Earth and Planetary Science Letters 410 (2015) 186–196

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Post-depositional remanent magnetization lock-in depth in precisely dated varved sediments assessed by archaeomagnetic field models

Anette Mellström[a,*,1], Andreas Nilsson[b,1], Tania Stanton[a], Raimund Muscheler[a], Ian Snowball[a,c], Neil Suttie[b]

[a] *Department of Geology – Quaternary Sciences, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden*
[b] *Geology and Geophysics, School of Environmental Sciences, University of Liverpool, Oliver Lodge Building, Oxford Street, Liverpool L69 7ZE, United Kingdom*
[c] *Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden*

ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form 13 November 2014
Accepted 16 November 2014
Available online 11 December 2014
Editor: P. Shearer

Keywords:
palaeomagnetic secular variation
post-depositional remanent magnetization
lock-in depth
lake sediments
radiocarbon wiggle-match dating
varves

ABSTRACT

Accurate and precise chronologies are needed to evaluate the existence and effect of a post-depositional remanent magnetization lock-in process on sedimentary palaeomagnetic records. Here we present lock-in modelling results of two palaeomagnetic records from varved lake sediments (lakes Kälksjön and Gyltigesjön) in Sweden by using model predictions based on archaeomagnetic data. We used the ^{14}C wiggle-match dating technique to improve the precision of the Kälksjön varve chronology in the period between 3000 and 2000 cal BP, which is characterized by pronounced palaeomagnetic secular variation. This method allowed us to infer an age model with uncertainties of ±20 years (95.4% probability range). Furthermore, we compared the palaeomagnetic record of Kälksjön to Gyltigesjön, which has a corresponding ^{14}C wiggle-matched chronology. The ages of palaeomagnetic features derived from the wiggle-matched varve chronologies are older than those predicted by the archaeomagnetic models. Lock-in modelling was performed with different filter functions to explain the temporal offset and the amplitude of the lake sediment palaeomagnetic data. The analyses suggest that a linear lock-in function with lock-in depths (the depth below which no more natural magnetic remanence is acquired) that range between 30 and 80 cm in Kälksjön and 50 and 160 cm in Gyltigesjön are most appropriate to explain the data. These relatively deep lock-in depths in sediments without a bioturbated ‘mixed-zone’ can be attributed to the relatively high organic contents and low density of the lake sediments, which contribute to a thick unconsolidated upper zone of the sediment sequence in which re-alignment of magnetic particles can take place.

1. Introduction

Palaeomagnetic data derived from lake sediments (e.g. Snowball et al., 2007; Haltia-Hovi et al., 2010; Stanton et al., 2010, 2011), marine sediments (e.g. Stoner et al., 2007; Barletta et al., 2010), igneous rocks and archaeological material (e.g. Hagstrum and Champion, 2002; Hervé et al., 2013) have shown evidence for strong palaeomagnetic secular variation (PSV) in the northern hemisphere around 3000–2000 cal BP. One of the most prominent changes in declination in Europe during the Holocene epoch is the movement from the easterly declination feature “f” to the western feature “e” at around 2800–2600 cal BP, according to the nomenclature used by Turner and Thompson (1981). This westerly swing in declination is accompanied by steep inclination values (feature “ε'”) and a low latitude virtual geomagnetic pole (VGP) position (see Stoner et al., 2013). Feature “f” has been recorded in sediment sequences and dated to ca. 2700 cal BP (e.g. Turner and Thompson, 1981; Snowball et al., 2007; Haltia-Hovi et al., 2010), and to ca. 2750 cal BP based on archaeomagnetic directions (Hervé et al., 2013). Different ages of the feature may result from, for example, insufficient dating control and subsequent age model uncertainties, but also from site-specific lock-in delay of the geomagnetic field signal in sedimentary successions. Palaeomagnetic data sets for the Holocene have been obtained from annually laminated (varved) lake sediments in Sweden and Finland (e.g. Saarinen, 1998; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002; Snowball et al., 2007; Haltia-Hovi et al., 2010; Stanton et al., 2010, 2011), which allow for construction of precise varve chronologies. Uncertainties could, however, arise due to for example missing and/or poorly preserved varves (Stanton et al., 2010; Ojala et al., 2012) and the accuracy of varve chronologies should

---

* Corresponding author.
E-mail address: Anette.Mellstrom@geol.lu.se (A. Mellström).

[1] Authors contributed equally to the study.

http://dx.doi.org/10.1016/j.epsl.2014.11.016

ideally be established through independent methods, such as ^{14}C dating and tephrochronology (e.g. Zolitschka et al., 2000). Besides potential chronological uncertainties, there are also uncertainties associated with the natural remanent magnetization (NRM) acquisition process (see e.g. Roberts et al., 2013). It has been shown that the magnetic particles may re-align to the geomagnetic field after deposition and acquire a post-depositional remanent magnetization (pDRM) (e.g. Irving and Major, 1964; Kent, 1973; Verosub, 1977). A pDRM is acquired gradually during compaction and dewatering until the magnetic particles cannot further align to the geomagnetic field and become locked into place by the non-magnetic sediment matrix (e.g. Irving and Major, 1964; Hamano, 1980). A pDRM can be acquired over a range of depth, which causes the recorded geomagnetic field signal to be smoothed and the NRM to be younger than the sediments that carry it; hence the so-called lock-in depth/delay. Although widely discussed, the vast majority of pDRM lock-in studies have focussed on marine sediment sequences, which normally have a mixed sediment surface layer caused by bioturbation (deMenocal et al., 1990; Roberts and Winklhofer, 2004; Sagnotti et al., 2005; Liu et al., 2008; Suganuma et al., 2010, 2011). Different lock-in functions (instant, constant, linear, cubic, exponential and Gaussian) have been proposed and some have been applied to marine sediments – with various outcomes – to estimate the depths at which the geomagnetic signal becomes locked-in (see e.g. Roberts and Winklhofer, 2004; Suganuma et al., 2011).

Snowball et al. (2013) made a minimum estimation of the pDRM lock-in depth in relatively organic-rich, non-bioturbated, varved sediments of Gyltigesjön in southern Sweden. Palaeomagnetic data from Gyltigesjön were compared to the reference curves for Fennoscandia (FENNOSTACK and FENNORPIS; Snowball et al., 2007) and the best fits to the reference data were obtained with lock-in depths of 21–34 cm. They emphasized that these estimates of lock-in depth were minimum estimates as the reference curves were also based on sedimentary data and, therefore, suffer from an unknown lock-in delay that would affect the results.

Here we apply a different approach and compare two precisely dated sediment-based palaeomagnetic secular variation data sets to predictions of time varying archaeomagnetic field models, which are constrained by thermal remanent magnetizations (TRMs) common to archaeological artefacts and lavas. Compared to pDRMs, TRMs are acquired almost instantaneously and in the absence of systematic dating errors the timing of PSV features predicted by models constrained by them should be fairly accurate. We focus our study on the geomagnetically dynamic period ca. 3000–2000 cal BP (Snowball et al., 2014) for which the signal to noise ratio in palaeomagnetic data sets is reasonably high. Following the dating method used by Snowball et al. (2010) and Mellström et al. (2013) we construct an accurate and precise ^{14}C wiggle-matched time scale (Pearson, 1986; van Geel and Mook, 1989) for varved lake sediments from Kälksjön in west-central Sweden (Zillén et al., 2003; Snowball et al., 2010) which also contain stable NRMs (Stanton et al., 2010, 2011). Specifically, we: (i) test and improve one specific period of the Kälksjön varve chronology (Stanton et al., 2010) by using the ^{14}C wiggle-match dating technique, (ii) compare an improved palaeomagnetic record from Kälksjön with the record from Gyltigesjön (Snowball et al., 2013), which also has a ^{14}C wiggle-matched chronology (Mellström et al., 2013), and (iii) compare both records to archaeomagnetic field model predictions (Korte et al., 2009; Pavón-Carrasco et al., 2009; Licht et al., 2013) before and after the application of different pDRM lock-in filters. We show the use of different lock-in filter functions to minimize the misfit between models and data and evaluate the pDRM lock-in depths (here defined as the depth below which no more natural magnetic remanence is acquired) in both sediment sequences.

Fig. 1. Map showing the lake locations. Modified from Stanton et al. (2010).

2. Study areas

2.1. Kälksjön

Kälksjön (60°09′13″N, 13°03′23″E, 98 m a.s.l) is located in west-central Sweden in the province of Värmland (Fig. 1). The lake has an area of 0.3 km^2 and the deepest point measures 14.2 m below the lake surface. The lake has three inlets in the eastern part and one to the north, and the outlet is located to the west. The catchment area of 4 km^2 is mostly covered by managed boreal forests consisting of spruce, pine and birch, and arable land is found in some parts close to the lake (Zillén et al., 2003). Kälksjön was once part of the ancient Lake Vänern (Björck, 1995), but became isolated in the early Holocene due to isostatic uplift (Zillén et al., 2003; Stanton et al., 2010). Kälksjön has varved sediments with a clastic–biogenic composition consisting of three to four laminae per year that relate to the seasonal climatic contrasts (Zillén et al., 2003; Stanton et al., 2010). This type of varve is commonly found in Swedish and Finnish lakes (e.g. Renberg, 1982; Saarnisto, 1986; Petterson, 1996; Ojala et al., 2000).

2.2. Gyltigesjön

Gyltigesjön (56°45′33″N, 13°10′37″E, 66 m a.s.l) is located in south-western Sweden in the province of Halland (Fig. 1). The lake has an area of 0.4 km^2 and contains two sedimentary basins, one in the northern and one in the southern part of the lake, with maximum water depths of approximately 12.3 and 18.5 m, respectively. The lake belongs to a valley system called Simlångsdalen. Four lakes are connected in this valley by the Fylleån River, and Gyltigesjön is the first lake to receive discharge. The river enters the lake from the north and has an outflow to the south. In addition, eight smaller streams enter the lake. The catchment area covers 182 km^2 and is dominated by forest, but wetlands, open land and water are also present (Guhrén et al., 2003). The coastal plain of Halland was deglaciated about 18 000–16 000 cal BP (Lundqvist and Wohlfarth, 2001). Following deglaciation, the area has a complex history with indications of significant sea-level variations (e.g. Berglund, 1992, 1995). The lake has an annual sedimentation cycle; however, the varves in the Gyltigesjön sediments are, by contrast to Kälksjön, mainly composed of biogenic materials with two dominant laminae per year (Snowball et al., 2013).