Synchronizing Holocene lacustrine and marine sediment records using paleomagnetic secular variation

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ABSTRACT

High sediment accumulation rates in lacustrine and shallow-marine archives around Iceland offer the potential to compare high-resolution paleoclimatic reconstructions from terrestrial and marine archives; however, direct comparisons are hampered by difficulties in stratigraphic correlation and in deriving accurate age models for lacustrine archives. Icelandic paleomagnetic secular variation (PSV) has the potential to synchronize these records. Here we compare Holocene PSV from a well-dated marine core on the North Iceland shelf with PSV from two lacustrine archives with comparable sediment-accumulation rates, HVT03–1A, a glacier-dominated lake, and HAK03–1B, in a nonglacial catchment. Geochemically characterized tephra layers combined with unique high-amplitude structures in the PSV records provide secure tie points every ~200 yr. Once the records are synchronized, the chronology from the marine core can be reliably transferred to the two lacustrine records. The resultant lacustrine age models reveal large changes in sediment accumulation rate at submillennial scales that escape detection in conventional age models with independent dates every ~1 k.y. Sediment accumulation rate changes occur at similar times in both lakes, despite very different catchment properties. Low and regular accumulation rates during the Holocene thermal maximum suggest regionally stable, vegetated catchments, followed by a stepped landscape destabilization during the transition into neoglaciation, culminating with maximum sedimentation rates during the Little Ice Age. PSV allows synchronization between multiple records from nearby marine and lacustrine archives, providing improved age models and a means of assessing leads and lags between marine and terrestrial environments.

INTRODUCTION

The dominant control on Holocene climate evolution involves insolation change controlled by Earth's irregular orbit about the sun, and changes in ocean-atmosphere circulation that redistribute heat and moisture. Paleoclimate records from terrestrial and nearby marine archives offer the potential to separate the influences of these two variables, and to evaluate leads and lags between climatic events recognized in each archive. Deciphering that comparison requires secure stratigraphic correlations.

Sedimentary archives, from which paleoclimate records are derived, often cannot be stratigraphically correlated or independently dated at sufficient resolution. High-latitude Holocene lake sediments frequently present additional chronological challenges due to a high flux of soil-derived aged carbon, reworking of terrestrial macrofossils, low rates of primary productivity, and in some cases a variable offset in the dissolved inorganic carbon pool linked to the dissolution of limestone (hard-water effect; Wolfe et al., 2004). Radiocarbon ages from independently dated levels may reveal discrepancies of 10^3 to 10^4 yr (e.g., Wolfe et al., 2004; Geirsdóttir et al., 2009). In marine environments, radiocarbon dating of carbonate exoskeletons may carry additional uncertainties due to poorly constrained reservoir corrections (ΔR).

To circumvent temporal uncertainties when comparing marine and terrestrial climate records, we exploit the unique signatures imparted by secular variation of Earth's magnetic field to synchronize sedimentary records from Icelandic marine and terrestrial archives. Secular changes of the inclination and declination of Earth's magnetic field at the time of sediment deposition or shortly after can be recorded in lacustrine and marine sediments. Continuous sediment cores recovered from these archives can, under favorable conditions, allow virtual geomagnetic pole (VGP) paths to be reconstructed (Fig. 1). Paleomagnetic studies on lavas covering the past 5 m.y. show that Iceland is characterized by elevated VGP dispersion relative to its latitude and therefore higher amplitude paleomagnetic secular variation (PSV) (Kristjansson and Jonsson, 2007). Plagued by dating difficulties and few regional records for comparison, prior PSV studies from Icelandic lake sediments (Thompson and Turner, 1985) and predictions from continuous spherical harmonic models (e.g., Korte et al., 2011) show little evidence for amplified PSV. In contrast, our new results are consistent with lava data (Kristjansson and Jonsson, 2007) showing that elevated secular variation (Fig. 1), including features that can be considered excursional, as defined by Barbetti and McElhinny (1972), characterize the Holocene paleo-geomagnetic record of Iceland. Such high-amplitude PSV is not observed at similar latitudes from Europe (Snowball et al., 2007; Haltia-Hovi et al., 2010) or North America (Barletta et al., 2008), and is not found in global VGP reconstructions (Nilsson et al., 2011), illustrating that Iceland provides a remarkable location to study the paleogeomagnetic field (Fig. 1). Amplified PSV, along with high sediment accumulation rates from magnetite-rich basaltic sources, result in exceptional magnetostratigraphic opportunities.

Secure land-sea correlations offer potential insights into the underlying mechanisms behind climate variability and abrupt climate change. Reliable synchronization is complicated when each record has independent age control with independent dating uncertainties. Prior work from marine records on the Icelandic and Greenlandic margins demonstrates that PSV synchronization can improve correlation between radiocarbon-dated paleoclimate records (Stoner et al., 2007). Previous attempts using the PSV record for land-sea correlations have, however, been limited by low sediment accumulation rates, bioturbation, and low-quality magnetization components (e.g., Vigliotti, 2006). PSV data from lacustrine (Stockhausen, 1998) and marine (Kotilainen et al., 2000; Ledu et al., 2010) archives have been correlated to PSV models such as CALS10k.1b (Korte et al., 2011) or to PSV master curves (Snowball et al., 2007; Haltia-Hovi et al., 2010), but direct correlations of terrestrial and marine high-resolution climate proxy records based on PSV synchronization were not previously accomplished. In this study PSV is used as a correlation tool to independently synchronize a well-dated high-resolution marine record with two nearby equally high-resolution, but less precisely dated, lacustrine sediment cores.

MATERIAL AND METHODS

PSV records were reconstructed from sediment cores recovered in 2003 with the GLAD200 hydraulic piston coring system (http://www.dosecc.org/) from two Icelandic lakes. Haukadalsvatn is a low-elevation lake (3.3 km², 32 m above sea level [asl], 42 m water depth) on the west coast of Iceland (Fig. 1) within an unglaciated catchment of Tertiary basalt. Core HAK03–1B consists of 18 m of lacustrine sediment spanning

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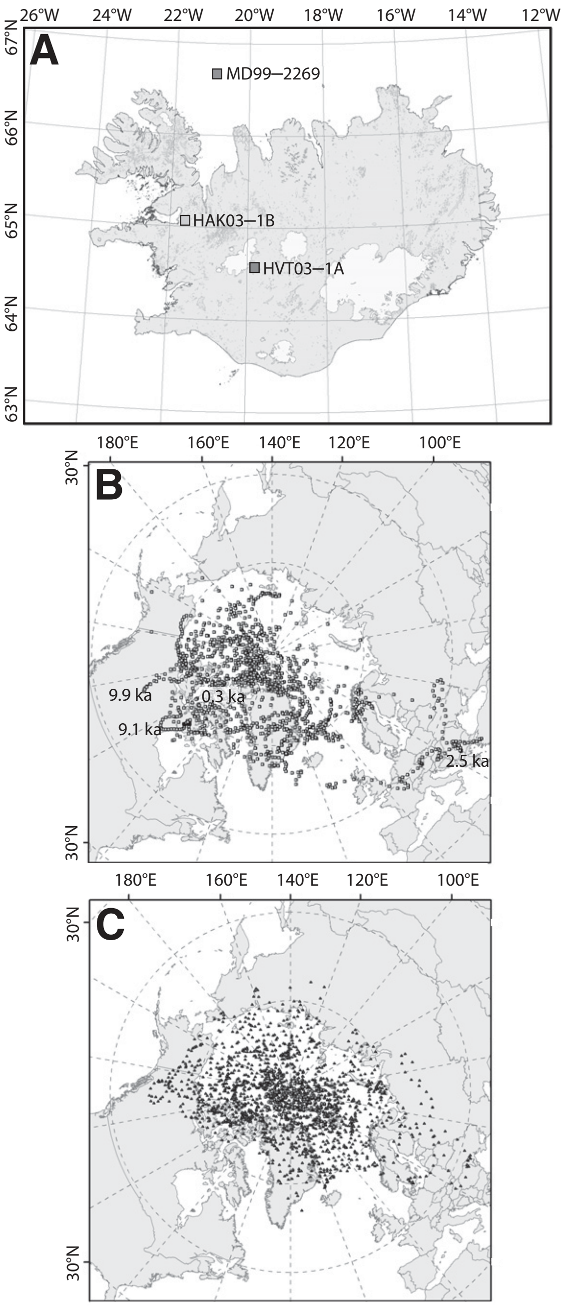

Figure 1. A: Location map of study sites in Iceland. Three core locations are indicated. B: Virtual geomagnetic pole (VGP) transformation of paleomagnetic data from Haukadalsvatn, Iceland (squares) from 0.3 to 10 ka. C: VGP transformation of MD99–2269 data (triangles) from 0.6 to 10 ka, and global VGP reconstructions of Nilsson et al. (2011) for past 9 k.y. (circles). Greater dispersion in Icelandic VGP reconstructions suggests that central North Atlantic region is particularly well suited to paleomagnetic secular variation synchronization.

the past 10 k.y. (Geirsdóttir et al., 2009). Hvítárvatn is a large proglacial lake (29 km^2, 420 m asl, 80 m water depth) located in the central highlands of Iceland. The lake is located within the neovolcanic zone where the surrounding bedrock is Pleistocene basalt and hyaloclastite with slightly different mineral composition than in the Haukadalsvatn area. Core HVT03–1A provides 16 m of continuous sediment deposition, beginning ca. 10.4 ka (Larsen et al., 2012). The grain size distribution of Hvítárvatn sediments is slightly more heterogeneous compared to Haukadalsvatn sediments. Primary productivity is relatively low in both lakes, with total organic carbon <~2% and biogenic silica <~18% (Geirsdóttir et al., 2009). Low organic carbon leads to negligible diagenetic alteration of the primary magnetic signal.

We utilize the PSV record obtained from marine core MD99–2269 from the shelf north of Iceland (Fig. 1; Stoner et al., 2007) as our reference. The MD99–2269 age model is based on 44 radiocarbon dates derived from 2 different cores that were synchronized by PSV, and chemically diagnostic tephras (Stoner et al., 2007). The accuracy of the MD99–2269 chronology was subsequently improved by calculating the evolution of the ΔR correction over time for the North Iceland Shelf (Kristjánsdóttir et al., 2007).

Reconstructing PSV from sediment cores relies on the recovery of undisturbed sediments in their original orientation. Horizontal laminations apparent visually and in X-ray radiography in both lake cores (except for the uppermost 1.5 m, disturbed by degassing and dewatering) indicate that the corer penetrated vertically, and recovered undisturbed sediment. The u-channels (2 × 2 cm square tubes) were filled with sediment by insertion into the pristine center of split core sections, avoiding any disturbed sediment at the margins. Paleomagnetic measurements of the u-channel samples were made using a 2G Enterprises superconducting rock magnetometer at the University of Florida (United States). Measurements were made at a 1 cm interval, although the width at half-height of the Gaussian-shaped response function (~4.5 cm) is such that each 1-cm-spaced measurement reflects smoothing of the signal over several centimeters (Weeks et al., 1993). The natural remanent magnetization (NRM) of the u-channel samples were measured before and after alternating field (AF) demagnetization at intervals of 5–10 mT, up to a peak field of 60 mT (Fig. DR1 in the GSA Data Repository[1]). Component magnetization directions for u-channel NRM data were calculated at 1 cm spacing from the 20–60 mT AF demagnetization interval using the standard principal component method. These component directions constitute the characteristic remanent magnetization (ChRM) directions, and the maximum angular deviation (MAD) values provide a measure of the precision of the ChRM and an indication of the magnetization quality. The sediments recovered from both Haukadalsvatn and Hvítárvatn meet the necessary criteria of quality of the component magnetization, coercivity, magnetic grain size, and homogeneity to produce reliable PSV records (Stoner and St-Onge, 2007). The sediment fill in both lakes preserves a strong, stable, single-component NRM. Component declinations and inclinations are well defined, as indicated by low MAD values, and the records can be correlated among the three cores, implying that they reflect PSV (Fig. DR1).

RESULTS

Correlating the lacustrine PSV records with our marine reference core relies on distinctive features in the PSV signal; additional constraints are provided by tie points derived from geochemically characterized tephra layers (Fig. 2). Tephra layers in marine core MD99–2269 were characterized by Kristjánsdóttir et al. (2007). The correlative tephra layers in the lake sediment cores were geochemically characterized (Jóhannsdóttir, 2006; T. Thordarson, 2012, personal commun.) (Table DR1 in the Data Repository). To obtain the most robust correlations we used the AnalySeries software (Paillard et al., 1996), and based the correlations on major declination features, tephras, and reconstructed inclination and intensity data in the depth domain (Figs. DR1 and DR2). This procedure provided 54 tie points in the HAK03–1B record, distributed unequally throughout the ~18-m-long core (Fig. 2). Four of the tie points are based on tephra (solid lines in Fig. 2). This density of tie points provides ~1 point, on

[1]GSA Data Repository item 2013148, Figure DR1 (down core component magnetization directions and the maximum angular deviation values for the lake cores), Figure DR2 (all tephra layers found in the cores), and Table DR1 (references for used tephra markers), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

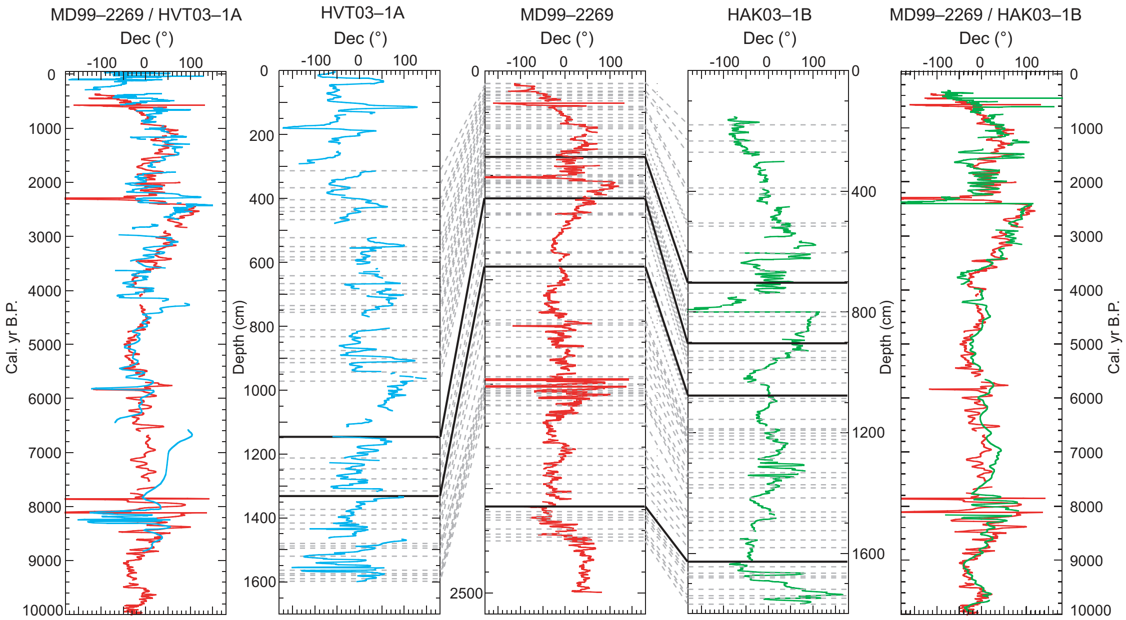

Figure 2. Magnetic declination records and tie points from our three sediment cores in their depth domain and on synchronized time scales (Cal. yr B.P.—calibrated years before present). Middle panel is marine reference curve (MD99–2269; Stoner et al., 2007). HVT03–1A declination record is correlated to MD99–2269 record by 47 tie points (dashed lines; solid lines indicate correlative tephras). Two synchronized records are superimposed in time domain (far left panel). HAK03–1B declination record is similarly correlated to MD99–2269 record through 54 tie points and 4 unique tephra. Two synchronized records are plotted in time domain in far right panel.

average, for every ~200 yr in the HAK03–1B record (ranging from 30 to 630 yr). In the HVT03–1A core, 47 points tie the 16-m-long core to the MD99–2269 PSV record; two were based on tephra (Fig. 2). This density of tie points provides ~1 point for every ~150 yr over the 10 k.y. interval (ranging from 2 to 510 yr). The correlation coefficient between declination curves in the marine reference core and HAK03–1B is ~0.6; for HVT03–1A, it is ~0.5. Once a robust synchronization between the lacustrine and marine cores is established in the depth domain, it is possible to transfer the marine core age model to the two lacustrine cores (Fig. 3).

The advantage of the PSV- and tephra-synchronized chronologies over the tephra-constrained chronologies alone is best shown by a comparison of the sedimentation rates calculated without use of PSV (conventional age model) and after use of PSV (Fig. 3). For both lakes, the PSV-derived age model captures centennial-scale sedimentation rate variability that is not evident from the conventional age model. For HAK03–1B, the largest discrepancies between the PSV-derived and conventional age models occur between 8 and 10 ka, where offsets are as large as 600 yr (Fig. 3). The 8 intervals of relatively high sediment flux into the lake, occurring at 10–9.5 ka, 8.4–7.8 ka, 4.3–4 ka, 3.8–3.6 ka, 2.5–2.2 ka, 1.8–1.6, 1.3–1 ka, and 0.8–0.4 ka, that are most apparent in the PSV-derived age model are interpreted to reflect periods of sudden vegetation die-back and landscape instability, allowing mobilization of poorly consolidated soil materials (e.g., Geirsdóttir et al., 2009).

The conventional HVT03–1A age model was based on a linear interpolation between the Saksunarvatn (10.3 ka) and H5 (ca. 7 ka) tephra markers (Fig. 3; Fig. DR2). However, the inherent assumption of a smoothly changing sedimentation rate is contradicted by the PSV-derived age models. The PSV tie points between these two tephras indicate

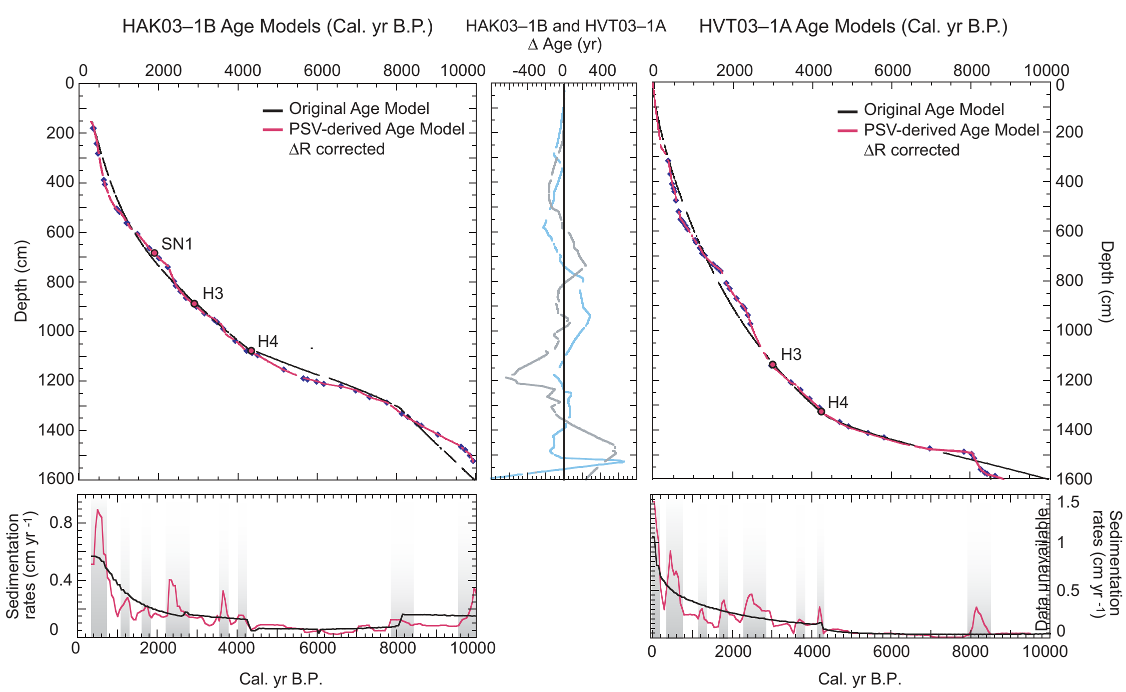

Figure 3. Age models for HAK03–1B and HVT03–1A based on paleomagnetic secular variation (PSV) correlations to core MD99–2269 compared to age models derived solely from independently dated tephra layers (Sn1, H3, and H4; Cal. yr B.P.—calibrated years before present). Middle panel shows difference in years between two age models (Δ Age) for HAK03–1B (gray) and HVT03–1A (blue). Two bottom panels show changes in sedimentation rates (cm yr^{-1}) calculated at 50 yr intervals for both cores using their PSV-derived age models. Eight intervals of increased sedimentation rate (gray bars) occur at similar times in both cores.

significant short-term variability in sedimentation rates. Between 8.5 and 8.2 ka, the sedimentation rate increases from 0.05 to 0.35 cm yr^{-1}, dropping rapidly again after 8.1 ka to below 0.05 cm yr^{-1} and remaining relatively low until 4.3 ka. This brief but dramatic increase in sedimentation rate is supported by similarly strong increases in magnetic susceptibility and sediment density over the same depth interval (Larsen et al., 2012). The sedimentation rate increases after 4.3 ka, and remains relatively high until present, suggesting that a substantial ice cap has been actively eroding in the catchment since 4.3 ka. Sedimentation rate changes after 3 ka are based on systematic changes in varve thickness, demonstrating that maximum sedimentation rates occurred during the Little Ice Age, when Langjökull was larger than at any time since at least 8 ka (Larsen et al., 2012).

The Haukadalsvatn and Hvítárvatn PSV-derived age models capture a high level of centennial-scale variability in sedimentation rates that was not evident in the conventional tephra-based age models. The PSV-derived age models imply that large-scale (5–10× background) changes in sedimentation rates occurred within a century in both the Haukadalsvatn and Hvítárvatn sediment records. The similarity in timing, direction, and magnitude of the sedimentation rate changes in both lakes with and without an ice cap suggests that changes in sedimentation rates reflect regional climate change recorded in Iceland, and emphasize the risk of relying solely on millennially spaced tie points.

CONCLUSIONS

The PSV records preserved in sediments from Haukadalsvatn and Hvítárvatn provide reliable records of geomagnetic field variations over the past 10 k.y., particularly for Haukadalsvatn, due to greater homogeneity of its sediment fill. Our results demonstrate the potential of PSV reconstructions to synchronize sediment cores from nearby marine and terrestrial archives and to greatly improve geochronologies for difficult to date sediment records. The new PSV-derived age models reveal nonlinear changes in sedimentation rate that were not resolvable from the conventional tephra-based age models. In Iceland, and presumably other settings, age models based on millennial-scale control points may be insufficient to capture important variations in the flux of sediment into the lake, and key climate perturbations may be missed or substantially underrepresented. PSV records offer the potential for high-resolution regional synchronization between different archives, including land and sea, from which an assessment of leads and lags between primary insolation forcing and changes in ocean-atmosphere circulation can be derived.

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