RADIOCARBON, Vol 44, Nr 1, 2002, p 225–237

WHY EARLY-HISTORICAL RADIOCARBON DATES DOWNWIND FROM THE MEDITERRANEAN ARE TOO EARLY

Douglas J Keenan

The Limehouse Cut, London E14 6N, United Kingdom. Email: doug.keenan@informath.org.

ABSTRACT. Several authors have claimed that radiocarbon dates in the Ancient Near East are too early. Herein, a hypothesis that might explain this is presented. Marine degassing of "old" carbon (i.e. ^{14}C-deficient C), induced by upwelling of old subsurface water, has been observed, in modern times, to cause century-scale ^{14}C ages in the surface atmosphere. A review of the Mediterranean Sea post-ice-age circulation concludes that the subsurface waters became very old, primarily due to millennia-long stagnation. It is hypothesized that as the stagnation ended, subsurface waters were brought towards the surface, where they degassed old carbon. Additionally, Anatolian dendrochronology is shown to not contradict the hypothesis.

1. INTRODUCTION

Many archaeologists studying the Ancient Near East have claimed (or complained) that radiocarbon dates are earlier than archaeo-historical dates for the early historical period: for Egypt (Görsdorf et al. 1998; Bonani et al. 2001), Sumer (Crawford 1991), Israel-Palestine (Bruins and van der Plicht 2001; Mazar 1992), Italy (Guidi and Whitehouse 1996), and the Aegean (Dickinson 1994), among others. Indeed, in a 2001 issue of *Radiocarbon* that was devoted to Ancient Near Eastern chronology, the introductory survey paper concluded that the "Collective evidence … clearly indicates … major chronological" disparities between ^{14}C and archaeo-history for the early historical period (Bruins 2001). Also, a 1989 summary review in *Radiocarbon* noted that the "incompatibility between … radiocarbon dates and the archaeologic/historic dates of Mesopotamia and Egypt" was a major problem (Weinstein 1989). Too-early ^{14}C dates occur from the earliest historical times until the mid second millennium BC. Disparities vary between about one and three centuries, depending on the historical period and location. The ^{14}C dates are from a variety of samples (many short-lived) and have been processed by numerous researchers; although there is scatter, the problem remains prevalent.

Consequently, some Ancient Near Eastern archaeologists have gone on record stating that they do not accept dates based on ^{14}C. For example, a reviewer of ^{14}C dates from Sardinia concluded: "I will only accept … dates provided by [^{14}C] as indicative when they do not blatantly contradict information already obtained by using [archaeological] methods" (Tinè 1998). And a respected Egyptologist says similarly: "I am mistrustful … [^{14}C dating] does not often match with historical dating" (Wiener et al. 1995). Too, some archaeologists have said that if they attempt to publish ^{14}C dates contradicting archaeo-historical chronologies, their papers are rejected (Nelson et al. 1990). One archaeologist, reviewing the situation for the eastern Mediterranean, concluded blandly: "… radiocarbon dates are invoked if they support a particular hypothesis … and dismissed if they do not" (Merrillees 1992).

Of course, it might be that there are errors in the archaeo-historical chronologies of the Ancient Near East. All such chronologies ultimately derive from (archaeo-historical synchronisms with) Egypt (James 1991; Knapp 1992). Hence, if there are errors in Ancient Near Eastern chronologies, then their genesis lies in Egyptian chronology. In fact, Egyptian chronology does not have secure foundations (Cryer 1995; Rohl 1995; Hagens 1996)—and some workers have argued for revising it. Arguments have been made for both earlier and later dates.

My purpose here is not to evaluate the chronology of the Ancient Near East. Rather, I wish to address a closely related question that persistently arises in discussions about that chronology: is it plausible that early-historical ^{14}C dates are too early?

Section 2 shows that the Mediterranean Sea was severely deficient in ^{14}C during the early historical period. Section 3 discusses how a ^{14}C-deficient sea can lead to ^{14}C-deficient surface air downwind from the sea. Section 4 hypothesizes that the ^{14}C-deficient Mediterranean caused ^{14}C dates in the Ancient Near East to be too early. The Excursus (following Section 4) briefly considers dendrochronology (there are no relevant varves).

2. THE OLD SEA

2.1. Stagnation Beginning

The modern oceanography of the Mediterranean Sea is briefly reviewed in the Appendix. The paleoceanography is known to have been very different. During the last ice ages, the Black Sea was actually a freshwater lake (with no input from the Mediterranean; Lane-Serff et al. 1997). As the ice ages ended, levels of the oceans, and thus the Mediterranean Sea, rose. Mediterranean water began pouring over what is today the Bosporus Strait, into what was then the Black Lake. The saline Mediterranean water, being much more dense than freshwater, flowed to the bottom of the Black Lake. The Black freshwater was therefore forced up and out of the lake. It flowed over the incoming Mediterranean water, through the Bosporus Strait, and out into the eastern Mediterranean (Lane-Serff et al. 1997; Aksu et al. 1999).

This caused a large reduction in the salinity, and hence density, of surface water in much of the eastern Mediterranean (Fontugne et al. 1989; Aksu et al. 1995; Kallel et al. 1997; Lane-Serff et al. 1997). Roughly concurrent with this was greater (freshwater) run-off from rivers discharging into the Mediterranean, most notably the Nile, and a substantial increase in the regional effective precipitation (Fontugne et al. 1994; Gasse and Van Campo 1994; Kallel et al. 1997; Martinez-Ruez et al. 2000; Roberts et al. 2001)—due to general climatic conditions, partially caused by orbital forcing (Rossignol-Strick 1983). That further reduced the surface-water salinity (and hence density).

The reduced-density surface water greatly diminished the formation of new intermediate water in the eastern Mediterranean, and the formation of new Eastern Mediterranean Deep Water (EMDW; see Appendix) was essentially stopped. The EMDW, and perhaps also some intermediate water, that were present beforehand largely stagnated (Vergnaud-Grazzini et al. 1989; Aksu et al. 1995; Lane-Serff et al. 1997; Kallel et al. 1997; Murat and Got 2000). The reduced-density surface water and reduced salt input from intermediate water likely also led to greatly diminished formation of Western Mediterranean Deep Water (WMDW), whose residence time (i.e. ventilation time) would then have increased manyfold (Kallel et al. 1997).

While waters stagnated, their oxygen content gradually decreased, as the oxygen was utilized for degradation of organic matter. The resulting near-anoxia was recorded clearly in sediments. The ^{14}C dates for its beginning vary, but 8250 ± 500 BC seems probable (Troelstra et al. 1991; Jorissen et al. 1993; Fontugne et al. 1994; Aksu et al. 1995; Thomson et al. 1995), dated by applying standard ^{14}C calibration (Stuiver et al. 1998). The stagnation likely began 500–1000 years earlier.

2.2. Waters Aging

In a stratified ocean or sea, subsurface waters acquire ^{14}C only from surface waters, which in turn acquire ^{14}C from the atmosphere. Hence, waters that have been below the surface and not mixed with surface waters for a long time are ^{14}C-deficient due to normal radioactive decay, and thus appear old (Siegenthaler 1989; Lassey et al. 1990). (Subsurface waters have been measured with ages as high as 2000 ^{14}C years in the Pacific Ocean.) During the Mediterranean stagnation, ^{14}C in

EMDW, and likely in some WMDW and perhaps too intermediate water, would not have been replenished and would have radioactively decayed; so these waters would appear old.

The stagnation is the main factor that would have resulted in old water. There are at least three additional factors that could have increased ageing, to an unknown degree.

First, the African and Eurasian/Anatolian tectonic plates converge in the eastern Mediterranean, forming the Hellenic Arc of volcanism (Keller et al. 1990), which discharges (^{14}C-depleted) carbon. The discharge is believed to be largely due to limestone decarbonization (Hubberten et al. 1990). There do not appear to be any estimates of the size of this discharge, but all additional carbon would have contributed to EMDW ^{14}C deficiency—and increased the concentration of total CO_2.

Second, the Black water that was emptied into the Mediterranean might also have been old (e.g. due to Black stratification). Indeed, Black ^{14}C dates from millennia prior to the ending of Black surface freshness are roughly 1000 ^{14}C years older than dates indicated by tephrachronology, varve counting, and paleogeomagnetic tests (Arthur and Dean 1998: Section 3). Additionally, a study found that the regional marine reservoir effect near an island in the Aegean, where Black water would have flowed, was roughly zero, or negative, at about the time when the Black freshwater started to be emptied and then increased to about 150 ^{14}C years during the next millennium or so (the study drew no conclusions for after that time) (Facorellis et al. 1998).

Third, surface water in the eastern Mediterranean might also have been old, for three reasons. First, it was substantially derived from Black freshwater. Second, it would have incorporated some of the old subsurface waters (whenever subsurface waters were formed). Third, ^{14}C-depleted carbon gases that were vented at the sea bottom might have accumulated to form bubbles, which could then rise and dissolve in overlying waters. At present, none of these factors can be even roughly quantified. Presumably, though, the effect of each became stronger later in the stagnation.

(One modeling study indicated that stagnating EMDW would diffuse upward and disperse after roughly 2500 years [Myers et al. 1998]. The model, however, assumed vertical diffusion that is an order of magnitude too big for largely stagnant water [Lueck and Mudge 1997]; thus the model's dispersion time is an order of magnitude too small. Also, the model indicated that EMDW would stratify during stagnation—even during 2500 years; stratification of EMDW is also indicated by studies of benthic foraminifera [Jorissen 1999]. Such stratification would inhibit diffusion.)

Furthermore, throughout the stagnation, organic matter (mainly CH_2O) and calcium carbonate ($CaCO_3$) would have been input to EMDW from the surface. To consider the fate of those inputs, I draw an analogy with the modern Black Sea, whose deep water has been stagnant for the last 1500 years or more (Jones and Gagnon 1994) (and Black deep water is also thus anoxic and sulfidic). In the deep water, a portion of the inputs are converted thusly: $2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S$ and $CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$ (Goyet et al. 1991). Large inputs over time have led to Black deep water having a total CO_2 concentration nearly double that of the deep waters of the modern Mediterranean and oceans (Goyet et al. 1991; Jones and Gagnon 1994: Table 2; Hiscock and Murray 2002). Additionally, the partial pressure of CO_2 in Black deep water is a few times higher than that in the deep waters of the modern Mediterranean and oceans (pCO_2 up to 3000 µatm: see Goyet et al. [1991]; data from a recent expedition indicates higher pCO_2 still—data from Hiscock and Murray [2002], with calculations by the author using the CO2SYS program [Lewis and Wallace 1998]).

During the stagnation, inputs of organic matter and calcium carbonate would have substantially increased the concentration of carbon in EMDW. To some extent, they would also reduce the average age of the carbon. Such inputs—originating from rivers, the atmosphere, and the Black Sea—would likely have been larger than in modern times (modern annual inputs contain > 1 Tmol C [Copin-Montégut 1993]). Indeed, sediments indicate that the input flux of organic matter was much larger during the stagnation than today (Martinez-Ruez et al. 2000; Calvert et al. 1992).

2.3. Stagnation Ending

The calibrated ^{14}C date for the end of EMDW stagnation (near-anoxia) is about 4500 BC (Thomson et al. 1995; van Santvoort et al. 1996). This date, however, should be considered as an earliest-possible date, because the samples might have been affected by the sea ^{14}C deficiency (the beginning date is unlikely to be so affected, since the relevant sediments were deposited near the start of the stagnation). Other studies indicate a date well after 4500 BC:

- A largely stagnant Mediterranean would be expected to reduce the efflux at Gibraltar (Kallel et al. 1997): sediments do indicate such a reduction, lasting from roughly 8000 BC to roughly 1000–0 BC (Vergnaud-Grazzini et al. 1989).
- Sediments in the Adriatic show that EMDW formation there was minute until nearly AD 400 (^{14}C dated, supported by tephrachronology). See below for discussion.
- Sediments in the Black Sea indicate that surface water there remained largely fresh until about AD 0–400 (Arthur and Dean 1998; Jones and Gagnon 1994).

The Mediterranean circulation during the stagnation differed greatly from the modern circulation. First, deepwater currents were pretty much non-existent (see above). Second, there is strong sedimentological evidence showing that surface currents in the easternmost Mediterranean flowed southward (Stanley and Galili 1996)—the reverse of today (this might have been due to the outflow of Black freshwater from the Aegean). Third, sea-surface salinity reconstructions suggest that currents flowed westward at the Sicilian-Tunisian Strait (Kallel et al. 1997)—again, the reverse of today likely due to outflowing Black freshwater. Fourth, in the Adriatic Sea, both surface and bottom currents were unlike modern ones (see below).

Mediterranean sediments display gradual increases in various benthic indicators prior to the appearance of those for fully developed modern conditions: this indicates that the stagnation ended slowly (Jorissen 1999). The primary cause of this was likely that the EMDW formation rate in the Adriatic was minute. Indeed, some Adriatic sediments show that surface waters there had low fluvial input (which is crucial for EMDW formation—see the Appendix) until roughly AD 200 ± 300 (Capotondi et al. 1999; Asioli 1996). Other studies have concluded that Adriatic surface currents did not attain their modern state until roughly AD 0 (Fontugne et al. 1989). Additionally, several benthic indicators point to extremely weak Adriatic EMDW formation until AD 400 ± 200 (Fontugne et al. 1989). Likely, then, most EMDW formation occurred directly in the open sea, rather than indirectly via the subsurface Adriatic (see Appendix). (Thanks to L Capotondi and M R Fontugne for helpful discussions on these points.)

The slow development of the modern circulation suggests that the ^{14}C-indicated date of 4500 BC, although perhaps too early, need not be in error by millennia. Rather, the date likely corresponds with when EMDW started recovering from near-anoxia, as new EMDW was formed. (In modern times, newly formed—hence oxygenated—EMDW sinks to the bottom of the basin, and this presumably also occurred when the stagnation was ending.) The ^{14}C-indicated date thus corresponds with when the stagnation started ending. The dates within a few centuries of year 0, on the other hand, correspond with when the modern circulation finished developing. Indeed, the ^{14}C-indicated date was obtained from the fraction of sediment that is derived from surface and upper-intermediate waters (from the remains of pelagic foraminifera); so it is only the (unknown) ages of those waters that would affect this date's accuracy.

2.4. Summary

After the end of the last ice age, much of the Mediterranean Sea stagnated. The stagnation was near-total for EMDW; it also affected other waters in the sea to an unknown degree. The stagnation began to end sometime after 4500 BC—possibly many centuries after. This ending was gradual. Because of the stagnation, the sea became very deficient in ^{14}C; other processes augmented this deficiency. EMDW was several millennia old and had a very high carbon concentration. The time required to empty out all the aged water is unknown, but the emptying would likely have been complete before the modern circulation was fully developed—i.e. roughly by year 0.

3. OLD AIR

3.1. Empirical Observations

Century-scale regional surface-atmospheric ^{14}C deficiencies are known to occur today (only) in areas where old seawater outcrops or upwells to the surface. The following examples have been reported:

- Along the coast of Ecuador, a study of the surface atmosphere ^{14}C age during 1992–1993 found that the age abruptly increased by over 350 ^{14}C years immediately after the onset of the upwelling of old Pacific water (related to El Niño) (Rozanski et al. 1995). The researchers attributed the age increase to oceanic degassing of ^{14}C-deficient CO_2. The measuring station is 250 km inland (and both location and $^{13}C/^{12}C$ rule out fossil fuel effects).
- In the northwestern United States, Olympic Peninsula, a study of tree rings grown during 1861–1885 found that tree-ring ^{14}C ages increased by about 125 ^{14}C years during 1868, coinciding with an extremely strong El Niño event (Damon et al. 1996). (A study of tree rings grown during 1930–1955 found a correlation between tree-ring ^{14}C ages and El Niño conditions generally, though there was no large-scale ^{14}C event [Jirikowic and Kalin 1993].)
- Around the Southern Ocean where old water out crops (Siegenthaler 1989; Braziunas et al. 1995), the surface-atmosphere ^{14}C age is about 175 ^{14}C years (Levin et al. 1987). The measuring station is on the coast of the Weddell Sea.
- In northwestern Thailand, a study of tree rings grown during 1952–1975 found that the ^{14}C ages of rings from 1953 and 1954 were roughly 200 ^{14}C years too old (Hua et al. 2000a, 2000b). The investigators suggested that this was due to exceptional monsoonal upwelling of very old water in the northern Indian Ocean. The location where the trees grew is about 225 km inland.
- Over the Arabian Sea, the surface-atmosphere ^{14}C age ranges over about 200 ^{14}C years (Bhushan et al. 1997; Dutta et al. 2000). There is no indication of effects by fossil fuels. Upwelling in the Arabian Sea occurs in summer, forced by the wind stress (and its curl); it also occurs in winter, forced by convective overturning—which is due to wind-induced evaporation and cooling.

Some researchers have been reluctant to accept the above evidences, for the following reason. With usual air–sea equilibration processes, the time required for seawater ^{14}C to reach equilibrium with the atmosphere is about 5–10 years (Lassey et al. 1990). And, air parcels remain over sea areas for only days at a time. Thus, those processes are far too slow to induce the regional surface-atmospheric ^{14}C deficiencies evidenced above (though Levin et al. [1987] argue that they are sufficient in Antarctica—and Braziunas et al. [1995] indicate that they are not). Furthermore, degassed carbon is believed to quickly disperse within the atmospheric boundary layer. Hence the theories conflict with the data. Nonetheless, the above evidences seem to well establish that century-scale regional surface-atmospheric ^{14}C deficiencies do occur.

3.2. Theoretical Considerations

I do not propose here a theoretical explanation for air-aging. Indeed, at present, I cannot estimate the ^{14}C-deficiency, areal extent, or duration of air-aging that would result under given geophysical (and biological?) conditions. In this (optional) subsection, though, I offer some considerations that might assist workers who plan to undertake the research that is needed to understand the air-aging process.

First, I list some factors that could potentially enhance air–sea gas exchange in areas where subsurface waters are brought to the surface:

- The sea mixed layer might not be the correct concept (for calculating gas exchange) in upwelling/overturning areas, where homogeneous water masses extend to substantial depths.
- Some dissolved (carbon-based) gas could exsolve during upwelling, due to its depressurization.
- The partial pressures of gases are greater in upwelled water than in advected water, and the gases are often at or near saturation.
- The above factors, together with deep-sea gas venting, might lead to underwater bubble formation, and some bubbles might then reach the surface.
- There might be some (unknown) effect involving air–sea moisture cycling, with ^{14}C-deficient moisture then blown over land.
- Biological processes might play a role, as biological activity tends to be large in upwelling areas.

Note that different factors might operate in different places—and sometimes together.

Second, I note that there are other reports indicating that CO_2 does not disperse within the surface atmosphere in the way that is theoretically expected. Studies have been made of ^{14}C-enriched CO_2 gas dispersion within a few kilometers of nuclear power stations in Canada (King and Carter 1999), Germany (Levin et al. 1988), and the United Kingdom (Otlet et al. 1990). These studies employed the standard model of gas dispersion (the Gaussian Plume model [Pasquill and Smith 1983]). The model often underestimated, by a small-integer factor, the observed $^{14}CO_2$ concentrations; it never significantly overestimated them. The underestimation generally increased with distance, particularly along the direction of the prevailing winds (which is what is relevant to the present work). Underestimation is problematic, since the model is expected to conservatively overestimate (the model is widely used in regulatory applications).

Neither the standard (Gaussian Plume) model nor any other model of gas dispersion that has been developed (Arya 1999; Pasquill and Smith 1983) can account for the CO_2 observations presented in this section (S P Arya, private communication, May 2001). For other gases, though, the model seems to work as expected, e.g. a study of tritium (as ^{3}HHO) dispersion from nuclear power stations in Canada found that the model significantly overestimated three-quarters of the observations and significantly underestimated only a tenth—by a factor of 2 at most (Chouhan and Davis 2001).

Note that nuclear power stations are essentially continuous point sources. In contrast, a large sea area is essentially a continuous line source, for an adjacent land mass. Simple geometry implies that gas concentration downwind from line sources declines much more slowly than gas concentration downwind from point sources. Degassing seas would thus be expected to induce large gas concentrations at substantial distance.

4. DISCUSSION

We now have three things to consider. First, we have evidence from archaeo-history that ^{14}C dates in and downwind from the Mediterranean Sea are too early (Section 1). Second, we have evidence that the sea was circulating severely ^{14}C-deficient carbon, during the time from which the ^{14}C dates appear to be too early (Section 2). Third, we have evidence that marine degassing of ^{14}C-deficient carbon can result in the surface-atmospheric carbon becoming ^{14}C-deficient (Section 3). It is thus natural to hypothesize that degassing by the Mediterranean led to the too-early ^{14}C dates.

We do not know if Mediterranean deep waters reached the surface in the same sea areas during the early historical period as they do in modern times. It seems reasonable, though, to assume this was broadly the case. In modern times, however, in the areas where deep waters reach the surface, they do so only intermittently during wintertime. How could intermittent wintertime-only old water account for the terrestrial ^{14}C dates being too early? I suggest three mechanisms, and also observe that these mechanisms might account for some of the scatter apparent in ^{14}C dates.

First, the main growing season for relevant ^{14}C-dated samples very likely included winter. Indeed, the region downwind from the Mediterranean receives almost all its precipitation around winter, at least in modern times (Taha et al. 1981; New et al. 1999) (and plants need moisture to grow). Additionally, the Nile floods, which occur in summer–autumn, imply that in Egypt almost all growing seasons include winter.

Second, intermediate water whose formation incorporated some EMDW would likely have had a high concentration of old carbon (see subsection 2.2). Hence it might have acted as a source of old carbon. In modern times, the principal areas where intermediate water could exchange carbon directly with the atmosphere are where convection occurs: where intermediate water forms and where WMDW forms. Secondary areas might exist at the straits where surface and subsurface waters mix: the Sicilian-Tunisian Strait (Wu and Haines 1996) and the Strait of Gibraltar (Bryden et al. 1994). These areas are upwind from the sites that are postulated to have had terrestrial ^{14}C deficiencies. (Mediterranean winds generally blow off the sea into Egypt, Israel-Palestine, etc. [Barry and Chorley 1998; Reddaway and Bigg 1996; Nicholson 1996].) Intermediate convection occurs much more than deep convection.

Third, bubbles of CO_2 might have formed in subsurface waters. If the waters were close to saturation, only a small perturbation—an injection of additional dissolved (inorganic) carbon, a change in temperature, a wave—would be needed. Some water might even have been above saturation, after being raised from the deep, since the saturation concentration increases with pressure. Once formed, bubbles escape to the surface.

Lastly, I note that the hypothesis solves a puzzle about ^{14}C dates (of charcoal samples) from Sudan; these dates are consistent with archaeo-historical chronology (Lange 1998)—why these? The answer seems to be that Sudan is so far downwind.

In conclusion, the hypothesis is plausible, and further research is required to verify or refute it. It would be ironic if the "cradle of civilization" turned out to be in just the right place and time to make its ^{14}C dates erroneous, but that might be the case.

ACKNOWLEDGMENTS

Appreciative thanks are offered to W J Ingram, A J T Jull, A G Maxwell, J W Murray, R M Porter, and the staff of the Science Reference and Information Service.

EXCURSUS

Anatolian Dendro-Archaeology

In some areas of the world, radiocarbon dating has been calibrated via dendrochronology. There is no dendrochronology for the region downwind from the Mediterranean (assuming that wind patterns in ancient times were similar to modern ones), but there is a dendrochronology for nearby Anatolia (roughly modern Turkey) (Kuniholm et al. 1996). In principle, this dendrochronology could be used to date some wood from nearby archaeological contexts, and thus assist in developing a chronology for the Ancient Near East. Unfortunately, reported attempts to put this principle into practice have encountered severe statistical problems. I first illustrate this with an example. (Thanks to R M Porter, for alerting the author to some of the problems, and P I Kuniholm, for comments on a draft of this section.)

Wood from a gateway was matched with the Anatolian dendrochronology (Kuniholm et al. 1993). Two statistical tests were employed: correlation (of rings widths from the gateway wood with ring widths from the master dendrochronology) and trend (number of years in which gateway and master ring widths increased or decreased together). The end date from the gateway wood was found to match three calendar dates (i.e. dates from the master dendrochronology) with very high confidence on both tests: 1258 BC, 1140 BC, and 981 BC. For 981 BC, the significance of the correlation was 99.99995% and of the trend, 99.5%. The investigators matched the wood to 1140 BC (correlation significance 99.9995%; trend significance 99.99999%). The high significances of the other two dates were attributed to randomness.

The exclusion of the 981 BC date is not credible. Additionally, the existence of three widely-separated dates with such high statistical confidence implies that there are serious problems with the statistical analyses that were employed. Hence, almost any conclusions based on those analyses should be regarded as being at least questionable.

The wood matched from the gateway had 218 annual rings. Those rings, though, were not from a single tree, but from a mini-dendrochronology that was constructed from fragments of 26 different trees, which had been used to build the gateway (Kuniholm et al. 1993). Almost all of those 26 trees had fewer than 80 rings recovered; most had fewer than 60. With fewer than 80 rings, dendrochronological dating can easily fail (Baillie 1995). Indeed, the Anatolian investigators themselves claim that at least 100 rings are typically needed to be certain of a match. The problem is compounded because in the Near East, during ancient times, wood was often reused. In fact, this still occurs in modern times; for example, the investigators have also concluded that the joist in a modern Turkish house is over 6000 years old (Kuniholm 2001). Thus, the matches claimed for some of the 26 trees could easily be false. Hence, the construction of the mini-dendrochronology is likely erroneous, at least in part.

Moreover, every other major dendrochronology known to us has been built using a single species of tree, with samples grown in similar climatic regimes. Yet Anatolian dendrochronological work (such as the gateway matching) has been done using a mixture of deciduous and coniferous trees, which sometimes have been taken from more than one of Anatolia's different climatic regimes. This plainly makes the above comparisons of ring widths fragile.

The Anatolian master dendrochronology is actually a floating chronology (i.e. it does not extend continuously from the past to the present: there are gaps). It is anchored in part by ^{14}C dating. The publication of this anchoring relied upon a data model that had 22% of the data lying outside the 2σ-confidence range (Kuniholm et al. 1996: Table 1). This problem was later fixed (Kromer et al. 1997), but it again illustrates the low quality of the statistical analyses employed in Anatolian dendrochronology.

The floating nature of the Anatolian dendrochronology introduces another concern: a wood sample might have grown at time for which there is no match with the master dendrochronology; hence dating requires extra care to avoid false-positive matching errors. There are also additional problems with Anatolian dendrochronological work, which will not be detailed here (e.g. the use of D-scores, which are meaningless, and inappropriate calculations in time series analyses [Yamaguchi 1986; Monserud 1986; Tong 1990]).

The gateway matching seems to be the work in Anatolian dendrochronology that has been published in most detail. Presumably, though, the same analyses (and principal investigators) have been employed in all such work. Furthermore, 218 rings is more than is usually available in dendrochronological dating: fewer rings would be expected to decrease the reliability of the analyses. In conclusion, Anatolian dendrochronology should be regarded as suspect and in need of independent scrutiny.

REFERENCES

Aksu AE, Yasar D, Mudie PJ. 1995. Paleoclimatic and paleoceanographic conditions leading to development of sapropel layer S1 in the Aegean Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 116:71–101.

Aksu AE, Hiscott RN, Yasar D. 1999. Oscillating Quaternary water levels of the Marmara Sea. *Marine Geology* 153:275–302.

Arthur MA, Dean WA. 1998. Organic-matter production and preservation and evolution of anoxia in the Holocene Black Sea. *Paleoceanography* 13:395–411.

Arya SP. 1999. *Air pollution meteorology and dispersion.* Oxford University Press.

Asioli A. 1996. High resolution foraminifera biostratigraphy in the central Adriatic basin during the last deglaciation. *Memorie dell'Istituto Italiano di Idrobiologia* 55:197–217. (See especially Figure 5)

Baillie MGL. 1995. *A slice through time: dendrochronology and precision dating.* Chapter 3. London: Batsford.

Barry RG, Chorley RJ. 1998. *Atmosphere, weather & climate.* Routledge. (See especially Figures 8.27, 8.29)

Bhushan R, Krishnaswami S, Somayajulu BLK. 1997. ^{14}C in air over the Arabian Sea. *Current Science* 73: 273–6.

Bonani G, Haas H, Hawass Z, Lehner M, Nakhla S, Nolan J, Wenke R, Wölfli W. 2001. Radiocarbon dates of Old and Middle Kingdom monuments in Egypt. *Radiocarbon* 43(3):1297–320. (See also Haas and Doubrava [1998], referenced by Bonani et al.)

Braziunas TF, Fung IY, Stuiver M. 1995. The preindustrial atmospheric $^{14}CO_2$ latitudinal gradient as related to exchanges among atmospheric, oceanic, and terrestrial reservoirs. *Global Biogeochemical Cycles* 9:565–84.

Bruins HJ. 2001. Near East chronology: towards an integrated ^{14}C time foundation. *Radiocarbon* 43(3):1147–54.

Bruins HJ, van der Plicht J. 2001. Radiocarbon challenges archaeo-historical time frameworks in the Near East: the Early Bronze Age of Jericho in relation to Egypt. *Radiocarbon* 43(3):1321–32.

Bryden HL, Candela J, Kinder TH. 1994. Exchange through the Strait of Gibraltar. *Progress in Oceanography* 33:201–48.

Calvert SE, Nielsen B, Fontugne MR. 1992. Evidence from nitrogen isotope ratios for enhanced productivity during formation of eastern Mediterranean sapropels. *Nature* 359:223–5.

Capotondi L, Borsetti AM, Morigi C. 1999. Foraminiferal ecozones, a high resolution proxy for the late Quaternary biochronology in the central Mediterranean Sea. *Marine Geology* 153:253–74. (See especially Figure 9)

Chouhan SL, Davis PA. 2001. Testing the atmospheric dispersion model of CSA N288.1 with site-specific data. *AECL* 12099. (Atomic Energy of Canada Limited report series: ISSN 0067-0367)

Copin-Montégut C. 1993. Alkalinity and carbon budgets in the Mediterranean Sea. *Global Biogeochemical Cycles* 7:915–25.

Crawford H. 1991. *Sumer and the Sumerians.* Cambridge University Press. p 18–20.

Cryer FH. 1995. Chronology: issues and problems. In: Sasson JM, editor. *Civilizations of the Ancient Near East.* Macmillan. p 651–64.

Damon PE, Burr G, Peristykh AN, Jacoby GC, D'Arrigo RD. 1996. Regional radiocarbon effect due to thawing of frozen earth. *Radiocarbon* 38(3):597–602.

Dickinson O. 1994. *The Aegean Bronze Age.* Cambridge University Press. p 17–20.

Dutta K, Bushan R, Somayajula BLK. 2000. Anthropogenic radiocarbon in Bay of Bengal. Paper presented at the 17th International Radiocarbon Conference. Judean Hills, Israel, June 2000.

Facorellis Y, Maniatis Y, Kromer B. 1998. Apparent ^{14}C ages of marine mollusk shells from a Greek island: calculation of the marine reservoir effect in the Aegean Sea. *Radiocarbon* 40(2):963–73.

Fontugne MR, Paterne M, Calvert SE, Murat A, Guichard F, Arnold M. 1989. Adriatic deep water formation during the Holocene. *Paleoceanography* 4:199–206.

Fontugne M, Arnold M, Labeyrie L, Paterne M, Calvert SE, Duplessy J-C. 1994. Paleoenvironment, sapropel chronology and Nile river discharge during the last 20,000 years as indicated by deep-sea sediment records in the eastern Mediterranean. In: Bar-Yosef O, Kra RS, editors. *Late Quaternary chronology and paleoclimates of the eastern Mediterranean*. Tucson: Radiocarbon. p 75–88.

Gasse F, Van Campo E. 1994. Abrupt post-glacial events in West Asia and North Africa monsoon domains. *Earth and Planetary Science Letters* 126:435–46. (See section 3.2)

Görsdorf J, Dreyer G, Hartung U. 1998. New ^{14}C dating of the archaic royal necropolis Umm El-Qaab At Abydos (Egypt). *Radiocarbon* 40(2):641–7.

Goyet C, Bradshaw AL, Brewer PG. 1991. The carbonate system in the Black Sea. *Deep-Sea Research* 38: S1049–S1068.

Guidi A, Whitehouse R. 1996. A radiocarbon chronology for the Bronze Age: the Italian situation. *Acta Archaeologica* 67:271–82.

Hagens G. 1996. A critical review of dead-reckoning from the 21st dynasty. *Journal of the American Research Center in Egypt* 33:153–63.

Hiscock WT, Murray JW. 2002. *Knorr 2001 cruise data*. [Available at http://www.ocean.washington.edu/cruises/Knorr2001/CruiseData.htm.]

Hua Q, Barbetti M, Jacobsen GE, Zoppi U, Lawson EM. 2000a. Bomb radiocarbon in annual tree rings from Thailand and Australia. *Nuclear Instruments and Methods in Physics Research B* 172:359–65.

Hua Q, Barbetti M, Zoppi U, Lawson EM. 2000b. Regional reduction of atmospheric ^{14}C by upwelling in the tropical Indian Ocean. Paper presented at the 17th International Radiocarbon Conference. Judean Hills, Israel. June 2000.

Hubberten H-W, Bruns M, Calamiotou M, Apostolakis C, Filippakis S, Grimanis A. 1990. Radiocarbon dates from the Akrotiri excavations. In: Hardy DA, editor. *Thera and the Aegean world III*. Volume 3. London: Thera Foundation. p 179–87.

James P. 1991. *Centuries of darkness* London: Jonathan Cape. (For references to reviews and follow-up work, see http://www.centuries.co.uk)

Jirikowic JL, Kalin RM. 1993. A possible paleoclimatic ENSO indicator in the spatial variation of annual tree-ring ^{14}C. *Geophysical Research Letters* 20:439–42.

Jones GA, Gagnon AR. 1994. Radiocarbon chronology of Black Sea sediments. *Deep-Sea Research* I 41:531–57.

Jorissen FJ. 1999. Benthic foraminiferal successions across Late Quaternary Mediterranean sapropels. *Marine Geology* 153:91–101.

Jorissen FJ and nine others. 1993. Late Quaternary central Mediterranean biochronology. *Marine Micropaleontology* 21:169–189.

Kallel N, Paterne M and seven others. 1997. Enhanced rainfall in the Mediterranean region during the last sapropel event. *Oceanologica Acta* 20:697–712.

Keller J, Rehren T, Stadlbauer E. 1990. Explosive volcanism in the Hellenic Arc. In: Hardy DA, editor. *Thera and the Aegean world III*. Volume 2. London: Thera Foundation. p 13–26.

King KJ, Carter B. 1999. Estimates of atmospheric ^{14}C Discharges from CANDU facilities. *CANDU Owners Group Reports* 176. (Additional data supplied by K J King, private communication, January 2002)

Knapp AB. 1992. Mesopotamia, history of (chronology). In: Freeman DN, editor. *The Anchor Bible dictionary*. Volume 4. Doubleday. p 714–20.

Kromer B, Fasani L, Kuniholm PI, Manning S. 1997. Precise absolute dates of archaeological sites by ^{14}C wiggle-matching of floating tree-ring sections. Paper presented at the 16th International Radiocarbon Conference. Groningen, The Netherlands. June 1997.

Kuniholm PI. 2001. *Aegean Dendrochronology Project December 2001 progress report*. [Available at http://www.arts.cornell.edu/dendro/2001news/adp2001.html]

Kuniholm PI, Tarter SL, Griggs CB. 1993. Dendrochronological report. In: Summers GD, editor. *Tılle Höyük 4*. Appendix 2. British Institute of Archaeology at Ankara.

Kuniholm PI, Kromer B, Manning SW, Newton M, Latini CE, Bruce MJ. 1996. Anatolian tree rings and the absolute chronology of the eastern Mediterranean, 2200–718 BC. *Nature* 381:780–783. (Annotations by C Renfrew on pages 733–4)

Lane-Serff GF, Rohling EJ, Bryden HL, Charnock H. 1997. Postglacial connection of the Black Sea to the Mediterranean and its relation to the timing of sapropel formation. *Paleoceanography* 12:169–74.

Lange M. 1998. Wadi Shaw 82/52: ^{14}C dates from a peridynastic site in northwest Sudan, supporting the Egyptian historical chronology. *Radiocarbon* 40(2):687–692.

Lassey KR, Manning MR, O'Brien BJ. 1990. An overview of oceanic radiocarbon. *Reviews in Aquatic Sciences* 3:117–46.

Levin I, Kromer B, Wagenbach D, Münnich KO. 1987. Carbon isotope measurements of atmospheric CO_2 at a coastal station in Antarctica. *Tellus* 39B:89–95.

Levin I, Kromer B, Barabas M, Münnich KO. 1988. Environmental distribution and long-term dispersion of reactor $^{14}CO_2$ around two German nuclear power plants. *Health Physics* 54:149–56.

Lewis E, Wallace DWR. 1998. Program developed for CO_2 system calculations. *ORNL/CDIAC* 105. Oak Ridge: Oak Ridge National Laboratory. (The CO2SYS program and documentation are available via http://cdiac.esd.ornl.gov/oceans/co2rprt.html)

Lueck RG, Mudge TD. 1997. Topographically induced mixing around a shallow seamount. *Science* 276: 1831–3.

Martinez-Ruiz F, Kastner M, Paytan A, Ortega-Huertas

M, Bernasconi SM. 2000. Geochemical evidence for enhanced productivity during S1 sapropel deposition in the eastern Mediterranean. *Paleoceanography* 15: 200–9.

Mazar A. 1992. *Archaeology of the land of the Bible*. Doubleday. p 28–9.

Merrillees RS. 1992. The absolute chronology of the Bronze Age in Cyprus. *Bulletin of the American Schools of Oriental Research* 288:47–52.

Monserud RA. 1986. Time-series analyses of tree-ring chronologies. *Forest Science* 32:349–72.

Murat A, Got H. 2000. Organic carbon variations of the eastern Mediterranean Holocene sapropel: a key for understanding formation processes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158:241–57.

Myers PG, Haines K, Rohling EJ. 1998. Modeling the paleocirculation of the Mediterranean: the last glacial maximum and the Holocene with emphasis on the formation of sapropel S_1. *Paleoceanography* 13:586–606.

Nelson DE, Vogel JS, Southon JR. 1990. Another suite of confusing radiocarbon dates for the destruction of Akrotiri. In: Hardy DA, editor. *Thera and the Aegean world III.* Volume 3. London: Thera Foundation. p 197–206. (See especially p 206)

New M, Hulme M, Jones P. 1999. Representing twentieth-century space–time variability. Part I: development of a 1961–90 mean monthly terrestrial climatology. *Journal of Climate* 12:829–56. [See also http://ipcc-ddc.cru.uea.ac.uk/cru_data/cru_index.html]

Nicholson SE. 1996. A review of climate dynamics and climate variability in eastern Africa. In: Johnson TC, Odada EO, editors. *Limnology, Climatology and Paleoclimatology of the East African Lakes*. Gordon and Breach. p 25–56. (See especially Figure 2)

Otlet RL, Walker AJ, Fulker MJ. 1990. Survey of the dispersion of ^{14}C in the vicinity of the UK reprocessing site at Sellafield. *Radiocarbon* 32(1):23–30.

Pasquill F, Smith FB. 1983. *Atmospheric diffusion.* John Wiley.

Reddaway JM, Bigg GR. 1996. Climatic change over the Mediterranean and links to the more general atmospheric circulation. *International Journal of Climatology* 16:651–61. (Additional data supplied by J M Reddaway, private communication 1998)

Roberts N, Reed JM. and nine others. 2001. The tempo of Holocene climatic change in the eastern Mediterranean region. *The Holocene* 11:721–36.

Rohl DM. 1995. *A test of time: pharaohs and kings.* London: Century. (See especially Chapters 1–6)

Rossignol-Strick M. 1983. African monsoons, an immediate climate response to orbital insolation. *Nature* 304:46–9.

Rozanski K, Levin I, Stock J, Guevara Falcon RE, Rubio F. 1995. Atmospheric $^{14}CO_2$ variations in the equatorial region. *Radiocarbon* 37(2):509–15.

van Santvoort PJM., de Lange GJ, Thomson J and four others. 1996. Active post-depositional oxidation of the most recent sapropel (S1) in sediments of the Eastern Mediterranean Sea. *Geochimica et Cosmochimica Acta* 60:4007–24.

Siegenthaler U. 1989. Carbon-14 in the oceans. In: Fritz P, Fontes J-C, editors. *Handbook of environmental isotope geochemistry 3*. Elsevier. p 75–137.

Stanley DJ, Galili E. 1996. Sediment dispersal along northern Israel coast during the early Holocene. *Marine Geology* 130:11–7.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration. *Radiocarbon* 40(3):1041–83.

Taha MF, Harb SA, Nagib MK, Tantawy AH. 1981. The climate of the Near East. In: Takahashi K, Arakawa H, editors. *World survey of climatology 9: climates of southern and western Asia.* Chapter 3. Elsevier. (See especially Table V)

Thomson J, Higgs NC, Wilson TRS, Croudace IW, de Lange GJ, van Santvoort PJM. 1995. Redistribution and geochemical behaviour of redox-sensitive elements around S1, the most recent eastern Mediterranean sapropel. *Geochimica et Cosmochimica Acta* 59: 3487–501.

Tinè S. 1998. Unacceptable anomalies or incorrect use of radiocarbon dating in Sardinia? In: Balmuth MS, Tykot RH, editors. *Sardinian and Aegean chronology.* Chapter 6. Oxford: Oxbow Books.

Tong H. 1990. *Non-linear time series* Oxford University Press.

Troelstra SR, Ganssen GM, van der Borg K, de Jong AFM. 1991. A Late Quaternary stratigraphic framework for eastern Mediterranean sapropel S1. *Radiocarbon* 33(1):15–21.

Vergnaud-Grazzini C. and six others. 1989. Mediterranean outflow through the Strait of Gibraltar since 18 000 years BP. *Oceanologica Acta* 12:305–24.

Weinstein J. 1989. Review: chronologies in the Near East. *Radiocarbon* 31(1):101–3.

Wiener M and 12 others. 1995. Discussion. *Ägypten und Levante* 5:121–32.

Wu P, Haines K. 1996. Modeling the dispersal of Levantine intermediate water and its role in Mediterranean deep water formation. *Journal of Geophysical Research* 101:6591–607.

Yamaguchi DK. 1986. Interpretation of cross correlation between tree-ring series. *Tree-Ring Bulletin* 46:47–54.

APPENDIX

Modern Oceanography of the Mediterranean Sea

The sole significant source of water for the Mediterranean is the surface Atlantic. This water flows into the Mediterranean through the shallow (300 m) Strait of Gibraltar and then spreads out eastward; it has a depth of roughly 150 m. Heat and dry continental air cause substantial evaporation, thereby increasing the water's salinity, and hence density. The salinity is naturally greatest in the eastern Mediterranean. There, during winter, cooling makes the surface water dense enough to cause it to sink some hundreds of meters, thereby forming intermediate water; the process involves substantial mixing with, and overturning of, previously formed intermediate water and, often, underlying deep water. Once formed, intermediate water spreads throughout the Mediterranean, beneath the surface water.

Deepwaters too are formed during winter. Some Eastern Mediterranean Deep Water (EMDW) forms concurrently with intermediate water. Most EMDW forms when intermediate water is cooled, thereby becoming denser, via mixing with surface water in the southern Adriatic (which is especially cold due to discharges from rivers, notably the Po—see Figure 1). Western Mediterranean Deep Water (WMDW) forms in northern parts of the western Mediterranean; the process involves substantial mixing and overturning of surface water, intermediate water, and previously formed WMDW. Outside the Adriatic, deepwater formation typically involves an unstratified "chimney" of water that extends from the deep to the surface.

EMDW and WMDW are kept separate by the shallow (350 m) Sicilian-Tunisian Strait, which effectively divides the Mediterranean into two basins. Newly formed deep waters typically sink to the bottom of their respective basins—a few kilometers—forcing older deep waters to upwell and eventually rejoin intermediate water.

Intermediate water and WMDW flow out of the Mediterranean through the Strait of Gibraltar, beneath the inflowing surface water, into the (intermediate) Atlantic. The efflux at Gibraltar is roughly 5% less than the influx, largely due to the surface-water evaporation. The total journey time of the water, from ingress to egress at Gibraltar, depends upon the path taken; it can be up to a little over a century.

Bibliography

Bethoux JP, Gentili B. 1999. Functioning of the Mediterranean Sea: past and present changes. *Journal of Marine Systems* 20:33–47.

Bryden HL, Candela J, Kinder TH. 1994. Exchange through the Strait of Gibraltar. *Progress in Oceanography* 33:201–48.

Harzallah A, Cadet DL, Crepon M. 1993. Possible forcing effects of net evaporation, atmospheric pressure, and transients on water transports in the Mediterranean Sea. *Journal of Geophysical Research* 98: 12341–50.

Robinson AR, Golnaraghi M. 1994. The physical and dynamical oceanography of the Mediterranean Sea. In: Malanotte-Rizzoli P, Robinson AR, editors. *Ocean processes in climate dynamics*. Kluwer Academic. p 255–306.

Schott F, Visbeck M, Send U, Fischer J, Stramma L, Desaubies Y. 1996. Observations of deep convection in the Gulf of Lions. *Journal of Physical Oceanography* 26:505–24.

Wu P, Haines K. 1998. The general circulation of the Mediterranean Sea from a 100-year simulation. *Journal of Geophysical Research* 103:1121–35.

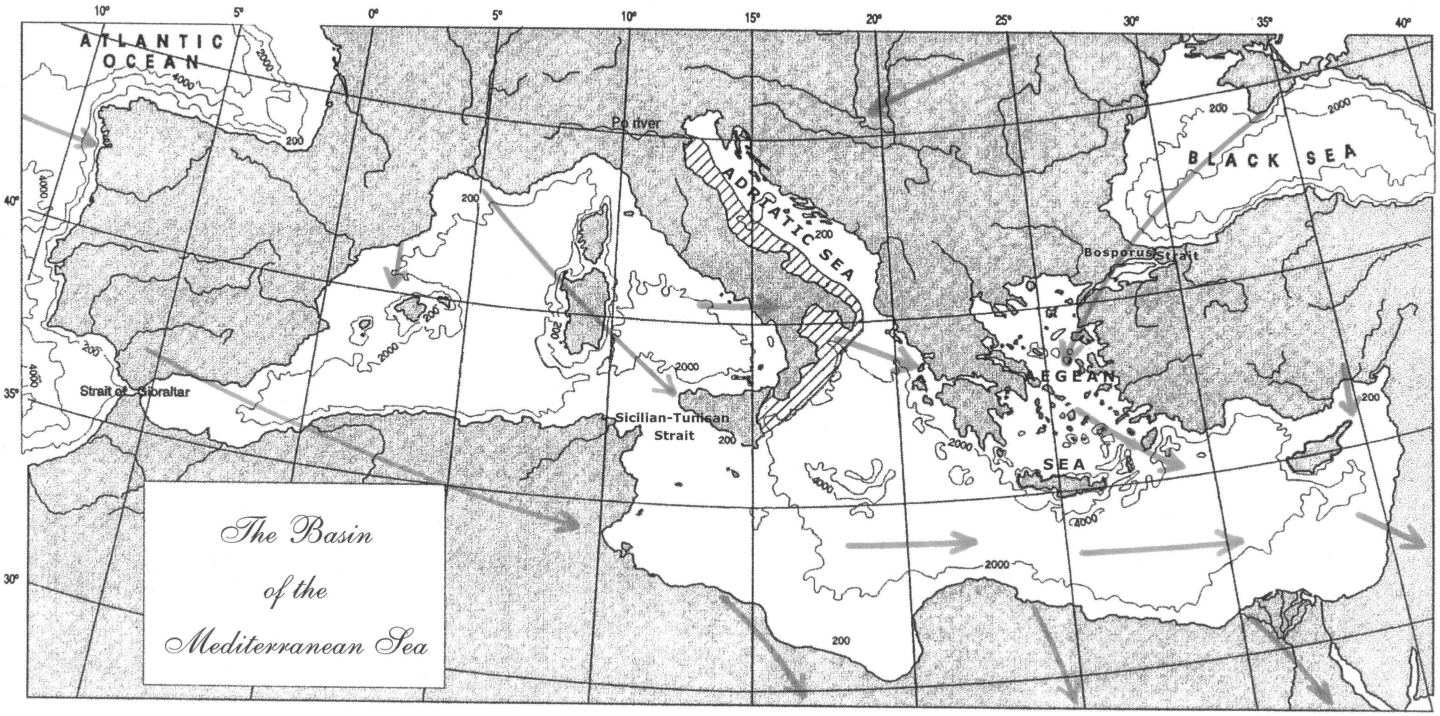

Figure 1 The basin of the Mediterranean Sea. Hatched area indicates the modern spread of freshwater from the Po river discharge. Arrows indicate modern January wind patterns. Adapted from Ariztegui et al. (2000), except wind patterns which are adapted from Barry and Chorley (1998), Nicholson (1996), and Reddaway and Bigg (1996).

https://doi.org/10.1017/S0033822200064833 Published online by Cambridge University Press