A volcanism-based chronology for ancient China—including the Mandate of Heaven

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We investigate a proposal of K.D. Pang and co-workers, who identified ancient Chinese texts that appear to record two major volcanic eruptions. The evidence presented by Pang, and substantial additional evidence, is reviewed: we conclude that Pang's identification of the texts as recording volcanism is correct, but that his designation of the volcanoes is incorrect. We also identify ancient texts recording an earlier eruption, during the reign of the legendary Yellow Emperor, in predynastic times. Data from ice cores and tree rings is combined to obtain a record of climate-perturbing eruptions during 2300–900 BC. The record is used to date the three Chinese eruptions: to 2037 BC, 1628 BC, and 1161 BC. The three dates, in conjunction with the ancient texts, lead to a precise chronology for ancient China. Additionally, the eruption of 1161 BC is hypothesized to be the root source of the Mandate of Heaven. Ancient Chinese texts also record that the first Chinese dynasty was founded during a great flood, which lasted over a century, and evidence of such a flood is reviewed herein. A companion paper argues that the flood was part of a near-global climatic upheaval, which was induced by the eruption of 2037 BC.

25 August 1999
Revised 12 September 2002
Revised 29 October 2021

Working draft: author's notes are {enclosed in braces}.

A version of this work was presented at the Second Worldwide Conference of the Society for East Asian Archaeology (University of Durham, England, 6–9 July 2000).

Introduction

The chronology and history of China prior to the first millennium BC have long been debated. For example, dates for the beginning of what is usually regarded as the second Chinese dynasty range across 1775–1450 BC (see below); there is no consensus on whether the first dynasty existed [von Falkenhausen, 1993a; Thorp, 1991; Chang, 1999]; and predynastic records are often argued to be mythical.

In the 1980s, K.D. Pang and co-workers identified ancient Chinese texts that appear to record two major volcanic eruptions [Pang, 1991]; this work, though, has found little acceptance among archaeo-historians. Herein, we review the evidence presented by Pang and substantial additional evidence. We conclude that Pang's identification of the texts as recording volcanism is correct, but that his designation of the volcanoes is incorrect. Additionally, we identify texts recording an earlier eruption, in predynastic times. The three eruptions are precisely dated via evidence from ice cores and tree rings. That leads to a chronology for ancient China that extends back to late predynastic times.

Ancient Chinese texts additionally record that the first Chinese dynasty (the Xia dynasty) was founded during the Great Flood, which lasted over a century. We survey strong evidence for the Great Flood. A companion paper [Keenan, 2000a] proposes that the flood was part of a near-global climatic upheaval, which was induced by the predynastic eruption. Herein, the eruption is dated to 2037±1 BC.

The three most important aspects of the traditional mythology of China are the Great Flood, the Yellow Emperor, and the Mandate of Heaven. Both the Yellow Emperor and the Mandate of Heaven have previously been regarded as unevidenced. We argue that there is good evidence for both: via the identification of the ancient texts that record volcanism.

The eruption of 1629–1628 BC

We believe that a key to resolving the chronology of ancient China lies in the following quotations, from ancient Chinese texts.

> The sun was dimmed
> Ice formed in [summer] mornings
> The earth emitted yellow fog
> Three suns appeared together
> Heavy rain toppled temples and buildings

Those quotations claim to describe events preceding a drought and famine which lasted about six years [Legge, 1865: p.129; Karlgren, 1946: p.328,333; Allan, 1984]. It has been proposed that they refer to the after-effects a large sulfurous volcanic eruption [Pang, 1991]. The sulfur forms an aerosol in the stratosphere, which reflects, refracts, and absorbs sunlight. The sun thus appears dimmed and Earth's surface is cooled [Sigurdsson, 1990; Strothers & Rampino, 1983; Rampino et al., 1988; Robock, 2000]. The sulfur also gives the "fog" its color. An apparent triple sun can be caused by the sun's image being partially refracted by ice crystals in the atmosphere [Walker, 1977]; a triple sun was occasionally observed during 44–42 BC, following the eruption of Etna, Italy [Strothers & Rampino, 1983].

The climatic anomalies described in the Chinese records are similar to those that followed the eruption of the volcano Tambora, in Indonesia, during 1815. That eruption is the greatest volcanic eruption of modern times (and it was much larger than the eruption of Krakatau in 1884, by virtually every measure) [Sigurdsson, 1990; Sigurdsson & Carey, 1992; Strothers, 2007; Simkin & Siebert, 1994]. During 1815–1817, in the lower basin of the Yellow River (Huang Ho), where ancient China was situated, there was abnormal cold as well as early or unusual frosts [Wilson, 1992]. During 1816, there was severe flooding; during 1817, there was drought [Wilson, 1992]. Also during 1817, in the province of Shanxi, summer frosts killed crops—which led to mass emigration from the province [Wood, 2014].

A large volcanic eruption injects sulfur into the stratosphere. The sulfur is then formed into an aerosol of sulfuric acid. The aerosol can take up to a year to form to its peak mass [Sigurdsson, 1990], after which it becomes extinct with a half-life of about eight months [Rampino et al., 1988: p.79; Robock, 2000]; the long residence time gives it hemispheric or even global dispersal.

The climatic after-effects of an eruption are typically due almost entirely to its sulfuric aerosol. {Elaborate on how.} (The tephra—volcanic ash, dust, etc.—tends to falls out of the atmosphere within only several weeks and thus normally has little effect [Gerstell et al., 1995; Robock, 2000].) The aerosol mass alone does not determine the after-effects: the state of the climate system is also important. Note that the aerosol mass has little relation to the volcanic explosivity index (VEI—assuming VEI > 3, which is needed for the eruption column to reach the stratosphere), although explosivity has traditionally been used as the measure of eruption size [Simkin & Siebert, 1994; Robock, 2000].

A causal link between major eruptions and the Chinese droughts is indicated by China's climatology. In winter, the prevailing winds blow in from the central-Asian mountains, and there is little precipitation. In summer, the prevailing winds are the monsoons that blow in from the adjacent oceans, and there are heavy rains. The fundamental forcing of monsoons is the land–ocean temperature difference [Meehl, 1994]. The aerosol would be expected to cool the land more than the oceans, due to land's much lower thermal inertia and heat capacity. Hence the temperature difference would be lessened, and thus the monsoons would be weakened or stopped [Li & Yanai, 1996]. If the resulting drought was sufficiently severe, it would likely continue after the cooling ended, as the region regained moisture [Bravar & Kavvas, 1991; Meehl, 1994]. Precipitation maps for 1817 show extreme dryness north of the Yellow River and extreme wetness along the southern coast [Academy of Meteorological Sciences, 1981]—i.e. the precipitation pattern expected with very weak monsoons.

Precipitation maps for 1816 show that extreme wetness was confined to parts of the lower basins of the Yellow and Yangtze rivers [Academy of Meteorological Sciences, 1981]. Similarly, in August 1963, five months after the large eruption of Agung, Indonesia [Sigurdsson, 1990; Simkin & Siebert, 1994; Self & Rampino, 2012], parts of the lower basin of the Yellow River and the middle basin of the Yangtze River experienced extremely heavy rainfalls, unprecedented in the instrumental record [Tao & Ding, 1981]. Analysis of the 1963 rainfalls showed that they were caused by poleward shifts in the tracks of storm vortices migrating off the Tibetan Plateau [Tao & Ding, 1981], and modelling studies have indicated that stratospheric aerosols induce poleward shifts in mid-latitude storm tracks [Robock, 1996; Haigh, 1996].

Ancient Chinese records are sometimes mythicized or corrupted; so they cannot be assumed to have historicity. In the above case, however, the corroboration of each record by the others and the extreme unlikelihood of each recorded event make it very probable that a major eruption did actually occur.

The date of the eruption, as implied by the records, would generally be regarded as during 1775–1450 BC (coincident with the end of the Xia dynasty {surely not by chance}) [Legge, 1865; Shaughnessy, 1990; Pang, 1991; von Falkenhausen, 1993a; {…}]. We argue below that the eruption occurred during 1629–1628 BC.

Greenlandic ice cores

Each winter, snow falls in Greenland. Little, if any, snow melts during the summer—although some is removed by wind. Thus, each year, a layer of snow is deposited, and remains. The layers of snow beneath the top are compressed by the layers above them; ultimately, they are compressed enough to be formed into ice.

Cores have been drilled from the Greenlandic ice. By careful inspection of a core, it is possible to discern the annual layers of ice. By counting the layers, it can be determined in which year a given layer originally fell as snow.

A sulfuric aerosol eventually falls out of the stratosphere and is deposited on Earth's surface. When that happens, some of the aerosol will be often be deposited on Greenland. By examination of the annual layers of ice in a Greenlandic ice core, it is possible to determine the layers in which sulfuric acid is present, and thus the years in which volcanic eruptions have occurred in the past [Zielinski et al., 1994; Clausen et al., 1997]. (The year of acid deposition dates the actual eruption to about 1–3 years earlier—allowing time for the aerosol to form, disperse, and deposit.)

As of 2002, volcanogenic-acid records for three Greenlandic ice cores that extend back at least 4000 years have been published. One of those ice cores, known as "DYE 3", is from southern Greenland. Another ice core, known as "GRIP", is from central Greenland; it was obtained by the same investigators who obtained the DYE 3 core (C.U. Hammer and colleagues, in Copenhagen). The third ice core, known as "GISP2", is also from central Greenland (28 km from the GRIP site); it was obtained by a different team of investigators [Zielinski et al., 1994; Gow et al., 1997; Meese et al., 1997]. Among the three ices cores, the DYE 3 core has the most accurate dating of its layers (due to conditions at the site). The GRIP dating is partially reliant on various synchronisms with the DYE 3 core [Johnsen et al., 2001]; thus, the dating of the GRIP core is essentially consistent with the dating of the DYE 3 core—by the construction. The GISP2 dating is independent of the other two cores.

(There is also an ice core from Antarctica that covers the second millennium BC [Cole-Dai et al., 2000]. Dating this core, however, has proved difficult; errors are believed to be ±60 years or more. Additionally, extra-tropical eruptions in one hemisphere tend to deposit little sulfuric acid in the polar region of the other hemisphere [Cole-Dai et al., 2000]. Hence the Antarctic core is not considered here.)

Counting ice layers is not exact. A comparison of the dating of layers in the GRIP and GISP2 cores is given by Clausen et al. [1997]. Clausen et al. based their comparison on sulfuric-acid peaks. They conclude that "GRIP and GISP2 records agree with respect to acidity and sulfate peaks at the same age levels, with only a ±10-year discrepancy at the 3000-year level", but also that earlier levels are problematic: "Between the ages 1000 B.C. and 2000 B.C. the uncertainty of the two timescales deviates too much to make a safe comparison".

Another comparison of the dating of the layers in the GRIP and GISP2 cores is given by Southon [2002]. Southon based his comparison on oxygen-isotopic records from the two cores. That comparison shows that the two records have major discrepancies for ice layers that are more than about 2500 years old.

That a discrepancy would begin with layers 2500 years old is unlikely to be a coincidence. Ice in central Greenland from between roughly 2500 and 7500 years ago is brittle and cracked (due to depth-related pressure), which makes layer-counting during that time span extremely difficult [Alley et al., 1997; Gow et al., 1997; Meese et al., 1997; Neff, 2014]. The dating of the GRIP core partially avoided that difficulty via synchronisms with the DYE 3 core.

Three methods were used on the GISP2 core to count layers within the brittle zone: electrical conductivity, laser-light scattering, and visual stratigraphy [Meese et al., 1997: tbl.2]. The cracked ice, however, made the electrical conductivity and laser-light scattering methods "difficult to apply" and "interfered … with the … measurements"; so visual stratigraphy "constituted the primary annual layer indicator" [Meese et al., 1997: p.26413–415]. Yet tens of meters of the GISP2 core brittle zone could not be dated by visual stratigraphy, due to poor core quality [Alley et al., 1997]. Those tens of meters represent a few centuries. Their dates were obtained by estimating the number of layers appropriate for the ice thickness [Alley et al., 1997]. That strongly suggests inaccuracies. Moreover, some ice was not recovered at all, and the brittle zone "constituted the zone of greatest core loss" [Gow et al., 1997: p.26560]. All this indicates that the main source of the dating discrepancy between GISP2 and GRIP/DYE 3 lies in layers in the brittle-ice zone.

One way to test the accuracy of the dates of ice-core layers is via ^{10}Be: the ^{10}Be concentration in an ice layer should be functionally related to ^{14}C concentrations in tree rings from the same year (for details, see Southon [2002]). Comparing those ^{10}Be and ^{14}C concentrations accurately and precisely is difficult [Finkel & Nishiizumi, 1997; Southon, 2002], but it is thought that errors are no more than about 20 years, and typically much less.

As of 2002, there is a ^{10}Be record available for the GISP2 core only. A comparison of that record with ^{14}C from tree rings indicates that the record is missing roughly 60 years from sometime during 1450–1350 BC [Southon, 2002]. Other discrepancies are suggested at other times within the brittle zone around this period. It seems, then, that the dating of the GISP2 core needs reinvestigation.

For the above reasons—especially the ^{10}Be record—when dating the eruptions, we shall rely upon the volcanism records from only two of the ice cores: GRIP and DYE 3. The relevant records for those two cores are presented in Table 1.

Precise dating via tree rings

There is a fair, but far-from-perfect, correlation between volcanic eruptions and tree-ring traumas over historical periods [LaMarche & Hirschboeck, 1984; Hughes, 1988; Villalba & Boninsegna, 1992; Baillie, 1995; Baillie, 1998]. The two main dendrochronologies that cover the second millennium BC and that have been (partially) published are from California and Ireland.

In California tree-ring trauma manifests as tree-ring frost damage. The volcanic forcing mechanism is believed to be understood: the volcanogenic aerosol forces conditions that result in generally cooler summers (this has been simulated with a general circulation climate model [Robock & Liu, 1994; Kirchner et al., 1999]) and are also conducive to outbreaks of cold air from the north [LaMarche & Hirschboeck, 1984].

In Ireland tree-ring trauma manifests as tree-ring narrowing. Unpublished dendrochronologies from England and Germany show that trees there, during the second millennium BC, grew extremely narrow rings each time that the trees in Ireland experienced ring-narrowing trauma [Baillie, 1990; Baillie, 1995] (with additional data supplied by M.G.L. Baillie, private communications, 1997). This implies that the Irish tree traumas were induced by major climatic events.

For Irish tree-ring narrowing events, the tree-growth pattern suggests that the likely cause was flooding [Baillie & Munro, 1988; Baillie, 1990; Baillie, 1995]. During the AD 1816 growing season (following Tambora's eruption), in the areas of Europe where the dendrochronologies of Ireland, England, and Germany are from, precipitation exceeded twice the normal amount and there were floods [Wilson, 1992]. That was due to a south-eastward shift of the Icelandic Low pressure center [Kelly et al., 1985; Wilson, 1992; Baillie, 1995: p.141], but how volcanism might force that is unknown.

For the European trees during 1816, though, signs of notable trauma are evident only in Ireland, and that trauma was not severe (data from the International Tree-Ring Data Bank [Grissino-Mayer & Fritts, 1997]). This might indicate that the post-Tambora climatic disturbance was less severe than those of the second millennium BC, discussed below. There is, however, an alternative explanation. During the second millennium BC, the trees showing trauma were generally those rooted in bogs; trees that were rooted in mineral soils show little, if any, trauma [Baillie, 1990]. By the AD 1800s, there were few bog-rooted trees; so it has been proposed that the lack of bog-rooted trees might account for some, albeit not all, of the weakness of tree-ring trauma subsequent to Tambora [Pilcher, 1996].

The lag from eruption to Californian frost damage is 0–2 years for historic eruptions, and it is believed that two years would be the maximum (due to the decay rate of the volcanogenic aerosols) [LaMarche & Hirschboeck, 1984]. For Irish trees, it seems possible that ring narrowing could begin as much as three years after an eruption (the flood mechanism suggests that an extra year of delay, relative to California, might occur before the onset of Irish trauma, because climate can affect processes in trees that alter growth in ensuing years). Thus, for Californian/Irish trees, if an eruption is matched with tree trauma, then it is possible to date the eruption with a maximum error of one/two years.

One goal of this section is to match precisely-dated tree-ring traumas with eruptions that are approximately dated via ice cores. Because the correlation between tree-ring traumas and eruptions is only fair, though, there is a problem: matching a particular tree-ring with an eruption whose date is known only approximately is unreliable. Herein, we address that problem by considering all the matches, simultaneously, across a broad time span: 2100–900 BC. During that time span, there were four major tree-ring traumas—see Table 1.

In Table 1, the tree trauma events of California and Ireland are compared with the volcanic events recorded in the GRIP (central Greenland) and DYE 3 (southern Greenland) ice cores. Using the ice-core dates given by the primary investigators, there are no matches. If, however, the dates from the DYE 3 core are shifted to be about 15–20 years later, all four tree traumas are matched with eruptions (the match is highly significant statistically: see Excursus 1). Dates for the GRIP core need to be shifted even less. Such shifts are within the error limits for the ice core dates. Moreover, the shifting is strongly supported by isotopic records from the ice cores: see Excursus 2.

As shown by Table 1, the dendrochronologies strongly suggest that there was a climatic perturbation that began in 1629 BC or possibly the first half of 1628 BC (since the growing seasons end about September). Since 1987, when a partial record for the southern Greenland ice core was first published [Hammer et al., 1987], several researchers have proposed that the climatic perturbation was linked with the eruption whose southern-Greenland spike is dated to 1644 BC [Baillie & Munro, 1988; Hughes, 1988; Hardy, 1990; Pang, 1991; Baillie, 1995]. As shown by Table 1, though, 1629–1628 BC is within the ice-core dating error bounds of two eruptions: dated to 1644/1636 BC and 1622/1618 BC.

There are historiographic reasons for linking the climatic perturbation with 1644/1636 BC, discussed below and in companion papers [Keenan, 1999; Keenan, 2000b]. There are also three scientific reasons. First, the isotopic record of the GRIP core indicates that the core's layers are dated too early (as per Excursus 2). Second, the sulfuric spikes of 1622/1618 BC are much smaller than those of 1644/1636 BC, in both ice cores [Hammer et al., 1987; Clausen et al., 1997]. Third, linking the tree traumas of 1628–1627 BC with the sulfuric spikes of 1644/1636 BC aligns other tree traumas with other sulfuric spikes (as shown in Table 1 and discussed in Excursus 1).

Hence, we infer that the proposals linking the climatic perturbation with the eruption dated to 1644/1636 BC are almost certainly correct. It then follows, from Table 1, that there was exactly one large volcanically-induced climatic perturbation during 1950–1200 BC and that the corresponding eruption was in 1629–1628 BC. We conclude that it was very probably the after-effects of this eruption that were recorded in the ancient Chinese texts.

The Greenlandic ice layers contain tephra from the eruption of 1629–1628 BC. The tephra has been retrieved and determined to have originated from the volcano Aniakchak, Alaska (57°N, 158°W) [Pearce et al., 2004; Coulter et al., 2012]. The caldera from Aniakchak's eruption is 10 km in diameter [Bacon et al., 2014], and the height of the sustained eruption column was probably over 25 km [Begét et al., 1992].

The eruption of 1162–1160 BC

There appear to be ancient Chinese records of one volcanic eruption after the eruption discussed above [Pang, 1991].

> In the summer … it rained dust
> For ten days the sky rained [grey] ashes
> There was heavy rainfall
> Frosts killed the … cereal crops
> It snowed in the sixth month and the snow was over a foot deep

The time of the sixth month is unknown, although June–September is most likely [Shaughnessy, 1990: p.133–150]; clearly, however, the time is supposed to have been highly unusual for a heavy snowfall. {*Mozi* 19 says "For ten nights in succession the sun shone and it rained earth" [Johnston, 2010], which has also been translated as "The night lasted for ten subsequent days; it rained soil for ten days" [Pines, 2008]. Maybe discuss the volcanic interpretation with Y. Pines or I. Johnston?}

Those Chinese records are from during the reign of King Di Xin. The reign of Di Xin is usually dated to sometime during 1175–1040 BC [Legge, 1865; Shaughnessy, 1991; Pang, 1991; Khayutina, 2020]. During 1600–900 BC, there appears to have been only one large climate-perturbing eruption: in 1162–1159 BC (see Table 1, allowing for possible delay from eruption to the beginning of tree-ring trauma). Thus, it seems likely that this eruption is the eruption indicated by the Chinese records (see further below).

We propose that the eruption was of the island volcano Thera (Santorini), Greece (36°N, 25°E). The eruption of Thera is known to have been extremely large. The stratospheric sulfur output of Thera's eruption is unknown, but is believed to have been greater than that of Krakatau [Sigurdsson et al., 1990].

The (calibrated) ^{14}C date for the eruption of Thera is roughly 1600 BC [Wiener, 2009; Manning, 2014: §1.V.1; Kutschera, 2020]. It has been proposed, however, that ^{14}C dates obtained downwind from the Eastern Mediterranean Sea are centuries too early, because the Sea was degassing ^{14}C-deficient carbon [Keenan, 2002b] (see also Keenan [2010]).

Companion papers [Keenan, 1999; Keenan, 2000b] cite ancient Egyptian texts describing what appears to be the eruption of Thera (during the reign of pharaoh Ahmose I). The usual Egyptological date for those texts is roughly 1500 BC. Egyptological chronology, though, is largely founded on Sothic dating. Sothic dating, however, has been shown to be fallacious, and so Egyptological chronology is left largely unfounded [Keenan, 2012]. The companion papers develop a new chronology for ancient Egypt that is consistent with dating the Egyptian texts to 1162–1159 BC, as well as with substantial additional evidence that has been ignored.

There is also direct evidence to support the ^{14}C and Egyptological dates of Thera's eruption being wrong. Specifically, there is a speleothem record from Anatolia. The record seems to record all the large sulfurous volcanic eruptions that occurred in either the Northern Hemisphere or the tropics, and it spans about 1650–1425 BC [Badertscher et al., 2014]. The record holds evidence of exactly one eruption during its span: in 1620±25 BC. At that time, Aniakchak had a very large eruption, as noted above. Ergo, Aniakchak seems to have been the only large sulfurous eruption during 1650–1425 BC. Thus, the speleothem record is strong evidence that Thera did not erupt during 1650–1425 BC, in contradiction to the ^{14}C and Egyptological dates.

Thera's main eruptive phase is believed to have lasted a few days, had an eruption column about 35 km high, and produced much tephra whose dispersal was roughly eastward [Sigurdsson et al., 1990; Guichard et al., 1993; Pearce et al., 2002]. Examination of the remains of insects on the island of Thera has shown that the eruption occurred during the summer [Panagiotakopulu et al., 2013]. Both the Chinese records and the Egyptian texts tell that the apparent eruption occurred in summer, consistent with the insect study. A summer date also implies that 1159 BC can be excluded from the date range: the eruption would have occurred too close to the end of the tree growing season to affect trees in the same year.

During summer, the Subtropical Westerly Jet Stream lies above Thera: see Figure 1. The jet stream is approximately 12 km above the surface of Earth. Thus, the jet stream would have entrained much tephra from Thera's eruption.

While the jet stream flows over the Asian land mass, its speed is increased. While the jet stream flows over the lower basin of the Yellow River, its speed is somewhat decreased (see Figure 1). Ergo, it is probable that an extended rain of ashes and dust would have fallen on the lower basin of the Yellow River—where ancient China was situated.

The eruption's column would also have injected much tephra into the atmosphere above the jet stream, for more than 20 km. After the eruption ended, some of that injected tephra would have drifted downwards into the jet stream, to then be entrained and transported to China. Thus, the rain of ashes and dust, experienced in China, would have lasted for more than just the few days of the eruption. Hence, the ancient record's claim of ten days is plausible. Additionally, in ancient China, a week was not seven days; rather, it was ten days [Shaughnessy, 1999; Henkin, 2021: p.160]: so the record's claim of ten days might be understood as referring to a week.

It has been previously claimed that the eruption of 1162–1160 BC was due to Hekla, Iceland (64°N, 20°W) [Baillie & Munro, 1988; Pang, 1991; Baillie, 1995]. Hekla's eruption, however, was likely smaller than Krakatau's [Simkin & Siebert, 1994]: it could not account for the Chinese records cited above, or for the Egyptian texts {…}. Additionally, Hekla's ^{14}C-implied date is well after 1159 BC [Dugmore et al., 1995; van den Bogaard et al., 2002]. See also Table 1.

As noted above, tephra from the eruption of 1629–1628 BC has been retrieved from Greenlandic ice cores. Tephra from the eruption of 1162–1160 BC is almost certainly present in Greenlandic ice cores. We hope that some of that tephra will eventually be retrieved—thereby confirming the identity of the volcano as Thera.

Origin of the Mandate of Heaven

The Mandate of Heaven is a tenet in China. According to the tenet, a man may be the king if and only if Heaven has commanded that he be the king. If a man has been commanded by Heaven to be the king, then that man is said to have received the *Mandate of Heaven*.

In China, the Mandate of Heaven is a core tenet of the traditional religion and of the traditional political ideology. The Mandate, and the philosophies that it begat, has been described as "the single most important political concept in Chinese history" [Zhao, 2013] and "the foundation for all Chinese political theory before … the twentieth century" [Allan, 2015].

The tenet seems to have been initially promulgated by the first king of the Zhou dynasty, King Wen [Allan, 2007; Tseng, 2011; Zhao, 2013; Khayutina, 2020]. Prior to the Zhou dynasty, China was ruled by the Shang dynasty. The Shang rule ended when the Shang were conquered by the Zhou. The last king of the Shang was Di Xin, during whose reign the eruption of c. 1161 BC is proposed to have occurred.

Ancient Chinese texts tell that the Mandate of Heaven was explicitly received by King Wen. The earliest extant texts tell that Wen alone received the Mandate;

some later extant texts tell that Wen and his son Fa (who became king upon Wen's death) received the Mandate together [Luo, 2015]. In either case, the Mandate was never explicitly received by anyone other than Wen and perhaps Fa: although many later kings claimed to hold the Mandate, those kings' receipt of the Mandate was always implicit, via general inheritance [Leung, 2019: p.28; {other references}]. In other words, the explicit receipt of the Mandate was a unique event in the history of China, according to the ancient texts.

The Chinese term conventionally translated as "Mandate of Heaven" is 天命. The character 天, which is translated as "Heaven", literally means "Sky" [Allan, 2007]. The character is also used in some terms relating to the weather.

The explicit receipt of the Mandate of Heaven, by Wen and perhaps his son, seems to have been via some event that was in the heavens/sky. The event has often been assumed to be astronomical, e.g. an eclipse or a passing of a comet. The ancient texts, however, do not say what the event was [Allan, 2007]. E.g. one text says "King Wen received the great Mandate that was in the Sky" and another text refers to "the precious Mandate that the Sky has sent down". (The first text is the Da Yu *ding* inscription: translation adapted from Allan [2007], Luo [2015], Khayutina [2019], and Leung [2019], with kind assistance from V.S. Leung. The second text is *Shang shu* 34: translation adapted from Karlgren [1950] and Allan [2015].)

The lives of Wen and Di Xin overlapped by decades. We hypothesize that the event that was taken to be the explicit receipt of the Mandate was the ashes/dust falling out of the sky for ten days during the reign of Di Xin. In other words, the event was deposition of tephra from Thera. That fits with the apparently unique nature of the event and with the event being in the sky even though there are no records specifying anything astronomical.

(The previous assumption about the event being astronomical was perhaps due, in part, to a misunderstanding. In modern Chinese, the term for "astronomy" is 天文 (which can be translated literally as "patterns in the sky/heavens"). The same term, though, had a broader meaning in premodern times: it included both astronomical and meteorological phenomena. Ignorance of the prior broader meaning has misled some investigations of ancient texts [Chapman, 2018].)

Consider too the frost-induced killing of the cereal crops during the reign of Di Xin, which seems to have been due to Thera's climatic perturbation. The killing frosts would presumably have been interpreted by the people as a sign that God/Heaven was displeased with their ruler, Di Xin. The Zhou would surely have wanted to exploit any such perceived displeasure. One way of doing that would be via concocting the Mandate of Heaven. Indeed, the Zhou claimed that if a king held the Mandate of Heaven, then grain harvests would be prosperous [Tseng, 2011: p.89–90].

There is circumstantial evidence that the Zhou were able to use their claimed Mandate in their war against Di Xin. Ancient texts tell that the Shang army was several times the size of the Zhou army; they also tell that the Shang knew the Zhou were considering an attack long beforehand. And one modern author has noted that the Zhou had attacked "a vastly superior, well-entrenched foe whose campaign armies alone probably outnumbered the entire Zhou population" [Sawyer, 1993: p.23]. Related considerations led the *Cambridge History of Ancient China* to discussing the "conundrum" as to how the Zhou conquered the Shang [Rawson, 1999].

About the conundrum, the *Cambridge History* says a possible resolution is that "a previously materially insignificant people, known as the Zhou, drew together a mass of loosely connected clans and tribes across [much of the region], and exploited all available resources, even including defectors from the Shang" [Rawson, 1999]. That resolution is supported by ancient texts. For instance, some texts tell that 800 feudal lords joined the Zhou (*Shiji* 108 [Ssu-ma, 1994]; *Bamboo Annals* V.1 [Legge, 1865]). And several texts tell of Shang defectors; in particular, one text tells that at the main battle between the Shang and the Zhou (the Battle of Muye), the front line of Shang troops attacked the troops behind them—causing the latter troops to flee and spilling huge amounts of blood (*Shang shu* 31 [Legge, 1865: p.315; Palmer, 2014]).

How did the Zhou persuade many feudal lords to join them and the front-line Shang troops to defect? We speculate that it was done by, inter alia, citing their receipt of the Mandate of Heaven. Indeed, since the rain of ashes/dust and the killing frosts etc. would have been experienced by some of the lords and troops, the Zhou did have what seemed to be strong evidence supporting their claim that Heaven was against the Shang king.

Some ancient texts tell that the main motivation for people turning against Di Xin was that Di Xin was a monstrous ruler. Those texts, however, were written many centuries after the Zhou conquest; earlier Zhou texts depict Di Xin as inept, but not monstrous [Pines, 2008]. The later texts were written for ideological purposes: those texts argue that a king should be overthrown only if the king is monstrous. Analysis of the various texts has concluded that the later texts embellished the depiction of Di Xin to support the ideologies of the authors [Pines, 2008].

After the Zhou defeated the Shang army, they gave the Shang people a choice. The Shang people could either (i) accept that the Zhou held the Mandate of Heaven and so should rule over them or (ii) be exterminated [Gentz, 2017; Shaughnessy, 2018]. That weakened resistance, by the Shang people, to Zhou rule. Later on, the Shang people were assimilated into the Zhou regime. And each of the next Zhou kings claimed that he had been bequeathed the Mandate—and that must be accepted by all people. Thus did the Mandate initially become established in China.

Chronology of ancient China

The chronology of China is generally agreed upon back to 841 BC [Shaughnessy, 1999; Wilkinson, 2000: p.180–181]. For prior to then, most proposed chronologies have relied on retrocalculated dates of astronomical events. Ancient records of those events, however, are known to have serious problems: errors, ambiguities, and fabrications [Legge, 1865; Legge, 1872; Shaughnessy, 1990; Shaughnessy, 1991; Barnard, 1993; Keenan, 2002a; Keenan, 2007; Stephenson, 2008]. Also, proposals attempting to use astronomical records have lacked rigor [Shaughnessy, 1990; Barnard, 1993; Keenan, 2002a; Keenan, 2007; Stephenson, 2008]. The critique by Keenan [2002a] concludes that "astro-historiographic chronologies of early China are unfounded".

There have been two main attempts to develop a chronology based on astronomical events. One attempt is based on planetary conjunctions. This attempt is considered by Keenan [2007], who concluded that it is unmerited; further discussion is in the Appendix. The other attempt is based on a purported solar eclipse. The purported eclipse is the primary basis of the Xia–Shang–Zhou Chronology Project, which involved about 200 researchers in China [(Various), 2000; Lee, 2002; Li, 2002; Liu, 2002b]. The Project's claims about an eclipse were strongly criticized by Keenan [2002a]. A rebuttal to that criticism was given the by lead astronomer on the Project [Liu, 2002a]. A partial rejoinder to the rebuttal was given by Keenan [2007], and what is effectively a full refutation of the rebuttal was given by Stephenson [2008]. To summarize, the two main attempts based on astronomical events are irredeemable.

Some chronologies have also been proposed based on the years, reign lengths, etc., given by ancient records. Those records, however, have essentially the same problems as the astronomical records [Legge, 1865; Karlgren, 1946; Hulsewé, 1990; Shaughnessy, 1991; von Falkenhausen, 1993b; Shaughnessy, 2008; Lai, 2017]. (For some remarks about why ancient Chinese texts generally tend to be especially unreliable, see e.g. Pines [2009] and Hein [2019] {and other references}.)

Various corrigenda for the records have been proposed, and there are many competing chronologies, which differ by up to three centuries around the mid second millennium BC [Shaughnessy, 1990; Shaughnessy, 1991; Barnard, 1996]. We do not consider those proposals here. We do though suggest how one corrigendum for the records is consistent with our proposed volcanism-based chronology. There are obviously many reasonable corrigenda; it seems useful, though, to show that one fits with our proposal.

First, we note that there is a traditional chronology (or "Common Scheme") according to which the rain of dust—herein dated to 1161±1 BC—occurred in 1149 BC [Legge, 1865: p. 139,186]. Thus, there is a discrepancy of about 12 years. The traditional chronology is based on records of reign lengths (all of which are recorded as a whole number of years). It has been pointed out that there were two methods of recording reign lengths: (i) *yunian*, where the commencement of a new ruler's reign was not proclaimed immediately, but rather once the following year had begun, and (ii) non-*yunian*, where a new ruler would proclaim the first year of his reign immediately. It has been proposed that the *yunian* method was first adopted in the fourth century BC, during the mid Warring States Period, and that the non-*yunian* method was used during the early Warring States Period [Hirase, 1993]. There is really no knowledge of which method was used prior to the Warring States Period (which began in 771 BC). Between the rain of dust and the Warring States Period there were 12 new kings. Possibly, then, the 12-year discrepancy results from having the reign lengths of the 12 kings incorrectly adjusted due to a misunderstanding of the *yunian* method.

We next briefly consider one set of records: the *Bamboo Annals* [Legge, 1865; Barnard, 1993; Nivison, 1993; Shaughnessy, 2006]. Those records are unique in that they both (i) give a full chronology (reign lengths, etc.) for prior to the rain of dust and (ii) were originally compiled before the third century BC. (During the third century BC, Emperor Shi Huangdi ordered that most books be burned and many scholars be executed; although some books were retained at the palace, they were largely destroyed in the civil war that followed the emperor's death. Thus, understanding Chinese history prior to the emperor's reign is especially problematic.)

The chronological records in the *Bamboo Annals* must be treated with the same cautions as other chronological records. The *Bamboo Annals* do, though, claim that the rain of ashes occurred 463 years after the triple sun was observed [Legge, 1865: p.125–126,139], and 1161±1 BC + 463 = 1624±1 BC. Because triple suns can be observed for at least two years after major volcanic eruptions (judging by Etna) [Strothers & Rampino, 1983], the discrepancy with the volcanism-based chronology is about 1–4 years, which is small enough to be due to rounding reign lengths (in the reckoning of 463) to whole years.

The date of the predynastic eruption discussed below can be very crudely estimated by considering the number of emperors after The Yellow Emperor, during whose reign the eruption seems to have occurred, until the triple sun. There appear to have been 22 such emperors [Legge, 1865; Karlgren, 1946; Ssu-ma, 1994; Loewe, 1994]. For the crude estimation, we assume an average reign length of 15–20 years (the average is about 17 years during 1628–1161 BC, according to the *Bamboo Annals*). The Yellow Emperor would then have reigned sometime in 2090–1955 BC.

The Yellow Emperor

Chinese records tell of three great disasters in ancient times [Watson, 1967]: the two discussed previously and one dated much earlier, prior to the first Chinese dynasty. The three disasters are listed together and described similarly in one record (*Mozi* 19 [Watson, 1967; Graham, 1993; Johnston, 2010]), which describes the earliest disaster as follows.

> …. The sun came out at night and for three days it rained blood. … Ice formed in summertime, the earth cracked open so that springs gushed forth, the [cereal crops] grew differently, and the people were filled with a great terror. ….
>
> (Adapted from Watson [1967] and Johnston [2010], with kind assistance from E.W. Maeder.)

After Krakatau's eruption, observers described the sun as being so dim it was "like the moon" [Simkin & Fiske, 1983], and Mesopotamian texts that are proposed in a companion paper [Keenan, 2000a] to refer to a large eruption claim that "the bright sun rose not, like the evening star it shone" [Kramer, 1969]. Raindrops can be colored blood-red by suspended dust: this occurred in Switzerland during October 1755 [Holford, 1982]; the source of the dust is uncertain, but Katla, Iceland, had a large eruption at about the same time [Simkin & Siebert, 1994] (see too below). The descriptions of summertime ice and of crops not growing normally are compatible with the after-effects of a large eruption.

Those events are recorded as occurring either before or during the reign of Emperor Zhuanxu (Gaoyang). Zhuanxu is recorded as reigning shortly after The Yellow Emperor (黃帝) [Legge, 1865: p.108–111; Ssu-ma, 1994: chap.1; Karlgren, 1946; Loewe, 1994]. Another text tells that during the reign of The Yellow Emperor, the sun and moon were dimmed and then misfortune hit the crops for a few years (*Chuang Tzu* 11 [Roth, 1993; Palmer, 1996]). Some texts also tell that during one summer of the reign of The Yellow Emperor "the heavens were wrapt in mist for three days" (*Bamboo Annals* [Legge, 1865: p.109]; *Song shu* 27 [Lippiello, 2001]). Those texts, which are generally extremely brief, describe at length the great consternation that the mist caused: the mist thus appears to have been exceptional.

In Mesopotamia, archaeological excavations found a layer of tephra, ½ cm thick [Weiss et al., 1993; Keenan, 2000a]. A companion paper [Keenan, 1999] proposes that the archaeo-historical date for this eruption is the 21st century BC, which is similar to the date range for The Yellow Emperor; also, the Mesopotamian-recorded eruption occurred a few decades before a centuries-long climatic upheaval [Weiss et al., 1993; Courty & Weiss, 1997; Keenan, 2000a]—likely the same upheaval as began in China shortly after the reign of The Yellow Emperor (see below). Elemental analysis of the Mesopotamian tephra suggests that its source was in nearby Anatolia [Weiss et al., 1993]. A large summertime eruption in or near Anatolia or North Mesopotamia would have supplied tephra to the Subtropical Westerly Jet Stream (as with Thera). Hence it is plausible that the three-day mist was of tephra and that it can be identified with the three-day rain of blood. The ancient records would then be similar to contemporary Indonesian accounts of Tambora's 1815 eruption, which tell that, due to tephra, the sun "appeared as observed through a thick mist" [Rampino, 1992]. A rain of tephra is also consistent with another record that claims The Yellow Emperor "dreamed that there was a strong wind which cleared away all the dust" (*Diwang shiji* 1 [Lippiello, 2001: n.20]).

The Yellow Emperor is recorded as having been given his name because of an "omen related to the earth's power" (*Shiji* 1 [Ssu-ma, 1994]). The omen comprised "phosphorous clouds" (*Zuozhuan* Ch'aou 17 [Legge, 1872]; *Song shu* 27 [Lippiello, 2001])—described as seemingly-luminescent vapors that were "like cloud but not cloud" and "like haze but not haze" [Schafer, 1977]. There were supposedly also some stars (or perhaps planets) at this time that appeared yellow [Legge, 1865: p.108; Lippiello, 2001], and they were known as "phosphor stars". These records thus appear similar to those claiming that "the earth emitted yellow fog", which followed, it is proposed above, from the eruption of 1629–1628 BC.

The reign of The Yellow Emperor is also recorded as including a season of heavy rains, which caused flooding, followed by years of drought (*Song shu* 27 [Lippiello, 2001], *Shanhaijing* [Lippiello, 2001: n.14,15; Karlgren, 1946: p.284–285], and other texts [Lippiello, 2001: n.14,15]). This indicates a climatic perturbation similar to that discussed for the eruption of 1629–1628 BC.

Considering the evidence collectively, it seems very likely that a climate-perturbing eruption occurred during the reign of The Yellow Emperor. There are known to be two such eruptions during 2300–1650 BC: one, in 2038–2036 BC, is evidenced by ice cores and Californian tree-ring frost damage; the other, in 1956–1953 BC, is evidenced by ice cores and Irish tree-ring narrowing (see Table 1). There are five indications for the first of those being the eruption during the reign of The Yellow Emperor.

First, the Californian frost damage in 2036 BC is the most severe on record, whereas the Irish narrowing in the 1950s BC is less severe than those in the 1620s BC and 1150s BC. Second, ^{14}C dates for the start of the post-eruption climatic upheaval, discussed below, imply that 2038–2036 BC is somewhat more probable than 1955–1953 BC [Keenan, 2000a]. Third, the Chinese texts indicate that 2038–2036 BC is somewhat more probable (see prior section). Fourth, as noted above, the proposed archaeo-historical date for the eruption in Mesopotamia is the 21st century BC. Fifth, 2038–2036 BC is much more plausible than 1955–1953 BC for Egyptian chronology [Keenan, 1999]. To conclude, we identify the Chinese-recorded eruption as that of 2038–2036 BC.

The Great Flood

The most celebrated of all ancient Chinese texts are those claiming that shortly after the reign of The Yellow Emperor there began the Great Flood, which likely lasted well over a century [Ssu-ma, 1994; Legge, 1865: p.54–73,121; Legge, 1895; Karlgren, 1946]. In no ancient text is the flood attributed to rainfall [Allan, 1991]: perhaps this is due to omission, but it indicates that the flood was hydrological.

The ancient texts tell that the floodwaters were eventually drained away via channels that took many years of intensive labor to construct. There are also texts claiming that the path of the lower Yellow River shifted substantially due to the channeling [Legge, 1895; Ssu-ma, 1994; Wang, 1983] (perhaps too the floodwaters contributed).

Before considering the flood texts further, we briefly review the hydrology of the Yellow River. The Yellow River system is divided into three sections: the mountainous upper basin, the plateau of the middle basin, and the plain of the lower basin. The middle section of the river flows mainly through the Loess Plateau, cutting into sand and loess deposits, and carrying away great quantities of silt. Most of that silt is then deposited in the lower basin. The bed of the lower Yellow River is thereby raised, making it prone to overflow. The result is frequent and disastrous floods, and a shifting of the path of the lower river; the mouth of the river has been known to shift by up to 500 km during the past 2000 years [Shi et al., 2002].

{The only good way to deal with the flood was to channel away the floodwaters: because levee constructions along the river banks would aggravate the deposition of excessive silts in the river channel, thereby elevating the river bed and so making the river more prone to flooding the plain of the lower basin.}

The ancient texts about the Great Flood are supported by several archeological reconstructions. Those reconstructions "suggest that flooding was … responsible for the collapse of [Neolithic] societies in the middle and lower Yellow River regions … around 2000 BCE" [Shelach-Lavi, 2015].

The ancient texts are also supported by many paleoenvironmental investigations. We next review some of those investigations.

In the lower basin of the Yellow River. Yu et al. [2020] studied sediments at a site that was priorly in the path of the Yellow River. The sediments included large deposits of silt from the Yellow River: evidence of extreme floods, lasting well over a century. A sample of sediment from near the bottom of the deposited silts was dated via OSL (optically stimulated luminescence) and determined to be 3780±360 years old; a sample of grains from about 35 cm below the silt sample was dated via ^{14}C and determined to be from 2400–2140 BC (2σ calibrated age range). Those dates are consistent with the flood beginning after 2036 BC. Yu et al. additionally note that fluvial deposits dated to about 4050–3800 years ago were also found at several archaeological sites.

In the middle basin of the Yellow River. Huang et al. [2010] and Huang et al. [2012] studied sediments at two sites on a tributary of the Yellow River—the Jing River. The sediments were found to include large deposits of silt: evidence of extreme floods. Huang et al., though, dated the floods to 4200–4000 years ago. Yu et al. [2020] cite Huang et al. [2012], note that the flood dates are well before the dates found for floods in the lower basin even though the floods in the two basins must have been synchronous, and then say that the discrepancy is "due likely to the large uncertainties in dating". Indeed, Huang et al. date sediments via OSL and ^{14}C with std. deviations that are large enough to allow dates that are consistent with the dates for floods in the lower basin. Moreover, Huang et al. [2010] say that "the major cultural layer of the late Neolithic ruins (4300−4000 a BP) occurs [underneath the] … palaeoflood [deposits]" and that "pottery shards retrieved from the slope wash … indicate that the overbank floods of the Jing River occurred between 4100 and 4000 a BP at the late stage of the late Neolithic settlement".

In the middle basin of the Yellow River. Zhang et al. [2019] studied sediments at a site on a tributary of the Yellow River—the Luo River. The sediments were found to evidence extreme floods. The sediments were initially dated via OSL and ^{14}C; the dates were then made more precise via archaeological correspondences. The floods were determined to have been 4000–3800 years ago.

In the middle basin of the Yellow River. A pollen record displays large spikes in both herb and tree pollen concentrations, unique in the last 9000 years, beginning sometime during about 3850–3500 ^{14}C BP [Zhou et al., 1996]. The large spikes strongly indicate heavy rainfall in the area. The date is to be compared with the ^{14}C ages of tree rings from 2030 BC, which are about 3650 ^{14}C BP [Reimer et al., 2020].

Outside the basins of the Yellow River. Sediments from the Yellow Sea might support a shift in the path of the Yellow River: they have been interpreted as indicating that about 4060±215 ^{14}C BP the mouth of the river shifted over 300 km, though this interpretation is uncertain [Xue et al., 1995]; moreover, an alluvial plain by the suggested pre-flood path of the river has dates as late as roughly 4800 ^{14}C BP at least [Wang, 1983]. {There are more references….}

(The foregoing focusses on the region of the Yellow River. There were other regions of China that also experienced the climatic upheaval. For some discussion of those regions, and how Neolithic societies seem to have been affected, see e.g. Liu & Feng [2012], Shen et al. [2015], and Sun et al. [2019].)

A companion paper [Keenan, 2000a] lists numerous severe century-long paleoenvironmental distresses throughout much of the world about 4000 years ago. The paper argues that those distresses were caused by a climatic upheaval that was triggered by the Mesopotamian/Anatolian eruption. It also describes the main underlying mechanism of the climatic upheaval—an extremely high phase of the winter North Atlantic Oscillation (NAO). The extent and mechanism of the climatic upheaval have previously been missed due to inaccurate dating.

The winter NAO likely played a role in the Great Flood. Indeed, an investigation found that the winter NAO is statistically correlated with East Asian summer monsoon rainfall [Sung et al., 2006]. And the Arctic Oscillation, which is closely related to the winter NAO, has also been found to be statistically correlated with East Asian summer monsoon rainfall [Gong & Ho, 2003]. Additionally, there is a statistical correlation between the winter NAO and the annual precipitation within the middle basin of the Yellow River; specifically, the correlation between the winter NAO and the annual precipitation is 0.2, rising to 0.4 for years that have a winter NAO index magnitude > 1.5, and rising to 0.5 for years that have a winter NAO index magnitude > 2.0 (for details of the calculations, see Excursus 3). To summarize, a great flood in China is well supported by the climatic upheaval's mechanism.

Ancient texts claim that the ruler who oversaw the channeling of the floodwaters also effectively founded the first Chinese dynasty (the Xia dynasty). There is no direct evidence for that, but the texts seem prima facie plausible: because a large mobilization of the populace resulting from strong and beneficial actions of a ruler likely would have much strengthened the government. Additionally, archaeological investigations show that there was no true civilization in the basin of the Yellow River until shortly after 2000 BC [An, 1991; Thorp, 1991; Underhill, 1996; Liu, 2000; {more-recent references}] and that the rise of civilization there was very rapid [Liu, 2000].

Finally, we note that some investigators have suggested that the Great Flood of ancient China is related to the biblical flood of Noah. A companion paper (in preparation) argues that although Noah's Ark is wholly fictitious, the biblical tale of the flood is based on a factual event: a flood induced by a comet or asteroid that crashed into the North Atlantic Ocean, roughly 10,000 years ago. By that argument, the biblical flood is unrelated to the Great Flood of ancient China.

Excursus 1: Tree–ice correlations

To roughly estimate the probability that all 4 tree traumas matched with eruptions, a Monte Carlo simulation was performed. The model was as follows. The period 2100–900 BC (the span of ice cores in Table 1) was considered as 400 triads of 3 consecutive years each. The 12 eruptions were represented by 12 randomly-selected groups of three consecutive triads—i.e. each eruption was considered to span nine years, to allow for small local dating errors (a conservative assumption). The 4 tree traumas were represented by 4 randomly-selected triads; in each run of the model, their dates were shifted (synchronously) by up to ten (i.e. 30 years) trying to get all 4 to match with eruptions. All 4 matching occurs about 9 times in every 10 000 runs.

Excursus 2: GRIP dating offset

There is an indication of an error in dating GRIP (and so DYE 3) in the ice layers above the brittle zone. In particular, there is a discrepancy between the oxygen-isotopic records of the GRIP and GISP2 cores over the time span 550 BC to AD 150: per Southon [2002]. The ages from GRIP are about 20 years greater than those from GISP2. The age difference is imprecise, partly because the GISP2 core was sampled only about once every 11 years, and the GRIP core about once every 3 years. Furthermore, the oxygen-isotopic discrepancy seems to have been determined visually, from graphs.

A variant of Southon's approach to determining the oxygen-isotopic discrepancy is described in Figure 2. Using the variant approach, the conclusion is that the optimal offset is 19 years—i.e. consistent with the conclusion of Southon.

There is evidence for the GISP2 dates being accurate back to at least 350 BC. In particular, for GISP2, there is a ^{10}Be record, which extends back to 350 BC; the ^{10}Be record seems to align with the ^{14}C record [Southon, 2002]. Furthermore, the GISP2 volcanogenic-acid record indicates eruptions in about 43 BC and AD 78, which is consistent with the dates for large eruptions of Etna (44 BC) and Vesuvius (AD 79) [Zielinski, 1995]. (A detailed comparison of the GISP2 and GRIP volcanogenic-acid record during the first millennium BC seems difficult.)

All of this strongly indicates that the GRIP core likely has its ages about 19 years too old, during the span from 550 BC to AD 150. That suggests that the core's ages are at least somewhat too old during centuries prior to 550 BC.

Excursus 3: NAO correlations

The correlation between the wintertime NAO and the precipitation in the middle basin of the Yellow River was calculated as follows. Monthly values of the NAO index were obtained from www.cru.uea.ac.uk/cru/data/; the NAO index for each winter was then calculated as the signed root–mean–squares of the monthly values for January–April. The middle basin of the Yellow River was taken to comprise the area spanning 35–40°N and 105–110°E; precipitation data for this area were obtained from the same web site as for the NAO data (which were updated from Hulme [1992]). Years analyzed were 1901–1998. {Should use more recent data too.}

Appendix: Planetary conjunctions

A chronology for ancient China has been proposed in several papers by David W. Pankenier. The proposed chronology is based on purported astronomical observations: specifically, it is based on texts that are purported to record three different conjunctions of the five planets that are visible with the naked eye.

The Xia–Shang–Zhou Chronology Project (noted above) had a working group devoted to "Conjunctions of the Five Planets …"—effectively, to Pankenier's proposed chronology. The conclusion of the working group, and the Project, was that conjunctions of the five planets should not be used for chronology: because the texts purported to record the conjunctions are very unreliable [Liu, 2002a; Liu, 2002b].

Pankenier's proposed chronology was also examined by Keenan [2002a]. Keenan [2002a] found that one of the three conjunctions did not occur, that the texts relied upon for another conjunction do not record a conjunction, and that records of the third conjunction are not reliable enough to form the basis of a chronology. Keenan [2002a] concluded that Pankenier's chronology "is without foundation".

A reply to Keenan [2002a] is given by Pankenier [2007]. Pankenier's reply was published in the *Journal of Astronomical History and Heritage*. The issue of the journal that includes the reply also includes a rebuttal from Keenan [Keenan, 2007]. The rebuttal considers each point of Pankenier's reply, and it concludes as follows.

> To summarise, Pankenier [2007] has no significant points that are valid. Moreover, Pankenier surely knows that many of the points raised by Pankenier [2007] are untrue. Additionally, it is noteworthy that the [Xia–Shang–Zhou] Chronology Project considered using planetary conjunctions for its work, but ultimately decided to reject this approach, because the records were considered too unreliable (see, for example, Liu [2002b: 2] and Liu [2002a: section 2]).

Pankenier does not appear to have published a rejoinder to Keenan's rebuttal.

In 2013, Pankenier published a book, *Astrology and Cosmology in Early China*. The book promotes his chronology based on planetary conjunctions. It is intended to supersede his previous papers on the topic. It does not, though, present any substantial new arguments for his chronology.

The book briefly cites the Xia–Shang–Zhou Chronology Project [(Various), 2000]. It does not, however, mention that the Project considered using planetary conjunctions—and rejected using them.

The book also references the paper by Barnard [1993]. The paper, which is entitled "Astronomical data from ancient Chinese records", is important because it presents detailed reasons in English for why the main textual records relied upon by Pankenier are unreliable. Barnard's paper, however, is not discussed anywhere in the book. Rather, the paper is just listed in the book's references.

The book cites Pankenier [2007] for one of its claims; it also repeats some claims of Pankenier [2007] without citing that paper. There is, however, no reference to the rebuttal of any of those claims by Keenan [2007]. Indeed, the book does not reference Keenan [2007].

Thus, there are publications that contain strong criticisms of Pankenier's proposed chronology and of the method Pankenier used for analyzing ancient texts. And the book ignores those publications.

There seems to be little purpose to discussing details of the book's claims about chronology, because those claims are already rebutted by other writings. (We refer the reader especially to Keenan [2007] and the discussion at the start of the above section "Chronology of ancient China".)

The conclusion here is essentially the same as the conclusion of Keenan [2007]. Pankenier's defense of his proposed chronology is unmerited, and Pankenier surely knows that it is unmerited; yet Pankenier continues to promote his proposal.

Acknowledgements. Appreciative thanks are offered to H.B. Clausen, W.J. Ingram, E.W. Maeder, D.M. Rohl, K. Rook, and the staff of the Science Reference and Information Service.

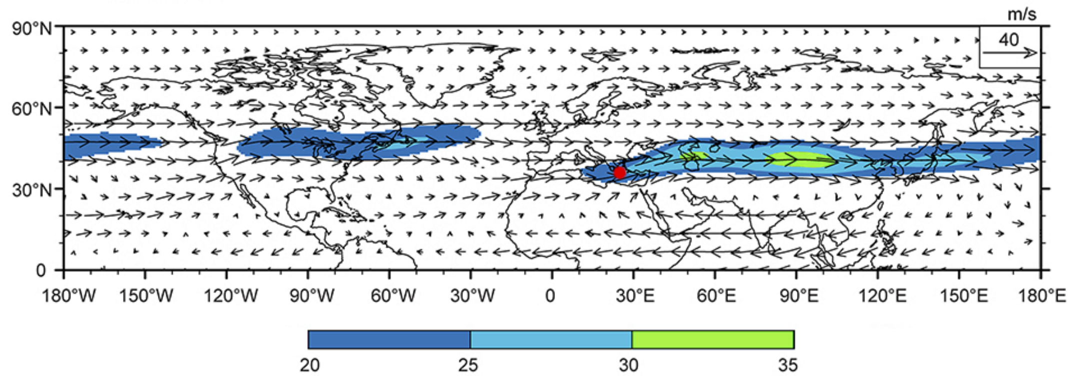

Figure 1: Subtropical Westerly Jet Stream during summer. The wind field (m/s) is for 200 hPa during June–July–August. The red dot denotes the volcano Thera (36°N, 25°E). Both Thera and the lower basin of the Yellow River (110–119°E) are located under the jet stream, as shown. (Figure is adapted from Zhou et al. [2020: fig.2].)

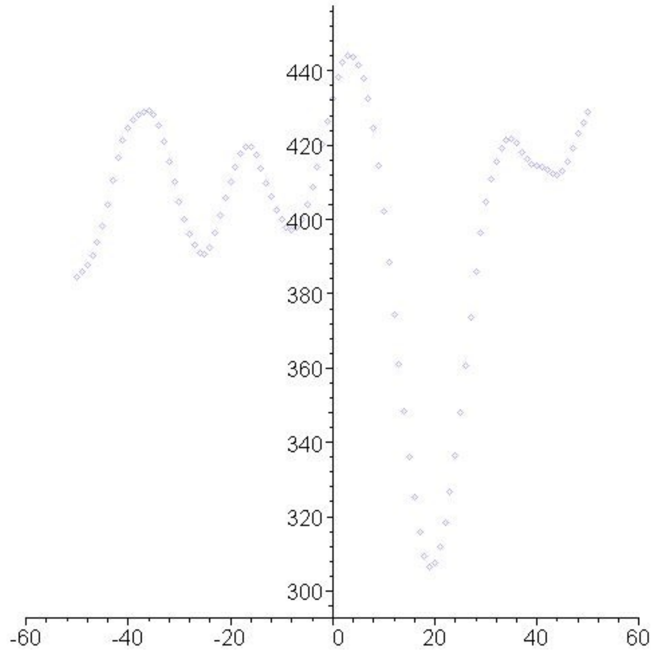

Figure 2: offsets between GRIP and GISP2 ice cores during BC 550 to AD 150. Oxygen-isotopic date for the GRIP and GISP2 cores is available from NSIDC [1997]. Let GRIP(*y*) denote the oxygen-isotopic value for year *y* from the GRIP core, calculated by interpolation if necessary. Similarly define GISP2(*y*) for the GISP2 core. Then do a least-squares analysis: find the value of *k* that minimizes $\sum_y (\mathrm{GRIP}(y-k) - \mathrm{GISP2}(y))^2$, where the sum is taken over all years from BC 550 to AD 150. The figure shows the value of the sum for different values of *k*. As shown, there is a strong minimum centered at $k = 19$ years. (This value is essentially the same as the value of Southon [2002], who proposed an offset of 20 years.) Using the same computation but taking the sum over a moving window of, say, 150 years, indicates that the 19-year offset largely begins somewhat earlier than AD 150, although it is difficult to state exactly when. (The 11-year solar cycle is also plainly visible in the figure, although that is not directly relevant here.)

Californian Trees	Irish Trees	Southern Core	Central Core
(300)	(300)	(900)	(900)
—	—	1064	1063
—	—	1074[*]	1073[*]
—	1159	1183	1182
—	—	1307	1302
—	—	1428	1425
—	—	1569	1566
—	—	1622	1618
1627	1628	1644	1636
—	—	1911	1910
—	—	1939	1938
—	1953	1968	1964
2036	—	2053	2045
(3400)	(2300)	(2100)	(2100)

Table 1: tree-ring traumas and ice-core volcanic records. All numbers are dates BC. Parenthesized dates at the top/bottom of a column indicate the beginning/ending of the tabulated record. Californian tree trauma is defined as having occurred when a certain portion of trees display frost damage [LaMarche & Hirschboeck, 1984]. Irish tree trauma is defined as having occurred when a certain portion of trees grew the narrowest rings of their lives [Baillie & Munro, 1988] (Irish tree data is from Baillie [1995: p.77] and M.G.L. Baillie, private communications, 1997). Tree-ring dating is believed to be exact. The Greenlandic ice cores are known as “DYE 3” and “GRIP”, respectively [Clausen et al., 1997]. Volcanic events shown are those identified by the primary investigators, based on acidity and sulfur measurements. (The acidity spike of 1569/1566 was not tested for sulfur for the original report [Clausen et al., 1997], but it has since been positively tested—H.B. Clausen, private communication, September 2002.) It is possible that a large eruption is not recorded in a particular ice core (e.g. the AD 1883 eruption of Krakatau [Clausen et al., 1997]); the cause is unclear [Robock & Free, 1995; Clausen et al., 1997]. More generally, the core-indicated size of an event seems to give little information [Clausen & Hammer, 1988; Robock & Free, 1995; Zielinski, 1995; Robock, 2000: §4.5]; hence each annual layer in a core is regarded here simply as either indicating or not indicating an eruption. Eruptions indicated by only one core are omitted. Ice-core dating errors are discussed in the main text. The inter-core alignment of volcanic events shown is that proposed by the primary investigators [Clausen et al., 1997: tbl.3].

[*] Ice layers also contain hydrochloric and hydrofluoric (volcanic) acids; these acids do not survive stratospheric transport and thus imply that the eruption was nearby, e.g. in Iceland [Clausen et al., 1997]. The date is consistent with the ^{14}C dates of the Hekla 3 eruption (the oft-proposed date in the first half of the 12^{th} century BC is not consistent with ^{14}C) [Dugmore et al., 1995; van den Bogaard et al., 2002]. Such nearby eruptions are high-latitude. They therefore tend to have their aerosols largely confined to near the pole (if they form in the stratosphere at all); hence they are unlikely to have substantially affected the hemispheric (or global) climate [Hammer et al., 1987; Graf, 1992] and so induced tree traumas.

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