Reconstruction of the Virtual Geomagnetic Pole (VGP) path at high latitude for the last 22 kyr: the role of radial field flux patches as VGP attractor.

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Abstract

Reconstruction of geomagnetic field changes has a strong potential to complement geodynamo modeling and improve the understanding of Earth's core dynamics. Recent works based on geomagnetic measurements pointed out that over the last two decades the position of the north magnetic pole has been largely determined by the influence of two competing flux lobes under Canada and Siberia.

In order to understand if the waxing and waning of magnetic flux lobes have driven the path of geomagnetic paleopoles in the past, we present an augmented and updated record of the chronology and paleosecular variation of geomagnetic field for the last 22 kyr derived from sedimentary cores collected along the north-western margin of Barents Sea and western margin of Spitsbergen (Arctic). The path of the virtual geomagnetic pole (VGP) has been reconstructed over this time period and compared with the maps of the radial component of the geomagnetic field at the core-mantle boundary, obtained from the most recent models. The VGP path includes centuries during which the VGP position is stable and centuries during which its motion accelerates. We recognize both clockwise and counterclockwise VGP paths, mostly developing inside the surface projection of the inner core tangent cylinder in the Arctic region. The VGP path seems to follow the appearance of B_r patches of normal magnetic flux, especially those located under Siberia and Canada areas, but also those that may cause peculiar paleomagnetic features such as the Levantine Iron Age Anomaly.

Keywords

Geomagnetic paleosecular variation; Relative paleointensity; Flux lobes; Levantine Iron Age Anomaly; Marine sediment cores; Arctic region

1 Introduction

Reconstruction of geomagnetic field changes has a strong potential to complement geodynamo modeling and improve the understanding of Earth’s core dynamics (Panovska et al., 2018 and reference therein). There is potential social relevance of the paleosecular variation (PSV) reconstruction, as demonstrated by the fact that in 2019 the World Magnetic Model, used for navigation, was updated a year in advance, as a consequence of the recent acceleration of north magnetic pole motion, see Livermore et al., (2020). The authors highlighted that over the past 50 years the north magnetic pole has traveled along a linear path that connects two patches of strong radial magnetic field (B_r) at the Core-Mantle Boundary (CMB) centered at high latitudes under Canada and Siberia. The time-dependent position of the pole along this path is related to a balance between the competing influences of the Canadian and Siberian geomagnetic flux lobes at the CMB. A decrease of the Canadian flux patch and a slight intensification of the Siberian flux patch cause an acceleration of the magnetic pole path toward Siberia. Did this relationship between the waxing and waning of geomagnetic flux lobes and the pole position occur also in the past? To answer this question, it is necessary to focus on indirect geomagnetic observations, such as those inferred from paleomagnetic measurements and analyses. The principal sources of paleomagnetic data are volcanic rocks, lake and marine sediments, and archeological artifacts. In the last decades, paleomagnetic data have been widely used to reconstruct the past geomagnetic field at different temporal and spatial scales. Several models have been produced, especially for the Holocene, constraining the morphology and variability of geomagnetic field at relatively high resolution (Constable et al., 2000, 2016; Campuzano et al., 2019; Donadini et al., 2009; Johnson and Constable 1995, Korte and Constable 2003, 2005; Korte et al., 2005, 2009; Korte and Holme, 2010; Nilsson et al., 2014; Osete et al., 2020; Pavón-Carrasco et al., 2009, 2010, 2014; Panovska et al., 2018 among others).

Some of these models analyze the presence of flux patches at the CMB in the northern hemisphere. Pavón-Carrasco et al. (2014) studied the last 14000 years from SHA.DIF.14k, a global geomagnetic field model based on archeomagnetic and volcanic data. For the last 9000 years, they highlighted the appearance of marked lobes of magnetic flux in high latitudes when the dipole moment was maximum. When the dipolar field decreased, a rupture of this dipolar pattern was observed and a weakened magnetic flux patches in the northern hemisphere with the appearance of new lobes in lower latitudes with low (or even reversed) values of B_r.

The new model SHAWQ-Iron Age by Osete et al. (2020) that spans from 3300 to 2000 BP improves the description of the evolution of the Levantine Iron Age Anomaly (LIAA) formerly observed by several authors in the Levantine region and later in the Mediterranean region (e.g. Shaar et al., 2016, 2017; 2018; Davies and Constable, 2017; Beguin et al., 2019; Rivero-Montero et al., 2021). According to Osete et al. (2020), the LIAA is related to a normal flux patch at the CMB below Arabian Peninsula, which was observed starting from around 2950 BP. After its appearance, it expanded towards the north-west and around 2600-2500 BP stationed under the European continent and then disappeared in situ. Rivero-Montero et al. (2021) however do not observe a clear westwards migration of the LIAA event and propose that the maximum geomagnetic intensity around 2500 BP occurred in a large region, from Western Europe to Turkey, at the same time. This recent result agrees with Davies and Constable (2017) work, who stated that this kind of feature could have originated from the CMB only in the case that its effect at Earth's surface was observed in a region >60°.

How does the appearance and disappearance of these flux patches impact the VGP motions at high latitudes? To investigate these issues, we reconstructed the geomagnetic field PSV for the last 22.2 calibrated kiloyears before the present (cal kyr BP_{2000}, with "present" fixed at 2000 CE) analyzing paleomagnetic and rock magnetic data from sedimentary cores collected from the north-western margin of the Barents Sea and western margin of Spitsbergen (Arctic). These paleomagnetic records might extend back in time the known information about the geomagnetic field variation in the recent geological time and provide constraints for the development of regional (Arctic) and global models of geomagnetic field variation.

Starting from paleomagnetic declination and inclination stack curves, the VGP path has been reconstructed and compared with maps of the radial component of the geomagnetic field at the CMB calculated using different global geomagnetic field reconstructions: GGF100k (Panovska et al., 2018), CALS10k.2 (Constable et al., 2016), SHAWQ-Iron Age (Osete et al., 2020) and SHAWQ2k (Campuzano et al., 2019).

2 Study Area and materials

The sedimentary cores, taken into account in this work, were recovered along the north-western margin of Barents Sea and western margin of Spitsbergen during the past years in the framework of several international research projects (Table S1).

In brief, the morphology of these continental margins was shaped by a series of advances and retreats of the Svalbard-Barents Sea ice sheet related to the Late Quaternary climatic changes (Patton et al., 2017). The paleo-ice stream produced deep erosion moving along cross-shelf glacial troughs (e.g. Kveithola and Storfjorden troughs), and massive deposition on the continental slope, resulting in the buildup of seaward-convex slope-aprons called Trough Mouth Fans (TMFs) (Pedrosa et al, 2011; Mattingsdal et al., 2014; Lucchi et al., 2013; Rebesco et al., 2013). In addition to glacigenic processes, the margin is characterized by persistent bottom currents flowing along the slope (contour currents, Jakobsson et al., 2007; Poirier and Hillaire-Marcel, 2011 among others). These currents are responsible for the development of sediment drifts in the areas shielded from direct glacigenic input, such as the Bellsund and Isfjorden drifts identified along the western continental margin of Svalbard (Rebesco et al., 2013). The studied sediment cores were collected in areas mainly affected by contouritic deposition:

- Calypso cores GS191-01PC and GS191-02PC, collected from the Bellsund and Isfjorden drifts, respectively.
- Piston core SV-04 and gravity cores EG-02 and EG-03 collected from the Storfjorden TMF.
- Gravity core GeoB17603-3 from the Kveithola TMF.

The cores were previously analyzed using a multidisciplinary approach (Lucchi et al., 2012, 2013, 2015; Sagnotti et al., 2011a and Caricchi et al., 2018, 2019) including Accelerator Mass Spectrometry (AMS) ^{14}C dating, lithofacies analysis, paleomagnetic and rock magnetic analyses.

In this work we refined the initial chronologies and core correlations as described in the next section.

3 Cores correlation and refining age models

3.1 Cross-core correlations

High-resolution core correlations were established comparing rock magnetic and paleomagnetic stratigraphic trends, by means of the StratFit software (Sagnotti and Caricchi, 2018). The correlation process is based on the Excel FORECAST function which implies a linear regression between subsequent pairs of selected tie-points. By doing this, it is possible to estimate the equivalent stratigraphic depth of the correlated curve in the depth scale of a selected master curve.

In this work, core GS191-01PC has been selected as the master curve (due to the higher number of age and lithological constraints) and the equivalent depth of SV-04, EG-02, EG-03, GeoB17603-3 and GS191-02PC (correlated curves) was then computed with StratFit. The choice of the tie-point pairs has been made taking into account the lithofacies (Lucchi et al., 2013; Caricchi et al., 2018, 2019), significant and coincident peaks and troughs of the curves of rock magnetic and paleomagnetic parameters (Sagnotti et al., 2011a; Caricchi et al., 2018, Caricchi et al., 2019), and the previously published age models (Sagnotti et al., 2011a; Caricchi et al., 2018, 2019, 2020). In figure 1 the correlation of the Anhysteretic Remanent Magnetization (ARM) stratigraphic trends (see Sagnotti et al., 2011a; Caricchi et al., 2018, 2019 for additional details about ARM parameters and their downcore variations) is shown as a representative example for the output of the high-resolution core correlation procedure.

The ARM curves of the correlative cores match closely that of the master core, as visualized in the graphs and testified by the correlation coefficients (R>0.75; Fig.1).

This correlation among cores collected far from each other and distributed along a 330 km-long transect crossing the north-western margin of the Barents Sea and western margin of Spitsbergen, allowed us to correlate paleoclimatic events along the entire margin and to obtain a new piece of knowledge that can be used as a benchmark for the reconstruction of the paleoclimatic evolution of this region.

In addition, the improvement of the cross-core correlation also allowed us to refine the formerly published age models, as reported in detail below.

3.2 Refined age models

The age model of the cores was originally established by taking into account the variation of the RPI, the paleomagnetic inclination and declination curves, the lithological constraints and the radiocarbon ages, which provided the main chronologic tie-points (Caricchi et al., 2019; 2020). For a second-order chronology refinement, in this study we also considered the results from the cross-core correlation process. Then, each core paleomagnetic record was also correlated with the most recent paleomagnetic stack curves and models. In particular, GICC05-GLOPIS75 has been taken into account because this stack benefits from the correlation of the ^{10}Be and ^{36}Cl records from the Greenland ice cores with GLOPIS-75. This correlation allows to precisely assess the rates of change of the field intensity during periods of large directional changes (i.e., the Laschamp and Mono Lake excursions) and during periods when a large decrease of the dipolar field intensity occurred without being associated with significant directional changes (Laj and Kissel, 2015). The use of paleomagnetic constraints in the correlation must be taken into account for global paleofield modeling purposes.

For this latter correlation, the target curves from stacks and models were computed at the EG-03 core location, which has been chosen as the reference location due to its central position in the study area. Regarding the RPI curves, for all cores we considered the RPI computed from the NRM/ARM ratio with the exception of the core GeoB17603-3, for which we used the RPI computed from the NRM/k ratio. The poor efficiency of the NRM/ARM normalization with respect to the NRM/k normalization, in this latter core, is attributed to the effects of diagenetic dissolution in the upper part of the sedimentary sequence, that caused a preferential depletion of fine-grained ferromagnetic minerals (which affects ARM intensity more than magnetic susceptibility k).

Correlation between paleomagnetic trends and target curves was accomplished by the StratFit software (Sagnotti and Caricchi, 2018), transferring records to a common age scale using the same method employed for cross-core correlation.

In order to compare data with different ranges of variation (e.g., RPI curves and models) we adopted the normalization method reported in the Supplementary Material (Appendix A). The intensity of the geomagnetic field, for the curves from geomagnetic models (e.g. GGF100k) and for GICC05-GLOPIS75, was rescaled only for the time interval overlapping the one spanned by the analyzed cores.

We point out that the paleomagnetic data for the time interval older than the Holocene for the EG-02, EG-03 and SV-04 cores are presented here for the first time.

Table S1 in supplementary material lists all the data, for each core, referred to the formerly published age models (Caricchi et al., 2019; 2020) and the newly refined age models.

3.2.1 GS191-02PC and GS191-01PC cores

These cores were compared with the reference RPI stack GICC05-GLOPIS75 (Laj and Kissel, 2015) and GGF100k model (Panovska et al., 2018) (Table S1, Fig. S1). This procedure allowed us to refine the age model for the older portion of the GS191-02PC between 11 and 17 m (Caricchi et al., 2019). The maximum age adjustment was for the core interval 13-16 m, which resulted in a shift in age of 2-3 kyr (Table S1, Fig. 2, Fig. S1a, b). The age model of GS191-01PC (Caricchi et al., 2019) was refined for the Holocene interval between 5 and 10 cal kyr BP_{2000} (2.14 – 5.89 m) with a maximum age shift of 123 yr (Table S1, Fig. 2, Fig. S1c, d).

3.2.2 EG-03 and EG-02 cores

These cores were compared with the CALS10k.2 (Constable et al., 2016) and SHA.DIF.14k (Pavón-Carrasco et al., 2014) models (Table S1, Fig. 2, Fig. S2).

For the EG-03 we refined the portion of the core between 1.4 and 2.6 m, with a maximum age shift of 950 yrs around 2.3 m (Table S1, Fig. 2, Fig. S2a, b). The age model of the EG-02 core was refined for the portion from 0.23 to 1.40 m with major adjustments of age shift 900 yrs between 0.35 and 0.45 m and 300-400 yrs between 1.30 and 1.40 m (Table S1, Fig. 2, Fig. S2c, d).

3.2.3 SV-04 core

SV-04 core was compared with RPI stack GICC05-GLOPIS75 (Laj and Kissel, 2015), GGF100k (Panovska et al., 2018), CALS10k.2 (Constable et al., 2016) and SHA.DIF.14k (Pavón-Carrasco et al., 2014) models (Table S1, Fig. 1, Fig. S3). We refined the age model for the interval depth between 1.01-1.57 m, with a maximum age shift of 800 yrs around 1.53 m. The new age models are now consistent with the identification of the Melt Water Pulse (MWP)-19ka (e.g Clark et al. 2004) and Heinrich event H-2 (e.g. Hemming 2004) as indicated by the lithological and compositional characteristics of sediments.

4 Geomagnetic field reconstruction

Paleomagnetic data from the cores were merged in a stack curve for the characteristic remanent magnetization (ChRM) declination and inclination (Fig. 3a,b), considering three main time intervals: i) 0.6-10 cal kyr BP_{2000}; ii) 10-14 cal kyr BP_{2000}; iii) 14-22.2 cal kyr BP_{2000}.

In detail, for the time range i) we used the data from the EG-02, EG-03, SV-04 and GeoB17603-3 cores; data from the cores collected in the sediments drift (GS191-01PC, GS191-02PC) were not used because of the poor quality of the paleomagnetic signal in the Holocene portion, which was probably affected by diagenetic dissolution of ferromagnetic minerals (Caricchi et al., 2019). For the time range ii) we used data from all the six cores. Only the data from the cores spanning older age intervals (SV-04, GS191-01PC, GS191-02PC) were used for the iii) time interval.

For the stacking process, paleomagnetic directions were grouped with an age sliding window of 200 yr from present-day up to 14 cal kyr BP_{2000}. The paleomagnetic directions within the 14 – 22.2 cal kyr BP_{2000} time range were grouped with an age sliding window of 600 yr (Fig. 3c). This procedure was necessary to ensure a number of data (N) higher than 5 for all the steps in the age interval 0.6 - 22.2 cal kyr BP_{2000} (Fig. 3c) and led to a different time resolution in the two time intervals.

The obtained PSV stack for paleomagnetic declination and inclination, called the NBS22.2k stack, was defined by computing a mean paleomagnetic direction for each time interval using Fisher statistics (Fisher, 1953).

Likewise, the NBS22.2k RPI stack curve was defined using the RPI data from the same cores. In this case, the arithmetic mean has been computed for the RPI data falling within sliding windows with the same spacing (200 and 600 yr) used for the PSV data (Fig. 4).

Afterward, the NBS22.2k PSV and RPI stack curves have been compared with the PSV and RPI variations expected according to the geomagnetic field models: CALS10k.2 (Constable et al., 2016); SHA.DIF.14k (Pavón-Carrasco et al., 2014); SHAWQ-Iron Age (Osete et al., 2020); SHAWQ2k (Campuzano et al., 2019); GGF100k (Panovska et al., 2018). The NBS22.2k RPI stack curve was also compared with the GICC05-GLOPIS75 stack curve (Laj and Kissel, 2015) (Fig. 5).

For this comparison, we also normalized all the curves by the method reported in the Supplementary Material (Appendix A) (Fig. 5). The NBS22.2k RPI stack is in general agreement with the models and GICC05-GLOPIS75 for the first 15 kyrs, with the exception of the SHA.DIF.14k around 11kyr, which shows a minimum in intensity not observed in the other models. SHAWQ family models show exaggerated minima at present-day and at about 2 and 3 cal kyr BP_{2000}. This is an artifact due to the normalization method and it is related to the fact that the SHAWQ family models have a much higher median value than other models extending to older periods, since in the last 3.3 kyr BP_{2000} the magnetic field was characterized by intensity values distinctly higher than for the older interval from 3.3 kyr BP to 10 kyrs BP_{2000}.

It is also evident a slight offset between the GGF100k model and the GICC05-GLOPIS75 that became more accentuated after 14 kyr. We can assume that this is related to the fact that spherical harmonic models provide regional predictions including non-axial-dipole contributions while the stack has attempted to average those out using a wide spatial distribution of records. Moreover, GGF100k and GICC05-GLOPIS75 used different records and potentially inconsistent time scales.

NBS22.2k inclination and declination curves show a really good match with the trends computed according to the models for the time interval between 14 cal kyrs BP_{2000} and Present. A mismatch with the GGF100k model became evident in the interval between around 14 and 18 cal kyr BP_{2000}. The sharp declination change and the inclination almost vertical between 2.6 and 2.4 cal kyr BP_{2000} (a time interval coeval with the LIAA) is a peculiar feature related to the fact that the VGP in this time period passed close to the cores position (see also Fig. 6) and accelerated its motion. A similar feature was also observed by Turner and Thompson (1981) in their pioneering study of PSV from lake sediments in Britain and named as “f-e event”. This event has also been recognized in various paleomagnetic records from southern Europe (e.g., Sagnotti et al., 2011b).

5 The VGP paths during the last 22.2 cal kyr BP_{2000}

We reconstructed the Virtual Geomagnetic Pole (VGP) path for the last 22.2 cal kyr BP_{2000} on the basis of the declination and inclination values of the NBS22.2k PSV stack curves, following the method by Noel and Batt (1990). The reconstructed VGP paths have been plotted in figure 6 according to six consecutive age intervals: i) 22.2 – 15 cal kyr BP_{2000} (Fig. 6a); ii) 15 – 11.8 cal kyr BP_{2000} (Fig. 6b), iii) 11.8 – 9.0 cal kyr BP_{2000} (Fig. 6c), iv) 9.0 – 6.2 cal kyr BP_{2000} (Fig. 6d), v) 6.2 – 3.2 cal kyr BP_{2000} (Fig. 6e), vi) 3.2 – 0.6 cal kyr BP_{2000} (Fig. 6f). The VGP moved mostly inside the surface projection of the inner core tangent cylinder, which intersects the Earth's surface at ca. ±69.5 of latitude, with a few exceptions: 1) from 15.8 to 15.4, 2) around 5.6 and 3) 3.2 cal kyr BP_{2000}. Moreover, the VGP path traced both clockwise and counterclockwise trajectories. For some centuries the VGP position was substantially stable, whereas for others it significantly accelerated its motion with rapid variations and large deviations from the position of a geocentric axial dipole (GAD).

In Figure 6g, the rate of change of the VGP path has been calculated as the distance covered by the VGP between two consecutive times (in degrees per yr). We also computed the mean and standard deviation of the rate of change for different time intervals; the periods between 14 and 22.2 cal kyr BP_{2000} and 8 and 10 cal kyr BP_{2000} show the lowest standard deviation, with values lower than 0.01 °/yr. This means that the rate of change for these periods is less variable. It is important to consider that for the older ages this could be due to a lower resolution, since the estimation of the VGP rate of change was calculated using a sliding window of 600 yrs. Future studies could help to better define this time interval. In the other time intervals, highlighted with braces in Figure 6g, the standard deviation is greater than 0.01 °/yr, reaching values up to 0.02 °/yr in the most recent period (0.6-3 cal kyr BP_{2000}). This means that the rate of change is more variable for these periods. It is worth noting that the maximum rate of change of the VGP occurs at the end of a sharp acceleration event during the Levantine Iron Age Anomaly times (3000 – 2700 BP, Shaar et al., 2016), terminating around 2.1 cal kyr BP. This increase of the rate of change could be due to the appearance of a third flux lobe in the Atlantic region, as observed in CALS10k.2 model, and the associated increased radial flux at low to mid latitudes in the Pacific (see Fig. S4 in the Supplementary Material). This pattern is however not well observed in the SHAWQ-Iron Age model. The analysis of the rate of change also points out an increase in the mean rate of change in the most recent times, with a value of around 0.05 °/yr for the period from 0.6 to 3.0 cal kyr BP_{2000}. In the rest of the record the mean rate of change oscillates between 0.01 and 0.03 °/yr. We will discuss in detail the time intervals with higher rates of change and standard deviation below. For a comparison with the rate of change of VGP using geomagnetic field models for different maximum harmonic degree see Figure S5 in the Supplementary Material.

As pointed out in Caricchi et al. (2020), the VGP path is possibly related to the time variability and temporary occurrence of geomagnetic radial field flux patches in the northern hemisphere, which seems to have the function of a VGP attractor. The hypothesis is that when the paleopole changes sharply its movement (in terms of position, path and/or velocity), this is due to the rapid (hundred years or less) evolution of B_r patches at the CMB, which appear or disappear, weaken or intensify and are commonly related to a significant contribution of the non-dipole magnetic field components (Fig. S6).

In order to verify this hypothesis, we computed the B_r at the CMB since 14 cal kyr BP_{2000}, using different models for different time intervals. The following models have been taken into account:

- i) The GGF100k for the time interval between 14 and 10 cal kyr BP_{2000} (Fig. S7)
- ii) The CALS10k.2 for the interval between 8.0 and 3.4 cal kyr BP_{2000} (Fig. S8)
- iii) The SHAWQ-Iron Age for the time interval between 3.0 to 2.2 cal kyr BP_{2000} (Figs. 7 and 8)
- iv) The SHAWQ2k for the time interval between 1.8 to 0.6 cal kyr BP_{2000} (Fig. 8)

We have not used the SHA.DIF.14k model because it spans the same time interval as the CALS10k.2 and SHAWQ family, which are more recent.

In detail, the B_r at the CMB has been calculated from the Gauss coefficients of the geomagnetic field models up to maximum harmonic degree 6 to avoid the effect of shorter time scales of the higher degrees, which are poorly resolved and affected by model parametrization. We calculated the B_r

values in a regular grid of 5,000 points around the world, by adding other additional 1,000 points within the Arctic circle to better constrain the grid at high northern latitudes.

The analysis confirmed that the VGP trajectory was driven by the temporary occurrence of normal B_r flux patches, as formerly suggested in Caricchi et al. (2020). This effect is particularly evident for the last 10 cal kyr BP_{2000} but it can be now extended back to the past. To help with the interpretation of the results, we have selected the normal flux patches (NFPs) that act as VGP attractors according to our interpretation. To do that, we have chosen different contour lines to highlight the most relevant and persistent NFPs for every time interval analyzed. The used contour levels are specified in the corresponding figure captions (see Figs. 7, 8 and S7 and S8 in the Supplementary Material). The selected NFPs have been marked with a white contour line in order to improve the visualization.

In order to quantify the NFPs effect over the VGP path, we have calculated the Flux Concentration Factor (FCF) (Eq.4 in Christensen et al., 2010). Based on the idea of the waxing and waning of radial magnetic flux lobes between Siberian and Canadian hemispheres, we calculated the global FCF and the FCF in northeastern hemisphere (Siberian region) and northwestern hemisphere (Canadian region) considering only normal magnetic flux (B_r<0 nT) and compared these estimates with the VGP positions to better evaluate if the normal flux concentrations attract the VGP positions. For the Siberian or northeastern hemisphere we use latitudes >= 0ºN and longitudes [0,180]ºE. For the Canadian or northwestern hemisphere we use latitudes >= 0ºN and longitudes [0,180]ºW. Results are summarized in Table S2 in the Supplementary Material. The FCF is a measurement of the flux concentration. According to Christensen et al. (2010), the maximum global FCF values are obtained when the flux emerges at a very concentrated place and penetrates uniformly over the rest of the globe, and FCF approaches zero when the flux emerges uniformly in one hemisphere and penetrates uniformly in the other hemisphere. For a purely dipolar field the global FCF is 0.8. If we observe global FCF values in Table S2, at 8.0 cal kyr BP_{2000} it is almost dipolar while at 3.0 cal kyr BP_{2000} it presents the highest values of FCF. It corresponds with the occurrence of the “Levantine Iron Age Anomaly” (see below for further details). Regionally, it might be expected that regions with higher values of FCF attract more the VGP because they represent zones with higher flux concentration. High values of FCF can be also obtained as a result of multiple areas of concentrated flux.

Focusing on VGP path from NBS22.2k stack (red curve in Figs. 7, 8 and S7, S8) we notice that the VGP bounced back and forth between the Arctic Canadian and Siberian shorelines; around 14 cal kyr BP_{2000} the paleopole was at high latitude near Canada and Alaska. Afterward, with a clockwise motion it moved toward Siberia (Siberian FCF > Canadian FCF, Table S2), possibly attracted by a flux patch that showed up at 13.4 cal kyr BP_{2000} in the area close to the Kola Peninsula. After, with a clockwise rotation the paleopole moved toward the Arctic Canadian and then returned toward the Russian shoreline of the Arctic Sea at 12.4 cal kyr BP_{2000}, possibly attracted by the flux patch below Russia (Siberian FCF > Canadian FCF). At 12.0 cal kyr BP the VGP returned toward Canada (Fig. S7). This movement is not well captured by FCF values as Siberian FCFs are higher than the Canadian one. However, we see a slight increase of Canadian FCF around 12.0 cal kyr and a NFP emerging in the Quebec region that is completely formed at 11.0 cal kyr BP_{2000} when the VGP is close to it. It is then observed a VGP movement towards Siberia up to 10.0 cal kyr BP_{2000}, which corresponds with an increase of FCF values in the Siberian/Northeastern hemisphere. The VGP path kept the same behavior during the time interval between 10.0 and 3.4 cal kyr BP_{2000} (Fig. S8). The more persistent the flux lobes were, the longer the VGP stationed in the same position. We also notice that when FCF is higher in the Canadian or Siberian hemisphere, the movement of the VGP is towards them (Table S2). At around 3.2 cal kyr BP_{2000} the paleopole moved sharply toward relatively low latitudes and at longitudes between two flux lobes between Canada and Siberia (although it is worth to mention that Canadian FCF > Siberian FCF at 3.2 cal kyr BP_{2000}). This displacement towards low latitudes could be due to the development of a NFP in the Levantine area and related to the “Levantine Iron Age Anomaly” (see below for more details).

From 3.0 to 2.6 cal kyr BP_{2000} the paleopole stationed at relatively low latitude (offshore Norway; Fig.7) possibly attracted by an already clearly formed low latitude flux patch, in association with the “Levantine Iron Age Anomaly” (LIAA). This anomaly is related to a normal flux patch at the CMB below the Arabian Peninsula, which appeared around 3.0 cal kyr BP, as highlighted by Osete et al. (2020). After reaching its highest value at around 2.95 cal kyr BP the flux patch expanded toward NW (Osete et al., 2020, Rivero-Montero et al., 2021), and the VGP moved in the same direction (Fig.7). This fact is especially remarkable because this B_r patch emerged from low latitudes. This finding can mean that either 1) this kind of strong geomagnetic anomalies due to the development of B_r patches at low-middle latitudes have a global effect on the VGP path, or 2) our sedimentary cores were affected by a regional geomagnetic effect, since they were close enough to the B_r patch.

After the flux patch related to the LIAA anomaly vanished in situ around 2.35 cal kyr BP (Osete et al., 2020), the VGP started to move clockwise toward higher latitudes attracted by the strengthened normal flux patches in North America. From 3.0 to 2.2 cal kyr BP_{2000} the interpretation of the FCF is very tricky due to the fact that the NFP at high latitudes is located between the Canadian and Siberian hemispheres and the FCF values are not very significant in these times.

With a clockwise path at 1.8 cal kyr BP_{2000} the VGP moved quickly toward the Siberia region (Siberian FCF > Canadian FCF). Then at 1.0 cal kyr BP_{2000} it reached Russia (Siberian FCF > Canadian FCF), and around 0.6 cal kyr BP_{2000} it returned toward Canada (the Canadian FCF shows a slight increase and the Siberian FCF decreases but it is still higher) (Fig. 8).

In order to test the plausibility of our hypothesis we performed a global analysis calculating the VGPs from the predictions of declination and inclination given by GGF100k, CALS10k.2 and SHAWQ family models at two other globally distributed locations from distant regions: the Levant region (30ºN, 38ºE) and Mexico (20ºN, 99ºW). As reported in Figures 7, 8, S7, S8 the VGPs positions are mostly close to the selected NFPs and mainly located in or moved toward the hemisphere with higher FCF (Canadian or Siberian). Obviously, this is just an example with two locations but the results are encouraging and it would be worth carrying out a deeper investigation in future.

Based on our analyses, we observe that the VGP motion in the polar region resembles that reported for the recent magnetic pole with direct geomagnetic measurements and is mostly related to the waxing and waning of radial magnetic flux lobes at CMB, preferentially located in Russia (Siberia) and North America (Canada). However, there are other possible explanations for these motions. For example, the large VGP shift that occurred between 3.0 and 2.6 cal kyr BP_{2000}, with the VGP moving from the Barents Sea toward low latitudes and North America is coincident with a growth of radial flux in the Pacific in CALS10k.2 model. It could be that the VGP path from the NBS22.2k stack is affected by this flux more than from the LIAA, but we notice that more recent models, such as SHAWQ-Iron Age, are not consistent with this hypothesis (Figure S4 in the Supplementary Material). As a final note, it is important to take into account that VGPs are difficult to interpret in the presence of non-dipole fields. More investigation is needed and new data and global reconstructions of the geomagnetic field will provide new evidences that may confirm our results. However, with our current knowledge, our findings could be important in future perspectives on the interpretation of the VGPs.

6. Conclusion

We reconstructed the variation of the geomagnetic field during the last 22.2 cal kyr BP_{2000} on the basis of paleomagnetic and rock magnetic data from sedimentary cores collected in the Arctic region. We obtained an improved stratigraphic correlation between cores that allowed us to refine the formerly proposed age model for such sedimentary cores (Caricchi et al., 2019, 2020). Following this refinement in stratigraphic correlation and dating, we merged the paleomagnetic data from the cores in PSV and RPI stack curves (that we named the NBS22.2k stack) spanning the last 22.2 cal kyr BP_{2000}.

The NBS22.2k PSV and RPI stacks show a satisfactory match with the trends predicted at the core location by various reference global geomagnetic field models (GGF100k, CALS10k.2, SHA.DIF.14k, SHAWQ-Iron Age, SHAWQ2k) and a global RPI stack (GLOPIS-GICC05), with the exception of a few time intervals comprised between 14.1-18.4 cal kyr BP_{2000} and 14.1-17.2 cal kyr BP_{2000} for inclination and declination respectively.

We reconstructed the Virtual Geomagnetic Pole (VGP) path on the basis of the NBS22.2k PSV stack. For the last 14 cal kyr BP_{2000}, the VGP path was overlaid on maps of the radial component of the geomagnetic field at the Core-Mantle Boundary computed from the most recent geomagnetic field models (GGF100k, CALS10k.2, SHAWQ-Iron Age and SHAWQ2k). Overall, we recognized centuries during which the VGP position was stable and centuries during which it accelerated its motion. This behavior is related to the appearance and disappearance of patches of strong radial magnetic field. The more the B_r flux lobes were persistent the longer the VGP stationed in the same position. We quantified this effect, calculating the Flux Concentration Factor (FCF) in Canadian and Siberian hemispheres. We observed that the VGP moves toward the hemisphere with higher FCF.

The VGP path described both clockwise and counterclockwise trajectories moving all around the Arctic region, mostly inside the surface projection of the inner core tangent cylinder. In some cases, it was characterized by westward drift, in others by eastwards drift and still in others it drifted toward lower latitudes, reaching Northern Europe. The largest VGP shift toward low latitudes occurred between 3.0 and 2.6 cal kyr BP_{2000} and is coeval with the paleomagnetic “Levantine Iron Age Anomaly” (LIAA); we associated both features to the development of a low latitude normal flux patch, which acted as a VGP attractor. However, different models could provide different results according to the type of data used as input, so more data are needed in order to constrain the VGP trajectories.

Summing up, during the last 14,000 yrs the northern hemisphere was characterized by the presence of transient patches of strong radial magnetic field flux patches that may have served as VGP attractors driving VGP position, path and speed. The present work highlights the importance of studying the variation of the geomagnetic field through the geologic past in order to improve the understanding of its behavior, place in a proper historical context its recent variation and provide constraints to predict its possible future evolution.

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All data presented in this paper are available as supplementary materials, they are published with a DOI via GFZ Data Services (Caricchi et al., 2022 https://doi.org/10.5880.fidgeo.2022.028) and they can be downloaded from the Thematic Core Service "Multi-scale laboratories" (https://epos -msl .uu .nl /dataset) of the European Plate Observing System (EPOS) and INGV repository. Three anonymous reviewers are kindly acknowledged for the precious suggestions that highly contributed to improve the paper. We also thank Hans Thybo for the careful editorial handling.

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Figures

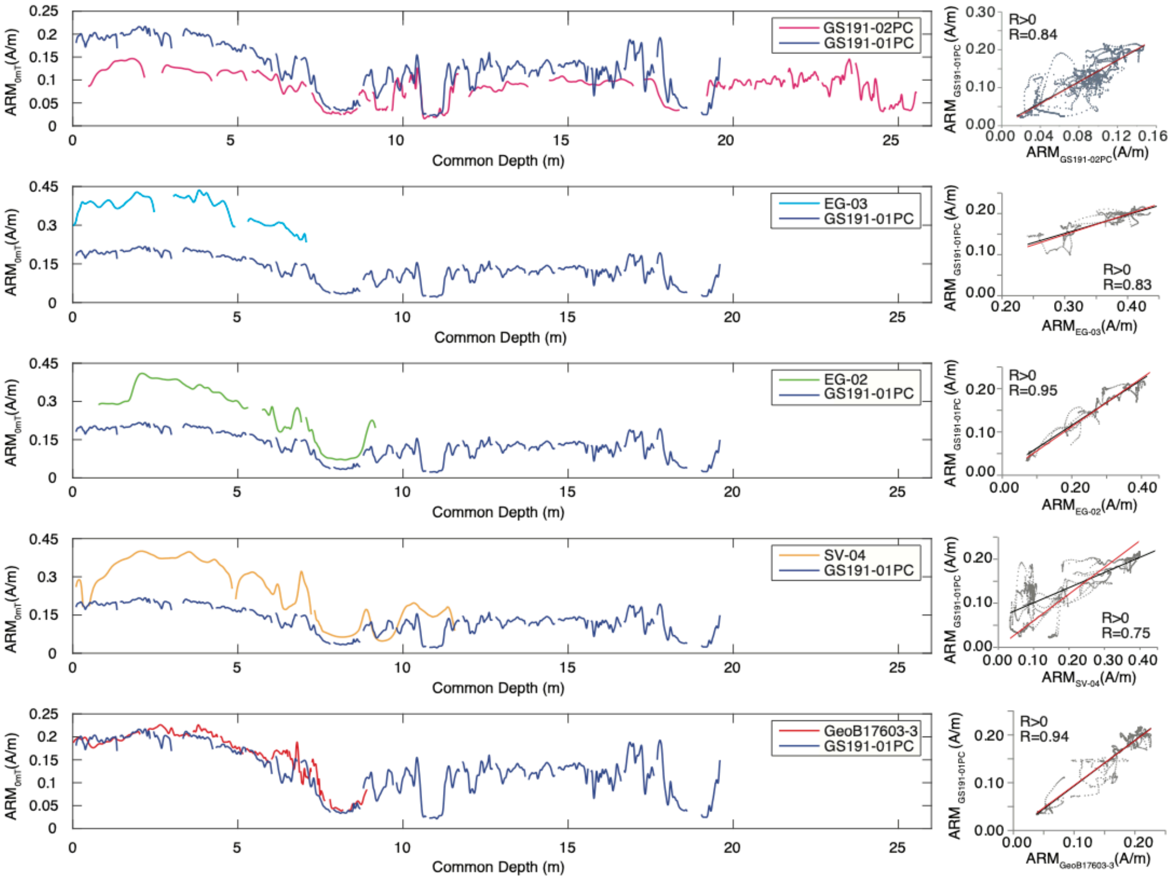

Figure 1. Correlation of the stratigraphic trends of Anhysteretic Remanent Magnetization (ARM) for the analyzed cores. GS191-01PC as the master curve and SV-04, EG-02, EG-03, GeoB17603-3 and GS191-02PC are the correlated curves (see the text for details). On the right side, the goodness of correlation is evaluated comparing the ARM values referred to a common depth. Linear fit passing through the origin ($y=ax$; red lines) and free intercept ($y=ax+b$, black lines) are shown. Correlation between GS191-01PC and GS191-02PC: $y=1.4419x$ $R^2=0.9552$, $y=1.401x+0.004$ $R^2=0.707$; Correlation between GS191-01PC and EG-03: $y=0.4958x$ $R^2=0.9926$, $y=0.4532x+0.0156$ $R^2=0.68874$; Correlation between GS191-01PC and EG-02: $y=0.5591x$ $R^2=0.9883$, $y=0.5263x+0.01$ $R^2=0.9119$; Correlation between GS191-01PC and SV-04: $y=0.6043x$ $R^2=0.8628$, $y=0.3442x+0.0665$ $R^2=0.5592$; Correlation between GS191-01PC and GeoB17603-3: $y=0.9426x$ $R^2=0.9873$, $y=0.9588x+0.0029$ $R^2=0.8919$.

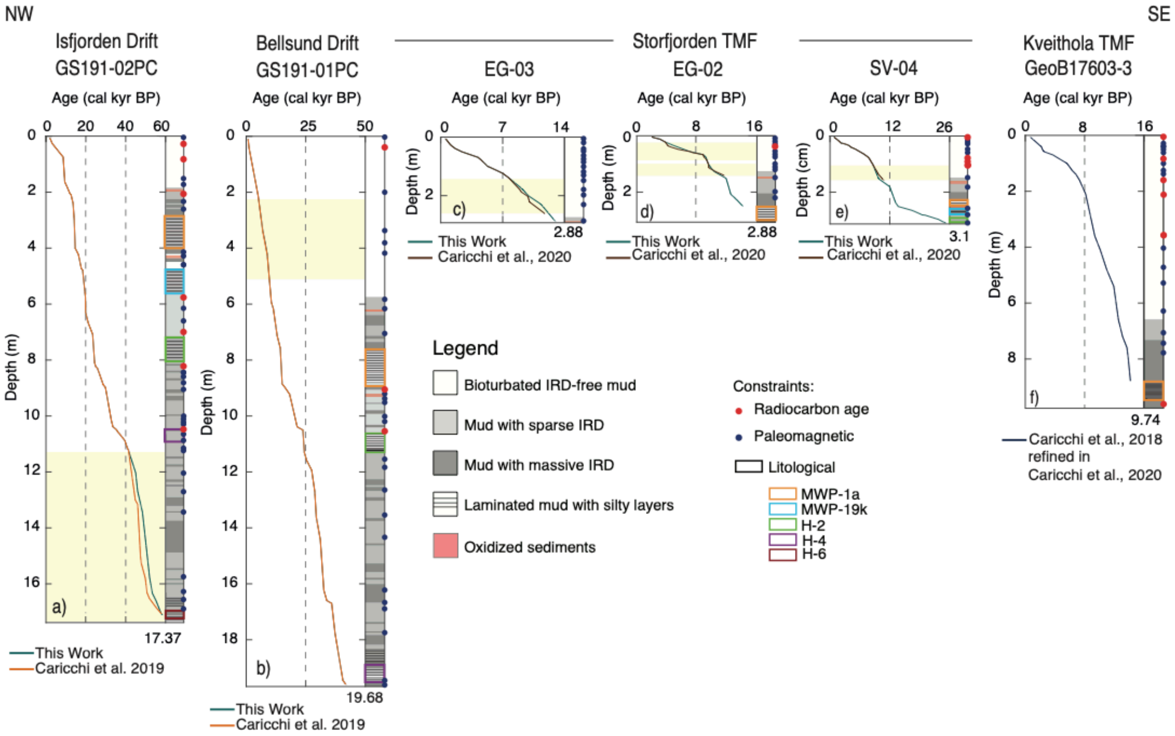

Figure 2 Comparison between old (Caricchi et al., 2019, 2020) and refined (this work) age models for the studied cores. The yellow rectangles highlight the portion of the cores where the age model was refined. The red dots indicate the available radiocarbon ages, the blue dots the paleomagnetic constraints and the colored rectangle the lithological constraints. Present refers to 2000 CE. MWP-1a = 14.65-14.31 kyr BP; MWP-19k (MWP-1A0) = 19 kyr BP; H2= 24 kyr BP; H4= 38 kyr BP; H6= ca 60 kyr BP.

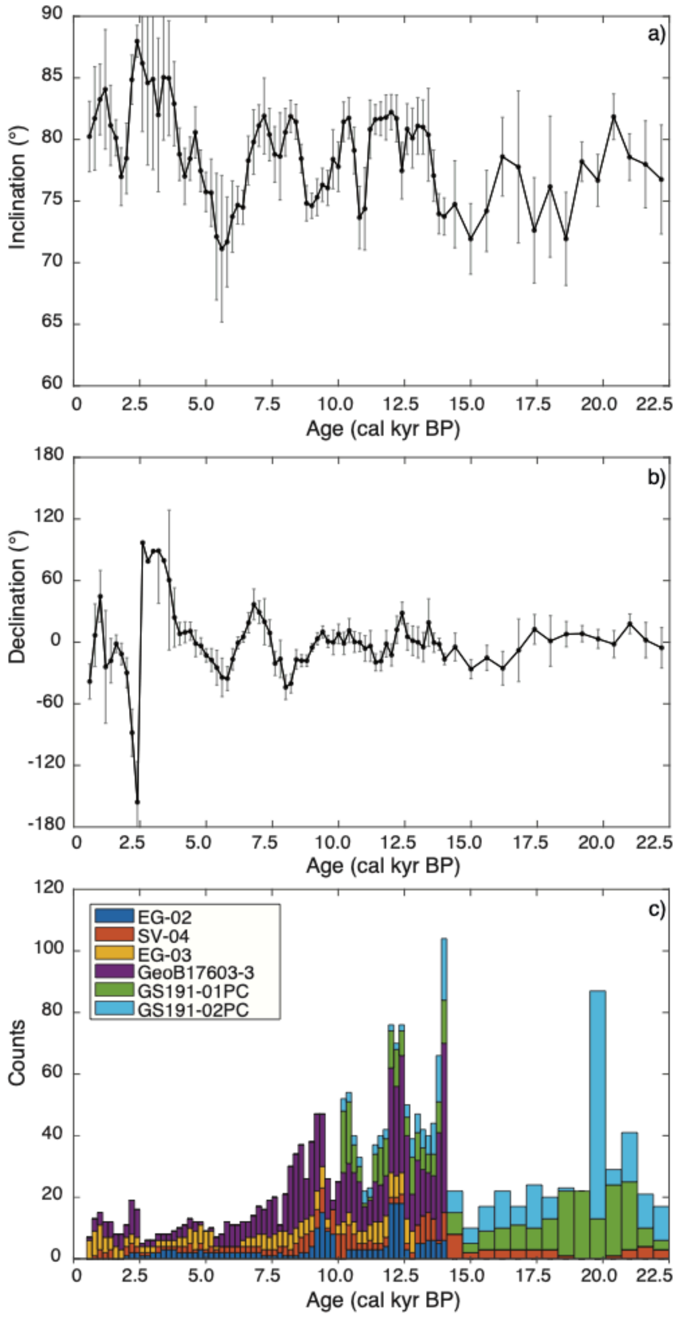

Figure 3 The NBS22.2k stack; paleomagnetic (a) declination, (b) inclination. The black circles indicate the mean value computed on data selected with a sliding window of 200 yr for the first 14 cal kyr BP and 600 yr for the interval between 14-22.2 cal kyr BP$_{2000}$. The error bars indicate the standard deviations computed taking into account the whole group of data in the sliding window. (c) Histogram showing the number of data across time and the various cores. Present refers to 2000 CE.

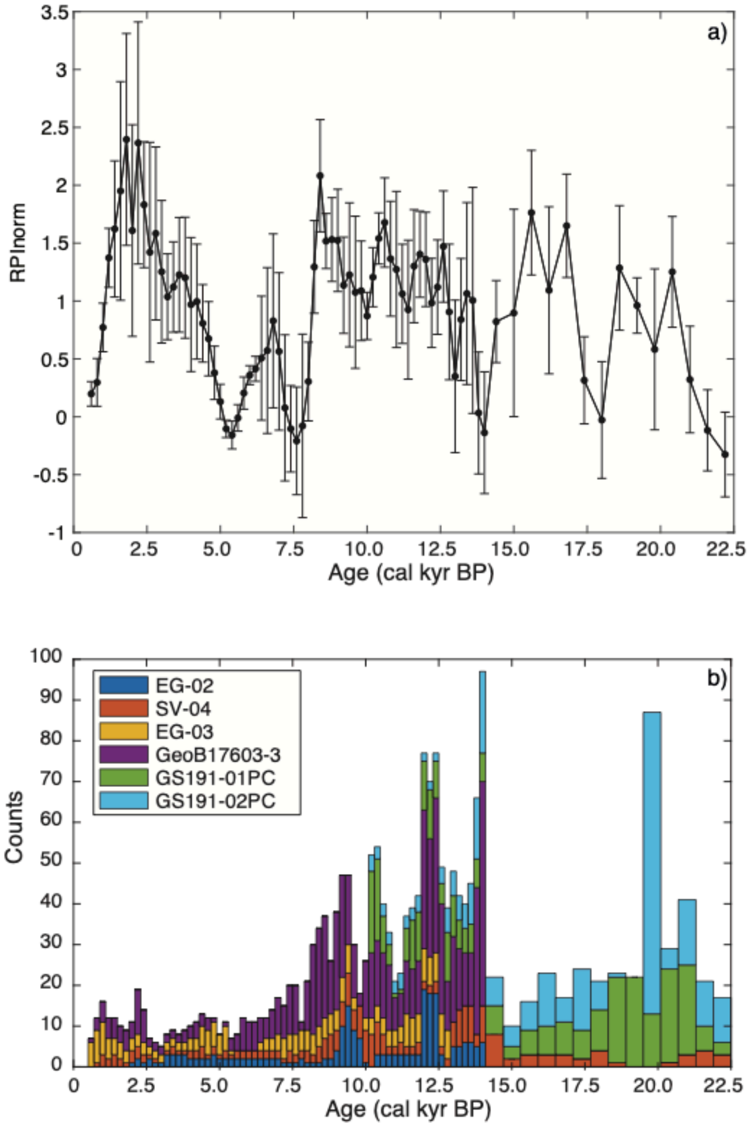

Figure 4 a) NBS22.2k RPI stack normalized to the median value according to the method reported in appendix (see Supplementary Material). The black circles indicate the mean value computed on data selected with a sliding window of 200 yr for the first 14 cal kyr BP_{2000} and 600 yr for the interval between 14-22.2 cal kyr BP_{2000}. The error bars indicate the standard deviations computed taking into account the whole group of data in each sliding window. (b) Histogram showing the number of data across time and the various cores. Present refers to 2000 CE.

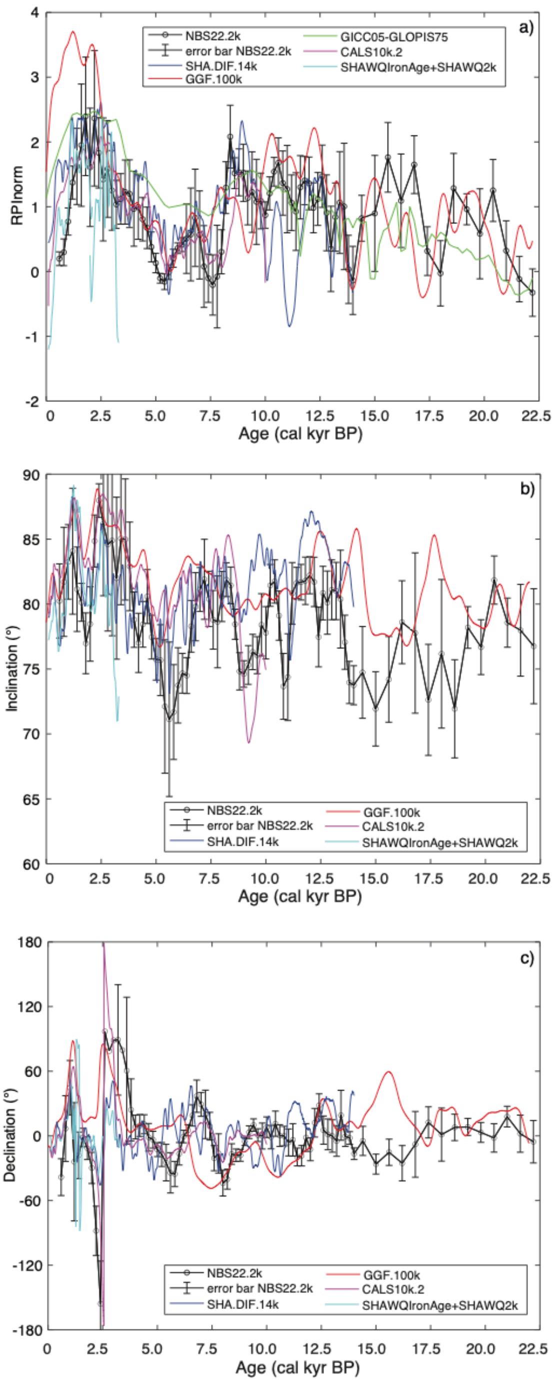

Figure 5 Comparison of the NBS22.2k RPI and PSV stack curves with predictions from the global geomagnetic field models; CALS10k.2 (Constable et al., 2016; purple curve); SHA.DIF.14k (Pavón-Carrasco et al., 2014; blue curve); SHAWQ-Iron Age (Osete et al., 2020) and SHAWQ2k (Campuzano et al., 2019; light blue curve); GGF100k (Panovska et al., 2018; red curve) and the GICC05-GLOPIS75 stack curve (Laj and Kissel, 2015, green curve). a) RPI intensity normalized median value according to the method reported in Appendix A (see supplementary material), (a) paleomagnetic (b) inclination and (c) declination. The geomagnetic field models were computed at the EG-03 core location, which has been selected as the reference location due to its central position in the study area. The intensity values from GGF100k and GICC05-GLOPIS75 were normalized only for the time period overlapping the age interval spanned by the NBS22.2k stack. Present refers to 2000 CE.

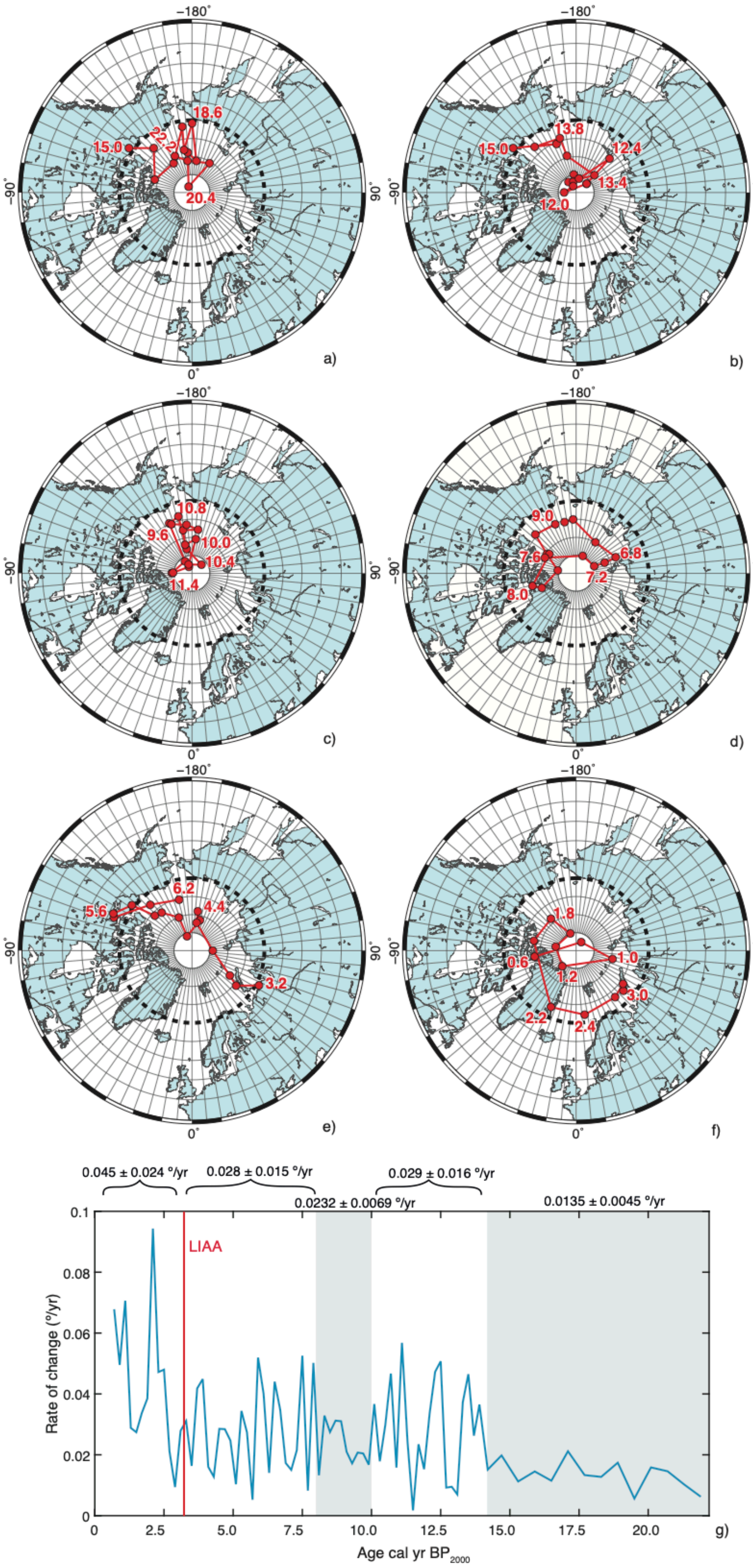
-180°
-90°
90°
0°
15.0
18.6
22.2
20.4
a)
13.8
15.0
12.4
13.4
12.0
b)
10.8
9.6
10.0
10.4
11.4
c)
9.0
7.6
6.8
7.2
8.0
d)
6.2
5.6
4.4
3.2
e)
1.8
0.6
1.0
1.2
3.0
2.2
2.4
f)
0.045 ± 0.024 °/yr
0.028 ± 0.015 °/yr
0.029 ± 0.016 °/yr
0.0232 ± 0.0069 °/yr
0.0135 ± 0.0045 °/yr
LIAA
Rate of change (°/yr)
0
0.02
0.04
0.06
0.08
0.1
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Age cal yr BP2000
g)

Figure 6 a-f) Reconstruction of the VGP path from paleomagnetic data of the NBS22.2k PSV stack, spanning the time interval from 22.2 to 0.6 cal kyr BP$_{2000}$. The black dashed circle indicates the surface projection of the inner core tangent cylinder (an imaginary cylinder coaxial with Earth's rotation axis and tangential to the inner core at the equatorial plane). Numbers in plots indicate the time in cal kyr BP$_{2000}$. Present refers to 2000 CE. The plots have been produced by GMT 5.4.3 (Wessel et al., 2013). g) Reconstruction of the VGP rate of change for the last 22.2 cal kyr BP$_{2000}$.

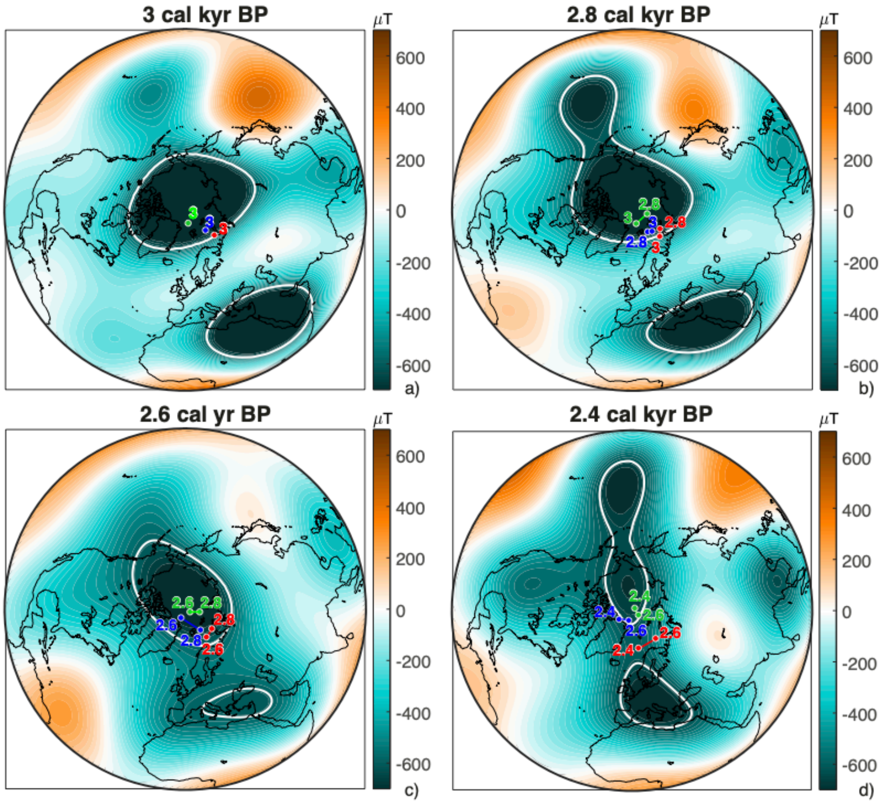

Figure 7 VGP path reconstruction of NBS22.2k PSV stack (in red), Levant (in blue) and Mexico (in green), overlaid on maps of the radial component of the geomagnetic field (in μT) at the Core-Mantle Boundary from SHAWQ-Iron Age model at (a) 3.0 cal kyr BP$_{2000}$, (b) 2.8 cal kyr BP$_{2000}$; (c) 2.6 cal kyr BP$_{2000}$, (d) 2.4 cal kyr BP$_{2000}$. Present refers to 2000 CE. White contour lines correspond to -580μT for (a-c) and -625μT for (d) and highlight the NFPs that act as VGP attractors according to our interpretation.

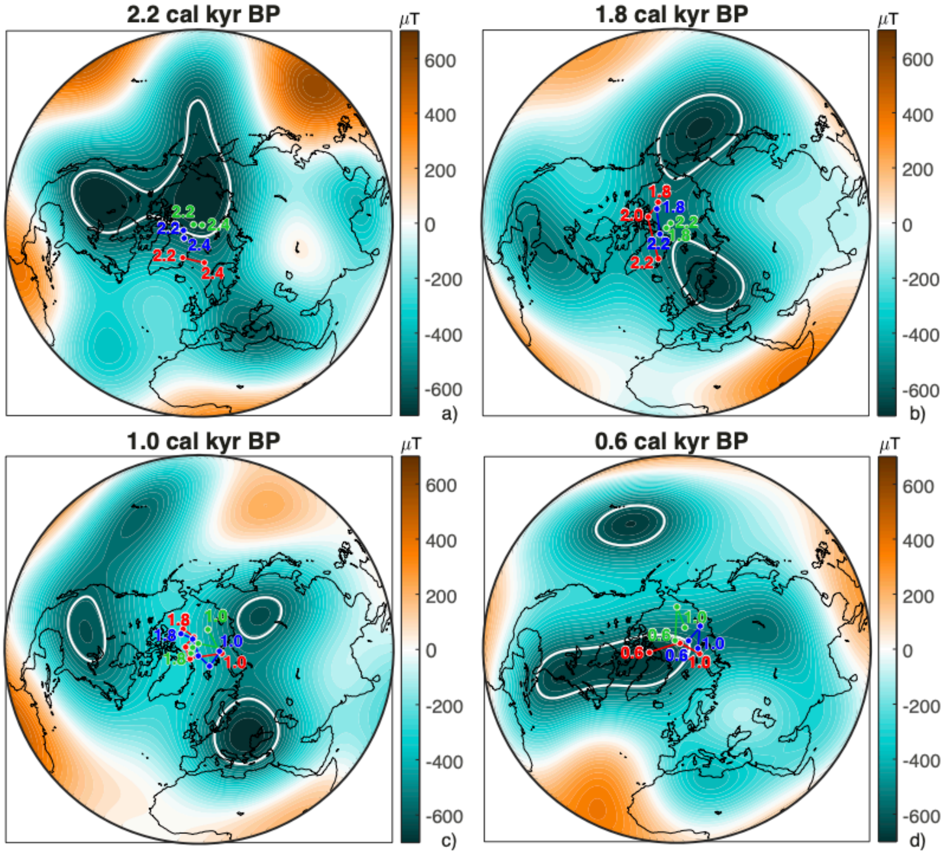

Figure 8 VGP path reconstruction of NBS22.2k PSV stack (in red), Levant (in blue) and Mexico (in green), overlaid on maps of the radial component of the geomagnetic field (in µT) at the Core-Mantle Boundary from SHAWQ-Iron Age model in (a) 2.2 cal kyr BP$_{2000}$ and SHAWQ2k in (b) 1.8 cal kyr BP$_{2000}$ (c) 1.0 kyr BP$_{2000}$ (d) 0.6 cal kyr BP$_{2000}$. Present refers to 2000 CE. White contour lines correspond to -625μT for (a) and -580μT for (b-d) and highlight the NFPs that act as VGP attractor according to our interpretation.

Supplementary material for

Reconstruction of the Virtual Geomagnetic Pole (VGP) path at high latitude for the last 22kyr: the role of radial field flux patches as VGP attractor.

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APPENDIX A

NORMALIZATION METHOD FOR RELATIVE PALEOINTENSITY CURVES AND MODELS

Each record has been scaled so that the location parameter (median) is equal to one, then interquartile range have been used to scale the variations about the median value.

1) As first step all records have been scale to median value as follow:

$$\mathrm{RPI_N} = \mathrm{RPI} / \mathrm{Median(RPI)} \qquad (1)$$

2) After $\mathrm{RPI_N}$ values have been translated so that the variations are about a median of zero

$$\mathrm{RPI_1} = \mathrm{RPI_N} - 1 \qquad (2)$$

3) Then $\mathrm{RPI_1}$ values have been scaled by interquartile range of RPI_1 to allow smooth records to have their variations amplified to simulate larger dynamic range.

$$\mathrm{RPI_2} = \mathrm{RPI_1}/\mathrm{IQR} \qquad (3)$$

4) In the and $\mathrm{RPI_2}$ values have been relocate to a median value of 1

$$\mathrm{RPI_3} = \mathrm{RPI_2} + 1 \qquad (4)$$

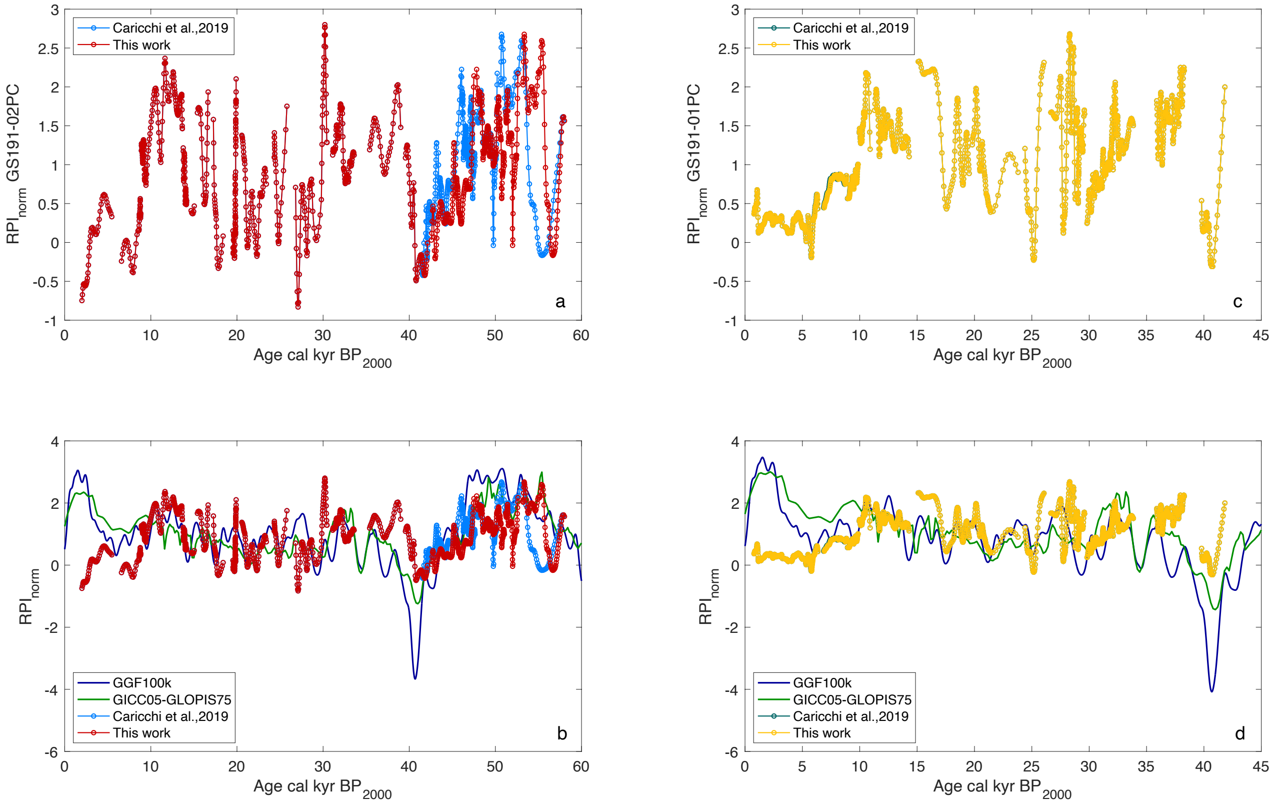


Figure S1 Comparison between RPI curves according to former (Caricchi et al., 2019) and new age models (this work) for cores GS191-02PC and GS191-01PC. RPI curves and models have been normalized following the method outlined in appendix A. RPI curves for the GS191-02PC and GS191-01PC cores are plotted together with the RPI curves from the GGF100k model and GICC05-GLOPIS75 stack. These curves have been normalized only for the time interval spanned by the analyzed cores.

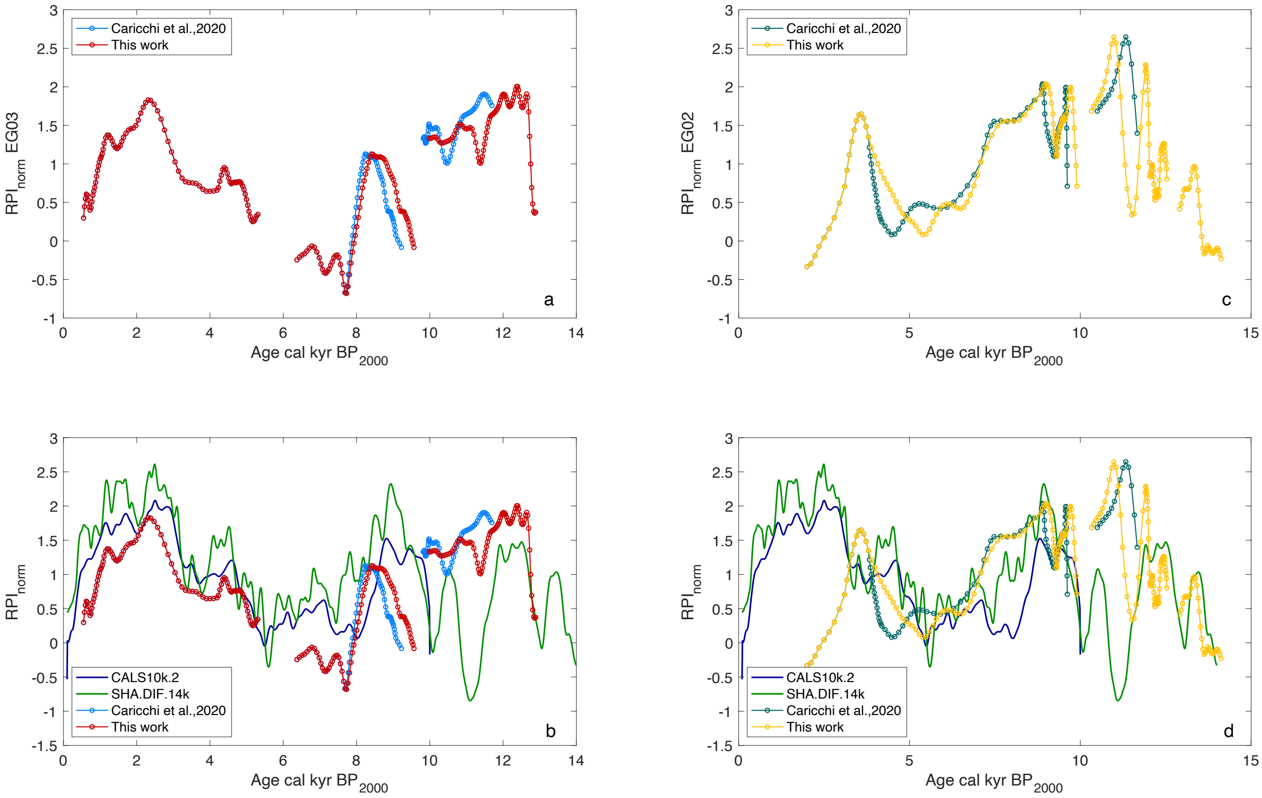


Figure S2 Comparison between RPI curves according to former (Caricchi et al., 2020) and new age models (this work) for cores EG-03 and EG-02. RPI curves and models have been normalized following the method outlined in appendix A. RPI curves for the EG-03 and EG-02 cores are plotted together with the RPI curves from to SHA.DIF.14k and CALS10k.2 models.

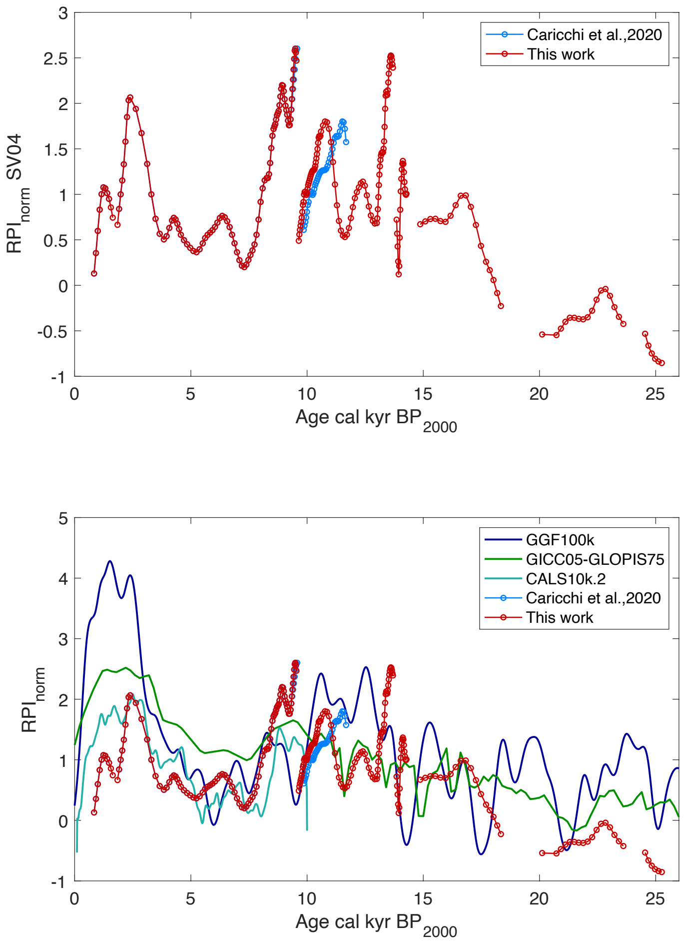


Figure S3 Comparison between RPI curves according to former (Caricchi et al., 2020) and new age models (this work) for SV-04. RPI curves and models have been normalized following the method outlined in appendix A. The RPI curves of the SV-04 core are plotted together with the RPI curves from the CALS10k.2 and GGF100k models and the GICC05-GLOPIS75 stack. The latter curves have been normalized only for the time interval spanned by the SV-04 core.

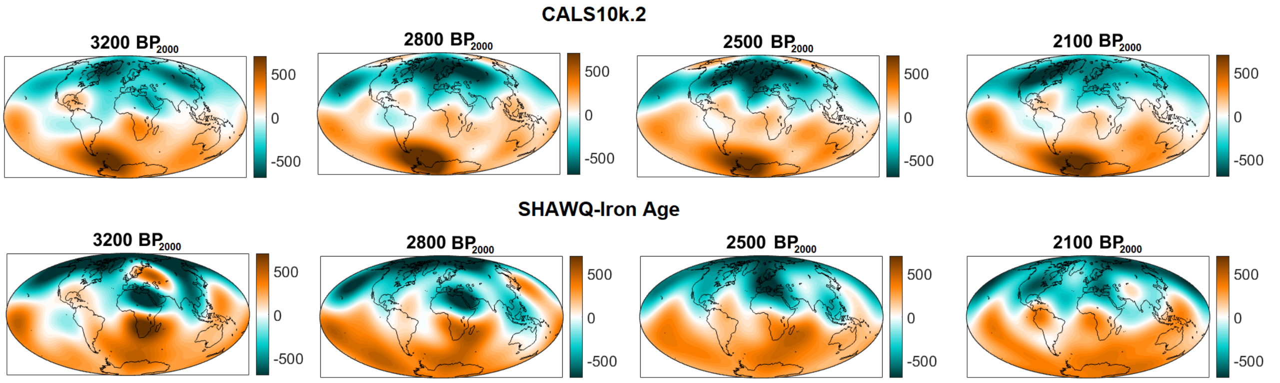


Figure S4. Maps of the radial field component of the geomagnetic field at CMB calculated using CALS10k.2 and SHAWQ-Iron Age models from 3.2 cal kyr BP$_{2000}$ to 2.1 cal kyr BP$_{2000}$.

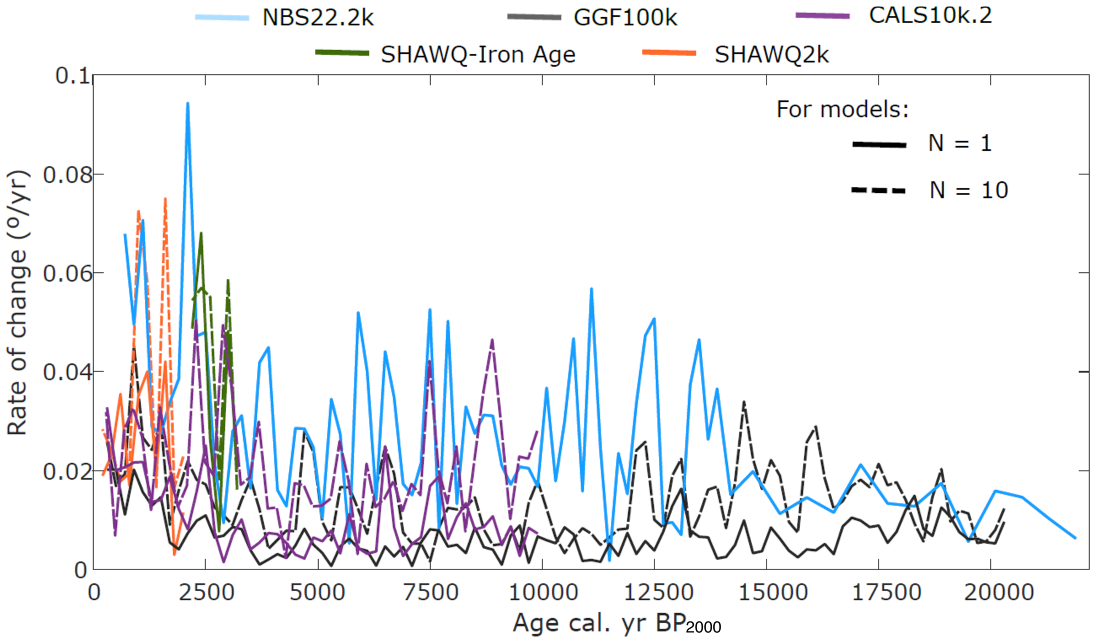
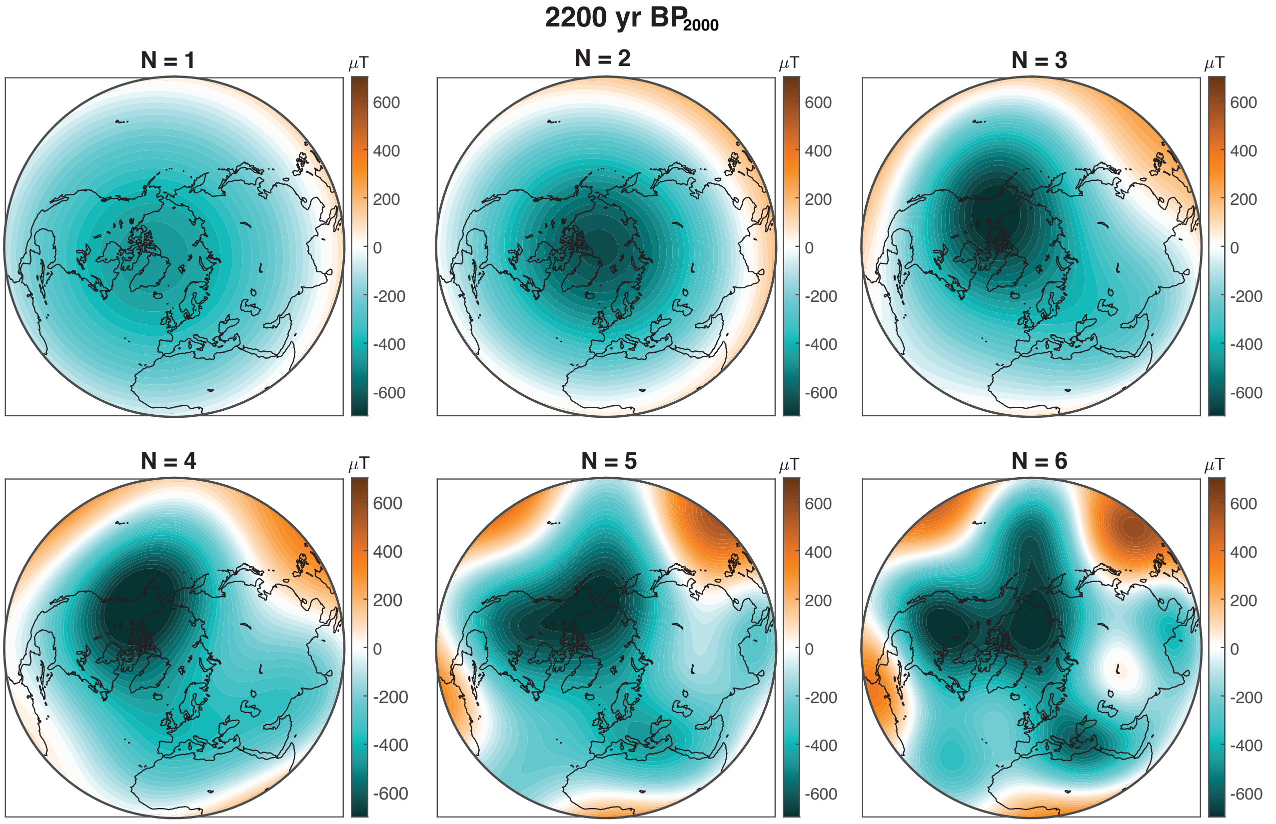


Figure S5 Rate of change of the NBS22.2 k VGP (blue) compared to the VGP calculated from models using maximum harmonic degree N = 1 (dipole) (solid lines) or N = 10 (dashed lines). In order to properly compare the various data sets, the rate of change of the VGP from the models has been calculated considering sliding windows of 200 yrs. See text and legend for more details about the models used. It is clear that there are times where the field behavior differs substantially from a pure dipole (N = 1). The effect of a significant non-dipole contribution is visible when calculating the mean and standard deviation for each curve, resulting in higher values (from 16% to 58% higher) for N=10 than for N=1.



2200 yr BP_{2000}

N = 1

N = 2

N = 3

N = 4

N = 5

N = 6

Figure S6 Maps of the radial component of the geomagnetic field (in μT) at the Core-Mantle Boundary from SHAWQ-Iron Age model in 2200 yr BP_{2000} calculated considering different maximum harmonic degree N: from N = 1 (dipole), N = 2 (dipole + quadrupole) up to N = 6 (the value chosen to carry out our study). Present refers to 2000 CE.

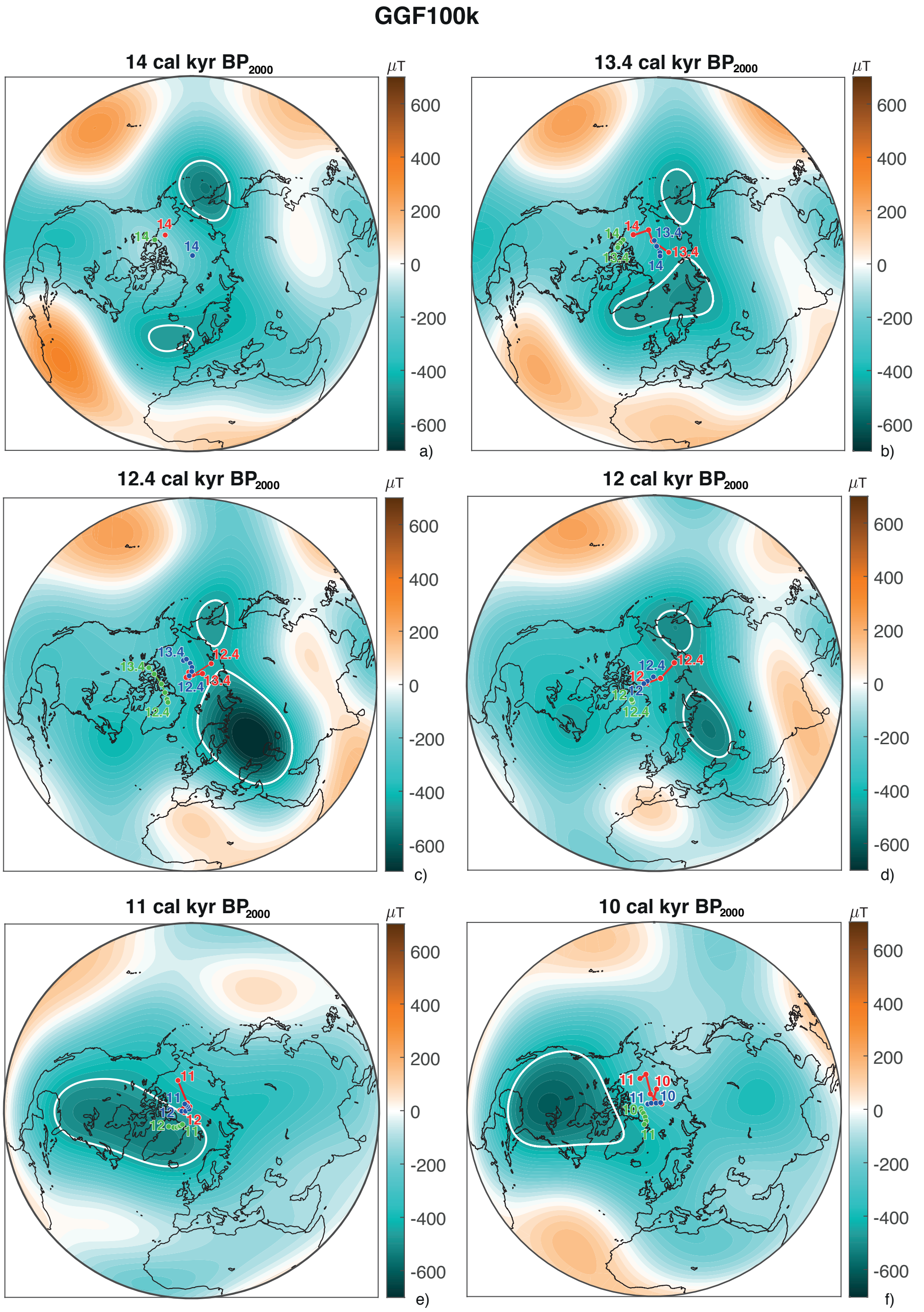


Figure S7 VGP path reconstruction from the NBS22.2k PSV stack (in red), Levant (in blue) and Mexico (in green), overlaid on maps of the radial component of the geomagnetic field (in μT) at the Core-Mantle Boundary from GGF100k model in (a) 14 cal kyr BP$_{2000}$, (b) 13.4 cal kyr BP$_{2000}$, (c) 12.4 cal kyr BP$_{2000}$, (d) 12 cal kyr BP$_{2000}$, (e) 11 cal kyr BP$_{2000}$ and (f) 10 cal kyr BP$_{2000}$. Present refers to 2000 CE.

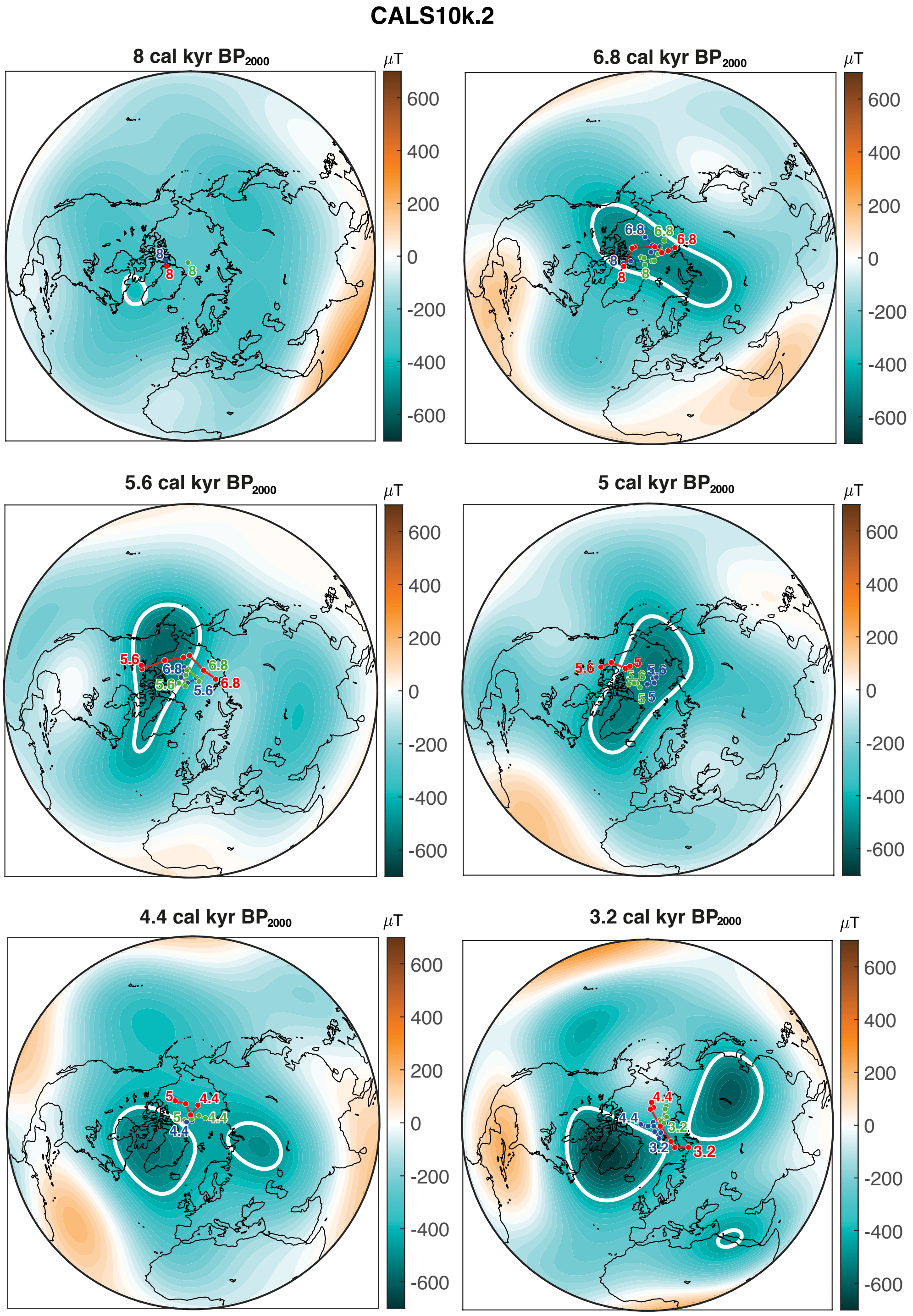


Figure S8 VGP path reconstruction from the NBS22.2k PSV stack (in red), Levant (in blue) and Mexico (in green), overlaid on maps of the radial component of the geomagnetic field (in µT) at the Core-Mantle Boundary from CALS10k.2 model in (a) 8 cal kyr BP$_{2000}$, (b) 6.8 cal kyr BP$_{2000}$, (c) 5.6 cal kyr BP$_{2000}$; (d) 5 cal kyr BP$_{2000}$; (e) 4.4 cal kyr BP$_{2000}$ and (f) 3.2 cal kyr BP$_{2000}$. Present refers to 2000 CE.