Times Change: The Current State of the Debate in Old World Chronology

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Questions of chronological contemporaneity are at the heart of current discussions of the interaction and reciprocal influence between the early civilizations of the Mediterranean world. In order to consider such interactions, whether in the broad terms of world systems theory and core-periphery analysis or with respect to more precise modalities of interaction, it is necessary to establish what phase of Civilization A was in contact with what phase of Civilization B. No wonder, then, that chronology exercises its fascination. However, as Kenneth Kitchen has observed, chronology is not an academic discipline but a disease (Kitchen, pers. comm. of 1 February 2003, for which I am most grateful), or as I would say, an addiction, and indeed once one is hooked, it is hard to recover, whatever the cost to the historical work for which the chronological information was initially sought. Moreover, one pursues chronology knowing that whatever is said may be obsolete by the time it is published.

Chronological progress with respect to the ancient Mediterranean civilizations of the third and second millennia B.C. requires bridging the gap between the "two cultures", scientific and humanistic, described half a century ago by the British scientist, novelist and distinguished civil servant C.P. Snow. According to Snow, the two cultures existed in a state of mutual disdain and in almost total ignorance of the basic premises of the other (Snow 1959; 1967; see also Muhly 2003). In Old World archaeology and ancient history the problem has been particularly acute at times, with some practitioners trained in art history, classics and Near Eastern or Egyptian studies lacking basic knowledge of the strengths and limitations of the relevant sciences or of statistics. Conversely, many scientists working on archaeological material are unable to gauge the strengths or partial limitations of Egyptian and Near Eastern text-based dating, or the current state of understanding of Egyptian astronomy, or the reliability of data and interpretations from sciences other than their own. Indeed, even with the broad disciplines of Old World archaeology and linguistics, an information explosion has resulted in many cases in increasing specialization and concomitant difficulties in communication across geographic and material-based specializations. Communication shows signs of improvement, however, as archaeometry develops as a major subdiscipline and more students are trained in archaeological science. Growing sophistication in science among archaeologists is accompanied, however, by growing complexity and the arrival of information, some of potential critical chronological importance, from new and unfamiliar sources and sciences.

Egyptian Astronomy, Texts and Interconnections

It seems appropriate to begin a synopsis of the current state of the debate in Old World chronology with the first of the sciences harnessed to the task, astronomy, and in particular the astronomical dates from Egypt. These of course come in two forms: Sothic dates, *i.e.*, observations of the first rising of the dog star Sirius, and lunar dates, based in Egypt on the day when the crescent moon is no longer visible (unlike Babylonia where lunar dates are measured from the first visibility of the new moon). A recent paper by the late Patrick O'Mara casts doubt on the reliability of the basic critical assertion of Censorinus, an Egyptian third century A.D. Roman grammarian, who reported that a heliacal rising of Sothis had occurred on Egyptian civil new year's day in A.D. 139. O'Mara notes that the date asserted was the birthday of Censorinus' great patron and that, uniquely in this case, Censorinus gave no data to support his statement. O'Mara accepts another text, the Canopus Decree, but argues that the resultant Sothic dates can vary by twelve years (O'Mara 2003). The Sothic calendar question is primarily relevant to Middle Kingdom Egypt, because of the importance of the date proposed by Parker (1950) of 1872 B.C. for a heliacal rising of Sirius recorded on a particular date in the seventh year of Senwosret III. R. Krauss

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believes that the Parker date is untenable because the attributions of the Illahun lunar dates on which Parker based his computations were incorrect and that on the basis of lunar dates the seventh year of Senwosret III falls in 1831–30 B.C. Krauss' lunar calculations imply an end date for the Twelfth Dynasty of 1760–59 B.C. (KRAUSS, this volume).

Lunar dates remain controversial in some respects. Calculation of crescent visibility is difficult because of the complexity of the moon's orbit and the requirement of extreme accuracy – Kepler thought the computation of the exact time of conjunction impossible – and because of the difficulty of developing impartial criteria of visibility at various possible locations. R.A. Wells argues that the original Egyptian lunar observations yield so large a number of alternative readings and dates that no determinate calendrical system can be demonstrated. Recent experimental archaeology shows that it is difficult to obtain agreement among observers as to the day on which the old lunar crescent is no longer visible (WELLS 2002; 1992; SPALINGER 1992a). R. KRAUSS (this volume) remarks that the experiments in question did not involve experienced professional observers as would likely have been the case in ancient Egypt, but also notes that dust storms or overcast skies can make observations difficult, particularly at certain times of the year.

R. Krauss believes, however, that 1479 B.C. can be established as the precise year of the accession of Tuthmosis III with a high degree of probability. He argues that it is possible in almost all cases to eliminate many of the alternative interpretations of recorded lunar sightings stressed by Wells by virtue of their incompatibility with historical and other data at various points in the chain of dates which the discarded alternative readings would require (KRAUSS, this volume). Confirmation is found in a historical chain buttressed by astronomical observations from various reigns which R. Krauss believes requires an accession date between 1479–76 B.C. for Tuthmosis III on independent grounds (I am most grateful to R. Krauss for making his cogent analysis available to me prior to publication).

If, however, astronomical uncertainty could be shown to exist, how significant a difference would it make for Egyptian absolute chronology, particularly for the New Kingdom? Recall that without reference to astronomy K. Kitchen, by adding the last known regnal years of rulers and analyzing other data, was able to affirm an accession date for Ramses II not later than 1270 B.C. at the very latest, but more likely between 1274 and 1279 B.C. (KITCHEN 1987; 1996, 1–13; 2002, 9). This result fits independently-derived Assyrian/Babylonian regnal dates considered accurate to within about a decade back to 1400 B.C., which are securely connected to Egyptian chronology through correspondence between Egyptian and Near Eastern rulers (KNUDTZON 1915; MORAN 1992; RAINEY 1978; COHEN and WESTBROOK 2000; DIETRICH and LORETZ 1985; ROHL and NEWGROSH 1988; CAMPBELL 1964; ALBRIGHT 1975). The prevailing Near Eastern chronology, as set forth by Brinkman, positing an eight-year overlap between the reigns of Ninurta-apil-Ekur of Assur and Meli-Shipak of Babylon (BRINKMAN 1972, 272–273; 1976, 31–33) has recently received confirmation through the discovery at Assur of tablets containing correspondence between these rulers (FRAHM n.d.; Brinkman, pers. comm.). The Kitchen schema is also consistent with the date of 925/26 B.C. proposed by Thiele half a century ago for the invasion by Shishak in the fifth year of Rehoboam reported in the Hebrew Bible (THIELE 1983), a date which cannot be moved by more than about a decade given the secure date of 853 B.C. in the Assyrian annals for the battle of Qarqar during the reign of Ahab. R. Krauss believes that Egyptian lunar observations independently establish 926/25 B.C. as the date of the invasion by Shishak/Shoshenq I as set forth in his contribution to this volume.

Because the lunar date closest to 1270–79 B.C. for the accession of Ramses II was already believed to be 1279 B.C. on the earlier analyses of Krauss, von Beckerath and Hornung, Kitchen reasoned that one or more pharaohs or high priests might have ruled or served slightly longer than their last known year. He accordingly accepted 1279 B.C. for the accession of Ramses II, and hence 1479 B.C. for the accession of Tuthmosis III via a series of texts covering the intervening two centuries. These dates thus form the basis of the current standard, widely accepted Egyptian Chronology for the New Kingdom (KITCHEN 1987; 1992; 1995; 1996, 1–13; 2002). If the lunar dates could no longer be maintained as suggested by R.A. Wells, then it would seem preferable to cite the critical Tuthmosis III accession date as c. 1475 B.C., rather than as 1479 B.C. (K. Kitchen has kindly informed me that he concurs with this suggestion in a pers. comm. of 25 February 2003, for which I am most grateful). The difference is accordingly minor. It is, however, far from clear that any change is necessary, for if R. Krauss is correct, then 1479 B.C. remains the exact year for the accession of Tuthmosis III and hence constitutes the earliest exact year date for any civilization at the present time. (Astronomy apart, the earliest certain annual date established via continuous written records is the year 911 B.C. from the Assyrian annals.) Both K. Kitchen and R. Krauss concur that if the accession year of Tuthmosis III is 1479 B.C., then texts and inscriptions suggest c. 1539 B.C. as the most likely date for the accession of Ahmose and the beginning of the New Kingdom. The conquest of Avaris and the expulsion of the Hyksos from Egypt between the eleventh and twenty-second year of Ahmose, but more likely closer to the latter (BIETAK 1996, 81; BOURRIAU 1997, 159) would thus occur between 1528 and 1517 B.C., followed by the first campaign of Ahmose in the Near East, including his three-year siege of the important site of Sharuhen. The appearance of considerable numbers of New Kingdom artifacts in the Near East presumably follows these events in time (see below).

ICE-CORE DATING

Let us now consider proposals for dating the Aegean Bronze Age by recent scientific observations, beginning with the argument from the Greenland ice cores. Work at the frontier of science with respect to the difficult extraction of the cores, the counting of their annual laminations, and the chemical analysis of glass shards, each much smaller than the width of the human hair, has led Hammer *et al.* to propose that the eruption of Thera, in the mature-to-final phase of Late Minoan IA, can be dated to 1645 ±4 B.C. (HAMMER *et al.* 2001; 2003). While some have expressed surprise that ice-core dating could be so precise, Hammer and Clausen note that the layers have been counted separately by themselves and two students, and that the counting was repeated years later with the same results (HAMMER, pers. comm.). Moreover, the ice-core record contained shards identified as coming from the eruption of Vesuvius in A.D. 79 in an ice-core lamination counted to be only one year away from the known date. 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 (Hammer, pers. comm. of 21 March 2001, for which I am most grateful). Accordingly, it appears that the 1645 ± 4 B.C. date range for the glass shards in question is likely to be correct. Leading proponents of the Aegean Long Chronology at one point advocated combining this date range with the dates resulting from a proposed upward shift of 22 +4/–7 years in the dates for the Anatolian floating tree-ring chronology (see below) which would place the growth spurt evident in the logs from Porsuk near the Cilician Gates in 1650 +4/-7 B.C. (MANNING *et al.* 2001). A date between 1650 and 1643 B.C. for the eruption is consistent with both claims.

While the date of the particles in the Greenland core seems reasonably secure, the Theran origin proposed for these glass shards is not. Only volcanic shards no larger than a few microns are light enough to reach Greenland from Thera before falling out of the stratosphere, but such minute particles are challenging to source chemically with sufficient precision to distinguish between similar eruptions, although it is possible to exclude clearly dissimilar sources. (See HAMMER *et al.* 2003; KEENAN 2003; PEARCE *et al.* 2004.)

It is clear from the papers cited that the terms of discussion have moved considerably since the presentation of the "Extended Abstract" by HAMMER *et al.* (2001) at the 2001 SCIEM EuroConference, which should not be regarded as surprising given the enormous challenge presented by the task. Proponents of the identification of the Greenland glass shards as Theran no longer believe that similarity in the bulk elements supports the proposition, or that a similar europium anomaly exists in the Theran and Greenland shards, but rather that the abundances of the remaining rare earth elements, with the exception of strontium, are sufficiently similar to constitute compelling evidence for Thera as the source of the Greenland shards (HAMMER *et al.* 2001; 2003). D.J. Keenan contends, however, that the similarities are no greater than those between the Greenland shards and tephra from the eruption of Toba in Indonesia in 75,000 B.P. with respect to the twelve Toba rare earth elements tested, and moreover, that differences in composition in four of the bulk elements between the Greenland and Theran shards preclude Thera as a likely source (Keenan, pers. comm. with accompanying data, for which I am most grateful; now see KEENAN 2003. For the Toba eruption, see PEARCE *et al.* 1999). The Dawson eruption in Alaska about 25,000 years ago also produced very similar tephra (PEARCE *et al.* 2003; KEENAN 2003). Indeed, the empirical evidence suggests that massive rhyolitic mantle-sourced eruptions tend in general to produce tephra with similar rare earth element compositions (KEENAN 2003).

PEARCE *et al.* (2004) after detailed study also declare that the dissimilarity in chemical constituents shows that the Theran eruption was not the source of the Greenland shards. Indeed, Pearce *et al.* go further, concluding that not Thera but Aniakchak in the Aleutian Chain, which experienced a mid-second millennium B.C. eruption, is the highly likely source of the Greenland shards on the basis of extremely close similarity of chemical composition (see also WIENER

2003, 875–876, n. 65; for Aniakchak see BEGÉT *et al.* 1992). S. Manning has kindly informed me that in light of the recent analysis he regards the ice-core data as irrelevant to the date of the Theran eruption (pers. comm., for which I am most grateful; see MANNING, this volume; RAMSEY *et al.* 2004).

A program of analysis of all glass shards in the ice-core record for the period between 1650 and 1500 B.C. would be desirable, but even a massive eruption would not necessarily leave an acidity signal on every square meter of Greenland (WIENER 2003; ROBOCK 2000 and pers. comm., for which I am most grateful; ROBOCK and FREE 1995).

DENDROCHRONOLOGY

The potential contribution of dendrochronology to Old World chronology is evident. Because of the century-long history of data collection and analysis in the southwest United States, excavators of Native American sites sometimes know the exact year each room in a building and each building at a site was constructed. It has even been possible in some instances to determine which communities shared common logging areas, and which did not (NASH 2000, 60–82). In England, Ireland and Germany, trees with recognizable overlapping years because of similar weather patterns enable us 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 Classical era and particularly during the Roman Empire, when the wood used was imported from the entire Roman world from the Baltic to the Levant and hence often reflects climate patterns that cannot be compared. A "floating chronology" has been constructed, however, that forms a continuous sequence from the twenty-seventh to the seventh century B.C., incorporating at its core a 1,028-year sequence of juniper logs from Gordion and including the juniper from Porsuk previously mentioned. The absolute dates of the floating chronology are now fixed in all likelihood to within +8/–10 years, as established by a comparison between fifty-two decadal radiocarbon determinations from the Anatolian junipers and the 1998 international calibration curve (INTCAL98) which is based on measurements of German and Irish oak, and by the fact that component parts of the Anatolian sequence end in closely dated historical contexts at Gordion in Phrygia and particularly at Ayanis in Urartu (NEWTON and KUNIHOLM 2004).

A prior suggestion that the floating chronology could be anchored absolutely by the appearance in the Anatolian sequence of tree-ring events 469 years apart, just as in the oaks of Ireland and England where the events are dated to c. 1628 and 1159 B.C., has been withdrawn in light of subsequent research (MANNING 1999, 313–314; 2004b; MANNING *et al.* 2001; RENFREW 1996). The event previously placed at c. 1159 B.C. has not been found in logs subsequently examined, indicating that the event may have been local. Moreover, radiocarbon measurements of the Anatolian juniper sequence by Manning, Kromer, Kuniholm and Newton against the European oak-based INTCAL98 calibration curve determinations and against their own measurements of German oak for the seventeenth and sixteenth centuries B.C. led to the conclusion that a better fit is obtainable by shifting the Anatolian floating sequence back 22 +4/–7 years, as described above. The adjustment would shift the previously proposed date for the major growth spurt experienced by all sixty-one of the Porsuk trees from the year 1628 B.C. to 1650 +4/–7 B.C. (MANNING *et al.* 2001). The result would thus fit the proposed date for the appearance of the glass shards in the Greenland ice core (whose relevance to the Theran eruption, however, is now widely debated, even by its former proponents, as noted above), while removing the Anatolian floating chronology from the 1628 B.C. date for a major climate event reflected in tree rings in the pines of California and the oaks of Germany, Ireland and England, previously identified with the Theran eruption by proponents of the Aegean Long Chronology, but now also deemed by most to be irrelevant (MANNING and SEWELL 2002; MANNING, this volume). Dendrochronological research thus far has revealed no indication of a significant growth anomaly in the trees of California, Ireland, England or Germany around 1650–40 B.C. While the Greenland Ice Core Project (GRIP) ice core witnesses a volcanic event around 1626 B.C., the signal is clearly much less pronounced than the 1645 ±4 B.C. event (CLAUSEN *et al.* 1997). It should be noted, however, that the magnitude of an acidity spike is only loosely correlated to the Volcanic Explosivity Index (VEI) of the eruption causing the spike (KEENAN forthcoming, 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 (ROBOCK 2000). Similarly, it now appears doubtful that any of the B.C. events visible in the Irish oaks are the result of volcano-induced weather anomalies (MANNING and SEWELL 2002; Manning, pers. comm. of 17 February 2003).

As to the growth spurt in the Porsuk trees now placed at 1650 +4/–7 B.C., however, Kuniholm argues that whatever the effects of the Theran eruption elsewhere, the trees used at Porsuk, 820 km. downwind of Thera, would probably have responded to the additional moisture resulting from rainstorms caused by the eruption. The local effects of non-local eruptions can vary significantly, however. The logs of Gordion, from a semi-arid zone in Anatolia where additional moisture might be expected to have a significant effect, do not show any unusual effect near this date (KUNIHOLM *et al.* 1996, 780–782; Kuniholm and Newton, pers. comm. of 19 November 2002, for which I am most grateful). Of course the identification of the Aniakchak eruption as the source of the glass shards in the Greenland ice core at 1645 ±4 B.C. suggests the possibility that the Porsuk log growth spurt of 1650 +4/–7 B.C., if caused by a weather-forcing volcanic event, may possibly be attributable to this Alaskan eruption also. Recent work on the Porsuk dating, however, suggests that there may be no overlap in dates (1653–50 B.C. best dates for Porsuk anomaly, 1645 ±4 B.C. for Aniakchak [Kuniholm, pers. comm.; Manning, pers. comm.]). It is particularly worth noting that the raising of the Porsuk logs' last ring dates to 1573 +4/–7 B.C. (pursuant to the revised radiocarbon/historical analysis discussed above) also removes the Porsuk evidence from the argument of silence against a post-1570 B.C. eruption of Thera consistent with the Aegean Short Chronology.

To date no indication of a growth anomaly possibly related to a volcanic eruption has been reported in the trees of Ireland, England, Germany or California for the period 1570–1470 B.C. (The initial California bristlecone pine database was severely limited with respect to the number of trees and extent of area examined for the relevant period [LAMARCHE and HIRSCHBOECK 1984]. 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].) 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, but further research and reflection have led to reconsideration of the value of this negative dendrochronological evidence. It is now well understood that many factors other than the degree of explosivity affect whether an eruption is represented in the tree-ring record. These 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 or 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 and condition of the trees at the time of the event (GRATTAN 2002; JACOBY 2002; BRUNSTEIN 1996; IRWIN and BARNES 1980; ALLARD *et al.* 1991). Conversely, many non-volcanic climate – and weather – related factors, including highly local conditions, can cause growth spurts or interruptions in trees.

RADIOCARBON DATING

Recent years have seen major progress in the science and art of radiocarbon dating. Improved techniques of measurement at high precision laboratories, including lengthened counting periods at accelerator mass spectrometry facilities and periods of measurement of up to ten days at radiometric measurement laboratories where feasible and affordable, more stringent pretreatment protocols, and increased cooperation between laboratories to reduce inter-lab measurement discrepancies, have all contributed to a narrowing of proposed date ranges published, which after calibration combine statistical and judgmental factors (KROMER *et al.* 2001, 2530; see in general SCOTT 2003, esp. 287; MANNING 2004a; forthcoming).[1] Within the past decade, however, high precision laboratories have

[1] The "State of Research" is well described by O. CICHOCKI *et al.* (2003, 102): "In order to measure radiocarbon ages it is necessary to find the amount of radiocarbon in a sample. This can be achieved either by measuring the radioactivity of the sample (the conventional beta-counting method) or by directly counting the radiocarbon atoms using a method called accelerator mass spectrometry (AMS). The main advantage of AMS over the conventional beta-counting method is the much greater sensitivity of the measurement. In AMS the radiocarbon atoms are directly detected instead of waiting for them to decay. The physical sample sizes required are typically 1000 times smaller, allowing much greater choice of samples and enabling very selective chemical pre-treatment. However, handling small amounts of sample material increases the danger of contamination. Since minute additions of non-genuine carbon can lead to

sometimes provided quite different date ranges for materials divided between them, as in the case of the reported dates a century apart for the Turin Shroud as well as for the control material of known first century B.C./A.D. date (TAYLOR 1997, 84–85). Examples of recent and more limited inter-laboratory measurement differences are provided in Manning (2004a). Some high precision laboratories acknowledge slight ongoing biases, *e.g.*, "a conservative upper limit of an additional unknown laboratory error in the Heidelberg facility is eight radiocarbon years" (KROMER *et al.* 2001, 2530).

The one standard deviation bands in which both radiocarbon ages and calibrated dates are normally stated (pursuant to the conventional Gaussian bell curve distribution) by definition provide only a 68% statistical chance of encompassing an accurate radiocarbon age or calibrated date under the best of collection and pretreatment circumstances. While the two sigma, 95% probability, bands for uncalibrated ^{14}C ages are twice those of the one sigma bands – *e.g.*, sixty years instead of thirty years – the calibrated bands quoted take into account various factors, including the number and duration of determinations, their precision (*i.e.*, similarity to one another) and the nature of their fit to the calibration curve. Such judgments are necessarily partly subjective (see *e.g.*, MANNING 1995, 126–129) and are sometimes open to dispute (WIENER 2003).

All statements of probability made in the course of analyzing ^{14}C determinations refer in the end to the degree of overlap between the one or two sigma ranges of radiocarbon determinations from selected samples of seeds or wood and the one or two sigma ranges of decadal calibration curve measurements taken from trees of known dates, both of which are subject to the uncertainties of regional variation, intra- and inter-year variation, and the potential presence of old carbon. The probabilities presented are, however, only measurement probabilities, not date probabilities (see *e.g.*, VAN DER PLICHT and BRUINS 2001), contrary to what readers or conference participants unfamiliar with the discourse of dating by radiocarbon may surmise. A measurement of the last rings of recently cut Theran wood which produced a ^{14}C age of 1,390 years was a high precision determination of high probability that correctly measured the overall carbon present, which included ^{14}C-depleted carbon absorbed from a nearby fumarole (BRUNS *et al.* 1980), thereby providing a wholly erroneous date.

A. GILBOA and I. SHARON (2003, 60, n. 14) observe that:

"*Precision is not the same as accuracy*. The ± figure provided by the lab with radiometric dates merely denotes the internal variation, *i.e.*, the standard deviation of a number of individual counting-periods on the same vial or accelerator runs on the same target. There are a host of other factors that could (minutely) affect the result: the microenvironment around the sample in the ground; postrecovery storage conditions; differences in chemical protocols for pretreatment; differences in the counting protocols; differences in equipment and its calibration, etc. Some of these sources of possible error are removed in the cleaning process or are neutralized by the appropriate use of standards and backgrounds (blank samples) – but are all? These issues are the subject of ongoing investigations. Finally, even when different labs do agree, the calendar age depends to a large extent on the accuracy at which the calibration curve for the relevant period has been determined and such factors as regional differences in the radiocarbon reservoir. Recent studies (*e.g.*, MANNING *et al.* 2001) indicate such inaccuracies exist, but they are small (*i.e.*, in the order of magnitude of individual decades)".[2]

incorrect results, the entire sample preparation has to be performed with utmost care, which is time consuming".
The rigor with which contaminants can be removed from seeds through pretreatment depends on the extent to which the sample consists of purely elemental carbon. Some Theran seeds, for example, may be more akin to humic acid compounds than to reduced elemental carbon, and hence must receive special treatment (HOUSLEY *et al.* 1999, 160). Rigorous pretreatment is also a necessity where seeds have been carbonized together with the baskets or sacks in which they were carried and stored, or with the wood or cloth tops of jars in which they were stored.

[2] The Gilboa and Sharon paper is noteworthy in its explicit statement of aims and procedures, a practice which should be made standard in all reports of radiocarbon dates: "With the aim of reaching measurement accuracy within the ±25 to ±40 (radiocarbon) year range, conventional radiometric counting was the preferred analytic method, rather than the less-practiced AMS (atomic mass spectrometry) technique. We set an acceptability threshold of 3 g clean carbon (after treating the specimen with hydrochloric acid and sodium hydroxide) while aiming for an ideal of 7 g carbon per specimen. The specimens were analyzed at the Weitzmann Institute's ^{14}C facility (WIS; for lab procedures, see GUPTA and POLACH 1985). To assure the desired precision, each sample was counted for 3,000 minutes" (GILBOA and SHARON 2003, 58).

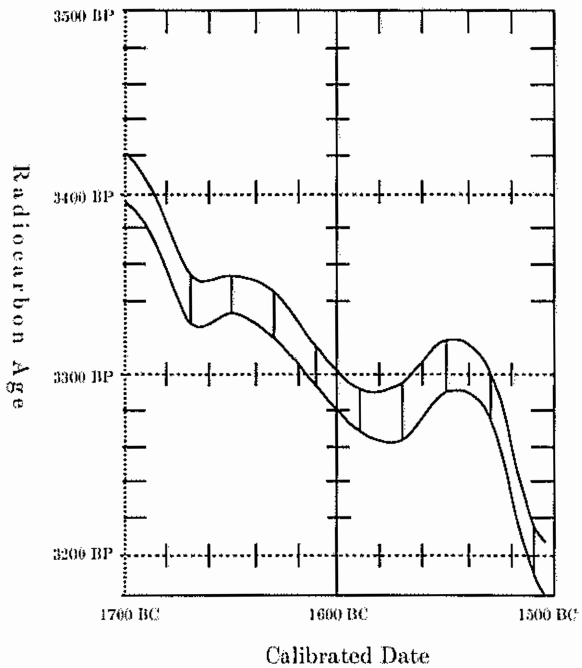

Fig. 1 Calibration curve, one standard deviation band from 1700 B.C. to 1500 B.C. (after W. Kutschera, pers. comm.). Of course the two standard deviation band depicts a still greater oscillation

The Manning *et al.* judgment cited is discussed in various contexts below, and may prove somewhat optimistic. In any event, it is important to note that differences "in the order of magnitude of individual decades" can be of critical importance in determining whether radiocarbon measurements fall within the oscillating portion of the calibration curve, consistent with either the Aegean Short Chronology or Aegean Long Chronology or an earlier date consistent with only the Aegean Long Chronology (Fig. 1).

In general, "halving the error limits on a radiometric age requires at least four times the number of determinations, or four times as much counting time . . ." (Buck and Millard 2003, VI). Such time-intensive measurements by either method are expensive and, given constraints on budgets, a practical question may often exist as to whether better overall results are likely to be achieved by obtaining less intensive determinations on a larger number of samples or more precise, but fewer determinations. In any event, differences of one to two decades strain the limits of the system of radiocarbon dating by measurement and calibration.

Of course neither the Gaussian standard bell curve distribution which determines the one and two sigma probability bands prior to calibration nor the stated calibrated ranges encompass such possible sources of error as stratigraphic disturbance of carbonized matter before recovery or contact with old carbon. Moreover, the Gaussian distribution is neither designed to reflect nor sufficient always to encompass such known variables as intra- and inter-year differences within the decadal calibration measurements, differing patterns of absorption in separate tree species or regional variation in the distribution of ^{14}C. The international calibration curve assumes uniform distribution of radiocarbon at the Earth's surface. Any known regional offsets such as those for the Southern Hemisphere, where F.G. McCormac *et al.* and M. Stuiver both recommend that 41 ±14 years be added to all measurements, must be applied to ^{14}C determinations prior to calibration. Moreover, such regional variations are not constant but rather vary over time, with differences in solar activity suspected as the cause (McCormac *et al.* 2002, 641; Knox and McFadgen 2001, 87; Stuiver *et al.* 1998, 1046).

The irregular absorption of ^{14}C because of solar, climatic and regional factors presents a wide array of issues. Changes in climate affect the growing season during which trees and seed-producing plants absorb most of their radiocarbon. For example, recent work by Manning *et al.* suggests that a marked climate change in Anatolia in the ninth-eighth centuries B.C. delayed the growing season of trees, resulting in aberrant ^{14}C determinations in this period as determined by comparison to rings of the same known date from the trees in Ireland and Germany used to establish the calibration curve (Reimer 2001; Kromer *et al.* 2001; Manning *et al.* 2001). P. Reimer has described succinctly the process at work:

"^{14}C is primarily produced at high latitudes in the lower stratosphere by the collision of cosmic ray-produced neutrons with nitrogen. During periods of high solar activity, distortion of Earth's geomagnetic field by the solar wind prevents charged particles from entering the atmosphere and little ^{14}C is produced, whereas ^{14}C production peaks during periods of low solar activity (solar minima). The atomic ^{14}C is quickly oxidized to $^{14}CO_2$ and enters the troposphere during the late spring, a period of high stratospheric-tropospheric exchange. By the next spring, the higher ^{14}C concentration in the atmosphere has been well mixed and diluted by exchange with other carbon reservoirs, particularly the surface ocean. The German trees, which grow mostly in the mid to late summer, take up more $^{14}CO_2$ during photosynthesis than do the Mediterranean trees, which grow in the spring and early summer" (Reimer 2001, 2495).

California bristlecone pines in one study consistently produced older ages than German and Irish oaks of the same known date, with an average offset of 35 years, due perhaps to differences in the growing season of the trees, with differences in species and altitude of the trees as other potential relevant variables (McCormac *et al.* 2002). 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. 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, however. Accordingly, unless the situation is markedly different for the oscillating calibration curve years of 1675 to 1525 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 rather than inter-laboratory measurement differences (Reimer, pers. comm. of 4 April 2002; see also Damon 1995b). 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" (Baillie and Brown 2002, 499). 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. The statistical method used to smooth the data introduces a further variable. Moreover, for much of the INTCAL98 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). Accordingly a single aberrant determination by one laboratory can have a significant effect on the shape of the calibration curve for a particular decade (Wiener 2003 and sources cited therein).

Measurements also are affected by the intra-year variation in radiocarbon described by Reimer. One study observed an intra-year variation between the winter low and the spring-summer high of up to thirty-two years, with an average difference of fourteen years (Levin *et al.* 1992; Levin and Hesshaimer 2000; see also Kromer *et al.* 2001). A study of plants in Canada (Milton *et al.* 1993, 489) noted ". . . the difficulty of attempting to correlate the ^{14}C signal in growing vegetation with an average annual, or even average summer, emission rate". The study reports, moreover, that more than 5% of a plant leaf's carbon content may be replaced in the course of a day (Milton *et al.* 1993, 492–493; I am indebted to D.J. Keenan for calling my attention to this research). Measurements of seeds from early crops – *e.g.*, winter wheat or barley – could thus be misleading when calibrated against trees whose major growth period during which they acquire most of their ^{14}C occurs in late spring. Many Mediterranean plants have growing seasons that include winter, differing in this respect not only from the European trees on which the calibration curve is based, but also to some degree from the trees of central Anatolia where winters are colder and cold weather lasts longer. Egypt of course has a much warmer climate and a different growing season, which must be considered in connection with ^{14}C measurements such as those now underway of seeds from Tell el-Dab^ca. In all cases where a difference in growing season exists, Aegean seeds are likely to give older radiocarbon age measurements than European or Anatolian trees, although the difference is likely to be within a decade except in unusual cases (see Keenan 2004). Egyptian seeds, however, may be in a separate category in this regard.

Inter-year variation within the decadal calibration determinations is potentially more troublesome still. Just as radiocarbon measurements can show no significant change over several centuries during which the intake of ^{14}C balances the half-life loss, conversely major differences in ^{14}C ages exist between adjacent decades at sections of the calibration curve where the slope is vertical or near vertical. Where dates proposed for major archaeological horizons are dependent on such sections of the calibration curve, the relevant decadal determinations should first be confirmed. In one such area of the INTCAL98 curve relevant to our understanding of the major Late Minoan IB destruction horizon in Crete, a supposed vertical portion of the calibration curve proved to be an illusion resulting from a single aberrant measurement of one log in one laboratory (Wiener 2003, 382). The example given is not unique; a calibration curve measurement has had a major impact on the study of the prehistory of Sweden (Shak-Nielsen 2003, 122).

The fact that adjacent decadal determinations from trees can produce significantly more widely spaced radiocarbon ages in vertical or sharply sloped portions of the calibration curve raises a question about mid-points within the decades. When a decadal measurement includes in the sample tested wood from both narrow rings representing years of little tree growth and wood from wider rings representing years of greater growth, the wider rings will provide a greater amount of the cellulose containing radiocarbon. Seeds absorbing their ^{14}C during a few weeks at differing points within the decadal spans may produce measurements different from the decadal averages. (Of course in the odd case where seeds are roasted and stored for export or as protection against a poor harvest, they may be recovered from a destruction level of a year falling in a decade different from the year of roasting, and thus also give a misleading indication of the date of the destruction.)

The decadal determinations comprising the INTCAL98 calibration curve are generally reliable and reproducible, but were often the product of a single measurement on one or few logs as noted and subject to shorter counting periods than those current today. I.U. Olsson notes that "it is important that a good pretreatment is applied on the wood used for calibration" (OLSSON 2003, 23). The INTCAL04 calibration curve now in preparation by an international team chaired by P. Reimer will make a significant advance in terms of precision and accuracy. New puzzles are likely to arise, however. For example, current planning envisages some smoothing of the calibration curve measurements to limit the effect of individual (and potentially misleading) decadal determinations by weighting each decadal measurement with the two preceding and two following decadal determinations. The result will reduce the risk of significant error for any single decade, while reducing the extent of individual decadal peaks and valleys employed for purposes of "wiggle-matching", as for example, in the comparison of the fixed European and floating Anatolian dendrochronological sequences. (I am grateful to S. Manning and P. Reimer for discussing these issues with me. An interesting approach to the problem of smoothing ^{14}C determinations is presented in GÓMEZ PORTUGAL AGUILAR *et al.* 2002.)

However precise the uncalibrated measurements, they remain dependent on the calibration curve adopted and the regional, time and climate sensitive data they encode (BRUINS and VAN DER PLICHT 1995, 218–219). Small differences in sample and calibration curve measurements can have major implications for Aegean Bronze Age chronology and history. For example, because of the steepness of the slope of the calibration curve in the period in question, the twenty-year span between 3340 and 3320 B.P. in uncalibrated ages can move calibrated central dates of the ± range (sometimes called the "mode of distribution") from about 1620 to about 1525 B.C., and a spike at 1675 B.C. can be included in the oscillating portion of the calibration curve by a further extension of twenty additional radiocarbon years. The addition of only 0.25% ^{14}C-depleted carbon to the total carbon of a sample, either because the old carbon is absorbed by the plant or tree in its lifetime or acquired from later contact and not removed through rigorous pretreatment, will result in a twenty-year shift.

With regard to regional variation, radiocarbon determinations from Southern Hemisphere tree-ring samples giving markedly earlier ages at times than samples from the Northern Hemisphere of the same known age have been variously attributed to the fact that more of the Southern Hemisphere is covered by water, which contains fifty times the amount of ^{14}C of the atmosphere (LERMAN *et al.* 1970; OLSSON 1979; 1987), to the gradual release of a sink of old carbon in the Weddell Sea in Antarctica, southeast of South America (LERMAN *et al.* 1970; KNOX and MCFADGEN 2001) and/or to upwellings of old carbon from major Pacific Ocean underwater volcanic vents, with the upwellings occurring in particular during El Niño events (KEENAN 2002). The major increase in the Southern/Northern Hemisphere gap during the Maunder Minimum, the period from about A.D. 1645 to 1715 when sunspots were extremely rare, corresponding to the middle and coldest part of the "Little Ice Age" during which Europe and North America at least were subject to bitterly cold winters, suggests the presence of a significant climate component in the hemispheric differences noted.

Measurements of modern, pre-nuclear test period shells of known age from the Mediterranean show a water reservoir radiocarbon addition of around 400 years, which then must be subtracted from marine determinations (SIANI *et al.* 2000; REIMER and MCCORMAC 2002). Whether upwelling of ocean or seawater containing old carbon is a plausible cause of anomalously early radiocarbon ages for short-lived terrestrial samples either in the Pacific or Mediterranean regions is a subject of dispute (KEENAN 2002; MANNING *et al.* 2002a). Keenan notes that the Mediterranean exhales carbon dioxide intermittently as a result of natural processes. Given the large concentration of CO_2 in seawater compared to the atmosphere, and its relative depletion in ^{14}C (resulting in the 400-year difference), the potential effect of episodic upwelling on coastal sites could be significant. Manning *et al.* conclude that there is "currently little evidence anywhere for a sustained large amplitude depletion of ^{14}C in terrestrial samples due to the influence of old CO_2 from the surface ocean and maritime air carried onshore" (2002a, 746). The question requiring consideration, however, is not the existence of "sustained large amplitude depletions", but rather the possibility of episodic, small amplitude effects. (The addition of only one-half of one percent of old carbon to a sample results in a forty-year increase in radiocarbon age, as noted above.)

The quotation from Manning *et al.* continues as follows:

"A limited number of measurements directly on maritime air show highly localized and variable results (Bhushan *et al.* 1997; Dutta *et al.* 2000); such small-scale depleted air parcels would be expected to dissipate rapidly over short distances with atmospheric mixing, as is observed in air-sampling stations in the Southern Ocean/Antarctica. Where differences of up to a few ‰ (or a few tens of ^{14}C yr) do occur in tree-rings, they appear to vary on a relatively short timescale and may be partly or wholly due to other causes (McCormac *et al.* 1995; Damon 1995a; Stuiver *et al.* 1998; Knox and McFadgen 2001; Kromer *et al.* 2001; Hogg *et al.* 2002; Hua *et al.* 2002)".

Of course for certain critical decades and events such as the date of the eruption of Thera, "a few tens of ^{14}C years difference" would be sufficient to cause major uncertainty, as noted above.

A further question arises as to whether the analysis cited takes into account reports of the release of significant amounts of ^{14}C-depleted carbon from major vents or fields of vents on land and under the sea, particularly those in plentiful supply in the Hellenic Arc, including at least one close to Thera. While a number of single-source volcanic eruptions have resulted in emissions of carbon-depleted gases over small distances measured only in meters or hundreds of meters as stated (Kromer *et al.* 2004), others (particularly those with multiple vents) have been shown to produce strong effects over greater distances (*e.g.*, Rogie *et al.* 2001 re carbon dioxide emission at Mammoth Mountain in California; Pasquier-Cardin *et al.* 1999 re venting in the Azores), sometimes to a distance of over ten kilometers (Olsson 1987, 20 re Kamchatka in the Aleutian Chain). Within the Mediterranean, Allard *et al.* (1991) report carbon dioxide production of 70,000 tons per day from the gas vents around Mt. Etna and strong effects measured fifteen kilometers away. The extensive gas field in northern Italy running between Florence and Naples includes one vent east of Naples which emits 280 tons of carbon dioxide per day, while the average diffuse CO_2 degassing from an area of 23,000 km.^{2} is about 18,000 tons per day (Rogie 1996; Cardellini *et al.* 2003; Rogie *et al.* 2000; Chiodini *et al.* 1999). These sources may affect Italian ^{14}C determinations and hence Italian prehistoric chronologies.

The critical question, however, involves sources in the Aegean, particularly those close to Thera. Of course we cannot know of sources that have disappeared or become quiescent as a result of eruptions or earthquakes since the Bronze Age. Moreover, still active vents may be invisible, with their gas escaping through the soil.

Dando *et al.* (1995a) report that:

"Greece and the Aegean is one of the seismically most active regions on Earth and has the highest seismic activity in Eurasia (Bath 1983; Makropoulos and Burton 1984). Geothermal areas are known in the northern and central Aegean as well as along the Hellenic Volcanic Arc (Dominico and Papastamatoki 1975; Holm 1988; Fytikas *et al.* 1989; Varnavas 1989; Varnavas and Cronan 1991)".

The Hellenic Arc of volcanoes stretches from Methana on the coast of the Peloponnese through Melos and Thera to Yali-Nisyros. The vent near Melos is today one of the most active sources of hypothermal fluxes in the world. The seafloor around Melos has "the world's largest known concentration of vents in shallow water" (Pain 1999, 39), and, although not an active volcano, its output of ^{14}C-free carbon is estimated at two to ten kilotons per day (Botz *et al.* 1996; Dando *et al.* 1995b; 2000). An earthquake near Melos in 1992 caused the eruption of gas vents all around the island and showed an increase of 65% in the number of vents (Pain 1999, 41). " 'Every fumarole on the shore blew out. And the sea boiled as the gas came out with such force. Stunned fish came to the surface' " (P.R. Dando, as quoted in Pain 1999, 41).[3]

Systematic surveys of submarine hydrothermal venting have not yet been conducted in the Aegean

[3] Discharges from the vicinity of Melos, however massive, would dissipate long before reaching Thera, particularly given the strength of Aegean winds. It is conceivable that in the special case of possible upwelling of old carbon from the Mediterranean, the old carbon content of the water would be augmented by massive discharges from underwater vents such as those described near Melos. On calm days such as occur during the spring and early summer growing season for plants the discharge of moisture against the hills of Thera from low clouds drifting in from the west is sufficiently frequent to be known as "the Poseidon irrigation system" (Doumas, pers. comm. of 1 December 2003). The chance that any particular radiocarbon determination would be affected in this manner is very slight, however.

(DANDO *et al.* 1995b, 661), but gas vents producing ^{14}C-depleted CO_2 have been noted in many places, for example near the islands of Thasos and Lesbos, with others undoubtedly existing elsewhere (DANDO *et al.* 2000). Vents rather than volcanism may be the source of much of the world's carbon (ROGIE 1996). The principal recent study notes that "only recently, it has been recognised that the quiescent, non-eruptive diffuse degassing is the principal mode of gas release from volcanoes, and that volcanic flanks play a fundamental role" (MÖRNER and ETIOPE 2002, 189). (The total extent of outgassing of old carbon worldwide is also discussed in GERLACH 1991, 249.) While dilution over space will render negligible the effects of isolated points of low magnitude discharges, higher magnitude, more numerous, distributed sources may combine to produce a regional effect. Degassing from vents has been known to increase markedly with seismic activity, as in the case of Melos (DANDO *et al.* 1995b) and numerous other earthquakes (GOLD and SOTER 1985; SOTER 1999).

Whatever the potential effect of outgassing elsewhere in the Aegean, a far more significant question in regard to ^{14}C measurements of Theran seeds and wood is presented by sources of old carbon on Thera itself. Today on Thera fumaroles, hydrothermal springs and higher than normal concentrations of ^{14}C-free CO_2 in soils persist (MCCOY and HEIKEN 2000a; 2000b; HOLM 1988, 203; BRUNS *et al.* 1980). Five kilometers to the northeast of Thera a major underwater source of ^{14}C-depleted carbon exists at the Columbo Bank (MCCOY and HEIKEN 2000a). F.W. McCoy describes Columbo Bank as a very dangerous volcano, perhaps the most dangerous in the southern Aegean today, about whose eruptive history little is known (pers. comm. of 21 February 2004, for which I am most grateful). Non-volcanic earthquakes also often trigger the release of ^{14}C-depleted gas from vents. Earthquakes are of course frequent on Thera; 109 earthquakes, most with a Richter magnitude of one to three, were reported in the four-year period from 1985–1988 (DELIBASIS *et al.* 1990, cited in MCCOY and HEIKEN 2000a, 48). F.W. McCoy and G. Heiken report that:

"[F]umaroles and hot springs are present on and around the Kameni islands, as well as on Thera near Athenios, Cape Exomiti, and Cape Therma (thermal springs at Cape Exomiti are now buried under a new harbor; those at Cape Therma with greatly diminished flow rate and temperature following the 1956 earthquake, according to local residents). High concentrations of helium and CO_2 are present in soils on central Thera and on southern Thera near Cape Exomiti, documenting gas emissions along fault lines presumably from active magma chambers (BARBERI and CARAPEZZA 1994; DELIBASIS *et al.* 1990)".

The publication by F. Barberi and M.L. Carapezza cited above reports the results of a soil gas survey conducted on Thera in 1993 that found several anomalous degassing sites, some along the Kameni and Columbo lines responsible for the historically documented volcanic activity on Thera, but also some related to a gas-leaking fault cutting a geothermal field in southern Thera. H.W. HUBBERTON *et al.* (1990) report that their tests did not show effects beyond 100 m. from a gas source (but without specifying wind conditions), while acknowledging that general conditions and sources of ^{14}C-depleted carbon at the time of the eruption are unknown. They contend that the scattered radiocarbon dates known prior to the 1990 date of their publication are unlikely to have been affected by the presence of old carbon and hence validate a high date for the eruption, finding possible support for their view in the purported evidence of Theran shards in the Greenland ice core at 1645 ±4 B.C. and the 1628–26 B.C. frost rings in trees, arguments since largely abandoned by proponents of the Aegean Long Chronology as noted above.

Carbon dioxide is 50% heavier than air and, if emitted in sufficient concentration, can easily accumulate in low-lying areas of cereal growth if not dissipated by winds; a few days per year of modest degassing in flat, calm weather is all that is required to affect plants. S. Soter gives the following highly simplified model as illustration:

"The growing season in Greece is about 180 days. Suppose the concentration of volcanic CO_2 near the ground equals that of the normal atmospheric CO_2 during one day in the growing season and is zero for the other 179 days. That brief exposure would provide 0.55%, or 1 part in 181, of volcanic CO_2 to the plants, which would produce an apparent radiocarbon age increment of about 40 years. The pre-industrial atmospheric CO_2 concentration was about 275 parts per million, and doubling it for one day would not be noticed. The amount of CO_2 needed before people even begin to feel ill effects is about 5000 ppm" (pers. comm. of 28 February 2004, for which I am most grateful).

Indeed, a few hours' exposure to ^{14}C-depleted carbon might suffice, for a plant leaf may replace over 5% of its carbon in a single day, as noted above. A plant growing in 1550 B.C. with only 0.25% of its carbon from volcanic CO_2 would have a calibrated date of about 1620 B.C., given the shape of the calibration curve – *i.e.*, a ^{14}C age increment of only twenty years in the critical span results in a calibrated increment of seventy years. Twenty-year differences challenge the best of radiocarbon measurements and the limits of the method. Of course not all ^{14}C determinations suggesting the possibility of an early date for the Theran eruption fall within this twenty-year period.

The sequence of earthquakes and eruptions at Thera in the Late Bronze Age is of particular relevance. At the beginning of Late Cycladic I/Late Minoan I, a massive earthquake struck Thera, the southern Aegean and most of Crete, causing such destruction at Akrotiri that ground floors in some places became basements beneath the leveled rubble (Nikolakopoulou 2003; Warren 1991; Marthari 1984; Palyvou 1984). Earthquakes are likely to cause the release of quantities of ^{14}C-free carbon from both terrestrial and underwater vents in the Hellenic Arc (as the 1992 earthquake at Melos demonstrated). "Earthquake swarms" precede most volcanic eruptions (Heiken and McCoy 1990, 29). Results of recent excavations suggest the occurrence of further earthquakes within LM IA between the initial major event and the Theran eruption (Rehak and Younger 1998, 101). S. Soter notes that "terrestrial outgassing in tectonically active areas is highly time-variable. In the years leading up to the paroxysmal Minoan eruption of Thera, the volcanic region may well have been emitting enormous quantities of 'dead' carbon dioxide" (pers. comm. of 15 May 2003).

The period immediately preceding the great eruption of Thera was marked by "precursor events" in the form of more than one large earthquake, most likely volcanic in origin (Cioni *et al.* 2000; McCoy, pers. comm., for which I am most grateful). The excavators believe that during the year or two before the final eruption, the settlement of Akrotiri suffered for a short time from minor seismic tremors and finally, toward the end, from a major and destructive tremor, causing the populace to abandon their houses and begin a massive reconstruction effort (C. Doumas, pers. comm. of 11 March 2004; Nikolakopoulou 2003). Then, a precursor eruptive phase "some weeks or months prior to the major phases of the eruption deposited a thin tephra layer extending to 8 cm. over southern Thera" (McCoy and Heiken 2000b, 1235). I. Nikolakopoulou (2003) describes a period of "intense seismic activity" for a brief interval before the final eruption, after which there exists evidence for outdoor work including "arrangement of debris and organization of workspaces, collecting and sorting building materials, gathering tools, transport of objects, food supplies and consumption" and indoor work including "abolishing accesses to parts of complexes, abolition of rooms, supports, protection and storing of objects, discarding of objects, repairs and renovations". Nikolakopoulou notes particularly the recovery of sacks and baskets full of barley and concludes that it is now evident that during the rearrangement of the settlement, provisions were made for food and fire. Accordingly, the possibility exists that some of the seeds and twigs found in the Volcanic Destruction Level (VDL) at Akrotiri from which ^{14}C measurements were taken had been grown and collected for those who remained after the precursor events, including not only the clearly identifiable events in the resettlement phase, but also the earthquakes which are believed to have occurred in the preceding decade (McCoy and Heiken 2000b), and which may have been accompanied by an increase in the number of fumaroles and release of old carbon.

Fumaroles send ^{14}C-depleted carbon into the atmosphere where it can be absorbed by the leaves of plants and trees. The soil gas in geothermal areas has elevated concentrations of old CO_2. Plants are known to acquire small amounts of carbon dioxide directly from the soil through their roots (Geisler 1963; Yorgalevitch and Janes 1988; Stolwijk *et al.* 1957; Skok *et al.* 1962; Splittstoesser 1966; Arteca *et al.* 1979). For example, one experiment used labeled $^{14}CO_2$ to demonstrate that eggplant roots are capable of taking up CO_2 from the soil environment and that the carbon so acquired can be translocated to the shoots (Baron and Gorski 1986). However, there seems to be no consensus regarding the magnitude of CO_2 uptake by plant roots. Whether the effect can add significant increments to the radiocarbon ages of plants grown in volcanic areas is yet to be determined. (I am grateful to S. Soter for informing me of the literature regarding root uptake of carbon.)

Further questions, apart from those related to the release of old carbon by gas venting, arise with regard to possible sources of old carbon in samples measured. River water used for washing storage jars to remove insect infestations may produce a "freshwater reservoir" or "hardwater" effect biasing ^{14}C determinations upward (Fischer and Heinmeier 2003, 449). N.-A. Mörner and G. Etiope (2002, 193) note that in the "Tethyan belt [which includes the Mediterranean region], high CO_2 fluxes are related to important crustal formations of . . . carbonate rocks [causing] high levels of CO_2 concentration in ground and groundwater". Finally, they also report that "the Precambrian bedrock includes stromatolites, marble and other carbonate bearing rocks [which] ... may give rise to the escape of CO_2" (197). The basement rocks of Thera and the other Aegean islands include metamorphosed limestone. The term "cretaceous" is derived from Crete, and one of its definitions is "chalky" (Soter, pers. reminder). Heating of limestone by metamorphism and volcanism generates old carbon dioxide, which can escape into the soil and atmosphere through fissures and faults, especially in connection with seismic activity.

The existence of known and potential sources of old carbon necessarily raises the question of whether there is a significant likelihood that such old carbon will be incorporated by the trees or seeds subsequently measured. S. Manning believes the possibility slight and undemonstrated, contending that it is unlikely that cereals and pulses dated by radiocarbon would have been planted or the trees grown in the vicinity of fumaroles or limestone sources (pers. comm.). The possibility exists, however, that the key seed samples, such as those from the jars found in the destruction deposit in rooms 3c and 5 of the West House and elsewhere, were all collected at the same time from the same location. C. Doumas (pers. comm.) notes that barley is grown today on the small hill across the road from the site of Akrotiri. Instances of old carbon effects extending over distances measured in kilometers are described above.

S. Manning contends in particular, however, that old carbon would not be present in short-lived samples in relatively consistent, limited amounts and hence would not explain ^{14}C determinations putatively supporting a date 50 to 150 years earlier than the date range proposed for the Theran eruption in accordance with the Egyptologically-based Aegean Short Chronology (Manning 1999, 236, and personal discussions for which I am most grateful). Here three caveats may be appropriate: (1) the atmospheric old carbon effect may have a restricted upper limit based on the magnitude and distance of the source if all the seeds tested come from plants growing in one area, with only a few outliers recording greater concentrations; (2) the studies which support the uptake of ^{14}C-depleted carbon through the root system of plants suggest that the uptake may saturate at a low but significant level; (3) a consistent upward bias may be caused by pretreatment which succeeds in removing almost all old superficially adsorbed carbon present but leaves a minute residue, a possibility that cannot be entirely excluded (see note 1). Nevertheless, the Manning argument will require serious consideration if it can be shown that samples from the VDL regularly provide dates earlier than the oscillating portion of the calibration curve, or samples from post-destruction periods, such as LM IB, regularly provide radiocarbon dates earlier than dates consistent with a post c. 1550 B.C. eruption.

The evidence to date, however, does not seem to support such a position. Most determinations fall within the oscillating portion of the calibration curve and are consistent with an eruption date between 1550 and 1525 B.C., or are so marginally higher as to fall easily within the range of measurement variation or error.[4] A threshold question exists regarding which determinations are accepted into the dataset and how these are combined. Biasing results, for example by including in the database a sample with 1% old carbon which adds about 80 years to a measurement while rejecting a sample containing 3% old carbon which adds about 245 years on the ground that the latter is an obvious outlier, must be avoided. Issues presented in the combining of determinations from archaeological samples are considered in Ashmore (1999).[5]

In the course of the attempt to provide dates for the Theran eruption and the major phases of the early Late Bronze Age in the Aegean, many radiocarbon measurements have been obtained in recent years from deposits other than the Theran VDL, for example from early LM/LH I, mature LM/LH I, LM IB/LH IIA and LM II contexts. These measurements have been placed in sequence and compared to the calibration curve, a process recently termed "sequence seriation" or "seriated sequence" analysis in place of "wiggle-matching" (a term now properly reserved for comparisons between series with known

[4] Early studies in particular produced "outliers" both earlier and later than the possible range of dates (Hubberton *et al.* 1990; Biddle and Ralph 1980; Michael 1978; 1980; Weinstein and Betancourt 1978; Weninger 1990). Some of those measurements did not come from short-lived samples or samples clearly associated with the VDL, and many of the samples did not undergo pretreatment of the kind now standard, however.

[5] The preceding pages have dealt in detail with the nature and extent of sources of old carbon and of its proposed paths of transmission to radiocarbon samples in order to redress partial and potentially misleading accounts in the current archaeological literature. Even if no old carbon were present in a sample, the problems posed by regional, inter- and intra-year variation and by the oscillating calibration curve would of course still be present.

intervals, such as decadal measurements of dendrochronological sequences of trees from different areas, species and/or measurement methods/laboratories). A detailed, informative description of the process and its utilization by the widely employed OxCal program is provided by its progenitor, C.B. RAMSEY (2001). All such seriation analyses, where the time intervals between the various phases cannot be established independently, are highly dependent statistically on the correctness of the "boundaries" incorporated in the seriation, such as "start LM IA" or "LM IB end". (Potential hazards in the application of Bayesian analysis to radiocarbon dates are considered in STEIER and ROM 2000; WIENER 2003.) Establishing the locations (dates) of the boundaries, however, encounters many of the same difficulties as establishing the date of the VDL directly, unlike the situation where a "boundary" date is fixed by dendrochronology or recorded history (*e.g.*, the tephra layer from the eruption of Vesuvius in A.D. 79). For example, attempting to establish an end of LM IB "boundary" on the basis of a set of dates at one site where the relationship in time of the particular deposit to other LM IB destructions is uncertain, other LM IB radiocarbon measurements of destruction levels are later and the INTCAL98 calibration curve at the relevant decade contains an erroneous measurement which could result in the lowering of the date by a decade or more (WIENER 2003, 34), appears to lack a solid basis. (See contra, MANNING, this volume; RAMSEY *et al.* 2004.) The consequence is historically significant, for the purported "boundary" would remove any overlap between the reign of Tuthmosis III and the LM IB period, a somewhat surprising prospect in light of the archaeological evidence.[6]

In the final analysis, and separate from the problems posed by the possible presence of old carbon and by regional, inter- and intra-year variation, we are left with the hurdle of the oscillating calibration curve of the late seventeenth and sixteenth century B.C. An analysis of radiocarbon measurements from Thera conducted by the VERA Laboratory of the University of Vienna (Kutschera, pers. comm.) focuses on the twenty-five critical Akrotiri samples (after culling from the data bank all samples with a one sigma range greater than 100 years and all those whose destruction layer origin could not be established). The study, which corrects the data presented at the 1998 SCIEM conference, concludes:

"But now we obtain – as a result of the calibration curve – two ranges, the first from 1640 B.C. to 1600 B.C. and the second from 1570 B.C. to 1530 B.C. . . . [T]he two peaks have almost the same size, so none of them has a preference over the other. That means in other words that measuring a lot of new samples from the destruction layer of Thera will not result in finding out which range is the true one. Thus ^{14}C dating – because of the shape of the calibration curve at that time – is not capable to distinguish between high and low chronology for the Thera event".

Similarly, W. Cavanagh, coauthor of the standard text on the *Bayesian Approach to Interpreting Archaeological Data* (BUCK *et al.* 1996), in discussing the study of the Eastern Mediterranean radiocarbon data published by MANNING *et al.* (2002b) concludes that the analysis ". . . in no way rules out the Aegean Low Chronology" (quoted in WIENER 2003, 391, n. 148). P. Reimer, the lead investigator in the INTCAL04 project, reaches the same conclusion: "It would indeed be difficult to distinguish dates between 1615 and 1525 B.C." (pers. comm. of 8 December 2003).

In the six intervening years since the completion of the VERA Laboratory study cited, many additional ^{14}C measurements have been added to the database at VERA and elsewhere. Studies under way utilizing the additional data will provide important new information and may alter the picture presented by the 1998 study. Unless significant numbers of precise measurements from relevant, rigorously collected, treated and analyzed samples provide dates outside the oscillating decades of the calibration curve,

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[6] The site of Chania, where a destruction produced radiocarbon dates possibly earlier than the radiocarbon dates of other LM IB destructions (MANNING 2002b; but *cf.* WIENER 2003) contained Alternating Style pottery, sometimes thought to represent a mature phase of LM IB on the evidence of the stratigraphy of one small plot at Kastri on Kythera (COLDSTREAM and HUXLEY 1972). The Stratigraphic Museum site at Knossos, however, contained Alternating Style pottery throughout the LM IB sequence (WARREN 1981). The example of error in decadal calibration measurements cited in connection with the Chania measurements is not unique; for example, in a few instances decadal measurements of trees in Anatolia and in Germany produced radiocarbon ages that were significantly at variance, probably as a result of measurement problems. (NEWTON and KUNIHOLM 2004. I am grateful to the authors for allowing me to see their important paper prior to publication; see also KROMER *et al.* 2001, fig. 3.)

however, radiocarbon dating will remain unable to provide convincing evidence of the date of the Theran eruption and the LM IA–IB transition.

Archaeological Evidence Based on Egyptian Chronology

Other papers in this volume present the Egypto-archaeological evidence for a mid-to-late sixteenth-century eruption of Thera. Foremost is the evidence from Cypriote pottery. The VDL at Thera contained the now well-known Cypriote White Slip I (WS I) bowl. While the vessel came from the 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" (Merrillees 2001, 92). The absence of Cypriote pottery in the material studied to date from the ongoing excavation of Akrotiri is not surprising, given the fact that only six examples of WS I have been reported for the entire Aegean (Merrillees 2001, 98–100). 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 its place within the general attraction of Minoan palatial culture of the New Palace Period, or indeed with the excellent Late Cycladic I pottery of Thera itself. The contemporaneity of WS I and the mature Late Minoan I pottery of the Theran VDL is also evident in the material excavated at Toumba tou Skourou and Ayia Irini on the northwest coast of Cyprus (Wiener 2003, 367 and sources cited therein). Of course the creation of the bowl in Cyprus could predate its destruction in the Theran eruption by many years, and in fact the bowl showed evidence of use and ancient repair.

The earliest certain appearance of WS I pottery in Egypt and the Near East comes in the Tuthmoside era, not before c. 1500 B.C., with the possible exception of WS I sherds found at Tell el-ᶜAjjul whose context, while somewhat uncertain, makes them potential candidates for an earlier arrival (Bergoffen 2001; Wiener 2003, 369). However, even if (1) WS I bowls of the type recovered from the VDL at Thera existed for two generations, or sixty years, before their first stratified appearance to date at Tell el-Dabᶜa, around 1500 B.C.; (2) one of the first examples produced arrived in Thera; (3) the use, repair in antiquity and destruction of the bowl in the Theran eruption all occurred within a decade and (4) there is some overlap between early stages of WS I production and Proto White Slip (which is stratified at Tell el-Dabᶜa in the final Hyksos stratum), then the date of the eruption would still move no earlier than 1550 B.C. Finally, it is important to recognize that the challenge to a seventeenth or early sixteenth century B.C. date for the Theran eruption posed by the contexts of Cypriote pottery is not limited to the position of WS I, but encompasses a sequence including Cypriote White Painted VI, Proto White Slip, Base-ring I and Red Lustrous Wheel-made wares, consisting of thousands of sherds from Tell el-Dabᶜa in Egypt, Tell el-ᶜAjjul in Canaan and various sites throughout the Eastern Mediterranean. The Tell el-ᶜAjjul sequence is notable for the numbers of Cypriote sherds of each phase of the sequence present. (See, for example, Bietak 2001; 2003a; Bietak and Hein 2001; Fischer 2003; Fischer and Sadeq 2002; Oren 1997; 2001; Bergoffen 2001; Wiener 2003, 369).

S. Manning has argued forcefully that the delay of at least a century between the arrival of a WS I bowl at Thera and its first documented appearance elsewhere could result from regionalism in Cyprus during Late Cypriote IA and from exclusive exchange relationships linking the major Cypriote southeast coast site of Enkomi with places in Egypt and the Near East including Tell el-Dabᶜa (Manning *et al.* 2002c). Manning regards the bowl from Thera as an early example of WS I produced on the northwest coast of Cyprus, an example of a type of pottery which does not reach Enkomi in any quantity until several generations later (Manning 1999, 119–129; see contra, the extended discussions in Bietak 2003b and Wiener 2003). Other Cypriote pottery specialists believe the Theran bowl comes from the west of Cyprus or the south coast (Popham 2001, 217; Merrillees 2001, 93; Karageorghis 1990, 57, n. 28; Bietak 2003a, 26–27) and, moreover, that it is not particularly early. (For the position of the decoration of the Theran bowl in relation to the Tell el-ᶜAjjul sequence, compare in the same volume the illustration in Merrillees 2001, 91 with Bergoffen 2001, 153, placing the decorative pattern of the Theran bowl about one-third of the way through the WS I sequence.) Merrillees (2001) suggests that the bowl belongs in the LC IA–IB transition. L. Crewe in her dissertation and article in this volume examining the limited surviving records of the Enkomi excavations concurs with S. Manning that the examples of WS I whose contexts there can be firmly identified are probably from late LC IB rather than LC IA deposits and hence later than the first appearance of WS I in the west of Cyprus. A delay of 100 or more years between the time a WS I bowl reaches Thera and the time the ware reaches the Near East and Egypt appears unlikely, however, particularly in light of the fact that the putative delay in question must also somehow affect all other wares in the sequence, including Proto White Slip, as noted above (discussion in Bietak 2003a; Bietak and Hein 2001; Wiener 2001; 2003; see contra, Manning *et al.* 2002c; Manning, this volume).[7]

In addition to the pottery evidence, the contexts of waterborne pumice from the Theran eruption found in Egypt and the Near East have been considered as evidence relating to the date of the eruption. At Tell el-Dab^ca Theran pumice in large quantities was found at five locations, three of which the excavator believes were workshops active during the reign of Tuthmosis III and not abandoned until late in his reign or the following reign of Amenophis II, in any event after c. 1450 B.C. (Bietak *et al.* 2001, 37, 89, 91; Bichler *et al.* 2003; 2002; Warren 1996, 287–288, *cf.* below). Pumice from the Theran eruption has also been found in Eighteenth Dynasty, likely post-1525 B.C., contexts at Tell el-ᶜAjjul and Tell Nami in Canaan (Bichler *et al.* 2003; 2002; Fischer 2003; Fischer and Sadeq 2002; Manning 1999, 145–150). Of course waterborne pumice could have been collected from the Nile Delta/Mediterranean Sea or imported as an abrasive at any time between the eruption and the date of use of the pumice. An eruption c. 1525 B.C., at the latest point in the indicated radiocarbon calibration range for the eruption, would mean a delay of two to three generations between the eruption and the date proposed for the abandonment of the Tell el-Dabᶜa workshops containing Theran pumice, whereas an eruption c. 1600 B.C. would require a delay of five to six generations. A difference of this nature would not be of great significance to the chronological debate. It is worth noting, however, that in one context, Workshop N in area H/I, the pumice may appear as early as the reign of Tuthmosis I, around 1500 B.C. (Bietak *et al.* 2001). Accordingly it is possible that Theran pumice was first used at Tell el-Dabᶜa within a generation of a putative c. 1525 B.C. eruption, and continued to be collected or imported for two generations thereafter.

At Tell el-ᶜAjjul, forty-eight samples of pumice from the Theran eruption were collected from various strata, beginning with a stratum containing material from the early Eighteenth Dynasty and Cypriote pottery of the Late Cypriote I A2/I B period, no earlier than c. 1540 B.C. and likely post-dating the conquest of Tell el-ᶜAjjul by Ahmose after 1525 B.C. This stratum and the one following contain examples of Cypriote White Slip I, Base-ring I and Red Lustrous Wheel-made wares, together with most of the pumice samples. No samples of Theran pumice have been found in the earlier Hyksos period strata at Tell el-ᶜAjjul. A small number of samples, however, were found in strata extending into the Iron Age (Fischer 2003, 289–290). Other sites provide examples of Theran pumice in use covering more than a millennium, from LH II through the Hellenistic period (Wiener in Wiener and Allen 1998, 25–27), but only in small amounts, not large quantities such as that found at Dabᶜa. Accordingly, while it is possible that the Theran eruption occurred much earlier than the date of the strata in which the Theran pumice at various places has been found, with the pumice collected or imported at the date of use, the fact that Theran pumice has yet to be found in pre-Eighteenth Dynasty strata remains significant, though clearly not conclusive.

Summation

The difficulties faced by archaeologists and prehistorians in following the ongoing discussions of Egyptian astronomy, confronting the purported ice-core and tree-ring evidence for a 1650 to 1628 B.C. date for the Theran eruption and understanding the nature and complexity of the problematic radiocarbon/statistical argument for the Aegean Long Chronology, on the one hand, and the reciprocal perplexity sometimes expressed by physical scientists concerning the textual plus archaeological evidence for the Aegean Short Chronology, on the other hand, indicate that the problem of the division between the "two cultures" is still with us. Even specialists in chronology who follow closely all developments hold differing positions, however. Those who regard the Egypto-archaeological evidence and in particular the generally prevailing Cypriote pottery analysis as unpersua-

[7] Of course the archaeological problems caused by the proposed Aegean Long Chronology extend beyond the Cypriote pottery sequence. The earlier the date proposed for the mature LM IA eruption of Thera, the greater the difficulties, including the required compression of both the MM III period in Crete and the Hyksos period in Egypt and the Egyptian contexts of Middle Minoan imports (see, *e.g.*, Warren 1984; Bietak *et al.* 2002; Wiener 2003). Similarly, the concomitant required extension of the LH I period of Mycenae from three to five or more generations poses difficulties in terms of, for example, the continuity of hands believed present in the metalwork through the sequence of burials (Graziado 1991; Dickinson 1977, 50–51; Kilian-Dirlmeier 1986).

sive, and the radiocarbon evidence for a Theran eruption date significantly earlier than 1550 B.C. as substantial, favor the Aegean Long Chronology, even though deprived of support from ice-core or tree-ring evidence. Conversely, those who believe the radiocarbon evidence unpersuasive because of some or all of the areas of uncertainty noted in this paper, and the Egypto-archaeological arguments for an Eighteenth Dynasty eruption date compelling, naturally favor the Aegean Short Chronology. At the least, the papers from this conference mark a major step forward in clarifying the issues.

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THE SYNCHRONISATION OF CIVILISATIONS IN THE EASTERN MEDITERRANEAN IN THE SECOND MILLENNIUM B.C. III

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