RESEARCH NOTE

A Late Holocene geomagnetic secular variation record from Erhai Lake, southwest China

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SUMMARY
A secular variation record of the geomagnetic field direction for the last 6.5 kyr has been obtained from the magnetization of sediment cores from Erhai Lake, southwest China. In order to make a comparison with this record, secular variation in east-central China was investigated by combining available magnetic field data from historical records and archaeomagnetic measurements since about 350 BC. The secular variation in Erhai Lake shows features consistent with the combined record, except for the oldest three observed declination swings in Sian from 720 to 900 AD. Many features of declination and inclination in China also occur in Japan. From 500 to 1000 AD, declination was westerly ranging from about $-20^\circ$ to $-5^\circ$ in Erhai Lake, east-central China, and Japan.

Key words: geomagnetic variation, palaeomagnetism, sediments.

INTRODUCTION

Lake sediments have the potential for providing high-quality records of the past geomagnetic field because of their high sedimentation rates and calm depositional environment. Palaeomagnetic records reconstructed from lake sediments usually cover time spans of several thousand years, so they are useful for studies of secular variation (SV) over periods of 10^2 to 10^3 years, which are beyond the limit of direct observation. The reliability of SV records from remanence in sediments has been confirmed by the agreement found with archaeomagnetic SV in Britain (Turner & Thompson 1982), and in Japan (Hyodo et al. 1993).

SV records from sediments or baked clays have been reported at many locations (Creer et al. 1983), and can be used as a dating tool at each location. There are not, however, sufficient data for global analyses because the SV sites are not uniformly distributed over the Earth's surface. In particular, there is a region from western to central Asia that is largely devoid of SV data. Erhai Lake, one target of our study, is in the southeastern part of this region.

In China, SV data for the past several thousand years are still scarce. There are historical records of observation (Smith & Needham 1967) and archaeomagnetic SV data (Wei et al. 1981; Wei 1983), but the resolution in time is low because of the scarcity of data points. In addition, they are mainly distributed in central to east China.

In this paper, we report on an SV record from Erhai Lake, southwest China. The features of the SV in Erhai Lake are compared with other SV records in China and Japan. Based on the comparison, we assess SV data from historical records and archaeomagnetic measurements in China.

SAMPLING

Erhai Lake is located in the western part of Yunnan province, southwest China, and is in the three rivers region of the eastern
Geomagnetic secular variations from Erhai Lake.

Tibetan Plateau. It is a fault basin elongated in a north–south direction, and is about 40 km long and 3–8 km wide, with an area of about 250 km². About 10 km west of the lake there are mountains higher than 3000 m, where Lower Proterozoic metamorphic rocks comprising gneisses, shists, granulites, migmatites, and marbles (the Cangshan Group) are exposed (Bureau of Geological & Mineral Resources of Yunnan Province 1990). To the north and east of the lake, Palaeozoic basic-eruptive and sedimentary rocks are exposed. From the foot of the mountains to the west, a gentle slope extends eastwards to the bottom of the lake. This slope continues to the eastern margin of Erhai Lake, where a fault scarp extends in a north–south direction. The depth of Erhai Lake increases towards the east, and the elevation of the lake surface is 1970 m. The lake has a number of inflow rivers on its western side, and drains out into the Mekong River through an outlet at the southwestern end (Fig. 1).

In May 1993, sediment core ER1 was taken from a flat-bottomed site 10 m deep in the southern part of the lake (Fig. 1), using a pneumatically driven piston corer. The core was 241 cm long and the sediment material changed from clay to silt at the base (Fig. 2). In November 1994, core ER3 was collected from the central part of the lake, about 20 km northwest of the ER1 site (Fig. 1). The ER3 site is 20 m deep, which is the maximum depth of the lake. A rise in the lake floor to a water depth of about 5 m occurs between the two coring sites. Core ER3 was 316 cm long, consisting of clay above the 217-cm level and silt below it (Fig. 2).

Each core was cut into sections of 1 m length or less. Palaeomagnetic samples 10 cm³ in volume were collected using cubic plastic capsules from the centre of each 7.6-cm-diameter core as follows. The capsule was pushed perpendicularly into a sediment surface, which had itself been cut perpendicular to the vertical axis of the core. The sediment core was pushed out of its tube in 2.5-cm segments with a piston, and then a palaeomagnetic sample was removed from each segment, as described above. The remaining part of each segment was used for other studies. A total of 98 specimens was taken from core ER1, and 135 specimens from core ER3. While these specimens were being taken, shell and wood fragments were collected at many levels for radiocarbon dating.

MAGNETIC MEASUREMENTS

A 2G superconducting rock magnetometer was used for measurements of remanent magnetization. Magnetic susceptibility was measured using a Bartington susceptometer, and a Natsuhara alternating field (AF) demagnetizer was used to isolate the magnetization components. Anhysteretic remanent magnetization (ARM) was imparted in a steady 50 mT field with a superimposed peak AF of 100 mT, and then measured. Changes of susceptibility in cores ER1 and ER3 do not completely match each other. There is a drastic change at 90 cm in ER1 and at 40 cm in ER3 (Fig. 3a), with similarly high values of >600 µSI above these levels. The high values correspond to the topmost parts, just above a zone containing...
plenty of shell fragments (Fig. 2) in both cores. However, the patterns of change are quite different in the lower parts, and even the topmost parts exhibit some small inconsistent fluctuations. Furthermore, the susceptibility values in ER1 are consistently higher than those in ER3. These differences may reflect different sources of sediments, because the two sampling sites are separated by about 20 km (Fig. 1). The rise in the lake floor between the two sampling sites, described above, may have divided the sedimentary basin into two if the water level was lower.

In spite of the different susceptibility changes, natural remanent magnetization (NRM) intensity normalized by susceptibility shows quite consistent changes between the two cores. Similar prominent features are connected by lines in Fig. 3(b). The correlated features 1–3 are in the topmost NRM high-intensity zone. Below feature 3, the normalized intensity changes agree with each other in absolute value in addition to fluctuations. Furthermore, the susceptibility values in ER1 are consistently higher than those in ER3. These differences may reflect diVerent sources of sediments, because the two sampling sites are separated by about 20 km (Fig. 1). The rise in the features 3 and 4, and stay at values >2.0 below feature 4 until just above feature 5 (Fig. 3b). These correlations are supported by lithological characteristics. Feature 4 coincides with the lowest level of the appearance of shell fragments, and feature 8 with the clay/silt boundary (Fig. 2). The \(^{14}\)C dates obtained from the two cores (Table 1) suggest that the correlated features in Fig. 3(b) are from the same age horizons.

Figure 3. Vertical plots of (a) susceptibility, (b) NRM intensity/susceptibility, (c) ARM intensity, (d) ARM intensity/susceptibility, and (e) NRM intensity/ARM intensity for sediment cores ER1 and ER3 from Erhai Lake.
The curves of ARM intensity and ARM intensity normalized by susceptibility (ARM/susceptibility) show a sudden increase at around 1 m (no. 4) (Figs 3c and d). It has been suggested from the acquisition curves of isothermal remanent magnetization saturated in a low field of 300 mT that magnetite is a dominant carrier in the Erhai Lake sediments (Ando 1998). Therefore, the increase in the ARM/susceptibility shows a decrease in the relative magnetic grain size (King et al. 1982). Such a sudden change in grain size above feature 4 should reflect a large change in the source of sediments in Erhai Lake.

NRM intensity normalized by ARM intensity (NRM/ARM) is shown in Fig. 3(e), in which the same levels as in Fig. 3(b) are connected. Similar changes in this ratio occur in the two cores, although the degree of fluctuation is higher than the NRM/susceptibility change. The NRM intensity of a sediment reflects many components in addition to the geomagnetic one, such as the quantity of magnetic minerals, grain size, and the effects of bioturbation and disturbance by water flow. However, the consistency in the normalized NRM intensity curves between the two cores is believed to be mainly caused by geomagnetic components. Differences between the NRM/susceptibility and NRM/ARM curves are explained by the magnetic grain-size changes shown by the ARM/susceptibility curve in Fig. 3(d). For example, the NRM/ARM curve does not show a rise above feature 4, in contrast to the NRM/susceptibility curve (Figs 3b and e). The suppressed values in NRM/ARM are caused by large ARM intensities due to fine magnetic grains, to which ARM is more sensitive than susceptibility. The small differences below feature 4 may be explained in the same way. The smooth change in the NRM/susceptibility curve may be because susceptibility is less sensitive to grain size.

These magnetically inhomogeneous sediments are unsuitable for a palaeointensity study. However, the consistent features in the normalized NRM intensity curves possibly reflect palaeointensity changes. The depths of the connected features in Fig. 3(b) will later be used as age horizons in the construction of a timescale.

Pilot samples selected every 50 cm in depth were progressively demagnetized in alternating fields (AF) from 5 to 90 mT. The result shows that all the samples from both cores have quite stable remanence, as shown by the vector end-point diagrams in Fig. 4. The remaining samples were all demagnetized at 10, 15, and 20 mT in AF for ER1, and in more than 10 steps of AF for ER3. Characteristic remanent magnetization (ChRM) was calculated using principal component analysis (Kirschvink 1980). ChRMs were obtained from 97 samples in ER1 and 134 samples in ER3. ChRMs were not obtained from two samples, one in each core, both of which were from the ends of 1-m core sections. The sediment structures in these cores may have been disturbed when being cut.

### DATING

Accelerator mass spectrometric (AMS) $^{14}$C dating was made using shell and wood fragments extracted from sediments at three levels in core ER1 and at seven levels in core ER3 (Table 1). A depth-age relation for ER3 was first determined as follows. Since the dates at 190.4 cm and 192.8 cm in core ER3 agree with each other within error ranges, an average of the two was used as a date at a middle depth, 191.6 cm. The same approach was taken for the dates at 251.2 cm and 253.4 cm in core ER3. The date of 3030 yr BP at 97 cm in core ER1, which may be regarded as a date for tie-line number 4 (Fig. 3b), is used for the date at a depth of 100 cm in core ER3. Using these dates in addition to the three $^{14}$C dates above 84 cm in ER3, and assuming that the top of the core is zero in age, a depth-age relationship was determined by linear interpolation, as shown in Fig. 5. All the $^{14}$C dates were calibrated using dendrochronological data (Stuiver & Reimer 1993) as shown in Table 1. The linear relationship between depths of 191.6 cm and 252.4 cm was extrapolated below 252.4 cm. Using the eight tie-lines in Fig. 3(b), which are dated using the depth-age relation in ER3 (Fig. 5), the depth scale in ER1 was converted to a time scale.

The depth-age relation in core ER3 (Fig. 5) shows a high sedimentation rate of about 2 mm yr$^{-1}$ in the depth range from 100 to 192 cm, while sedimentation rates are about 0.3 and 0.4 mm yr$^{-1}$ respectively above and below it. A similar pattern is obtained in core ER1. The high sedimentation rate begins just above the clay/silt boundary, and ends at the lowest level of the appearance of shell fragments in both cores (Fig. 2). These facts may imply a large event in the palaeoenvironmental history of Erhai Lake. A similar pattern of increase in sedimentation rate has been observed in Siling-Co (Lake), central Tibet, with sedimentation rates of 0.7 mm yr$^{-1}$ over the period 3 to 4 kyr BP (conventional radiocarbon years), and 0.10 and 0.15 mm yr$^{-1}$ after and before it, respectively (Kashiwaya et al. 1995). It was shown that an increase in water level accompanied these changes. The rapid sedimentation in Siling-Co may be

<table>
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<th>Core</th>
<th>Depth (cm)</th>
<th>Conventional $^{14}$C years</th>
<th>Calibrated dates (calendar years)</th>
<th>Sample material</th>
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<td>56.9</td>
<td>1320 ± 150</td>
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<td>Wood</td>
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<td>1840 ± 100</td>
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<td>Shell</td>
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</table>

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**Figure 4.** Representative results of progressive AF demagnetization for specimens in cores (a) ER3 and (b) ER1. Solid/open circles show projections on the horizontal/vertical plane. The declination is relative.

**Table 1.** Results of AMS radiocarbon dating in Erhai Lake.
Declination and inclination logs are plotted on a timescale in Figs 5(a) and 6(a), respectively. The declination variations between the two cores are quite consistent, having corresponding maxima and minima, as labelled alphabetically (Fig. 6a). It should be noted that the rapid swings ‘g’ to ‘l’ are resolved due to the high sedimentation rate mentioned above. There are, however, some differences in the inclination variations between the two cores (Fig. 7a). The features ‘b’, ‘c’, and ‘d’ are not seen in the inclination record for ER1, and the maxima ‘g’ and ‘i’ in ER1 are somewhat lower than those in ER3. However, other features in ER3 are well reproduced in ER1, as labelled by Greek letters.

The cause of the differences in the inclination variations is uncertain at present. The absence of some features in ER1 may be caused by alterations of remanence during coring, sample cutting, or transportation. The lowered inclination peaks can be explained by the filtering effect of the post-depositional magnetization process (Hyodo 1984) and/or non-vertical penetration of the corer tube in coring. At least the filtering effect causes the smoothing of the palaeomagnetic record of ER1, because the amplitudes of the declination swings ‘c’, and ‘g’ to ‘i’ in ER1 are attenuated (Fig. 6a). Such a difference in filtering may be caused by a difference in sedimentology.

Figure 5. The depth–age relation in core ER3. The solid circles represent the data obtained in core ER3, and the open square is transferred from core ER1.

Figure 6. Secular variations of declination in East Asia. (a) Records from cores ER1 and ER3 in Erhai Lake, smoothed by a running average of five points. The features are labelled by Roman letters (see text). (b) Historical records of observations (solid and open squares) and archaeomagnetic data (solid circles) in China (see text). The numbers 1–9 indicate the observation sites in Fig. 8. The archaeomagnetic data points show a median age with an age range and a mean declination with 95 per cent confidence limits. Declination in Luoyang since 1945 calculated from DGRF (IAGA division V et al. 1995) is shown by a thick line. (c) Records in southwest Japan from sediments (solid circles with 95 per cent confidence limits), archaeomagnetic data (Hirooka 1971, 1983; Maenaka 1990) (open triangles), and historical records of observation (Imamichi 1956) (solid squares).
DISCUSSION

Historical records of observations of geomagnetic declination have been made in China since 720 AD. Smith & Needham (1967) compiled 18 records from 720 to 1829 AD, with observation sites located in nine areas between 23° and 41° N latitude, and 98° and 121° E longitude (Fig. 8). 17 of these are plotted in Fig. 6(b) with black and white squares numbered the same as the sites in Fig. 8 (One observation in the historical records is not shown by a numerical value).

The plot of historical records shows (Fig. 6b) that similar declination values have been observed simultaneously at distant sites. For example, in 1708 AD the declination was 2° W in Shenzhen (no. 8 in Fig. 8), and 3° W in Jiayuguan (no. 9 in Fig. 8), about 1800 km east of Shenzhen. In addition, declination was 0° in Guangdong (no. 7 in Fig. 8) in 1817, and 1.5° W in Beijing (no. 4 in Fig. 8), about 1900 km north of Guangdong, in 1827 AD. The regional differences are thus sufficiently small that the declination composite curve shows a smooth change from 15° W in 1086 AD to near 0° in modern time.

The three oldest historical observations, 3.4° E in 720 AD, 15° E in 850 AD, and 7.5° E in 900 AD, shown by open circles in Fig. 6(b), are all in Sian. They are the only easterly declinations in the historical records, and show fluctuations larger in amplitude than those after 1086 AD.

In Luoyang, about 400 km east of Sian (Fig. 8), archaeomagnetic studies (Wei et al. 1981) have provided seven reliable declinations, shown by solid circles with error bars in Fig. 6(b). The declination of 11° W for 618–907 AD corresponds to the Sian data for 720 AD and 850 AD, and the declination of 17.1° W for 960–1127 AD corresponds to the Sian data for 900 AD. In spite of the short distance between Luoyang and Sian, the declination data are discrepant by 15°–25°. Considering the small regional difference in declination since 1086 AD noted above, it is likely that the three Sian data points

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are erroneous. The Luoyang archaeomagnetic declinations from about 100 to 1000 AD are in accord with the historical records after 1086 AD, if the Sian data are discarded (Fig. 6b).

The historical and archaeomagnetic declination change pattern (Fig 6b) is consistent with that of 'd-c-b-a' in the declination from Erhai Lake (Fig. 6a). The linear trend from 'c' to 'b' correlates especially well with that of the combined data, except for the Sian data. The declination curves from Erhai Lake are adjusted so that the maximum 'b' is set to 0°, considering that the declination of 0° in 1817 was in Guangdong, near Erhai Lake.

Many features of declination variations in Erhai Lake and east-central China may be correlated with those of the SV record in Japan (Fig. 6c). The magnetic field direction in Japan kept an easterly declination from 200 AD to 350 AD, and then swung westwards with a peak at about 550 AD. These changes correled well with the features from 'd' to 'c' in China (Figs 6a and b), although there may be differences in phase of <100 years. From 500 AD to 1100 AD, the field in Japan kept a westerly declination from -20° to -10°, just like the archaeomagnetic SV in China. There was no easterly declination swing corresponding to the Sian data from 720 AD to 900 AD in Japan. Although from 1100 to 1800 AD the declination changes were different in Japan and China, they were consistent again after 1800 AD.

The archaeomagnetic studies in Luoyang (Wei et al. 1981) provided 17 inclination data points from bricks dating from 400 BC to 1840 AD (Fig. 7b). These are steeper by about 10° than the inclination from Erhai Lake. The difference can be explained by the fact that Luoyang is located about 9° farther north in latitude than Erhai Lake. In spite of the large distance between them, about 1500 km, the features of maxima and minima, '5-6-5-6', in core ER3 (Fig. 7a) are reproduced well in the Luoyang archaeomagnetic data (Fig. 7-b). The features β and δ are slightly different in phase. The differences may be due to regional fields.

The inclination features '5-6-5-6' are also seen in the SV record from magnetization of sediments in Japan (Fig. 7c), although the amplitude is somewhat smaller. As already pointed out by Hyodo et al. (1993), the archaeomagnetic inclination record in Japan (Hirooka 1971, 1983; Maenaka 1990) shows high-frequency fluctuations before 1300 AD, which are inconsistent with the sedimentary record (Fig. 7c). Such fluctuations are also not seen in the SV records in China (Figs 7a and b). The archaeomagnetic inclination records in China are similar to the sedimentary record in Japan.

The above comparison of SV records reveals that many SV features can be traced from Japan to east-central China, and farther to Erhai Lake in southwest China, over a distance of more than 3500 km. A similar result for SV analyses has been obtained in North American SV records (Lund 1996). These facts provide some constraints on the extension and life of non-dipole fields.

CONCLUSIONS

A palaeomagnetic secular variation record during the last 6.5 kyr was obtained from the natural remanence of sediment cores in Erhai Lake, southwest China. For the last 2 kyr, the declination and inclination in Erhai Lake show features fairly consistent with those of secular variation in both historical records and archaeomagnetic data in east-central China. Many features of secular variation in China are also found in Japan. From 500 to 1000 AD, declination was westerly ranging from about -20° to -5° in Erhai Lake, east-central China, and Japan. The three historical records of declination in Sian from 720 to 900 AD, which are easterly ranging from +5° to +15°, are probably erroneous.

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