{14}C age (yrs. B. P.)[d]	Beta sample number
TMA8	4.5	22.9	Wood	3510 ± 70	167955
B2A-27	-2.9	9.1	Org. sed.[c]	9510 ± 110	118775
B12-43	-1.7	14.6	Org. sed.	5870 ± 90	118776
B12-44	-2.7	15.9	Org. sed.	6910 ± 140	118777
C7-69	-9.4	15.9	Org. sed.	13800 ± 180	120087
C7-70	-5.8	12.2	Org. sed.	13990 ± 330	120507
C7-70	-6.0	12.3	Org. sed.	11110 ± 110	120506
C8-98	-7.8	24.7	Org. sed.	13960 ± 40	120088
C8-99	-1.3	18.1	Org. sed.	8070 ± 40	120505
I3-1	3.0	17.3	Org. sed.	4740 ± 50	120543
I3-1	-2.3	22.5	Org. sed.	17150 ± 220	120544
I3-1	-23.3	43.5	Wood	9410 ± 50	121907
I3-1	-23.3	43.5	Org. sed.	11310 ± 80	120545
E8-9	-6.1	38.6	Org. sed.	12960 ± 180	120089
E8-10	-0.5	33.1	Org. sed.	7050 ± 120	120504
F5-19	1.7	22.1	Org. sed.	4360 ± 70	120500
F5-19	-0.1	23.9	Org. sed.	7330 ± 120	120501
G5-2	2.1	21.8	Org. sed.	5570 ± 90	120502
G5-2	0.4	23.5	Org. sed.	5100 ± 80	120503
G6-19	1.5	31.4	Org. sed.	5100 ± 70	120090
L11-43	6.9	9.8	Org. sed.	8970 ± 180	118778
L11-44	8.2	12.7	Org. sed.	11320 ± 50	118779
M4-43	8.7	26.8	Org. sed.	6430 ± 80	119169
M4-43	7.3	28.2	Org. sed.	5300 ± 120	119170
M12-8	8.5	9.9	Org. sed.	10300 ± 50	119171
M12-8	7.6	10.8	Org. sed.	6900 ± 50	119172
M12-8	4.4	14.0	Org. sed.	6090 ± 100	119173
N13-2	0.9	13.4	Org. sed.	8610 ± 40	169299
P3-1	11.1	20.8	Org. sed.	7080 ± 80	120546
P3-1	-5.8	37.7	Org. sed.	11510 ± 190	120547
P3-1	-15.2	47.1	Org. sed.	11110 ± 90	120548

[a]Meters above or below mean sea level.
[b]Meters below ground surface.
[c]Bulk organic-rich sediment samples.
[d]All ages are uncalibrated radiocarbon ages reported as years Before Present (B.P.). Present is defined as A.D. 1950. $^{13}C/^{12}C$ ratio is assumed to be –25‰ relative to PDB-1. Reported errors are 1 sigma statistics.

6000 years (location C8). We attribute the age inversions to reworking of older materials in the fluvio-deltaic system of the Santa Maria River, a common feature in such settings elsewhere (Stanley and Hait, 2000). Based on these anomalies, Stanley and Hait (2000) recommend using the youngest radiocarbon age as an indicator of burial age of the underlying deposit, which for our data set is 4360 ± 70 yr B.P. Relying on the 3530 ± 70 yr B.P. radiocarbon age for the piece of wood 0.75 m above the base of the dune sheet, we therefore infer that the burial age of the upper alluvium is 3.5–4.3 ka, which is thereby the maximum age of the Guadalupe dune sheet.

This 3.5–4.3 ka age for inception of the Guadalupe dune sheet is consistent with the 4160 yr B.P. age for sediments beneath the Morro Bay parabolic dunes 40 km to the north (Orme, 1990; Orme and Tchakerian, 1986). Relying on basin models suggesting that coastal dunes form as a result of sea-level recession during colder climatic events (Dupré et al., 1980; Dupré, 1991; Muhs, 1992), the 3.5–4.3 ka age for the Guadalupe dune sheet is consistent with glacial advances in the Sierra Nevada (Clark and Gillespie, 1996) and San Bernardino Mountains (Owen et al., 2003), as well as short-duration lakes in the Mojave Desert (Enzel et al., 1989). Our data suggest that this mid-Holocene cold episode identified in these inland regions may also involve sea-level recession.

Samples collected near the base of the upper alluvium yielded ^{14}C ages of 9410 ± 50 yr B.P. (Beta 121907; –23 m msl), 11,310 ± 80 yr B.P. (Beta 120545; –23 m msl), and 11,110 ± 90 yr B.P. (Beta 120548; –15 m msl; Table 1). The 9.4 ka and 11.3 ka ages were split from the same sampling interval and represent wood and bulk organic sediment, respectively. The lack of agreement between the radiocarbon samples taken at the same elevation illustrates the well-known problems associated with radiocarbon dating of both bulk and deltaic sediments. Following Abbott and Stafford (1996), the 9.4 ka wood fragment is probably the most reliable radiocarbon age, because the bulk sediment radiocarbon age may reflect reworked older organic material or an averaging of reworked older and younger organic material. In their study of Arctic lakes, Abbott and Stafford (1996) also noted that incorporation of younger organic material in modern systems altered the accuracy of bulk material ages by ±2000 years.

Owing to these potential inaccuracies, we conservatively interpret the age of the upper alluvium–lower alluvium contact and the corresponding change in depositional environment from fluvial (gravel) to estuarine (clay to fine sand) to be 9–11 ka. Relying on sedimentation models for California coastal basins (Dupré et al., 1980; Dupré, 1991; Muhs, 1992), we infer that the change to an estuarine depositional environment indicates that rising sea level began to reach the present Santa Maria valley 9–11 ka. The 9–11 ka age correlates well with the resumption of global warming and sea-level rise at the end of the Younger Dryas Stade noted in Greenland ice cores (Fig. 3; Dansgaard, et al., 1993), and in the nearby Santa Barbara Channel (Behl and Kennett, 1996; Cannariato et al., 1999; Friddell et al., 2003).

CONCLUSIONS

Using borehole stratigraphy and 31 ^{14}C dates (Table 1), we interpret the age of the 27–31 m thick upper alluvium of Worts (1951) at the mouth of the Santa Maria basin to be between 3.5–4.3 ka and 9–11 ka. The radiocarbon ages are inverted in several boreholes, which we attribute to reworking of older sediments. Studies of deltaic sequences elsewhere have shown that the youngest age, 4.3 ka in the case of the younger alluvium in the Santa Maria River valley, best indicates the time of burial by fluvio-deltaic facies (Stanley and Hait, 2000). This inference is confirmed by the 3.5 ka age 0.75 m above the upper alluvium/dune sheet contact. Consequently, the maximum ages of the Guadalupe dune sheet and estuarine upper alluvium are 3.5–4.3 ka and 9–11 ka, respectively. Because minimal or no uplift has been inferred for the Santa Maria valley, we conclude that the facies changes in the Santa Maria basin are related to eustatic sea level transgression and recession driven by climatic changes.

Basin models show that the estuarine and dune sands are typically deposited during transitions to interglacial and glacial climate conditions, respectively (Dupré et al., 1980; Dupré, 1991; Muhs, 1992). The 3.5–4.3 ka age for the Guadalupe dune sheet correlates well with mid-Holocene ages for extensive dune complexes at Morro Bay and in Baja California (Orme and Tchakerian, 1986; Orme, 1992), the Sierra Nevada and San Bernardino glaciations (Owen et al., 2003), recession of pluvial lakes in the Mojave Desert (Enzel et al., 1989), and circulation changes in the Santa Barbara Channel (Friddell et al., 2003). Relying on the correlation of dune deposition with other proxy records throughout California, we infer that 3.5–4.3 ka sea-level receded, exposing a portion of the sand-covered offshore shelf to the prevailing onshore winds, which resulted in the initiation of the present Guadalupe dune sheet and other morphologically similar dune sheets along the Pacific Coast of North America. Muhs (1992), Orme (1992), and others have dated dune deposits correlative with the last glacial maximum and Younger Dryas. Orme (1992) determined a minimum age of 23 ka for paleodunes south of the Santa Maria valley at Point Sal and suggested that younger dune deposits in the area were probably initiated during the last glacial maximum and again during the Holocene. Our data show that the large dune sheet at Guadalupe was deposited in the middle Holocene.

The initiation of estuarine deposition (upper alluvium) in the Santa Maria River valley at 9–11 ka is consistent with a renewed or continuing marine transgression following the Younger Dryas Stade (Dansgaard et al., 1993; Behl and Kennett, 1996; Cannariato et al., 1999). Our conclusion is supported by the Santa Barbara Channel marine record, which also demonstrates climate-induced changes in relative sea level and ocean circulation at the end of the Younger Dryas.

Acknowledgments: Unocal Corporation provided funding and access for this study. We would like to thank Ian Kaplan of Global Geochemistry for his thoughtful discussion of radiocarbon dating. An earlier draft of this paper benefited greatly from the comments of two anonymous reviewers, Matthew Kirby, John Dixon, and Antony Orme.

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