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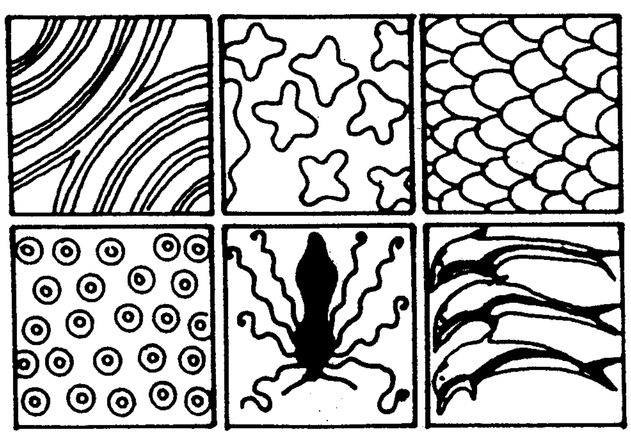

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TIME OUT: THE CURRENT IMPASSE IN BRONZE AGE ARCHAEOLOGICAL DATING

"Chronology is the spine of history," said the Danish ancient historian Rudi Thomsen,[1] and so it is, for it is impossible to make sense of the past without knowing what happened first and what happened next. For example, until the controversy as to the date of the eruption of the Thera volcano is settled, who can say whether Minoan Crete in the final phase of the New Palace Period in the mid-second millennium B.C. was in contact with the Hyksos from the Near East, who conquered the Nile Delta and much of Lower Egypt during the Second Intermediate Period which followed the Middle Kingdom in Egypt, or with the emergent Egypt of the New Kingdom. Similarly at issue is whether the vast trading network connecting Mesopotamia with Anatolia via the Assyrian Trading Colonies, with its links to Crete indicated by a number of very similar seal impressions found at Karahöyük in Anatolia and in the Old Palace at Phaistos in Crete,[2] is coterminous only with the Old Palace Period on Crete, or extends into the Knossos-centered New Palace Period as well. E. Fiandra once described the complex, literate, palace-centered society of Minoan Crete in the second millennium B.C. as the westernmost extension of a vast palatial system stretching from the Indus Valley through the Near East and Egypt to Crete.[3] Without sufficient chronological resolution it is not possible to analyze the nature of the interconnections between these societies. Without some degree of chronological resolution, it is difficult to consider seriously world systems models, interaction between primary and secondary civilizations or between core, margin and periphery, the consequences of military campaigns and climatic events, economic impacts of other cultures, or cultural influence via the "Versailles Effect."

This paper attempts to survey and critique both the current state of dating by Egyptian and Babylonian/Assyrian historical and astronomical chronologies and the current state of science-based dating by radiocarbon measurements, tree rings and ice cores. The discussion will focus on the ongoing controversy concerning the date of the eruption of the volcano on Thera (Santorini). Proponents of the Egypto-archaeologically based Aegean Short Chronology place the event between 1560 and 1480 B.C. (at the outermost limits, with some preferring a date before 1530). Leading advocates of the Aegean Long Chronology now place the eruption between 1650 and 1643 B.C., in place of their previous advocacy of 1628 B.C. The 1650-43 B.C. range results from the area of overlap between the Manning *et al.* dendro-radiocarbon date range for the anomaly in the Porsuk section of the Anatolian floating tree-ring sequence of 1650 +4/-7 B. C. and the Hammer *et al.* ice-core date of 1645 ±4 B.C. (1645 +4 = 1649 B.C., with a year of leeway to 1650 B.C. to allow for the possibility of an eruption in the year prior to the year of the putative arrival of its ejected glass shards in the Greenland ice).[4]

1 E. HALLAGER, "Final Palatial Crete: An Essay in Minoan Chronology," *Studies in Ancient History and Numismatics Presented to Rudi Thomsen* (1988) 11.

2 J. ARUZ, "Crete and Anatolia in the Middle Bronze Age: Sealings from Phaistos and Karahöyük," *Aspects of Art and Iconography: Anatolia and Its Neighbors. Studies in Honor of Nimet Özgüç* (1993) 35-54 and works cited therein, including S. ALP, *Zylinder- und Stempelsiegel aus Karahöyük bei Konya* (1968) and D. LEVI, "L'Archivio di Cretule a Festòs," *ASAtene* 19/20 (1957-1958) 7-192 and "Sulle origini minoiche," *La Parola del Passato* 24 (1969) 241-264.

3 E. FIANDRA, "Ancora a proposito delle cretule di Festòs: Connessions tra i sistemi amministrativi centralizzati e l'uso delle cretule nell'età del bronze," *BdA* 60 (1975) 21, fig. 14 and "A che cosa servivano le cretule di Festòs," *Pepragmena tou B' Diethnus Kritologikou Synedriou* (1968) vol. 1, 383-397.

4 The terms "Aegean Long Chronology" and "Aegean Short Chronology" are employed to distinguish clearly the Aegean division from the "High-Middle-Low" debates in Near Eastern (Babylonian/Assyrian) and in Egyptian dating (see, *e.g.*, P. ÅSTRÖM [ed.], *High, Middle or Low? Acts of an International Colloquium on Absolute Chronology Held at the University of Gothenburg 20th-22nd August 1987*, Parts 1-3 [1987-1989]. The current consensus in favor of the Egyptian Middle Chronology and recent dendro/radiocarbon evidence supporting the Middle Babylonian Chronology is discussed *infra*.)

This paper thus addresses both the chronology of prehistory and the prehistory of chronology. The interrelated chronologies of Egypt, the Levant, Anatolia and the Aegean are considered against the background of emerging scientific methods of dating and the efforts of prehistorians trained in art history, classics, ancient history and/or anthropology to assess the contributions and limitations of scientific methods of dating and to incorporate appropriately the data provided. Of course interdisciplinary research requires informed communication between disciplines.

Archaeological Evidence

The last fifteen years have seen a dramatic change with respect to Egyptian New Kingdom chronology, which has now been freed from partial dependence on partly disputed astronomical calculations. Largely as a result of the work of K. Kitchen and others on the troubled chronology of the Third Intermediate Period which followed the collapse of the unified, centralized rule of the New Kingdom at the close of the second millennium B.C., there now exists a practically continuous sequence of textual sources allowing New Kingdom dates to be fixed in all likelihood to within about a dozen years. Single year dates have been proposed on the basis of Egyptian lunar observations and our understanding of them. The

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The term "modified Aegean Short Chronology" refers to a proposed eruption date for Thera and a boundary between LM IA and LM IB around 1560-1550 B.C., rather than the 1530-1520 B.C. period proposed in P. WARREN and V. HANKEY, *Aegean Bronze Age Chronology* (1989). In a postscript on p. 215, Warren and Hankey note the possibility that the eruption could have occurred c. 1550 B.C. Warren, however, in a number of more recent publications (P. WARREN, "Aegean Late Bronze 1-2 Absolute Chronology: Some New Contributions," *Sardinian and Aegean Chronology: Towards the Resolution of Relative and Absolute Dating in the Mediterranean. Proceedings of the International Colloquium "Sardinian Stratigraphy and Mediterranean Chronology," Tufts University, Medford, Massachusetts, March 17-19, 1995* [1998] 323-331) has suggested a date for the eruption around 1500 B.C., based partly on the appearance of Theran tephra in a deposit at Tell el-Dab'a in Egypt from a stratum of that date or later. The lower the date proposed the further it is from the oscillating portion ending about 1535 B.C. of the ^{14}C calibration curve, and the harder it is to reconcile with the bulk of the radiocarbon data. Placing the Theran eruption with its LM IA pottery in the decade around 1500 B.C. also becomes hard to reconcile with the LM IB or LH IIA pottery found at Teti Pyramid Tomb NE 1 and at Kom Rab'a (C. FIRTH and B. GUNN, *Teti Pyramid Cemeteries* [1926] 69-70; J. BOURRIAU and K. ERIKSSON, "A Late Minoan Sherd from an Early 18th Dynasty Context at Kom Rabi'a, Memphis," *Ancient Egypt, the Aegean, and the Near East: Studies in Honour of Martha Rhoads Bell* [1997] 95-120). Both P. MOUNTJOY (*Regional Mycenaean Decorated Pottery* [1999] vol. 1, 17, table 1) and E. CLINE (*Sailing the Wine-Dark Sea: International Trade and the Late Bronze Age Aegean* [1994] 7, table 1) have followed the modified Aegean Short Chronology.

The most recent version of the Aegean Long Chronology, combining Greenland ice-core research and dendro/radiocarbon dating (see discussion *infra*) puts the eruption of Thera a century earlier between 1650 and 1643 B.C. (S.W. MANNING, C.B. RAMSEY, C. DOUMAS, T. MARKETOU, G. CADOGAN and C.L. PEARSON, "New Evidence for an Early Date for the Aegean Late Bronze Age and Thera Eruption," *Antiquity* 76 [2002] 733-744 [hereafter MANNING *et al.* (*Antiquity, supra* n. 4)]; S.W. MANNING and C.B. RAMSEY, "A Late Minoan I-II Absolute Chronology for the Aegean—Combining Archaeology with Radiocarbon," *The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium BC [II]. Proceedings of the SCIEM2000 EuroConference, Haindorf, 2-6 May 2001* [forthcoming 2003; hereafter MANNING and RAMSEY (*SCIEM2000, supra* n. 4)]; S.W. Manning, personal communication). A brief summary of the Aegean Long Chronology position was presented by H.J. BRUINS in "The Minoan Thera Eruption: Dating and Geoarchaeological Benchmarking," at the Irene Levi-Sala Annual Research Seminar: Thera–Akrotiri: Cosmopolitan Harbor Town in the Aegean, Ben-Gurion University, Beer Sheva, 23 May 2002. S.W. MANNING in *A Test of Time* (1999) [hereafter MANNING (*Test of Time, supra* n. 4)] refers to a putative 1560 B.C. eruption as a "modified Long Chronology" position, notwithstanding the fact that 1560 B.C. is only thirty to forty years from the Aegean Short Chronology eruption date of 1530-1520 B.C. and ten years from the Warren and Hankey "Postscript" date of 1550 B.C., but sixty-eight years from the then current Aegean Long Chronology putative eruption date of 1628 (now 1650-43 B.C.).

C.U. HAMMER, G. KURAT, P. HOPPE and H.B. CLAUSEN, "Recent Ice Core Analysis Strengthen[s] the Argument for a Mid 17th Century BC Eruption of Thera," extended abstract presented at *SCIEM2000 EuroConference, Haindorf, 2-6 May 2001* (hereafter HAMMER *et al.* [*supra* n. 4]); D.J. KEENAN, "Tephra Retrieved from the GRIP Ice Core Is Not from Thera" (forthcoming) and will also be available at http://www.informath.org.

most likely date range for the accession of Tuthmosis III, in whose reign interconnections with the Aegean and Cyprus become marked, is the Egyptian Middle Chronology range of 1479-1465 (conventionally cited currently in the form of an astronomically disputed absolute lunar date of 1479 B.C.).[5] Former proponents of a High Egyptian Chronology astronomical accession date of 1504 B.C., such as E. Wente, have now accepted 1479 B.C. as the more likely.[6] A recent analysis by R. Krauss contends that of the proposed lunar dates, 1479 B.C. is the most likely on astronomical grounds. R. Wells, an astronomer at the University of California at Berkeley, and A. Spalinger, an Egyptologist at the University of Auckland in New Zealand, have concluded, however, that the original lunar observations were unreliable and modern readings of them flawed, with the result that exact years for the New Kingdom are no longer available astronomically, leaving Egyptian texts as the sole chronological guide.[7] The texts in question include king lists, inscriptions with regnal years, funerary inscriptions or other texts stating how long high officials served under each pharaoh, and temple records of length of service of priests and lists of successive sacred Apis bulls.[8]

Similarly, Assyrian chronologies are fixed from 911 B.C. and the combined Babylonian/Assyrian chronology is believed to be established within about eleven years beginning c. 1400 B.C.[9] Because of interconnections between Egyptian and Near Eastern chronologies, such as the correspondence contained in the tablets found principally at the new Egyptian capital established by Akhenaton at Tell el-Amarna in Egypt between Akhenaton plus Tutankhamun and the Near Eastern rulers Assur-uballit, Burnaburiash II and Kadashman-Enlil I, written between 1349 and 1336 B.C. on the standard Egyptian Middle Chronology, it is not possible to move dates after 1400 B.C. in Egypt by more than a decade without a corresponding shift in Near Eastern dates and v. versa.[10]

The fixing of Egyptian absolute chronology within narrow limits from the beginning of the New Kingdom c. 1550-30 B.C. (together with restrictions preventing major extension of the total length of either the preceding Egyptian dynasties in Thebes or of the Hyksos reign in the delta in the preceding Second Intermediate Period which separates the Egyptian Middle Kingdom from the New Kingdom) has profound implications for Near Eastern and/or Aegean chronology via interconnections between Near Eastern and/or Aegean material and Egyptian

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5 K.A. KITCHEN, "The Basics of Egyptian Chronology in Relation to the Bronze Age," *High, Middle or Low?* (*supra* n. 4) Part I (1987) 37-55; "History of Egypt (Chronology)," *The Anchor Bible Dictionary*, vol. 2 (1992) 322-331; *The Third Intermediate Period in Egypt (1100-650 B.C.)* (Second Edition with Supplement, 1996); "The Historical Chronology of Ancient Egypt: A Current Assessment," *ActaArch* (1996) 1-13; "Ancient Egyptian Chronology for Aegeanists," *Mediterranean Archaeology and Archaeometry* 2:2 (2002) 5-12.

6 Wente has now accepted the analysis of B.M. BRYAN (*The Reign of Thutmose IV* [1991]) limiting the reign of Tuthmosis IV to twelve years at most (personal communication, for which I am most grateful).

7 R. KRAUSS, "Errors and Corrections in Egyptian Chronology," *SCIEM2000* (*supra* n. 4). The accuracy of Egyptian lunar sightings is challenged in a paper by R.A. WELLS ("The Role of Astronomical Techniques in Ancient Egyptian Chronology: The Use of Lunar Month Lengths in Absolute Dating," *Under One Sky: Astronomy and Mathematics in the Ancient Near East* [2002] 459-472). See also R.A. WELLS, "Re and the Calendars," *Revolutions in Time: Studies in Ancient Egyptian Calendrics* (1992) 1-37 and A.J. SPALINGER, "Thoth and the Calendars," *Revolutions in Time: Studies in Ancient Egyptian Calendrics* (1992) 45-83.

8 For example, see the inscriptions of Ineni, J.H. BREASTED, *Ancient Records of Egypt*, vol. 2: *The Eighteenth Dynasty* (1906, reprinted 2001) 18-20, 40-44, 47-48, 142-143. A suggestion to add a decade or two between reigns in the unsettled period around 1200 B.C. was answered by Morris Bierbrier's showing that certain officials who lived into their nineties would accordingly have required life spans of about 110 years, and others instead of retiring in their eighties would still have been serving when they reached the century mark (M.L. BIERBRIER, *The Late New Kingdom in Egypt, c. 1300-664 B.C.* [1975] 15).

9 J.A. BRINKMAN, *Materials and Studies for Kassite History*, vol. 1 (1976) and personal communication, for which I am most grateful.

10 Abandonment of the astronomically derived date would allow the accession date of Ramses II to be moved by fifteen years at the most. It is frustrating to receive on occasion papers asking for comments on proposals to move dates in one area and upon inquiry as to what corresponding change is proposed in the other, to receive the reply, "I don't control that material."

material in particular excavation strata. For example, thousands of sherds of Cypriote pottery from Tell el-Dab'a in Egypt[11] and Tell el-'Ajjul in Palestine[12] and significant amounts from many other sites in the Near East are found in the stratigraphic sequence already established in Cyprus,[13] with certain types found only in New Kingdom strata, which begin at the time of the conquest of the Hyksos capital at Avaris–Tell el-Dab'a by the Egyptian Pharaoh Ahmose toward the end of his reign, c. 1530-20 B.C. The date of the capture of Avaris depends on the dates for the reign of Ahmose and the point within it when the conquest occurs. The maximum span is 1550 B.C. (earliest possible accession and conquest in first year) to 1500 B.C. (accession c. 1520 B.C. and conquest c. eighteenth year). 1530-15 B.C. seems the most likely range, in accordance with the analysis by Kitchen, with the exact date partly dependent on the accession date of Tuthmosis III if the previously accepted lunar date of 1479 B.C. is disregarded. (The current commonly employed date of c. 1530 B.C. for the beginning of the Eighteenth Dynasty levels at Dab'a is utilized in this paper to avoid confusion. If the date is lowered, the challenge to the Aegean Long Chronology becomes correspondingly greater.)

In Cyprus the period encompassing the end of the Middle Bronze Age and the beginning of the Late Bronze Age (c. 1700-1500 B.C.) witnessed the emergence of social complexity and incipient state formation with major enlargement of sites, construction of fortifications, an increase in the number of weapons, and the first appearance of writing. Intensive exploitation of the island's massive copper deposits begins and contact with both the civilizations of the Near East and Minoan Crete intensifies. The first script of Cyprus has twenty out of twenty-two signs in common with the Linear A script of Crete and is accordingly known as Cypro-Minoan.

Cypriote pottery, including serving and drinking vessels as well as containers for products, appears in quantity in the Near East during the Middle Bronze Age and the amounts increase during the transition to the Late Bronze Age. Two types in particular, metal-imitating dark Base-ring (BR) and wares decorated with a white slip (WS), the latter impervious to liquids and pleasant to the touch, are exported in large numbers. In both cases chronological evolution is observable—Proto Base-ring (PBR) is followed by BR I and BR II, Proto White Slip (PWS) precedes WS I and WS II. Accordingly both wares if found in secure contexts can provide chronological markers wherever they are found. (Drawings of BR I and WS I are provided in Pl. LXXa).

Low numbers of diagnostic vessels and sherds at a few sites may of course raise questions of reliability of contexts, of survivals/heirlooms, or of wares overlapping chronologically, sometimes due to regional patterns in production and use. However, when thousands of vessels and sherds are involved and the sequence both in Egypt and at sites in the Near East datable by Egyptian finds mirrors the stratigraphic sequence known from Cyprus, chronological ceramic horizons can be established.

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11 M. BIETAK and I. HEIN, "The Context of White Slip Wares in the Stratigraphy of Tell el-Dab'a and Some Conclusions on Aegean Chronology," *The White Slip Ware of Late Bronze Age Cyprus. Proceedings of an International Conference Organized by the Anastasios G. Leventis Foundation, Nicosia, in Honour of Malcolm Wiener, 29-30 October 1998* (2001) 171-194.

12 C. BERGOFFEN, "The Base Ring Pottery from Tell el-'Ajjul," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware. Proceedings of a Colloquium held in the Royal Academy of Letters, History and Antiquities, Stockholm, 18-19 May 2000* (2001) 31-50; "The Proto White Slip and White Slip I Pottery from Tell el-'Ajjul," *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 145-155. The current excavation of Tell el-'Ajjul directed by Peter Fischer has already added 830 Cypriote vessels/sherds (from a total of 941 ceramic imports), the majority from clear stratigraphic contexts, to the more than 1,100 excavated by Petrie (P. FISCHER "The Preliminary Chronology of Tell el-'Ajjul: Results of the Seasons 1999 and 2000," *SCIEM2000* [*supra* n. 4]; P. FISCHER and M. SADEQ, "Tell el-'Ajjul 2000: Second Season Preliminary Report," *Egypt and the Levant* 12 [2002] 109-153).

13 K. ERIKSSON, "Cypriote Proto White Slip and White Slip I: Chronological Beacons on Relations between Late Cypriote I Cyprus and Contemporary Societies of the Eastern Mediterranean," *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 51-64.

The final Hyksos stratum at Tell el-Dab'a sees the appearance of Cypriote PWS while the earliest New Kingdom stratum contains WS I.[14] In the Near East, Cypriote WS I pottery also appears in the same strata as Egyptian New Kingdom material with only a few sherds possibly, but not necessarily, slightly earlier.[15] The Volcanic Destruction Level (VDL) at Thera contained massive amounts of Late Minoan IA material and a Cypriote WS I bowl (Pl. LXXa). While the vessel came from the early A.D. 1870 exploration and not the current excavations, Merrillees' careful study concludes that "there can be no doubt about the provenance and stratification of the Cypriote White Slip bowl."[16]

No Cypriote pottery has been reported to date from the current excavation of Akrotiri. Examination by Cypriote pottery specialists of the tens of thousands of sherds recovered in the excavation is planned for the next seasons. The absence of Cypriote pottery thus far in the current excavation is not surprising, given the fact that only six examples of WS I have been reported for the entire Aegean.[17] While WS I eating and drinking vessels were attractive practically and aesthetically in the Near East in comparison with local wares, in the Cyclades WS I could not compete with Minoan pottery and the general attraction of Minoan palatial culture of the New Palace Period,[18] or indeed the excellent Late Cycladic I pottery of Thera itself.[19] In any event, the contemporaneity of WS I and the Late Minoan I (LM I) pottery of the Theran Volcanic Destruction Level is evident in the material excavated at Toumba tou Skourou and Ayia Irini on the northwest coast of Cyprus (*infra*).

How is it possible to explain the presence of a WS I bowl in Thera prior to 1650-43 B.C. on the Aegean Long Chronology, when pottery of this type does not appear in Egypt or the Near East and cannot be shown to exist in Cyprus until at least 130 years later? Sturt Manning contends that PWS and WS I were in use for a century in the west of Cyprus, from where one of the earliest examples of WS I was exported to Thera, before they arrived in any number in southeast Cyprus, where the emergent polity at Enkomi formed the largest site in Cyprus at the time and the most directly accessible by sea from the Nile Delta and the Near East. The Manning argument posits a preferential exchange relationship between the Hyksos capital at Tell el-Dab'a (together perhaps with other Hyksos sites where WS I arrives late) and Enkomi.[20] No WS I pottery has been found at Enkomi in clear Middle Cypriote or beginning Late Cypriote I contexts, leading to the corollary argument that PWS and WS I were in use for a century in the northwest of Cyprus while White Painted IV, V and VI continued in use in the southeast. The appearance of fortifications and improved weapons in Cyprus at the transition from Middle to Late Bronze previously noted may support the view of internal barriers to exchange, at least between certain areas at particular times. Evidence from sites in Cyprus

14 BIETAK and HEIN (*supra* n. 11).

15 ERIKSSON (*supra* n. 13).

16 R.S. MERRILLEES, "Some Cypriote White Slip Pottery from the Aegean," *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 92. Merrillees also notes (p. 90) that the Thera WS I bowl was repaired in antiquity, thus accentuating the possibility that some time elapsed between its manufacture and its deposition in the Volcanic Destruction Level at Thera. Although M.R. POPHAM ("General Discussion," *The White Slip Ware of Late Bronze Age Cyprus* [*supra* n. 11] 217), ERIKSSON ([*supra* n. 13] 61) and S.E. DUNN (*The Chronology of the Aegean Late Bronze Age with Special Reference to the 'Minoan' Eruption of Thera* [Ph.D. thesis, University of Durham, 2002]) have questioned Manning's assertion that the Theran bowl can be placed early in the WS I sequence on stylistic grounds, the detailed analysis of this question by C. BERGOFFEN supports Manning's position with regard to the placement of the Theran bowl within the WS I sequence ("Early Late Cypriot Ceramic Exports to Canaan: White Slip I," *Leaving No Stones Unturned. Essays on the Ancient Near East and Egypt in Honor of Donald P. Hansen* [2002] 23-41).

17 MERRILLEES (*supra* n. 16) 98-100 and references therein, especially CLINE (*supra* n. 4).

18 M.H. WIENER, "Beyond the Versailles Effect: Interactions at the Beginning of the Late Bronze Age," lecture presented at the University of Athens on 20 November 1998, to be published in the proceedings of the University (forthcoming).

19 M. MARTHARI, "The Local Pottery Wares with Painted Decoration from the Volcanic Destruction Level of Akrotiri, Thera: A Preliminary Report," *AA* (1987) 359-379.

20 MANNING (*Test of Time*, *supra* n. 4) 119-129, especially 125.

and abroad presented at the 1998 White Slip Ware Conference and confirmed by the results of recent excavations, however, makes the hypotheses of long-lasting major internal Cypriote barriers to trade and exchange of goods and stimuli, and of highly directional exchange abroad, difficult to accept.[21] The evidence encompasses a long sequence of wares beginning with the Middle Cypriote period, which appear in the same order at Tell el-Dab'a in Egypt and at various places in the Near East as they do in Cyprus.[22] The latest evidence comes from Ashkelon on the seacoast of Canaan, where it has been possible to correlate stratigraphically over fifty types of pottery and over forty seal impressions of late Twelfth and Thirteenth Dynasty rulers at Ashkelon with scarabs and pottery from the Tell el-Dab'a sequence.[23]

At the time of transition to Late Cypriote, PWS is followed stratigraphically by WS I and PBR by BR I. At Hala Sultan Tekke on the south coast of Cyprus, for example, PWS appears clearly stratified below WS I, separated by a layer of brick.[24] Hala Sultan Tekke is about eighty kilometers from Enkomi, the principal site in southeast Cyprus, with no natural barriers or known fortifications separating the sites. It is difficult to understand how first PWS and then WS I could each arrive in succession at one or both sites with a delay of four to five generations.

21 M.H. WIENER, "The White Slip I of Tell el-Dab'a and Thera: Critical Challenge for the Aegean Long Chronology," *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 195-202. See also M. BIETAK, "The Late Cypriot White Slip I Ware as an Obstacle of the High Aegean Chronology," *Sardinian and Aegean Chronology* (*supra* n. 4) 321-322; "Towards a Chronology of Bichrome Ware? Some Material from 'Ezbet Helmi and Tell el-Dab'a," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware* (*supra* n. 12) 175-201; BIETAK and HEIN (*supra* n. 11).

22 M. BIETAK, *Avaris, the Capital of the Hyksos: Recent Excavations at Tell el-Dab'a* (1996); "The Center of Hyksos Rule: Avaris (Tell el-Dab'a)," *The Hyksos: New Historical and Archaeological Perspectives* (1997) 87-130; E.D. OREN, "Early White Slip Pottery in Canaan: Spatial and Chronological Perspectives," *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 127-144; BIETAK and HEIN (*supra* n. 11) 171-194. Robert Merrillees contends that the designation in various works by Johnson, Maguire, Bietak and Hein, Eriksson and Wiener of White Painted Pendent Line Style (White Painted III and IV) wares as Middle Cypriote is misleading because their use continues into the Late Cypriote IA period, although he acknowledges that their floruit is earlier. The authors cited refer, however, not to a small number of survivors, but to the great bulk of WP III and IV production. Merrillees also proposes an early beginning of LC IA around 1650 B.C., versus (for example) Eriksson's 1530 B.C. (R. MERRILLEES, "The Relative and Absolute Chronology of the Cypriote White Painted Pendent Line Style," *BASOR* 326 [2002] 1-9 and works cited therein [p. 2] and K.O. ERIKSSON, "Late Cypriote I and Thera: Relative Chronology in the Eastern Mediterranean," *Acta Cypria. Acts of an International Congress on Cypriote Archaeology Held in Göteborg on 22–24 August, 1991*, Part 3 [1992] 155). The net result in terms of Egyptian relative and absolute chronology does not change: White Painted III and IV are found in Second Intermediate Period contexts, whereas WS I and BR I appear in New Kingdom levels, reaching their peak numbers in both Egypt and the Levant in the reign of Tuthmosis III (E. Oren, personal communication of 25 August 2002, for which I am most grateful).

23 M. BIETAK, L.E. STAGER and K. KOPETZKY, "Ashkelon–Tell el-Dab'a Synchronisation Project," workshop at the Third International Congress on the Archaeology of the Ancient Near East, Paris, 15–19 April 2002; L.E. STAGER, "The MBIIA Ceramic Sequence at Tel Ashkelon and Its Implications for the 'Port Power' Model of Trade," *The Middle Bronze Age in the Levant. Proceedings of an International Conference on MB IIA Ceramic Material, Vienna, 24–26 January 2001* (2002). The Aegean Long Chronology requires raising and extending the dates of the latest Hyksos levels at Tell el-Dab'a proposed by the excavators (MANNING [*Test of Time*, *supra* n. 4] 327-329), revisions which the Ashkelon evidence, among other factors, renders unlikely. The Bietak, Stager and Kopetzky analysis places Tell el-Dab'a levels G 1-3 and Ashkelon Phase 13 c. 1750-1710 B.C., close to the date range of 1765-1716 B.C. that MANNING *et al.* (*Antiquity*, *supra* n. 4) 742 propose on the basis of a small number of radiocarbon measurements for early LM IA (*infra*). Both the Tell el-Dab'a and Ashkelon deposits contain examples of Classical Kamares ware, "one of the most popular Cretan ceramic products to be exported during MM IIB" (Stager, quoting J.A. MACGILLIVRAY, *Knossos Pottery Groups of the Old Palace Period* [1998] 76, pl. 12 and fig. 3.3). MM IIB is tied to the early part of the Thirteenth Dynasty between 1780 and 1750 B.C. by finds in Egypt and elsewhere.

24 E. HERSCHER, Comment, *The White Slip Ware of Late Bronze Age Cyprus* (*supra* n. 11) 218 and "Early Base Ring Ware from *Phaneromeni* and Maroni," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware* (*supra* n. 12) 11-21.

Tell el-Dab'a in Egypt exhibits the same clear stratigraphic sequence. Recent seasons at Dab'a have more than doubled the twenty examples, eleven clearly stratified, of PWS and WS I reported earlier and have confirmed the stratigraphic sequence: PWS in the final Hyksos level, WS I in the following New Kingdom strata.[25] The stratigraphic sequences at Tell el-'Ajjul and Megiddo follow the pattern as well.[26] Eriksson's survey of the Egyptian evidence concludes that the great bulk of the BR I found in Egypt comes from contexts attributable to the reign of Tuthmosis III, which begins c. 1479 B.C. on the Middle Chronology.[27] Bergoffen's recent restudy of the Cypriote pottery excavated at Alalakh at the mouth of the Orontes River on the south coast of Turkey concludes that neither WS I nor BR I can be securely located before Level V, which she believes begins no earlier than 1500 B.C. Indeed, with the exception of some WS I sherds from a house in Level V, probably Level VB, which Bergoffen and others thus believe corresponds to the reign of Idrimi somewhere between about 1460 and 1420 B.C., there is no instance of WS I before Level IV, which Bergoffen begins in 1430/25 B.C.[28] Oren's review of the Near Eastern evidence concludes emphatically that there is no documented BR I before the beginning of the New Kingdom in Egypt.[29] Bergoffen, however, notes two sherds and one juglet out of hundreds of BR I sherds and vessels at Tell el-'Ajjul in Canaan near the modern Gaza as possible exceptions, since their context could be earlier than the Tell el-'Ajjul stratum containing Eighteenth Dynasty material.[30] Establishing the stratigraphic sequence of Petrie's excavations at Tell el-'Ajjul long after the fact poses a significant challenge. The analysis of tomb deposits at Toumba tou Skourou and Ayia Irini on the northwest coast of Cyprus reinforces the links between the Late Minoan IA period (which witnesses, at or near its close, the eruption of Thera), the LC IB period in Cyprus with its major production of WS I and BR I, and the New Kingdom in Egypt beginning about 1550 B.C.,[31] particularly after the expulsion of the Hyksos from Tell el-Dab'a and the Nile Delta around 1530 B.C.

One or a few pots may reach far shores and be buried or destroyed with a delay of over a century, but not thousands of pots and potsherds in a sequence covering centuries. Manning, as noted, has proposed that Late Cypriote wares such as PWS and WS I plus PBR and BR I are produced in the west of Cyprus at a time when the eastern part of the island continues to use Middle Cypriote wares and that as a general rule only wares from eastern Cyprus reach Egypt and sites in the Near East in the Hyksos period.[32] At Tell el-'Ajjul (perhaps the capital of the kingdom of Sharuhen), however, the thousands of sherds of Cypriote pottery found included

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25 BIETAK and HEIN (*supra* n. 11) 171-194; M. Bietak, personal communication of 30 July 2002. Manning (personal communication) has raised the question whether the discovery and excavation of the main commercial area of Dab'a might change the present picture.

26 See n. 13 *supra*.

27 K.O. ERIKSSON, "Cypriot Ceramics in Egypt During the Reign of Thutmosis III: The Evidence of Trade for Synchronizing the Late Cypriot Cultural Sequence with Egypt at the Beginning of the Late Bronze Age," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware* (*supra* n. 12) 51, 65.

28 C. BERGOFFEN, "The Cypriote Pottery from Alalakh," *SCIEM2000* (*supra* n. 4) and personal communication, for which I am most grateful. Also, C. BERGOFFEN, *The Cypriot Bronze Age Pottery from Sir Leonard Woolley's Excavations at Alalakh (Tell Atchana)* (forthcoming).

29 E.D. OREN, "The Diffusion of Base-Ring Pottery in the East Mediterranean - Contextual and Chronological Aspects," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware* (*supra* n. 12) 127; "Cypriot Imports in the Palestinian Late Bronze I Context," *OpAth* 9 (1969) 127-150.

30 BERGOFFEN (*The Chronology of Base-ring Ware and Bichrome Wheel-made Ware, supra* n. 12).

31 K.O. ERIKSSON, "A Close Shave: The New Evidence for Chronology of Egyptian New Kingdom *Mechak* Razors Found in Late Cypriot I Tombs in Northwestern Cyprus," *Contributions to the Archaeology and History of the Bronze and Iron Ages in the Eastern Mediterranean: Studies in Honour of Paul Åström* (2001) 183-199. Eriksson notes in addition to the pottery linkages the appearance in this context of two razors of a type not known before the New Kingdom in Egypt. She concludes her analysis of the tomb deposits on the northwest coast of Cyprus as follows (p. 197): "I cannot find any truth in an argument that would suggest that 'LC IB may have begun before the end of the SIP' (MANNING [*Test of Time, supra* n. 4] 181) or that it covers only 'the 18th Dynasty to the early years of Tuthmosis III' (MANNING [*Test of Time, supra* n. 4] 191-192)."

32 S.W. MANNING, "The Chronology and Foreign Connections of the Late Cypriot I Period: Times They Are A-Changing," *The Chronology of Base-ring Ware and Bichrome Wheel-made Ware* (*supra* n. 12) 69-94.

sherds of WS I from the west-northwest of Cyprus. Tell el-'Ajjul was itself in close contact with Tell el-Dab'a in Egypt, as indicated by a wide body of material.[33] Moreover, Tell el-Yahudiyeh juglets from Hyksos territory arrive in northwest Cyprus across the putative divide and make a sufficient impression for them to be copied by Cypriotes in local clay. Manning notes, however, that the Tell el-Yahudiyeh juglets from southeast Cyprus are generally imports as distinguished from the local imitations common in the northwest, perhaps indicating a regional distinction in the degree of contact with Egypt and the Near East. Thus for Manning the proposed concentration at Tell el-Dab'a of imports from the southeast of Cyprus is reflected in reverse in the pattern of Cypriote imports from Egypt.[34] Whether such regionalism in internal and external exchange is likely to continue for a century is the question at issue. The Manning hypothesis further requires a production of WS I continuing for about 200 years from c. 1660 B.C. at the latest to c. 1460 B.C., a considerably longer span than many archaeologists working in Cyprus would expect, given the amount of WS I found to date.

The Aegean Long Chronology position requires a minimum of 130 years, or five generations, between the arrival of an early WS I bowl on Thera prior to about 1660 B.C. and the first definite arrival of early and mature WS I at Tell el-'Ajjul and mature WS I at Tell el-Dab'a, Alalakh and other sites in the Near East. (The c. 1660 B.C. date provides one to two decades between the first production of WS I in Cyprus and the export of an example to Thera, the use and ancient repair of the bowl in question,[35] and its terminus in the Theran eruption between 1650 and 1643 B.C. on the current version of the Aegean Long Chronology.) Unless WS I, BR I, RL (Red Lustrous) or other contemporary Cypriote wares are waiting to be found in early/middle Hyksos contexts at Dab'a or elsewhere to eliminate or reduce the interval in time, the Cypriote pottery sequence remains a major obstacle to a 1650-43 B.C. date for the eruption.[36]

Pumice from the Theran eruption has been found in quantity at Tell el-Dab'a in Egypt and in lesser amounts at Tell el-'Ajjul and at Tell Nami in Canaan in New Kingdom post-Ahmose contexts–after 1525 B.C. on the Egyptian Middle Chronology–and not earlier.[37] The Theran pumice from Tell el-Hebwa also appears to be from a New Kingdom context. All pumice examined to date found in earlier contexts, on the other hand, comes from older eruptions of Hellenic Arc volcanoes at Kos, Nisyros or Yali in the Dodecanese.[38] Large lumps of waterborne pumice such as those found at Tell el-Dab'a would have reached the Nile Delta within months of the eruption, raising the question whether it is likely that such pumice would have lain on the shore unused for about 150 years as required by a Theran eruption date between 1650 and 1643 B.C. The most recent study of the stratigraphy of the area of the pumice deposit at Dab'a notes the existence of two substantial strata of New Kingdom material

33 E. OREN, "The 'Kingdom of Sharuhen' and the Hyksos Kingdom," *The Hyksos: New Historical and Archaeological Perspectives* (1997) 253-283. With regard to pottery, see P.E. MCGOVERN, *The Foreign Relations of the "Hyksos:" A Neutron Activation Study of Middle Bronze Age Pottery from the Eastern Mediterranean* (2000) 70-74, together with critiques of the study by S.J. BOURKE in *BASOR* 326 (2002) 90-94 and Y. GORAN in *BibO* (forthcoming).

34 MANNING (*supra* n. 32) 83; MANNING (*Test of Time, supra* n. 4)182-185. O. NEGBI suggests the possibility of a chronological distinction as well, with local imitations of Tell el-Yahudiyeh ware produced after their importation had ceased, presumably as a result of the destruction of Hyksos sites and trade by Ahmose and his successors ("Cypriote Imitations of Tell el-Yahudiyeh Ware from Toumba tou Skourou," *AJA* 82 [1978] 137-149).

35 For the evidence of ancient repair of the WS I bowl from Thera, see MERRILLEES (*supra* n. 16) 90.

36 For RL see K. ERIKSSON, "A Preliminary Synthesis of Recent Chronological Observations on the Relations between Cyprus and Other Eastern Mediterranean Societies during the Late Middle Bronze-Early Late Bronze II Periods," *SCIEM2000* (*supra* n. 4). Similarly, H. Catling, in a letter of 17 April 2002 describes the Long Chronology position regarding a pervasive century-long continuance of regionalism in Cypriote pottery as falling within the category of the "remotely conceivable hypothesis."

37 FISCHER (*supra* n. 12); FISCHER and SADEQ (*supra* n. 12); MANNING (*Test of Time, supra* n. 4) 145-150; E-mail, M. Bietak to M.H. Wiener, 22 February 2002.

38 C. PELZ and M. BICHLER, "Classification of Archaeologically Stratified Pumice by INAA," *Journal of Radioanalytical and Nuclear Chemistry* 248:1 (2001) 81-87.

with the palace containing the Minoan frescoes (see *infra*) in the second phase, followed by a stratum containing the pumice, to which Manfred Bietak, the Director of the Austrian excavation, assigns a date, based on the scarabs and pottery found in the stratum with the pumice, not earlier than the reign of Tuthmosis I beginning in 1504 B.C. on the Egyptian Middle Chronology, and perhaps later.[39] Of course Theran pumice in a deposit of this date is separated from a putative eruption around 1550 B.C. on the modified Aegean Short Chronology by at least fifty years, allowing Long Chronology advocates to argue that an interval of 150 years is not significantly different from fifty years with regard to a secondary pumice deposit.

No Theran pumice has been noted to date in the quite extensive areas exposed in the excavation of the pre-1530 B.C. Hyksos capital at Tell el-Dab'a. The possibility remains, however, that Theran pumice arrived and was used by the Hyksos before their expulsion from the Delta at the beginning of the New Kingdom, but that its use was confined to a specific area which has not yet been found, such as a metallurgical workshop where the pumice would have been desirable as an abrasive. The Theran pumice from the post-1500 B.C. New Kingdom context at Tell el-Dab'a comes from what appear to be workshop areas. Similarly at Tell el-'Ajjul Theran pumice occurs in level H5, believed to postdate the New Kingdom conquest of the Hyksos; no pumice has appeared to date in the small areas of earlier levels excavated.[40] Deliberate importation of pumice during the New Kingdom but not earlier has been suggested by Manning as another possible explanation for the fact that no Theran pumice to date has been found in Hyksos contexts. Pieces of pumice from the Theran eruption, but not the large quantity uncovered at Dab'a, have frequently been found in later, and in some cases much later, contexts, with at least fourteen different uses indicated.[41] The Tell el-Dab'a deposit itself included one piece of pumice from an earlier eruption of the volcano on the island of Kos in the Dodecanese.

If the significant quantity of waterborne Theran eruption pumice from the post-1500 B.C. deposit at Tell el-Dab'a appears to suggest a late date within the Aegean Short Chronology horizon for the Theran eruption, the Aegean pottery found in Egypt suggests an earlier date. The Volcanic Destruction Level at Thera produced hundreds of thousands of vessels and sherds, none later than mature Late Minoan IA. No Late Minoan IB or the related Late Helladic IIA is present on Thera. Conversely, Egypt has thus far produced no LM IA, with one possible but disputed exception, perhaps suggesting that the Hyksos occupation of the Nile Delta during the LM IA period thwarted much Egyptian contact with Crete. Vessels or sherds accepted by many scholars as LM IB or LH IIA have been reported in contexts believed to be not later than the reign of Tuthmosis I (c. 1504-1492 B.C. on the Egyptian Middle Chronology), and perhaps as early as Ahmose (c. 1550-1525 B.C. on the Egyptian Middle Chronology), suggesting a date for the eruption in the sixteenth century B.C. and perhaps in the third quarter of the sixteenth century, prior to 1525 B.C. The possibility remains, however, that the sherds in question are of the LM IA period (in the case of the Kom Rabi'a example) or arrive in the reign of Tuthmosis III (in the case of the example from Teti Pyramid Tomb NE 1 at Saqqara).[42]

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39 M. BIETAK, J. DORNER and P. JÁNOSI, "Ausgrabungen in dem Palastbezerk von Avaris. Vorbericht Tell el-Dab'a/'Ezbet Helmi 1993-2000," *Egypt and the Levant* 11 (2001) 37, 89, 91.

40 BIETAK (*Avaris, the Capital of the Hyksos, supra* n. 22); FISCHER and SADEQ (*supra* n. 12) 133-134, 139, 140, table 3.

41 A review of the evidence for the use of small amounts of pumice from the Bronze Age Theran eruption for over a millennium after the event is provided by Wiener in M.H. WIENER and J.P. ALLEN, "Separate Lives: The Ahmose Tempest Stela and the Theran Eruption," *JNES* 57 (1998) 26.

42 BOURRIAU and ERIKSSON (*supra* n. 4); WARREN (*supra* n. 4). In addition, local imitations of rhyta of LM IA shape were found in the Eighteenth Dynasty levels at Tell el-Dab'a (R. KOEHL, "Minoan Rhyta in Egypt," *Krete-Aigyptos: Politismikoi Desmoi Trion Chilietion* [2000] 94-100). If the eruption of Thera in a mature or final phase of LM IA occurs c. 1650-1643 as proposed by advocates of the Aegean Long Chronology, then these copies in local clay must either have been made about one hundred years after the production of rhyta of this shape ceased in Crete, or have been used for a similar period, surviving the expulsion of the Hyksos, or been removed from Hyksos levels, perhaps from tombs.

A date prior to 1525 B.C. also finds some support from the radiocarbon evidence, inasmuch as the flattening or oscillation of the radiocarbon curve ends at that point (see *infra*). The pumice evidence is accordingly suggestive but inconclusive. Other chronological problems posed by the proposed Aegean Long Chronology, including depictions in tombs built during the reign of Tuthmosis III of objects resembling those found in the destructions marking the end of the LM IB period in Crete, are considered *infra* in the discussion of proposed radiocarbon dates for the period.

Overall, the archaeological/Egyptological case for a Theran eruption between 1560 and 1480 B.C. in accordance with the Aegean Short Chronology is a strong one. It is against this background that we must appraise the evidence from more recent sciences, some still in their youth.

Summary of Current Science-Based Aegean Long Chronology Position

Aegean Long Chronology advocates long supported a proposed Theran eruption date of 1628 B.C. based on indications of a major climate-forcing event believed to be of volcanic origin in the long-lived trees of California, Ireland and England and shorter-lived German oaks at that date, supported by radiocarbon determinations from material in Aegean contexts which appeared to be consistent with such a date.[43] (Many of the initial ^{14}C dates, particularly from Theran samples, were subsequently discarded as coming from samples which lacked proper pretreatment or complete carbonization.) Recent work on Greenland ice cores and analysis of the Anatolian floating chronology in comparison with the 1998 restatement of the radiocarbon calibration curve, together with doubts as to whether the 1628 B.C. event was volcanic in origin, have led proponents of the Aegean Long Chronology to propose a date between 1650 and 1643 B.C. The 1650-43 B.C. range results from combining Hammer *et al.*'s proposed ice-core date of 1645 ±4 B.C. with a proposed dendro/radiocarbon-based date for a major positive growth anomaly in the logs from Porsuk near the Cilician Gates in Turkey of 1650 +4/-7 B.C. The 1650-43 B.C. range thus fits both proposals.[44] This paper examines each aspect of the proposed dating in detail.

Ice-Core Dating

Ice-core dating is the most recent arrival on the scientific scene. Under favorable conditions in polar regions where summer melting is restricted, annual snowfalls provide observable laminations—that is to say, ice cores, like trees, provide annual layers. These layers

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43 P.P. BETANCOURT and G.A. WEINSTEIN, "Carbon-14 and the Beginning of the Late Bronze Age in the Aegean," *AJA* 80 (1976) 329-348; P.P. BETANCOURT, H.N. MICHAEL and G.A. WEINSTEIN, "The Radiocarbon Chronology of LM IA and LM IB," paper presented at An International Symposium on Archaeometry and Archaeological Prospection, University of Pennsylvania, Philadelphia, 16–19 March 1977; P.P. BETANCOURT, H.N. MICHAEL and G.A. WEINSTEIN, "Calibration and the Radiocarbon Chronology of Late Minoan IB," *Archaeometry* 20 (1978) 200-203; G.A. WEINSTEIN and P.P. BETANCOURT, "Problems of Interpretation of the Akrotiri Radiocarbon Dates," *Thera and the Aegean World. Papers Presented at the Second International Scientific Congress, Santorini, Greece* (1978) vol. 1, 805-814; P.P. BETANCOURT, "Dating the Aegean Late Bronze Age with Radiocarbon," *Archaeometry* 29 (1987) 45-49; P.P. BETANCOURT and H.N. MICHAEL, "Dating the Aegean Late Bronze Age with Radiocarbon: Addendum," *Archaeometry* 29 (1987) 212-213; H.N. MICHAEL and P.P. BETANCOURT, "Further Arguments for an Early Date," *Archaeometry* 30 (1988) 169-182.

44 I am indebted to S. Manning for this observation. In MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4) Manning gives the more inclusive dates 1650-1620 B.C. in describing the Aegean Long Chronology position with respect to the eruption of Thera, thereby leaving open the possibility of returning to 1628 B.C. (which would of course necessitate disavowing either the proposed shift of 22 +4/-7 years in the Anatolian floating chronology or the asserted link between the 1650 +4/-7 B.C. event in the Porsuk logs from the eruption). The term "Anatolian floating chronology" refers to the continuous 1,503-year sequence of logs with overlapping rings, consisting of 1,028 years from Gordion, 321 years from Porsuk, 164 from Acemhöyük and 435 from Kültepe.

sometimes contain evidence of volcanic events in the form of micro-particles carried through the stratosphere.[45] Cores drilled in Greenland have produced evidence of major eighteenth and nineteenth century A.D. volcanic eruptions in the appropriate known years, and the most legible core, known as Dye 3, has produced evidence of the eruption of Vesuvius only one year earlier at most than the known date of the eruption, reportedly confirmed by comparing the micro-particles found in the core with samples collected from the vicinity of Vesuvius.[46]

The most recent cores extracted are known as the North GRIP and GRIP cores, after the acronym of the Greenland Ice Core Project from north and central Greenland. Work on the dating of the annual layers and the analysis of the chemical composition of the micro-particles contained in these layers in comparison to the chemical composition of known volcanic eruptions has been carried out under the supervision of Claus Hammer of the Department of Geophysics at the University of Copenhagen, together with his colleague H. B. Clausen.[47]

It is the GRIP core which has produced the current focus of intense interest. At a conference in Austria in April 2001 Hammer presented an "extended abstract"[48] of a paper stating that evidence of the Theran eruption had been found in a layer redated, on the basis of comparison to the more securely datable Dye 3 core from southern Greenland, to 1645 ±7 B.C. Subsequent analysis, including analyses of two other cores known as North GRIP and GISP2 (Greenland Ice Sheet Project Core 2), has reduced the stated error range to ±4 years. While some have expressed surprise that ice-core laminations could be dated so precisely, Hammer notes that the layers have been counted separately by himself, Clausen, and two students, and that the counting was repeated years later.[49]

It is the comparison of the chemical composition of the shards from the Greenland ice core with tephra from the Bronze Age eruption of Thera which is critical, but currently controversial. While only volcanic shards no larger than a few microns can reach Greenland from Thera before falling out of the stratosphere, such minute particles are very difficult to source chemically and isotopically. Major constituent analysis by Scanning Electron Microscopy (SEM) was performed on 174 particles from Greenland and thirty-eight from the Theran eruption. Rare earth element (REE) analysis by Secondary Ion Mass Spectrometry (SIMS) was performed on nine glass shards from the Greenland GRIP core and four glass shards from Thera. In each case one shard was eliminated from the final comparison because of evident contamination in the course of eruptive process. None of the shards exceeded ten microns in size, much less than the thickness of a human hair. The Hammer *et al.* "extended abstract" of 2001 stated that the glass shards from the GRIP core were "of very similar composition to the Theran pumice and glass. Not only has the tephra the same bulk mineral composition as Thera, but also the REE composition closely resembles the abundance of rare earth elements in the Theran ash, including an europium anomaly." The final report, however, concludes that the composition of the bulk elements (major constituents) is not unique to Thera and that the uncertainty of the europium values is quite high.[50] It is accordingly the analysis of the other REE which appears critical. Hammer *et al.* (2003) maintains that the similarities in these

45 MANNING (*Test of Time*, *supra* n. 4) 264-265. For a recent volcanic ash tracking model and the effect of prevailing winds, see C. SEARCY, K. DEAN and W. STRINGER, "PUFF: A High-Resolution Volcanic Ash Tracking Model," *Journal of Volcanology and Geothermal Research* 80 (1998) 1-16.

46 The putative one-year error–A.D. 79, the actual year of the eruption, rather than A.D. 80, when the tephra should have reached Greenland, in Hammer's view–is attributed by Hammer to a difficult-to-read ice-core lamination in the year A.D. 1936, when one year could be read as two. C.U. Hammer, personal communication of 21 March 2001, for which I am most grateful.

47 C.U. Hammer is directly responsible for dating the layers and analyzing atmospheric and stratospheric circulation patterns of particles; G. Kurat of the Naturhistorisches Museum in Vienna and Peter Hoppe, an astrophysicist at the Max-Planck Institute for Chemistry in Mainz are responsible for the chemical measurements of the major and the trace constituent elements.

48 HAMMER *et al.* (*supra* n. 4).

49 C.U. Hammer, personal communication.

50 HAMMER *et al.* (*supra* n. 4); HAMMER *et al.* (*SCIEM2000, supra* n. 4).

elements establish a compelling case for identifying the Theran eruption as the source of the Greenland shards, whereas a critique of the Hammer *et al.* paper by D. J. Keenan argues that the data, after taking account of the problems of measurement, does not adequately support the conclusion, and that tephra from the c. 75,000 B.C. eruption of Toba in Indonesia has a profile as similar as the Theran tephra to the Greenland shards for the twelve Toba rare earth elements measured. The Greenland shards clearly exhibit significantly greater concentration of strontium than the Theran samples, but this is attributed by Hammer *et al.* to the contamination of the Greenland core by seawater, although the seawater content of Greenland ice far from the sea is generally *de minimus*. The Keenan article further contends that major discrepancies in four of the bulk elements actually preclude the possibility of a Theran origin for the Greenland shards.[51]

Claus Hammer has described the identification of volcanic sources of ice-core particles adroitly as "fingerprinting with reservations."[52] Max Bichler of the Atomic Institute of the Austrian Universities has compared the GRIP team data provided to date by Hammer *et al.* and by Kurat with his own neutron activation analysis of the glass phase of the upper pumice layer of the Minoan eruption of the Thera volcano and found a certain degree of correspondence, but has reserved judgment as to whether the eruption of Thera is the likely source of the shards in the Greenland ice core.[53]

The question arises also whether the glass of a volcano other than Thera could resemble the overall chemical composition of the glass shards from Greenland. A major eruption of Vesuvius/Avellino in the century preceding and perhaps including 1645 B.C. had a different profile. Few of the approximately 600 volcanoes active today have been analyzed, however. The eruption around 75,000 years ago of the Toba volcano in Indonesia produced REE abundances for the twelve elements tested which generally resemble those of the Theran and Greenland shards.[54] Only an eruption of the magnitude of VEI (Volcanic Explosivity Index) greater than 3 is likely to reach the stratosphere. There are on average three eruptions of VEI 4 or greater each decade, and one of 5 or greater every thirty years.[55] The c. 1645

51 M. DE ANGELIS, J.P. STEFFENSEN, M. LEGRAND, H. CLAUSEN and C. HAMMER, "Primary Aerosol (Sea Salt and Soil Dust) Deposited in Greenland Ice during the Last Climatic Cycle: Comparison with East Antarctic Records," *Journal of Geophysical Research* 102 (1997) 26,681-26,698. I am grateful to D.J. Keenan for providing this information and reference. See also KEENAN (*supra* n. 4) with regard to the discrepancies between the Theran and Greenland concentrations of the bulk elements silicon, iron, aluminum and sodium.

52 C.U. Hammer, personal communication of 20 March 2001, for which I am most grateful. Prof. Peter Fischer at Göteburg regards the information made available thus far as inconclusive regarding the volcanic source of the GRIP glass shards. He notes that the now-superseded 3f equipment used to perform the SIMS analysis of the Greenland glass shards in Mainz was restricted by its sputter intensity, which resulted in a rapid destruction of samples that limited the number of cycles available for analysis (personal communication of 15 October 2002, for which I am most grateful). See also P. SCHMID, C. PELTZ, V.M.F. HAMMER, E. HALWAX, T. NTAFLOS, P. NAGL and M. BICHLER, "Separation and Analysis of Theran Volcanic Glass by INAA, XRF and EPMA," *Mikrochimica Acta* 113 (2000) 143.

53 M. Bichler, personal communication, for which I am most grateful.

54 D.J. Keenan, personal communication with accompanying data, for which I am most grateful. For the Toba eruption, see N.J.G. PEARCE, J.A. WESTGATE, W.T. PERKINS, W.J. EASTWOOD and P. SHANE, "The Application of Laser Ablation ICP-MS to the Analysis of Volcanic Glass Shards from Tephra Deposits: Bulk Glass and Single Shard Analysis," *Global and Planetary Change* 21 (1999) 151-171. The composition of tephra from a given volcano may change over time: For example, a recent analysis of the volcanism of Mt. Etna concludes that it has become more calc-alkaline during its evolution (P. SCHIANO, R. CLOCCHIATTI, L. OTTOLINI and T. BUSÀ, "Transition of Mount Etna Lavas from a Mantle-Plume to an Island-Arc Magmatic Source," *Nature* 412 [2001] 900-904). Variation in trace-element composition between individual glass shards from the Theran eruption found in Gölhisar Gölü, a lake in southwest Turkey, is discussed in N.J.G. PEARCE, W.J. EASTWOOD, J.A. WESTGATE and W.T. PERKINS, "Trace-element Composition of Single Glass Shards in Distal Minoan Tephra from SW Turkey," *Journal of the Geological Society* 159 (2002) 545-556.

55 D.M. PYLE, "The Application of Tree-ring and Ice-core Studies to the Dating of the Minoan Eruption," *TAW* III, vol. 3: chronology, 167-173 quoted in MANNING (*Test of Time*, *supra* n. 4) 282.

signal is the only major signal present at all three Copenhagen deep drilling sites, Dye 3, GRIP and North GRIP,[56] suggesting some combination of the following factors at work: 1) a major eruption ejecting massive amounts of aerosol, 2) a proximate source, 3) a conducive atmospheric circulation and distribution pattern, 4) the absence of countervailing factors such as rapid atmospheric washout conditions.

Claus Hammer believes that it may be possible to exclude some Alaskan volcanoes as likely candidates on geographic grounds given what is known about atmospheric circulation patterns, whereas there is a high probability that a massive mid-latitude Northern Hemisphere eruption such as Thera would leave some trace in the ice layers in central Greenland.[57] The June 1912 eruption of Novarupta (Katmai) in Alaska, however, appears to have had an effect on climate as far south as Southern California,[58] unless the event clearly marked in the tree-ring record for that year had some other cause. An effect on climate indicated in tree rings does not necessarily imply the arrival of micro-particles, however. Near-equatorial eruptions such as those of Tambora and Krakatau have reached both Antarctica and Greenland (although Krakatau is only represented in the GISP2 core and not in GRIP, North GRIP or Dye 3), and an eruption of A.D. 1259 is represented in both areas, unless the ice-core signals are caused by separate eruptions in the same year or two.[59] A signal in the Greenland ice is thought to originate in the eruption around A.D. 1450 of Kuwae in the Vanuatu Islands in the Pacific Ocean at 15°S latitude.[60] Clausen *et al.* summarize the evidence as follows: of the twenty-seven major events identifiable in the Dye 3 ice-core record, some 15% are non-volcanic in origin, and of the remaining twenty-three events, Iceland accounts for some 40%, while the equatorial and high northern latitude regions each cover about 15%.[61] Both Alaskan and Siberian eruptions have been proposed for the seventeenth century B.C. The Hayes Volcano in the Cook Inlet in Alaska (61.62°N) produced a major eruption, evidenced by the most extensive set of tephra layers ever noted in the region, about 3,650 years B.P.[62] The Kamchatka Peninsula in Siberia, another highly active volcanic zone, is also located around 60°N, whereas all of Greenland lies above 60°N. Winds over the Kamchatka Peninsula come generally from the west and northwest, and those from the west may continue toward Greenland, about one-third of the globe distant (versus about two-thirds of the globe between Thera and Greenland).[63] Proximity of the volcanic source affects at least the intensity of signals in ice cores.[64] An eruption of Mount St. Helens in southern Washington state in the United States (46°N) in

56 C.U. Hammer, personal communication of 16 January 2001, for which I am most grateful.

57 HAMMER (*supra* n. 56).

58 MANNING (*Test of Time*, *supra* n. 4) 277.

59 H.B. CLAUSEN, C.U. HAMMER, C.S. HVIDBERG, D. DAHL-JENSEN, J.P. STEFFENSEN, J. KIPFSTUHL and M. LEGRAND, "A Comparison of the Volcanic Records Over the Past 4000 Years from the Greenland Ice Core Project and Dye 3 Greenland Ice Cores," *Journal of Geophysical Research* 102 (1997) 26,715; C.U. HAMMER, H.B. CLAUSEN and W. DANSGAARD, "Greenland Ice Sheet Evidence of Post-glacial Volcanism and Its Climatic Impact," *Nature* 288 (1980) 230-235; J. COLE-DAI, E. MOSLEY-THOMPSON and L.G. THOMPSON, "Annually Resolved Southern Hemisphere Volcanic History from Two Antarctic Ice Cores," *Journal of Geophysical Research* 102 (1997) 16,761-16,771; G.A. ZIELINSKI, "Stratospheric Loading and Optical Depth Estimates of Explosive Volcanism over the Last 2100 Years Derived from the Greenland Ice Sheet Project 2 Ice Core," *Journal of Geophysical Research* 100 (1995) 20,952; J. SOUTHON, "A First Step to Reconciling the GRIP and GISP2 Ice-Core Chronologies, 0–14,500 yr B.P.," *Quaternary Research* 57 (2002) 32-37.

60 ZIELINSKI (*supra* n. 59) 20,939, table 1.

61 CLAUSEN *et al.* (*supra* n. 59) 26,721.

62 J.R. RIEHLE, "A Reconnaissance of the Major Holocene Tephra Deposits in the Upper Cook Inlet Region, Alaska," *Journal of Volcanology and Geothermal Research* 26 (1985) 37-75. Eight other Alaskan eruptions in the mid-second millennium B.C. of unknown magnitude are noted by T.P. MILLER and R.L. SMITH ("Late Quaternary Caldera-forming Eruptions in the Eastern Aleutian Arc, Alaska," *Geology* [May 1987] 434-438). Uncalibrated radiocarbon ages are conventionally stated as "B.P.," or "Before Present," with "present" defined as A.D. 1950.

63 SEARCY *et al.* (*supra* n. 45).

64 ZIELINSKI (*supra* n. 59) 20,940.

the eighteenth-seventeenth century B.C. left ashfall in Alberta, Canada, about 900 kilometers from its source.[65] The standard reference work, Simkin and Siebert's *Volcanoes of the World* written in 1994, lists for the years broadly around 1650 B.C. three eruptions of volcanoes in the Kamchatka Peninsula, one in Japan, and one in Colombia. The Japanese eruption is assigned an assumed VEI of 4, the others none.[66]

The Greenland ice cores drilled to date do not contain any indication of a volcanic event between 1560 and 1480 B.C., the Aegean Short Chronology span for the Theran eruption. Of course, not all elements which reach the stratosphere come down, and not all which come down necessarily descend on every square meter of the earth's surface.[67] Hammer estimates that it would have taken six to nine months for particles from the A.D. 79 eruption of Vesuvius to reach Greenland.[68] Clausen *et al.*[69] have noted that there are many more acid peaks in the Dye 3 core from southern Greenland than in the central Greenland GRIP core, and both Warren and Buckland *et al.*[70] have discussed the lack of correspondence between recorded eruptions and indications of them in the ice-core data. Wind erosion of deposited aerosols or sampling problems may cause eruptions to be missed in ice-core data. For example, a distinct signal from the 1982 El Chichón eruptions (28 March, VEI 4+; 3 April, VEI 5)[71] is missing from the GISP2 ice core, although such evidence exists in other snow pits in Greenland.[72] Indeed, individual volcanic signals can be missing from one of two or more ice-core records in close proximity to one another.[73] It seems to be the case, however, that known massive eruptions of VEI 6 or greater, particularly those from the Northern Hemisphere, are represented in at least one of the cores. Thera has been estimated at VEI 6.9 at the minimum, and recent estimates suggest the likelihood of an eruption of significantly greater magnitude.[74] Accordingly, it is worth noting that dendrochronological research thus far has revealed no indication of a significant growth anomaly in the trees of California, Ireland, England or Germany between 1660 and 1630 B.C. Many factors other than the volcanic explosivity of an eruption affect the likelihood that it will be reflected in the tree-ring record, however (see *infra*).

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65 D.R. MULLINEAUX, J.H. HYDE and M. RUBIN, "Widespread Late Glacial and Postglacial Tephra Deposits from Mount St. Helens Volcano, Washington," *Journal of Research of the U.S. Geological Survey* 3:3 (1975) 332-333 and J.A. WESTGATE, D.G.W. SMITH and H. NICHOLS, "Late Quaternary Pyroclastic Layers in the Edmonton Area, Alberta," *Pedology and Quaternary Research. Symposium held at Edmonton, Alberta, May 13 and 14th, 1969* (1970) 179-187; J. BEGÉT, O. MASON and P. ANDERSON, "Age, Extent and Climatic Significance of the c. 3400 BP Aniakchak Tephra, Western Alaska, USA," *The Holocene* 2:1 (1992) 51-56.

66 T. SIMKIN and L. SIEBERT, *Volcanoes of the World* (1994)[2] 183.

67 S.W. Manning believes that a massive eruption of VEI 7 magnitude such as Thera may have been, would produce so voluminous an amount of ejecta as to make it likely that every square meter of Greenland would receive micron-sized sulphates. S.W. Manning, personal communication; see also M.R. RAMPINO, S. SELF and R.B. STOTHERS, "Volcanic Winters," *Annual Review of Earth and Planetary Sciences* 16 (1988) 73-99 cited in MANNING (*Test of Time, supra* n. 4) 272. See F.W. MCCOY and S.E. DUNN, "Modelling the Climatic Effects of the LBA Eruption of Thera: New Calculations of Tephra Volumes May Suggest a Significantly Larger Eruption than Previously Reported," presentation at the Chapman Conference on Volcanism and the Earth's Atmosphere, Thera, Greece, 17-21 June 2002. D.J. KEENAN states, however, that the mass of a volcanogenic aerosol has only a weak relation to the volcanic explosivity index ranking of the eruption (*supra* n. 4 [subsection 3.3]).

68 HAMMER *et al.* (*supra* n. 4); ZIELINSKI (*supra* n. 59) and A.S. PALMER, T.D. VAN OMMEN, M.A. J. CURRAN, V. MORGAN, J. SOUNEY and P. MAYEWSKI, "High Precision Dating of Volcanic Events (A.D. 1301-1995) Using Ice Cores from Law Dome, Antarctica," *Journal of Geophysical Research* 106 (2001) 28,089-28,096 have proposed times of up to three years for the ejecta of eruptions to reach Greenland and Antartica.

69 CLAUSEN *et al.* (*supra* n. 59) 26,707-26,723.

70 P. WARREN, "Absolute Dating of the Bronze Age Eruption of Thera (Santorini)," *Nature* 308 (1984) 492-493 and P.C. BUCKLAND, A.J. DUGMORE and K.J. EDWARDS, "Bronze Age Myths? Volcanic Activity and Human Response in the Mediterranean and North Atlantic," *Antiquity* 71 (1997) 581-593.

71 SIMKIN and SIEBERT (*supra* n. 66) 246.

72 ZIELINSKI (*supra* n. 59) 20,945.

73 A. ROBOCK and M.P. FREE, "Ice Cores As an Index of Global Volcanism from 1850 to the Present," *Journal of Geophysical Research* 100 (1995) 11,549-11,567 cited in ZIELINSKI (*supra* n. 59) 20,945.

74 See n. 67, especially McCOY and DUNN and KEENAN.

Additional data appear necessary before a convincing inference can be drawn from the ice-core evidence regarding the date of the Theran eruption. Further analysis of additional glass shards from the Greenland 1645 ±4 B.C. layer and studies of the rare earth element composition of a significant number of comparanda from other volcanic eruptions (particularly from the Siberian and Aleutian arcs) may resolve the issue.

Dendrochronology

Most trees native to temperate zones almost always display one growth ring per year. Variations in the width of the rings in many cases can be directly correlated with climatic conditions during the annual growing season for each tree genus. Because of the century-long history of dendro data collection and analysis in the southwest United States, excavators of Native American sites sometimes know the exact year each room in a building was constructed. It has even been possible in some instances to determine which communities shared common logging areas, and which did not.[75] In England, Ireland and Germany it has been possible, by using trees with recognizable overlapping years due to weather patterns, to construct continuous chronologies back to the Neolithic. In the Near East and Aegean the sequence is not yet complete, due in part to gaps during the period of the Roman Empire, when much of the wood used was imported from the Baltic area and reflects incompatible climate patterns. The work accomplished to date and the gaps that remain are depicted in Pl. LXXb and 3.[76] A "floating chronology" has been constructed, however, that forms a continuous sequence from the twenty-third to the seventh century B.C., incorporating at its core a 1,028-year sequence of logs from Gordion. Sequences from Porsuk (321 years), Acemhöyük (164 years) and Kültepe (435 years) provide other critical components. The absolute dates of the floating chronology are now fixed to within twenty-five years at most, as established by a large number of decadal radiocarbon determinations (radiocarbon ages determined using ten annual rings per measurement) and by the fact that component parts of the entire sequence end in closely dated historic contexts at Gordion in Phrygia and at Ayanis in Urartu.

Indeed, until very recently it seemed that the "floating chronology" was precisely anchored by the appearance of "marker events" in the logs from both Gordion and Porsuk indicating climate-forcing events 469 years apart, paralleling major anomalies in oaks from Ireland and England, where the dates are established at 1628 and 1159 B.C. *et sec.*[77] The analysis of timbers from a temple built by Rusa II at Ayanis appeared initially to confirm these dates. Ayanis was believed on the basis of texts found at Bastam in Urartu to be the fifth, and last, of the fortress towns built by Rusa II, who is known to have died around 645 B.C. Thus the years 655 to 651 B.C. assigned to the last rings of the temple timbers on the basis of the 1628 and 1159 B.C. match seemed a perfect fit.

This apparent anchoring of the Anatolian floating chronology, which had provided the basis for Kuniholm's support for the Low to Lower Middle Babylonian Chronologies,[78] has

75 P.I. KUNIHOLM, "Dendrochronology and Other Applications of Tree-ring Studies in Archaeology," *Handbook of Archaeological Sciences* (2001) 35-46; M.K. HUGHES, P.I. KUNIHOLM, H. EISCHEID, G. GARFIN, C.B. GRIGGS and C. LATINI, "Aegean Tree-Ring Signatures Explained," *Tree-Ring Research* 57:1 (2001) 67-73; and S.E. NASH, "Seven Decades of Archaeological Tree-Ring Dating," *It's About Time: A History of Archaeological Dating in North America* (2000) 60-82, especially 65 and 78.

76 The illustrations were provided for use in this paper by Peter Kuniholm, Director of the Laboratory for Near Eastern and Aegean Dendrochronology, to whom I am much indebted.

77 MANNING (*Test of Time, supra* n. 4) 313-314. Manning remarks that these tree-ring events "are the only major tree-ring growth anomalies in the entire second millennium B.C. in the Irish dendrochronology" and hence make a "clear case" for tying the absolute Irish dates to the Anatolian floating chronology.

78 P.I. KUNIHOLM, "Archaeological Evidence and Non-evidence for Climatic Change," *Philosophical Transactions of the Royal Society of London* A 330 (1990) 247-256 in which a successful wiggle-match of eighteen sets of Gordion rings against a high precision German oak curve was reported as supporting the prior anchor; P.I. KUNIHOLM, B. KROMER, S.W. MANNING, M. NEWTON, C.E. LATINI and M.J. BRUCE, "Anatolian Tree Rings and the Absolute Chronology of the Eastern Mediterranean 2220-718 BC," *Nature* 381 (1996) 780-783.

recently been superseded by the results of additional ^{14}C analyses of the dendro dates of the floating Anatolian sequence by Manning, Kromer, Kuniholm and Newton.[79] Their paper analyzes radiocarbon dates derived from selected decadal samples of wood from Gordion,[80] compares the results to the standard international 1998 radiocarbon calibration curve plus the authors' own measurements on German oak for the seventeenth to sixteenth century B.C., and concludes that a better fit can be obtained by shifting the Anatolian floating chronology back 22 +4/-7 years.[81] The adjustment would shift the previously proposed date for the major seventeenth century B.C. volcanic or other climate-forcing event indicated in the Anatolian trees from 1628 B.C. to 1650 B.C. +4/-7 years. The result would thus fit the proposed ice-core date, while removing the Anatolian floating chronology from the 1628 B.C. date for a major climate-forcing event reflected in tree rings in the long-lived trees of California and the shorter-lived oaks in Germany, Ireland and England, previously identified by proponents of the Aegean Long Chronology with the Theran eruption.[82] The shift would also move the later Anatolian tree-ring event from beginning c. 1159 B.C. to c. 1181, thus detaching it from the c. 1159 B.C. event noted in the Irish and English oaks. Peter Kuniholm kindly informs me, however, that the twelfth-century anomaly in the Anatolian trees is now seen as focused between 1174 and 1162 B.C., again assuming the correctness of the proposed 22 +4/-7 year shift. The sequence of logs from Porsuk, the Anatolian site near the Cilician Gates, 800 km. downwind of Thera, in which a massive growth episode begins in the ring now dated 1650 +4/-7 B.C., would now end not in 1551 but in 1573 +4/-7 B.C.[83] Kuniholm has argued that whatever the effects of the Theran eruption elsewhere, the trees used at Porsuk, assuming they came from the general vicinity, would in all likelihood have responded to the additional moisture resulting from rainstorms caused by the eruption. The raising of the Porsuk log felling (last ring) date to 1573 +4/-7 B.C. removes the Porsuk evidence from the argument against a post-1560 B.C. eruption of Thera pursuant to the Aegean Short Chronology. Kuniholm and Newton note that for the period 1560-1520 B.C. the Anatolian floating chronology is represented by only six trees of the species *Juniperus* sp., all from Gordion and hence possibly out of the area of the Theran ash fall (in comparison, for example, to the thirty-eight trees of three different species which provide the evidence for the 1650 +4/-7 B.C. event at Porsuk). Kuniholm concludes accordingly that the Anatolian dendrological database to date may be insufficient with respect to the preservation of any record of the eruption of Thera if it occurred later than 1573 +4/-7 B.C.[84]

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79 S.W. MANNING, B. KROMER, P.I. KUNIHOLM and M.W. NEWTON, "Anatolian Tree Rings and a New Chronology for the East Mediterranean Bronze-Iron Ages," *Science* 294 (21 December 2001) 2532-2535. S. Manning is Reader in Archaeology at the University of Reading in the U.K. and the author of the book *A Test of Time*; B. Kromer is Director of the Heidelberg Radiocarbon Laboratory; P.I. Kuniholm is Director of the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University; M. Newton is also at the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University.

80 MANNING *et al.* (*supra* n. 79) 2535, n. 5.

81 Fig. 3 of B. KROMER, S.W. MANNING, P.I. KUNIHOLM, M.W. NEWTON, M. SPURK and I. LEVIN, "Regional $^{14}CO_2$ Offsets in the Troposphere: Magnitude, Mechanisms, and Consequences," *Science* 294 (21 December 2001) 2531, depicts the improved fit with the calibration curve obtained by the proposed 22 +4/-7 year shift.

82 While the GRIP ice core witnesses a volcanic event around 1626 B.C., the signal is clearly much less pronounced than the 1645 ± 4 event (CLAUSEN *et al.* [*supra* n. 59]). It should be noted, however, that the magnitude of an acidity spike is only loosely correlated to the VEI of the eruption causing the spike (KEENAN [*supra* n. 4] table 1). Among the other factors which influence the magnitude are the sulfur content of the eruption, the prevailing circulation conditions in the stratosphere and atmosphere, and the location of the eruption.

83 P. Kuniholm, personal communication of 17 May 2002; MANNING *et al.* (*supra* n. 79) 2534-2535

84 KUNIHOLM *et al.* (*supra* n. 78) 781-782; P. Kuniholm and M. Newton, personal communication of 19 November 2002, for which I am most grateful.

To date no indication of a growth anomaly possibly related to a volcanic eruption has been reported in the trees of Ireland, England, Germany and California for the period 1560-1480 B.C.[85] The absence of any such indication during the period favored by advocates of the Aegean Short Chronology for the Theran eruption was once a major tenet of the Long Chronology position. Further research and reflection have led to reconsideration of the value of this negative evidence. First, it is now well understood that many factors other than degree of explosivity affect whether an eruption is significantly reflected in the tree-ring record. They include the proximity of the volcano, the amount of aerosol released, its sulfur content, prevailing circulation conditions in the stratosphere and atmosphere, offsetting or reinforcing weather factors such as El Niño/La Niña conditions, the time of year in relation to the growing season of the trees in question, whether the trees exist in a robust or marginal environment with respect to temperature and water, and the age of the trees and their condition at the time of the event.[86] Conversely, many non-volcanic climate and weather related factors, including highly local conditions, can cause growth spurts or interruptions in trees. Manning has questioned whether any of the growth anomalies in the B.C. Irish sequence can be firmly attributed to the climate-altering effects of a volcanic eruption.[87] Since no indication has been reported to date of a growth event in the dendro data from Ireland, England, Germany or California for the Aegean Long Chronology current proposed date-range for the Theran eruption of 1654-1643 B.C.,[88] it is difficult to maintain an argument based on the lack of corresponding dendro evidence for the Aegean Short Chronology proposed eruption range of 1560-1480 B.C.

This change in dates for the Bronze and Iron Age dendrochronology resulting from the proposed 22 +4/-7 year shift has major consequences for Near Eastern history. The date for construction of the Waršama Palace at Kültepe becomes 1832 +4/-7 B.C., and for the Sarıkaya Palace at Acemhöyük 1774 +4/-7 B.C. The date of the earliest alphabetic writing in central Anatolia moves from 718 B.C. to 740 +4/-7 B.C.[89]

85 The initial California bristlecone pine database was small with respect to the number of trees and extent of area examined for the relevant period (V.C. LaMARCHE Jr. and K.K. HIRSCHBOECK, "Frost Rings in Trees as Records of Major Volcanic Eruptions," *Nature* 307 [1984] 121-126). Work now underway at the University of Arizona Laboratory of Tree-Ring Research seeks to expand the database with respect to the period 1675-1450 B.C. (unpublished report of Director T.W. Swetnam of 7 June 2002).

86 J. GRATTAN, "Role of Volcanic Eruptions in Human History and Civilization," Chapman Conference (*supra* n. 67); G.C. JACOBY, "The Laki Eruption and Observed Effects on Europe and North America," Chapman Conference (*supra* n. 67); F.C. BRUNSTEIN, "Climatic Significance of the Bristlecone Pine Latewood Frost-ring Record at Almagre Mountain, Colorado, U.S.A.," *Arctic and Alpine Research* 28 (1996) 65-76.

Moreover, the effect of eruptions on weather is not uniform. The 1991 Pinatubo eruption among others resulted in winter warming and summer cooling, whereas in many cases including the 1783 Laki eruption the consequences are summer cooling and regional winter warming (S. RAMACHANDRAN, "A SKYHI GCM Study of Winter Warming and Summer Cooling Due to Pinatubo Aerosols," Chapman Conference [*supra* n. 67]; T. THORDARSON and S. SELF, "Atmospheric and Environmental Effects of the 1783-1784 Laki Eruption: A Review and Reassessment," *Journal of Geophysical Research* 108 [2003] 4011. See generally K.K. HIRSCHBOECK, F. NI, M.L. WOOD and C.A. WOODHOUSE, "Synoptic Dendroclimatology: Overview and Outlook," *Radiocarbon* 38 [1996] 205-223, especially 215). The dramatic cold temperatures caused by some major eruptions can be highly local in nature. (For example, the 1815 eruption of Tambora froze certain areas in the northeastern United States, causing some farmers to abandon their farms and move to Oregon, while other areas suffered significantly less. Contemporary records show that while the temperatures in Brunswick, Maine were much below average in 1816, the weather in New Haven, Connecticut was only slightly cooler than normal, and nowhere near as cold as it had been in 1812 [H. SIGURDSSON, *Encyclopedia of Volcanoes* (2000) 11; W.R. BARON, "1816 in Perspective: The View from the Northeastern United States," *The Year without a Summer: World Climate in 1816* (1992) 124-144, especially 130. Also see H. STOMMEL and E. STOMMEL, *Volcano Weather: The Story of 1816, The Year without a Summer* (1983), especially chapter 2]).

87 S.W. MANNING and D.A. SEWELL, "Volcanoes and History: A Significant Relationship? The Case of Santorini," *Natural Disasters and Cultural Change* (2002) 246-291 and Manning, personal communication of 17 February 2003. See M.G.L. BAILLIE and D.M. BROWN, *An Overview of Oak Chronologies* (1988) 543-548.

88 M.G.L. Baillie (re Ireland), personal communication of 19 February 2003 for which I am most grateful; D.J. Keenan, personal communication of 14 February 2003 and KEENAN (*supra* n. 4) table 1.

89 MANNING *et al.* (*supra* n. 79) 2534; G.K. SAMS, "Midas of Gordion and the Anatolian Kingdom of Phrygia," *Civilizations of the Ancient Near East* (1995) vol. 2, 1155.

The robustness of the proposed shift is considered *infra* in the discussion of problems of radiocarbon dating, where cautious acceptance is advised. Historical considerations may also support, however tenuously, the proposed upward shift in dates. As to the Urartian evidence, a reconsideration of the Bastam texts questions whether Ayanis is in fact described as the fifth and last of the fortresses built by Rusa, while at Ayanis itself the absence of references in the inscription to later building activities elsewhere mentioned suggests that Ayanis is one of the earlier of Rusa's foundations. The excavators of Ayanis also now prefer higher dates on independent historical grounds, in order to allow more years for reigns for the successors of Rusa II.[90] The new proposed radio/dendro date of 673 +4/-7 B.C. for the logs is accordingly now deemed a better fit for the historical evidence.

At Gordion, the date previously given of 718 B.C. for the felling of the logs used in the construction of what is called the Midas Tomb falls between dates given in Assyrian texts for his rule. The texts tell us that Mita of Muski–almost certainly Midas of Phrygia–is ruling between 717-709 B.C. and in some texts Sargon of Assyria, whose accession date is 722 B.C., asserts that Mita never submitted to Sargon's predecessors. If king and scribe are accurate, then Mita (Midas) would have begun his reign before 726 B.C., when Sargon's immediate predecessor Shalmaneser V came to the throne.[91]

The approximately sixty-year-old male buried in the tomb, if buried in 718 B.C. during the reign of Midas as suggested prior to the proposed 22 +4/-7 year shift in the Anatolian floating tree-ring sequence, could conceivably have been a much-loved uncle, tutor or companion of Midas, but given the vast scale of the enterprise–the tumulus was fifty-three meters in height and had a diameter of 300 meters–and great wealth of funerary gifts, it seems more likely that the tumulus was intended as a dynastic gesture, perhaps a tomb built at Midas' command at his accession for his putative father Gordius about whom little is known or for some other venerated ancestor.[92] Accordingly, a date for the Midas tumulus at the beginning of his reign is perhaps more likely than a date in the middle of his reign, thereby giving some support to a date c. 740 +4/-7 B.C. rather than 718 B.C.

Accordingly, the proposed upward revision of 22 +4/-7 years for the Anatolian floating chronology, and the support thus provided for the Middle Babylonian Chronology, should be accepted provisionally, subject to the caveats stated in the following section on radiocarbon dating, as the best approximation of calendar dates for the Near East in the late third, second and early first millennium B.C.

Radiocarbon Dating

It is perhaps ironic that dendrochronology, which holds high promise at some point of freeing Near Eastern and Aegean history and prehistory from the hazards of radiocarbon dating, for the moment partly relies on ^{14}C analysis to provide dendro dates for the Eastern

90 MANNING *et al.* (*supra* n. 79) 2534; A. ÇILINGIROĞLU, M. SALVINI (eds), *Ayanis I: Ten Years' Excavations at Rusahinili Eiduru-Kai 1989-1998* (2001) 15-19; for earlier arguments see A. ÇILINGIROĞLU and M. SALVINI, " 'Rusahinili in Front of Mount Eiduru': The Urartian Fortress of Ayanis (7th Century B.C.)," *SMEA* 35 (1995) 111-124.

91 Variant later Latin and Armenian versions of a lost Greek text of the fourth century A.D., the *Chronicles* of Eusebius, give accession dates for Midas of 742 and 738 B.C. respectively. Unfortunately these texts are chronologically wholly untrustworthy, given their major errors in dating where dates can be independently determined. (I am most grateful to Keith DeVries for this information.) See generally, O.W. MUSCARELLA, "The Iron Age Background to the Formation of the Phrygian State," *BASOR* 299/300 (1995) 91-101.

92 O.W. MUSCARELLA, "King Midas' Tumulus at Gordion" (review of R.S. YOUNG *et al.*, *Three Great Early Tumuli. The Gordion Excavations, Final Reports*, vol. 1 [1981]), *Quarterly Review of Archaeology* (December 1982) 7-10. A photograph illustrating the enormous size of the Midas Mound Tumulus accompanied by photographs of the wooden structure and cross sections used in creating the Anatolian floating chronology, taken by Peter Kuniholm, appear on pages 487-488 of MANNING (*Test of Time*, *supra* n. 4). Acceptance of the hypothesis that the volcanic event represented in the Greenland ice core at the reported date of 1645 ±4 B.C. is also the event represented in the Anatolian tree-ring sequence at the ^{14}C derived date of 1650 +4/-7 B.C., irrespective of whether either measurement represents the eruption of the Theran volcano, provides a period of overlap in the two measurements between 1650/49 and 1643 B.C., in turn implying a date for the Midas Mound between 740/39 and 733 B.C.

Mediterranean. Accordingly it is appropriate to examine next the current state of the art of radiocarbon dating. The progress made in recent years is surely significant. For example, thirty years ago the beginning of Troy I was dated anywhere between 3400 and 2800 B.C., whereas today, as a result of the careful work on numerous samples by Korfmann *et al.*, the range has been narrowed to within perhaps 100 years of 2900 B.C. Problems of aberrant dates from the Troad remain, however, including widely disparate dates from a single piece of wood, a circumstance also encountered in connection with the dating of an early LM IA context at Trianda on Rhodes (see *infra*).[93] Improvements in dating techniques during the late 1990s and the steady accumulation of additional data hold promise for the future. At the same time, it is necessary to note ongoing problems, many inherent in the method itself.[94]

(Readers not already conversant with the somewhat arcane procedures and logic of radiocarbon dating may at this point wish to consult the survey in standard English contained in the Appendix entitled "Problems of Measurement, Calibration and Probability in Radiocarbon Dating" *infra.*)

Some of the causes of ^{14}C measurement anomalies have long been known, but others have come to the fore more recently. Problems include those of collection and pretreatment of samples,[95] inter-lab measurement differences, calibration issues, and the irregular absorption of radiocarbon because of solar, climatic and regional factors. Local and species-dependent factors affecting the growing season and absorption of radiocarbon by trees are also under investigation.[96] High precision laboratory measurements have given quite different radiocarbon ages for samples of carbonized matter divided between them. Measurements of

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93 M. KORFMANN, "Der Prähistorische Siedlungshügel Hisarlik: Die 'zehn Städte Troias'—von unten nach oben," *Troia: Traum und Wirklichkeit* (2001) 347; G. MANSFELD, "Die Kontroll-ausgrabung des 'Pinnacle E4/5' im Zentrum der Burg von Troia," *Studia Troica* 11 (2001) 201-203. A study of calibrated radiocarbon measurements of Irish oaks of known Neolithic date concluded that one-third of the group produced measurements more than 200 years from the true dates, with a bias toward dates earlier than the true dates (M.G.L. BAILLIE, "Checking Back on an Assemblage of Published Radiocarbon Dates," *Radiocarbon* 32 [1990] 361-368).

94 Admirable explanations and analyses of radiocarbon dating and its difficulties are available in M.J. AITKEN, *Science-based Dating in Archaeology* (1990) 56-119 and in S.W. MANNING, *The Absolute Chronology of the Aegean Early Bronze Age* (1995) 126-142. (A critique of one of the three methods of presentation of radiocarbon data employed in the Manning work involving the application of modes is provided by T. WHITELAW, *Antiquity* 70 [1996] 232-234).

95 Seeds present particular collection and pretreatment issues inasmuch as they are frequently not fully carbonized when found, and may absorb moisture which will affect measurements. Substances used to render seeds more stable such as paraloid may have a similar effect (I am greatly indebted to S. Manning for clarifying this problem for me). With regard to the pretreatment of paleosols, see C. HATTÉ, J. MORVAN, C. NOURY and M. PATERNE, "Is Classical Acid-Alkali-Acid Treatment Responsible for Contamination? An Alternative Proposition," *Radiocarbon* 43 (2001) 177-182.

96 See F.G. MCCORMAC, M.G.L. BAILLIE, J.R. PILCHER and R.M. KALIN, "Location-Dependent Differences in the ^{14}C Content of Wood," *Radiocarbon* 37 (1995) 395-407; MANNING (*Test of Time, supra* n. 4) 241, n. 1143; M.G. OGURTSOV, G.E. KOCKAROV, M. LINDHOLM, M. ERONEN and Y.A. NAGOVITSYN, "Solar Activity and Regional Climate," *Radiocarbon* 43 (2001) 439-447; R. COOKE, "Time is of the Essence," *Newsday* (22 January 2002); J.E. RICHEY, J.M. MELACK, A.K. AUFDENKAMPE, V.M. BALLESTER and L.L. HESS, "Outgassing from Amazonian Rivers and Wetlands as a Large Tropical Source of Atmospheric CO_2," *Nature* 416 (2002) 617-620; M. STUIVER and T.F. BRAZIUNAS, "Anthropogenic and Solar Components of Hemispheric ^{14}C," *Geophysical Research Letters* 25 (1 February 1998) 329-332. For standard errors in the calibration curve, see M. JONES and G. NICHOLLS, "Reservoir Offset Models for Radiocarbon Calibration," *Radiocarbon* 43 (2001) 123.

Geomagnetic shifts have also been suggested as a potential complicating factor (B. VAN GEEL and H. RENSSEN, "Abrupt Climate Change around 2,650 BP in North-West Europe: Evidence for Climatic Teleconnections and a Tentative Explanation," *Water, Environment and Society in Times of Climatic Change* [1996] 21-41), but research is sparse and there is no indication to date that Holocene ^{14}C wiggles result from changes in geomagnetic field intensity (J. BEER, A. BLINOV, G. BONANI, R.C. FINKEL, H.J. HOFMANN, B. LEHMANN, H. OESCHGER, A. SIGG, J. SCHWANDER, J. WANDER, T. STAFFELBACH, B. STAUFFER, M. SUTER and W. WÖLFLI, "Use of ^{10}Be in Polar Ice to Trace the 11-year Cycle of Solar Activity," *Nature* 347 [1990] 164-166 cited in D. MAUQUOY, B. VAN GEEL, M. BLAAUW and J. VAN DER PLICHT, "Evidence from Northwest European Bogs Shows 'Little Ice Age' Climatic Changes Driven by Variations in Solar Activity," *The Holocene* 12:1 [2002] 2).

the Shroud of Turin, for example, produced both major variation between individual intra-lab measurements and significant inter-lab differences between the Arizona, Oxford and Zurich labs, with a difference of over 100 radiocarbon years between the Arizona and Oxford labs. Samples from excavated contexts near the beginning of the first century A.D., tested for the purpose of comparison with the Turin Shroud, produced similar differences.[97] A recent test of eight samples of Irish oak from the period 655 to 505 B.C. by the Belfast and Seattle laboratories succeeded, however, in reducing the difference between these two laboratories for the eight samples to 3.6 ±5.2 years.[98] This result may be indicative of claimed improvements in dating techniques beginning in the late 1990s.[99]

Bronze Age radiocarbon readings require major corrections in the range of two to three hundred years via calibration through comparison with measurements of tree rings of known chronological date. The earlier the radiocarbon age, the greater the correction required; 11,000 radiocarbon years equal 13,000 calendar years.[100] The calibration curve, however, is itself an artificial construct.[101] The current internationally recommended standard calibration curve, the 1998 INTCAL98 dataset, combines in its Middle and Late Bronze Age portion data from the 1993 Belfast laboratory curve based on Irish oak and the Seattle curve based on German oak.[102] The Heidelberg radiocarbon dates are 30 ±3 years earlier at the maximum than the Belfast 1993 dates for wood of the same calendar age at c. 8000 B.P.[103] Subsequent analysis has revealed problems in the Belfast 1993 data, and the Belfast 1986 dataset is now preferred. Because the Irish oak ages measured by Belfast are bidecadal and the German oak ages measured by Seattle decadal, the measurements of German oaks are heavily overweighted on the 1998 curve now in standard use.[104] The statistical method used to smooth the data introduces a further variable.[105] For much of the calibration curve, only one log of known calendar age was tested for a given period to obtain the corresponding level of ^{14}C (or in the case of the German oak as distinguished from the Irish and North American trees, one log for each laboratory).[106] Accordingly a single aberrant determination by one laboratory can have a significant effect in distorting the shape of the calibrated curve.

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97 R.E. TAYLOR, "Radiocarbon Dating," *Chronometric Dating in Archaeology (Advances in Archaeological and Museum Science)*,vol. 2 (1997) Chap. 3.

98 E-mail, P.J. Reimer to M.H. Wiener, 2 April 2002; C.B. RAMSEY, "Development of the Radiocarbon Calibration Program," *Radiocarbon* 43 (2001) 355-363.

99 S.W. Manning, personal communication of 29 May 2002.

100 S. NEMECEK, "Archaeology's Dating Game: Matching Radiocarbon Dates to the Calendar," *Scientific American* 283 (September 2000) 84.

101 "However, it must be remembered that it is not a curve, but a probability band" (MANNING [*supra* n. 94] 128).

102 M. STUIVER, P.J. REIMER, E. BARD, J.W. BECK, G.S. BURR, K.A. HUGHEN, B. KROMER, G. MCCORMAC, J. VAN DER PLICHT and M. SPURK, "INTCAL98 Radiocarbon Age Calibration, 24,000–0 cal BP," *Radiocarbon* 40 (1998) 1041-1083.

103 MANNING (*Test of Time, supra* n. 4) 242.

104 E-mail, P.J. Reimer to M. H. Wiener, 9 April 2002.

105 The utilization of some method of smoothing is necessary, however, because a simple conversion results in artificial spreading and clumping of calendar dates as a consequence of the interaction of the spread of measurement statistics and changes in the slope of the calibration curve (F.B. KNOX and B.G. MCFADGEN, "Least-Squares Fitting Smooth Curves to Decadal Radiocarbon Calibration Data from AD 1145 to AD 1945," *Radiocarbon* 43 [2001] 87). The nature of the problem and of the kind of solution generally adopted is clearly stated in J.C. VOGEL, A. FULS, E. VISSER and B. BECKER, "Pretoria Calibration Curve for Short-Lived Samples, 1930-3350 BC," *Radiocarbon* 35 (1993) 73, as follows: "The construction of a calibration curve . . . requires some discussion. On the one hand, the individual data points, of necessity, have to scatter on both sides of the actual correlation curve to the degree prescribed by the uncertainty of the measurements. A line connecting successive points would thus show erratic variations that do not correspond to the actual changes in ^{14}C, and some smoothing is necessary. On the other hand, the smoothing procedure should not dampen or eliminate the real 'wiggles' in the curve. We feel that the best compromise in this situation is to use a spline curve with 'tightness', $S = 1$, *i.e.*, a curve that passes within $1\ \sigma$ from 68% of all the data points, but smooths out unsubstantiated variations." The inherent, intractable nature of the difficulty presented is discussed in detail in MANNING (*supra* n. 94) 127-129.

106 I thank Paula J. Reimer for this information.

Measurement problems are to some extent inherent and unavoidable. For example, recent high precision, double-counted measurements of a piece of wood with thirty ring years from an early Late Bronze Age context from Rhodes produced measurements with mean dates eighty radiocarbon years apart for adjacent decadal samples, and the outermost rings ending in bark did not give the most recent dates.[107] Not every "excursion" on the calibration curve necessarily reflects actual mean differences in atmospheric radiocarbon in the decade in question. An example of how a single deviant measurement has affected the prevailing INTCAL98 calibration curve for the decade 1525-15 B.C. is considered *infra*.[108]

In addition to the problems of regional variation in radiocarbon ages considered *infra*, there exists the possibility that locality-specific factors may affect radiocarbon measurements in ways not yet fully understood.[109] For example, investigators have noted the possibility that measurements of Irish bog oaks and German river oaks may be affected by potentially differing concentrations of ^{14}C in their respective water reservoirs.[110] Whether fumaroles of old gases affecting rocks and soil near volcanoes and/or an "island effect" resulting from ^{14}C escaping from seawater reservoirs (which contain about fifty times the amount of carbon as the atmosphere) could result in the general or random distortion of radiocarbon measurements of samples obtained from volcanic islands such as Thera to produce earlier dates has been considered by Olsson[111] and Sulerzhitzky.[112] Of course it is important not to confuse data from tests of the atmosphere conducted after major eruptions with readings from samples from Thera which were buried under the tephra by the action of the volcano. Whether volcanic fumes emitted prior to the final eruption could have affected the seeds from which ^{14}C measurements were taken is a matter of speculation. In 1980 Bruns *et al.* noted the presence at Thera of hot carbon dioxide sources, partly submarine and hence capable of introducing seawater into the atmosphere, around a bay on the Kameni Islands in the Theran caldera, which appeared to produce dates 1,390 years too early for current short-lived samples, thus raising the possibility of aberrant measurements caused by a similar Bronze Age source.[113]

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107 The decadal measurements in question were 3410 ±45 B.P. and 3490 ±45 B.P. at one standard deviation, hence ±90 at two standard deviations. Accordingly, this date range may be sufficient in itself to account for the distance in dates between adjacent decadal measurements.

108 See p. 391-392 *infra*.

109 In northern Minnesota, PaleoIndian assemblages, typical of those which elsewhere date not later than 7000 B.P., give dates of 1500 to 2000 B.P. The bedrock at the northern Minnesota sites is Precambrian "craton," *i.e.*, old parts of the earth's crust that have been little deformed, a correlation not yet connected to a satisfactory explanation. Northern Minnesota sites also frequently provide radiocarbon ages for hearth residues which are 500 years different than associated food residues (G. Rapp, personal communication of 22 April 2002, for which I am most grateful).

110 VAN GEEL and RENSSEN (*supra* n. 96) 21 report that an unanticipated ^{14}C reservoir effect complicates dating raised-bog deposits, with individual ^{14}C dates appearing to be 100 to 250 years too early.

111 I.U. OLSSON, "Carbon-14 Dating and Interpretation of the Validity of Some Dates from the Bronze Age in the Aegean," *High, Middle or Low?* (*supra* n. 4) Part2 (1987) 4-38; "The Radiocarbon Contents of Various Reservoirs," *Radiocarbon Dating. Proceedings of the Ninth International Conference, Los Angeles and La Jolla, 1976* (1979) 613-618.

112 Sulerzhitzky notes that eruptions of the Kamchatka and Kurile Island volcanoes produced samples with up to fifty-three percent inactive gases (L.D. SULERZHITZKY, "Radiocarbon Dating of Volcanoes," *Bulletin Volcanologique* 35 [1970] 85-94). Olsson reports that one sample of air collected from the 1973 eruption of Heimaey in Iceland contained only three percent of contemporary atmosphere (OLSSON, "Carbon-14 Dating and Interpretation of the Validity of Some Dates from the Bronze Age in the Aegean" [*supra* n. 111] 20). Evidence for fumaroles in antiquity on the island of Melos is presented in A.J. HALL, E. PHOTOS-JONES, A. McNULTY, D. TURNER and A. McROBB, "Geothermal Activity at the Archaeological Site of Aghia Kyriaki and Its Significance to Roman Industrial Mineral Exploitation on Melos, Greece," *Geoarchaeology* 18 [2003] 333-357. See also R.M. CHATTERS, J.W. CROSBY III and L.G. ENGSTRAND, *Fumarole Gaseous Emanations: Their Influence on Carbon-14 Dates. Washington State University Technical Extension Service Circular* 32 (1969).

113 M. BRUNS, I. LEVIN, K.O. MÜNNICH, H.W. HUBBERTEN and S. FILLIPAKIS, "Regional Sources of Volcanic Carbon Dioxide and Their Influence on ^{14}C Content of Present-day Plant Material," *Radiocarbon* 22 (1980) 532-536; Steven SOTER, an astrophysicist at the American Museum of Natural History who is responsible for radiocarbon work at the Early Bronze Age and Hellenistic site of Helike in the Argolid, has observed that:

Variation in solar activity creates significant problems. High solar activity in terms of sunspots and solar flares results in fewer cosmic rays and less ^{14}C production for trees to absorb, whereas times of minimum activity during the eleven-year sunspot cycle may cause ^{14}C production at high latitudes to double in comparison with the eleven-year average.[114] Fitting the fluctuating eleven-year sunspot cycle into the decadal measurements provided by the 1998 calibration curve is a significant challenge, and one that tests the inherent limits of radiocarbon dating with respect to translating radiocarbon ages into calendar years. The authors of the 1998 calibration curve propose twenty years as the upper limit for single year change induced by the eleven-year cycle, with a standard deviation of eight radiocarbon years between adjacent annual rings. Of course the longer ^{14}C remains in the stratosphere before it is incorporated into living matter, the less the effect of the eleven-year cycle. Manning has observed that the behavior of radiocarbon in the stratosphere and atmosphere is at present a matter of theory rather than of observation.[115] Minze Stuiver, the head of the 1998 international calibration effort, has suggested the two hundred-year sunspot cycle, changes in the earth's magnetic field and the effect of ash clouds resulting from volcanic eruptions as additional possible sources of anomalies in radiocarbon measurements and in the calibration curve.[116]

Regional variation in radiocarbon is a major current issue. Southern Hemisphere trees give older radiocarbon ages than Northern trees of the same calendar dates, a condition initially attributed to the fact that more of the Southern Hemisphere is covered by oceans, which contain carbon reservoirs about fifty times those of the atmosphere. Recently, however, Bernd Kromer, the Director of the Heidelberg Radiocarbon Laboratory, has suggested that the older Southern Hemisphere readings result from the gradual release of a sink of old pre-Holocene carbon trapped in the Weddell Sea in Antarctica, southeast of South America.[117]

"Aside from irreducible calibration problems, the data may well be distorted by even larger *systematic* errors due to poorly understood sources of natural contamination. Such effects are all too often ignored, but can easily undermine the value of any statistical average. . . Carbon dates for occupation horizons based on contained wood or charcoal are often overestimated due to remobilization and deposition of older carbon. . . adding only 1% 'dead' carbon to a sample of any age would produce an apparent age increment of 80 years. . . In our carbon dating of horizons from the Helike delta, we would regard any agreement within 80 years among samples from the same deposit to be unusually good." (letter of 21 April 2003, for which I am most grateful).

114 KROMER *et al.* (*supra* n. 81) 2531; I. LEVIN, R. BÖSINGER, G. BONANI, R.J. FRANCEY, B. KROMER, K.O. MÜNNICH, M. SUTER, N.B.A. TRIVETT and W. WÖLFLI, "Radiocarbon in Atmospheric Carbon Dioxide and Methane: Global Distribution and Trends," *Radiocarbon After Four Decades: An Interdisciplinary Perspective* (1992) 503-518. For a more recent assessment of atmospheric variations, see I. LEVIN and V. HESSHAIMER, "Radiocarbon—A Unique Tracer of Global Carbon Cycle Dynamics," *Radiocarbon* 42 (2000) 69-80.

115 S.W. Manning, personal communication. Cf. generally LEVIN and HESSHAIMER (*supra* n. 114) and V. HESSHAIMER, M. HEIMANN and I. LEVIN, "Radiocarbon Evidence for a Smaller Oceanic Carbon Dioxide Sink Than Previously Believed," *Nature* 370 (1994) 201-203. I am grateful to P.I. Kuniholm for reminding me of these articles.

116 STUIVER *et al.* (*supra* n. 102). An early (1993) article by Stuiver and Braziunas discusses solar, geomagnetic and ocean forcing as all playing a role in atmospheric ^{14}C change over time periods ranging from one year to a millennium. The abstract of the article states that "in the single-year time series the variance in the 2-6 year periodicity range is attributable to El Niño–Southern Oscillation (ENSO) ocean perturbations. A 10-11-year component is partially tied to solar modulation of the cosmic ray flux, and multidecadal variability may relate to either solar modulation or instability of the North Atlantic thermohaline circulation. For the early Holocene bidecadal ^{14}C record we derive a 512-year atmospheric ^{14}C periodicity which relates to instabilities in North Atlantic thermohaline circulation. . . . The ubiquitous 206-year ^{14}C cycle is assigned either to solar modulation, or to solar modulation modified by climate (ocean) response" (M. STUIVER and T.F. BRAZIUNAS, "Sun, Ocean, Climate and Atmospheric $^{14}C_2$: An Evaluation of Causal and Spectral Relationships," *The Holocene* 3:4 [1993] 289-305).

117 J.C. LERMAN, W.G. MOOK and J.C. VOGEL, "^{14}C in Tree Rings from Different Localities," *Radiocarbon Variations and Absolute Chronology. Proceedings of the 12th Nobel Symposium* (1970), I am grateful to P.J. Reimer for calling this publication to my attention; KNOX and MCFADGEN (*supra* n. 105) 87; B. Kromer, personal communication, for which I am most grateful.

Accordingly Stuiver recommended subtracting twenty-four years from radiocarbon ages of Southern Hemisphere trees before applying the calibration curve, based on comparisons from the seventeenth to nineteenth century A.D. Recent analysis of the 900-year period A.D. 950-1850 shows that the offset is not constant, but varies periodically between eight and eighty years, with a periodicity of ~130 years, and a recommended correction of 41 ±14 years for dates outside the range examined. McCormac *et al.* propose in a forthcoming paper that the periodicity is caused by solar-induced changes in atmospheric circulation, but also suggest the possibility that the stratospheric injection of ^{14}C into the troposphere is involved. The paper notes that the geophysical interpretation has "profound implications for the exchange of carbon between the ocean and atmosphere."[118] Such effects may not be limited to the Southern Hemisphere. Rings of the same calendar date from western North America differ from those in the British Isles by -20 to +60 radiocarbon years, with the British dates generally older. The mean standard deviation is fourteen years. Research in the course of establishing the 1998 calibration curve disclosed a mean difference of 24.2 ±6 years between Belfast measurements of Irish oak and Seattle measurements of German oak for the critical years 1700 to 1500 B.C.[119]

In a companion article to the Manning *et al. Science* article discussed, Kromer *et al.*[120] describe episodes of marked regional variation, which they suggest may be caused by periods of unusually wet and cold climate, such as that proposed for the early eighth century B.C., when the Turkish juniper determinations show a mean variation of -30 years compared to the German oaks.[121] Mediterranean, Aegean and Western Anatolian trees have a principal growth season beginning in the spring, unlike the oaks of Central Europe which lay down a substantial amount of their overall carbon storage in July and August.[122] The authors suggest that as a consequence of climatic conditions, the trees of Central Europe may have experienced a shift in growing season to later in the summer, while the Anatolian trees enjoyed favorable moisture and temperature leading to early growth,[123] resulting in differing periods of major annual absorption of radiocarbon from the atmosphere. They further suggest that a period of minimum solar activity at that time may have affected stratospheric heating and circulation, adding to the impact of ^{14}C seasonality.[124] A recent major study reports that identifying the general circulatory processes at work by which a small change in solar activity may result

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118 STUIVER *et al.* (*supra* n. 102) 1045-1046. F.G. McCORMAC, P.J. REIMER, A.G. HOGG, T.F.G. HIGHAM, M.G.L. BAILLIE, J. PALMER and M. STUIVER, "Calibration of the Radiocarbon Time Scale for the Southern Hemisphere AD 1850-950," *Radiocarbon* (forthcoming). I am most grateful to P.J. Reimer, one of the co-authors, for calling this recent work to my attention, providing me with the manuscript and allowing me to refer to the work.

119 Eight measurements of sections of the same Irish trees by the two laboratories for the years 655 to 565 B.C. in a generally flat part of the calibration curve showed an inter-lab mean difference of only 3.6 ± 5.2 years, as noted above. Accordingly, unless the situation is markedly different for the broadly oscillating calibration curve years of 1650 to 1535 B.C., much of the 24.2 ± 6 year difference between the Irish and German oak from the 1700 to 1500 B.C. period is likely to be the result of regional variation (P.J. Reimer, personal communication of 4 April 2002). M.G.L. Baillie and D.M. Brown at Belfast caution that "the full implications of the regional calibration off-sets have not yet been fully appreciated by the archaeological community" (M.G.L. BAILLIE and D.M. BROWN, "Oak Dendrochronology: Some Recent Archaeological Developments from an Irish Perspective," *Antiquity* 76 [2002] 499). KROMER *et al.* (*supra* n. 81) 2530 state that "a conservative upper limit of an additional, unknown laboratory error in the Heidelberg facility is eight radiocarbon years."

120 KROMER *et al.* (*supra* n. 81) 2529-2532.

121 See P. J. REIMER, "A New Twist in the Radiocarbon Tale," *Science* 294 (21 December 2001) 2494-2495.

122 KROMER *et al.* (*supra* n. 81) 2531.

123 The KROMER *et al.* (*supra* n. 81) analysis argues that apart from periods of known or presumed cold climate, there are no significant radiocarbon variations between Aegean/Anatolian trees and those of Europe.

124 KROMER *et al.* (*supra* n. 81) 2531.

in a large change in climate such as that suggested for 2650 B.P. "involves a considerable degree of speculation, since the effect of solar variability on the Holocene climate is still controversial."[125]

The existence of intra-year radiocarbon seasonality seems clear, however. One recent study reports a seasonal swing of eight to thirty-two years in atmospheric radiocarbon readings between the summer high and the winter to early spring low, with a mean standard deviation of fourteen radiocarbon years.[126] A mean difference of fourteen years also exists with respect to measurements of adjacent years in tree rings, with measures of adjacent annual rings sometimes varying by seventy radiocarbon years, one major reason why decadal averages are used in the calibration curve.[127] Stuiver *et al.* observe that "the ^{14}C content of a 10-yr wood sample, however, is not necessarily a perfect reflection of the atmospheric ^{14}C level of that decade. Tree-ring ^{14}C does not represent the seasons equally because a major portion of the wood is formed in spring and early summer. Tree-ring thickness also differs from year to year, causing variable annual ^{14}C contributions to the decadal average."[128] It is important to note that Aegean seeds submitted for radiocarbon dating may encounter similar difficulties. Seeds of barley, chick pea and bitter vetch in the Aegean typically have a May-June growing season similar to the period when trees lay down most of their carbon storage, and depending on the type of seed may need as little as three to four weeks between germination and harvest; accordingly their carbon intake may be affected even by brief solar events, although the effect of solar events, however intense, may be ameliorated by the fact that current models of atmospheric mixing propose a residence time for ^{14}C in carbon dioxide in the atmosphere of ten to twenty years as noted above.

The Kromer *et al.* analysis argues that apart from certain prolonged periods of cold and wet climate, no significant regional variation exists between Aegean/Anatolian trees and the trees of Western Europe represented in the Bronze Age portion of the calibration curve, which also provide the specific comparisons for the Gordion sequence cited in the Manning *et al.* *Science* paper. Here Kromer *et al.* rely on a comparison of radiocarbon dates obtained from the 1998 calibration curve established on German and Irish oaks with those from Turkish junipers from Western Anatolia for the twenty-three decades from A.D. 1420 to 1649. The authors report no meaningful offset, *i.e.*, a mean offset of 1.4 years. Behind this benign mean, however, there lurks considerable "noise." All the Turkish pine radiocarbon ages are older than the German oak for the century A.D. 1440-1540, with substantial variations and a mean difference of seventeen radiocarbon years. In the periods A.D. 1420-1440 and 1550-1640 the Turkish pines are younger, again with substantial variations and a mean difference of -14 radiocarbon years.

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125 B. VAN GEEL, J. VAN DER PLICHT, M.R. KILIAN, E.R. KLAVER, J.H.M. KOUWENBERG, H. RENSSEN, I. REYNAUD-FARRERA and H.T. WATERBOLK, "The Sharp Rise of $\Delta^{14}C$ *ca.* 800 cal BC: Possible Causes, Related Climatic Teleconnections and the Impact on Human Environments," *Radiocarbon* 40 (1998) 545; VAN GEEL and RENSSEN (*supra* n. 96). See also G. BOND, B. KROMER, J. BEER, R. MUSCHELER, M.N. EVANS, W. SHOWERS, S. HOFFMANN, R. LOTTI-BOND, I. HAJDAS and G. BONANI, "Persistent Solar Influence on North Atlantic Climate During the Holocene," *Science* 294 (2001) 2130, regarding the possible effect of climate on North Atlantic Deep Water as a mechanism for amplifying solar signals and transmitting them worldwide. I thank Sturt Manning for calling my attention to these studies. Uncalibrated radiocarbon ages are conventionally stated as "B.P.," or "Before Present," with "present" defined as A.D. 1950, as noted *supra*. Thus "2650 B.P." equals 700 B.C. uncalibrated, but becomes about 800 B.C. after calibration.

126 R.A. HOUSLEY, S.W. MANNING, G. CADOGAN, R.E. JONES and R.E.M. HEDGES, "Radiocarbon, Calibration and the Chronology of the Late Minoan IB Phase," *JAS* 26 (1999) 167; LEVIN *et al.* (*supra* n. 114) 503-518; LEVIN and HESSHAIMER (*supra* n. 114) 69-80.

127 MANNING (*supra* n. 94) 126-142; S. BOWMAN, *Radiocarbon Dating* (1990) 43-49.

128 STUIVER *et al.* (*supra* n. 102) 1042. Some and perhaps much of the reported variation is of course caused by the difficulties of measurement, as expressed in the one and two standard deviation bands provided with ^{14}C dates. B. Kromer, the Director of the Heidelberg radiocarbon laboratory, has observed (personal communication) that it is unfortunate that because of the ease of multiplication by one, the citation of one sigma probability bands became the standard practice; one sigma 68% measurement probability data, which do not encompass possible pre-laboratory sources of error, may provide misleading input for the calibration process.

The overall mean difference of 1.4 years for these years thus appears somewhat fortuitous. Moreover, we have already noted a number of potential issues of general significance in this regard, including:

1) inter-lab measurement variability
2) inter-species variation
3) site-specific problems magnified by the small number of trees measured
4) regional variation in general in the absorption of radiocarbon.

Could any of these result in 1998 radiocarbon calibration curve dates that are earlier than calendar dates for the periods in question, and/or Gordion radiocarbon dates later than the calendar dates, thus negating the need for a 22 +4/-7 year shift in the Anatolian floating chronology? There is no reason to assume that any of the variables would narrow the 22 +4/-7 years proposed for the shift or that the combined effects would be cumulative and not offsetting. Nonetheless, there remains a possibility of some constant factor or combination of factors distorting dates by about twenty years.[129] George (Rip) Rapp has observed that the proposed 22 +4/-7 year shift tests the limits of our current knowledge, and that we are perhaps twenty years away from having a workable model of the basic physical processes at work with respect to atmospheric distribution of radiocarbon.[130] Nevertheless, while no group of disparate decadal or other radiocarbon determinations would have a calendar resolution in the twenty-year range, the forty-four decadal measurements whose internal calendar relationship is exactly known, and which provide a superior "wiggle-match" to the 1998 calibration curve when moved *in toto* and placed 22 +4/-7 years earlier make a respectable, and on present knowledge acceptable, case for the revised dates supporting the Babylonian Middle Chronology. Sturt Manning's proposal that the recommended shift should be accepted at the 95% confidence level seems apt.[131] The case is buttressed to some extent by the historical considerations discussed above in the section on dendrochronology.

The Long and the Short of Aegean Chronologies

Our final topic is the current state of the ongoing attempt to date the Theran eruption and the LM I period in the Aegean by radiocarbon. In addition to the general issues of radiocarbon dating already considered, one particular problem is paramount. Just as tree rings of the same absolute date may provide quite different ^{14}C ages, so tree rings a century apart may provide radiocarbon ages that are the same. Such a case occurs in the seventeenth-

129 Three logs from Gordion, two of them from the Midas Mound, were used *in toto* to obtain the Anatolian floating chronology radiocarbon determinations, but for much of the span the ^{14}C measurements came from a single log of the three (MANNING *et al.* [*supra* n. 79] 2535, n. 5).

130 G. Rapp, personal communication of 22 April 2002, for which I am most grateful. D.J. KEENAN in a paper entitled "Why Early-Historical Radiocarbon Dates Downwind from the Mediterranean are Too Early," *Radiocarbon* 44 (2002) 225-237, offers a speculative hypothesis involving the marine degassing of 'old' carbon (*i.e.* ^{14}C-deficient C) induced by upwelling of old subsurface water combined with changes in putative post-glacial Mediterranean circulation patterns as a possible theoretical explanation for a number of Eastern Mediterranean ^{14}C dates that appear to be too early. Y. FACORELLIS, Y. MANIATIS and B. KROMER, "Apparent ^{14}C Ages of Marine Mollusk Shells from a Greek Island: Calculation of the Marine Reservoir Effect in the Aegean Sea," *Radiocarbon* 40 (1998) 963-973; G. SIANI, M. PATERNE, E. MICHEL, R. SULPIZIO, A. SBRANA, M. ARNOLD and G. HADDAD, "Mediterranean Sea Surface Radiocarbon Reservoir Age Changes Since the Last Glacial Maximum," *Science* 294 (2001) 1917-1920. P.J. Reimer (personal communication of 17 October 2002, for which I am most grateful) notes that there is unfortunately no data for the marine reservoir correction required for the Mediterranean between about 4400 cal. B.P. (about 2450 B.C.) and the nineteenth century A.D. Measurements comparing ^{14}C ages of plankton and associated tephra layers, and of paired shell and charred samples from single contexts support reservoir ages comparable to modern pre-atomic bomb measurements.

131 Personal communication. Work underway by Manning seeks to extend the measurements cited of Anatolian and German wood for A.D. 1420-1650 by ^{14}C determinations from German and Irish trees for the period A.D. 1350-1860, in order to consider three anomalous periods known as the Spörer episode, the Maunder Minimum episode and the short term cooling episode of A.D. 1800-1830. To end sole reliance on the Gordion wood, Manning and his colleagues plan ^{14}C measurements of wood from Ayanis for the period 1000-600 B.C.; from Karahöyük for 2000-1800 B.C.; and from Porsuk for 1750-1550 B.C. I am grateful to Sturt Manning for providing this information.

sixteenth century B.C., a period marked by the notorious flattening, or oscillating, calibration curve. For example, a radiocarbon age of 3315 B.P. intersects with calibration curve dates of both 1615 and 1535 B.C. and most decades between (Pl. LXXIa).[132]

The technique known as wiggle-matching attempts to circumvent this problem by examining whether a series of dates will fit the parameters of the oscillating curve. The technique is applicable, however, only where the internal relationship of the dates can be independently determined, as in the case of a piece of wood spanning many decades. A site with very clear stratigraphy is also a potential candidate, but subject to the realization that successive construction, repair, and/or destruction levels at a site may be separated by fifty years or by five, and that in the latter case the difference is below ^{14}C recognition. Moreover, in some cases the time between the events for which dates are sought will be less than the standard deviation stated for the measurements. It is particularly important to distinguish the wiggle-matching of radiocarbon determinations from two datasets whose internal sequences are established at the one-year level, as in the case of the calibration curve based on consecutive long sequences and the 1,503 consecutive-year Anatolian floating sequence discussed *supra*, on the one hand from the attempt to match disparate determinations to observe where the span of radiocarbon ages fits the oscillations of the calibration curve, as in the case of seeds from a single context or from multiple, somewhat related ones, as in the examples discussed *infra* on the other hand.

In *A Test of Time* (1999), Manning concluded that radiocarbon dates indicated a 70-30 or greater probability of an early date for the Theran eruption and the Aegean Long Chronology, as proposed by Housley *et al.* at the 1989 Theran Congress.[133] A paper by Manning *et al.* in *Antiquity* (2002) and another paper by Manning and Ramsey presented at the SCIEM Haindorf conference held in 2001 (forthcoming, 2003) go further, and state on the basis of some additional ^{14}C measurements and remeasurements that the issue is now closed and the Aegean Long Chronology established beyond doubt.[134] It is difficult to believe that any small number of additional ^{14}C determinations from disparate contexts could have so dramatic an effect, given the inherent problems in radiocarbon dating discussed above, and hard to see how these new measurements in particular can support so sweeping a statement.

The analysis in each case begins with the carbonized branch of wood from Trianda on Rhodes (AE1024) with thirty years of rings noted above. The ages obtained from the branch are internally inconsistent, with adjacent decades measuring eighty radiocarbon years apart (OxA-10729, 10730) and an inner decade giving a later radiocarbon date than the outer rings ending in bark (OxA-10728). The width of the probability band—forty-five radiocarbon years at one standard deviation, 68.2% likelihood assuming the "noise" in the count follows a standard bell curve, and ninety radiocarbon years at two standard deviations, 95% probability on the same assumptions—may explain the discrepancies in radiocarbon dates from the thirty-year branch. The calibration curve has a steep slope in the relevant area, with the radiocarbon ages 3400-3320 B.P. representing about ten calendar years, adding to the uncertainty in dates.[135] Manning has observed (personal communication) that because there are few fully satisfactory datasets in archaeology we must make use of what we have. He contends that the outer decade of the branch at two sigma confidence provides a 1774-1680 B.C. range with an estimated probability (see Appendix, *infra*) of 0.734 after wiggle-matching, tending to support the

132 B. WENINGER, "Theoretical Radiocarbon Discrepancies," *TAW* III, vol. 3: Chronology, 216-231. Weninger contended that the Theran radiocarbon determinations then available strongly supported the Aegean Short Chronology placing the eruption c. 1550-1500 B.C. once two obvious "outliers" (consisting of radiocarbon determinations more than 500 years too early from seeds from the same jars as the seeds which provided appropriate measurements) were eliminated.

133 R.A. HOUSLEY, R.E.M. HEDGES, I.A. LAW and C.R. BRONK, "Radiocarbon Dating by AMS of the Destruction of Akrotiri," *TAW* III, vol. 3: Chronology, 207-215. (BRONK is also the RAMSEY of *supra* n. 4 and n. 98.)

134 MANNING *et al.* (*Antiquity*, *supra* n. 4); MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4). I am most grateful to S.W. Manning for allowing me to see these papers prior to publication. In reciprocity I provided S. Manning with an initial draft of this paper prior to the publication of Manning and Ramsey, thereby facilitating comment in that paper on certain of the concerns raised in this publication.

135 I am grateful to S. W. Manning for his reminder in this regard.

Aegean Long Chronology. It should be noted, however, that one of the decadal radiocarbon determinations produced a later date, and that even a 1680 B.C. date for an early Late Minoan IA context is consistent with an LM IA period running from 1680 to 1550 B.C., with an eruption of Thera at the end of the period, in accordance with the modified Aegean Short Chronology.[136] The span of 1765-1716 B.C. that Manning *et al.* in *Antiquity* propose as most likely for early LM IA based on the Trianda ^{14}C determinations covers a chronological period generally assigned on the basis of Egyptian scarabs of pharaohs and astronomical/textual records to the end of the Twelfth and beginning of the Thirteenth Dynasties, a period which instead exhibits links to Middle Minoan IIB rather than LM IA, both in Egypt and in Canaan.[137] Accordingly the proposed chronology would require a MM III period (MM IIIA and B combined) no longer than one generation at most.[138]

Because the piece of carbonized wood (wedge-shaped and about 2.7 cm. x 2.6 cm. in section)[139] which provided the three decadal radiocarbon determinations for early LM IA at Trianda retains its outer bark, it cannot have been the survivor of a piece of furniture or tool made earlier, and in all probability was not from a beam, but could have been part of the inner packing of a collapsed wall or ceiling constructed earlier.[140] Here the question of number of samples available is critical; while one or a few pieces of wood retaining outer bark may come from construction packing, it is unlikely that numerous samples would all come from such a source. A large sample base from a specific context would also serve as a corrective to many other problems of radiocarbon dating.

The analysis of the Trianda thirty-year branch also illustrates the nature of the decisions required in the statistical analysis of radiocarbon data. For example, the measurement of the outer rings of the branch produced a segment of the two sigma probability distribution at 1865-1833 B.C. for the stated early LM IA context, a date 125 years too early on the Long Aegean Chronology and 250 years too early on the Short.[141] The segment is included in the distribution, but with a low probability of 0.188 and hence minor effect on the proposed calibrated date. On the other hand, another charcoal sample[142] from a stated early LM IA horizon at Trianda which provided a two sigma (standard deviation) probability band at 3245 B.P. ±90, 1622-1426 B.C. calibrated, consistent only with the Aegean Short Chronology, is excluded on the ground of poor agreement with the other samples from Trianda, few though they are. Even at one standard deviation the Trianda measurements for the end of LM IA, Theran eruption, horizon cover a wide range extending into the fifteenth century B.C. (See in this connection the comment by W. Cavanagh in n. 148 *infra*.) Judgment is critically required in the application of the calibration curve to uncalibrated radiocarbon measurements. Whereas

136 A further question may arise from the fact that it is sometimes difficult to distinguish "early LM IA" from "early Neopalatial," *i.e.*, MM IIIB or MM IIIB-LM IA transitional. The area of the site in which the piece of bark was discovered has not yet been published in detail.

137 See n. 23 *supra*.

138 The Aegean Long Chronology position according to the radiocarbon dates proposed for Trianda and for the sites of Akrotiri, Myrtos-Pyrgos and Chania discussed below is as follows:

End MM II	c. 1750 B.C.
MM III	c. 1750-1725 B.C.
LM IA	c. 1725-1600 B.C.
LM IB	c. 1600-1520 B.C., with late, post-major destruction, LM IB at Mochlos, Ayia Irini and Trianda perhaps lasting until 1450 B.C. and substantially overlapping with LM II in Central Crete.

139 S.W. Manning, personal communication of 26 June 2002, to whom I again express my thanks.

140 The problem of disparate radiocarbon dates from single contexts occurs with some frequency, and raises the question not only of the robustness of the system of measurement plus calibration correction, but also whether with regard to sample selection the chance of "throw-ups" from the digging of foundations or wells, or from reconstruction following earthquakes, outweighs the chance of post-depositional downward migration of samples in the archaeological record, both in general and in a particular context. Wood samples present a particular problem of possible reuse or long use. For a noteworthy discussion of radiocarbon analysis of wood in general, see MANNING (*supra* n. 94) 133-134.

141 The mid-nineteenth century B.C. is tied archaeologically to the Twelfth Dynasty in Egypt, the Assyrian Colony Period in the Near East and Middle Minoan II in Crete, as noted *infra*.

142 OxA-10623 in MANNING *et al.* (*Antiquity*, *supra* n. 4) table 1.

the two standard deviation, 95.4% bell curve confidence level is statistically always twice that of the one standard deviation distribution (*e.g.*, ±90 years vs. ±45 years), the calibrated distribution is often given as asymmetrical and depends on the judgment of the investigator. Even at the precalibration measurement stage, standard deviation bands omit pre-laboratory measurement sources of potential uncertainty involved in the process of selection and collection of samples.

The Manning *et al. Antiquity* paper next considers radiocarbon ages obtained from samples from Thera itself.[143] Out of the multitude of past measurements available, only four samples, the measurements from the Copenhagen laboratory, are selected, on the grounds that only these are likely to have been completely carbonized at the time of the eruption and subject to proper pretreatment. Even these samples present a problem, however, inasmuch as seeds from the same room (Room 6) of the same structure (the West House) destroyed at the same time in the volcanic destruction, give significantly disparate radiocarbon readings with broad probability bands for each sample.[144] At one standard deviation, 68% bell curve probability, the determinations support a seventeenth-century eruption date but by no means rule out a sixteenth-century one; at two standard deviations, 95.4% probability, seventeenth and sixteenth-century dates appear about equally plausible.[145] (On this very limited radiocarbon evidence, however, dates later than 1530 B.C. become progressively less likely, assuming that the Theran ^{14}C determinations do not suffer from any of the multiple problems or anomalies of radiocarbon dating discussed heretofore.)

The Manning *et al.* paper adds two new Theran Volcanic Destruction Level samples to the Theran dataset, a twig with three years' growth and another twig with six years, divided for analysis into three segments of two years each.[146] Except for the three-year twig, all the ^{14}C determinations fall within the area of the oscillating, or flattening, calibration curve.[147]

143 Doubts in general about ^{14}C determinations on samples from Thera are long-standing (P.E. NELSON, J.S. VOGEL and J.R. SOUTHON, "Another Suite of Confusing Radiocarbon Dates for the Destruction of Akrotiri," *TAW* III, vol. 3: Chronology, 197-206), and include references to the possibility of fumaroles emitting old gases and the possibility of an ocean reservoir impact–the so-called "island effect." No empirical data have been published to date in support of these suggestions, however. See also KEENAN (*supra* n. 130).

144 W.L. FRIEDRICH, P. WAGNER and H. TAUBER, "Radiocarbon Dated Plant Remains from the Akrotiri Excavation on Santorini, Greece," *TAW* III, vol. 3: Chronology, 193-195, table 3. Such a situation is not unique. Three seeds of barley from a covered jar found in the LM II destruction of the Unexplored Mansion at Knossos produced a wide range of radiocarbon ages which, when combined, produced a calibrated range of 1540-1310 B.C. at one standard deviation. M.R. POPHAM, *The Minoan Unexplored Mansion at Knossos* (1984) and P. WARREN, "The Aegean and the Limits of Radiocarbon Dating," *Acta Archaeologica* 67 (1996) 283-290.

145 I am indebted to S. MANNING for discussing the Theran Copenhagen measurements with me. See, in general, K.L. RASMUSSEN, H. TAUBER, N. BONDE, K. CHRISTENSEN and P. THEODÓRSSON, "A 23-Year Retrospective Blind Check of Accuracy of the Copenhagen Radiocarbon Dating System," *Radiocarbon* 41 (1999) 9-15; M. SCOTT, "Bias, Accuracy, and Precision," *Radiocarbon* 41 (1999) 221-222.

146 MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4) add eight determinations from Oxford (HOUSLEY *et al.* [*supra* n. 133]). Previously Manning had rejected the Oxford determinations, saying "the Copenhagen laboratory carefully and deliberately selected only fully carbonised seeds (three samples) and a twig of *Tamarix* with ten growth rings. FRIEDRICH *et al.* (*supra* n. 144) deserve great credit for recognizing the humic acid situation, and for adopting a deliberate strategy to avoid it. All other currently published samples are either known to be less than appropriate, or are not explicitly known to be fully carbonised–and so must be treated with suspicion" (MANNING [*Test of Time*, *supra* n. 4] 239). One of the Oxford measurements (OxA-1557) strongly supports the Short Chronology. As to this, Manning noted that "the Oxford laboratory produced some rather odd data. For example, in the Oxford data, it seems extraordinary that the date for normally processed OxA-1557 is 3240 ±60 BP, whereas the supposed 'residue' age (OxA-1692) for seeds from the same batch (2070) is 3325 ±60 BP, some 85 radiocarbon years older, despite the removal of the supposed older 'contaminant' (OxA-1693) aged 3420 ±60 BP which is a further 95 radiocarbon years older again! Such results simply do not make sense!" (p. 237).

147 MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4). Manning has argued that some of these ^{14}C determinations show a 60-40 probability in favor of the Long Chronology, on the ground that they intersect the oscillating calibration curve for thirty years consistent with the Long Chronology versus twenty years consistent with the Short (see MANNING [*Test of Time*, *supra* n. 4] 248, fig. 48), but all such statements are of course subject to the cautions stated in regard to the determination of probability, the construction of the calibration curve, the small size of the dataset, and the problems inherent in radiocarbon dating in general.

Manning *et al.* note that the measurement of the three-year twig gives a radiocarbon age earlier than the point where the oscillation in the calibration curve begins, and accordingly the measurement of this single sample clearly supports the Long Chronology. A significant number of radiocarbon determinations with this result from various areas of the Volcanic Destruction Level at Thera would indeed present a strong case for the Long Chronology, but a single determination from one twig must be treated with caution in view of the inherent uncertainties in the radiocarbon measurement and calibration process. A substantial number of similar determinations from short-lived material would be required before a convincing radiocarbon case could be made for the Aegean Long Chronology on the basis of Theran samples.[148]

The final datasets examined in the Manning *et al.* (*Antiquity*) and Manning and Ramsey papers are ^{14}C dates from seeds from Myrtos-Pyrgos and Chania in Crete from Late Minoan IB destruction contexts. Proponents of the Aegean Short Chronology have generally placed these destructions after the accession of Tuthmosis III c. 1479 B.C. on the Egyptian Middle Chronology, in light of the similarity of objects depicted on the walls of Egyptian tombs during his reign and objects typical of Neopalatial Crete in LM IB.[149] The potential problems posed for radiocarbon dating of material with a very brief growing season by intra-year atmospheric radiocarbon seasonality were noted above. Several seed caches stored together from the same harvest, perhaps gathered the same day, may reflect the same atmospheric carbon and local absorption conditions, and in this respect provide one datum point, not several. The eight seed cluster samples of barley and bitter vetch collected from an LM IB destruction level at Myrtos-Pyrgos provide a classic example. All of the seeds were found in a covered jar, the best conceivable archaeological context, since none of the seeds is likely to have fallen from thatch in a roof of earlier date. All of the seeds, however, were probably collected at the same time or at points close in time. Moreover, the Myrtos-Pyrgos seed determinations, if considered separately from the Chania determinations, could easily accommodate a calibrated date c. 1470-60 B.C.,[150] consistent with the Short Chronology.

The final set of ^{14}C determinations analyzed by Manning *et al.* (*Antiquity*) come from seeds of barley, bitter vetch and peas found at Chania in western Crete. The eight seed clusters measured produced a rather wide span of uncalibrated dates. For this, Manning *et al.* (*Antiquity*) offer a singular explanation:

148 William Cavanagh, co-author of C.E. BUCK, W.G. CAVANAGH and C. D. LITTON, *Bayesian Approach to Interpreting Archaeological Data* (1996), kindly responded to my request for comments on this paper by stating that he concurred with the foregoing analysis of the article in *Antiquity* by MANNING *et al.* (*Antiquity*, *supra* n. 4). Dr. Cavanagh added the following comment, for which I am most grateful:

"In plotting the length of LM IA against the end date at Trianda, MANNING *et al.* suggest that 'the *most probable* fit is an LM IA end date of 1610-1590 B.C.' This is misleading and rather like quoting the mean ^{14}C date without its standard deviation. It may be the mode of the distribution, but the probability that the phase-length/phase end falls outside the indicated area appears to be over ninety percent. In fact, one standard deviation covers a very wide range descending well into the fifteenth century B.C. in calibrated years. Hence their analysis in no way rules out the Aegean Low Chronology.

"Similarly, with regard to their Bayesian analysis based on the Trianda early LM IA data and the Akrotiri Volcanic Destruction Level data, there again seems to be a strong one sigma region in the sixteenth century B.C. Accordingly, I am puzzled and not entirely happy about stressing the modes of probability distributions rather than the one or two sigma ranges which are standard when discussing ^{14}C dates. All-in-all, I do not see that these results can rule out a date for the Volcanic Destruction Level at Thera in the earlier part of the range 1560-1480 B.C., although a date after about 1530 becomes increasingly difficult on these data.

"In addition to the Bayesian analyses, MANNING *et al.* also introduce 'wiggle-matching,' here using the term not in its usual sense as covering a known sequence of dated tree rings, or even in the looser sense of referring, for example, to a stratified sequence of sediments for which the sequence of deposits is known and an estimate can be made of the intervals between the sediments. In the best of circumstances and using a good sequence of dates, there are real dangers in using highly subjective visual matching of graphs (the method used here) or *ad hoc* statistical methods based on least squares. In brief, I think the wiggle-matching argument must be viewed with serious reservations."

149 WARREN and HANKEY (*supra* n. 4) 138-144; H. MATTHÄUS, "Representations of Keftiu in Egyptian Tombs and the Absolute Chronology of the Aegean Late Bronze Age," *BullInstClSt* 40 (1995) 177-194.

150 HOUSLEY *et al.* (*supra* n. 126) 161; MANNING *et al.* (*Antiquity*, *supra* n. 4) 737, 741-742.

> [T]here is significant internal variation within the set from 3208 to 3338 BP in the new data (3150 to 3380 BP in the previous data), although the actual *calendar* age of the samples should be close to identical. The unique explanatory solution to these two observations is that the Chania data must derive from a year or two during the short but dramatic gradient in atmospheric $^{14}CO_2$ levels c. 1525-1515 BC.[151] (See Pl. LXXb)

An obvious question arises: is the "short but dramatic gradient" in the calibration curve which provides the "unique explanatory solution" for the placement on the curve of the Myrtos-Pyrgos and Chania measurements the result of a dramatic decadal change in atmospheric radiocarbon, or of a calibration curve aberration based on a wayward single measurement from one log for the decade in question? Inquiry reveals that the "dramatic gradient" in the calibration curve is an illusion. Paula Reimer (one of the principal authors of the 1998 INTCAL98 calibration curve) has replied to a request for information on this point by stating that "the steepness of the calibration curve between 1515 and 1525 B.C. is partly due to one bidecadal measurement by Belfast on Irish oak" which lowers the overall decadal measurement critically, notwithstanding the fact that the German oaks are weighted more heavily. Pl. LXXIc, provided by Dr. Reimer, depicts the position of this single radiocarbon determination outside the probability band which constitutes the calibration curve, and the effect of this single measurement on the slope of the curve. Recent reexamination of the Irish oak by Reimer at the Lawrence Livermore National Laboratory and McCormac at Queen's University Belfast has confirmed that the earlier bidecadal measurement centered at 1510 B.C. is anomalous. Dr. Reimer concludes that "the steep slope disappears." The next revision of the international calibration curve will incorporate this correction.[152]

The analysis by Manning *et al.* (*Antiquity*) concludes that:

> If the calendar gap between the Chania and Myrtos-Pyrgos destructions of the end of LM IB is non-existent to short (0-5 years), then the Myrtos-Pyrgos destruction best fits around 1519-1512 BC; if the gap was longer, then the Myrtos-Pyrgos destruction progressively lies later on the effective plateau in the calibration curve c. 1515-1455 BC.[153]

Even on this hypothesis (disregarding the fact that the two standard deviation span of the radiocarbon determinations for each of the four new Chania seeds measured ranges from ±52 to ±54 years, the possibility that any of the seeds measured from Chania could have been burned in an earlier fire, the chance of partial initial carbonization resulting in contact or pretreatment problems, and the requisite correction to the calibration curve just described), there is no difficulty in accommodating the probability distribution posited within the Aegean Short Chronology.[154]

None of the other LM IB destruction context radiocarbon measurements in Crete, the Cyclades or Dodecanese, moreover, have produced dates as early as those from Chania, a fact which Manning and Ramsey recognize as troubling.[155] Finally, even accepting all of the assumptions of the Manning *et al.* argument while deleting the wayward calibration curve measurement produces a best (if by no means conclusive) fit of the Myrtos-Pyrgos and Chania

151 MANNING *et al.* (*Antiquity, supra* n. 4) 741.

152 E-mail messages of 17 May 2002 and 7 February 2003 for which I am deeply indebted.

153 MANNING *et al.* (*Antiquity, supra* n. 4) 741.

154 In terms of the historical context, it perhaps should be noted that even if the mature or final LM IB destructions at Myrtos-Pyrgos and Chania which ended LM IB occupation in the area are the work of a common and likely Mycenaean enemy it does not necessarily follow that they occurred in the same five-year span. Driessen and MacDonald propose an LM IB period with successive destructions (J. DRIESSEN and C.F. MACDONALD, *The Troubled Island: Minoan Crete before and after the Santorini Eruption* [1997]). J.A. MacGillivray (personal communication) has observed in this connection that the great Ottoman force of 100 warships and 50,000 troops which landed in the west of Crete in 1645 required more than another twenty years to subjugate Candia. Another fifty years was required for the subjugation of east Crete. P. Warren (personal communication) has noted that conversely it took Metellus Creticus only three years to complete the Roman conquest of Crete.

155 MANNING *et al.* (*Antiquity, supra* n. 4) 741-742 and MANNING and RAMSEY (*SCIEM2000, supra* n. 4).

LM IB destruction radiocarbon measurements around 1490 B.C., compatible with even the original Warren and Hankey proposed date of 1530-20 B.C. for the end of LM IA and the Theran eruption.

In sum, there exist today only a limited number of high caliber Late Minoan I and Late Cycladic I radiocarbon measurements in relation to the span of time involved, too limited in amount and ambiguous in result to build a firm radiocarbon argument for the Aegean Long Chronology. Future work, of course, may alter this picture.

The current version of the Aegean Long Chronology requires the extension of the LM IA period for thirty-five to fifty-five years after the eruption of Thera (from a presumed eruption date c. 1645 B.C. to a transition from LM IA to LM IB between 1610-1590 B.C.) and an LM IB period in Crete of at least sixty-five to ninety-five years, with the mature LM IB destructions placed between 1525-1515 B.C. as noted above.[156] Manning and Ramsey further propose a "late Late Minoan IB" phase continuing at Ayia Irini in Keos, Trianda on Rhodes, and Mochlos on the north-northeast coast of Crete until 1460-1430 B.C. (overlapping LM II in Central Crete).[157] LM IB including the proposed late phase would thus have a duration of between 130 and 180 years (1610-1590 to 1460-1430).

Each proposition is highly problematic in archaeological terms. As to the proposed extension of LM IA, the excavation of Mochlos has disclosed structures with LM IB pottery in foundation deposits directly over the tephra, turned to fine sand, from the eruption. While an abandonment for ten to twenty years after the eruption might be undetectable in the stratigraphy of the site, an abandonment of thirty-five to fifty-five years would in all likelihood be observable by an excavation focused on this central issue, as was the case at Mochlos.[158] The excavators of Palaikastro on the east coast of Crete also believe that LM IB follows closely on the eruption.[159] It is difficult to believe that the marine motifs of the Volcanic Destruction Level at Thera can be separated by fifty years from the very similar motifs of the Marine Style pottery of LM IB Crete.[160] That three generations or more could separate the administrative use of the same Minoan gold ring as evidenced by its impressions, originally attached to parchment documents, found in the LM IA Volcanic Destruction Level at Thera and in what appear to be final LM IB destruction levels on Crete is possible, but does not seem

156 MANNING *et al.* (*Antiquity*, *supra* n. 4) and MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4).

157 MANNING and RAMSEY (*SCIEM2000*, *supra* n. 4) . See J.S. SOLES in R.A. TOMLINSON, "Archaeology in Greece 1995-96," *AR* 42 (1996) 46. Both Mochlos and Psiera on the north coast of Crete appear to contain a post-canonical LM IB destruction stratum marked by continuing use of LM IB decorative motifs on pottery including pottery differing somewhat in shape from that of the prior LM IB destruction level. The frequency of various pottery types differs as well. The succeeding phase sees the arrival of vessels known from Knossos in LM II-IIIA1 such as Ephyraean goblets. (I am grateful to P. Betancourt for providing the foregoing information.) Accordingly it is important to establish the precise stratigraphical position of the carbonized samples from the "LM IB destruction" at Mochlos. Palaikastro in east Crete appears to have suffered a second destruction when east Cretan LM IB wares were in use but LM II pottery had already appeared, including an Ephyraean goblet from central Crete (J.A. MACGILLIVRAY, "The Re-occupation of Eastern Crete in the Late Minoan II-IIIA1/2 Periods," *La Crète mycénienne. Actes de la Table Ronde internationale organisée par l'École française d'Athènes [1991]* BCH suppl. XXX *[1997]* 275-278). MacGillivray also cites R.C. BOSANQUET, "Excavations at Palaikastro," *BSA* 9 (1902-1903) 274-387. The LM IB destruction at Myrtos-Pyrgos marks the abandonment of the site; the LM IB destruction at Chania, with its similar pottery including examples of late LM IB Alternating Style, marks a major destruction not followed by further LM IB pottery.

158 J.S. SOLES and C. DAVARAS, "Theran Ash in Minoan Crete: New Excavations on Mochlos," *TAW* III, vol. 3: Chronology, 89-95; J.S. SOLES, S.R. TAYLOR and C.J. VITALIANO, "Tephra Samples from Mochlos and Their Chronological Implications for Neopalatial Crete," *Archaeometry* 37 (1995) 385-393. See also P. WARREN, "LM IA: Knossos, Thera, Gournia," *MELETEMATA*, 893-903, presenting evidence from the recent excavations at Knossos seen as supporting only a brief post-eruption extension of LM IA and a total LM IA period of not more than a century.

159 The excavators also suggest that a major flooding episode in MM III may mark the 1650 or 1628 event, a sequence consistent with the Aegean Short Chronology (J.A. MACGILLIVRAY, L.H. SACKETT and J.M. DRIESSEN, "Excavations at Palaikastro, 1994 and 1996," *BSA* 93 [1998] 240-242).

160 L. MORGAN, *The Miniature Wall Paintings of Thera: A Study in Aegean Culture and Iconography* (1988) 34-38.

likely. Paintings from closely datable Theban tombs of Egyptian nobles show Aegean-looking emissaries carrying objects similar to those known from LM IB destructions, and metal vessels of types known in LM IA/LH I, in tombs built no earlier than c. 1460 B.C. on the Egyptian Middle Chronology, and perhaps as late as 1435 B.C., whereas depictions of metal vessels known from the Aegean in LM II/LH IIB and IIIA1 contexts are depicted in tombs beginning around 1440 B.C. The Aegean Long Chronology would require one of several possible explanations: that the objects are heirlooms; that they remain in circulation as gifts exchanged between Near Eastern and Egyptian courts for decades; that emigré Aegean metalsmiths continue producing objects, shapes and decorative motifs no longer employed in the Aegean; or that old pattern books are used by the tomb painters.[161]

The summary of archaeological evidence for the date of the eruption presented earlier in this paper notes that the Aegean Long Chronology requires a minimum gap of 130 years between the latest possible date for the manufacture of a WS I bowl in Cyprus and the earliest appearance of WS I pottery in Egypt or in definable contexts in the Near East. The comparison does not depend on one bowl, however, since tomb assemblages in northwest Cyprus contain WS I pottery in association with LM IA pottery typical of the type which marks the Theran Volcanic Destruction Level. Moreover, the chronological argument does not rest on one ceramic type, but covers a long range of styles which appear in the same stratigraphic sequence at Tell el-Dab'a in Egypt as they do in Cyprus and in the Near East at sites stretching from Alalakh to Tell el-'Ajjul.

Thus, even if it were clearly evident that the limited number of high resolution, secure context and treatment, radiocarbon measurements presently available favor the Aegean Long Chronology notwithstanding the many ^{14}C problems noted, there would remain the task of weighing the radiocarbon evidence together with the ice-core evidence as it stands against the well-constrained Egyptian chronological data and its archaeological correlates, where the evidence strongly favors the Aegean Short Chronology. It is ironic that an ice core and radiocarbon-based retreat from the 1628 B.C. date previously proposed for the Theran eruption in favor of a 1650-1643 B.C. range results in a higher date, which is even more difficult from the archaeological standpoint. The irony is compounded by the fact that it was the observation in the tree-ring record of a climatic event in 1628 B.C. in the bristlecone pines of California, later confirmed in the oaks of Ireland, England and Germany, combined with the absence of any indication in these trees of a later major climatic event in the relevant time frame, which provided a significant part of the initial impetus, together with the first publication of "early" Theran radiocarbon dates, for the Aegean Long Chronology.[162]

161 The appearance in early Eighteenth Dynasty contexts of imitations in local clay of Minoan rhyta of LM IA shape, about 100 years after the date proposed for the end of LM IA in Crete pursuant to the Aegean Long Chronology, is noted in footnote 42, *supra*. The identification of the types of Aegean metal vessels depicted in the Egyptian tombs has been made by H. MATTHÄUS (*supra* n. 149). See also C. MACDONALD, "Chronologies of the Thera Eruption" (review of S.W. MANNING [*Test of Time, supra* n. 4], *AJA* 105 [2001] 531). The MacDonald review also considers a number of other archaeological problems with the Aegean Long Chronology. Moreover, the Aegean Long Chronology requires in addition the extension of the Shaft Grave period at Mycenae well beyond the approximately three generations proposed by studies of the material from them (O. DICKINSON, "Arts and Artefacts in the Shaft Graves: Some Observations," *TEXNH*, 45-49; S. DIETZ, *The Argolid at the Transition to the Mycenaean Age. Studies in the Chronology and Cultural Development in the Shaft Grave Period* [1991]; G. GRAZIADIO, "The Process of Social Stratification at Mycenae in the Shaft Grave Period: A Comparative Examination of the Evidence," *AJA* 95 [1991] 403-440).

162 S.W. MATTHEWS, "What's Happening to Our Climate?," *National Geographic* (November 1976) 609-610; BETANCOURT and WEINSTEIN (*AJA, supra* n. 43). I thank S. Manning for calling my attention to the correspondence in time of these publications. MANNING *et al.* (*Antiquity, supra* n. 4) 742 and MANNING and RAMSEY (*SCIEM2000, supra* n. 4) contend that the radiocarbon probability bands viewed as a whole center on a range of 1650-20 B.C. for the event, independent of proposals based on ice-core and tree-ring evidence.

Further work will provide information on general problems of radiocarbon dating such as regional variability, local anomalies and long and short term temporal instability, as well as additional measurements on Aegean material. Dendrochronological research is ongoing, and it may be possible to analyze additional glass shards from the Greenland ice core. While awaiting further data from what are sometimes called the hard sciences, let us give due weight to the recent advances in Egyptian text-based dating and to the knowledge gained of chronological interconnections between Egypt, the Eastern Mediterranean and the Aegean world. There is wisdom still in the study of texts and pots. Perhaps one day there will appear in a secure Aegean context an object bearing the datable cartouche of a pharaoh, or in a secure Egyptian context a diagnostic Aegean artifact, thereby settling the current impasse between the Long and Short Aegean Chronologies once and for all.

I am indebted to a number of distinguished scholars for sharing their knowledge about the complex matters considered in this paper, and thank John Bennet, Philip Betancourt, Max Bichler, Alan Boegehold, Richard Brilliant, Hector Catling, William Cavanagh, Keith DeVries, Peter Fischer, Douglas Keenan, Kenneth Kitchen, Gero Kurat, Rip Rapp, Anthony Spalinger, Minze Stuiver, Ronald Wells, Paul Zimansky and, in particular, Claus Hammer, Peter Kuniholm, Maryanne Newton, Paula Reimer, Peter Warren and especially Sturt Manning for their advice and assistance. I am especially grateful to those who gave their unstinting assistance in spite of knowing that my views would not be fully compatible with theirs. I should also like to thank Jayne Warner and her assistants Marta Ameri, Jason Earle and Anna Russakoff for their indefatigable assistance in locating articles from publications difficult to obtain, in checking citations and in a myriad of ways.

Malcolm H. WIENER

Appendix
Problems of Measurement, Calibration and Probability in Radiocarbon Dating

Radiocarbon or ^{14}C is produced by cosmic rays in the stratosphere and upper troposphere, and is distributed through the atmosphere, oceans and other waters, and other carbon reservoirs. When an organism dies, carbon is no longer absorbed and the existing ^{14}C decays, with half disappearing in about 5,568 years (the current agreed international measurement of the "half-life"). Each annual ring of a tree absorbs carbon during the year in which that ring grows. If the age of a ring is known independently, the accuracy of the carbon age obtained can be checked, thereby providing the basis for calibration of radiocarbon dates.

Radiocarbon chronologies depend on the collection of sufficient appropriate samples from clearly defined contexts. ("One date is no date," says the proverb.) Today, high precision laboratories determine radiocarbon ages for the samples collected.[163] This process is by no means straightforward. For example, the longer the count, the greater the accuracy. A few ^{14}C samples have been "double-counted," which in radiocarbon parlance means not counted twice, but rather counted twice as long. There is, however, no standard protocol on counting time, since requirements will vary by laboratory method and by the sample analyzed. (Double-counting means generally double cost, as well as double use of limited accelerator or other equipment time.)

The process results in radiocarbon measurements incorporating a standard deviation assessment, partly theoretical and partly empirical, and hence partly subjective.[164] This standard deviation (generally about ±30 years for good samples measured in recent years at high-precision laboratories, particularly when double-counted) represents a 68.2% "probability" that the radiocarbon age falls within these parameters, on the assumption that the scatter pattern, or "noise," follows a standard bell curve ("Gaussian") distribution. This means, of course, that after accepting the assumptions required by the method, there is still about a one in three chance that the true radiocarbon age lies outside the one standard deviation band.

The next step is to adjust the radiocarbon ages obtained for any known systemic offset, such as the minus 41 ±14 years for Southern Hemisphere determinations recommended by McCormac *et al.* for all periods except the years A.D. 950-1850, where research indicates a fluctuating offset varying between 1 and 10%, or eight to eighty years, and a periodicity of fluctuation of 130 years. The recommended 41 ± 14 year offset represents the mean difference between radiocarbon age measurements of trees of known date in the Northern and Southern Hemispheres. Recognition of regional offsets is a recent phenomenon; until about a decade ago the prevailing assumption was that the distribution of atmospheric radiocarbon was largely uniform. Other regional, local, temporal or species-dependent offsets may await discovery.

The next stage is calibration, via comparison of the radiocarbon ages obtained by the laboratory with the radiocarbon calibration curve. The calibration curve currently employed by international agreement is the INTCAL98 curve.[165] The calibration curve, however, is not a true curve but an oscillating probability band, created by obtaining radiocarbon determinations from decadal or bidecadal sections of known absolute date from long-lived trees. Thus the calibration curve is itself an artificial construct, based (for the second millennium B.C.) on measurements of two sets of decadal samples of German oak and one bidecadal set of Irish oak. Erratic measurements are possible. For the decade 1525-1515 B.C., for example, the combined measurement, as a result of one apparently wayward determination on one Irish log, appears to be in error as noted above.

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163 "Basics of Radiocarbon Dating" (http://www.informath.org/Basic14C.pdf); AITKEN (*supra* n. 94) 56-119; MANNING (*supra* n. 94) 126-142.

164 MANNING (*supra* n. 94) 128.

165 STUIVER (*supra* n. 102). The history of calibration curves proposed and withdrawn is well described by MANNING (*Test of Time, supra* n. 4) 232-255 and MANNING (*supra* n. 94) 126-142.

It is of course apparent that in radiocarbon dating the term "probability" is used in a special sense quite distinct from its meaning in ordinary discourse. Manning notes that "routine radiocarbon dating and calibration are not straightforward, and are governed by inherent biases and preferences."[166] M. J. Aitken, the now-retired Director of the Oxford Radiocarbon Laboratory, concludes that "conversion to calendar date is confusing because of the irregular form of the calibration curve; the difficulty of translating error limits from one time-scale to the other is particularly acute and here we are inevitably in the hands of the statisticians."[167]

Readily available large-scale, cost-effective computer power now allows the utilization of computationally intense statistical approaches. In recent years Bayesian Probability Theory has been employed in the analysis of radiocarbon ages. Named after Thomas Bayes, an eighteenth-century mathematician, Bayesian analysis attempts to refine the data from the typical scatter of ^{14}C ages obtained from measurements of samples by establishing "boundary" conditions, permitting probabilities to be adjusted as contexts change.[168] The invocation of probability theory is in itself no guarantee of improvement in accuracy in radiocarbon dating; rather the manner of its application is critical. Employed cautiously where the database is sufficient and the archaeological justification clear, probabilistic analyses can potentially improve calibrated ^{14}C ranges. Manning states the position precisely:

> In basic terms, the method is very promising, and where there is real historical guidance, as in the case of Egypt, the objectivity rating goes up. Where there is no real basis other than intuition for the length of the calendar intervals between the dates to be matched, there is, however, the danger of self-fulfilling prophecy. The analysis of significant numbers of dates from a significant number of phases is the only way around this trap, as the more constraints, the more likely there will be only one 'right' fit or answer.[169]

166 MANNING (*supra* n. 94) 136.

167 AITKEN (*supra* n. 94) 93.

168 For example, because the lengths of the reigns of the Tuthmosside pharaohs are independently known, Bayesian boundaries could be established with respect to radiocarbon measurements securely attached to their successive reigns. As another illustration, consider the case of a burial or a destruction deposit containing a scarab of an Egyptian pharaoh. The date of the deposit cannot be earlier than the beginning of the reign of the pharaoh, although it may of course be later if the scarab is an heirloom. If the same deposit contains carbonized material which provides radiocarbon ages, some earlier than the beginning of the reign and some later, a Bayesian boundary may be invoked, and carbon ages earlier than the pharaoh's reign discounted in calculating the mean. The appropriateness of such a procedure, although at first impression obvious, is in fact not clear-cut, and is subject to the objection that it combines incommensurate realms. For example, if a closed deposit produces a range of ^{14}C measurements, and the high end is excluded for a reason such as that given in the example, the possibility remains that the low end is also faulty, but the problem is undetected because no known external boundary has been crossed. In such a situation eliminating some of the ^{14}C measurements obtained would skew the radiocarbon determination.
An excellent presentation of Bayesian analysis, notable for its clarity of expression, is provided in BUCK *et al.* (*supra* n. 148). Chapter 9 of the book (pp. 201-252) addresses directly the interpretation of radiocarbon results. See also C.E. BUCK, J.B. KENWORTHY, C.D. LITTON and A.F.M. SMITH, "Combining Archaeological and Radiocarbon Information: A Bayesian Approach to Calibration," *Antiquity* 65 (1991) 808-821. It is worth noting that Bayesian analysis has aroused controversy among statisticians (J.J. O'CONNOR and E.F. ROBERTSON, "Thomas Bayes," http://turnbull.dcs.st-and.ac.uk/history^/Mathematicians/Bayes.html), and has sometimes been applied in surprising contexts. For example, in A.D. 1763 cleric Richard Price presented a paper to the Royal Society arguing that Bayesian Theory, applied to the accounts of Biblical witnesses, established the probability of the literal occurrence of miracles described in the New Testament. Currently, Oxford Professor of the Philosophy of the Christian Religion Richard Swinburne contends that Bayesian Probability Theory indicates a 97% likelihood of the literal occurrence of the Resurrection (E. EAKIN, "So God's Really in the Details," *The New York Times* [11 May 2002] B9).

169 MANNING (*supra* n. 94) 141.

It is important to bear in mind that the current dataset of reliable Late Minoan I radiocarbon measurements is 1) small in relation to the span of time to be filled (about 300 years, from c. 1725 B.C. for early LM IA to c. 1425 B.C. for the end of "late" LM IB, according to proponents of the Aegean Long Chronology); 2) subject to the uncertainties, defined and as yet undefined, described in discussion of radiocarbon dating, *supra*; and 3) connected by wiggle-matching via Bayesian Probability Theory boundaries, none of which can be independently fixed in time, and none of which has a known distance in time from any other, although their temporal sequence (*e.g.*, pre- and post-eruption, or LM IA and LM IB) is known. Whether the application of Bayesian analysis can significantly increase the level of confidence in a dataset of this nature is open to question.[170] It may be appropriate here to recall the maxim: "When data require a heavy dose of statistics to explain what Mother Nature is doing, obtain more data."[171] Similarly, Minze Stuiver (the Founder and lifetime Director of the Seattle Radiocarbon Laboratory and lead author of the 1998 INTCAL98 standard international calibration curve that provides the basis for all the radiocarbon dates cited in the paper) has observed that in fifty years of working with radiocarbon determinations he has never known a case where disorderly underlying data could be rescued by complex statistical analysis.[172]

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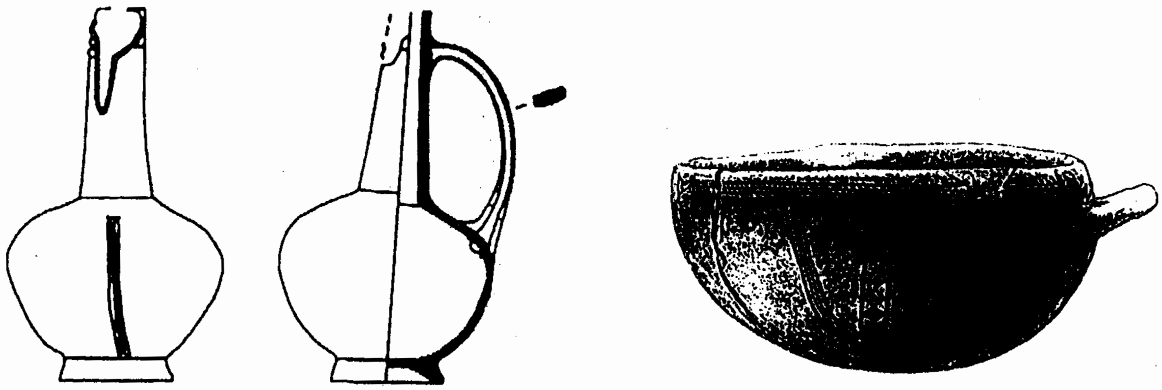
170 The absence from the article of a statistical appendix–*i.e.*, equations of the kind that uniformly accompany Bayesian analyses (see, *e.g.*, BUCK *et al.* [*supra* n. 148] 231 and BUCK *et al.* [*supra* n. 168] 820)–may strengthen the impression that it is the manner and terminology of Bayesian Probability Theory, rather than the substance, which is here deployed. Cf. n. 148, *supra*.

171 I thank S.E. Dunn for reminding me of this adage.

172 Personal communication, for which I am most grateful. Peter Warren, in kindly commenting upon a draft of this paper, reminded me of an important paper of his own published in 1996 (*supra* n. 144) which discusses problems of probabilistic analysis of ^{14}C dates in similar terms, and cautions that while "archaeological wiggle-matching may lead to better chronological understanding," the "ever more complex statistical manipulation of sample dates may convey a sense of unreality, with a failure to recognize sufficiently inherent limitations and sometimes deep problems in the data" (p. 283).

LIST OF ILLUSTRATIONS



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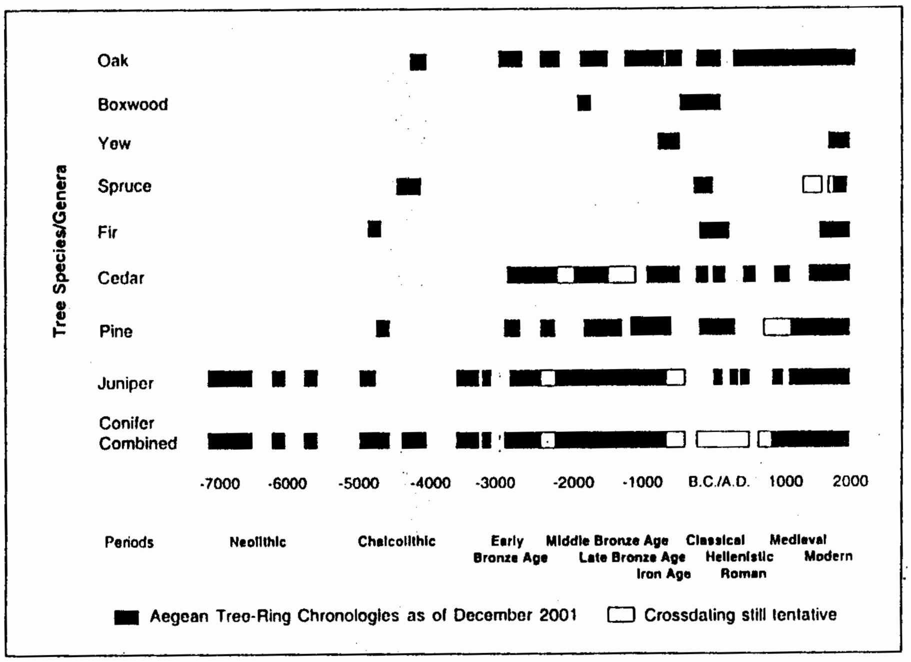
Tree Species/Genera
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Yew
Spruce
Fir
Cedar
Pine
Juniper
Conifer Combined
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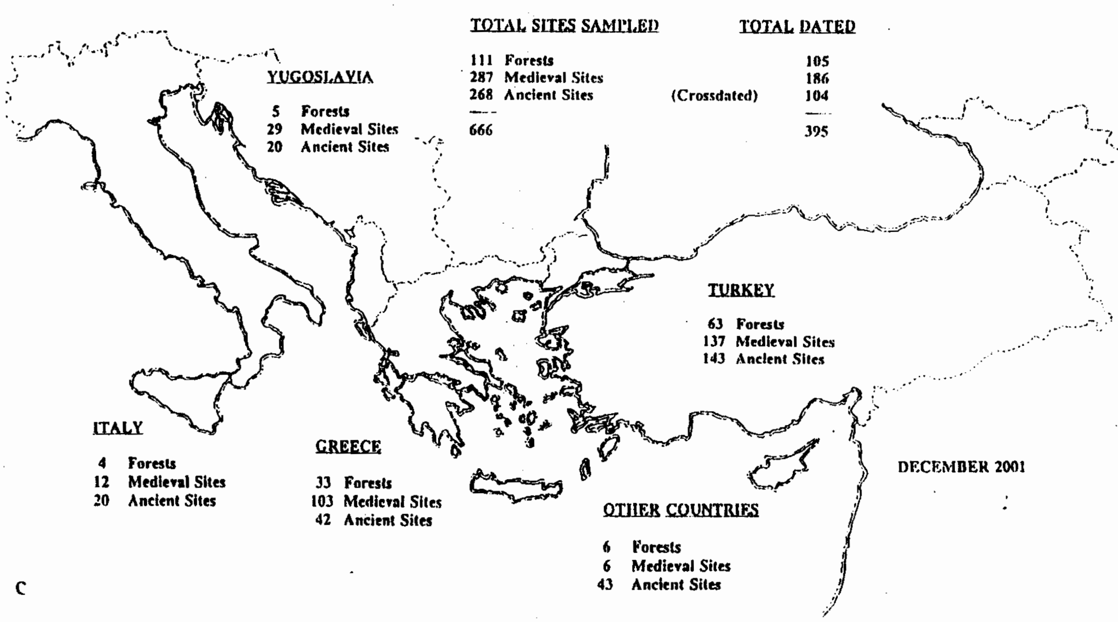
-6000
-5000
-4000
-3000
-2000
-1000
B.C./A.D.
1000
2000
Periods
Neolithic
Chalcolithic
Early Bronze Age
Middle Bronze Age
Late Bronze Age
Iron Age
Classical
Hellenistic
Roman
Medieval
Modern
Aegean Tree-Ring Chronologies as of December 2001
Crossdating still tentative

b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TOTAL DATED
111 Forests
287 Medieval Sites
268 Ancient Sites
666
(Crossdated)
105
186
104
395
YUGOSLAVIA
5 Forests
29 Medieval Sites
20 Ancient Sites
TURKEY
63 Forests
137 Medieval Sites
143 Ancient Sites
ITALY
4 Forests
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GREECE
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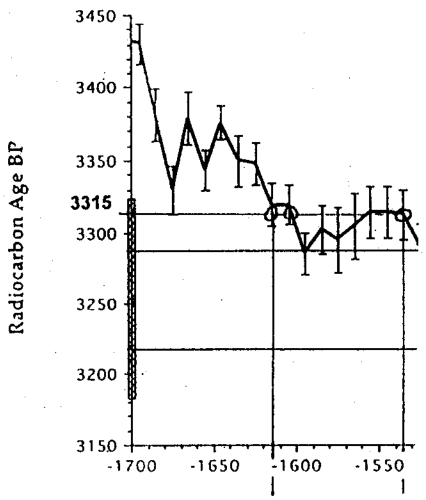
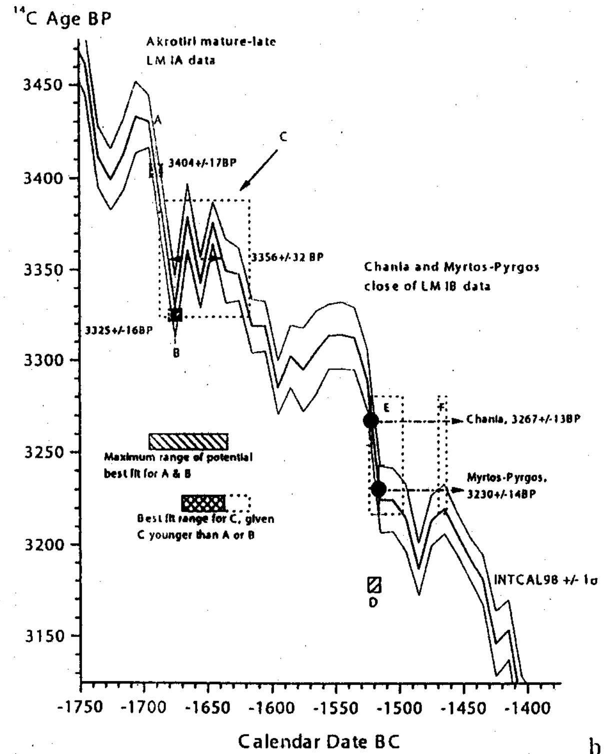
42 Ancient Sites
OTHER COUNTRIES
6 Forests
6 Medieval Sites
43 Ancient Sites
DECEMBER 2001

c



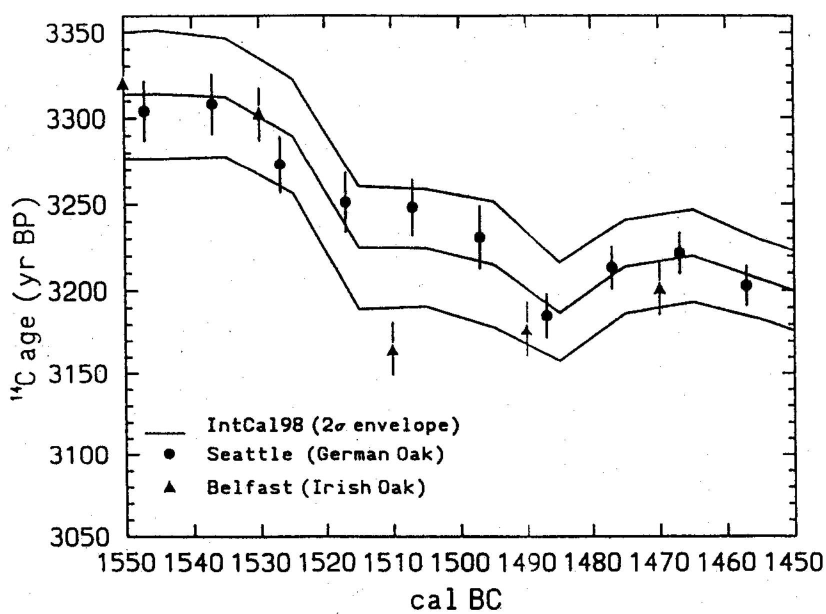
Radiocarbon Age BP
3450
3400
3350
3315
3300
3250
3200
3150
-1700 -1650 -1600 -1550
1615
1535

a



^{14}C Age BP
Akrotiri mature-late LM IA data
A
C
3404+/-17BP
3356+/-32 BP
3325+/-16BP
B
Chania and Myrtos-Pyrgos close of LM IB data
E
F
Chania, 3267+/-13BP
Myrtos-Pyrgos, 3230+/-14BP
Maximum range of potential best fit for A & B
Best fit range for C, given C younger than A or B
D
INTCAL98 +/- 1σ
3450 3400 3350 3300 3250 3200 3150
-1750 -1700 -1650 -1600 -1550 -1500 -1450 -1400
Calendar Date BC

b



^{14}C age (yr BP)
3350 3300 3250 3200 3150 3100 3050
IntCal98 (2σ envelope)
Seattle (German Oak)
Belfast (Irish Oak)
1550 1540 1530 1520 1510 1500 1490 1480 1470 1460 1450
cal BC

c

ABBREVIATIONS

Archanes	Y. SAKELLARAKIS and E. SAKELLARAKI, *Archanes: Minoan Crete in a New Light* (1997).
Emergence of Civilisation	C. RENFREW, *The Emergence of Civilisation: the Cyclades and the Aegean in the Third Millennium B.C.* (1972).
MELETEMATA	P.P. BETANCOURT, V. KARAGEORGHIS, R. LAFFINEUR, W.-D. NIEMEIER (eds), *MELETEMATA. Studies in Aegean Archaeology Presented to Malcom H. Wiener as he enters his 65th Year, Aegaeum* 20 (1999).
Minoan Architectural Design	D. PREZIOSI, *Minoan Architectural Design. Formation and Signification* (1983).
PM	Sir A. EVANS, *The Palace of Minos at Knossos,* vol. I-IV (1921-1935).
TAW III	D.A. HARDY *et al.* (eds), *Thera and the Aegean World III,* vol. 1-3, (1990).
TEXNH	*TEXNH: Craftsmen, Craftswomen and Craftsmanship in the Aegean Bronze Age, Proceedings of the 6th International Aegean Conference, Temple University (18-21 April 1996) Aegaeum* 16 (1997)
Urbanism	K. BRANIGAN (ed.), *Urbanism in the Aegean Bronze Age, Sheffield Studies in Aegean Archaeology* (2001).