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An estimate of post-depositional remanent magnetization lock-in depth in organic rich varved lake sediments☆

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ABSTRACT

We studied the paleomagnetic properties of relatively organic rich, annually laminated (varved) sediments of Holocene age in Gyltigesjön, which is a lake in southern Sweden. An age–depth model was based on a regional lead pollution isochron and Bayesian modelling of radiocarbon ages of bulk sediments and terrestrial macrofossils, which included a radiocarbon wiggle-matched series of 873 varves that accumulated between 3000 and 2000 Cal a BP (Mellström et al., 2013). Mineral magnetic data and first order reversal curves suggest that the natural remanent magnetization is carried by stable single-domain grains of magnetite, probably of magnetosomal origin. Discrete samples taken from overlapping piston cores were used to produce smoothed paleomagnetic secular variation (inclination and declination) and relative paleointensity data sets. Alternative temporal trends in the paleomagnetic data were obtained by correcting for paleomagnetic lock-in depths between 0 and 70 cm and taking into account changes in sediment accumulation rate. These temporal trends were regressed against reference curves for the same region (FENNOSTACK and FENNORPIS; Snowball et al., 2007). The best statistical matches to the reference curves are obtained when we apply lock-in depths of 21–34 cm to the Gyltigesjön paleomagnetic data, although these are most likely minimum estimates. Our study suggests that a significant paleomagnetic lock-in depth can affect the acquisition of post-depositional remanent magnetization even where bioturbation is absent and no mixed sediment surface layer exists.

1. Introduction

Annually laminated (varved) freshwater lake sediments formed in Sweden and Finland during the Holocene contain stable natural remanent magnetizations (NRMs) which have improved reconstructions of paleomagnetic secular variation (PSV) and relative paleointensity (RPI) in northern Europe (e.g. Saarinen, 1998, 1999; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002; Ojala and Tiljander, 2003; Haltia-Hovi et al., 2010). Amalgamated data from several varved sites form the basis of regional PSV and RPI reference curves (Snowball et al., 2007), which have been used to date non-varved sequences in the Baltic Sea (Lougheed et al., 2012) and detect discontinuities in individual varve chronologies (Stanton et al., 2010).

In spite of numerous studies of marine and lacustrine sediments, including laboratory-based re-deposition experiments, uncertainties about the natural magnetization process still exist. One source of uncertainty is the so-called "paleomagnetic lock-in depth,'" which causes a time delay between the deposition of sediment and the acquisition of a natural remanent magnetization (NRM). In the simplest case of a pure depositional remanent magnetization (DRM) Tauxe et al. (2006) argue that there is no significant paleomagnetic lock-in depth because the particles align to the geomagnetic field in the water column and cannot be realigned after deposition. They conclude that salinity controlled flocculation in the water column may play an important role, particularly in low salinity environments where a small change in salinity may have a large effect on the size of flocs that can contain magnetic particles. Another view, however, is that previously magnetised particles (they can be of detrital origin, or formed in the water column by, for example, magnetotactic bacteria) fall out of suspension in the fluid and are simultaneously aligned by the torque that the

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geomagnetic field imposes on them. These magnetised grains are free to move in the sediment matrix until the non-ferromagnetic sediment surrounding them becomes so consolidated that they cannot be realigned by subsequent changes in the strength and direction of the geomagnetic field (Irving and Major, 1964). Thus, this type DRM has been called post-depositional remanent magnetization (PDRM). A PDRM is probably locked-in over a range of depths, which means that the primary geomagnetic field signal is only visible as a smoothed signal in sedimentary paleomagnetic data. The degree of signal smoothing, therefore, depends to a large extent on the sediment accumulation rate (Roberts and Winklhofer, 2004), with the result that relatively short-lived features in geomagnetic field behaviour cannot be recorded by relatively slowly accumulating sediments. Another, related, aspect of marine and lacustrine sediments that affects the paleomagnetic lock-in depth is the influence of burrowing or crawling benthic fauna, which cause the top part of a sediment column to be mixed to the extent that no net magnetic remanence can be acquired by this layer. The thickness of the mixed layer can be substantial in marine sedimentary environments if deep burrowing fauna is present. Roberts and Winklhofer (2004) applied a mixed layer thickness of 10 cm in a modelling study of PDRM acquisition in sediments, but acknowledged that it can extend to 30 cm and more during large mixing events. As pointed out by Roberts et al. (2013) quantified estimates of paleomagnetic lock-in depth have remained difficult to obtain.

Our understanding of NRM acquisition by sediments is further complicated by the growing awareness that ferrimagnetic minerals can precipitate in lacustrine and marine environments through biogeochemical processes, but we know little about how these minerals contribute to the NRM. In particular, single-domain particles of magnetite (Fe_3O_4) can be produced by magnetotactic bacteria (MTB) and completely dominate the ferrimagnetic properties of lake and marine sediments where they are preserved as magnetofossils (e.g. Snowball, 1994; Snowball et al., 2002; Roberts et al., 2011) Similarly, greigite (Fe_3S_4) magnetofossils may also be widespread in sedimentary environments, but their presence in marine sediments has only just been appreciated (Reinholdsson et al., 2013). Roberts et al. (2011) state that “Further work is needed from a range of settings to better understand the timing of biogeochemical remanence acquisition associated with magnetofossils.” Such work requires not only high quality paleomagnetic data and identification of the magnetic remanence bearing minerals, but also independent, accurate and precise dating control (e.g. Stanton et al., 2010).

Varved sediments that have accumulated in Swedish lakes during the Holocene produce high quality paleomagnetic data (Snowball et al., 2007), which is consistent with the observation that the concentration of magnetite magnetofossils (determined by magnetic properties) is positively correlated to the organic carbon content in this sedimentary environment (Snowball et al., 1999, 2002). One of the preconditions to the formation of varved sediments is the absence of crawling or burrowing fauna and, therefore, it can be expected that a paleomagnetic lock-in depth, if present, would be determined by sediment consolidation and/or the location where magnetic grains of biogeochemical origin are produced.

In an effort to expand the network of Holocene PSV and RPI data sets based on varved freshwater lake sediments in Fennoscandia (Snowball et al., 2007) we were attracted to the lake of Gyltigesjön in the province of Halland (Fig. 1). This lake is situated at 56.5° N and further south than the other sites included in the network. The sediment sequence in Gyltigesjön was first studied by Guhrén et al. (2003, 2007) as part of a nationwide study of human impact, acidification and subsequence ecosystem response to liming. Guhrén et al. (2003) reported the occurrence of distinct laminations in the upper 0.6–0.7 m of the sediment column in the deepest part of the lake (~19 m). They were only able to recover the top 4.2 m of sediment and did not study the upper laminations in any detail, although they interpreted them as varves. They did, however, detect the Roman (~AD1) peak in atmospheric lead pollution (Renberg et al., 2001) at a sediment depth of 3.5 m, which would represent an average sediment accumulation rate of 1.75 mm/a for the last 2000 years. This rate is substantially higher than the other Swedish varved sites included in FENNOSTACK and FENNORPIS (maximum of 0.7 mm/a in Frängsjön) and the more recently studied site of Kälksjön in the province of Värmland (also ~0.7 mm/a — Stanton et al., 2010).

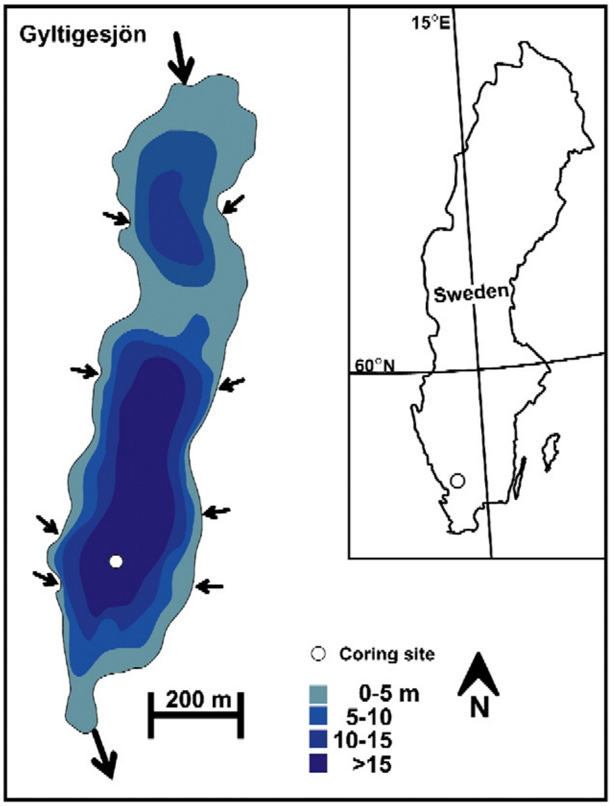

Fig. 1. Site location. The inset shows an outline map of Sweden and the approximate location of Gyltigesjön (circle) in the south. The coring location at the lakes deepest point of approximately 19 m is marked by the white circle. Large (small) arrows show major (minor) inflows and outflows. The bathymetry is based on Guhrén et al. (2003).

In this paleomagnetic study of Gyltigesjön sediments we combine the radiocarbon wiggle-match dating of a floating varve chronology (Mellström et al., 2013) with additional terrestrial macrofossil ^{14}C dates to provide an accurate and precise timescale for the last ca. 8000 years. Through modelling of the effect of different lock-in depths, which takes into account changes in sediment accumulation rate, and statistical comparison to the regional PSV reference curves we are able to provide a minimum estimate of the paleomagnetic lock-in depth in Gyltigesjön sediments, which have magnetic properties consistent with an assemblage dominated by non-interacting single-domain magnetite magnetosomal magnetite.

2. Site description

2.1. Geography

Gyltigesjön is located in the province of Halland in southern Sweden, at a height of 66 m above sea level (Fig. 1). It is the first in a series of lakes in the valley of Simlångsdalen, through which the relatively large river Fylleån flows. Eight smaller streams also flow into Gyltigesjön and the catchment area is estimated to a total of 182 km^2 (Guhrén et al., 2003). Gyltigesjön is elongated, trends from the north to the south and has a surface area of 0.4 km^2. It is also characterised by two distinct sedimentary basins. The first is in the north-east and has a maximum depth of approximately 12 m. A sill separates this basin from a larger