Investigations of temporal changes in climate and the geomagnetic field via high-resolution radiocarbon dating

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Abstract

Geological archives have shown periods of abrupt climate change in the relatively stable Holocene epoch (last ca. 11 700 years). One of these periods was around 2800 cal BP. Several records, mainly from Europe, reveal a shift towards wetter, cooler and windier conditions. There are, however, indications for a global extent of the climate change. The climate change coincides with a distinct increase in the atmospheric radiocarbon (^{14}C) concentration, which has been interpreted to be a result of decreased solar activity. Therefore, a solar-induced climate change has been suggested. In addition to changes in solar activity, geomagnetic field records also show prominent variations around 3000-2000 cal BP. In order to investigate the temporal development of past changes in climate and the geomagnetic field it is crucial to establish accurate and precise chronologies for such reconstructions. Well-constrained chronologies are crucial to determine leads and lags in the climate system as well as to investigate climate forcing factors, such as the potential influence of changes in solar activity. Furthermore, highly-resolved and well-dated geomagnetic field records are needed to improve our understanding of geomagnetic field variations and to evaluate suggested linkages between geomagnetic field and climate change. The general aim of this thesis is to improve the dating of changes in climate and the geomagnetic field via linking ^{14}C results of closely spaced samples to the ^{14}C calibration curve – the ^{14}C wiggle-match dating technique – with focus on the period around 3000-2000 cal BP.

The ^{14}C wiggle-match dating technique was successfully applied to construct an accurate and precise chronology of the annually laminated (varved) sediments of Lake Gyltigesjön in south-west Sweden for the period around 3000-2000 cal BP. With this technique, it was possible to estimate the old-carbon effect (^{14}C reservoir age) in the lake sediments. The bulk sediment based chronology was validated by comparison to the ^{14}C ages of plant macrofossils. Similarly, the ^{14}C wiggle-match dating technique was used to test the accuracy of a varve chronology of Lake Kälksjön in west-central Sweden for the same time period. The constructed chronologies of Lake Gyltigesjön and Lake Kälksjön have uncertainties of only ±30 and ±20 years (95.4% probability range), respectively. The well-constrained chronologies enabled investigations of the post-depositional remanent magnetisation lock-in effect and its influence on records of palaeomagnetic secular variation.

In addition, the hypothesis of a solar-induced climate change in southern Sweden around 2800 cal BP was investigated. The peat record of Undarsmosse in south-west Sweden has previously indicated a change to increased storminess and wetter conditions around this period. The ^{14}C wiggle-match dating technique was applied to constrain the timing of these events. Within the age model uncertainties, the shift towards wetter and windier conditions in southern Sweden can be regarded synchronous with the climate changes inferred from other sites in Europe. The recorded changes, therefore, support the hypothesis of a shift in the larger-scale atmospheric circulation, possibly induced by decreased solar activity.

Key words: Radiocarbon dating, wiggle-matching, ^{14}C, 2800 cal BP, climate change, solar activity, palaeomagnetism, lake sediments, varves, post-depositional remanent magnetisation, PDRM, lock-in, peat deposits, Sweden

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This thesis is based on the four papers listed below, which are appended to the thesis. Paper I and Paper II have been published in the indicated journals. Paper III has been submitted to the journal indicated and Paper IV is a manuscript.

Paper I: Mellström A, Muscheler R, Snowball I, Ning W, Haltia E (2013). Radiocarbon wiggle-match dating of bulk sediments – How accurate can it be? *Radiocarbon* 55 (2-3): 1173-1186.

Paper II: Snowball I, Mellström A, Ahlstrand E, Haltia E, Nilsson A, Ning W, Muscheler R, Brauer A (2013). An estimate of post-depositional remanent magnetization lock-in depth in organic rich varved lake sediments. *Global and Planetary Change* 110: 264-277.

Paper III: Mellström A, Nilsson A, Stanton T, Muscheler R, Snowball I, Suttie, N. Application of archaeomagnetic field models to infer post-depositional remanent magnetization lock-in depth in precisely dated varved sediments. Submitted to *Earth and Planetary Science Letters*.

Paper IV: Mellström A, Van der Putten N, Muscheler R, de Jong R, Björck, S. A shift towards wetter and windier conditions in southern Sweden around the period of a solar minimum ca. 2700 cal BP. Manuscript.

Table of Contents

1. Introduction

Numerous geological archives reveal periods of abrupt climate change even in the relatively stable Holocene epoch, i.e. during the last 11 700 years (e.g. Mayewski et al., 2004; Wanner et al., 2008; Wanner et al., 2011). One such period occurred around 2800 years ago. It is characterised by several changes, which include: (i) a distinct increase of the atmospheric ^{14}C concentration (Reimer et al., 2013), which has been interpreted to be a result of decreased solar activity (e.g. van Geel et al., 1998), (ii) palaeoclimatic records indicating a change towards wetter, cooler and windier climate in Europe (e.g. van Geel et al., 1996; Speranza et al., 2002; Martin-Puertas et al., 2012) possibly also visible in globally distributed records (e.g. van Geel et al., 2000; Chambers et al., 2007; Van der Putten et al., 2008) and (iii) prominent variations in the geomagnetic field recorded around 3000-2000 cal BP (e.g. Snowball et al., 2007; Knudsen et al., 2008). The timing of the climate shift has been discussed and several palaeoclimatic records indicate that it occurred simultaneously with the increased atmospheric ^{14}C concentration, therefore suggesting a climate change induced by decreased solar activity (e.g. van Geel et al., 1998; Speranza et al., 2002). A delay between the increased ^{14}C and a climate change has been observed in some studies and attributed to an influence of the ocean, suggested to be responsible for complex climate patterns (Plunkett, 2006; Swindles et al., 2007; Plunkett and Swindles, 2008). Accurate and precise chronologies are crucial in order to improve our understanding of the causes and mechanisms behind the observed changes. For example, well-dated geological archives are the pre-requisite to constrain the timing of climate changes relative to solar activity variations and to investigate their spatial development. Insufficient chronological control restricts comparisons between different palaeoclimatic records and the relation to external forcing factors, and feedback mechanisms can only be reliably investigated with well-constrained chronologies. Furthermore, highly-resolved palaeomagnetic records are needed to evaluate the geomagnetic field influence on the increased atmospheric ^{14}C concentration at around 2800 years ago and to address the hypothesised geomagnetic field-climate connection (e.g. Dergachev et al., 2004; Gallet et al., 2005; Courtillot et al., 2007).

Annually laminated (varved) lake sediments can provide valuable information on both palaeoclimatic conditions (e.g. Ojala and Alenius, 2005; Brauer et al., 2008; Snowball et al., 2010) and palaeomagnetic changes (e.g. Saarinen, 1998; Snowball et al., 2007; Haltia-Hovi et al., 2010; Stanton et al., 2010). In addition, the preserved seasonal deposition signal in the sediments allows for the construction of high-resolution chronologies. However, there are uncertainties associated with varve chronologies in form of e.g. possible missing varves (Ojala et al., 2012) and the chronologies should therefore, ideally, be validated with independent techniques, such as radiocarbon (^{14}C) dating (e.g. Stanton et al., 2010). Radiocarbon dating also has its limitations e.g. due to requirements for the availability of suitable materials and the need for calibration of ^{14}C ages. Terrestrial plant macrofossils are the preferred material for ^{14}C dating since they are supposed to reflect the atmospheric ^{14}C signal at the time of sediment deposition (e.g. Törnqvist, 1992). However, macrofossils might be scarcely distributed, or absent, in the sediments and the age determination instead might have to rely on ^{14}C dating of bulk sediment samples. Yet, bulk sediments can be contaminated by old carbon derived from e.g. soil and vegetation from the catchment area, and these sources contribute to a ^{14}C reservoir effect that causes relatively old ages compared to the time of deposition (e.g. Olsson, 1986; MacDonald et al., 1991; Björck and Wohlfarth, 2001). One way to overcome these problems is to apply the ^{14}C wiggle-match dating technique (Pearson, 1986; van Geel and Mook, 1989). With this technique, a series of closely spaced samples are ^{14}C dated to match the variations in the ^{14}C calibration curve (Reimer et al., 2013). The ^{14}C wiggle-match dating technique has previously been applied successfully to improve chronologies of e.g. lake sediment records (Hormes et al., 2009; Snowball et al., 2010; Blaauw et al., 2011) and cores from peat deposits (Kilian et al., 1995; Kilian et al., 2000; Speranza et al., 2000; Mauquoy et al., 2002; Blaauw et al., 2003;

Chambers et al., 2007; Mauquoy et al., 2008). This adaptation of the ^{14}C dating method can be used to recognise and estimate the ^{14}C reservoir effect in lake sediments (e.g. Snowball et al., 2010).

Even with very good time-scales, there are often still uncertainties associated with the definition of climatic and palaeomagnetic changes. For example, with a gradual change in climate proxy data there can be some ambiguity for the definition of the start of a reconstructed change or proxy records might react delayed to climate forcing. Palaeomagnetic records based on sediments can include the effects of a post-depositional remanent magnetisation (PDRM) lock-in process (e.g. Irving and Major, 1964; Verosub, 1977; Roberts et al., 2013). This process implies that the primary geomagnetic signal is locked into the sediments over a depth range, which causes the recorded signal to be delayed with respect to deposition and smoothed. These effects need to be taken into account when interpreting palaeoclimatic and palaeomagnetic records.

1.1 Project aims

The main aim of this thesis is to improve our knowledge about the temporal development of climate and geomagnetic field variations and possible linkages to external forcing using the ^{14}C wiggle-match dating technique. The focus was on the period around 3000-2000 cal BP since it is characterised by prominent changes in the atmospheric ^{14}C concentration, and therefore, provides an opportunity to investigate the possible connections between solar, climate and geomagnetic field changes. More specifically, the aims were to:

- Evaluate the accuracy of chronologies inferred with the ^{14}C wiggle-match dating technique of bulk sediment samples from ca. 3000 to 2000 cal BP.

- Construct a well-constrained chronology for the varved lake sediments from Lake Gyltigesjön in south-west Sweden around 2800 cal BP that can be used for geomagnetic field reconstructions and for future palaeoclimatic investigations.

- Test and improve the varve chronology of Lake Kälksjön (Stanton et al., 2010) in west-central Sweden for the period between ca. 3000 and 2000 cal BP.

- Determine the timing of geomagnetic field changes recorded in the sediments from Gyltigesjön and Kälksjön and to investigate the presence and effects of a post-depositional remanent magnetisation lock-in process.

- Test the hypothesis of a solar-induced climate change in southern Sweden around 2800 cal BP and to investigate relationships between the temporal and spatial development of the reconstructed climate changes, and potential external forcing factors.

2. Background

2.1 Cosmogenic radionuclides

Cosmogenic radionuclides are produced by reactions of galactic cosmic ray (GCR) particles with atoms in the atmosphere. The GCRs consist of approximately 87 % protons, 12% alpha particles and 1% heavier nuclei (Masarik and Beer, 1999). The production rates of cosmogenic radionuclides (such as ^{14}C and ^{10}Be) vary with the influx of GCRs, which is dependent on the solar magnetic field shielding and the strength of the geomagnetic field. Low solar activity and/or low geomagnetic field intensity leads to an increased GCR influx and higher radionuclide production rates, and vice versa for high solar and geomagnetic shielding (e.g. Masarik and Beer, 1999). Variations in solar activity are, therefore, reflected in the radionuclide production rates; hence, cosmogenic radionuclide records can be used to reconstruct solar activity if one corrects for the influence of the geomagnetic field. The geomagnetic field is considered to dominate the radionuclide production rates on relatively long time-scales (more than 3000 years) and changes in solar activity are assumed to be responsible for changes on shorter time-scales (less than 1000 years) (e.g. Beer, 2000). However, short-term variations in the geomagnetic field intensity cannot be disregarded as an explanation for variable radionuclide production rates (Snowball and Sandgren, 2002; St-Onge et al., 2003; Snowball and Muscheler, 2007). Highly-resolved palaeomagnetic records can be used to disentangle the influence of solar activity and geomagnetic field on the radionuclide production rates.

The atmospheric ^{14}C concentration varies both with changes in production rate and with changes in the global carbon cycle (e.g. Siegenthaler et al., 1980). Nevertheless, changes in ^{14}C production rates and in the carbon cycle can be disentangled by combining information from ^{14}C and ^{10}Be records, because of their common production signal but different depositional processes (e.g. Muscheler et al., 2000; Muscheler et al., 2004).

2.1.1 Radiocarbon dating

The method of ^{14}C dating was developed in the 1940s by W.F. Libby and co-workers (e.g. Libby et al., 1949). ^{14}C is produced in the upper atmosphere in a reaction between secondary cosmic ray neutrons and nitrogen atoms:

$$n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p$$

The two stable isotopes ^{12}C and ^{13}C represent about 98.9% and 1.1%, respectively, of all carbon on Earth, and only 1.18$10^{-10}$% of the carbon isotopes are in the form of the radioactive ^{14}C (Olsson, 1968). The produced ^{14}C oxidises to $^{14}CO_2$ and is incorporated into the global carbon cycle. All living plants absorb ^{14}C and it is passed through the food web. As long as organisms are alive the uptake of ^{14}C is replenished through photosynthesis or dietary uptake. After death, the ^{14}C uptake stops while the ^{14}C continues to decay to nitrogen through beta decay. The half-life of the radioactive isotope ^{14}C was estimated to 5568±30 years (Libby half-life, Libby et al., 1949), but re-estimated later on to 5730±40 years (Cambridge half-life, Godwin, 1962). The Libby half-life is still used to calculate ^{14}C ages. The radioactive decay of ^{14}C constitutes the foundation of radiocarbon dating. By counting the beta decay with the conventional technique, or measuring the isotopic ratios with accelerator mass spectrometry (AMS) an age of an organic substance can be obtained. AMS detects low $^{14}C/^{12}C$ ratios (commonly 10^{-12} to 10^{-16}) and is nowadays widely used for ^{14}C measurements (e.g. Hellborg and Skog, 2008). In order to calculate a ^{14}C age, the measured samples are related to a standard of known activity and corrected for isotopic mass fractionation, which occurs, for example, when metabolic processes preferentially incorporate the lighter carbon isotopes (for methods see e.g. Stuiver and Polach, 1977; Mook and van der Plicht, 1999; van der Plicht and Hogg, 2006). The rate of radioactive decay of ^{14}C limits the use of this method back to about 50 000 years ago.

The measured ^{14}C age is not the same as a calendar age due to variations in the atmospheric ^{14}C concentration and a ^{14}C calibration curve is used to obtain calibrated ages (cal BP) (Reimer et al., 2013). For ^{14}C ages and calibrated ages, 'before present' ('BP') refers to before the year AD 1950. The ^{14}C calibration curve is based on ^{14}C determinations of tree-rings with known ages and covers the last ca. 12 550 years. Beyond this age the curve is extended by floating tree-ring chronologies and ^{14}C dating of corals, foraminifera, speleothems, and plant macrofossils and extends to 50 000 cal BP (Reimer et al., 2013).

The ^{14}C calibration curve reveals increases and decreases of the atmospheric ^{14}C concentration ($\Delta^{14}C$). $\Delta^{14}C$ (‰) is expressed as the $^{14}C/^{12}C$ ratio in relation to a standard corrected for fractionation and decay (Stuiver and Polach, 1977). A decrease in the ^{14}C age versus calendar age implies an increase of the ^{14}C content in the atmosphere. For some sections of the calibration curve, the ^{14}C ages are relatively constant and show plateaus, which reflect decreasing ^{14}C in the atmosphere. If a ^{14}C age of a sample lies on a so-called ^{14}C age plateau, it leads to a wide range of possible calendar ages. For periods with pronounced drops of the ^{14}C age versus calendar age, a more precise calendar age determination can be made. The wiggles in the ^{14}C calibration curve can be utilised to achieve accurate age estimates with the ^{14}C wiggle-match dating technique (Pearson, 1986; van Geel and Mook, 1989). The wiggle-matching technique can be performed by using different approaches (e.g. Blaauw et al., 2003; Snowball et al., 2010). Commonly, Bayesian methods are used that are incorporated in freely available ^{14}C calibration software packages, e.g. OxCal (Bronk Ramsey, 2009), Bpeat (Blaauw and Christen, 2005) and Bacon (Blaauw and Christen, 2011).

The period around 3000-2000 cal BP shows pronounced variations in the atmospheric ^{14}C concentration (Reimer et al., 2013) (Figure 1). Thus, the ^{14}C calibration curve of this period provides a suitable structure for the wiggle-matching approach. Two rapid increases of atmospheric ^{14}C concentration are recorded for this period, at 2795-2675 and 2365-2290 cal BP, both associated with a $\Delta^{14}C$ change of approximately 20‰, separated by a 310-years long ^{14}C age plateau.

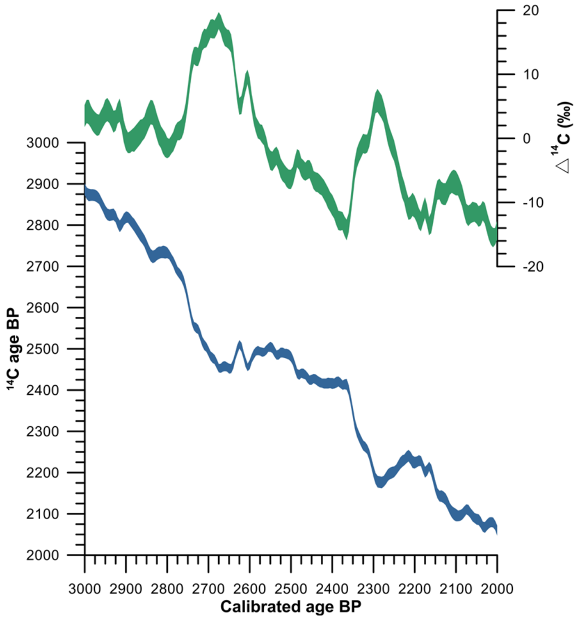

Figure 1. IntCal13 ^{14}C calibration curve (blue) and the atmospheric $\Delta^{14}C$ (green) for the period 3000-2000 cal BP, both shown with 1σ error (Reimer et al., 2013).

2.2 Palaeomagnetism

Palaeomagnetism is a geophysical method used to reconstruct past changes in the geomagnetic field direction and intensity, based on the natural remanent magnetisations (NRMs) acquired by sediments, igneous rocks and archaeological artefacts, ideally at the time of their formation. Palaeomagnetic data are used for e.g. relative dating of suitable geological records and for reconstructions of tectonic plate movements (outlined by Butler, 1992). With regards to the latter part of the Quaternary period, increased attention has also been given to obtain reliable estimates of changes in geomagnetic field strength (e.g. St-Onge et al., 2003; Snowball et al., 2007; Snowball and Muscheler, 2007; Knudsen et al., 2008), and such reconstructions can be used to evaluate the geomagnetic field influence on cosmogenic radionuclide production rate. The geomagnetic field is generated by fluid convections in the Earth's outer core and can be explained by a dynamo mechanism (Butler, 1992). The geomagnetic field can be described by a dipole field, which simplified can be viewed as a magnet with two poles; one in the north and the other in the south. In addition to the dominant dipole field, there is a dynamic non-dipole field suggested to derive from currents between the core and mantle, which varies on shorter periodicities than the dipole field (<3000 years) (Butler, 1992). Both dipole and non-dipole changes are incorporated in the concept of palaeomagnetic secular variations (PSV). Ideally, the PSV records are composed of absolute intensity, declination and inclination data. The intensity refers to the strength of the geomagnetic field. Because of non-dipole contributions and magnetic pole movements, the angle between the magnetic north and geographic north varies and this angle is referred to as the declination. Inclination is the angle between the vertical component of the geomagnetic field and a plane tangent to the Earth's surface. Inclination is steepest at the magnetic poles (±90°) and shallowest at the magnetic equator (0°).

2.2.1 Post-depositional remanent magnetisation

Magnetic particles align to the geomagnetic field in the water column and in the simplest case the initial alignment is preserved in the sediments as a depositional remanent magnetisation (DRM). Studies carried out several decades ago showed the possibility that magnetic particles may re-align to the geomagnetic field after deposition and acquire a post-depositional remanent magnetisation (PDRM) (e.g. Irving and Major, 1964; Kent, 1973; Hamano, 1980). The PDRM is eventually locked into the sediments after compaction and dewatering of the sediments (e.g. Løvlie, 1976; Verosub, 1977) and this process could depend on the physical and chemical properties of the sediments. This 'lock-in depth' causes a delay between the age of the sediment and geomagnetic signal and smoothing of the primary geomagnetic field signal (e.g. Lund and Keigwin, 1994; Roberts and Winklhofer, 2004). The occurrence of a PDRM acquisition and the lock-in depth has been extensively discussed (e.g. deMenocal et al., 1990; Sagnotti et al., 2005; Suganuma et al., 2010 Suganuma et al., 2011), mainly in a context of marine sediments that have a mixed (bioturbated) surface layer. The depth of the bioturbated layer has been suggested as an important factor determining the lock-in depth (e.g. Liu et al., 2008). The existence of a significant lock-in depth/delay in marine sediments has, however, been questioned mainly based on the effect of particle flocculation inhibiting re-alignment after deposition and potential time-scale uncertainties (Tauxe et al., 2006). The lock-in process in lake sediments and its implication for palaeomagnetic reconstructions have previously also been discussed (e.g. Snowball and Sandgren, 2004; Haltia-Hovi et al., 2010). Due to difficulties to recover unconsolidated surface sediments intact for palaeomagnetic analyses the determination of lock-in depth/delay in lake sediments has been problematic.

Estimates of the PDRM lock-in depth/delay in marine sediments have been made by e.g. comparing depth offsets between stratigraphic markers with known ages, such as the last geomagnetic reversal (Matuyama-Brunhes boundary, ca. 780 000 years ago) and oxygen isotope ages (e.g. deMenocal et al., 1990). The lock-in process in lake sediments has been estimated by e.g. comparing palaeomagnetic data from lake sediments with archaeomagnetic data, for which a lock-in process can be excluded (Stockhausen, 1998).

3. Study areas

The location of the three studies sites are shown in Figure 2. Gyltigesjön and the peat bog of Undarsmosse are both located in the province of Halland in south-west Sweden. Kälksjön is located in the province of Värmland in west-central Sweden.

Figure 2. Location map showing the three study sites.

3.1 Gyltigesjön

Gyltigesjön (56°45'33"N, 13°10'37"E, 66 m asl) has an area of 0.4 km^2 and is connected to three other lakes (Töddesjön, Simlången and Brearedssjön) by the Fylleån River in the valley of Simlångsdalen. Gyltigesjön is the first lake in this chain. The inlet is situated in the northern part of the lake and the outlet is to the south. In addition, eight smaller streams enter the lake. The lake has two deeper basins separated by a sill. One basin is located in the northern part of the lake and the other in the southern part with depths of about 12.3 and 18.5 m, respectively. The lake sediments are varved, but in contrast to other varved lakes located further north and northeast in Sweden (e.g. Snowball et al., 1999; Zillén et al., 2003), the sediments show mainly a biogenic composition with two dominant laminae per year (Paper II). Water temperature and oxygen levels were measured in the deepest part of the lake in March 2013. Low levels of oxygen (<2 ml O_2/l) and a temperature about 4°C was found below a water depth of 17 m (Paper II). The stratified water and the lack of oxygen in the bottom waters favour the preservation of varved sediments.

The catchment area covers a total of 182 km^2 and consists mostly of forest (61%), but wetlands (25%), open land (8%) and open water (6%) are also present (Guhrén et al., 2003). The main bedrock types in the catchment are augen granite and gneiss (Karlqvist et al., 1985). The Quaternary deposits nearby the lake and around the main river inlet are primarily of glaciofluvial origin (Daniel, 2006). The average turnover time for the water is about 11 days (Guhrén et al., 2003). Daily discharge data are available from a hydrological station at Simlången (SMHI, 2014). Monthly data between AD 1952-2013 show largest discharges (8 m^3/s) between November and January and the lowest are found for June and July (3 m^3/s).

3.2 Kälksjön

Kälksjön (60°09'13"N, 13°03'23"E, 98 m asl) has an area of 0.3 km^2 and a maximum water depth of 14.2 m. The lake has three inlets in its eastern part and one to the north. The outlet is in the western part of the lake. The catchment area covers 4 km^2 and consists mostly of managed boreal forest (spruce, pine and birch), and arable land is present in the area nearby the lake (Zillén et al., 2003). The Kälksjön chronology extends back to ca. 9200 cal BP (Stanton et al., 2010) when the lake became isolated from the ancient Lake Vänern (Björck, 1995). Since the lake is located below the highest coastline, clays and silts, but also glaciofluvial deposits like sand and gravel are common in the catchment area (Zillén et al., 2003) and the bedrock is mainly gneissic (SGU, 2014).

The lake was investigated as a part of a search for lakes with varved sediments by Zillén et al. (2003). The varved sediments of the lake have a clastic-biogenic composition, commonly found in Swedish and Finnish freshwater lakes (e.g. Renberg, 1982; Saarnisto, 1986; Petterson, 1996; Ojala et al., 2000), with three to four laminae per year that deposit in different seasons (Zillén et al., 2003; Stanton et al., 2010). A water temperature profile and oxygen levels were measured in March 2003 (Zillén, 2003; Stanton, 2011). The temperature approximated 4°C in the bottom parts of the water column and a lack of oxygen was found below a water depth of 13 m. These conditions are assumed to be present during most of the year, thus, contributing to the preservation of varves (Zillén, 2003). Two short seasonal turnovers may, however, occur (Zillén, 2003). No discharge data are available for Kälksjön. However, monthly data from two nearby stations (located within approximately 25 km) show that the largest discharge occurs between April and May, with a smaller discharge peak in November (SMHI, 2014).

3.3 Undarsmosse

The Undarsmosse peat bog (56°47'46"N, 12°39'22"E, 20 m asl) is situated on the coastal plain of Halland, about 2.5 km east to the present day coastline. Isolation of the Undarsmosse basin from a marine bay into a lake has been estimated to ca. 10 250 ^{14}C BP (Berglund, 1995). Today, Undarsmosse is an ombrotrophic bog with an area of about 1.2 km^2 and the vegetation is dominated by species of *Ericaceae* and *Sphagnum* (de Jong, 2007). The peat bog is surrounded by low bedrock hills to the east and west, and flat areas are present to the north and to the south. Clay deposits are common in the vicinity of the bog (Påsse, 1988). Sandy sediments are found mainly to the west in the northern part of the basin and tills are common both to the east and west of the bog (Påsse, 1988).

4. Materials and methods

4.1 Fieldwork

Sediment cores were recovered from Gyltigesjön when the lake was ice-covered between January and March 2010, and in February 2011. Coring took place at the deepest part of the lake located using a plumb-line and a hand-held echo-sounder. The top sediments (about 0.8 m) were recovered using a freeze-coring technique (Renberg and Hansson, 1993). Three sediment sequences (GP1-2 and GP4) were recovered with a rod-operated piston corer (Snowball and Sandgren, 2002) in 5 m long PVC tubes and one sequence (GD0a) in a 3 m long PVC tube. These cores cover depths between about 18.7 and 27.0 m below the lake surface at a depth of 18.5 m. Furthermore, a cable-operated Uwitec ('Niederreiter') percussion piston corer was used to recover sediment sequences in 3 m long PVC tubes (GD1-4) that extend between about 19.5 and 31.5 m depth. A deeper penetration into the sediments was not possible with the available equipment. All sediment sequences were cut into about 1.0-1.5 m long sections and stored in a cold room at a temperature of about 4°C. Additional cores with a length of 1.5 m each (GPR1-3) were recovered between about 19.5 and 26.0 m depth using a modified rod-operated Russian corer (Jowsey, 1966).

Fieldwork at Kälksjön was previously conducted from the deepest part of the lake when it was ice-covered in March 2002 and 2003 (Stanton et al., 2010), and in February 2008. A rod-operated piston corer was used to recover four overlapping sediment sequences (KP1-4) in 5 m long PVC tubes (Stanton et al., 2010; Stanton et al., 2011). Four sediment sequences (K6-9) were further recovered by a 1.5 m long modified rod-operated Russian corer and used to construct the chronology (Snowball et al., 2010; Stanton et al., 2010). Two 5 m long parallel sediment sequences (KP5-6) were also recovered with a modified rod-operated piston corer. All sequences cover the depths of about 14.25-21.0 m below the ice-covered lake surface (14.2 m deep). The sediment cores recovered by the piston corer were cut into sections of about 1.5 m.

Fieldwork at Undarsmosse took place in 2003 as a part of the PhD study by de Jong (2007). Two parallel and overlapping cores extending to a depth of about 3.4 m were retrieved from the north-central part of the bog with a Russian corer and described in field before storage in a freezer. Prior to this study the cores were sub-sampled (1 or 2 cm segments) and stored in plastic boxes at a temperature of 4°C.

4.2 Core correlation and composite depth scale

Visual stratigraphy (distinct varves) and magnetic susceptibility were used to correlate the sediments cores from Gyltigesjön and to construct a composite depth scale (Paper II). Distinct features, observed in both lithology and magnetic susceptibility, were used as tie points. The depth scales of the cores GP2 and GP4 were adjusted to the depths between tie points in the core GP1 by applying linear interpolation. The freeze core retrieved from the uppermost part of the sediment column was linked to the core GD0a by identifying distinct varves present in both cores. Surface susceptibility scanning was performed for all cores at 0.4 cm resolution using a Bartington Instruments Ltd MS2E1 sensor coupled to a TAMISCAN-TS1 conveyor. However, these measurements were only used to correlate the deeper core sections of GD3 and GD4. For the other cores (GD0a, GP1, GP2 and GP4), volume specific magnetic susceptibility (χ) was measured (see section 4.5).

A detailed description of correlations between the Kälksjön cores is provided by Stanton et al. (2010; 2011). The two additional cores, KP5 and KP6, were correlated to the chronology cores and assigned varve ages by using distinct marker varves and magnetic susceptibility correlations.

4.3 Sediment characterisation

The Gyltigesjön sediment sequence was divided into nine different units based on the stratigraphy and magnetic susceptibility profiles. The organic and carbonate contents of the sediments were estimated by measuring loss-on-ignition. A total of 59 sediment samples (1 cm^3 each) were analysed at about 20 cm increments. The samples were first dried at 105°C overnight before ignited at 550°C and 950°C for four and two hours, respectively (Heiri et al., 2001).

Laminations in the upper 60-70 cm of the Gyltigesjön sediments were previously noted and described as varves by Guhrén et al. (2003). Liming has been conducted annually since AD 1982 (Guhrén et al., 2003) and the start of this activity is marked as a distinct layer in the freeze core. Thus, an annual sediment deposition above this layer could be confirmed. A visual inspection of the sediment cores revealed that the laminated structure extends to a depth of about 9 m (ca. 8000 cal BP) (Paper II). Detailed analyses of the lamination structure were conducted on a total of 19 thin-sections of sediment blocks (cores GPR1 and GPR2), which covered the time period between 3000-2000 cal BP. The sediment blocks covered 10 cm each with overlapping sections of 2 cm. The sediment blocks were frozen with liquid nitrogen (Brauer et al., 1999) and freeze-dried for 48 hours before impregnated with Araldite resin and polished (thickness of about 20-25 µm). The analyses further confirmed the presence of varves in the lake sediments (Paper II). A detailed description of the characterisation of the Kälksjön sediments can be found in Zillén (2003), Snowball et al. (2010) and Stanton et al. (2010).

4.4 Chronology

An effort was undertaken to obtain an as accurate and precise time-scale as possible of the three records of Gyltigesjön, Kälksjön and Undarsmosse. This was achieved with the ^{14}C wiggle-match dating technique whereby the variations in the atmospheric ^{14}C concentration are identified in the sediment/peat samples. This makes it possible to connect the time-scales to the absolutely dated tree-ring chronology that underlies the Holocene part of the ^{14}C calibration curve (Reimer et al., 2013).

4.4.1 Gyltigesjön

Several steps were performed in order to construct a ^{14}C wiggle-matched chronology of the Gyltigesjön sediments around 3000-2000 cal BP (Paper I), which involved: (i) varve counting and sub-sampling, (ii) pre-treatment, graphitisation and AMS ^{14}C dating, and (iii) age modelling. In the following the different steps are described.

Varve counting was performed on the fresh sediments from the cores GP1 and GP2 (composite depths from 448 to 527 cm below the sediment surface). The counting was performed independently by two investigators using a stereomicroscope. The sediments were divided into sections of 50 years and uncertain varves were counted as 0.5 years with an error of ±0.5 years, identical to the method used for the Greenland ice-core chronologies (e.g. Rasmussen et al., 2006). A total of 873 varves were counted with an error estimate of ±34 varves. A series of 15 closely spaced (every 50 year) bulk sediment samples, along with three plant macrofossils found in the core GP4, were ^{14}C dated. The sampling depths of the macrofossils were identified in the varve counting cores (GP1 and GP2) by marker varves.

All bulk sediment samples were pre-treated with 2% HCl to remove carbonates. The plant macrofossils were small and fragile, thus, only allowing for a weak chemical pre-treatment. A less aggressive version of the standard acid-base-acid (ABA) method with 0.25% NaOH and 1% HCl was used to remove possible contaminants. All samples were graphitised using a semi-automated graphitisation line (Unkel, 2006) before ^{14}C measurements at the Single Stage AMS facility at Lund University, Sweden (Skog et al., 2010; Adolphi et al., 2013).

The age modelling was performed using OxCal version 4.1 (Bronk Ramsey, 2009) with the IntCal09 ^{14}C calibration curve (Reimer et al., 2009) and the implemented V_Sequence deposition model (Bronk Ramsey, 2008), which considers the relative ages between the samples and the estimated errors. The age modelling approach described by Snowball et al. (2010) was applied to construct the chronology. The reservoir effect was estimated by systematically subtracting ^{14}C ages from the bulk sediment samples using the age model agreement index to determine the best fit. The chronology was validated by including macrofossil ^{14}C determinations in the age modelling.

The Gyltigesjön chronology was further extended to cover ca. 6400 cal BP (Paper II). To do so four additional plant macrofossils from the core GP4 were ^{14}C dated. A P_Sequence deposition model (Bronk Ramsey, 2008) and the previously used V_Sequence model for the period 3000-2000 cal BP were combined to build the age model. A lead pollution isochron at AD 1850 identified by Guhrén et al. (2003) was further included in the model. ^{14}C dating was also performed on nine bulk sediment samples for other periods than 3000-2000 cal BP; however, they were not included in the final age model due to the unknown reservoir effect for these periods (Paper II).

4.4.2 Kälksjön

Stanton et al. (2010) constructed a varve chronology for the Kälksjön sediment sequence extending to 9193±186 cal BP. They tested the varve chronology by using independent dating techniques including: measuring lead isotope ratios (^{206}Pb/^{207}Pb) (see e.g. Renberg et al., 2001) in the upper part of the sediment sequence, ^{14}C dating on 12 bulk sediment samples distributed throughout the sequence and correlation between the palaeomagnetic data obtained from the Kälksjön sediments and the FENNOSTACK PSV curve for Fennoscandia (Snowball et al., 2007). With these methods, they discovered 270 missing years in the sediments younger than 1000 cal BP and 230 years too many in the sediments older than 8000 cal BP. Uncertainties may still exist and the ^{14}C wiggle-match dating technique was therefore applied to test and improve the varve chronology around 3000-2000 cal BP (Paper III) using the same routine applied to the above-mentioned sediments of Gyltigesjön. The most recently recovered sediment cores, KP5 and KP6, were used for ^{14}C dating of 19 bulk sediment samples and four macrofossils samples, respectively. Sub-sampling was performed at known time intervals to ensure that the structure of the ^{14}C calibration curve is well-captured by the ^{14}C dates. The depth of each sub-sample was identified in the chronology cores (K7 1-2) and assigned a varve age (Stanton et al., 2010). A similar routine of pre-treatment, graphitisation, AMS ^{14}C measurements and age modelling as previously described for the Gyltigesjön sediments was applied (see section 4.4.1). The only exception is that some samples, later on in the project, were graphitised with an Automated Graphitisation Equipment (AGE) (Wacker et al., 2010).

4.4.3 Undarsmosse

De Jong et al. (2006) constructed an age model of the Undarsmosse peat sequence based on ^{14}C dating of 14 samples. All samples except one were composed of bulk peat. The age model was constructed by individual ^{14}C age calibration of the results. Subsequently, a combination of a 7th and 10th degree polynomial fit to the calibrated ages was used for the final age model (de Jong et al., 2006).

In order to improve the age constraints around 2800 cal BP the ^{14}C wiggle-match dating technique was applied (Paper IV). In total 13 plant macrofossil samples, covering ca. 3200-2200 cal BP, were carefully selected and ^{14}C dated. All samples underwent pre-treatment, graphitisation and AMS ^{14}C dating according to the previously described routines (see section 4.4.1). Age modelling was performed using OxCal version 4.2 (Bronk Ramsey, 2009) with the IntCal13 ^{14}C calibration curve (Reimer et al., 2013) and the implemented P_ Sequence deposition model (Bronk Ramsey, 2008). To allow for variations in the peat accumulation rate a function for variable k-values was added to the model. In this case, variations were allowed between 0.01 and 100 cm^{-1} with the base value set to 1 cm^{-1} (Bronk Ramsey and Lee, 2013).

4.5 Palaeomagnetic and mineral magnetic measurements

The palaeomagnetic and mineral magnetic measurements for the Gyltigesjön sediments (cores GD0a, GP1-2 and GP4) are in detail described by Snowball et al. (2013; Paper II) and for the Kälksjön sediments (cores KP1 and KP3) by Stanton et al. (2010; 2011) and in Paper III (KP5-6). Data treatment and the PDRM lock-in depth modelling are described in Papers II and III.

All magnetic measurements were carried out at the Palaeomagnetic and Mineral Magnetic Laboratory at Lund University. Sediment sub-sampling was conducted at 3 cm intervals using standard palaeomagnetic cubes (2x2x2 cm external dimensions, internal volume 7 cm^3) that were stored at a temperature of 4°C. A 2G-Enterprises superconducting rock magnetometer (model 755R) was used to measure natural remanent magnetisation (NRM) demagnetisation and alternating field (AF) anhysteretic remanent magnetisation (ARM) acquisition and demagnetisation. The ARM was induced using a 100 mT AF with a biasing direct current field of 0.05 mT. For both Gyltigesjön and Kälksjön samples, the inclination and declination were determined using principal component analysis (Kirschvink, 1980) between demagnetisation intervals of 30-60 mT. Relative palaeointensity (RPI) was determined for the Gyltigesjön sediments and for the Kälksjön cores KP5 and KP6 by dividing the NRM intensity values with the ARM values obtained at AF demagnetisation steps at 30, 40 and 50 mT, respectively, and an average was produced of the three RPI estimates. A pseudo-Thellier technique (Tauxe et al., 1995) was used to obtain RPI estimates for the Kälksjön cores KP1 and KP3 (see Stanton et al., 2011).

A Redcliffe 700 BSM pulse magnetizer was used to induce a saturation isothermal remanent magnetisation (SIRM), which was measured with a Molspin Minispin magnetometer. Volume specific magnetic susceptibility (χ) was measured with a Geophyzica Brno (now Agico) KLY-2 magnetic susceptibility bridge. Following the measurements the samples were oven dried at 40°C and the dry mass specific magnetic SI units of χ, ARM and SIRM were calculated. In order to investigate grain size variations ratios of SIRM/χ, χARM/SIRM and χARM/χ were calculated; with higher values indicating finer grain sizes of magnetite (Oldfield, 2007). Magnetic properties were also determined using first order reversal curves (FORCs) (Harrison and Feinberg, 2008) and measurements were carried out with a Princeton Measurements Corporation alternating gradient magnetometer (PMC AGM 2900-2).

4.6 Pollen and aeolian sand influx analyses

Estimations of aeolian sand influx (ASI), which have been used as a proxy for (winter) storminess (Björck and Clemmensen, 2004), and pollen analysis were previously carried out for the Undarsmosse peat sequence by de Jong et al. (2006). In the following the analyses conducted and described by de Jong et al. (2006) are summarised. Pollen analysis was performed on samples (2 cm^3) taken at irregular sampling intervals. The preparations followed standard methods for pollen analysis (Berglund and Ralska-Jasiewiczowa, 1986; Moore et al., 1991). In order to obtain pollen concentration and influx data *Lycopodium* tablets were added prior to further treatment (Stockmarr, 1971). Following counting, the Tilia software (Grimm, 1992) was used to calculate concentrations and percentages. ASI (grains/cm^2/year) was calculated based on mineral grain content. Sub-sampling with a known volume was carried out every cm. The samples were first dried at 105°C overnight and then ignited at 550°C for 4.5 h and the ignition residue was treated with 10% HCl. The remaining quartz grains were divided into different classes based on their sizes. In Paper IV, the ASI values were re-calculated based on the new ^{14}C wiggle-matched time-scale for Undarsmosse.

4.7 Macrofossil analysis

Plant macrofossil analysis was carried out for the period around 3400-1600 cal BP to investigate local vegetation changes at Undarsmosse and to complement the published pollen data. The analysis was carried out on a total of ten samples (3-5 cm^3). After weighing each sample the volume was determined by immersing it in a known volume of water. The samples were treated with 5% NaOH overnight and subsequently sieved through a mesh (0.250 mm). The macrofossils retained on the sieve were stored in 200 ml of water and the content was examined using a stereomicroscope. Dominant remains were quantified by taking a sub-sample with a known volume from the initial sample (Janssens, 1983; Van der Putten et al., 2009). More rare remains were counted for the complete sample. The number of each taxon was calibrated for a standard sample volume. Finally, the diagrams were constructed using the Tilia and Tilia graph software (Grimm, 2007).

5. Summary of papers

Author contributions for the following papers are listed in Table 1.

5.1 Paper I

Mellström A, Muscheler M, Snowball I, Ning W, Haltia E. (2013). Radiocarbon wiggle-match dating of bulk sediments – How accurate can it be? Radiocarbon 55 (2-3): 1173-1186.

The aim of Paper I was to explore the potential of the ^{14}C wiggle-match dating technique on bulk samples from varved sediments and to establish an accurate and precise chronology for the sediments of Gyltigesjön in southern Sweden covering the period around 3000-2000 cal BP. Since terrestrial plant macrofossils might be scarcely distributed in sediments, the focus was on investigating the accuracy of a bulk sediment based age model.

The age modelling was performed in OxCal

Table 1. Author contributions to Papers I-IV.

	Paper I	Paper II	Paper III	Paper IV
Fieldwork	I. Snowball A. Mellström W. Ning	I. Snowball A. Mellström E. Ahlstrand A. Nilsson W. Ning	I. Snowball	-
Sediment description	A. Mellström	A. Mellström E. Ahlstrand I. Snowball	-	-
Varve composition	A. Mellström I. Snowball	A. Mellström A. Brauer I. Snowball		
Varve counting	A. Mellström W. Ning	-	-	-
Loss-on-ignition	-	A. Mellström	-	
^{14}C sample preparation and graphitisation	A. Mellström	A. Mellström	A. Mellström	A. Mellström
Age modelling	A. Mellström	A. Mellström I. Snowball	A. Mellström	A. Mellström
Palaeomagnetic sampling and measurement	-	E. Ahlstrand W. Ning I. Snowball E. Haltia	I. Snowball T. Stanton A. Nilsson	-
Lock-in modelling	-	A. Nilsson	A. Nilsson N. Suttie	-
Macrofossil identification/ analysis	E. Haltia	E. Haltia	-	N. Van der Putten
Data interpretation	A. Mellström R. Muscheler I. Snowball	I. Snowball A. Mellström E. Haltia A. Nilsson W. Ning R. Muscheler A. Brauer	A. Mellström A. Nilsson T. Stanton R. Muscheler I. Snowball N. Suttie	A. Mellström N. Van der Putten R. Muscheler R. de Jong S. Björck

version 4.1 (Bronk Ramsey, 2009) using a V_ Sequence deposition model (Bronk Ramsey, 2008). The age model was based on ^{14}C dating of 15 bulk sediment samples. The results revealed a misfit between the structure of the variations in measured ^{14}C ages and the structure of the ^{14}C calibration curve. This misfit can be removed by subtracting an old-carbon (^{14}C reservoir) age that was estimated to ca. 260 ^{14}C years. The ^{14}C reservoir age is not necessarily constant for all of the samples as assumed in the first approximation. A revised total ^{14}C error was therefore calculated and included in the modelling to account for this effect. The age model was validated, and the estimated ^{14}C reservoir effect was confirmed, by including ^{14}C results of three macrofossil samples in the modelling.

In order to evaluate the age uncertainties we compared three models established based on ^{14}C dating of: (i) 15 bulk sediment samples, (ii) 15 bulk sediment and three macrofossil samples, and (iii) only the three macrofossil samples. The results showed that the bulk sediment based age model has an uncertainty of ca. ±30 years (95.4% probability range). A similar result was obtained when macrofossils were included. The age model only based on the macrofossil ^{14}C results has an uncertainty of ca. ±60 years.

This study illustrates the opportunity to estimate the ^{14}C reservoir effect with the ^{14}C wiggle-match dating technique. We emphasized the possibilities to construct accurate chronologies solely based on bulk sediment samples using this method. Finally, we indicated future prospects based on this well-constrained chronology.

5.2 Paper II

Snowball I, Mellström A, Ahlstrand E, Haltia E, Nilsson A, Ning W, Muscheler R, Brauer A. (2013). An estimate of post-depositional remanent magnetization lock-in depth in organic rich varved lake sediments. Global and Planetary Change 110: 264-277.

In Paper II the entire sediment sequence retrieved from Gyltigesjön was investigated. This included: the construction of a composite depth scale, sediment characterisation, determination of the organic content, age modelling including the ^{14}C wiggle-matched sequence around 3000-2000 cal BP (Paper 1) and additional ^{14}C dating of macrofossils. The study focused on the palaeomagnetic properties of the lake sediments covering the last ca. 6400 years.

High-quality palaeomagnetic data have previously been obtained from varved lake sediments in Sweden and Finland (e.g. Ojala and Saarinen, 2002; Snowball and Sandgren, 2002; Haltia-Hovi et al., 2010) encouraging the investigation of the palaeomagnetic properties in sediments from Gyltigesjön. Mineral magnetic data and first order reversal curves indicated that the natural remanent magnetisation in Gyltigesjön is carried by single-domain magnetite grains with magnetic properties characteristic of bacterial magnetosomes. The main aim of the study was to test for the influence of a post-depositional remanent magnetisation (PDRM) lock-in process in the sediments. The PDRM lock-in depth was estimated by comparing the Gyltigesjön palaeomagnetic data (declination, inclination and relative palaeointensity) from four stacked and smoothed cores to the palaeomagnetic secular variation reference curves for Fennoscandia (FENNOSTACK and FENNORPIS; Snowball et al., 2007). The highest correlation between the records was found when lock-in depths of about 21 to 34 cm were assumed for the Gyltigesjön sediments. These depth ranges are probably minimum estimates since the underlying data sets that contribute to the reference curve also might be influenced by unknown lock-in delays.

The study detected a significant PDRM lock-in depth in the Gyltigesjön sediments. Most important, the study illustrated the possibility for a PDRM lock-in process to occur in sediments even in the absence of a mixed (bioturbated) surface layer.

5.3 Paper III

Mellström A, Nilsson A, Stanton T, Muscheler R, Snowball I, Suttie N. Application of archaeomagnetic field models to infer post-depositional remanent magnetization lock-in depth in precisely dated varved sediments. Submitted to Earth and Planetary Science Letters.

The existence and extent of a PDRM lock-in depth/delay in varved lake sediments was investigated in more detail in Paper III. This paper focused on two parts, first the establishment of an accurate chronology for the palaeomagnetic data and second, the modelling of a lock-in depth/delay. The period around 3000-2000 cal BP was investigated since it is characterised by strong geomagnetic field intensity and distinct palaeomagnetic secular variations, such as the northern hemispheric westerly declination swing from so-called feature "f" at around 2700 cal BP to feature "e" (e.g. Turner and Thompson, 1981; Snowball et al., 2007; Haltia-Hovi et al., 2010).

The varved lake sediments of Kälksjön were investigated, which previously have shown high-quality palaeomagnetic data (Stanton et al., 2010; Stanton et al., 2011). Since a varve chronology could have uncertainties in form of e.g. missing varves (Ojala et al., 2012), the ^{14}C wiggle-match dating technique was applied to test and improve the varve chronology. The age model was based on ^{14}C dating of 19 bulk sediment samples, with known relative ages between the samples, and four terrestrial plant macrofossils. This allowed for an estimation of the reservoir age (150 ^{14}C years) in the lake sediments and establishment of an age model with an uncertainty of only ±20 years (95% probability range).

Relative declination and inclination data from Kälksjön were compared to the Gyltigesjön palaeomagnetic record (Paper II), which has a similar ^{14}C wiggle-matched chronology (Paper I), and to the archaeomagnetic models ARCH3k.1, ARCH3k_cst.1 (Korte et al., 2009) and A_FM-M (Licht et al., 2013) that are based on archaeomagnetic material unaffected by a lock-in delay process. The comparison revealed older palaeomagnetic ages in the lake records. Subsequently, a PDRM lock-in depth modelling was performed using different lock-in filter functions. The best fit was – for both lakes – achieved with a linear function, with modelled lock-in depths of about 30-90 cm in Kälksjön and 50-160 cm in Gyltigesjön. In addition, the lock-in model was able to explain the reduced amplitude of variation seen in the lake sediment data. The study provided evidence for significant and deep lock-in depths in both lake sediment records, possibly due to the high organic content of the sediments and progressive sediment consolidation due to de-watering.

5.4 Paper IV

Mellström A, Van der Putten N, Muscheler R, de Jong R, Björck, S. A shift towards wetter and windier conditions in southern Sweden around the period of a solar minimum ca. 2700 cal BP. Manuscript.

In Paper IV we focused on the climate change that has been reported at around 2800 cal BP. An increasing number of records show a shift towards cooler, wetter and windier conditions in Europe around this period, suggested to be induced by a shift towards low solar activity (e.g. van Geel et al., 1996; van Geel et al., 1998; Speranza et al., 2002; Martin-Puertas et al., 2012). In this paper we investigated the possibility for such a climate change in southern Sweden.

A peat record from Undarsmosse in south-west Sweden has previously shown increased aeolian sand influx (ASI) and increased influx of *Sphagnum* spores around this period, interpreted to reflect intensified storminess and a wetter bog surface (de Jong et al., 2006). A new age model was constructed using the ^{14}C wiggle-match technique based on 13 carefully selected macrofossil samples and four bulk samples previously used to construct a chronology (de Jong et al., 2006). The mean uncertainty of the resulting age model was estimated to ca. ±90 years (95.4% probability range).

A macrofossil analysis of the peat record showed a previously undetected vegetation change, from a woody fen with presence of *Pinus* to a bog dominated by diverse moss species, such as *Sphagnum*. This fen-bog transition represents a shift towards wetter conditions and is dated to 3035-2540 cal BP (95.4% probability range). The large age uncertainties arise mainly from a contemporaneous change in the peat accumulation rate (possible hiatus). The period with increased ASI occurred slightly after the fen-bog transition, based on the stratigraphic order of the samples. The increased storminess started earliest around 2765 cal BP (95.4% probability range) with a modelled mean age of 2680 cal BP.

A summary of the climate changes observed in other well-dated (^{14}C and ^{10}Be wiggle-matched) records in Europe was presented. Within our age model uncertainty, the timing of the fen-bog transition and the increased ASI recorded in Undarsmosse could be synchronous with the climate changes inferred from the other palaeoclimatic records. In addition, we also provided a summary of the primary suggested Sun-climate hypothesis and the physical mechanisms that possibly could explain the recorded changes. In conclusion, the changes recorded in Undarsmosse most likely occurred as a result of a shift in the larger-scale atmospheric circulation, possibly induced by decreased solar activity.

6. Discussion

6.1 Radiocarbon wiggle-match dated chronologies - How accurate?

The chronologies of the varved lake sediments of Gyltigesjön and Kälksjön and the peat sequence of Undarsmosse, spanning ca. 3000-2000 cal BP, were all constructed using the ^{14}C wiggle-match dating technique. However, the age models of the varved lake sediments (Paper I and III) are based on ^{14}C dating of bulk sediment samples, with known relative ages between the samples, validated with macrofossil ^{14}C results. The peat sequence was constructed mainly using ^{14}C dating of macrofossils (Paper IV). The robustness of using the ^{14}C wiggle-match dating technique to construct chronologies of lake sediments and peat deposits, and their uncertainties, will be addressed in the following sections.

6.1.1 ^{14}C reservoir effect

Uncertainties with an old-carbon (^{14}C reservoir) effect associated with ^{14}C dating of bulk sediment samples are well-known (e.g. Olsson, 1986; MacDonald et al., 1991). The ^{14}C reservoir effect can vary between different sites and is not necessarily constant through time (e.g. Stanton et al., 2010; Oldfield et al., 1997) which complicates the construction of accurate chronologies based on ^{14}C dating of bulk samples. Studies have previously shown the unreliability of such chronologies and in consequence, the use of terrestrial plant macrofossil ^{14}C dates have been recommended (e.g. Barnekow et al., 1998; Björck et al., 1998). Bulk sediment samples are composed of a mixture of organic materials derived from different sources and the ^{14}C age of a sample reflects the mix of the dated fractions. There are many potential sources for the old-carbon effect including: direct in-wash of old material from soils and vegetation in the catchment and transportation of dissolved inorganic carbon to the lake, possibly originating from calcareous bedrock and soil (hard-water effect) (e.g. Björck and Wohlfarth, 2001). Estimations of the ^{14}C reservoir effect have been made by comparing ^{14}C ages of bulk sediments with macrofossil samples (e.g. Björck et al., 1998) and by comparing bulk ^{14}C ages with ^{14}C ages corresponding to absolute ages inferred from varve counting (e.g. Stanton et al., 2010). As shown by Snowball et al. (2010) the ^{14}C reservoir age in lake sediments can also be estimated using the ^{14}C wiggle-match dating technique of bulk sediment samples. A similar ^{14}C wiggle-match dating approach was applied successfully to the Gyltigesjön and Kälksjön sediments for the period around 3000-2000 cal BP and the age modelling showed the presence of a ^{14}C reservoir effect estimated to ca. 260 and 150 ^{14}C years, respectively (Paper 1 and III). It is difficult to determine the influencing factors for the reservoir effect in Gyltigesjön and Kälksjön, but calcareous bedrock is absent in the catchments and a significant hard-water effect can therefore be excluded. The time-varying reservoir effect in the Kälksjön sediments (Stanton et al., 2010) may arise as a result of changes in the lake and surrounding catchment related to shifts in the climate and environmental conditions. Reservoir age variations in the Gyltigesjön sediments for other periods than around 3000-2000 cal BP are unknown but can,

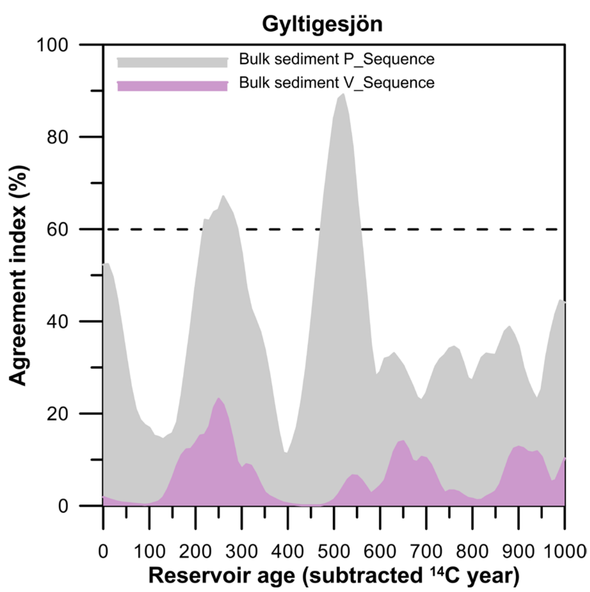

Figure 3. Age model agreement indices for the Gyltigesjön sediments constructed using P_Sequence (grey shading) and V_Sequence (purple shading) deposition models (Bronk Ramsey, 2008) and the IntCal09 calibration curve (Reimer et al., 2009) implemented in OxCal version 4.2 (Bronk Ramsey, 2009). Assumed ^{14}C reservoir ages were subtracted from 0 to 1000 at 10-year intervals. The dashed line shows the limit for a good agreement (Bronk Ramsey, 2009).

however, be expected.

The probability of successfully estimating the reservoir effect using the ^{14}C wiggle-match dating technique depends on the amplitude and variability of the reservoir age. In both studied lakes the reservoir age was rather small and constant for the period around 3000-2000 cal BP otherwise the ^{14}C dates would not have reflected the structure of the ^{14}C calibration curve. This method is therefore restricted to sites characterised by small reservoir variations, and the structure of the calibration curve determines the limit for such variations for this technique to work. The amplitude of the reservoir effect can also be estimated and confirmed with ^{14}C dating of macrofossils (Paper I and III).

As shown in Papers I and III the ^{14}C wiggle-match method worked well for the sediments when including the additional varve-based information about the relative ages between subsequent ^{14}C determinations. In the following, tests are carried out to investigate whether it would be possible to estimate the ^{14}C reservoir age and construct accurate chronologies with the ^{14}C wiggle-match dating technique for non-varved lake sediment sequences, solely based on bulk sediments. For this purpose, age models of the Gyltigesjön sediments were constructed using a P_Sequence deposition model (Bronk Ramsey, 2008), similarly applied to the Undarsmosse peat record (Paper IV), taking depth information into account instead of known relative ages between the samples. ^{14}C reservoir ages were subtracted from the ^{14}C ages from 0 to 1000 year at 10-year intervals similarly to the approach presented in Paper I. Figure 3 shows the resulting age model agreement indices in comparison to the corresponding routine using a V_Sequence model (Paper I). Two distinct agreement indices peaks are revealed with potential ^{14}C reservoir ages; about 250 and 500 ^{14}C years (Figure 3). The grey shading in Figure 3 indicates that it could be difficult to estimate the correct reservoir age without any complementary information from other dating methods. By including ^{14}C dating of macrofossils the best estimate of the reservoir age can immediately be identified (see Papers I and III), which in this particular case has an age of 260 ^{14}C years. The age model constructed using V_Sequence shows the highest agreement index at this particular reservoir age. However, the strong relative age constrains lead to the lower agreement index (Figure 3). This exercise shows that the ^{14}C wiggle-match dating technique potentially can be applied to non-varved lake sediments and the ^{14}C reservoir effect can be estimated. However, additional dating information might be required to pinpoint the correct estimate, via methods such as e.g. ^{14}C dating of macrofossil samples or palaeomagnetic dating of the sediments.

6.1.2 Known versus unknown relative ages

The number of years between each sample selected for ^{14}C analysis can be included in the age modelling in cases of varved lake sediments. This provides an advantage when performing the age modelling since the relative age between each sample is constrained and unexpected accumulation rate changes do not need to be accounted for. The age modelling instead relies on accurate varve counting and estimation of the error and this information can be included in the V_Sequence deposition model (Bronk Ramsey, 2008) in the calibration software OxCal (Bronk Ramsey, 2009) which was used to construct the lake sediment chronologies (Papers I and III). The final age models for the Gyltigesjön and Kälksjön sediment sequences (around 3000-2000 cal BP, Paper I and III) are based on ^{14}C wiggle-match dating of bulk sediment and macrofossil samples with mean uncertainties of ca. ±25 and ±15 years (95.4% probability range), respectively.

The Undarsmosse age model was built based on ^{14}C dating of carefully selected macrofossils and some previously available bulk sample ^{14}C dates (de Jong et al., 2006) using a P_Sequence deposition model (Bronk Ramsey, 2008) allowing for variable accumulation rates (Paper IV). The age model has a mean uncertainty of ±90 years (95.4% probability range) and the larger errors, compared to the lake chronologies, are to a large extent associated with potentially large changes in the peat accumulation rate.

Figure 4 and Table 2 show a comparison between the final age-depth models for all three sites together with the corresponding age-depth relationships using different deposition models and individual calibration of ^{14}C samples. These comparisons illustrate the uncertainties associated with age models based on known, respectively unknown relative ages between the ^{14}C samples. The results show that age model uncertainties for Gyltigesjön and Kälksjön are reduced by a factor of about 1.5 and 4, respectively, when applying the V_Sequence (know relative age) compared to the P_Sequence deposition model. However, the P_Sequence deposition model still reduces age model uncertainties by a factor of about 4 and 2, respectively, when comparing the result to an age model based on individual calibration of the ^{14}C results (Figure 4 and Table 2).

The final age model for the Undarsmosse peat sequence was compared to a corresponding P_Sequence deposition model with a fixed rigidity (k-value 1.4 cm^{-1}). This was the value for the most rigid age-model yielding still an acceptable agreement index (above 60%; Bronk Ramsey, 2009). The mean age uncertainty is slightly smaller for the age model using a fixed k-value. However, due to apparent prominent changes in peat accumulation rates in the sequence (Paper IV), it is reasonable to assume that more realistic age uncertainties are obtained by allowing for a wider range of variations (variable k-value function; Bronk Ramsey and Lee, 2013). Finally, the Undarsmosse age models were compared to individual calibration of ^{14}C samples and the final age model uncertainties were narrowed about 1.5 times with the ^{14}C wiggle-match dating technique compared to individual calibration of the ^{14}C samples (Figure 4 and Table 2).

In conclusion, as expected the age models increase in accuracy by including more independent information, such as relative ages between the samples. Individual ^{14}C age calibration can lead to large age uncertainties, especially in cases when the measured ^{14}C age fall onto age plateaus in the ^{14}C calibration curve. Including stratigraphic information and some constraints on the possible sedimentation rates (P_Sequence deposition model) already reduces the age model uncertainty considerably. Reliable constraints on the relative calendar age between the ^{14}C samples (V_Sequence deposition model) can lead to very well-constrained time-scales even in the presence of a reservoir effect

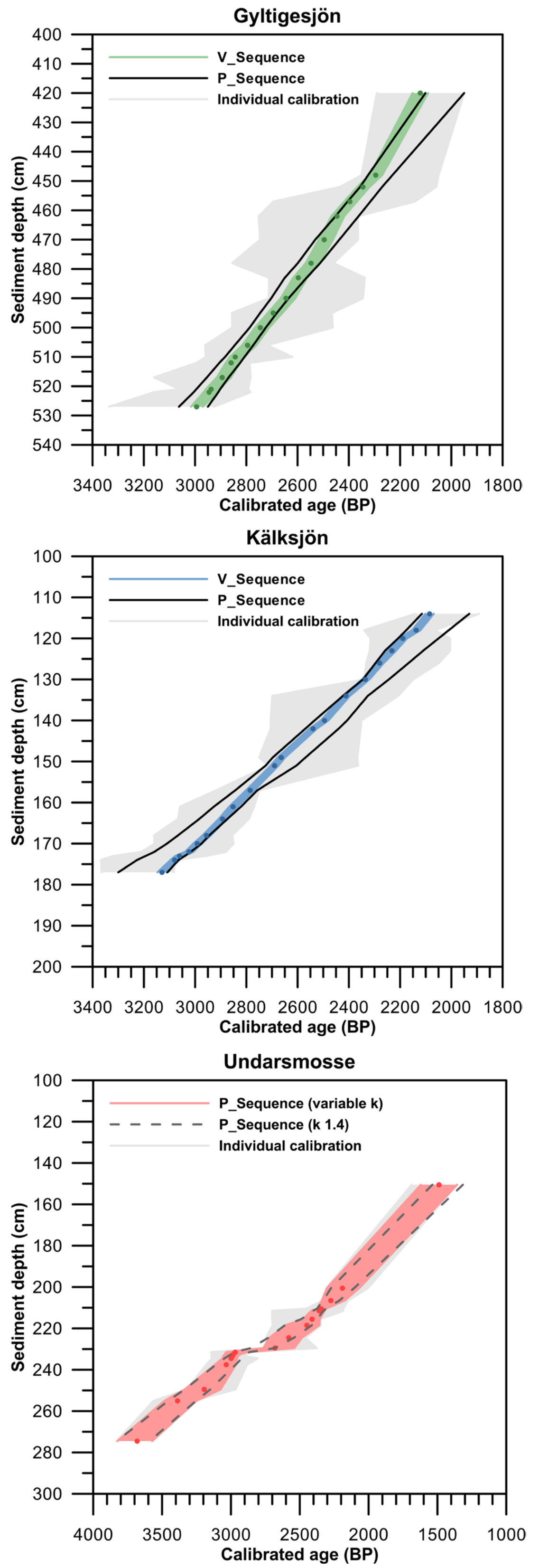

Figure 4. Comparison between different age-depth models of Gyltigesjön, Kälksjön and Undarsmosse. The final age models used in Papers I-IV are indicated by green/blue/pink shading. Mean ages for the final age models are indicated by filled circles.

*Table 2. Average age uncertainties associated with different deposition models (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013) and calibration of individual ^{14}C samples. All ranges are given by the 95.4% probability range. *Final age model used for the respective record.*

Record	V_Sequence	P_Sequence variable k	P_Sequence determined k	Individual sample calibration
Gyltigesjön	±27*	±44	-	±180
Kälksjön	±16	±67	-	±154
Undarsmosse	-	±89*	±76	±154

under the precondition that the variations are fairly small and constant. However, in such cases it is possible to construct accurate and precise age models that can be used to study the relative timing of regional climate change (Snowball et al., 2010) or to study the timing between solar and climatic changes (Martin-Puertas et al., 2012).

6.1.3 Validation of a varve chronology

In the preceding sections the robustness of chronologies constructed using the ^{14}C wiggle-match dating technique has been discussed. Since chronologies with small age uncertainties can be established using this technique it can additionally be applied to validate varve chronologies (see Paper III). The ages obtained with the ^{14}C wiggle-match approach were compared with the corresponding ages from the corrected varve chronology of Kälksjön (Stanton et al., 2010). Figure 5 shows the age discrepancies between the two chronologies. The wiggle-match dated chronology yields about 215 years older ages than the corrected varve chronology. In Paper III we concluded that the age offset, based on the ^{14}C wiggle-match dating results, most likely is a result of missing varves in the varve chronology. This interpretation is based on several lines of arguments: (i) the ^{14}C wiggle-match age model has small age uncertainties, (ii) the age model was determined based on both ^{14}C dating of bulk sediment samples and ^{14}C dating of macrofossils, and (iii) it was confirmed with paired bulk sediment-macrofossils ^{14}C samples.

The final ^{14}C wiggle-matched age model for Kälksjön (see Figure 4) was constructed based on information about the relative varve age estimates between ^{14}C dates; it is therefore relevant to investigate to what extent uncertainties in the varve chronology might affect the ^{14}C wiggle-matched age model. The strategy for this was outlined in Paper III. A large number of missing years between 3000-2000 cal BP can be excluded since it would have resulted in a misfit between the ^{14}C dates and the ^{14}C calibration curve. We tested the sensitivity of the age model results to uncertainties in the relative age estimates between ^{14}C dates by increasing the error estimates by a factor of two and five, respectively. With these tests, the age model uncertainty increases with additionally ±6.5 and ±12.5 years, respectively. We can conclude that the ^{14}C wiggle-match dating results for the period

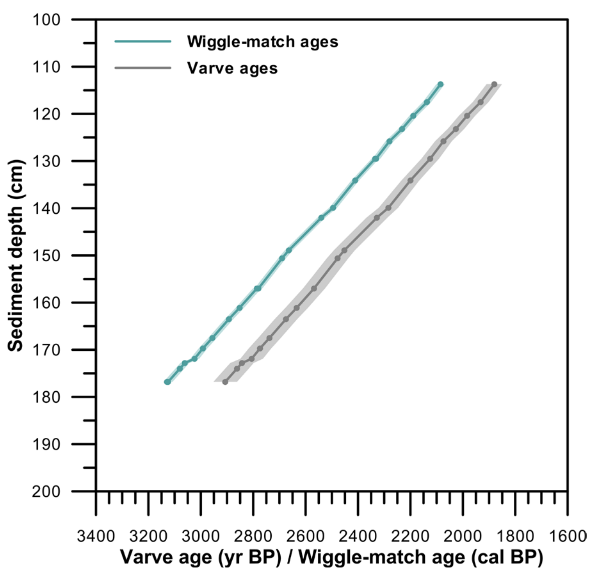

Figure 5. Comparison between the ^{14}C wiggle-matched ages (Paper III) and the ages obtained from the corrected varve chronology of Kälksjön (Stanton et al., 2010). The mean ages are indicated by filled circles. The ^{14}C wiggle-match results suggest an offset to the previous age model by about 215 years.

around 3000-2000 cal BP are robust even in cases of potential uncertainties between the relative age estimates. Snowball et al. (2010) applied the ^{14}C wiggle-matching technique to constrain the timing of a cold episode recorded in the lake sediments around 8200 cal BP and their results were in accordance with the ages obtained from the corrected varve chronology. The missing years are therefore likely to be found in the parts of the sediment sequence younger than 3000-2000 cal BP.

One potential source of uncertainty for the varve chronology of Kälksjön relates to the method of correcting the chronology via comparisons of different palaeomagnetic data sets. Ages of palaeomagnetic directional features might not be the same for different sites due to uncertainties regarding, e.g., a PDRM lock-in delay, which will be discussed in the following section.

6.2 Geomagnetic field reconstructions around 3000-2000 cal BP

In Papers II and III the uncertainties associated with the occurrence of a PDRM lock-in process in lake sediments were illustrated. Even with well-constrained chronologies, as in the case for both Gyltigesjön and Kälksjön (see section 6.1.2), the ages obtained for the palaeomagnetic changes might not represent the real timing of the geomagnetic field signal due to the lock-in delay.

6.2.1 Timing of geomagnetic field changes

Well-dated and reliable PSV features have the potential to be used as independent dating tools for different records. One of the features suitable for this propose is the distinct declination swing from feature "f" to feature "e" recorded in Europe around 3000-2200 cal BP (Turner and Thompson, 1981; Saarinen, 1998; Snowball et al., 2007; Haltia-Hovi et al., 2010; Stanton et al., 2010; Hervé et al., 2013). The timing of this swing is, however, not consistent between different records. As an illustration, the start of the swing has been dated to 2670 cal BP in the FENNOSTACK PSV curve for Fennoscandia based on lake sediments (Snowball et al., 2007). A PSV curve of two of the included lakes (Mötterudstjärnet and Furskogstjärnet) in central Sweden shows a corresponding swing dated to 3000 cal BP (Zillén, 2003) and a PSV curve of two other included lakes in northern Sweden (Sarsjön and Frängsjön) shows an age of 2595 cal BP (Snowball and Sandgren, 2002). Such age differences may be associated with e.g. chronological problems, stacking of the data, ambiguities to pinpoint the timing of changes and a lock-in delay which may be

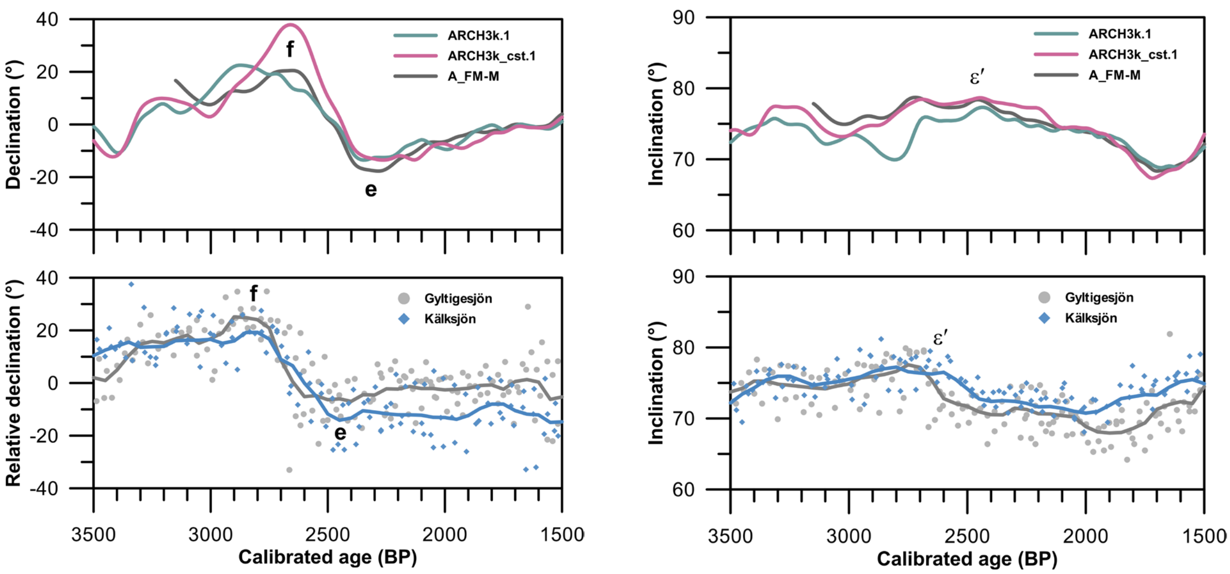

Figure 6. Declination and inclination data for Gyltigesjön and Kälksjön and the archaeomagnetic model predictions for Kälksjön: ARCH3k.1 and ARCH3k_cst.1 (Korte et al. 2009) and A_FM-M (Licht et al., 2013) (Paper III). Gyltigesjön and Kälksjön data are shown by stacked core data and the lines represent data smoothed with a 150-year running window at 50-year time steps.

different at various sites depending on the sediment properties.

The declination and inclination data from Gyltigesjön and Kälksjön, plotted on their respective ^{14}C wiggle-match time-scale, show a fairly similar timing of the features around 3000-2000 cal BP (Figure 6) (Paper III); here the declination feature "f" is recorded at around 2800 cal BP. However, archaeomagnetic model predictions (Korte et al., 2009; Licht et al., 2013) indicate a younger age for this feature (ca. 2650 cal BP) but also for other features, such as the accompanied inclination peak (ε') dated to ca. 2700 cal BP in the lake sediment records. As shown by the PDRM lock-in modelling presented in Paper III, the age discrepancies and diminished amplitude of the palaeomagnetic changes inferred from Gyltigesjön and Kälksjön can be explained by the occurrence of deep lock-in depths in both lakes. The main arguments previously presented against the occurrence of significant lock-in depths have centered on time-scale uncertainties and flocculation of particles preventing re-alignment to the geomagnetic field after deposition (Tauxe et al., 2006). Since the time-scales are well-constrained for both lakes age uncertainties can be disregarded as an influencing factor for the apparent age offset. The effects of particle flocculation are considered to be of minor importance in freshwater lakes (see Papers II and III).

6.2.2 Geomagnetic field intensity and implications for the ^{14}C production rate

The geomagnetic field intensity was in general high around 3000-2000 cal BP as shown by different records (e.g. Snowball et al., 2007; Knudsen et al., 2008). Increased geomagnetic field intensity is also shown by the palaeomagnetic records from Gyltigesjön (Paper II) and Kälksjön (Stanton et al., 2010; Stanton et al., 2011) (Figure 7). The Gyltigesjön RPI data (Paper I) are only based on one core (GP1) which limits the possibilities of interpreting this record. The Kälksjön record (Stanton et al., 2010; Stanton et al., 2011) is based on four different cores (KP1, 3, 5 and 6) and can be considered to be more reliable.

Variations in the geomagnetic field strength influence the radionuclide production rates, possibly on centennial and millennial time-scales (e.g. Snowball and Sandgren, 2002; St-Onge et al., 2003). The palaeointensity records from both lakes (Figure 7) can, after normalisation, be used to calculate the geomagnetic field influence on the ^{14}C production rate. The palaeomagnetic data from the lake sediments were transferred to a ^{14}C production rate using the results of Masarik and Beer (1999) and Wagner et al. (2000). Figure 8 shows the ^{14}C production rate based on the relative palaeointensity

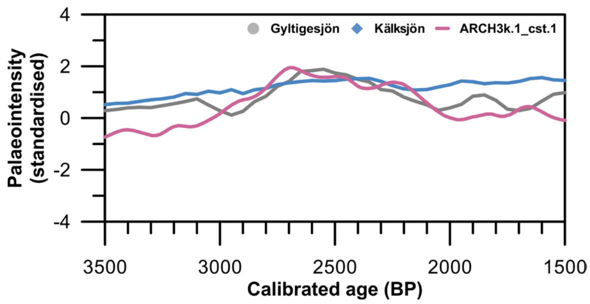

Figure 7. Standardised relative palaeointensity estimates from Gyltigesjön (core GP1) and Kälksjön (cores KP1, 3, 5 and 6), smoothed with a 150-year running window at 50-year time steps, and the prediction of the archaeomagnetic model ARCH3k_cst.1 (Korte et al., 2009).

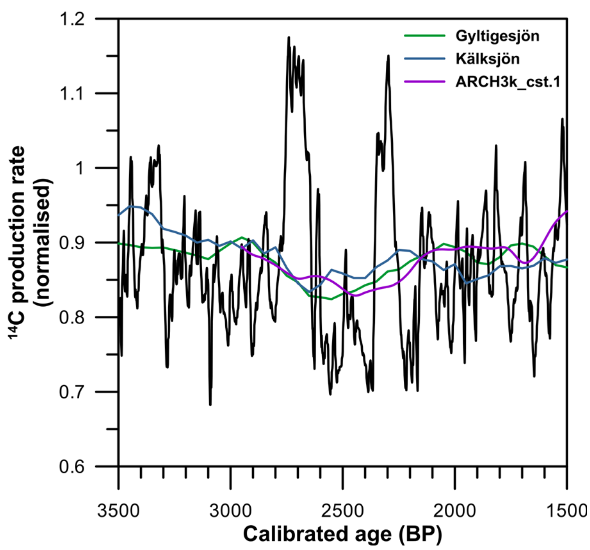

Figure 8. ^{14}C production rate calculated based on RPI estimates from the Gyltigesjön and Kälksjön palaeomagnetic records, and based on the dipole moment from the archaeomagnetic model ARCH3k_cst.1 (Korte et al., 2009) in comparison with the normalised ^{14}C production rate (Muscheler et al., 2005) inferred from the IntCal13 calibration curve (Reimer et al., 2013). The lake records are normalised so that the intensity and relative variations fit the archaeomagnetic field model over this period.

(RPI) estimates from Gyltigesjön and Kälksjön in comparison with the normalised ^{14}C production rate (Muscheler et al., 2005) for the period around 3500-1500 cal BP. The geomagnetic field signal is here assumed to be locked-in immediately at the time of sediment deposition, which as previously shown is not the case (Paper II and III). The ^{14}C production rate is therefore also calculated based on the dipole moment according to the archaeomagnetic model ARCH3k_cst.1 (Korte et al. 2009), which was used as an input signal for the lock-in modelling in Paper III. A similar trend of ^{14}C production rate is indicated based on all three data sets, i.e. the geomagnetic field modulates the ^{14}C production rate. The longer trend of ^{14}C production rate can be explained by a geomagnetic field modulation. However, the high ^{14}C production rate peaks at around 2700 and 2300 cal BP, respectively, cannot be explained by a lower geomagnetic field intensity but can instead be attributed to a decrease in solar activity.

6.3 Global synchronous climate change around 2800 cal BP?

6.3.1 Overview

A compilation of evidence for a global climate change around 2800 cal BP was presented by van Geel et al. (1996). They showed data from Europe, America, Japan and New Zealand that indicate a change to colder and wetter climate with glacier expansions and higher ground-water levels. Drier conditions were for the same period indicated for tropical Africa and Caribbean (van Geel et al., 1996). Since then numerous studies from the northern hemisphere, and especially peat archives from Europe, have demonstrated a shift towards wetter, colder and windier climate around 2800 cal BP (e.g. Speranza et al., 2002; Swindles et al., 2007; Plunkett and Swindles, 2008; Martin-Puertas et al., 2012). Furthermore, records from the southern hemisphere have shown a climate change around

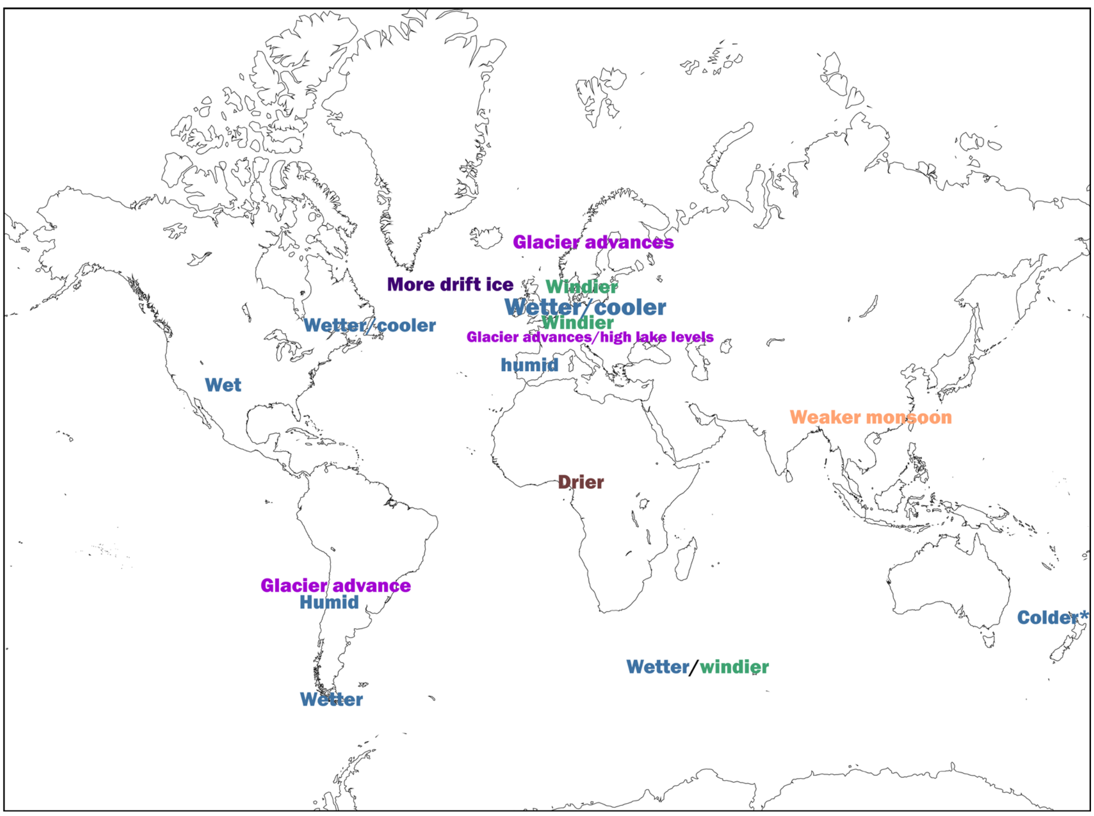

*Figure 9. Overview map of the climate changes reported from different parts of the world around 2800 cal BP (see Table 3 for details and references). *Marks a record where the interpretation presented in the paper was indicated to be less certain.*

the same period indicating a globally synchronous climatic event (e.g. van Geel et al., 2000; Chambers et al., 2007; Van der Putten et al., 2008). An overview of selected records showing a climate change around 2800 cal BP is summarised in Figure 9 and compiled in Table 3.

6.3.2 Spatial and temporal distribution

One key site where a climate change around 2800 cal BP has been reported is the raised peat bog of Engbertsdijksveen in eastern Netherlands (e.g. van Geel, 1978; Kilian et al., 1995; van Geel et al., 1996; Blaauw et al., 2004). Van Geel (1978) presented a palaeoecological study from this site and noted a shift to oceanic and possibly colder conditions at the Sub-boreal to Sub-atlantic transition. This peat sequence was further ^{14}C wiggle-match dated to constrain the timing of macro- and microfossil changes (Kilian et al., 1995). Subsequently, the ^{14}C wiggle-matched time-scale was used to refine the assessment of the timing of the vegetation change to the wetter demanding *Sphagnum cuspidatum* and *Sphagnum papillosum*, and then to *Sphagnum imbricatum* (van Geel et al., 1996). This vegetation change was placed at 2750 cal BP and the authors highlighted that it occurred contemporaneously with the steep increase in atmospheric ^{14}C content (van Geel et al., 1996). Numerous studies of peat records in Europe have further indicated a wet-shift around 2800 cal BP (Table 3). The accuracy of the chronologies varies and the applied climate proxies differ in the various studies. Analyses of macro- and microfossils, along with peat humification (decomposition) and testate amoebae, have commonly been applied to reconstruct the climate in different peat records (Table 3). ^{14}C wiggle-match dating has been applied in some cases to improve the time-scale around 2800 cal BP (Table 3). By using this technique, a shift to increased abundance of the moss *Sphagnum* section *Cuspidata* was dated to ca. 2810 cal BP, followed by decreased arboreal pollen percentages in the peat bog of Pančavská Louka in Czech Republic (Speranza et al., 2000; Speranza et al., 2002). This change was interpreted to reflect a shift to wetter and cooler conditions (Speranza et al., 2002). A delayed climatic response of about 100 years in comparison to other European peat sequences has been reported from Irish peat records raising questions about oceanic versus continental climate variability (Plunkett, 2006; Swindles et al., 2007; Plunkett and Swindles, 2008). The ^{14}C wiggle-match technique was applied to date the peat sequence of Glen West in Ireland (Plunkett et al., 2004). This record and the peat bogs of Dead Island and Slieveanorra showed increased water tables (reconstructed by testate amoebae analysis), less humified peat and an increase of *Sphagnum* section *Cuspidata*, at around 2700 cal BP (Swindles et al., 2007). Further analyses of macrofossils and testate amoebae of the Glen West record reinforced the hypothesis of a delayed climatic reaction in oceanic settings (Plunkett and Swindles, 2008). Similarly, a delayed wet-shift (at 2690 cal BP) has also been reported from the bog of Butterburn Flow in northern England (Mauquoy et al., 2008). As discussed in Paper IV, there are also indications for a shift to wetter climate in southern Sweden around 2700 cal BP recorded in the peat sequence of Undarsmosse (represented by a fen to bog transition), possibly related to the climate changes recorded in the above-mentioned peat bogs. The lake level reconstruction of Lake Bysjön in southernmost Sweden (Digerfeldt, 1988) shows a distinct lake level maximum at 2500 ^{14}C BP, corresponding to a mean calibrated age of about 2600 cal BP.

There are several records in Europe indicating a shift in the atmospheric circulation and more storminess events around 2800 cal BP (Table 3). For example, increased varve thickness (intensified diatom blooms) of the lake sediments of Meerfelder Maar in Germany was constrained to 2759±39 cal BP and interpreted to be caused by wind-induced upwelling in early spring season (Martin-Puertas et al., 2012). The peat record of Undarsmosse (de Jong et al., 2006; Paper IV), Store Mosse (de Jong, 2007) and Hyltemossen (Björck and Clemmensen, 2004) in southern Sweden show increased aeolian sand influx – indicating increased storminess – with a start at around 2700-2600 cal BP. Similarly, coastal dune fields on the west-coast of Denmark show increased aeolian activity at 2750-2650 cal BP (Clemmensen et al., 2001; Clemmensen et al., 2009).

Other climate records have also pointed to changed climatic conditions in Europe, such as a peak in ice-rafted debris in the North Atlantic at 2800 cal BP (Bond et al., 1997), increased flood intensity in Germany at 2800 cal BP (Czymzik et al., 2013), higher lake levels in France and Switzerland at 2750-2350 cal BP (Magny, 2004) and high-stands of the Caspian Sea at 2600 cal BP (Kroonenberg et al., 2007). Moreover, glacier advances in Switzerland have been dated to about 2765-2550 (Holzhauser et al., 2005) and in Norway to 2800 cal BP (Nesje et al., 2001) and 2750 cal BP (Matthews et al., 2005).

Palaeoclimatic proxy records from different parts of the world provide evidence for a world-wide extent of this climate event. For example, a compilation of evidences from Chile demonstrate glacier advances and vegetation changes around 2800 cal BP, thus suggesting a global climatic event (van Geel et al., 2000). Analyses of macrofossils and peat humification in a mire in the Valle de Andorra, Tierra del Fuego, indicated a shift to wetter mire conditions around 2706 cal BP and the chronology was well-constrained using the ^{14}C wiggle-matching technique (Chambers et al., 2007). The authors of this study highlighted the identical timing for the climate change as recorded in peat records in north-west Europe. Another southern hemispheric peat record from Ille de la Possession (Iles Crozet) in the southern Indian Ocean showed a shift to wetter and windier climatic conditions around 2800 cal BP (Van der Putten et al., 2008) strengthening the hypothesis of a globally synchronous climate event.

Conversely, some records e.g. in Cameroon and other parts of central Africa, indicate a shift to drier conditions around 2700 cal BP, possibly related to a weakened monsoon activity (Van Geel et al. 1996). A weakening of the Asian monsoon circulation has been shown around 2700 cal BP by an oxygen isotope study of a stalagmite from the Dongge Cave in China (Wang et al., 2005). The reasoning for monsoon circulation to be responsible for drier conditions in Africa was also inferred in a climate modelling study and attributed to differences in cooling between continental areas and the oceans (Renssen et al., 2006).

6.3.3 Potential uncertainties with chronologies, climate proxy data and the spatial distribution

In order to evaluate the possibility of a global synchronous climate change around 2800 cal BP a variety of uncertainties need to be considered. These include: (i) dating accuracy and precision, (ii) variability and reliability of the data, (iii) definition of the change and (iv) spatial differences. These issues will briefly be addressed here.

Good chronological control is fundamental for determining the timing between climatic events in different proxy records. Several of the records that show a climate change around 2800 cal BP have been dated with the ^{14}C wiggle-matching technique (see Table 3). With this method, the age of different climate changes can be constrained with small uncertainties. However, even with a high dating quality the age uncertainties can still be relatively large depending on e.g. the structure of the ^{14}C calibration curve and the sediment properties. For example, the ^{14}C wiggle-match dating technique was applied to the Undarsmosse peat record as described in Paper IV. Yet the average age uncertainty for the sequence around 3600-1600 cal BP remains fairly large (±90 years, 95.4% probability range) and the possibility to investigate leads and lags in the climate system becomes restricted. For this particular study, a distinct change in peat accumulation was detected using this dating technique. If such accumulation rate changes cannot be excluded they will contribute to increased age model uncertainties. Furthermore, the possibility to accurately determine the timing of climate shifts decreases substantially if the chronology is constructed based only on a few ^{14}C dated samples. As an example, a ^{14}C sample dated to fall onto the ^{14}C age plateau around 2500 cal BP will result in a calibrated age with a range of more than 300 years (see Figure 1). The difficulties concerning chronological issues and their implications for comparison and alignment of different proxy data have previously been outlined (e.g. Blaauw et al., 2007). Potential limitations of comparing the timing between climate reconstructions due to chronological uncertainties have been pointed out for some records around 2800 cal BP (e.g. Vorren et al., 2012).

Table 3. Compilation of selected records showing a climate change around 2800 cal BP.

Site	Archive	Proxy	Change	~ Timing (cal BP)	Reference
Wiggle-matched records					
Butterburn Flow (England)	Peat	Testate amoebae	Wet shift	2690	Mauquoy et al. (2008)
Carbury Bog (Ireland)	Peat	Macrofossils	To oceanic conditions	2800	van Geel et al. (1998)
Draved Mose (Denmark)	Peat	Macrofossils	Wet shift	2798±15.5	Kilian et al. (1995)
Engbertsdijksveen (The Netherlands) Eng-1: Eng-VII: Eng-XIV: Eng-XV:	Peat	Macrofossils	From warm and dry to wetter and cooler conditions	2812±6.5 2750 2800 2734±12.5 2765±3.4 2735	Kilian et al. (1995) van Geel et al. (1996) Beer and van Geel (2008) Kilian et al. (1995) Kilian et al. (1995) Blaauw et al. (2004)
Fochtelooër Veen (The Netherlands)	Peat	Macrofossils	Wetter conditions	2750	van Geel et al. (1998)
Glen West (Northern Ireland)	Peat	Humification Macrofossils, humification, testate amoebae	From dry to colder/wetter conditions	2690 2700	Plunkett (2006) Swindles et al. (2007) Plunkett and Swindles (2008)
Meerfelder Maar (Germany)	Lake sediments	Varve thickness	To more windy conditions	2759±39	Martin-Puertas et al. (2012)
Pančavská Louka (Czech Republic)	Peat	Micro- and macrofossils	Wetter and cooler conditions	2808	Speranza et al. (2000; 2002)
Undarsmosse (Sweden)	Peat	Micro- and macrofossils Aeolian sand influx	Wetter/cooler conditions More storminess	3035-2540 (2σ) 2765-2524 (2σ)	Paper IV
Valle de Andorra, Tierra del Fuego (Argentina)	Peat	Macrofossils, humification	From dry to wetter conditions	2733 (dry peak) 2706 (wetter)	Chambers et al. (2007)
Peat records					
Abbeyknockmoy (Ireland)	Peat	Macrofossils	Wetter conditions	2750	Barber et al. (2003)
Ben Gorm Moss (Scotland)	Peat	Humification	Wet phase	2850, 2600 (dry 2750)	Langdon and Barber (2005)
Bjørnbreen (Norway)	Peat	Sedimentology	Glacier extent peak	2750	Matthews et al. (2005)
Bolton Fell Moss (England)	Peat	Macrofossils	Wetter conditions	2580	Barber et al. (2003)
Coom Rigg Moss (England)	Peat	Humification	Wet shift	2710	Mauquoy and Barber (1999)
Craigmaud Moss (Scotland)	Peat	Macrofossils, humification	Wet phase	2700	Langdon and Barber (2005)
Dead Island (Northern Ireland)	Peat	Humification, testate amoebae, macrofossils	Wetter/cooler	2700	Swindles et al. (2007)
Dosenmoor (Germany)	Peat	Macrofossils	Cooler/wetter	2750-2600	Barber et al. (2004)
Felecia Moss (England)	Peat	Humification, macrofossils	Wet shift	2660	Mauquoy and Barber (1999)
Ile de la Possession, (Iles Crozet, sub-Antarctica)	Peat	Macrofossils, diatoms, mineral magnetic measurements	Wetter and windier conditions	2800	Van der Putten et al. (2008)
Langlands Moss (Scotland)	Peat	Macrofossils, testate amoebae, humification	Wet phase	2900 (dry 2700)	Langdon and Barber (2005)
Lilla Blacksjömyren (Sweden)	Peat	Macrofossils, testate amoebae	Wetter conditions	2600	Andersson and Schoning, 2010
Longbridge Moss (Scotland)	Peat	Macrofossils, testate amoebae, humification	Wet phase	2900 (dry 2700)	Langdon and Barber (2005)
Mallachie Moss (Scotland)	Peat	Macrofossils, testate amoebae, humification	Wet phase	2800	Langdon and Barber (2005)
Mongan Bog (Ireland)	Peat	Macrofossils	Wetter conditions	2750	Barber et al. (2003)
Nordan's Pond Bog (Canada)	Peat	Macrofossils, humification, testate amoebae	Wet shift	2500	Hughes et al. (2006)
Rystad, Lofoten (Norway)	Peat	Humification	Wet shift	2600	Vorren et al. (2012)
Shirgarton Moss (Scotland)	Peat	Macrofossils, testate amoebae, humification	Wet phase	2750	Langdon and Barber (2005)

Table 3 (continued).

Site	Archive	Proxy	Change	~ Timing (cal BP)	Reference
Peat records					
Slieveanorra (Northern Ireland)	Peat	Humification, testate amoebae, macrofossils	Wetter/cooler	2700	Swindles et al. (2007)
Svanemose (Denmark)	Peat	Macrofossils	Short wet period	2650	Barber et al. (2004)
Talla Moss (Ireland)	Peat	Microfossils, humification	Wet shift	2600	Chambers et al. (1997)
Temple Hill Moss (Scotland)	Peat	Humification, testate amoebae, (macrofossils)	Wet shift Wet phase	2800 (2550-2350 wettest) 2700-2450	Langdon et al. (2003) Langdon and Barber (2005)
Lake records					
Ammersee (Germany)	Lake sediments	Flood layer thickness	Higher mean flood intensity	2800	Czymzik et al. (2013)
Bysjön (Sweden)	Lake sediments	Sedimentology	Higher lake level	2600	Digerfeldt (1988)
Caspian Sea (Russia)	Lake sediments	Lagoonal deposits	Major high-stand	2600	Kroonenberg et al. (2007)
Josedalsbreen area (Norway)	Lake sediments	Sedimentology	Glacier advance, dry conditions	2800	Nesje et al. (2001)
Lac Ossa (Cameroon)	Lake sediments	Microfossils	Dry phase	2800	van Geel et al. (1998)
Lake Pupuke (New Zealand)	Lake sediments	Isotope geochemistry	Colder conditions	2800	Heyng et al. (2014)
Stacked Southern Alps records	Lake sediments	Flood deposits	High flood activity	2700-2300	Wirth et al. (2013)
Zoñar Lake (Spain)	Lake sediments	Sedimentary microfacies, XRF	Humid period	2600–2460 (gradual onset)	Martin-Puertas et al. (2009)
26 lake records (Switzerland, France)	Lake sediments	Sedimentology	Higher lake levels	2750-2350	Magny (2004)
Storm records					
Coastal dune fields (Denmark)	Dunes	Aeolian activity	More windy conditions	2650 2750	Clemmensen et al. (2001) Clemmensen et al. (2009)
Dunes (Northern Ireland)	Dunes	Geomorphology, stratigraphy and sedimentology	Dune instability Sand accumulation	3100-2400	Wilson et al. (2004)
Hyltemossen (Sweden)	Peat	Aeolian sand influx	More storminess	2725 (peak)	Björck and Clemmensen (2004)
Store Mosse (Sweden)	Peat	Aeolian sand influx	More storminess	2600	de Jong and Lagerås (2011)
Other selected records					
Dongge Cave (China)	Speleothems	Isotope geochemistry	Weak Asian monsoon	2700	Wang et al. (2005)
Encierro valley (Chile)	Moraines	Sedimentology	Glacier advance, humid	2760	Grosjean et al. (1998)
Gorner glacier (Switzerland)	Glacier	Dendrochronologically dated advance	Glacier advance	2552	Holzhauser et al. (2005)
Great Aletsch glacier (Switzerland)	Glacier	Dendrochronologically dated advance	Glacier growth	2763-2550	Holzhauser et al. (2005)
Lower Grindelwald glacier (Switzerland)	Glacier	^{14}C dated advance	Glacier advance	2550	Holzhauser et al. (2005)
North Atlantic region	Marine sediments	Ice-rafted debris	More ice drift	2800	Bond et al. (1997)
Pink Panther Cave (USA)	Speleothems	Isotope geochemistry	Wet	2700	Asmerom et al. (2007)

Another uncertainty involves the variability between climate proxy data from different cores. In a study by Blaauw and Mauquoy (2012), attention was given to the proxy variability on a core-to-core basis within the peat bog of Engbertsdijksveen in the Netherlands, for which a climate change around 2800 cal BP has been reported. Based on their analyses of different proxies and cores, the uncertainties of reconstructing the climate based on single core data were illustrated and the need of using multiple cores and climate proxies for a solid interpretation were highlighted. The ambiguous recording and timing of a climate change in different cores from this peat bog for the period around 2800 cal BP was further discussed (Blaauw and Mauquoy, 2012).

Different climate proxies do not necessarily show a similar timing of the changes. This was illustrated by e.g. Langdon et al. (2003) when investigating the peat bog of Temple Hill Moss in south-eastern Scotland. They used analyses of peat humification, testate amoebae and plant macrofossils to reconstruct the climate. The first two of these proxies indicated a wet-shift around 2800 cal BP while the latter indicated a shift to a wetter bog already around 3150 cal BP. Moreover, it is not always straightforward to determine when a change in climate proxy data actually occurred. Gradual changes and fluctuations in the data could complicate the interpretation. Reconstructions of the glacier extent in e.g. Norway, as previously mentioned (section 6.3.2), show a peak at 2750 cal BP. However, the glacier extent gradually increased from a minimum at ca. 3950 cal BP (Matthews et al., 2005) and might therefore be unrelated to the suggested shift towards wetter/cooler conditions around 2800 cal BP. The aeolian sand influx (proxy for storminess variation) record of Undarsmosse (de Jong et al., 2006; Paper IV) can be highlighted as an example for which the determination of the timing of the events could be elusive. The first sand influx peak after 2800 cal BP is dated to a mean age of ca. 2660 cal BP (Paper IV). Nevertheless, it does not necessarily mark the start of a period with increased storminess. Sand influx increases of smaller magnitudes were dated to ca. 3000 cal BP, and interestingly, the period with largest sand influx did not occur until approximately 2400 cal BP.

An additional factor to consider is the spatial distribution of the recorded changes and differences between sites and archives. For example, the mire in the Valle de Andorra, Tierra del Fuego, indicate a shift to wetter conditions around 2710 cal BP (Chambers et al., 2007), while the peat bog on Isla de los Estados, east of mainland Tierra del Fuego, shows a minimum in wetness and wind activity between 3000 and 2500 cal BP (Björck et al., 2012). The effects of climate changes in peat bogs could vary between sites depending on the sensitivity to changes in precipitation and temperature (e.g. Charman et al., 2009) and possibly on different accumulation rates and the mire size (e.g. Plunkett, 2006). Also the location for the study sites, such as in oceanic and continental areas, could be important (e.g. Plunkett and Swindles, 2008). In southern Sweden the peat record of Undarsmosse indicates wetter climate around 2700 cal BP (Paper IV). However, the lake record of Gyltigesjön located within the same province (Figure 2) does not show any distinct changes in e.g. varve thickness, carbon content or magnetic susceptibility around this period (Ning, 2011; Paper II). The varve characteristics were studied using thin-sections of the sediments (Paper II). However, due to the method of freeze-drying of the sediments severe cracks were created (Figure 10) which inhibited detailed studies of the varve thickness and measurements of micro-XRF to determine potential elemental variations. Nevertheless, due to differences between the archives a climate change recorded in the peat sequence may not be visible in the lake sediment record.

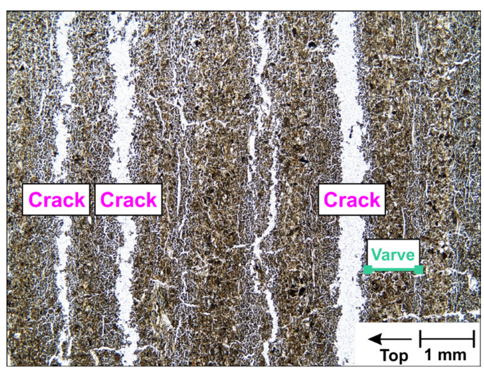

Figure 10. Photograph of a thin-section showing the varved structure of the Gyltigesjön sediments. The problems with both vertical and horizontal cracks are illustrated.

6.3.4 Forcing factors

The climate changes recorded in different parts of the world around 2800 cal BP have primarily been linked to reduced solar activity since the change occurred simultaneously with the increasing atmospheric ^{14}C concentrations (e.g. van Geel et al., 1998; Speranza et al., 2002; Martin-Puertas et al., 2012). Most of the existing hypotheses to explain a Sun-climate connection remain controversial and they involve different feedback mechanisms (see e.g. Rind, 2002). Satellite-based measurements of the total solar irradiance have been conducted since 1978 and show a change of about 0.1% between the maximum and minimum irradiance during the 11-year solar cycle (Fröhlich and Lean, 2004). Therefore, different mechanisms have been proposed to explain a solar-induced climate change in spite of the supposedly small variations in total solar irradiance (see e.g. Gray et al., 2010). Two hypotheses have been presented to explain the Sun-climate connection around 2800 cal BP (van Geel et al., 1998; van Geel and Renssen, 1998; van Geel et al., 2000). The first involves a change in the solar UV radiation influencing the stratospheric ozone production (Haigh, 1994; Haigh, 1996; Shindell et al., 1999). This hypothesis suggests that decreased solar UV radiation lead to decreased production of stratospheric ozone and thus lower stratospheric temperatures which in turn influence the atmospheric circulation patterns (e.g. van Geel et al., 1998). The second hypothesis considers the influence of galactic cosmic rays on cloud formation (Friis-Christensen and Lassen, 1991; Svensmark and Friis-Christensen, 1997), with increased galactic cosmic rays leading to increased cloud cover resulting in cooling and increased precipitation (e.g. van Geel et al., 1998).

In addition to solar forcing, changes in ocean circulation have been suggested to contribute to the climate change around 2800 cal BP (e.g. van Geel et al., 1998; Renssen et al., 2006; Plunkett and Swindles, 2008). The thermohaline circulation in the North Atlantic leads to a northward heat transport (e.g. Stuiver and Braziunas, 1993), and a disruption of the deep water formation responsible for this circulation (by e.g. increased fresh-water influx) can lead to colder climate in the northern hemisphere, which has been suggested to explain cooling episodes during the last deglaciation and also the wide-spread cooling event recorded around 8200 cal BP (reviewed by e.g. Rohling and Pälike, 2005). There are also indications for reduced oceanic circulation in the North Atlantic around 2800 cal BP (Oppo et al., 2003; Hall et al., 2004), which could have reinforced the cooling (van Geel and Renssen, 1998). Climate variability around 2800 cal BP has been attributed to oceanic influences (Plunkett, 2006; Swindles et al., 2007; Plunkett and Swindles, 2008) and its effect could possibly be amplified by decreased solar activity (Renssen et al., 2006). Complex couplings between the atmospheric-oceanic-terrestrial systems could therefore play an important role for the climatic development (e.g. Renssen et al., 2006). Furthermore, another possible contributor for locally-regionally variable climate is the North Atlantic Oscillation, which is the effect of air pressure differences between the Azores high and Icelandic low, which influences winter climate and weather variability in Europe (e.g. Wanner et al., 2001).

A geomagnetic field-climate connection has, in addition to solar forcing, been hypothesised, also with some focus on the period around 2700 cal BP (e.g. Dergachev et al., 2004; Gallet et al., 2005; Courtillot et al., 2007). For example, a geomagnetic field excursion "Sterno-Etrussia" has been suggested to occur simultaneously with the declination feature "f" associated with a reduction of the geomagnetic field intensity, which in turn could influence the increased ^{14}C production and thereby the climate (Dergachev et al., 2004). However, the reduction in geomagnetic field intensity around this period has been questioned since absolute palaeointensity data indicate that the strongest geomagnetic dipole moment of the last 50 000 years occurred around this period (Knudsen et al., 2008). If the changes in the geomagnetic field would have been the main cause for the high ^{14}C production rate at 2700 cal BP (see Figure 8) a major decline of the geomagnetic dipole field must have occurred, but this is not supported by available palaeomagnetic data (Snowball and Muscheler 2007). Moreover, the results of this study (Figure 8) does not support a significant geomagnetic field contribution for the

^{14}C production rate peak at 2700 cal BP and the increased ^{14}C production rate is instead attributed to decreased solar activity.

7. Conclusions

The following main conclusions have been reached based on the discussion and the results in the papers appended to the thesis:

- The ^{14}C wiggle-match dating technique can be applied to accurately date annually laminated (varved) lake sediments and peat deposits. This dating technique can be used to achieve robust chronologies using bulk sediments and possibly also to construct accurate chronologies for sediments that are not varved.

- The ^{14}C wiggle-match dating technique can be used to identify and evaluate the presence and effect of old reworked carbon in lake sediments in cases when this effect is relatively small and constant. This dating technique can further be applied to validate varve chronologies.

- Accurate and precise chronologies have been constructed for the lake sediment sequences of Gyltigesjön in south-west Sweden and Kälksjön in west-central Sweden around ca. 3000-2000 cal BP and the age models have uncertainties of only ±30 and ±20 years (95.4% probability range), respectively.

- The lake sediments of Gyltigesjön are varved for the last ca. 8000 years and a high-quality palaeomagnetic record has been obtained from the sediments covering the last ca. 6400 years

- The Gyltigesjön and Kälksjön palaeomagnetic records both show evidence of alignment of magnetic particles to the geomagnetic field after deposition and the geomagnetic signal is locked-in (PDRM lock-in depth/delay) at relatively large depths. This has implications for the interpretations of palaeomagnetic records since the sediment age will then not represent the true age of the geomagnetic signal.

- The distinct increase of atmospheric ^{14}C concentration at 2800 cal BP reflects a minimum in solar activity. However, changes in geomagnetic field intensity can explain the longer-term structure of radionuclide production rates around this period.

- The distinct change to wetter, cooler and windier climate as reconstructed in different parts of the world around 2800 cal BP could have occurred as a result of decreased solar activity. Spatial and temporal differences of climate changes around that time could potentially be attributed to e.g. oceanic influences. However, in many cases the dating accuracy and uncertainties in the interpretation of climate proxy records restrict robust conclusions of the temporal and spatial distributions of climate changes and its forcing factors.

- A change towards wetter and windier climate in southern Sweden recorded in the peat sequence of Undarsmosse around 2700 cal BP is most likely related to a shift in the larger-scale atmospheric circulation, which potentially can be explained by the decreased solar activity during this period.

8. Future prospects

The chronological control of the change to the wetter conditions and increased storminess recorded in the Undarsmosse peat sequence in southern Sweden around 2700 cal BP is restricted (see Paper IV) due to a drastic change in peat accumulation (possible hiatus) around the same period. In order improve age constraints for the observed changes in southern Sweden other records showing potential climatic changes around this period can be dated with the ^{14}C wiggle-match method. For example, the Store Mosse record located in the same province as Undarsmosse and Gyltigesjön, shows increased aeolian sand influx at around 2600 cal BP (de Jong and Lagerås, 2011). The difference in timing might be a result of chronological uncertainties. By applying the ^{14}C wiggle-match dating technique on the Store Mosse peat sequence the timing of storminess events could be further constrained. Moreover, assessment of changes in local bog surface wetness using plant macrofossil analysis and testate amoebae analysis in the same peat sequence could improve our understanding of atmospheric changes in a more regional context.

As previously discussed (see section 6.3.3), the proxy methods applied to the Gyltigesjön sediment sequence do not indicate a clear climatic change around 2800 cal BP. However, investigations of additional environmental proxies could provide further insights into possible climatic changes during this period. For example, geochemical methods such as XRF core scanning (elemental composition) in combination with the characterisation of different components in the lake sediments (e.g. biogenic silica content) could be performed to obtain information on changes in the productivity within the lake system versus input from the catchment area.

Furthermore, the ^{14}C wiggle-match dating technique can be applied to constrain the timing of other periods showing rapid climate changes. This technique is in particular useful for periods with pronounced variations in the atmospheric ^{14}C concentration as seen in the ^{14}C calibration curve. The dating technique is therefore especially helpful in studies of the potential connection between changes in climate and solar forcing, since such solar-induced changes in the cosmic ray flux and possible climate changes are recorded in the same core, i.e. leaving little uncertainty in the relative timing of solar and climate changes. The ^{14}C wiggle-match dating technique can also be applied to other lake sediment sequences in order to improve the chronology of geomagnetic field variations, and to validate varve chronologies. Detailed studies of the post-depositional remanent magnetisation lock-in depth are desirable for improving our understanding of past geomagnetic field variations. Robust reconstructions of geomagnetic field variations allow for further investigations of its influence on cosmogenic radionuclide production rates. In addition, this could help to improve solar activity reconstructions based on cosmogenic radionuclides.

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Svensk sammanfattning

Klimatet har varit relativt stabilt under den nuvarande interglaciala epoken (Holocen) som inleddes för ungefär 11 700 år sedan. Genom klimatrekonstruktioner från olika geologiska arkiv såsom iskärnor, sjösediment och torvmossar har det ändå påvisats att snabba förändringar i klimatet har inträffat under denna epok. En sådan tidsperiod inträffade för omkring 2800 år sedan och den är intressant ur flera olika perspektiv. Allt fler studier har rapporterat om en förändring till kallare, blötare och blåsigare klimat omkring denna period. Detta har främst rapporterats från områden i Europa men studier från andra delar av världen indikerar på liknande förhållanden. Omkring samma period ökade även den atmosfäriska koncentrationen av kol-14, vilket har kopplats ihop med en minskning av solaktiviteten. Eftersom klimatförändringen inträffade när solaktiviten minskade har hypoteser lagts fram om att klimatet ändrades till följd av låg solaktivitet. Samtidigt har studier även visat på markanta variationer i jordens magnetfält omkring 3000-2000 år sedan.

Kosmogena radionuklider (som t ex kol-14) bildas genom reaktioner mellan galaktisk kosmisk strålning och atomer i atmosfären. Den inkommande galaktiska kosmiska strålningen regleras i sin tur av solaktiviteten och variationer i jordens magnetfält. En låg solaktivitet och/eller en låg styrka hos det jordmagnetiska fältet möjliggör en ökad produktion av kosmogena radionuklider och vice versa. Variationer i kol-14 kan därför användas för att rekonstruera variationer i solaktivitet och jordens magnetfält. Den atmosfäriska variationen av kol-14 är känd genom en kalibreringskurva som är baserad på kol-14-mätningar av trädringar med en bestämd ålder. Den nuvarande absoluta daterade trädringsbaserade kalibreringskurva sträcker sig tillbaka till omkring 12 550 år sedan.

För att kunna undersöka utbredningen av klimatförändringar och vilka faktorer som styr dessa förändringar, till exempel en möjlig påverkan av solaktivitet, är det viktigt att datera klimatförändringar med hög tidsupplösning. Väldaterade förändringar av jordens magnetfält kan hjälpa oss att förstå dessa variationer och dess inverkan på till exempel produktionen av kol-14 på olika tidsskalor, och således kan påverkan från jordens magnetfält och solaktiviten urskiljas. Kronologier med hög tidsupplösning kan uppnås genom dateringar med kol-14-metoden. Dateringar av endast ett fåtal prover kan medföra stora åldersosäkerheter beroende på strukturen på kalibreringskurvan för kol-14. Osäkerheter på omkring 350 år kan till exempel fås vid kalibrering av ett prov daterat till 2500±50 kol-14-år. För att minska åldersosäkerheten kan flertalet prover dateras för att matcha strukturen på kalibreringskurvan, en så kallad ”wiggle-match”.

Syftet med denna avhandling var att förbättra tidsupplösningen för rekonstruktioner av förändringar i klimatet och jordens magnetfält med

fokus på perioden omkring 3000-2000 år sedan genom att datera flertalet prover med en kol-14 wiggle-match-metod. De geologiska arkiv som har använts är sjösediment från Gyltigesjön i Halland och från Kälksjön i Värmland. Båda dessa sjöar utmärker sig genom att de har årslaminerade (varviga) sediment vilket möjliggör högupplösta kronologier. Även en torvmosse i Halland, Undarsmosse, har studerats då en tidigare studie av denna har indikerat på en ökad stormfrekvens och blötare klimat med start omkring 2800 år före nutid (nutid refererar till år 1950 i kol-14-sammanhang).

Syftet med den första artikeln var att undersöka noggrannheten på en åldersmodell som konstrueras med kol-14 wiggle-match-metoden vid användandet av bulksediment för perioden omkring 3000-2000 år sedan. Vanligtvis dateras företrädelsevis prover av terrestra makrofossiler eftersom de antas reflektera den atmosfäriska halten av kol-14 vid depositionen. Förekomsten av makrofossiler kan dock vara begränsad, alternativt att de förekommer i för små mängder för att kunna dateras. Att datera bulksediment kan vara problematiskt då provet består av en blandning av olika organiska komponenter som inte nödvändigtvis reflekterar den atmosfäriska kol-14-halten. Detta innebär att provet kan vara ”kontaminerat” av gammalt kol, en så kallad kol-14 reservoareffekt, vilket ger upphov till en felaktig ålder vid datering. Med detta i åtanke tillämpades wiggle-match-metoden på bulksediment från Gyltigesjön. En relativ tidsskala mellan varje sedimentprov kunde konstrueras genom att räkna årslamineringarna mellan proven som kol-14-daterades. Genom att använda kalibreringsprogram för kol-14-dateringar och systematiskt subtrahera potentiella reservoaråldrar från kol-14-åldern kunde denna effekt bestämmas. Genom att datera terrestra makrofossiler kunde den uppskattade reservoaråldern även verifieras, och en åldersmodell producerades med en osäkerhet på endast ±30 år. Resultaten i artikeln visar att kol-14 wiggle-match-metoden kan tillämpas för att konstruera kronologier med hög tidsupplösning, även vid datering av endast bulksediment.

I den andra artikeln undersöktes det palaeomagnetiska arkivet bevarat i Gyltigesjön, vilket sträcker sig tillbaka till ungefär 6400 år före nutid. Med hjälp av den högupplösta kronologin för perioden omkring 3000-2000 år sedan tillsammans med ytterligare kol-14-dateringar konstruerades en kronologi för denna period. På väg mot sjöbotten riktar de magnetiska mineralerna in sig mot jordens magnetfält och denna signal kan bevaras i sedimenten. De magnetiska mineralerna kan härstamma från berggrund i avrinningsområdet men även bildas av magnetotaktiska bakterier som använder dessa för orientering. I denna artikel visades det att den magnetiska signalen troligtvis utgörs av magnetit som kan vara producerat av magnetotaktiska bakterier. Tidigare studier har visat att de magnetiska partiklarna kan rikta in sig mot jordens magnetfält även efter depositionen, och att detta kan fortskrida ända till de magnetiska partiklarna blir fastlåsta genom kompaktion. Detta innebär att åldern på sedimenten och den riktiga åldern för den magnetiska signalen inte överensstämmer. Existensen och utbredningen av denna effekt har varit omdiskuterad i flera årtionden med tvetydiga resultat. Syftet med artikeln var att undersöka om denna effekt förekommer i Gyltigesjön. Genom att jämföra palaeomagnetisk data från Gyltigesjön med referenskurvor sammansatta från andra sjöar i Sverige och Finland kunde existensen av denna effekt påvisas. Förekomsten av en sådan effekt måste tas i beaktande vid analys av palaeomagnetisk data från sedimentarkiv.

I den tredje artikeln tillämpades kol-14 wiggle-match-metoden på sjösediment från Kälksjön omkring 3000-2000 år före nutid för att testa och förbättra en varvkronologi som tidigare konstruerats. Ett liknande tillvägagångssätt som användes i den första artikeln upprepades för att konstruera en motsvarande kronologi. Den producerade åldersmodellen har en osäkerhet på endast ±20 år. Palaeomagnetisk data från Kälksjön jämfördes med motsvarande data från Gyltigesjön och resultatet visade på jämförbara åldrar för de jordmagnetiska variationerna. Dessa resultat jämfördes sedan med arkeomagnetisk data som däremot indikerar yngre åldrar för motsvarande variationer i magnetfältet, vilket antyder att signalen i sjösedimenten låses in efter depositionen. Genom modellering av olika funktioner för denna effekt visades det att magnetiska signalen låses in relativt djupt ned i sedimentsekvensen.

Den fjärde artikeln fokuserade på den abrupta klimatförändringen omkring 2800 år före nutid och dess potentiella koppling till solaktivitet. En ny åldersmodell konstruerades för Undarsmosse med hjälp av flertalet kol-14-dateringar av noggrant utvalda makrofossiler. En makrofossilanalys utfördes även för att undersöka förändringar i den lokala vegetationen. Resultatet visade på en vegetationsförändring daterat till omkring 2700 år före nutid. Denna förändring åtföljdes av ett ökat sandinflöde som tyder på ökad stormaktivitet. På grund av en låg ackumulation av torv, alternativt ingen alls, omkring denna period är åldersosäkerheten relativt stor (medel på ca. ±90 år). En minskad eller avsaknad ackumulation av torv kan ha ett samband med bränder i området då ett dominerande lager av träkol återfanns i ett prov daterat till denna period. Inom felmarginalen för åldersmodellen kan förändringen till ett blötare klimat och ökad stormaktivitet kopplas ihop med klimatförändringarna som har rapporterats från många områden i Europa. Resultaten i artikel visar på att en förändring inträffade i den atmosfäriska cirkulationen omkring 2700 år före nutid, vilket kan bero på minskad solaktivitet.

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