Palaeomagnetic methods and results

Forty-five orientated samples were obtained for analysis from beds A, C, D and F (Fig. 3 and Supplementary Information 1, Fig. 6). Plastic sample cubes (8 cm^3) were inserted into cleaned sediment sections, or into sediment monoliths, and orientated using a magnetic compass. The NRM and the low-field magnetic susceptibility (κ) of the samples were measured at the Centre for Environmental Magnetism & Palaeomagnetism, Lancaster University, using an AGICO JR6A spinner magnetometer and a Bartington Instruments MS 2 susceptibility meter. All samples were stored in field-free mu-metal boxes (field <30 nanoTesla) during the demagnetisation process. To isolate the ChRM components of the NRM, all samples were subjected to reversing, tumbling, stepwise AF demagnetisation in fields up to 100 mT (Molspin AF demagnetiser). This treatment is much more effective than static AF demagnetisation, for greigite-bearing samples, since it cancels the large GRMs generated by greigite in AF (ref. S1). Based on previous experience with similar organic-rich, Plio-Pleistocene sediments from East Anglia, thermal demagnetisation was precluded[S2-3].

Magnetic polarity measurements were accompanied by magnetic and mineralogical analyses in order to determine the timing and reliability of the acquired magnetic signal. A particular problem with the East Anglian sediments is the formation of the ferrimagnetic iron sulphide, greigite. Although this mineral can form syn-depositionally in anoxic, organic-rich sediments, preserving a reliable chemical remanent magnetisation[S4], it can also be responsible for much later post-depositional diagenetic remagnetisation[S2,5-6]. Therefore, identification of the mineral carrying the magnetic remanence is critical. The sediments have high ratios of saturation isothermal remanence (SIRM) to magnetic susceptibility (SIRM/κ, 23–62 kiloamperes per metre), and heating experiments indicate that much of the total NRM (~ 65–80 %) is unstable even at low heating temperatures (55–60 °C). Such behaviour is characteristic of greigite. Critically, however, most of the reversed polarity ChRM for the Happisburgh sediments is not carried by greigite, but by low quantities of stable, probably detrital, minerals with higher coercivities (> ~50 mT).

For samples from beds C, D and F, initial NRM values range up to 190 milliamperes per metre (mA/m) and have directions similar to the present-day field. Upon tumbling AF demagnetisation, a normal polarity overprint component was extracted in fields up to ~50 mT, which has directions similar to the modern field (Fig. 4a, SI Fig. 1a). In AFs above 60 mT, seven samples have a linear trajectory with a reversed polarity component (Fig. 4a, SI Fig. 1), that moves towards the origin of the vector component diagram. In 21 of the samples, the remaining part of the NRM (~10–15 %) typically traced a great circle path towards reversed polarities (Fig. 4b, SI Fig. 1b), which indicates the near simultaneous removal of more than one magnetisation component. Out of 41 samples in beds C, D and F, three failed to provide useful data (i.e. no normal or reversed components were isolated via principal component analysis). The four basal samples from Bed A had much weaker initial NRMs (< ~5 mA/m), lower SIRM/κ ratios (SI Table 1) and negative inclinations. In these samples, demagnetisation removed a small normal polarity overprint with linear demagnetisation trajectories at low fields (10–15 mT), revealing a negative-inclination, but with an anomalous easterly declination, in AFs up to ~50 mT (Fig. 4c). This component (>15–50 mT) is a composite direction composed mostly of a reverse polarity direction, with a smaller normal polarity overprint.

In total, using principal component analysis as implemented in LINEFIND (ref. S7), 42 normal polarity overprint components (extracted in AFs up to 50–70 mT), 11 reversed or anomalous reversed polarity ChRMs (extracted in AFs from 15–50 and from 50–100 mT) and 21 great circle trends towards reversed polarity (extracted in fields from ~ 10–100 mT) were isolated (SI Fig. 1b, SI Table 1). The Fisher means of the directions[S8] are also summarised in SI Table 1, together with estimates of the mean direction in beds C, D and F, based on the intersections of the great circles and on combining the ChRM directions and great circles[S9]. The Happisburgh samples thus consistently have reversed magnetic polarity ChRMs, which are interpreted as a primary, detrital remanent magnetisation.

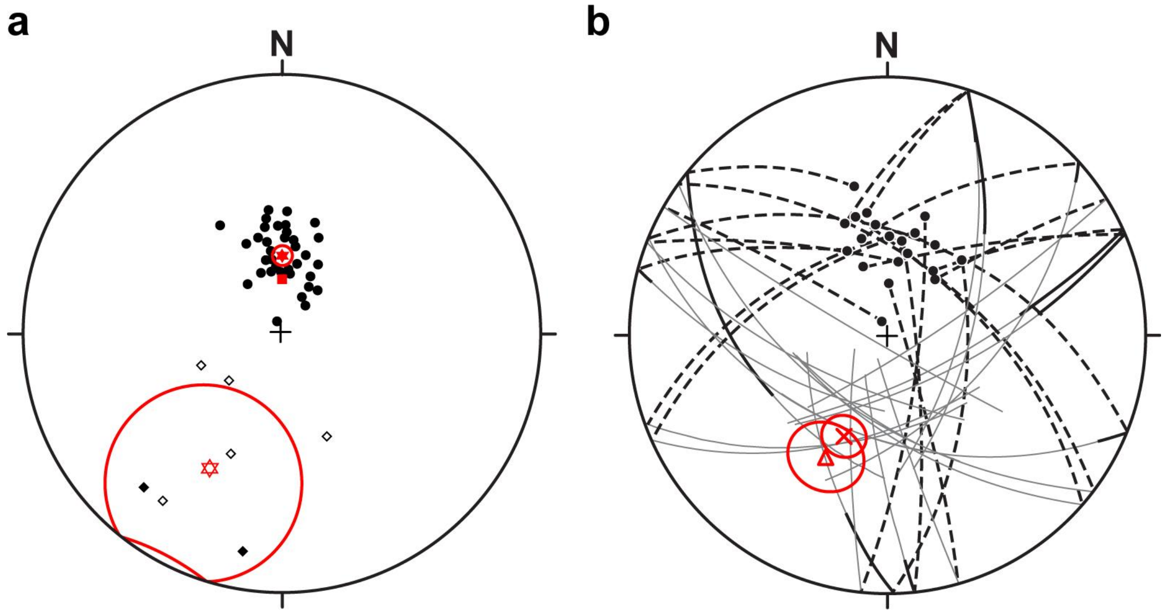

Figure 1. Summary stereoplots of palaeomagnetic results. (**a**) Normal polarity overprints (black circles) and reversed polarity ChRM components (diamonds) isolated by principal component analysis of AF demagnetization results from beds C, D and F, together with their Fisherian mean directions (red stars) and 95% confidence cones (red circles). The red square indicates the present-day field direction. Filled/open symbols denote lower/upper hemisphere. (**b**) The observed great circle trends (beds C, D, F) with thick dashed/solid lines indicating lower/upper hemisphere, and their upper hemisphere extensions (thin grey lines). The initial NRMs (the starting point of the great circle trends) are shown by the dots. The mean direction of the intersections of the great circles is shown by the red cross with the 95 % confidence cone[S9]. The combined ChRM and great circle mean is shown by the red triangle with the 95 % confidence cone (see SI Table 1).

Table 1. Summary of palaeomagnetic results. Mean directions for the normal (N) and reversed (R) components and great circle trends isolated in sediments from beds C, D and F, and in Bed A, with the AF demagnetization ranges over which they were extracted

Beds	**NRM** [mA/m]	**SIRM/κ** [kA/m]	**Component**	**n**	**D** [°]	**I** [°]	**α_{95}** [°]	**k**	**Demag. range** [mT]
C, D, F	35.6 ± 47.3	35.4 ± 17.5	N-components	38	2.0	57.2	4.0	34.4	10–60
			R-components	7	207.2	-28.9	30.6	4.9	70–100
			Great circle intersection	21	203.4	-55.6	6.8	23.0	10–80
			Great circles + R-components	21+7	207.3	-46.7	11.4	6.5	10–80; 70–100
A	3.3 ± 1.8	25.4 ± 6.7	N-components	4	336.1	47.4	20.2	21.7	0–15
			R-components	4	83.6	-39.8	18.8	24.9	15–50

n = the number of isolated components; α_{95} denotes the angle of the cone of 95 % confidence about the mean; k denotes the Fisher precision parameter. The mean values (± 1 standard deviation) of the initial NRM and SIRM/κ ratio are also given.

Supplementary References

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