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Paleomagnetic evidence for the Gothenburg geomagnetic excursion during the Pleistocene–Holocene transition recorded in the Paleo-Danyang Lake, eastern China

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ABSTRACT

This paper aims to identify the Gothenburg geomagnetic excursion as a stratigraphic marker and presents the results of a paleomagnetic investigation of deposits within the southern part of the Paleo-Danyang Lake area of eastern China. These paleomagnetic data provide evidence for the Gothenburg geomagnetic excursion at 12,494 to 13,081 cal year BP at depths of 6.5–7.2 m within the paleo-lake. We also analyzed the spatial distribution of localities that both record and do not record the excursion event and the estimated timing of this excursion event in East Asia. The presence of uninterrupted sedimentation at a high depositional rate during the Pleistocene–Holocene transition appears to be the key factor in preserving evidence for this excursion in the localities that record this event. The non-existence of the excursion appears to be the result of low sedimentation rates, under-sampling and the presence of sedimentary hiatuses associated with erosion. The fact that these types of excursions can be correlated between sedimentary cores separated by angular distances of less than 30° on Earth's surface means that the Gothenburg excursion can be used to correlate between lacustrine and marine deposits in East Asia (and potentially further afield) as well as being useful for chronostratigraphic purposes. Comparisons between cave stalagmite $\delta^{18}O$ records and the polarities of the lacustrine sediments also indicate that the timing of the Gothenburg geomagnetic excursion is consistent with an abrupt decrease in temperature since the last deglaciation although the meaning of this correlation requires further research.

1. Introduction

Magnetostratigraphy is a useful geochronological tool that is based on the fact that geomagnetic reversals are globally recognizable phenomena. The successful use of magnetic field reversals as global stratigraphic markers has led researchers to attempt to identify paleomagnetic markers other than the very clear and easily identifiable geomagnetic excursions (Merrill and Mcfadden, 2005). The term excursion was originally used to refer to the displacement of a virtual geomagnetic pole (VGP) by more than 40° from the geographic pole (Barbetti and Mcelhinny, 1972). This term is now commonly used to describe a displaced VGP that is in the opposite hemisphere from where it is expected to be (Merrill and Mcfadden, 1994). However, the evidence for some geomagnetic excursions from the paleomagnetic record in sediments deposited during the Brunhes epoch is not as compelling as the theoretical arguments for the presence of these excursions (Verosub, 1982). This includes the Gothenburg magnetic excursion or 'flip', which was originally identified in southern Scandinavia, appears to have lasted no longer than about 1000 years, and generated particularly striking inclination changes (Mörner and Lanser, 1974; Mörner, 1977). This excursion has appearently been documented in numerous localities in Europe (Mörner, 1986; Gus'kova et al., 2012), America (Banerjee et al., 1979; Nami, 1999, 2015), Asia (Zhao and Zhang, 1981; Wang et al., 1986; Chen, 1988; Ma and Sun, 1994; Zhu et al., 1998; Li et al., 1999; Ge et al., 2008; Liu et al., 2012; Krainov et al., 2017), Africa (Haag et al., 1999), and Oceania (Lund et al., 2007; Nelson et al., 2009). However, the presence of the Gothenburg excursion has not exclusively been accepted as some researchers suggest that a number of

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factors, including reinforcement syndrome, a psychological phenomenon observed in scientific research wherein a discovery is repeatedly reinforced by further data (Watkins, 1972), mean that this excursion has not been reliably verified (Thompson and Berglund, 1976). In addition, the structure of the geomagnetic field is likely to have been complex at this time and this event does not appear to be a global marker, meaning it could be recorded at some locations but not at others (Merrill and Mcfadden, 2005). All of this means that the validity of the Gothenburg excursion remains controversial.

Geomagnetic excursions tend to be short events that may not be recorded in a given area as a result of several factors (Merrill and Mcfadden, 2005), including: (1) low sedimentation rates; (2) the presence of a finite magnetization lock-in zone, where a smooth representation of fluctuations in the magnetic field is recorded and made permanent (Denham and Chave, 1982); (3) the remagnetization or physical disruption of the sediments deposited during the excursion, or; (4) analytical errors and under-sampling. This means that the definitive establishment of a geomagnetic excursion requires careful fieldwork, laboratory work, and analysis, as well as evidence from more than one field site.

Previous research generated high resolution magnetostratigraphic data from recent sediments within Gucheng Lake which is located in the eastern part of the Paleo-Danyang Lake region of eastern China (Ma and Sun, 1994). These sediments provided evidence for a reversed polarity event at a depth of ~12.5 m within core corresponding to an age of 10,307–9727 year BP, suggesting that these sediments may record evidence for the Gothenburg excursion. However, the original analysis of the sediments lacked data such as anisotropy of magnetic susceptibility (AMS) analyses or X-radiography, meaning that it was uncertain whether this apparent reversal was real or was an artifact created during post-sedimentary disturbance. This study presents new paleomagnetic data from the southern Paleo-Danyang Lake area generated during a detailed study of the magnetic stratigraphy recorded within the BZK0402 core (details are given below). The ages of the sediments within the core were accurately determined by accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating, allowing the constraining of sedimentation rates using linear interpolation and extrapolation methods. This study also presents new data that provide insight into the number and distribution of places that record the Gothenburg excursion and the number and distribution of places that do not record this excursion in East Asia and discusses the reasons for the non-existence of this excursion in this region. This paper also establishes a relationship between the Gothenburg excursion and contemporaneous climate change although at this stage this remains a correlation rather than a definitive causal relationship. Finally, this paper indicates the Gothenburg excursion has potential as a regional chronological marker that can be used to correlate between different types of depositional environment within East Asia.

2. Study area

The Paleo-Danyang Lake is located within the Middle and Lower Yangtze River metallogenic belt along the northern margin of the Yangtze block in eastern China (Fig. 1A). The evolution of fault-controlled depressions in this region during the last phase of Yanshanian tectonism caused this area to subside and gradually form a broad limnetic depression. The southernmost mountains in this region at this time also continued to rise, causing the further subsidence of this depression. Quaternary tilting in this region generated an increase in erosion and the volume of debris flows, leading to the washing down of a large quantity of sediment from upstream regions and generating the deltaic tract of the Shuiyang and Qingyi rivers. The early Holocene evolution of this area involved the formation of a lake within this infilled depression as a result of the blocking of flow to the Yangtze River (Li, 1989).

The early development of the Paleo-Danyang Lake led to water covering an area of 4130 km^2. The lake then continued to subside and receive eroded sedimentary material from the surrounding mountains that was carried by the Qingyi and Shuiyang rivers. The infilling and reclamation of the depression-hosted lake eventually led to its disappearance (Dai and Zhao, 1992), although the region still contains a number of waterbodies of various sizes that represent remnants of the paleo-lake, including the Shijiu, Gucheng and Nanyi lakes (Fig. 1B).

3. Materials and methods

This paper focuses on the magnetostratigraphy of the Paleo-Danyang Lake using data generated from the BZK0402 drill core. Drilling was undertaken along the southern edge of the Paleo-Danyang Lake at 30°59′29″N, 118°46′31″E, at an altitude of approximately 10 m. The location is approximately 1 km east of the Shuiyang River and 13 km southwest of Nanyi Lake and generated 13.2 m of cored sedimentary material. The sediments intercepted were formed in a typical fluvial–lacustrine environment associated with the existence of the Paleo-Danyang Lake in this area until the time of the Spring and Autumn Period in China (514–476 BCE; Dai and Zhao, 1992). The sediments and lithologies intercepted in this drillcore include nine natural intercalated ooze, clay, silty clay and fine sand sedimentary units before the drill hit gravel layers and eventually bedrock at the base of the hole.

Magnetic stratigraphy samples were collected for precise dating at depths between the top of the hole and a depth of 7.5 m, where the drilling intercepted gravel layers that could not be sampled. Oriented block samples were generally obtained at 0.2 m intervals, although this was dependent on core recovery (overall recovery was 94.7%), resulting in some sampling intervals being as large as 0.4–0.5 m. Samples were taken by pushing a hollow non-magnetic cube with a size of $2 \times 2 \times 2\,cm^3$ directly into halved unconsolidated sediment cores. Semi-consolidated sediments were initially carefully cut using a thin stainless-steel spatula before the plastic sampling cubes were pressed into the halved core. A total of 40 samples for Alternating Field (AF) demagnetization analysis were obtained during this study.

The paleomagnetic analysis of the sediment was undertaken using a 2G-755R Superconducting Rock Magnetometer in the Paleomagnetic and Rock Magnetism Laboratory of the Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China. These measurements were undertaken within three months of sample retrieval to minimize possible alteration. Sample processing and analysis was undertaken in a magnetically shielded environment and alternating demagnetization specimens were directly measured using a 2G-755 Superconducting device. The measurements were performed in 15 steps at 0, 50, 80, 100, 120, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, and 800 Gauss for systematic demagnetization. The reliability of the paleomagenetic signal carried by the samples was assessed on specimens at the same depth obtained from the other split half of the sediment samples using AMS analysis employing a KLY-3S Kappabridge system in the State Key Laboratory for Mineral Deposits Research, Nanjing University, China.

The core was dated using three samples from the middle part of the uppermost core in an area relatively enriched in organic matter where the dark sediments vary in color from blue gray to black. These samples were dated using the AMS ^{14}C dating approach at the Xi'an Accelerator Mass Spectrometry Center, Xi'an, China. The resulting radiocarbon ages were converted into calibrated ages using the INTCAL 13 calibration curve (Reimer et al., 2013) and the OxCal 4.3 Web interface, with the results given as calibrated ages in Table 1. Here, we report calibrated ages as calendar ^{14}C ages before CE 1950 (cal year BP) with two standard deviation (2σ) uncertainties.

4. Results

The original data generated during this study, including results of the paleomagnetic analysis and the radiocarbon dating of the BZK0402 core, are available at the Mendeley Data website (https://doi.org/10.

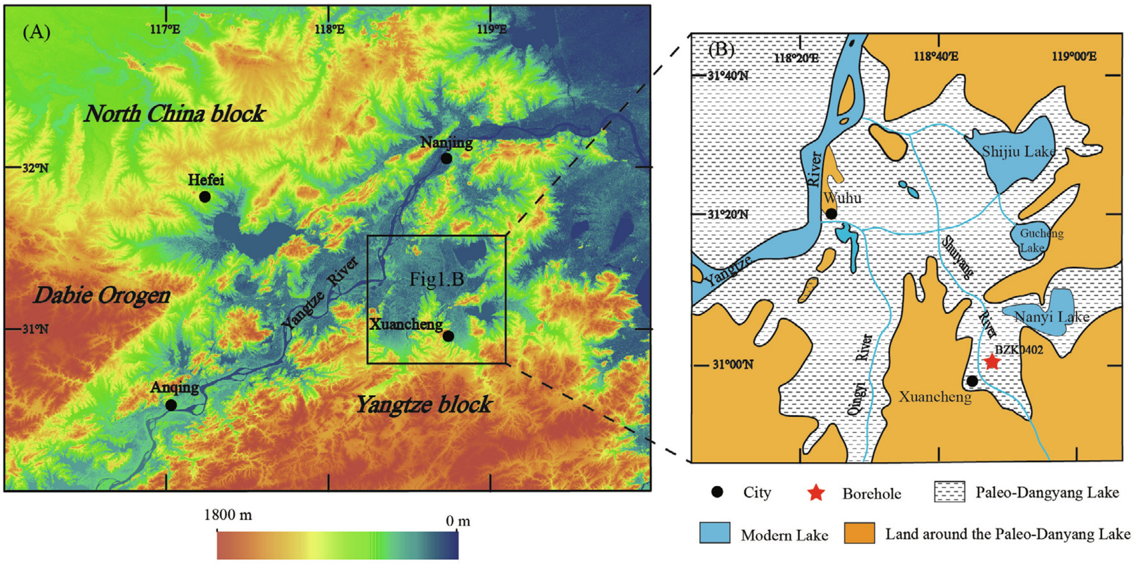

Fig. 1. Maps of the study area. (A) Digital elevation model showing the Middle and Lower Yangtze River metallogenic belt and a black rectangle outlining the region of the Paleo-Danyang Lake. (B) Detailed image of the area around the Paleo-Danyang Lake, showing the extent of the lake, modern waterbodies, and the location of the drilling site shown as a star.

Table 1
Results of the radiocarbon dating of the BZK0402 core.

Lab code	Depth (m)	Material dated	Conventional radiocarbon age (yr BP)	2 Sigma calibrated radiocarbon age (cal yr BP, 95% probability)	Mean calibrated radiocarbon age (cal yr BP)
XA20535	2.95	Ooze	6770 ± 30	7670–7581	7625.5
XA20536	4.85	Ooze	9420 ± 35	10,741–10,571	10,656
XA20537	6.85	Clay	10,925 ± 40	12,872–12,703	12,787.5

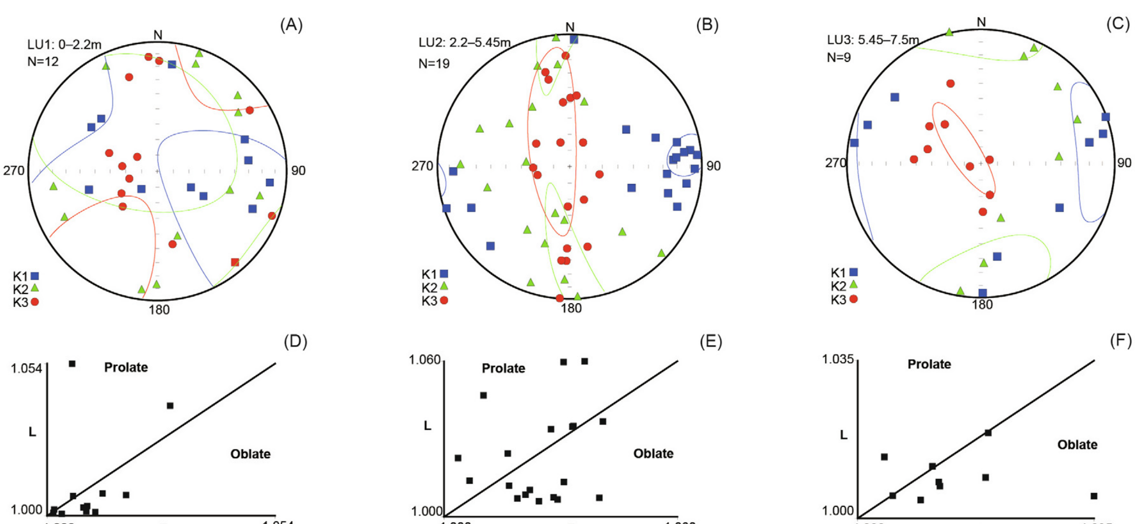

Fig. 2. AMS data for samples from the BZK0402 core, which is divided into three lithological units, LU1 (0–2.2 m), LU2 (2.2–5.45 m), and LU3 (5.45–7.4 m). (A–C) Stereographic projections of the K1 (blue squares), K2 (green triangles) and K3 (red circles) axes. (D–F) Diagrams showing variations in magnetic lineation (L) versus magnetic foliation (F). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

17632/89dk6gvdt7.1).

4.1. AMS

Before any analysis of the paleomagnetic data obtained during this study it is important to ensure that these data represent primary data rather than artifacts generated during any post-sedimentary disturbance of the core. Here, we use AMS, an approach that enables the recognition of core deformation, in this case by soft sediment deformation primarily of the ooze sediments in the core (Rosenbaum et al, 2000; Shimono et al, 2014). This analysis divided the BZK0402 core above a depth of 7.5 m into three depositional units, namely LU1 (0–2.2 m, silty clay, clay, fine sand), LU2 (2.2–5.45 m, ooze), and LU3 (5.45–7.5 m, silty clay, clay, silty clay). The LU1 unit contains yellowish silty clay with interbedded clay and fine sand layers whereas LU2 is generally covered by a dark-gray to gray ooze that has sedimentary

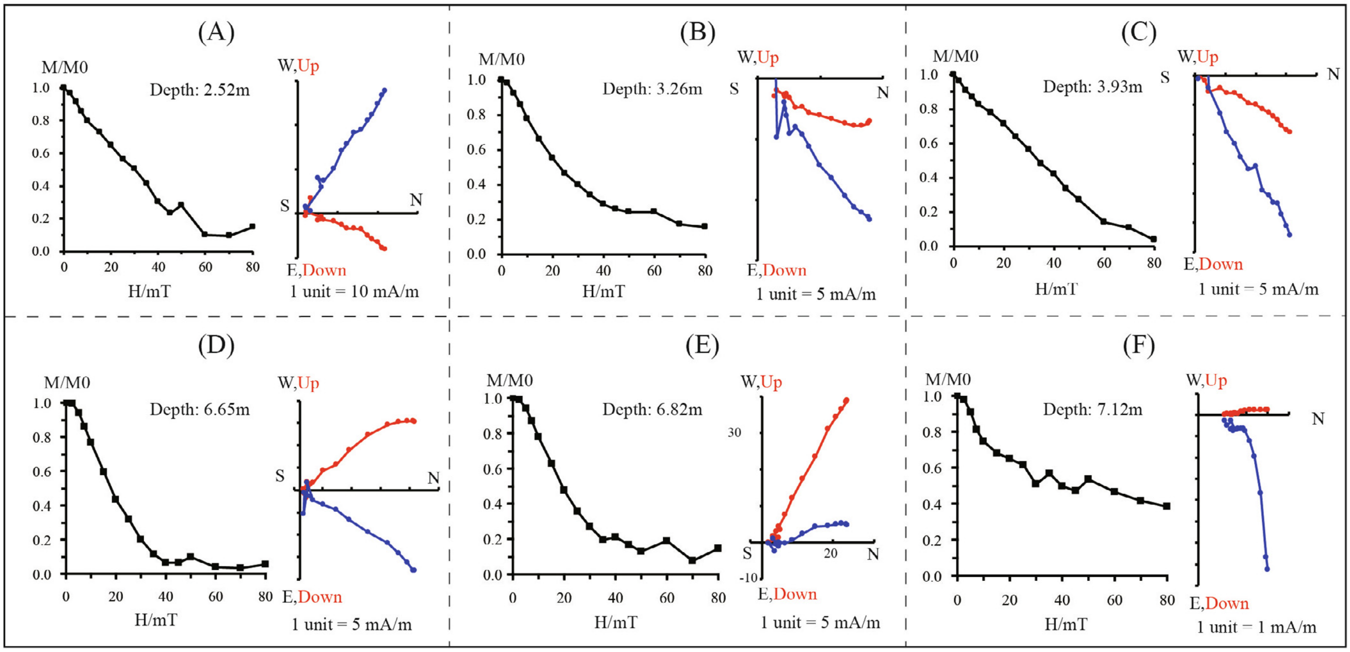

Fig. 3. Remanence decay curves (left) and orthogonal vector plots (right) for the stepwise AF demagnetization data for representative samples from the study area where blue squares indicate horizontal projections and red circles indicate vertical projections. (A–C) Samples with normal polarity. (D–F) Samples with reverse polarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

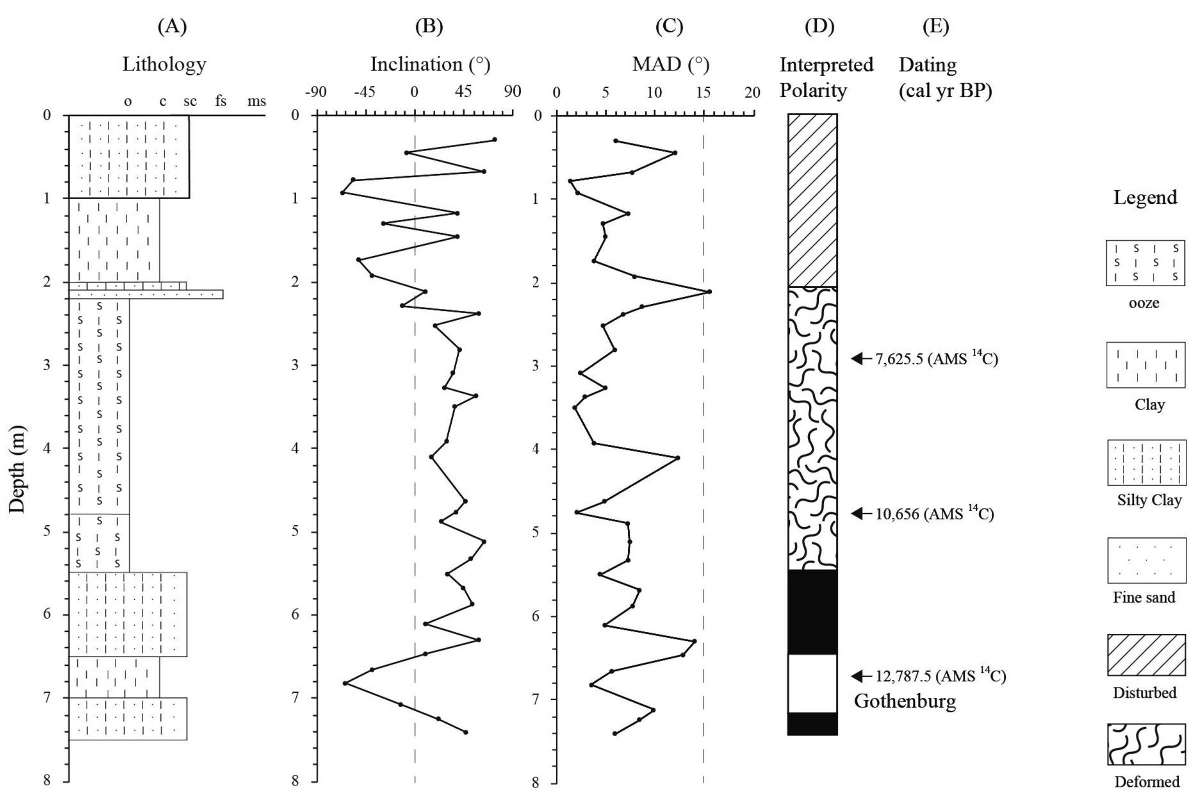

Fig. 4. Stratigraphic column for the BZK0402 core, showing variations in lithologies (o: ooze; c: clay; sc: silty clay; fs: fine sand; ms: medium sand), the magnetostratigraphy of the sediments (MAD: maximum angular deviation), and the results of radiocarbon dating. Black bars indicate sediments with normal polarity, white bars indicate sediments recording reversed polarity, and gray bars indicate disturbed sediments.

characteristics indicative of deposition in a lacustrine environment. The LU3 unit contains gray silty clay with interbedded clay layer. The ruleless distribution (Fig. 2A, D) of the AMS data sets obtained from the unit LU1 indicates that these sediments have been disturbed by post-sedimentary deformation. The declinations of the maximum axes (K1) of specimens in the LU2 unit cluster within the 90–270° specimen axis, reflecting the directions of the surface of the split core (Fig. 2B). The magnetic foliation (F) and magnetic lineation (L) values for these sediments indicate that the AMS ellipsoids are oblate and have variable prolate components (Fig. 2E) that are indicative of sampling-induced

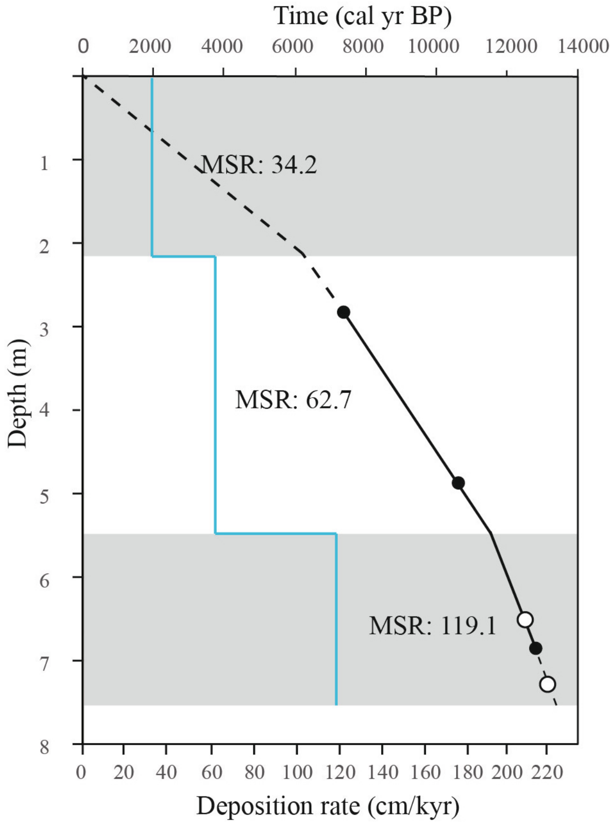

Fig. 5. Diagram showing variations in linearly extrapolated depth–age relationship (black line) and sedimentation rates (blue line) recorded within the BZK0402 core. Black solid circles represent the three ages given in Table 1 and the two unfilled circles represent the span of the Gothenburg geomagnetic excursion recorded in the core. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deformation, rather than any soft-sediment deformation-related process.

The majority of the measured samples in unit LU3 have K3 axes that are close to vertical (perpendicular to the bedding plane) and K1 axes that are close to horizontal (Fig. 2C). The values of F is larger than L (Fig. 2F), indicative of an oblate AMS ellipsoid. This AMS behavior is consistent with a primary sedimentary fabric, indicating that the original sedimentary fabric of these sediments was preserved after deposition and that any paleomagnetic data obtained for these sediments will not have been disturbed.

4.2. Paleomagnetism and dating

Paleomagnetic demagnetization results were evaluated using orthogonal diagrams (Zijderveld, 2013) and principal component directions were computed using a least-squares fitting technique that employs at least three successive data points to define a linear trend clearly directed towards the origin of the orthogonal plot (Kirschvink, 1980). All measurements and processing were undertaken using the PaleoMag 3.1 software package (Jones, 2002). Representative examples of the demagnetization behavior of the BZK0402 core samples are shown in Fig. 3. The characteristic remanent magnetization (ChRM) of the samples is generally between 40 and 60 mT for AF demagnetization, with samples with maximum angular deviation (MAD) values > 15° excluded from further analysis. The core was not horizontally oriented, meaning that only magnetic inclination (Inc) data were used during magnetostratigraphy construction. The variations in ChRM inclination directions, MAD angles and radiocarbon dating results are shown with respect to depth in Fig. 4, with samples with negative directions critically evaluated (e.g., Fig. 3D–F). One of the three negative sample at a depth of 7.12 m is located in a silty clay layer between the other two negative samples that were located within clay layers, indicating that they do not correspond with the clay layer intercalated with the upper and lower silty clay.

The AMS ^{14}C dating undertaken during this study indicates the sediments at the top of the core were deposited during the Holocene. This dating also indicates that all of the sediments intercepted within this drillcore were deposited during the Brunhes normal chron. A possible geomagnetic excursion during the Pleistocene–Holocene transition, constrained by reliable ChRM data from 26 discrete samples (omitting 11 disturbed samples and excluding the three further samples), is present at depths of 2.2–7.5 m within the sediments in the BZK0402 core. The two negative samples at depths of 6.65 m and 6.82 m are located in a clay layer and the other further negative sample at a depth of 7.12 m is located in a silty clay layer. Only one geomagnetic excursion has been identified at this time, namely the Gothenburg geomagnetic excursion. This strongly suggests that the excursion identified within the BZK0402 core during this study represents the Gothenburg excursion.

4.3. Sedimentation rate

The sedimentation rates recorded within the BZK0402 core vary somewhat between different lithological units (Fig. 5). The three radiocarbon ages obtained during this study (Table 1) yield a mean sedimentation rate of 62.7 cm/kyr between depth of 2.2 and 5.45 m. Linear interpolation yielded ages of 11,612 and 12,494 cal yr BP for depths of 5.45 and 6.5 m, respectively. Further linear extrapolation yields ages of 6430 and 13,081 cal yr BP for depths of 2.2 and 7.2 m, respectively. The ages and associated sedimentation rates within the interval between the polarity reversal and the lithological boundaries within the drillcore are given in Table 2. The drillcore at depths of 6.5–7.2 m, representing the geomagnetic excursion recorded in the core, occurred between 12,494 and 13,081 cal yr BP, yielding a sedimentation rate of circa 119.1 cm/kyr.

The sedimentation rates recorded within the core gradually reduce from an initially high rate. The Gothenburg excursion recorded within the core is also a short event. This means that the uninterrupted sedimentation at a high depositional rate during the Pleistocene–Holocene transition in the study area is an advantageous factor in terms of the recording of this short duration excursion.

Table 2
Boundary ages and sedimentation rates recorded within the BZK0402 core.

Depth (m)	Boundary type	Age (cal yr B.P.)	Sedimentation rate (cm/kyr)
2.2	Derived from AMS ^{14}C	6430	34.2
5.45	Derived from AMS ^{14}C	11,612	62.7
6.5	Top of Gothenburg excursion	12,494	119.1
7.2	Bottom of Gothenburg excursion	13,081	119.1
7.5	Derived from AMS ^{14}C	13,333	119.1

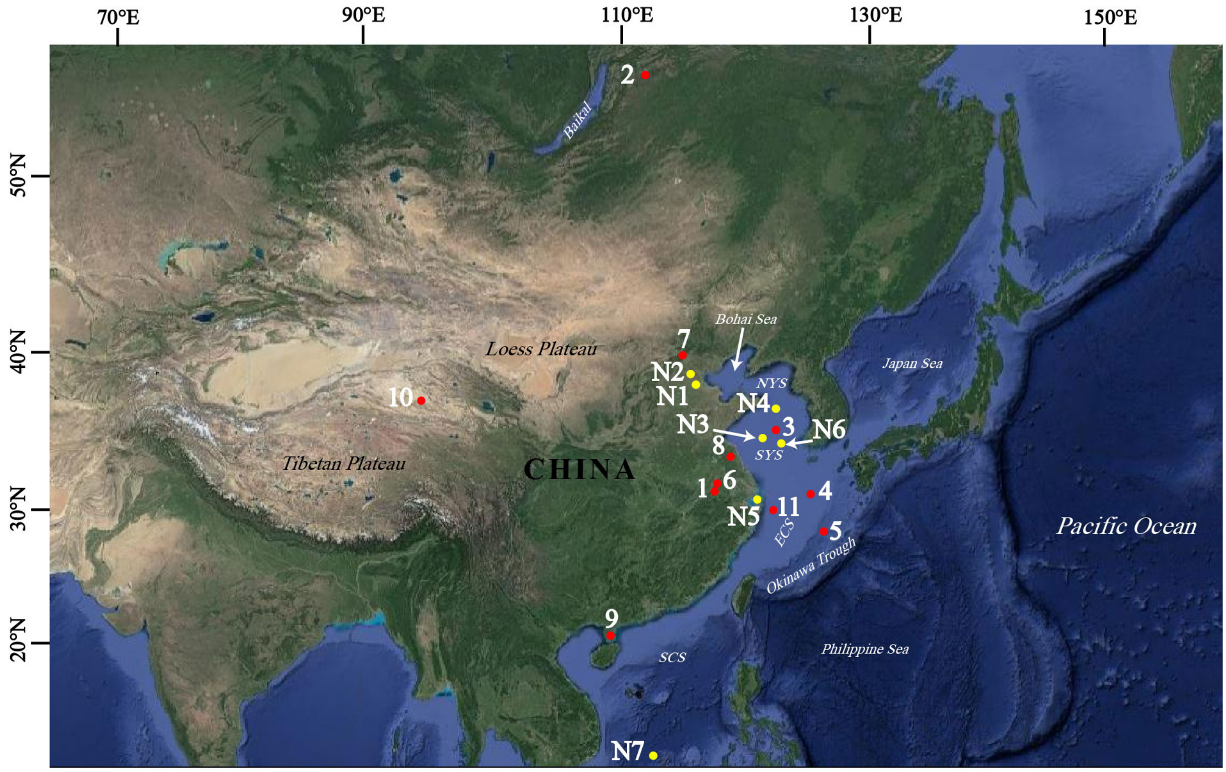

Fig. 6. Map of East Asia outlining areas where the Gothenburg excursion has been established (red circles) and areas where the excursion is not recorded (yellow circles) reflecting either the absence of the excursion or under-sampling that did not allow this brief excursion to be identified. The lack of accurate published coordinates for the Gucheng Lake core (6), the Qingfeng section (8), the Tianyang Volcanic Lake core (9), and the DC1 core (11) means that these locations are approximate rather than entirely accurate. See Tables 3 and 4 for details of individual locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

5.1. Factors affected the quality of paleomagenetic data obtained from the BZK0402 core

Dimensional distortion is a well-known problem associated with all sediment coring methods. The magnetic fabric of soft sediments can be used to identify post-sedimentary deformation, either as a result of soft sediment deformation or during sampling, and AMS has been extensively used to identify this type of disturbance of magnetic mineral orientation fabrics. No visually disturbed samples were used to determine inclination values, meaning only those with clear demagnetization vector paths to the origin were used for inclination value calculations. In addition, the sediments between the top of the core and a depth of 2.2 m yielded unstable inclinations that are indicative of disturbance and do not reflect the real behavior of the geomagnetic field. This is also consistent with the AMS behavior of the measured specimens within the LU1 unit, indicating that the sediments within this unit have been disturbed and the associated paleomagnetic data may be unreliable. This is similar to research on core obtained from Gucheng Lake within Gaochun County, Jiangsu Province, China, where similar analysis identified a layer that had undergone ploughing to a depth of 1.7 m (Ma and Sun, 1994), suggesting that the LU1 samples from the study area have been anthropogenically disturbed in a similar fashion.

The AMS data generated during this study also indicates that the samples from unit LU2 appear to have been deformed (Fig. 4B). However, it remains unclear whether this deformation has changed the paleomagnetic orientation of these samples. The radiocarbon dating of the BZK0402 core indicates that the sediments within the unit LU2 were deposited during the Early–Middle Holocene Brunhes normal chron. The stable ChRM inclination directions within the LU2 section also indicate that the artificial AMS caused by coring and sampling has negatively affected the quality of the paleomagnetic data obtained from these samples although these samples appear to not have been affected by any other type of deformation. The same phenomenon has also been identified in samples taken from the Okhotsk Sea where Shimono et al. (2014) argued that the resulting paleomagnetic directions were not affected because the inclination average was close to that predicted by a geocentric axial dipole (GAD). This is similar to the situation in the study area, suggesting that the paleomagnetic data obtained from the LU2 samples may well be valid even though they have been slightly disturbed during sampling. Finally, the lack of any preferred alignment relative to a specimen axis in the LU3 samples (Fig. 2C) suggests that this unit remains entirely undisturbed, indicating that the paleomagnetic data for this unit is reliable.

5.2. Favorable conditions for the preservation of the Gothenburg excursion in East Asia

The Gothenburg excursion was first identified in East Asia in 1981 within the DC1 core drilled in the East China Sea (ECS) between the Pacific Ocean and the Eurasian continent (Zhao and Zhang, 1981). This was followed by identification of the excursion within continental sediments (Zhu et al., 1992, 1993), lacustrine sediment cores (Chen, 1988; Krainov et al., 2017; Ma and Sun, 1994), and cored sea bottom sediments from the East China and Yellow seas (Ge et al., 2008; Li et al., 1999; Liu et al., 2012, 2014). However, determining whether the Gothenburg excursion is a valid event requires consideration of all of the available evidence, including the number, spatial distribution and characteristics of the areas that both record and do not record this excursion event (Merrill and Mcfadden, 2005). The distribution of localities that record the Gothenburg excursion in East Asia are shown in Fig. 6 and Table 3 provides details for each of these locations, including their depositional environments, the material dated, the dating

Table 3
Locations and details of areas with well-established evidence for the Gothenburg excursion during the Pleistocene–Holocene transition in East Asia.

No	Site	Location	Environment	Material dated	Method used	Radiocarbon age (yr BP)	Sedimentation rate (cm/kyr)	AMS data	Reference
1	Paleo-Danyang Lake (BZK0402 core)	30°59′29″N, 118°46′31″E	Fluvial–Lacustrine	Clay, Ooze	AMS ^{14}C	13,081–12,494◇	119.1	Yes	This paper
2	Northern Transbaikalia (Baunt-2014 core)	55°11′15″ N, 113°01′45″ E	Lacustrine	Diatom ooze	AMS ^{14}C	13,200–13,100◇	59.8*/44 (MSR)	No	Krainov et al. (2017)
3	SYS (NHH01 core)	35°13′N, 123°13′E	Shelf	Benthic foraminifera	AMS ^{14}C	9470–8450◇	45	Yes	Liu et al. (2012, 2014
4	ECS (EY02-1 core)	30°44′ N, 126°34′ E	Shelf	Benthic foraminifera	AMS ^{14}C	12,681–10,206◇	42	No	Ge et al. (2008)
5	Okinawa Trough (DG9603 core)	28°08.869′N, 127°16.238′ E	Slope	Planktonic foraminifera shells	AMS ^{14}C	12,911–11,953	13.57	No	Li et al. (1999); Xu et al. (2013)
6	Gucheng Lake	?	Lacustrine	Ooze	^{14}C, AMS ^{14}C	10,307–9727	138*/160 (MSR)	No	Ma and Sun (1994)
7	Fenzhuang section, Beijing	40.2° N 116° E	Lacustrine	Peat, Ooze	^{14}C	14,000–13,700	51.9*	No	Zhu et al. (1998)
8	Qingfeng section, Jiangsu Province	?	Lacustrine	Ooze, Clay	^{14}C	11,060–10,760	40.8*	No	Zhu et al. (1992)
9	Tianyang Volcanic Lake	?	Lacustrine	Clay	^{14}C	13,000–12,000	18.96*	No	Chen (1988)
10	Qaidam Basin, central Asia (Dabusan Lake core)	37.1° N 95.4° E	Lacustrine	Salt clay	^{14}C	15000–9000	165(MSR)	No	Wang et al. (1986)
11	ECS (DC1 core)	?	Shelf	?	^{14}C	> 11,510 ± 570	160*(MSR)	No	Zhao and Zhang (1981)

References: ?: not given; *: sedimentation rates were calculated using the ages provided in the reference; ◇: calibrated radiocarbon ages were provided; MSR: mean sediment rate for the entire core.

approach used, the resulting calculated sedimentation rates, and whether AMS analysis was undertaken to verify the quality of the paleomagnetic data obtained from each location. The depositional environments that record the existence of the Gothenburg excursion include fluvial–lacustrine, continental slope, and shelf environments, each of which are discussed in detail below.

5.2.1. Lacustrine sedimentary environments

The lacustrine sediments that record the Gothenburg excursion in East Asia include the Qingfeng section, which is located in Jiangsu Province and records a reversed polarity event at depths of 4.83–4.68 m at 11,060–10,760 yr BP, yielding a sedimentation rate of 40.8 cm/kyr (Zhu et al., 1992). In addition, core from the Fenzhuang section in the Beijing area also records the Gothenburg reversed polarity event at depths of 7.31–7.14 m depth. These depths reflect an age of 14,000–13,700 yr BP and yield a sedimentation rate of 51.9 cm/kyr (Zhu et al., 1993). The presence of similarly rapid sedimentation rates and similar lithological associations within these two sections indicate both of these areas record similar sedimentary environments. The lithological association of peat, ooze, and clay indicate that these sediments were most likely deposited in a swampy lacustrine environment. Two cores drilled through high sedimentation rate environments within the Paleo-Danyang Lake also record the Gothenburg excursion, namely a core drilled in Gucheng Lake (Ma and Sun, 1994) and the BZK0402 core that forms the focus of this study, which was drilled 35 km to the southwest of Gucheng Lake.

The northern and southern edges of East Asia also contain areas with lacustrine sediments that record the geomagnetic Gothenburg excursion. The Tianyang Volcanic Lake is located in the southeastern part of the Leizhou Peninsula in China and contains a lake basin that has continuously been filled with Quaternary porous sediments, resulting in a 222.42 m thick sedimentary package. The reversed polarity event within these sediments is located at a depth of 6.45–7.38 m at 13,000–12,000 yr BP, yielding a sedimentation rate of 18.96 cm/kyr (Chen, 1988). The Baunt-2014 core within the northern part of the Republic of Buryatia, Russia also records this reversed polarity event at a depth of 5.9 m depth in sediments deposited at 13,200–13,100 cal yr BP, yielding a sedimentation rate of 59.8 cm/kyr. The Lake Baunt sediments records both the Gothenburg and Mono Lake excursions within a 13.7 m thick sedimentary succession that has an estimated basal age of 28–30 ka (Krainov et al., 2017).

The Dabusan Lake core in central Asia also records a reversed polarity event at a depth of 20–30 m with an age of 15,000–9000 cal yr BP (Wang et al., 1986) that is consistent with the Gothenburg excursion. The high sedimentation rate in this area (165 cm/kyr) together with the presence of a sediment package > 500 m in thickness may have again provided an environment where the evidence for such a short duration event may have been preserved.

5.2.2. Continental shelf environments

The continental shelf forms the linkage between continent and ocean and as such is a globally important reservoir for terrigenous sediments. Extensive continental shelf environments are located to the east and south of China in the Yellow Sea, the ECS, and the South China sea (SCS). The NHH01 core from the southern Yellow Sea (SYS) records a reverse polarity excursion at a depth of 4.26–3.84 m. AMS ^{14}C dating of this core yielded a mean sedimentation rate of 45 cm/kyr that prevailed since 10,200 cal yr BP. This rate yields a duration of 9470–8540 cal yr BP for the Gothenburg reverse excursion within this core (Liu et al., 2012). The DC1 (26 m long in a water depth of 31 m; Zhao and Zhang, 1981) and EY02-1 (70.2 m long in a water depth of 80 m; Ge et al., 2008) cores within the ECS also record the presence of the Gothenburg excursion. The former recorded the excursion at a depth of 18.86–19.4 m with a mean sedimentation rate of 160 cm/kyr, whereas the latter intercepted the excursion at a depth of 9.62–8.58 m with a sedimentation rate of 42 cm/kyr and a linearly extrapolated

Table 4
Locations and details of areas without evidence of the Gothenburg excursion during the Pleistocene–Holocene transition in East Asia as a result of low sedimentation rates, under-sampling, and/or sedimentary hiatuses associated with erosion.

No.	Site	Location	Environment	Material dated	Method used	Core length (m)	Sedimentationrate (cm/kyr)	Sampling intervals (m)	Reason for absence	Reference
N1	Bohai Bay Basin (CK3 core)	38°9.2′N, 117°32.5′E	Deltaic	Peat	AMS ^{14}C	500	10.9$^{\diamond}$ (MSR)	0.5	R2	Xu et al. (2015, 2018)
N2	Bohai Bay (BZ2 core)	39°1′N, 117°8′E	Deltaic	Quartz fraction	OSL	203.6	6.4$^{\diamond}$ (MSR)	0.5	R2	Yao et al. (2010, 2012)
N3	Western SYS (CSDP-1 core)	34°18′N, 122°22′E	Deltaic-Shelf	Bivalve mollusk shell	AMS ^{14}C	3.4*/ 300.10	30	0.1	R2	Liu et al. (2016, 2018)
N4	Northern SYS (DLC70-3 core)	36°38′15″N, 123°32′56″E	Shelf	Benthic foraminifera	AMS ^{14}C	0*/71.20		0.2	R2	Mei et al. (2016)
N5	Northern ECS (ECS-DZ1 core)	30°29′29″N, 122°03′00″E	Shelf	Quartz fraction of silty grains	OSL, AMS ^{14}C	55.5*/ 153.6	640	0.5	R2	Yi et al. (2014); Wang et al. (2015)
N6	SYS (EY02-2 core)	34°30′N, 123°30′E	Shelf	Benthic foraminifera	AMS ^{14}C	2.5*70	6 (MSR)	continuous	R1	Ge et al. (2006)
N7	Southern SCS (ODP Hole 1143C)	9°21.72′N, 113°17.11′E	Slope	Biostratigraphic data	biological events	512.1	~5.49$^{\diamond}$ (MSR)	0.5–1.0	R1	Wu et al. (2017)

References: ?: not given; SYS: South Yellow Sea; ECS: East China Sea; MSR: mean sediment rate; *: depth of Holocene sediments; $^{\diamond}$: mean sedimentation rate within the Brunhes Chron considering the referenced age of ~0.781 Ma for the Matuyama/Brunhes (M/B) boundary; R1: low sedimentation rate or under-sampling; R2: sedimentary hiatus caused by erosion.

calendar age of 12,681–10,206 cal yr BP. These contininental shelf environments and the lacustrine environments outlined in Section 5.2.1 that record the Gothenburg excursion all have one thing in common, namely high to very high sedimentation rates. This suggests that a high sedimentation rate may be required to preserve evidence of this recent and short duration event.

5.2.3. Continental slope environments

The Okinawa trough is located close to the edge of the eastern ECS continental shelf and contains a continuous record of environmental changes within both oceans environments and the adjacent landmasses (Saito et al., 1998). The DG9603 core (5.85 m long in a water depth of 1100 m) was taken from the mid-Okinawa Trough and contain a continuous accumulation of semipelagic abyssal ooze (Xu et al., 2013). Paleomagnetic analysis undertaken on continuous samples from this core led to the identification of the Gothenburg excursion at a depth of 107–120 cm, with AMS ^{14}C ages yielding an age span of 12,911–11,953 yr BP and an associated mean sedimentation rate of 13.57 cm/kyr (Li et al., 1999). The continuous samples from this core combined with knowledge of the sedimentation rate in this area allows a theoretical calculation of the minimum amount of sample needed to identify the Gothenburg excursion. Combining the required presence of evidence of the excursion within at least three hollow non-magnetic cube with a size of $2 \times 2 \times 2$ cm^3 with the 1 ka duration of the excursion (Mörner and Lanser, 1974) yields a minimum sedimentation rate required to preserve evidence of the excursion of 6 cm/kyr. This indicates that high sedimentation rate, the presence of a stable sedimentary environment, and frequent enough sampling are all required in order to provide favorable conditions for the preservation of evidence of the Gothenburg excursion.

5.3. Why is the Gothenburg geomagnetic excursion not recorded in some areas?

As discussed above Section 5.2, the sediments that record the existence of the Gothenburg excursion include those deposited in fluvial–lacustrine, continental slope, and shelf environments. In comparison, some contemporaneous sediments in East Asia deposited in deltaic, shelf, and slop environments do not record this excursion, with the locations of these sediments also shown in Fig. 6. The characteristics of these sites, including their depositional environments, the material dated, the dating methods used, the resulting calculated sedimentation rates, the sampling intervals, and the probable reason(s) evidence of the Gothenburg excursion is absent from these sediments are given in Table 4 and are discussed in detail below.

5.3.1. Low sedimentation rate or under-sampling

Paleomagnetic studies have also been undertaken on the 70 m long EY02-2 core, which was obtained at a water depth of 70–80 m within the SYS and does not record the Gothenburg excursion despite benthic foraminifera dating and assemblage analysis indicating that the onset of the Holocene occurs at a depth of 2.5 m within the core. The lack of evidence of the excursion probably reflects a combination of the brevity of the excursion and the low mean sedimentation rate during the Holocene in this core, potentially leading to the occlusion of the excursion during sampling and analysis (Ge et al., 2006).

ODP Hole 1143C (length of 512.1 m at a water depth of 2772 m) was drilled in the southern part of the SCS within a continental slope environment similar to that present within the Okinawa Trough. Magnetic stratigraphy samples were generally obtained at 0.5–1.0 m intervals (Wu et al., 2017) and the sediments record a mean sedimentation rate of 5.49 cm/kyr with the Matuyama/Brunhes (M/B, 0.781 Ma) paleomagnetic reversal identified at a depth of ~42.84 m within the core. The sedimentation rate in this area means that the ≥0.5 m length paleomagnetic samples obtained from this area span time intervals > 9.1 ka. This contrasts with the known duration of the Gothenburg excursion (generally < 1 ka; Mörner and Lanser, 1974), meaning that this excursion would be located most likely within the center of one of these 0.5 m sampling intervals and therefore may be occluded by the surrounding non-excursion sediments.

5.3.2. Erosion-related hiatuses in sedimentation

Erosion-related hiatuses in sedimentation can also possibly remove evidence of the Gothenburg excursion from sedimentary sequences. This is exemplified by a transgression within the area of the ECS, the northern Yellow Sea (NYS) and the Bohai Strait at 11.6–11.3 ka BP followed the end of the Younger Dryas (Liu et al., 2004, 2007; Li et al., 2014; Tian et al., 2017). This transgression was probably triggered by a rapid sea-level rise event known as meltwater pulse 1B (MWP-1B; Bratton et al., 2002; Fairbanks, 1989). The AMS ^{14}C ages from the

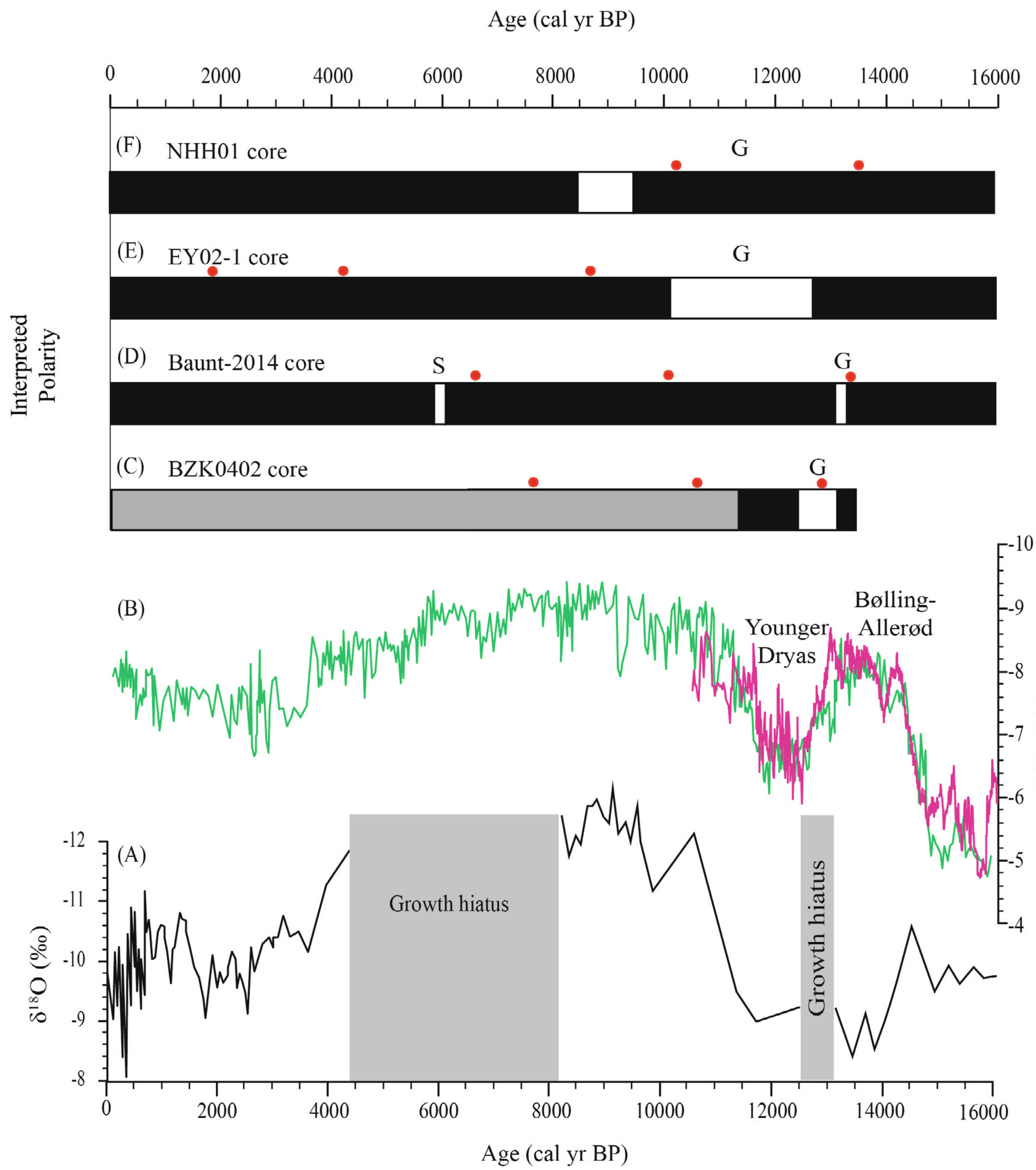

Fig. 7. Comparison between the $\delta^{18}O$ records of cave stalagmites and the polarities of cores recording the Gothenburg geomagnetic excursion event with calibrated AMS ^{14}C ages (red circles) in East Asia; G: Gothenburg geomagnetic excursion; S: Solovki geomagnetic excursion. (A) $\delta^{18}O$ values for the 20120824-13 Yelang Cave stalagmites (black; Zhao et al., 2015). (B) $\delta^{18}O$ values for the D4 Dongge (green; Dykoski et al., 2005) and Hulu (red; Wang et al., 2001) cave stalagmites. (C–F) Polarities of the BZK0402, Baunt-2014, EY02-1 and NHH01 cores, where black bars indicate sediments with normal polarity, white bars indicate sediments recording reversed polarity, and gray bars indicate disturbed sediments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

DLC70-3 core in this region (length of 71.2 m at a water depth of 73 m) indicate the absence of a post-11 ka BP sedimentary record within the SYS mud area, primarily as a result of the erosion of Holocene sediments (Mei et al., 2016). This clearly means the excursion cannot have been recorded within this core. Preservation of thick fluvial deposits was favored in fluvial channels in this area (Liu et al., 2010), and the CSDP-1 core (300.1 m long at a water depth of 52.5 m) is located in an interfluve area between major river channel systems. A subsequent post-glacial transgression caused marine sediments to fill the fluvial channels, whereas thin fluvial deposits on some of the interfluve plains could have been eroded away by a retreating shoreface in response to the sea-level rise after the Last Glacial Maximum (LGM; Liu et al., 2016, 2018). Records from the ECS-DZ1 core (153.6 m long at a water depth of 12 m) within the subaqueous inner-shelf of the ECS yield largely consistent early Holocene sea level histories (Wang et al., 2015; Yi et al., 2014). However, neither the ECS-DZ1 core nor the CSDP-1 core records the Gothenburg excursion during the Pleistocene–Holocene transition. This again probably relates to the fact that these areas have undergone erosion during post-glacial transgression, leaving to the removal or disturbance of the sediments that would otherwise have recorded this excursion.

An early Holocene transgression event is also well documented along the Fujian coast (Ge et al., 2018). Records from the southwestern coast of the SYS and the Bohai coastal plain also yield largely consistent early Holocene sea level histories (Gao et al., 2017; Tian et al., 2017). The Holocene transgression is marked by a transition in sedimentary facies from coastal marshes and tidal flats to shelf deposits within the Bohai Sea area (Liu et al., 2009). This indicates that the coastal zone in this area was most likely undergoing pervasive and intensive erosion, potentially explaining why the BZ2 core recovered near Bohai Bay (Yao et al., 2010, 2012) and the CK3 core recovered from the southwestern Bohai Bay Basin (Xu et al., 2015, 2018) do not record the Gothenburg excursion. The lack of evidence of the Gothenburg excursion in these two cores may reflect their near-shoreline locations, both of which were significantly influenced by sea-level fluctuations between the late Pleistocene and the Holocene.

5.4. Correlation between the Gothenburg excursion and climate change

Speleothems can undergo continuous deposition of calcium carbonate over long periods of time, with previous work on speleothems recovered from the coastal Hulu (Wang et al., 2001) and Dongge (Dykoski et al., 2005) caves and the inland Yelang cave (Zhao et al., 2015) identifying rapid shifts in monsoon intensity within East Asia. Speleothem $\delta^{18}O$ data provide evidence of dryer climates during the Younger Dryas event and wetter climates during the Bølling–Allerød (BA) and Holocene Optimum events as a result of solar insolation trends (Fig. 7). We can compare these $\delta^{18}O$ records of cave stalagmites and the polarities of the cores recording the Gothenburg excursion event with calibrated AMS ^{14}C ages from East Asia. This diagram excludes cores that record the excursion event but do not have calibrated AMS ^{14}C ages and the estimated age of the Gothenburg geomagnetic excursion recorded in the EY02-1 core was calculated by linear extrapolation. However, the fact that dated radiocarbon samples were located exactly within the excursion event means that the timing of the Gothenburg excursion recorded in the Baunt-2014 and BZK0402 cores are probably the most reliable estimates of the timing of this event. In addition, the age of the excursion recorded in the NHH01 core is significantly different from the timing of the excursion within the other samples shown in Fig. 7, indicating this is a somewhat unique case. These data indicate that the timing of the Gothenburg geomagnetic excursion is consistent with the known decrease in temperature since the last deglaciation recorded within speleothem $\delta^{18}O$ data (Fig. 7), providing evidence of a correlation between a geomagnetic excursion and climatic change. This connection between geomagnetic, cosmogenic and climate changes has been the focus of recent research (Bakhmutov, 2006; Valet et al., 2014, 2019) that identified synchronous variations in magnetic and cosmogenic records within three Indian Ocean cores (Valet et al., 2019). However, despite the presence of this correlation, the relationship between the geomagnetic field, solar insolation and climate changes is relatively complex, it remains unclear whether these correlations are entirely causative, and the details of the processes within these relationships require further research.

6. Conclusions

The analysis of the BZK0402 core obtained from the Paleo-Danyang Lake in eastern China enabled the identification of the Gothenburg geomagnetic excursion at a depth of 6.5–7.2 m with an age of 12,494–13,081 cal yr BP. This area, and others that record the Gothenburg excursion in East Asia, all have undergone uninterrupted sedimentation at a high sedimentation rate during the Pleistocene–Holocene transition, meaning this may have been a key factor in preserving the evidence of this excursion in this region (and elsewhere). Contemporaneous sediments in East Asia that do not record the excursion record low sedimentation rates, have been under-sample and/or record sedimentary hiatuses associated with erosion, all of which appear to be key factors in the lack of evidence of this excursion in the samples obtained from these areas. Knowledge of these factors can be used to identify areas likely to record the Gothenburg excursion and assuming that excursion fields are not dominated by harmonics with degree higher than 6, these excursions can be used to correlate between sedimentary cores separated by angular distances of less than 30° on Earth's surface. This means that the Gothenburg excursion can be used to correlate between sedimentary cores in East Asia and can be used as an additional chronological marker during the Pleistocene–Holocene transition.

Comparisons between the $\delta^{18}O$ records of cave stalagmites and the polarities of lacustrine sediments indicate that the timing of the Gothenburg geomagnetic excursion is consistent with the timing of an abrupt temperature decrease since the last deglaciation. However, the relationship between the geomagnetic field, solar insolation and climate changes is relatively complex and requires further research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jseaes.2019.104140.

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