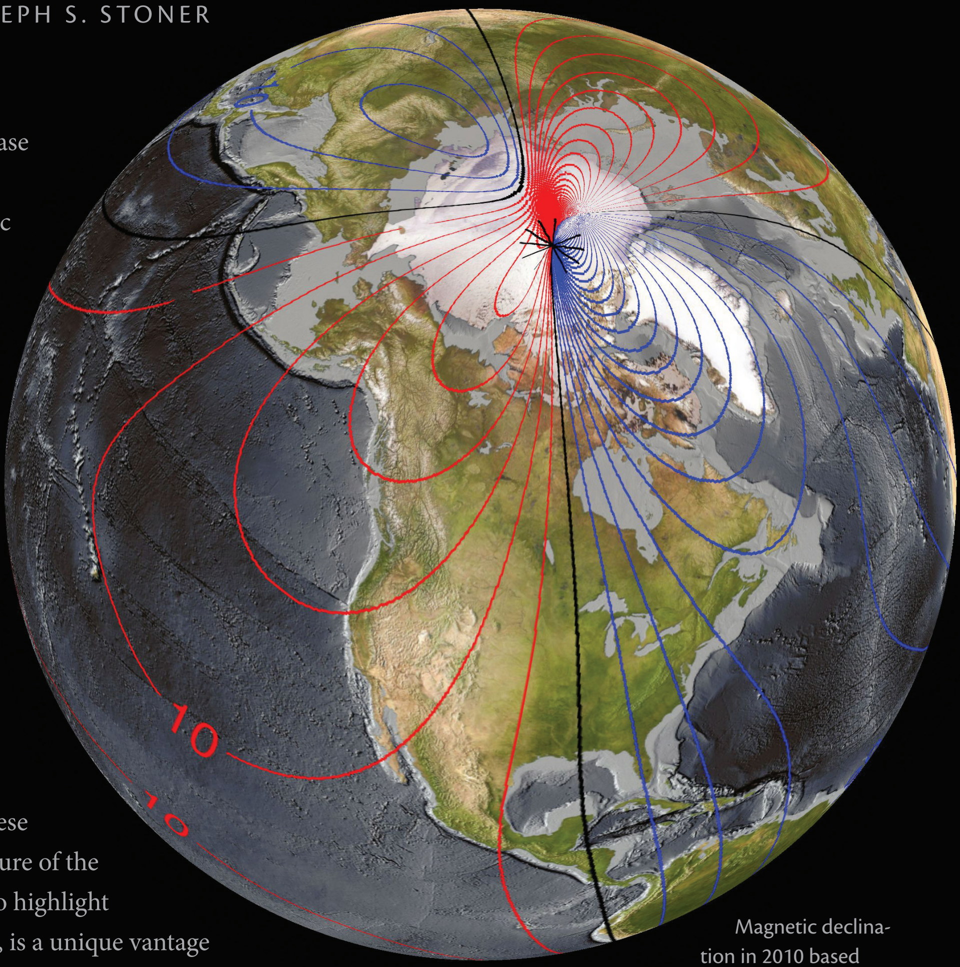
PALEOMAGNETISM NEAR THE NORTH MAGNETIC POLE

A Unique Vantage Point for Understanding the Dynamics of the Geomagnetic Field and Its Secular Variations

BY GUILLAUME ST-ONGE AND JOSEPH S. STONER

ABSTRACT. Along with the dramatic decrease in global geomagnetic field intensity, recent observations demonstrate that the geomagnetic field in the Arctic has dramatically changed over the last century. This change is best illustrated by the recent migration of the North Magnetic Pole (which has been in the Canadian Arctic for the last 400 years) into the Arctic Ocean. Because historical records are short, paleomagnetic studies are needed to put these recent Arctic geomagnetic changes into a proper temporal context. This paper presents an overview of Arctic geomagnetism, paleomagnetism, and recent efforts to move our understanding forward by looking at recent or emerging high-resolution Holocene records from the Low and the High Arctic. These paleomagnetic records attest to the unique nature of the geomagnetic field in the High Arctic. They also highlight how the Arctic, and especially the High Arctic, is a unique vantage point for studying geodynamo processes associated with the tangent cylinder model of convective flow within Earth's core that could lead to differences in the behavior of the geomagnetic field observed at Earth's surface, and possible relationships to paleomagnetic secular variations at mid-latitudes.



Magnetic declination in 2010 based on the tenth generation International Geomagnetic Reference Field. *Source: National Oceanic and Atmospheric Administration*

INTRODUCTION

Like most Arctic phenomena, the geomagnetic field in this region is both poorly understood and critically important to the global system. Historical observations document dramatic behavior: for example, the North Magnetic Pole (NMP; the location where inclination is 90°) has migrated more than 1,700 km over the last century (e.g., Olsen and Mandea, 2007). Placed in the context of the present decline in intensity of the dipole field (Gubbins et al., 2006), such behavior could foretell an impending reversal or excursion (e.g., De Santis et al., 2007). Because historical records are short (~ 400 years), paleomagnetic studies are needed to put the Arctic geomagnetic field into a proper temporal context. Over the last decade, paleomagnetists have begun exploring whether Arctic sediments might provide a high-resolution archive of past geomagnetic behavior. Such data can provide fundamental geophysical observations on Earth's core and the geodynamo, while also possibly providing a critically needed high-resolution stratigraphic dating tool for paleoceanograhic and paleoclimate studies.

Understanding ongoing geomagnetic change and NMP movement has been hindered by limitations of both historical and paleogeomagnetic data. Historical observation-based reconstructions (Jackson et al., 2000) augment the few direct observations of NMP location (Figure 1) but only extend back to 1590 AD, revealing no motion analogous to the ongoing NMP migration. Based on these model reconstructions, the NMP over this time interval underwent limited motion, restricted to a small region of the Arctic centered over the Canadian Arctic Archipelago (Figure 1). Compared to the historical geomagnetic record, paleomagnetic records provide additional information on the past, possibly including NMP migration over a larger area. Unfortunately, paleomagnetic records from the polar regions are rare due the logistical difficulties of obtaining them. Records with the temporal resolution and chronological accuracy required to document centennial or shorter prehistoric geomagnetic change, necessary to provide context for ongoing polar-field changes, are exceedingly rare and just beginning to emerge.

This paper presents an overview of Arctic geomagnetism and paleomagnetism and describes recent efforts to move our understanding forward by looking at high-resolution Holocene records from the Low and High Arctic. As highlighted here, paleomagnetic records from the High Arctic may be key to understanding current dramatic geomagnetic changes, as well as the unique nature of the Arctic geomagnetic field.

> "THE HIGH ARCTIC MAY BE KEY TO UNDERSTANDING THE CURRENT DRAMATIC GEOMAGNETIC CHANGES, AS WELL AS THE UNIQUE NATURE OF THE ARCTIC GEOMAGNETIC FIELD."

ARCTIC GEOMAGNETISM

Historical observations and geodynamo theory attest to the unique properties of the geomagnetic field of the North Polar region (e.g., Bloxham et al., 1989; Haines and Newitt, 1997; Olson and Aurnou, 1999; Jackson et al., 2000; Hulot et al., 2002; Newitt et al., 2002; Chulliat et al., 2010a,b). Numerical dynamo models, which explain the origin of the geomagnetic field and its secular variation by convection in the electrically conducting fluid in the outer core (e.g., Glatzmaier and Roberts, 1995), predict that both outer core convection and the magnetic field generated could be substantially different at high polar latitudes. According to dynamo theory (e.g., Kono and Roberts, 2003), Earth's solid inner core affects the pattern of convection within the liquid outer core, which in turn affects the geomagnetic field. The High Arctic is located within the surface expression of the "tangent cylinder." The tangent cylinder, described by a latitudinal circle at ~ 69.5° North and South (Figure 2), is defined as the region in the outer core (where Earth's magnetic field is generated) in which a theoretical cylinder tangent to the solid inner core and parallel to the axis of

Guillaume St-Onge *(guillaume_st-onge@uqar.qc.ca) is Professor and Canada Research Chair in Marine Geology, Institut des sciences de la mer de Rimouski (ISMER), and GEOTOP, Université du Québec à Rimouski, Rimouski, QC, Canada.* **Joseph S. Stoner** *is Associate Professor, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA.*

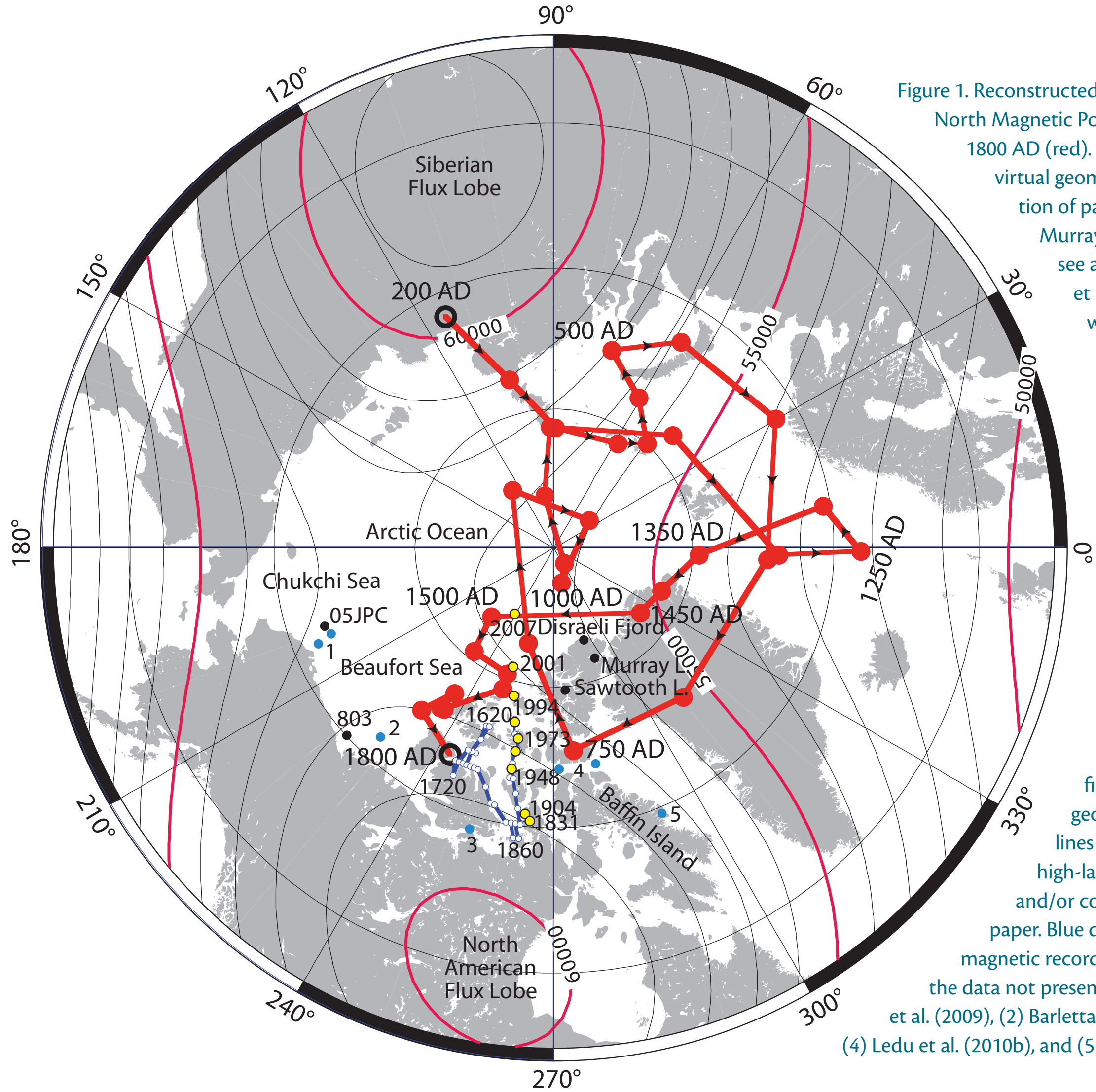


Figure 1. Reconstructed location and movement of the North Magnetic Pole (NMP) every 50 years from 200 to 1800 AD (red). The reconstruction is based on virtual geomagnetic pole (VGP) transformation of paleomagnetic data from Lower Murray Lake (inclination and declination; see also Cook et al., 2008, and Besonen et al., 2008) averaged over a 100-year window every 50 years. A black open circle indicates the starting (200 AD) and ending (1800 AD) points of the VGP track, while arrowheads indicate the direction of the migration. The blue dashed line shows NMP historical motion calculated from Jackson et al. (2000), and yellow dots indicate direct NMP observations. Note NMP migration over the last 1,800 years and the abrupt shift from Fram Strait to North America from 1350 to 1500 AD, with most of the migration occurring from 1450 to 1500 AD. The figure also illustrates present-day geomagnetic field intensity contour lines (in nT), the two current dominant high-latitude flux lobes, and the locations and/or cores (black dots) presented in this paper. Blue dots show the locations of paleomagnetic records mentioned in the text, but with the data not presented, and are from: (1) Lisé-Pronovost et al. (2009), (2) Barletta et al. (2010), (3) Ledu et al. (2010a), (4) Ledu et al. (2010b), and (5) Andrews and Jennings (1990).

rotation would separate distinct convective regimes. Because it is the convective movement of liquid iron in the outer core that generates the geomagnetic field, different flow regimes theoretically could generate distinctly different geomagnetic characteristics. Large-scale flow within the tangent cylinder is thought to be moving, above and below the solid inner core, as an upwelling polar vortex (Olson and Aurnou, 1999; Aurnou et al., 2003) that rises close to the pole and descends close to the tangent cylinder in a motion similar to that of a hurricane. However, outside the tangent cylinder where Coriolis forces are more important, convection is organized into a columnar/helical fashion with both upwelling and downwelling columns parallel to the rotation axis and offset from the pole by the inner core (Figure 2). Downwelling convective structures that extend through the whole of the fluid outer core are thought to generate much of the main field at mid-latitudes. These features are not symmetrically distributed around the solid inner core but, at least historically, are thought to be concentrated at fixed locations where they produce magnetic flux concentrations or lobes (Bloxham and Gubbins, 1985) like the North American and Siberian flux lobes illustrated in Figure 1. This persistent nonaxisymmetric morphology of the geomagnetic field is hypothesized to reflect lower mantle boundary conditions (likely temperature anomalies) that help organize core convection (Bloxham and Gubbins, 1987). How these anomalies vary relative to one another may be a main driver of paleomagnetic secular variation (PSV) at mid-latitudes, while the PSV of the Arctic over the tangent cylinder could be distinctly different.

Direct field observational data collected over the last two centuries, though limited to a few spot readings, have captured some of the dynamics of the Arctic's geomagnetic field. On June 1, 1831, at Cape Adelaide on the western coast of Boothia Peninsula, James Clark Ross first observed the NMP, or dip pole (defined as the point on Earth where the inclination is +90°) (Ross, 1834, 1835). In 1904, during the first successful journey into Northwest Passage waters, Roald Amundsen noted that the NMP had moved north only by fewer than 50 km. (Amundsen, probably best known for being the first to reach the South Pole in 1911, also conducted research in the Arctic and is the namesake of the Canadian icebreaker CCGS *Amundsen*.) However, by 1947, Paul Serson and Jack Clark, Canadian scientists from the Dominion Observatory, observed that the NMP had migrated to Allen Lake on Prince of Wales Island, about 400 km northwest of Amundsen's reported position. In 1994, the NMP was found in Noice Peninsula, southwest of Ellef Ringnes Island, and by 2001 it had made its way to the Arctic Ocean (81.3°N, 110.8°W). By 2007, it had moved north again (83.95°N, 120.72°W; Newitt et al., 2009), and it is now predicted to be slightly north of 85°N in the Arctic Ocean (Olsen and Mandea, 2007; Figure 1; for more information see also: http://gsc.nrcan.gc.ca/geomag/nmp/expeditions_e.php). These observations document ~ 1,700 km of NMP migration over the last century, with much of it occurring over the last few decades at speeds of > 50 km yr^{-1}, reaching almost 60 km yr^{-1} in 2003 (Olsen and Mandea, 2007). It is also interesting to note that the present trajectory of the NMP is from the North American toward the Siberian flux lobe (Figure 1). In the next section, we will try to assess whether PSV in the Arctic is indeed different by looking mostly at high-resolution Holocene paleomagnetic records from the Arctic.

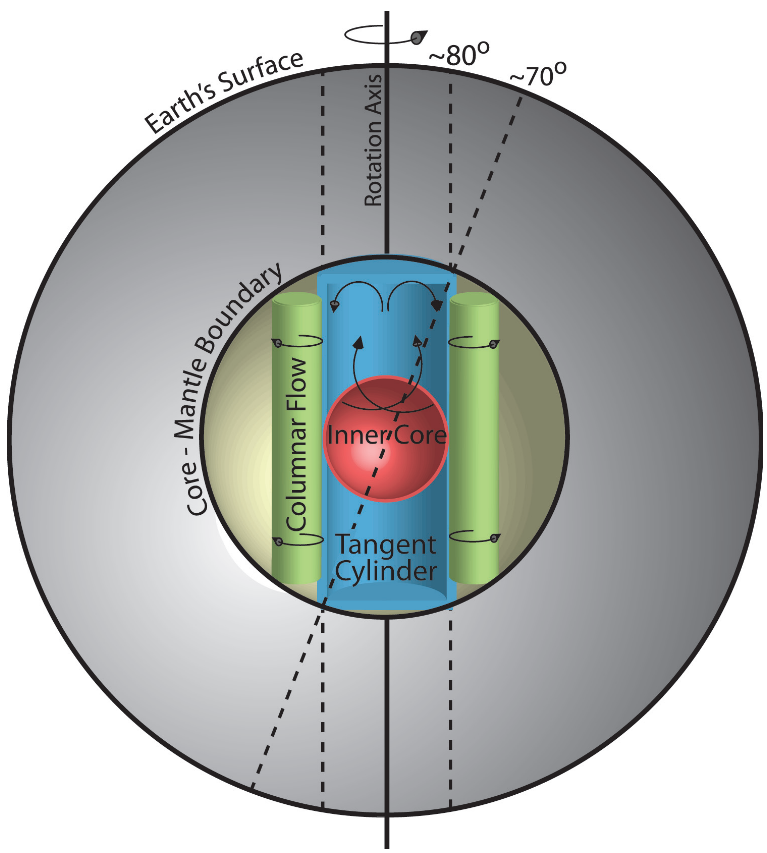


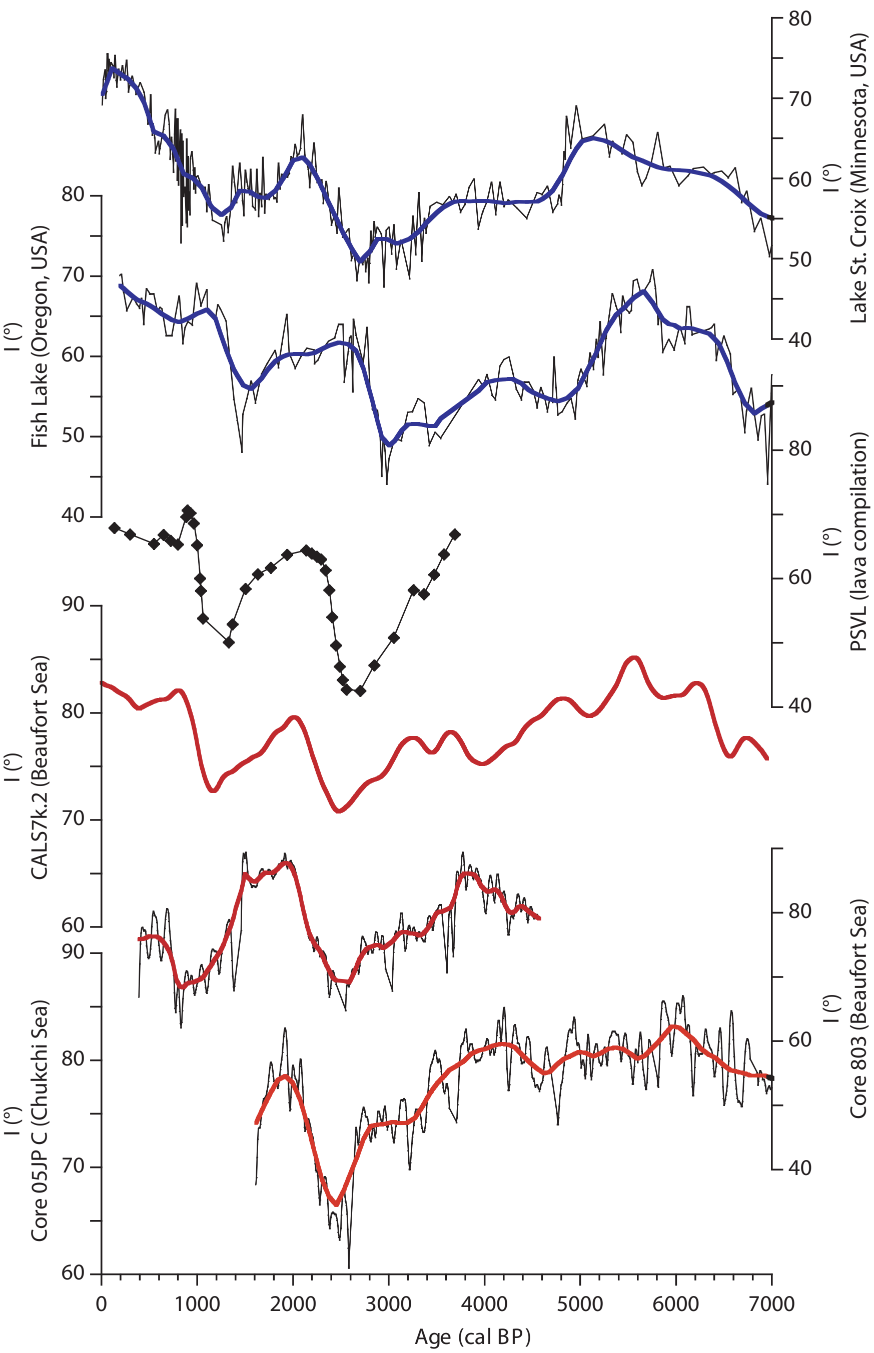
Figure 2. Schematic illustration of Earth's core and convective flow regimes within and outside the tangent cylinder that could lead to differences in the behavior of the geomagnetic field observed at Earth's surface. *From Lawrence et al. (2009)*

ARCTIC PALEOMAGNETISM

Pleistocene Records and Arctic Chronology

Paleomagnetic studies have been undertaken at various Arctic Ocean locations (e.g., Steuerwald et al., 1968; Clark, 1970; Witte and Kent, 1988; Løvlie et al., 1986; Nowaczyk et al., 1994, 2000, 2001, 2003; Schneider et al., 1996) and at Lake El'gygytgyn in Siberia (Nowaczyk et al., 2002). The results from these studies are only marginally related to the scope of this paper as they have significantly lower temporal resolution. However, these records suggest that the polar field may be unique because a significant portion of the Brunhes normal polarity chron (i.e., the last 780,000 years, when the geomagnetic field polarity was similar to the one we observe today) appears to be represented by sediments that are reversely magnetized.

Although those studies are controversial, they point to the importance and difficulties of establishing robust chronologies from Quaternary Arctic sedimentary sequences. Interpreting the reversely magnetized sediments as apparent reversals (e.g., Steuerwald et al., 1968; Clark, 1970; Witte and Kent, 1988), excursions (e.g., Lovlie et al., 1986; Jakobson et al., 2000; Nowaczyk et al., 2003; Spielhagen et al. 2004; O'Regan et al., 2008), or the result of a diagenetically induced self-reversed chemical remanent magnetization (Channell and Xuan, 2009; Xuan and Channell, 2010) will yield totally different age models that can vary by an order of magnitude. On the other hand, Holocene sediments can be dated more easily by radiocarbon, but establishing robust chronologies is still quite challenging in the Arctic for several reasons, including calcium carbonate dissolution, unknown radiocarbon reservoir correction, and the absence of paleomagnetic records to use as chronostratigraphic template. In the last few years, some of these challenges were met successfully as new radiocarbon and varve-dated paleomagnetic records began to emerge and now include high-resolution records from the Beaufort Sea (Barletta et al., 2008), the Chukchi Sea (Lisé-Pronovost et al., 2009), and a pair of High Arctic varved lacustrine records from Ellesmere Island (Murray and Sawtooth Lakes; Besonen et al., 2008; Cook et al., 2008). Some of these new records have been used, for example, to help establish the chronologies of Holocene paleoceanographic records from the Chukchi Sea (Lisé-Pronovost et al., 2009; Ortiz et al., 2009; Darby et al., 2009) and, by combining radiocarbon-based chronologies with geomagnetic model outputs (Korte and Constable, 2005), from the Beaufort Sea (Barletta et al., 2010) and the Northwest Passage (Ledu et al., 2010a,b).



Low Arctic Paleomagnetic Records

An important finding emerging from Holocene Low Arctic records from the eastern shelf of Baffin Island, the Beaufort and Chukchi Seas, and the Northwest Passage (Andrews and Jennings, 1990; Barletta et al. 2008, 2010; Lisé-Pronovost et al., 2009; Ledu et al., 2010a,b) is that their patterns of variability are consistent with PSV records from the mid-latitudes of North America (e.g., Verosub et al., 1986; Lund and Banerjee, 1985), as well as with a northwestern US lava flow compilation (Hagstrum et al., 2002) and the spherical harmonic geomagnetic field model output of Korte and Constable (2005)

Figure 3. Comparison of Low Arctic and mid-latitude paleomagnetic records from North America. The figure illustrates inclinations from sediment cores 05JPC and 803 (Chukchi and Beaufort Seas; Barletta et al., 2008), CALS7K.2 inclination output for the location of cores 803 and 05PJC (Korte and Constable 2005), western United States paleosecular variation from lava-flow (PSVL) compilation (Hagstrum and Champion, 2002), Fish Lake sediments (Oregon, USA; Verosub et al., 1986), and Lake St. Croix sediments (Minnesota, USA; Lund and Banerjee, 1985). The Fish Lake and Lake St. Croix data were calibrated using the Stuiver et al. (1998) radiocarbon calibration curve. The continuous red and blue curves in the sedimentary inclination records represent weighted functions. Notice the similarity of the Arctic and other North American paleomagnetic records. Note that the Fish Lake chronology is thought to be 280 years too old (Hagstrum and Champion, 2002; St-Onge et al., 2003).

(Figure 3). This consistency suggests that, at least in the North American Low Arctic (from ~ 69° to 74°N), geomagnetic field behavior is coherent at the continental scale, and that this behavior is typical of North American paleomagnetic records. This observation has important chronostratigraphic implications. It suggests that it may be possible to use well-dated mid-latitude PSV records as a template for dating North American Arctic sediments collected outside of the tangent cylinder, and to assess the validity of a selected radiocarbon reservoir correction (at least in a first-order manner) by comparing Arctic records with those derived from well-dated lava flows or spherical harmonic geomagnetic field model outputs. Both of these types of records are less influenced by radiocarbon reservoir effects.

However, these results call into question whether the high rates of secular variation observed in the historical record (Figure 1) are representative over longer time intervals, or whether the lower-latitude North American Arctic is not far enough north to capture a potentially distinct geomagnetic field behavior generated within the tangent cylinder. Paleomagnetic records obtained as far north as possible are likely the key to answering this question. The Holocene varved lacustrine records of Lower Murray and Sawtooth Lakes (Ellesmere Island) located at ~ 81°N and 79°N, respectively, provide this unique perspective. The PSV and relative paleointensity records of both sites can be correlated and are now reproduced in several duplicate cores from both lakes (Stoner et al., 2009). The overall correlation is particularly striking for the last 1,000 years (e.g., Besonen et al., 2008), when the varved chronologies of both cores are the strongest. As we extend this record back in time, Lower Murray Lake appears to preserve a superior varved record (Cook et al., 2008). Comparisons with the marine records extending further back in time bear this out, and only the Lower Murray Lake record is presented here.

High Arctic Paleomagnetic Records

Despite logistical difficulties, dating challenges, and an almost vertical magnetic field, paleomagnetic results from the High Arctic are extremely promising. They reveal important differences in PSV and relative paleointensity behavior of High Arctic sites compared to other recently published records from the North American Arctic (Figure 4). These differences tend to support the unique nature of the geomagnetic field during the Holocene at very high latitudes above the tangent cylinder and can now be reproduced in marine records from Disraeli Fjord, at the northernmost tip of Ellesmere Island (~ 83°N; Figure 5; see also Figure 1 for location). In addition, the Ellesmere Island lacustrine PSV record seems to show sudden directional changes that are consistent with rapid and potentially abrupt shifts in NMP position. These shifts are picked up particularly well when we look at

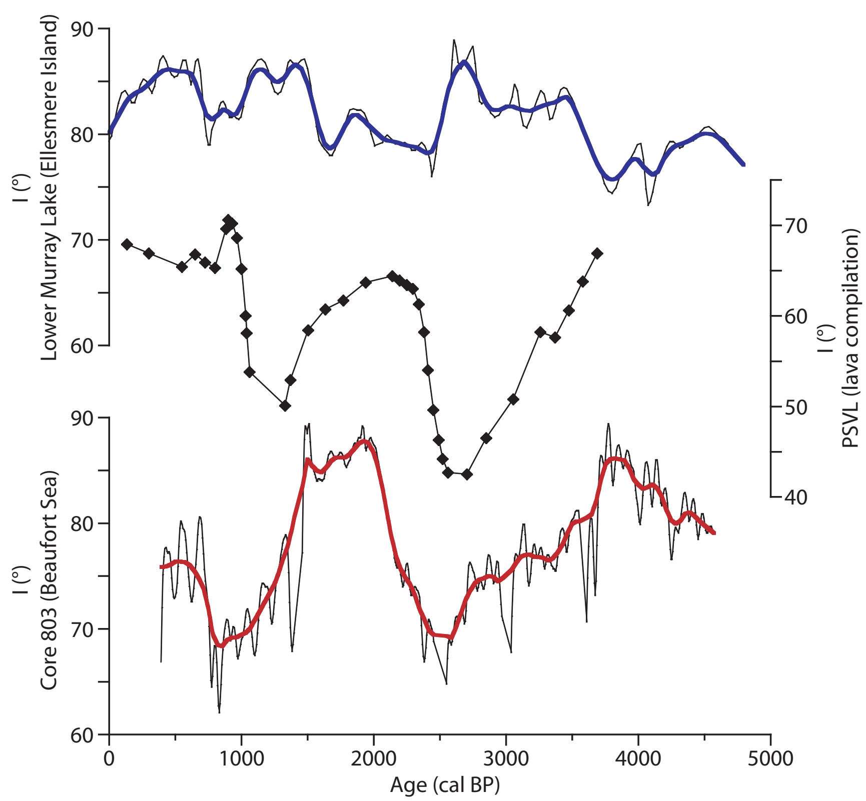


Figure 4. A comparison of high and low North American Arctic paleomagnetic records illustrates inclinations from sediment core 803 (Beaufort Sea; Barletta et al., 2008), the western United States paleosecular variation from lava flows (PSVL) compilation (Hagstrum and Champion, 2002), and Lower Murray Lake sediments (Ellesmere Island; Cook et al., 2008; Besonen et al., 2008). Note the similarity between core 803 (Beaufort Sea) and the PSVL record (see also Figure 3) and their striking difference from the Lower Murray Lake record.

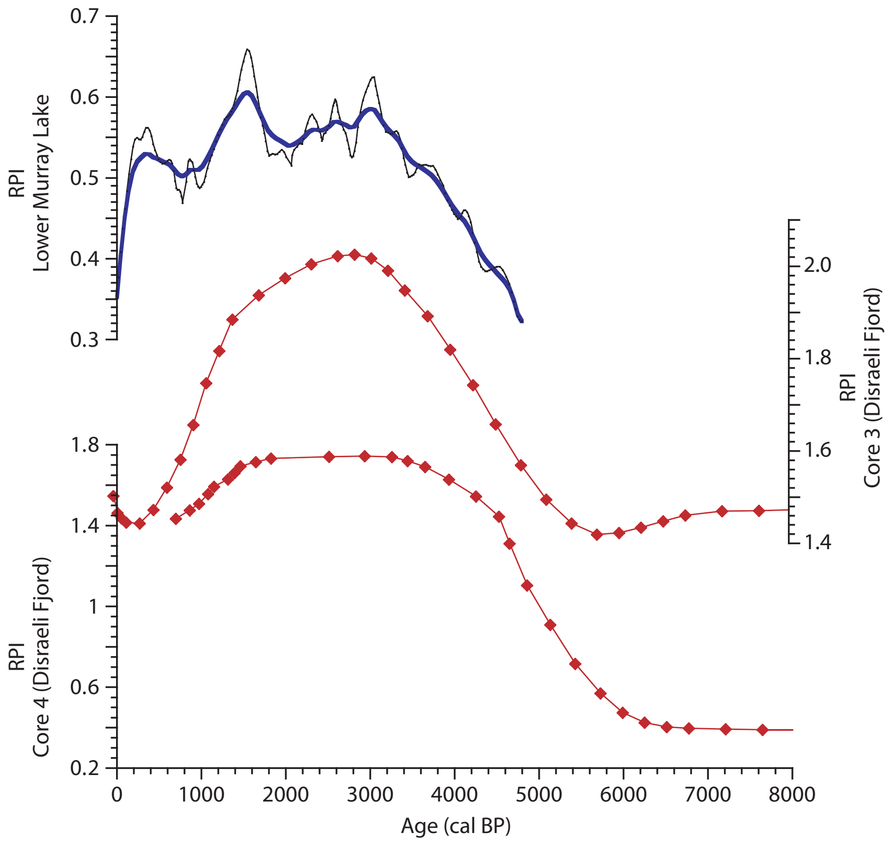


Figure 5. Relative paleointensity (RPI) records from Ellesmere Island shown in cores 3 and 4 from Disraeli Fjord (recent work of D. Antoniades, P. Francus, R. Pienitz, G. St-Onge, and W.F. Vincent) and the Lower Murray Lake sediment record (Cook et al., 2008; Besonen et al., 2008). Even though the temporal resolution of the Murray Lake record is much higher, the general trend is similar in the lacustrine and fjord cores.

virtual geomagnetic poles, or VGPs[1], and indicate that the recent NMP migration is not unusual in the recent geological past. For example, in 1350 AD, the VGP approximation for the NMP position was near Fram Strait and then moved rapidly toward North America, with most of the migration occurring from 1450 to 1500 AD (Figure 1). Thus, historical reconstructions just missed the last significant geomagnetic change by fewer than 200 years. Because initial compass readings were being made in Europe at that time, it is interesting to speculate on how such a significant change might have affected early compass-based navigation.

Toward deriving a better understanding of how the polar geomagnetic field compares to that of the rest of the world, comparing the rapid NMP migration described above with other observed abrupt geomagnetic features from the paleomagnetic record needs to be considered. The most prominent of these comparisons are abrupt century-scale changes in direction and intensity observed in recent mid-latitude European archeomagnetic studies (i.e., changes in Earth's magnetic field behavior recorded in artifacts) and termed archeomagnetic jerks (Gallet et al., 2003). Documented to have taken place four times over the last 3,000 years, the most recent jerk occurred at the end of the fourteenth century, just prior to the abrupt NMP shift mentioned above (Figure 1). Archeomagnetic jerks are postulated to reflect episodes of maximum geomagnetic field hemispheric asymmetry (Gallet et al., 2009) that are followed by abrupt directional shifts. The most recent shift observed around 1450 AD could be the latest in a number of abrupt shifts recorded in the Ellesmere Island lacustrine sediments over the last few millennia (Stoner et al., 2009). These intriguing possible connections between the mid-latitude and the polar fields are just beginning to be explored.

CONCLUSIONS

We presented a brief overview of Arctic geomagnetism and paleomagnetism with a focus on recent Holocene high-resolution paleomagnetic records from the Low and High North American Arctic. These new records reveal the unique nature of the geomagnetic field in the High Arctic, whereas the low North American Arctic exhibits geomagnetic behavior typical of other mid-latitude North American PSV records. The High Arctic data illustrate that abrupt changes in the position of the North Magnetic Pole occurred during the Late Holocene. Some of these changes, like the abrupt shift of the NMP that occurred around 1450 AD, appear to be at least temporally related to processes occurring at mid-latitudes (archeomagnetic jerks). This observation suggests that although the

[1] The point on Earth's surface at which a magnetic pole would be located if the observed paleomagnetic direction—inclination and declination—at a particular location were due to a dipolar field. Note that more than 90% (Tauxe, 2010) of today's geomagnetic field is dipolar.

record from the High Arctic is unique, NMP behavior there may be related to processes influencing the main field at mid-latitudes. Finally, we also highlighted how the Arctic, and especially the High Arctic, offers a unique vantage point for studying geodynamo processes associated with the tangent cylinder, as well as the opportunities the Arctic offers to explore possible relationships between flux lobes, archeomagnetic jerks, and paleomagnetic secular variations.

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