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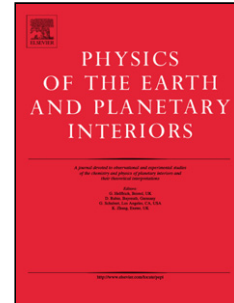
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Simulations of a Time-Varying Non Dipole Field During  
Geomagnetic Reversals and Excursions.

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## Abstract

Reversals and excursions have been simulated by decreasing the axial dipole field to zero while leaving up a time-varying non-dipolar field similar to the CAL7K model (Korte and Constable, 2005). We also envisaged the situation in which the total field changes sign. We first investigated the relationship between the non-axial dipole structure of the historical and present field snapshots and the virtual geomagnetic poles (VGP). The accumulation of VGPs in the vicinity of large flux concentrations in South Atlantic and Australia is constrained by the equatorial dipole. Only a few sites directly above the anomalies are associated with VGPs in their vicinity. Therefore, it seems delicate to associate recurring clusters of VGPs during reversals with magnetic flux concentrations at the CMB. The individual VGPs resulting from simulations of reversals show all kinds of trajectories, some being very simple with longitudinal confinement, while others are complex with alternances of slow and fast changes as well as loopings of VGPs. Preference for a specific longitude frequently happens in individual records, but this is not systematic. A direct consequence is that records of different reversals from a global array of sites are effectively dominated by preferred longitudinal bands. Thus, a time-varying non-dipolar transitional field can generate anisotropy of the VGP distribution. Smearing of the signal by sedimentary records considerably amplifies the longitudinal confinement of the VGPs. Overall, these simulations account for most characteristics reported in detailed reversal records, and thus strongly support the concept of a non-dipolar transitional field. We also simulated field excursions by assuming either a vanishing dipole followed by its return to initial polarity or by a short episode with the opposite polarity preceding its restoration. The model accounts for the different characteristics inherent to the volcanic and sedimentary records of the recent excursions. The simple structure of sedimentary VGP paths dominated by a large loop between northern and southern latitudes partly results from smearing of the signal. Therefore, these records do not fully describe the complexity of the excursions and remain exclusively sensitive to very low degree harmonics. Most detailed studies of excursions exhibit reversed directions which cannot exist without a very short dipolar episode of opposite polarity.

## INTRODUCTION

The model of a dominating non-dipolar field during reversals and excursions was formulated since the publication of the first reversal records (Cox et al, 1963; Dagley and Lawley, 1974). Indeed, very low field intensity was rapidly reported in studies, which implied that the dipole was either very weak or null. Since then, two basic scenarios of the reversing field have been defended. The first one considers that the existing records show evidence for recurring field behaviour during successive reversals. This hypothesis was strongly influenced by Laj et al (1991) who noticed a bimodal distribution of the longitudes of the transitional poles for several sedimentary records of reversals going back into the Miocene (Figure 1a). Because the recurrence occurs over such a long period of time, it was suggested that Earth's mantle was involved in the process of field reversal. Following these observations derived from sedimentary sequences, Love (1998) analyzed volcanic records and noticed that a similar bimodal distribution was also visible (Figure 1b), although the asian VGPs did not appear to be exactly located within the same longitudinal band as those from sediments. Using a smaller volcanic database dealing mainly with sites in the vicinity of Australia and Americas, Hoffman (1992) noticed the existence of clusters of VGPs (Figure 1c) over Australia and south America, thus within the same two longitudinal bands as the VGPs from sediments, which led him to propose that the sedimentary VGP paths are actually showing a smeared picture of the volcanic VGPs. This emphasizes the importance of the processes linked to the acquisition of magnetization in sediments. There is also a dominance of transitional VGPs from 11 records of the last reversal within two distinct pairs of clusters near Western Australia and within Siberia and in the southwestern Atlantic and northeastern Canada (Hoffman, 1990). Hoffman and Singer (2004) observed that the primary locations of the clusters of VGPs near western Australia, and to lesser extent in southwest Atlantic correspond to locations of the present non-dipolar field at Earth's surface with the largest vertical field component. Therefore, this reversal model which involves a control of the lower mantle on the dynamo processes prevailing during the transition implicitly assumes that flux patches remained essentially stationary with time. Stationary flux lobes at high northern and southern latitudes, but somehow different from the previous ones, were also revealed by downward continuation of the recent and historical field measurements at or above the Earth's surface to the core-mantle boundary (Jackson et al, 2000). Recent models (Korte and Constable, 2005) conclude to the persistence of flux lobes in the northern hemisphere during the past thousand years and to the presence of more vague negative flux lobes over the Indian ocean which could resemble a similar feature of

the historical field GUFM model. Several authors (Kelly and Gubbins, 1997) argue that the same flux patches persist in the time-averaged field models derived from global data distributions over time intervals as long as 5 Myr, thus giving additional support to some control of the field by the lower mantle.

The second type of reversal model defends the concept of a time-varying non-dipolar transitional field with characteristics and time constants similar to the present field. Due to the complex and rapidly changing geometry of the non-dipolar field, one do not expect a simple morphology of the VGP paths. In the absence of long-term standing feature, there is no reproducible field pattern in the secular variation, thus no evidence for preferred VGP clusters as well as for preferred longitudes during reversals (Valet et al, 1992; Prévot et al, 1993). This is justified by the fact that the geographical distribution of the sites contained in the archeomagnetic and paleomagnetic databases is not appropriate for constraining spherical harmonic analyses beyond degree 2 (Carlut and Courtillot, 1998; Valet et al, 2008). Accordingly, the presence of long-term standing non-zonal features emerging from global field models would be rather fortuitous.

Several other characteristic features of the reversing field have been suggested, most being related to dynamical aspects of the transition. Apparent rapid changes alternating with periods of standstill are frequent in volcanic records (Hoffman, 1991) but they can either have an actual geomagnetic origin or reflect the episodic character of the volcanic eruptions. Similar alternances also appear in sedimentary records obtained with very high resolution (Channell and Lehmann, 1997; Valet and Herrero-Bervera, 1993), thus closer to that of the volcanic records. The presence of extremely fast directional changes has also been reported in a detailed volcanic record obtained at the Steens Mountain (Coe and Prévot, 1989; Coe et al, 1995). Hoffman (2000) also noticed the absence of VGPs between the equator and 30°N in a compilation of records of the last reversal and suggested that this could reflect a barrier to reversal. When this apparent barrier was surmounted the pole would transit the equator at relatively fast rate. These dynamical aspects are important, as they can indicate whether magnetic flux is controlled by processes inherent to the core or is partly linked to the influence of the lower mantle.

The development of high resolution studies has greatly contributed to the detection of very short episodes during which the field direction significantly departs from the range of standard secular variation and can even reach the opposite polarity before returning to its initial state. The origin and succession of these excursions have important consequences as they reveal field

instabilities and may drastically change our concept of a geomagnetic field characterized by long periods of stable polarity. Given their frequency and their coincidence with intervals of low field intensity that are relatively well documented by multiple records of paleointensity for the last million years, it is realistic to consider that field excursions punctuated the history of the geomagnetic field. Their frequency in numerical (Dormy et al, 2000) as well as in experimental dynamos (Berhanu et al, 2007) is also consistent with this assumption. However, despite these recent advances, the database for records of excursions remains much smaller than for reversals. The Laschamp event (Bonhommet, 1970) is the best documented episode with very recent detailed sedimentary records (Lund et al, 2005; Laj et al, 2006) from various locations (Figure 1c) and several volcanic data that we have summarized in Figure 1d (Chauvin et al, 1989; Plenier et al, 2007). It is interesting that, similarly to reversals, volcanic VGPs appear to be rather scattered. A different picture emerges from the VGP paths of the most detailed sedimentary records which are relatively confined within the same large loop (shown in Figure 1d). This led Laj et al (2006) to suggest that the field geometry remains dominantly controlled by the dipole and therefore that both the dipolar and non-dipolar fields decay during these periods. Because the sense of the loop is different during the Laschamp and the Icelandic events, they consider that the  $g_1^1$  term dominates during the first phase of one excursion and  $h_1^1$  its second phase, whereas the opposite situation prevails during the other excursion. A recent modelling (Lanci et al, 2008) of the same high resolution records of the Iceland Basin Excursion favors a large reduction of the dipole but remaining higher than the non-dipole field throughout the excursions process, except for a very short period.

## SIMULATIONS OF REVERSALS

Virtual geomagnetic poles (VGPs) have always been conveniently used for testing simple field geometries (Fuller et al, 1979). It was rapidly established that different VGP paths were recorded at distinct sites during the same reversal and hence that the field was not dipolar. It was also shown that the distance of the VGPs from their site meridian was incompatible with a dominant axial symmetry. The VGPs have been used to test the existence of recurrent or standing features during different transitions. If we consider more complex field geometries, the representation of VGPs has less interest but remains useful to test predictions of simple models and to reveal dynamical aspects of the transitional process. Several authors (Constable, 1992; Quidelleur and Valet, 1996; Heller et al, 2003) have investigated the configuration of VGPs during a transition simulated by the decay, vanishing and reemergence of the axial dipole while leaving the remaining non-axial dipole field unchanged. Recently, Brown et al (2007)

proposed the same scheme but with a time-varying harmonic content obeying the CALS7K-2 model by Korte and Constable (2005). The basic assumptions behind this approach are that the dipole component decays or grows independently from the non-dipole field and that the non-dipole components vary randomly within some boundaries that are defined from our knowledge of the historical field. This separation between the axial dipole and the rest of the field can be defended since the non-dipolar terms have correlation times in the order or less than a couple of hundred years (Hulot and LeMouél, 1994) while the characteristic time constants of the axial dipole is much longer, in the order of 2000 years. LeMouél (1984) has shown that if fluid flow at the surface of the core is geostrophic, then the axial dipole is not involved in the process that builds up the secular variation. Under this assumption and following Brown et al (2007), it is thus reasonable to consider that the strength of the dipole field does not influence the secular variation of the non-dipole field, which implies to treat it separately.

However one can also assume that there is no strong indication that the core is in tangentially geostrophic regime during a reversal and thus no reason to consider that the axial dipole does not mix up with other harmonics, which is e.g. the case of reversal models defending a coupling between the dipole and quadrupole families (Merrill and McFadden, 1988). With one or two exceptions (that are likely caused by remagnetization processes) all paleomagnetic records have revealed that the dipole strongly decreases prior to any transition and that during this phase the radial component of the field remains dominant. There is no large deviation of the VGPs away from the rotation axis which would be expected for relatively high field strength if the non-dipole components grow in a substantial manner. Using the harmonic coefficients of the archeomagnetic CALS7K model we have simulated the decrease and subsequent recovery of the axial dipole in the opposite sense (as well as for the entire dipole) in presence of a time-varying non dipole field. In Figure 2, we plot the evolution of total field intensity as a function of VGP latitude. It is interesting that the two most complete (directional and paleointensity) volcanic records of reversals obtained so far at Steens Mountain (Prévot et al, 1985) and Hawaii (Herrero-Bervera and Valet, 2005) follow the same evolution as the model, indicating that in all cases the non-dipole field became dominant below the same threshold. Thus, the evolution of the non dipole/dipole ratio is similar to the predictions of the model and there is no reason, in the present state of knowledge, to envisage that the non-dipole components would behave differently (at least in terms of amplitude) during reversals.

These observations do not exclude the alternative scenario in which the total field reverses and not only the axial dipole. We are not opposed to this situation but we are faced to a major limitation for simulating this process since we have no indication as to when the non-dipolar



part of the field reverses and even if all terms reverse synchronously. We also note that most harmonic coefficients of the CALS7K archeomagnetic model changed sign during the past 3kyr. When dealing with snapshots of the field (particularly for exploring the characteristics of the modern field in terms of VGP positions) we can easily arbitrarily reverse all coefficients and compare the two approaches. For complete simulations of reversals, we did attempt some comparisons between the two models. We were forced to assume that all terms would reverse at the same time, which, as mentioned earlier, is not realistic. Indeed, the immediate effect was to introduce a large discontinuity in the reversing process. When plotted in terms of VGP positions, this was mostly equivalent to move their positions by  $180^\circ$  in longitude between the two hemispheres, and thus to break the continuity of the trajectories. For these reasons, we gave much less credit to this approach, which would require a more thorough treatment. Note however that the dominant features that are explored in this paper remain basically unchanged.

As for any model, the present approach has some limits and several physical basis can be discussed. However, we will see that this simple model describes all the major characteristics of the reversals observed in the paleomagnetic records. We follow the same philosophy as for predictions derived from numerical simulations of dynamos which, despite being very far from the Earth's dynamo, can predict many features of the geomagnetic field.

As mentioned above, the time-varying non-dipolar components were generated from the spherical harmonic coefficients described by the CALS7K model. However, we restrained the time period to the past 3 ka because the former 4 kyr are too poorly documented (Valet et al, 2007). Korte and Constable (2005) and Brown et al (2007) discussed the limits and imperfections of the CALS7K model caused by poor site distribution, limited temporal coverage, uncertainties in dating and determinations of some local field directions as well as paleointensity estimates. There is also a risk that the combination of volcanic and sedimentary records has increased the noise instead of improving the quality of the results (Valet et al, 2007). For these reasons, we do not claim that CALS7K provides a correct description of the field geometry. However, it has the merit of being the first model describing its evolution over such a long period. Keeping in mind these imperfections, it is reasonable to consider that CALS7K can be used as a generator of non-dipolar variations with time constants and characteristics that are quite similar to those of the actual non-dipolar field (Hulot and LeMouél, 1994).

Decay and recovery of the dipole were assumed to occur at the same rate. There is growing evidence in favour of an asymmetry between the two phases (Valet et al, 2005), but this aspect does not really concern the transitional period itself and thus has no effect on the field

geometry. Whether the entire dipole or only the axial dipole decreases prior to reversals can be debated. In order to explore distinct field configurations, the model has been run over different time periods separated by 500yr. We paid attention to the fact that the transitional directions would always occur within the 3 kyr period documented by the records. The first transitional directions appear when the dipole reaches about 15-20% of its present mean value and the transition last for about 1500 yr. This gives the possibility of studying four distinct transitional configurations for reversals with starting times separated by 500 years, since we are primarily interested by transitional directions. One can argue that this is too short a duration. We remind that estimates of reversal durations vary from less than one thousand to fifteen thousand years (Clement, 2004) and that they change for the same reversal depending on site location. Based on detailed dating of lava sections that recorded the last reversal, it has been recently claimed that the process could last as long as 18 kyr (Singer et al, 2005). However this estimate cannot be compared with the present simulations dealing with the onset and termination of the polarity switch but with the overall pattern of field intensity. We consider that, given the large number of records and attempts to obtain records of the last reversal, the depletion of transitional VGPs during this transition must be seen as an evidence of its extreme rapidity.

Sedimentary records were simulated by a convolution of the original signal using a function that mimicks the acquisition of magnetization. Despite some controversial discussions on this matter (Verosub, 1977; Katari et al, 2000; Katari and Bloxham, 2001; Carter-Stiglitz et al, 2006), it seems reasonable (and there is now an overall consensus) to envisage a magnetization process with at least half of the magnetic grains being very rapidly locked-in just below the surface (i.e. below the bioturbated layer) while the other half is progressively locked within the lower 20 centimeters. This takes into account a small delay linked to the bioturbated layer and preserves the initial polarity since 50% of the magnetization is locked-in within a few centimeters. Following previous studies, we used the exponential response function proposed by Meynadier and Valet (1996). This model accounts for smearing present in most sedimentary records, even over a short time period. Other choices could have been justified, but they would not affect the characteristics of the results.

## TESTING MODEL PREDICTIONS AGAINST DATA

### *Selection of reversal records*

Controversial interpretations regarding reversals depend on the selection of paleomagnetic records. So far, no consensus has been reached to define basic criteria aimed at selecting appropriate reversal records that are detailed and accurate enough to extract suitable

constraints. A large number of studies have been published for sediments that can be selected in different ways. We will not discuss here the validity of these selections, but we notice that the major features frequently reported from sedimentary records are a dominant longitudinal confinement of the transitional VGP paths within preferred longitudinal bands (seen in compilations of data but not in all individual records) and that a transition duration can vary between 1 and 12 kyr. Love (1998) compiled all volcanic records with VGPs latitudes lower than  $60^\circ$  (see Figure 1b). Each individual flow was treated as a single time event, implying no correlation between successive flows, or identically that the duration between flows was larger than the typical correlation times of secular variation. Love (1998) concluded that the database is consistent with the suggestion of preferred longitudinal bands over America and eastern Asia. Two other compilations of records have been considered by Hoffman (2000) and by Hofmann and Singer (2004). The first one deals with the records of the last reversal that have been incorporated in Love's and Mazaud's (1997) data. Hoffman (2000) found that each of five recordings examined from sites between latitudes  $45^\circ\text{S}$  and  $45^\circ\text{N}$  contain a VGP cluster in western Australia while the three remaining ones display significant VGP behavior in the South Atlantic. After dealing with the same reversal recorded from multiple sites, Hoffman and Singer (2004) turned to records of multiple reversals from a particular region. They considered three volcanic records of successive reversals from the Society island (Brunhes-Matuyama, Upper Jaramillo and the Punaruu excursion) and noticed that all contain again a number of sequential VGPs near western Australia, not unlike the Matuyama-Brunhes field behavior.

In many cases, compilations do not always rely on considerations linked to the resolution and overall quality of the records. In addition, sedimentary records can be controversial as they are poor recorders of fast field changes in presence of low field intensity during reversals. For these reasons, Valet and Herrero-Bervera (2003) proposed to consider high quality records from sequences of overlying flows (to avoid any problem of stratigraphy) with at least 5 full normal, 5 full reverse directions and a minimum of 8 intermediate VGP positions between  $60^\circ\text{S}$  and  $60^\circ\text{N}$ . Only six volcanic records (Coe et al, 2004; Chauvin et al, 1990; Herrero-Bervera and Valet, 1999, 2005; Herrero-Bervera et al, 1999; Prévot et al, 1985) shown in Figure 3 satisfy these requirements. Just below this category, the Greenland dataset (Riisager and Abrahamsen, 2000) provides a very detailed description of a 60 Ma old transition and was also taken in consideration despite very few normal and reverse polarity data. This selection is limited to 7 volcanic records and may be seen as not fully representative with respect to the large amount of data published so far. However, volcanic records which do not meet a minimum resolution do not really provide adequate information for the present exercise. The unique record from the

Society island that satisfy these criteria is the Upper Jaramillo which exhibits two VGPs in the vicinity of Australia. However it is also noteworthy that this record exhibits two other larger clusters in the East Equatorial Pacific and to the east of Mexico, that are not related to flux patches. In the bottom right planisphere of the same figure we have plotted all VGPs together. The main characteristics (Valet and Herrero-Bervera, 2003) appearing in all planispheres as well as in the compilation are the existence of three preferred longitudinal sectors, but also the presence of numerous clusters of VGPs at various locations of the globe. Altogether, there is no evidence for a dominance of the Australian and South American clusters. Actually, they are even completely absent from most records, the Australian cluster being mostly controlled by the 60 Ma old record from Greenland while the South American one is constrained by the record of the last reversal from Hawaii.

***Is there a significant relationship between flux concentrations and VGP positions?***

Because it has been suggested a link between the transitional field during recent reversals and the present field (Constable, 1992; Heller et al, 2003; Hoffman, 2002), it is interesting to explore first some pictures of a transition that would be dominated by a “static” non-dipolar field before considering a time-varying transitional field. We used the 2005 IGRF model to calculate the VGP positions for an array of sites every  $10^\circ$  of longitude and latitude between  $80^\circ\text{S}$  and  $80^\circ\text{N}$ . The upper planisphere in Figure 4 shows the vertical component of the non-axial dipole field (NAD) at the surface for year 2000. The two zones in southwest Atlantic and Australia associated with the most intense vertical non-axial dipolar field flux concentration are the same ones as those found in records of the last reversal (Hoffman, 2000) and records from the Society island hotspot. According to Hoffman and Singer (2004), when the axial dipole has almost vanished (a situation that would prevail during reversals), these localized flux concentrations at core surface largely define the structure of the residual field.

If these zones play a dominant role on the VGP distribution, sites in the vicinity of Australia should have their VGPs governed by the steep inclination of the non-axial dipole linked to the anomaly. The south Atlantic anomaly is a positive anomaly and should thus generate north VGPs in its proximity. Similarly, the negative Australian anomaly will be associated with south VGPs. In Figure 4a we show the distribution of the north VGPs corresponding to year 2000 NAD field derived from the IGRF geomagnetic field model for a global coverage of sites (separated by  $10^\circ$  of longitude and  $10^\circ$  of latitude). As already pointed out by Constable (1992), there is a large concentration of VGPs along the western coast of Americas. The south VGPs plotted in Figure 4b (which are equivalent to the north VGPs after changing the sign of all

Gauss coefficients) are predominantly found within the Australasian longitudinal sector. We note that these two largest concentrations of VGPs do not exactly coincide with the flux concentrations. The north VGPs are spread out over much lower latitudes than the South Atlantic flux, while the cluster of south VGPs extends far beyond the equator where there is no significant anomaly. It is thus important to investigate the role of the equatorial dipole because its north pole points in South America and its south pole is located in Indonesia. The pictures obtained after removing the equatorial dipole in Figures 4c and 4d display much more uniform distributions. The previous concentrations of VGPs have significantly decreased and have moved in longitude and latitude. Except for a few datapoints, they do not match any more with the flux concentrations.

At this stage, it is interesting to determine the geographical extent of the area that remains sensitive to these flux concentrations. We have selected the sites located within the two anomalies (Figure 4 e, f) . To those, we added the Pacific area (Figure 4 g) because Hoffman and Singer (2004) have reported that their south VGPs are located in Australasia. Their VGP positions (Figures 4 h, i, j) appear to be linked to the flux concentrations, which may be expected at least for the Australian and South Atlantic locations. This is more surprising for the Pacific sites given their distance to the Australian anomaly. After removing the equatorial dipole, the South Atlantic North VGPs (Figure 4 k) are still apparently controlled by the flux concentration in this area, but the south VGPs from Australia (Figure 4 l) are considerably spread out in latitude and there is almost no VGP remaining at the vertical of the field concentration. Finally, the VGPs positions from the Pacific sites (Figure 4 m) are quite scattered and do not appear to be related to the Australian flux concentration. The NAD field at these sites is thus essentially sensitive to the south pole of the equatorial dipole, likely more than for other locations given the weak non dipole field in the Pacific.

We infer that the equatorial dipole field is mostly responsible for generating apparent clusters of VGPs but there is no direct relation with the field anomalies generated by flux concentrations. Given its rapid and permanent evolution, it is delicate to envisage that the equatorial dipole is responsible for recurrent clusters during reversals. One can argue that the time-averaged field over the past 400 years shows similarities with today's field but this is meaningless when we consider the variance. However reversal records from volcanics are almost instantaneous spot readings of the field and the drift of the dipole has persisted over the past 400 years. Flux concentrations with similar magnitude as those of the present field can only induce significant field deviations in their immediate vicinity. The successive reversal records from Tahiti (Hoffman, 2004) with VGP clusters in Australia do not belong to this

category. This is also not the case for the 11 Matuyama-Brunhes records (Hoffman, 2000) that are from sites scattered about the globe.

We have also computed several snapshots of VGP positions corresponding to the non-axial dipolar field predicted by the CALS7K model for the past 4 kyr. We used the same array of sites as in the previous section and the same time periods as Korte and Constable (2005) for their predictions of the non-radial component at the CMB. If one assumes a mantle-controlled flux beneath mid-low latitudes sites like Australia, there must be a link between the VGP positions reflected by the clusters at the surface and the field at the core surface. In other words, it is also pertinent to deal directly with the magnetic field at the CMB. We note in passing that within the limitations inherent to the model, the archeomagnetic field is very rapidly changing at the core surface, which does not suggest any direct link with the mantle. For year 1800, the VGPs are concentrated over the American continent and they are absent from the rest of the world. Further back in time, we observe different field configurations, and the successive snapshots of VGPs plotted in the left column of Figure 5 never show any relationship with the field pictures at the CMB that are shown in the right column. More specifically the blue zones of downward field do not match with the north VGP positions shown in the right column. Therefore, it is obvious that the mirror image of these north VGPs which would reflect the south VGPs neither correlates with the red areas of upward field. Neither is there any persistence of VGPs over Americas, nor any evidence for alternance between Eastern-Asia and America. We infer that there is no direct relation between NAD patches and transitional VGPs. We are well aware that this exercise was restrained to a very narrow time window.

### ***Time-varying transitional field***

#### ***Morphology of VGP paths***

In Figure 6 are plotted the VGP paths (between 60°N and 60°S) corresponding to simulations of five different reversals (i.e. at different time periods) recorded at the same sites as the detailed paleomagnetic records shown in Figure 3. Some trajectories are longitudinally confined while others display a much more complicated structure, but most are rarely scattered over the globe, which goes against the concept that dominating non-dipolar components would be characterized by a sort of random walk of the VGPs. The simulations also show some concentrations of VGPs at various stages of the transitions with preference for western Europe and south Africa. However, the clusters do not coincide with any specific feature of the field and thus do not reflect long-term standing anomalies. The diversity of their locations in the most detailed paleomagnetic volcanic records shown in Figure 3 is also compatible with this

hypothesis. The snapshots of VGPs derived from the present and historical field shown in Figures 4 and 5 indicate that the existence and location of clusters is simply a consequence of the complex organization of the non-axial dipole field. These observations also support that many clusters of VGPs in paleomagnetic volcanic records reflect sampling of lava flows associated with short periods of intense volcanic activity. We believe that this most plausible cause must be regarded before invoking a relationship with the lower mantle.

#### *Longitudinal preference of VGPs*

The geographical distribution of VGPs depends on field geometry and could tell us about a possible link between core and mantle. Alternatively, we can also speculate that a specific harmonic content can generate recurring features, provided that there is limited variability in the evolution of the field so that similar configurations would be repeated over some periods. We first investigated VGP distributions generated by the time-varying NAD components of the CALS7K model at sites distributed every  $40^\circ$  of longitude and  $10^\circ$  of latitude. The results shown in Figure 7 (a,b) were obtained for two different field geometries and two reversals of opposite sense. The VGPs of the first transition are relatively scattered but show little preference for the African longitude. This tendency is more marked in the second case with a large depletion of points over the Pacific hemisphere. The next step was to investigate possible consequences linked to the acquisition of magnetization in sediments. We reproduced the same worldwide site distribution and the same two transitional geometries. The individual “sedimentary” VGPs (Figure 7 c,d) are more longitudinally confined than in the previous case. In both cases, the density distribution of VGPs differs from the original dataset. There is a large depletion over the Pacific ocean and a much denser concentration over Africa at the expenses of other areas like America. Clearly, the time-averaging process inherent to the magnetization of sediments accentuated the preference for the dominant longitudinal band.

A more complete view can be obtained by considering five successive reversals recorded from the same array of sites. The VGP distribution (Figure 8a) exhibits two little concentrations over Americas and western Pacific and a marked preference for Africa shown in the histogram of Figure 8b. The simulations of sedimentary records accentuated the dominant features (Figure 8c). The two secondary bands have disappeared leaving a flat histogram (Figure 8d) with the exception of the very large peak over Africa which has been considerably amplified.

The results of these simulations suggest two comments. First, despite its time evolution which only covers 3 kyrs, the non-dipolar field geometry of the transitional field shows preferred longitudinal VGP paths. This is not valid at all sites, nor for any period of time, but

strong enough to imprint the statistics of reversal records. The second remark is that the sedimentary records do not reflect the actual structure of the transitional field and considerably reinforce the existence of the preferred longitudinal bands. In order to extract information about the transitional field geometry and/or to detect recurring features, it is thus critical to rely on multiple records of the same reversals. The last reversal which in principle should be easier to detect in geological sequences, is effectively documented by a large number of sedimentary records, but there is only one high resolution record (Channell and Lehman, 1997).

In order to have some clue about the origin of preferred bands, we attempted to discern which spherical harmonics (or combination of harmonics) govern their existence. Different field configurations have been computed for two reversals of opposite sense after successively removing terms of degree higher than 4, 3 and 2. The presence of preferred bands of longitudes was reinforced after removing the degree 3 terms, thus leaving only the dipole and the quadrupole (Figure 9). However, the bands disappear without the  $g_2^2$  and  $h_2^2$  terms (Figure 9a) and are even more marked with these last two terms in the absence of  $g_2^1$  and  $h_2^1$  (Figure 9b). Lastly, we considered the two reversals separately and isolated the dominant role of  $h_2^2$ . We are aware that these simulations do not have any real physical meaning. Notwithstanding, it is interesting that the occurrence of preferred VGP longitudes is accounted by very low degree harmonics.

#### *Dynamics and duration of the transition*

Dominant characteristics of the VGP paths are the presence of large loops as well as periods of apparent standstill alternating with relatively rapid changes. The variations in VGP latitudes and field intensity as a function of time give some clue about the dynamics of the transition. In Figure 10, we show the Steens Mountain record from Oregon (Prévot et al, 1985) and the record of the Upper Jaramillo from Tahiti (Chauvin et al, 1990). We simulated distinct R-N and N-R reversals at the same sites and noticed several similarities with the actual records. The very rapid directional jump reported at the Steens Mountain (Coe and Prévot, 1989; Coe et al, 1995) is associated with a large looping of VGPs which follows the first phase of the transition when the pole moved from south to north and coincides with the lowest paleointensity (Figure 10a). Similar rapid variations can also be seen in some predictions of volcanic VGP paths with an episode of looping and very low field intensity (Figure 10b). The same remark holds for the record from Tahiti. The time interval of 50 years between two successive datapoints gives a scale for the rate of field changes which is intermediate between a few degrees per day proposed for the Steens Mountain and 0.1 degree per year for the present-day secular variation.



Shorter variations are not excluded and were actually obtained from simulations at other sites. Directional jumps were also reported by Brown et al (2007) who concluded to geometric effects as a result of specific combinations of harmonics. Following the same idea, it is interesting that Backus (1983) suggested that mixing of harmonic modes maybe responsible for the geomagnetic jerks, which was subsequently refuted by Courtillot et al (1984).

The plots in Figure 10 may also provide information concerning the duration of the transitions. If we consider that the limit at  $60^\circ$  of latitude defines the boundaries of the transitional field, we obtain transitional durations of about 2000 years. This is relatively shorter than current estimates (Clement, 2004), but there is a very large variability and most values found in the literature are derived from sediments which may overestimate the length of transitional intervals. Here, the value of 2kyr is constrained by the rate of the dipole changes. We cannot exclude a scenario involving slower dipolar changes, which evidently increases the complexity and the duration of the transition. This would imply that episodes are missing in the most detailed volcanic records since a longer transitional period would be associated with additional field variations and thus more complex VGP paths. The morphology of the most detailed sedimentary VGP paths of the last transition (Channell and Lehman, 1997) may be consistent with this hypothesis. There is also no reason that each reversal had the same duration. In the present state of the art, we consider that the overall resemblance between the predicted transitional paths and the most detailed existing records is an indication that a 2kyr duration is reasonable.

#### SIMULATIONS OF EXCURSIONS

The Laschamp event being the only excursion documented both by volcanics (Bonhommet, 1970; Chauvin, 1989, Roperch, 1988; Levi, 1990; Plenier, 2007) and by a large number of recent sedimentary records (Nowaczyk et al, 1994; Lund et al, 2005; Laj et al, 2006; Vlag et al, Leduc et al, 2006), this event primarily retained our attention. In Figure 11a all intermediate VGPs published so far from volcanic flows in the Massif central are plotted along with the large loop of the sedimentary VGPs shown in Figure 1d. We remind that the chronology of the flows in the Chaîne des Puys is not unambiguously established because of the absence of overlying lavas in a single sequence. It is striking that the Laschamp as well as the Icelandic event and many others (Channell, 2006) exhibit VGPs of reversed polarity even in sedimentary records. These reversed directions cannot be induced from remagnetization processes, nor from smearing or other effects in sediments (Rochette, 1992; Langereis et al, 1992; Barton and

McFadden, 1996; Roberts and Winklhofer, 2004) and must thus be seen as an intrinsic geomagnetic feature (Valet et al, 2008).

We simulated field excursions using the same approach as for reversals. We computed an axial dipole decreasing to zero and then growing back with the same polarity but also a scenario in which the dipole decay was followed by a short episode of growth in the opposite polarity before returning to the initial situation. Among various computations performed at the location of Laschamp we can isolate several VGP paths with more or less similar positions and equivalent dispersion as in the paleomagnetic records (Figure 11b). However, we were not able to produce VGPs reaching high southern latitudes with a dipole that only decays to zero. The trajectory shown in Figure 11b was obtained with a reversed field reaching 20% of its initial strength. A dominant characteristic of simulated VGP paths is the presence of large loopings. The existence of loops was reported in numerous records of excursions (Lund et al, 2005). Recently, Laj et al (2006) gathered very high resolution marine records of the Laschamp (40ka) and the Icelandic events (190ka) which describe a large similar loop in opposite sense for each excursion (Figure 12a). They interpreted this recurrent pattern by a relatively simple and probably dipolar geometry during the two events and pointed out the role of the equatorial dipole. Since the total field is considerably reduced during the excursions, the hypothesis of a dipolar “transitional” field implies that both the axial dipolar and non-dipolar components decreased together, which seems unlikely (but maybe not impossible) given their widely different time constants. In addition, this scenario depicts a very smooth loop due to the rotation of the equatorial dipole and cannot be reconciled with the dispersion of VGPs inherent to the few detailed volcanic records of excursions.

Interestingly, the VGP paths recorded at the various sites are quite similar to those derived from the present non-dipole model after smearing the signal to simulate the acquisition of magnetization in sediments (Figure 12b). This is not surprising as the smoothing process filters the high-degree harmonics and thus enhance the contributions of the quadrupole and equatorial dipole. In fact, this process is even larger if we integrate the time-averaging over the sample size or the window length of pass-through measurements. Finally, it is important to note that, as shown by the records (Laj et al, 2006), the simulations predict also that the sense of looping change for different excursions. This depends on the evolution of the harmonic content.

Such similarities between excursions controlled by the present-day non-dipole field and the paleomagnetic records of the last excursions suggest that the harmonic content of the field was not strikingly different during the Laschamp period than from during the past 3kyr. These results also suggest similar mechanisms during the first phase of reversals and excursions, both

being characterized by the emergence of time-varying non-dipolar components prior to reversal of the axial dipole. Similar complexity of the reversal process is predicted by multiscale dynamo models (Narteau et al, 2007).

## CONCLUSION

These series of simulations have revealed several interesting characteristics of the VGP paths during reversals and excursions. We have been dealing first with the present non-axial dipole field and noticed that the largest flux concentrations do not induce significant anomalies, at least not large enough to concentrate the pole positions, except for sites lying in their close vicinity. Clusters of VGPs derived from the present NAD field are actually linked to the equatorial dipole. Therefore, we disclaim the existence of a systematic and direct link between persisting patches of magnetic flux and VGP locations, unless they would be considerably more intense than at the present time during field reversals, although there is no evidence from the paleomagnetic records obtained so far. Another surprising observation is that, despite a complex non dipolar and rapidly changing transitional field, the superposition of VGPs from multiple reversals depicts some large scale organization with marked and persistent preference for some longitudinal bands. However, individual VGP paths exhibit very different configurations, some with longitudinal preference while some others are quite scattered all over the globe. These results that are derived from a quasi-random evolution of the non-dipole field disclaim any long-term persisting pattern of the field and thus fail to see any link with the lower mantle.

Simulations of field excursions using the same non-dipole model account for the major features of the paleomagnetic records with large loopings of the pole in alternance with more complex episodes. In contrast, an excursionsal field governed by the equatorial dipole (thus assuming a concomittent decrease of the axial dipole and non-dipole terms) produces a large loop of the VGPs but fails to reproduce the scatter of the VGPs positions inherent to the volcanic records. The loop of the sedimentary VGP paths is notably amplified by smearing of the signal in sedimentary records which reinforces low degree harmonics and can thus generate distortion of the initial signal. Finally, paleomagnetic directions of opposite polarity are extremely unlikely without a short period of opposite dipole with a strength of at least 15-20% of initial intensity.

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## Figure captions

Figure 1: (a) Compilations of reversal records from (a) sediments (redrawn from Laj et al, 1991) and (b) from volcanics (Love, 1998). (c) selection of VGPs clustering over Australia and eastern south America (Hoffman, 1992). (d) Compilation of sedimentary (Laj et al, 2006) and (e) volcanic records of the Laschamp event (Plenier et al, 2007).

Figure 2: Field intensity as a function of VGP latitude derived from simulations of reversals assuming either a decrease of the axial dipole or a decrease of the total dipole. The results are compared with the two most detailed volcanic records of reversals including a determination of the full vector. The changes predicted by the model are globally the same as those reflected by the data which supports the concept that the strength and the amplitude of the non dipole field remain globally the same.

Figure 3: VGP paths of the seven most detailed volcanic records of reversals. The bottom left larger planisphere shows all VGPs together.

Figure 4: Top: Vertical component of the non-axial (NAD) dipole field at the surface at year 2000. (a-f): north (black dots) and south (red dots) VGPs calculated from the NAD field at year 2000. North (resp. south) VGPs were calculated with respect to the positive (resp. negative) flux concentration in south Atlantic (resp. Australia) - (a-b): north and south VGPs for all sites separated by  $10^\circ$  of longitude and latitude between latitudes  $80^\circ\text{N}$  and  $80^\circ\text{S}$ . (c-d): same but without the equatorial dipole. (e-g) selections of sites used for the calculations of the VGPs shown for the total NAD ( h - j) and after removing the equatorial dipole (k-m).

(c) Same as (a) but restricted to the american sites shown in (e). The VGPs are mostly found in the vicinity of south America, but not directly above the American continent. (d) Same as (a) but restricted to the eastern Asian sites shown in (f). The VGPs lie to the west of the United States and across south Eurasia without relation with the site location.

Figure 5: Left column – Snapshots of the VGP positions corresponding to the non-axial dipole fields derived from Korte and Constable (2005) at different periods during the past 5kyr. Right column – corresponding snapshots of the radial component of the non-axial dipole contribution at the CMB (redrawn from Korte and Constable, 2005).

Figure 6: VGP paths of four different reversals (plotted between  $60^\circ\text{S}$  and  $60^\circ\text{N}$ ) recorded at three distinct sites. Note the diversity in structure and geometry of the paths as well as in the dynamical aspects of the transitions.

Figure 7: Intermediate VGPs (between  $45^\circ\text{S}$  and  $45^\circ\text{N}$ ) of two different reversals (a,b) with starting times separated by 500 years and recorded from sites distributed every  $40^\circ$  of longitude and  $10^\circ$  of latitude. (c, d) Simulations of the same reversals recorded by sediments.

Figure 8: (a) Positions of VGPs for five N-R and five R-N reversals recorded at the same sites as in Figure 8. (c) Same reversals recorded in sediments. (b, d) The VGP preference for the african sector is very strongly reinforced by the sedimentary records which do not reflect the original field.

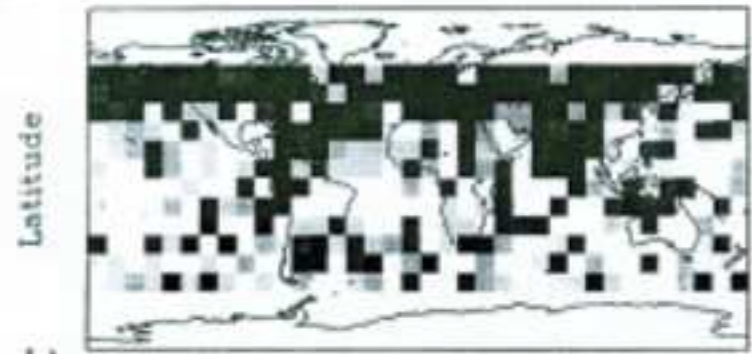
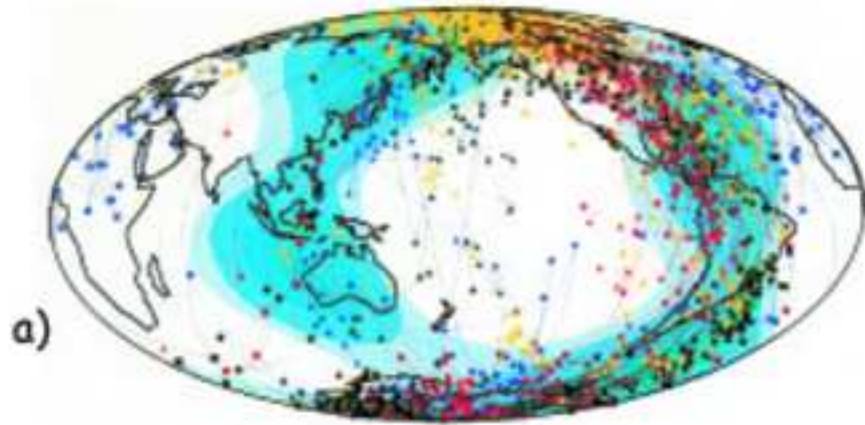
Figure 9: a) VGP positions obtained for the same reversals as in Figure 8 with a field restrained to degrees 1 and 2 - a) without  $g_2^2$  and  $h_2^2$  - b) without  $g_2^1$  and  $h_2^1$ .

Figure 10: VGP latitude as a function of time derived for two simulated transitions (b and d) at the same sites as the paleomagnetic records (a and c). Despite the relatively short time period explored by the model, the similarities with these very detailed reversal records from volcanic sequences suggest that the timing is appropriate.

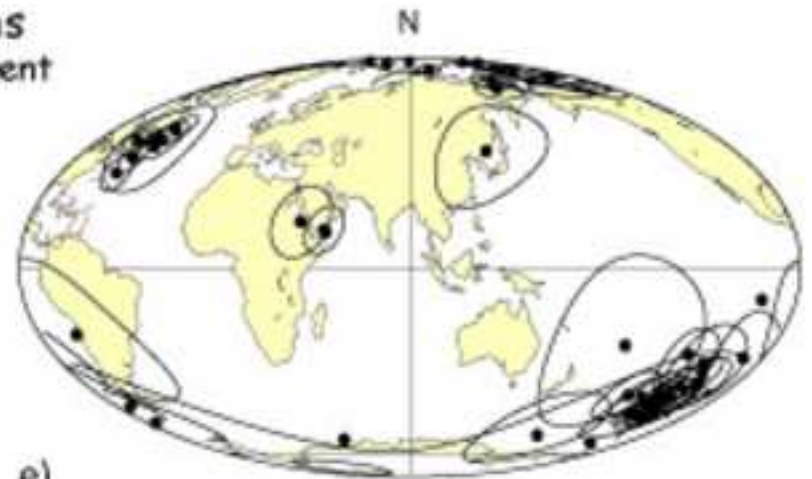
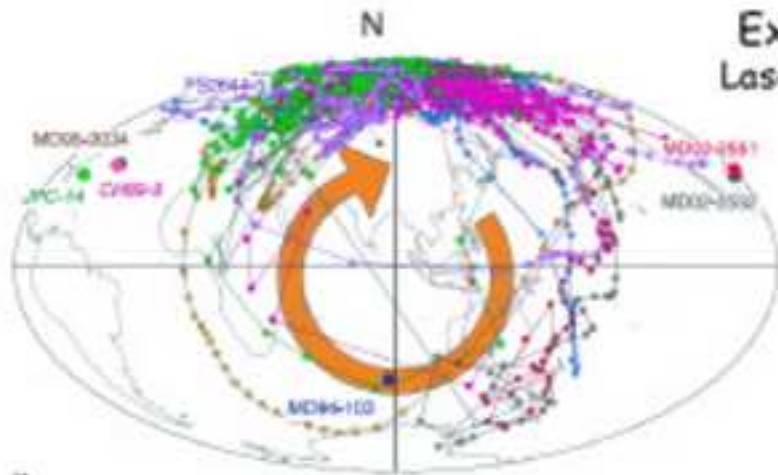
Figure 11: (a) Volcanic VGPs of the Laschamp event. The blue area depicts the loop which contains the VGPs of the sedimentary records (Laj et al, 2006). (b) Simulation of a volcanic excursion recorded at Laschamp.

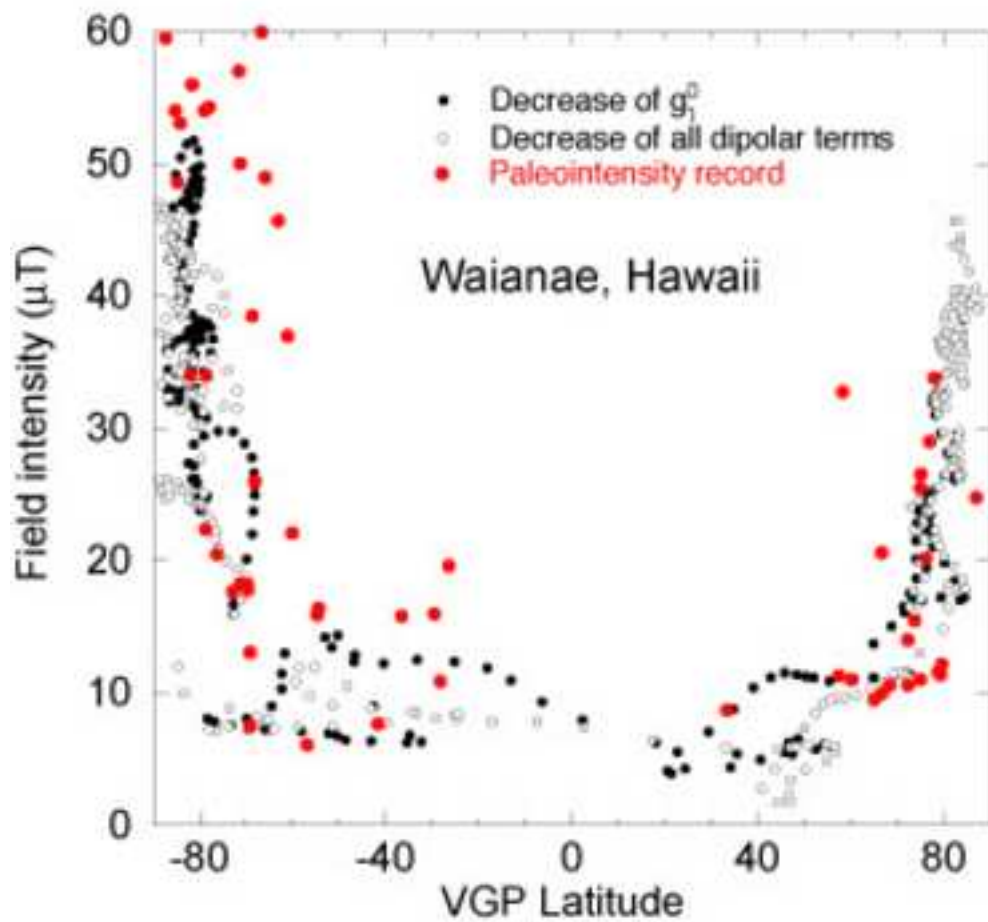
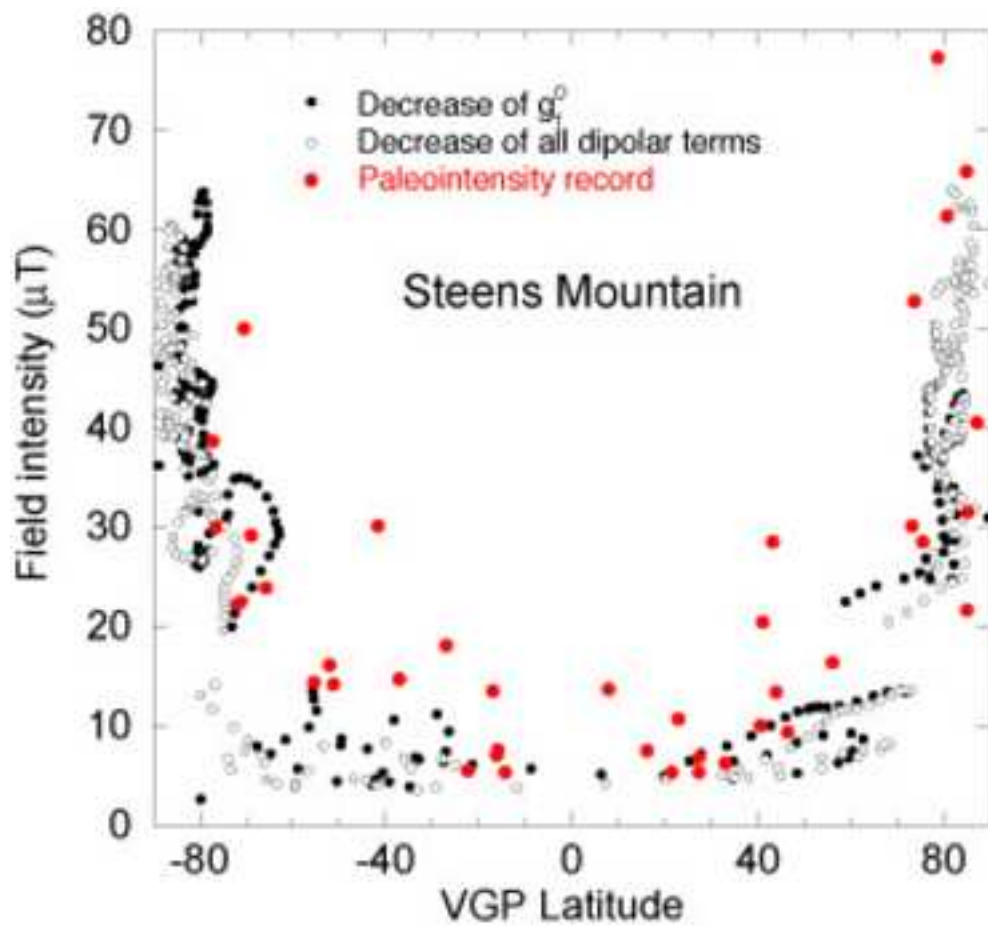
Figure 12: (a) VGP paths of different sedimentary records of excursions (redrawn from Laj et al, 2006). (b) Simulations of four distinct excursions recorded at the same sites. The surprising similarity with the actual records suggests that the characteristics of the non-axial dipole field were not so different from the present ones during the Laschamp event.

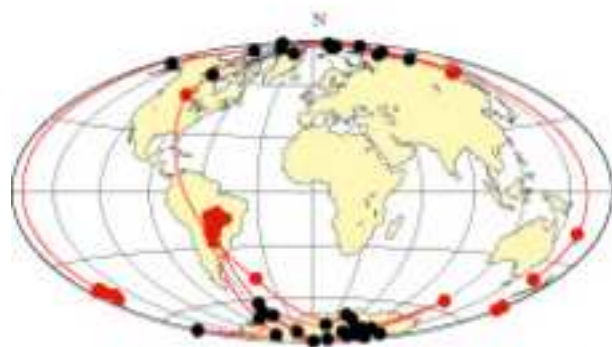
### Reversals



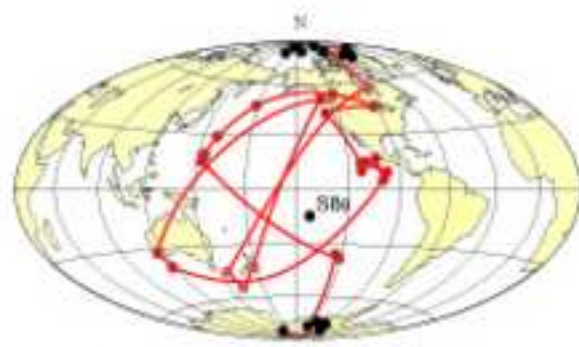
### Excursions Laschamp event



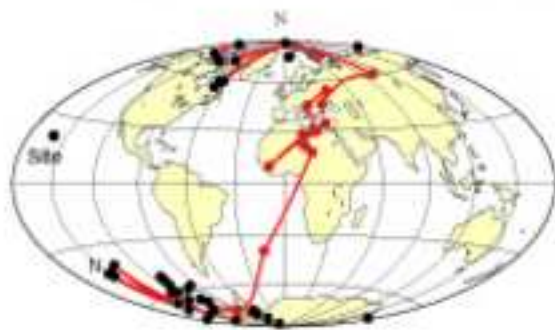




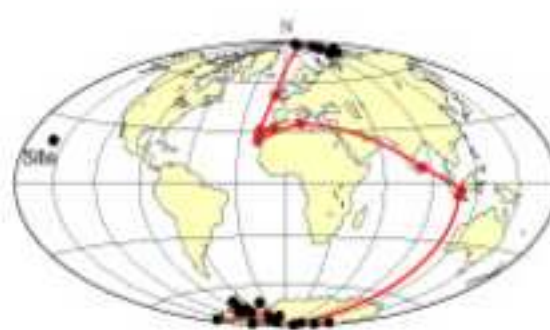
Matuyama-Brunhes 0.78Ma (R-N)



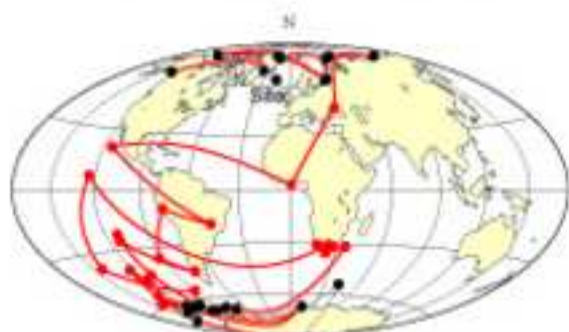
Upper Jaramillo 0.99Ma (N-R)



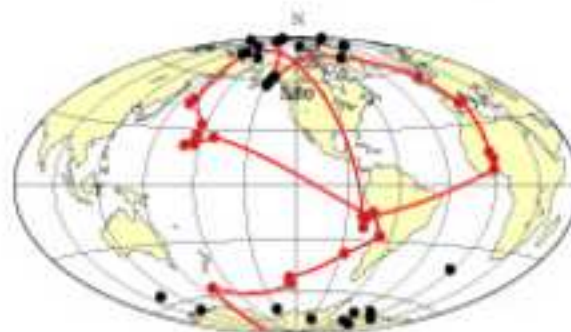
Lower Mammoth 3.33Ma (N-R)



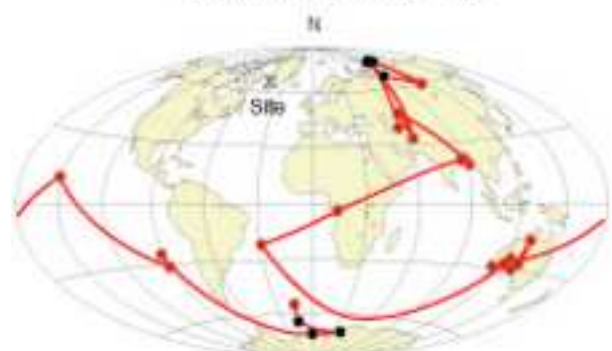
Gilbert-Gauss 3.58 Ma (R-N)



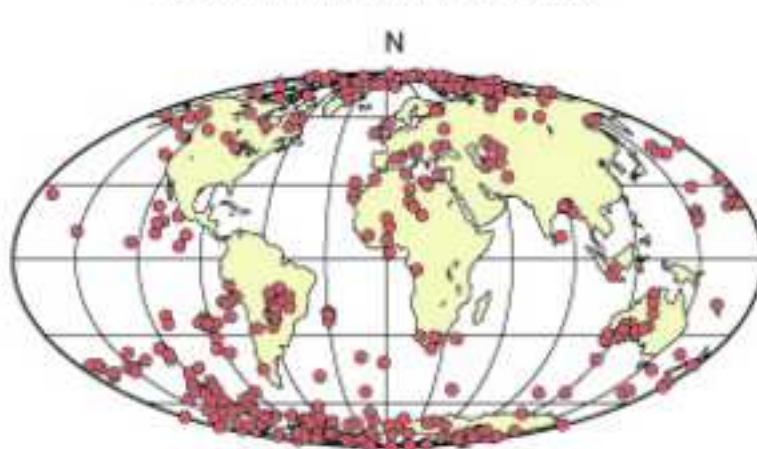
Iceland 12.1Ma (R-N)



Steens Mountain R-N (15.3Ma)



Greenland 61 Ma (R-N)



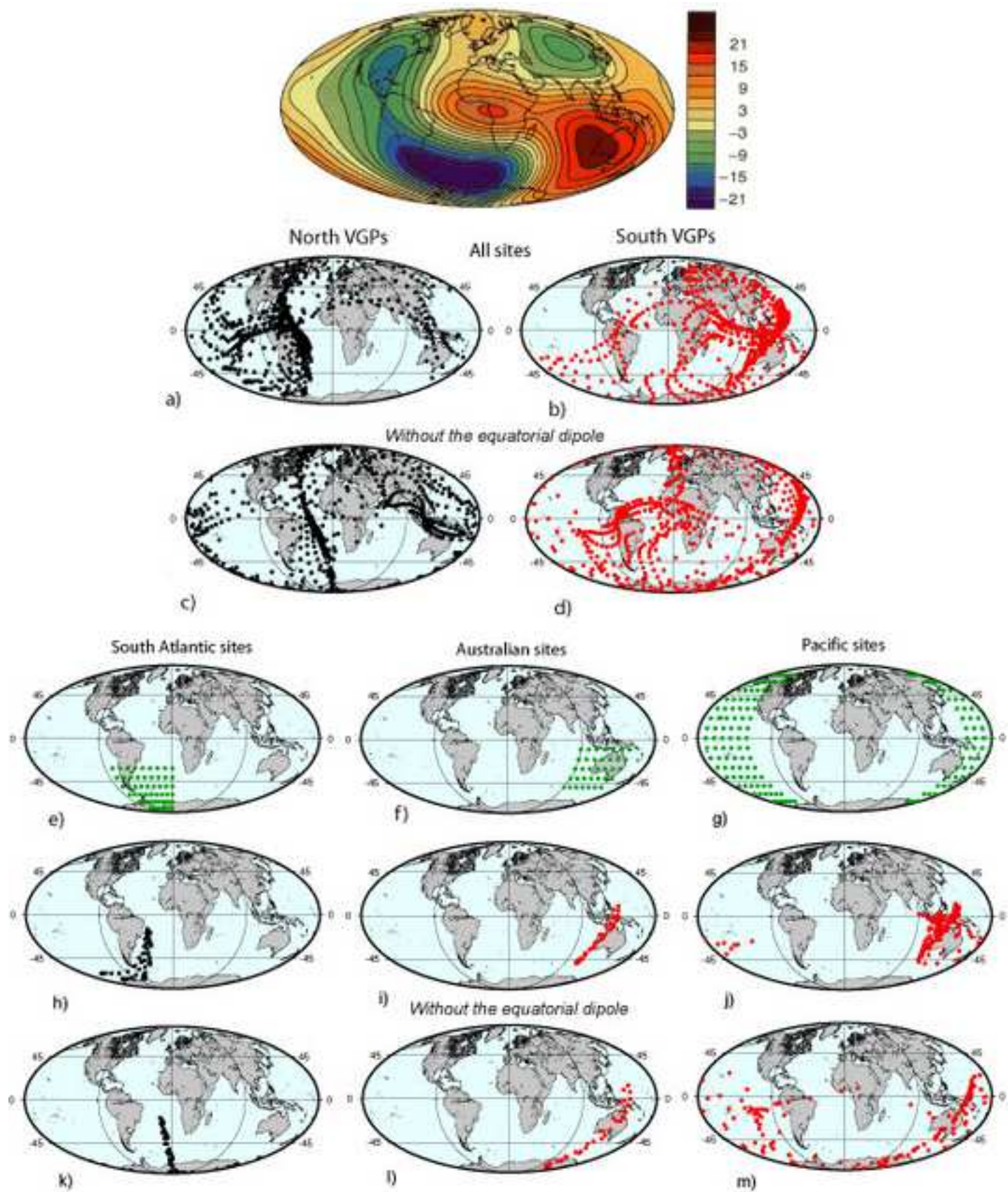
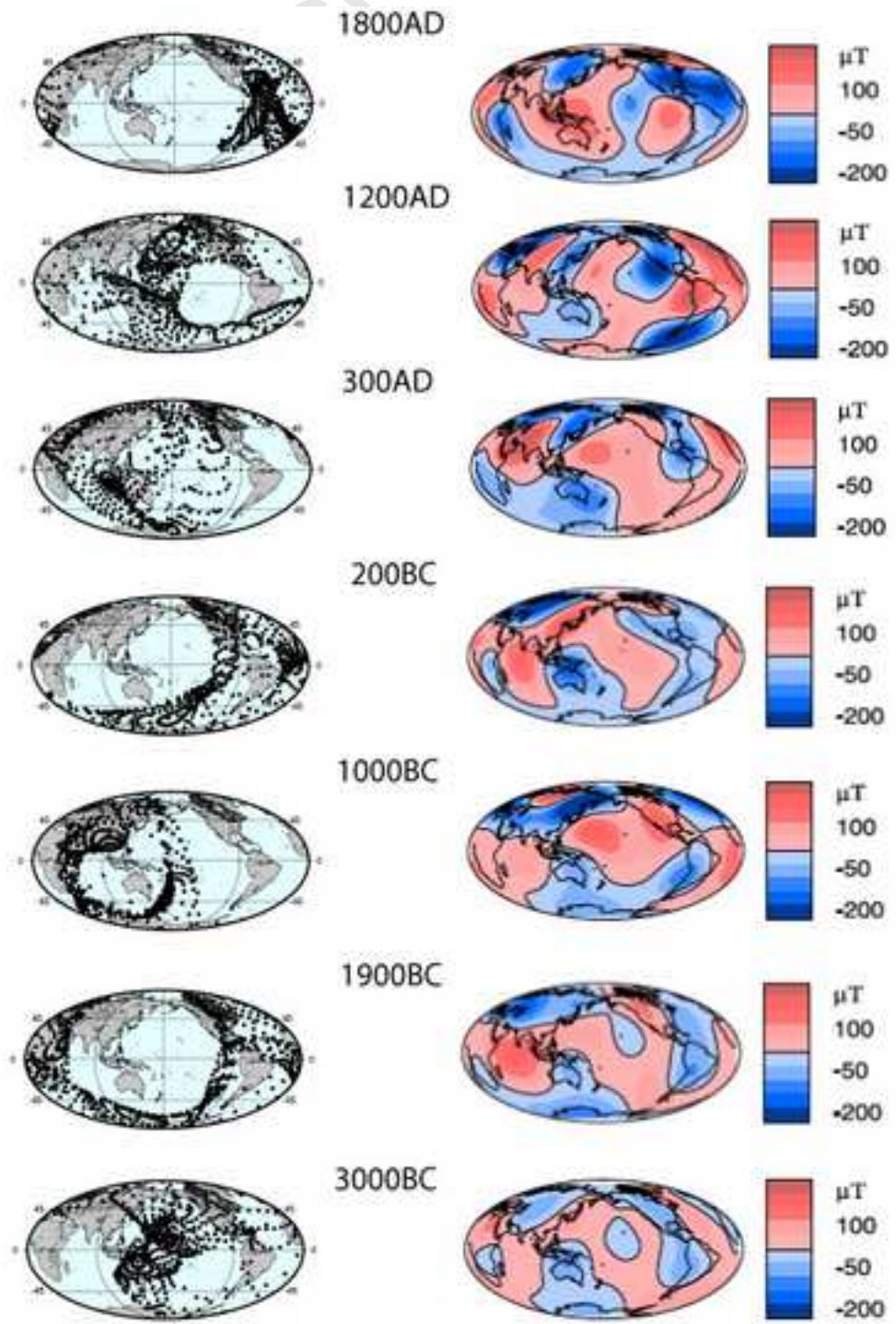
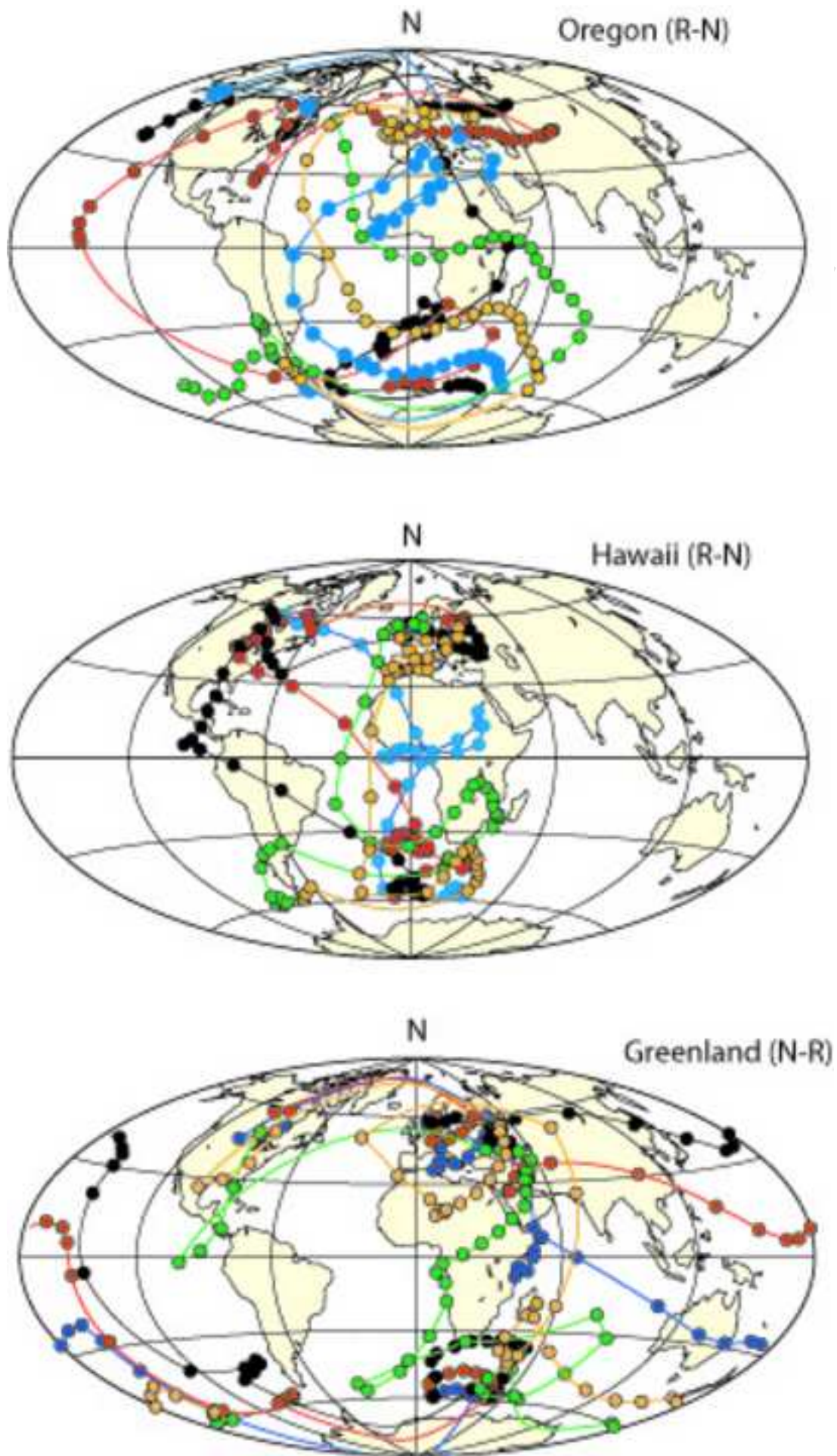


Figure 4

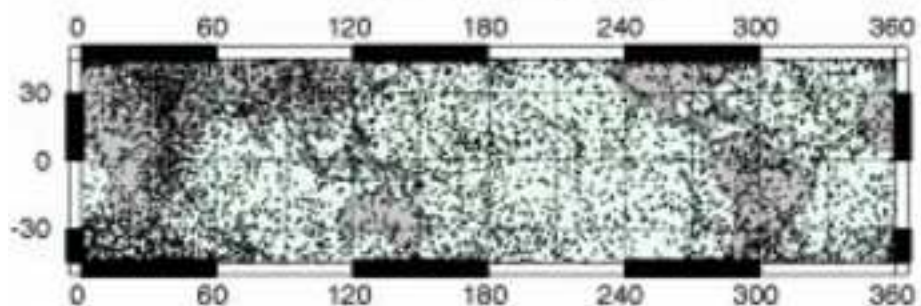




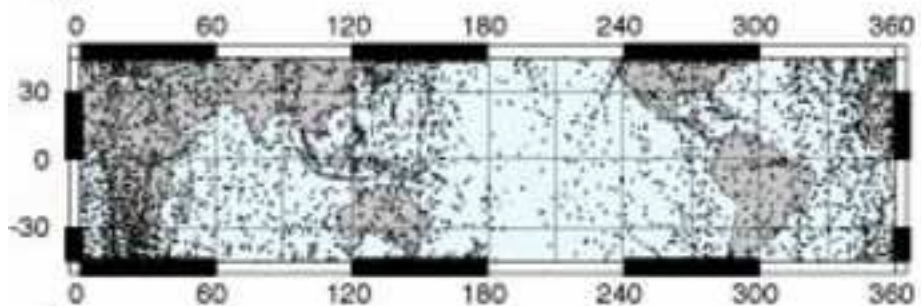


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2300BC - 300BC

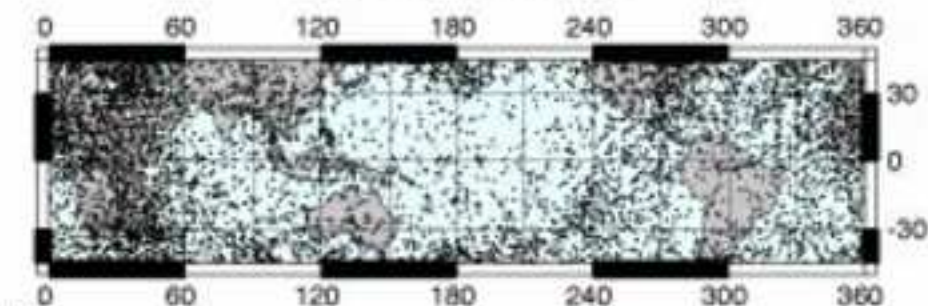


a)

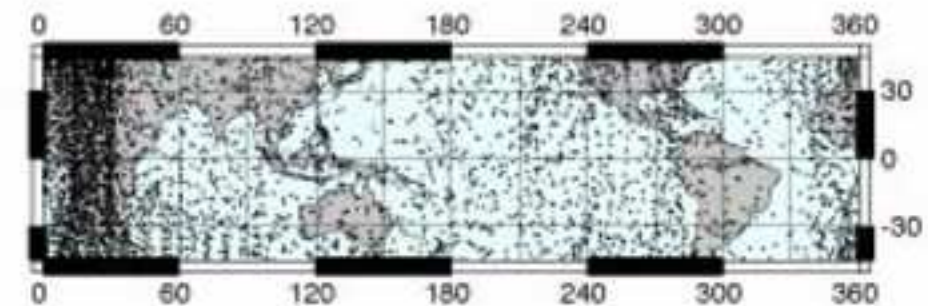


c)

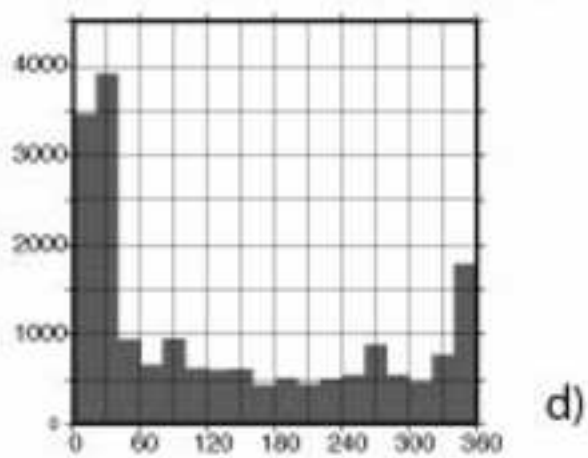
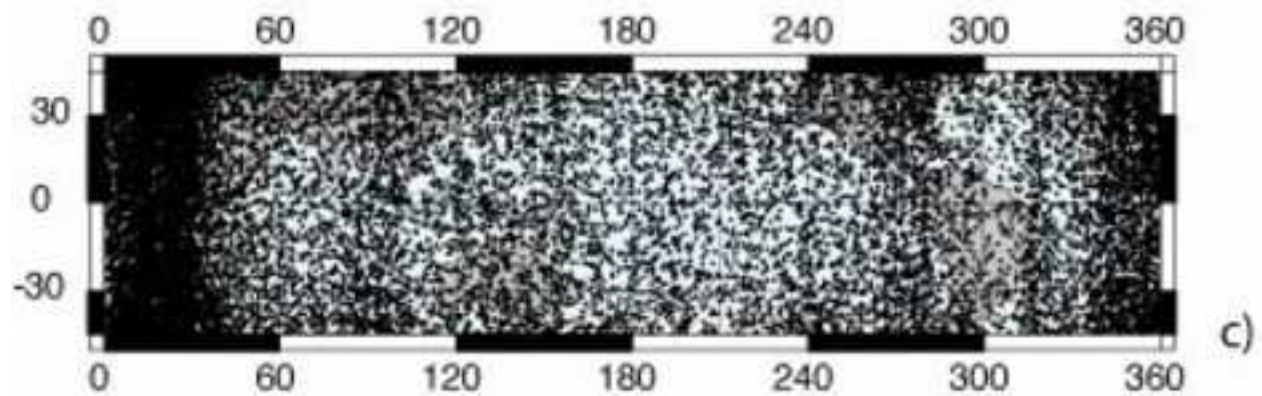
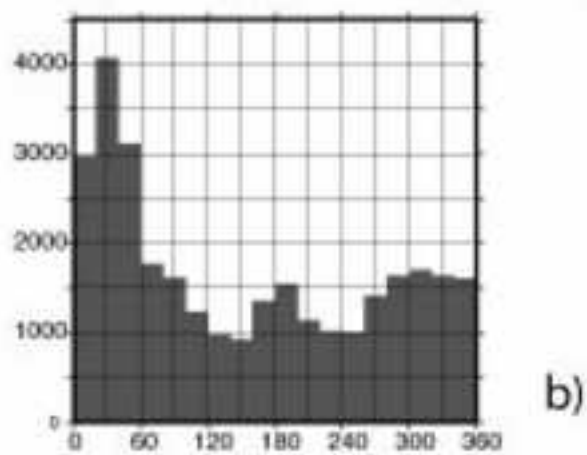
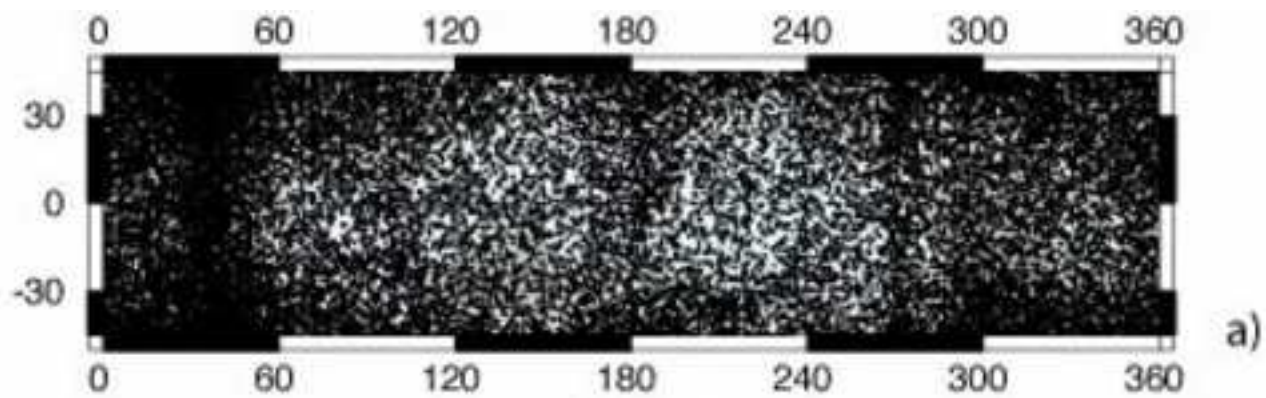
300BC - 2000AD

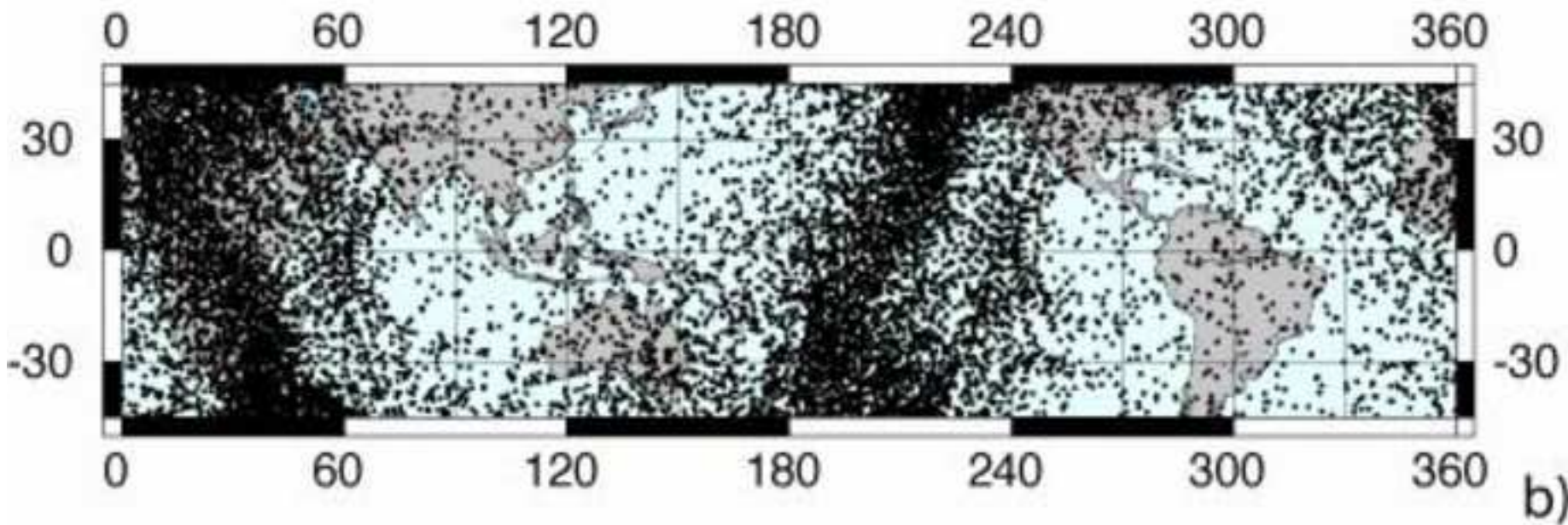
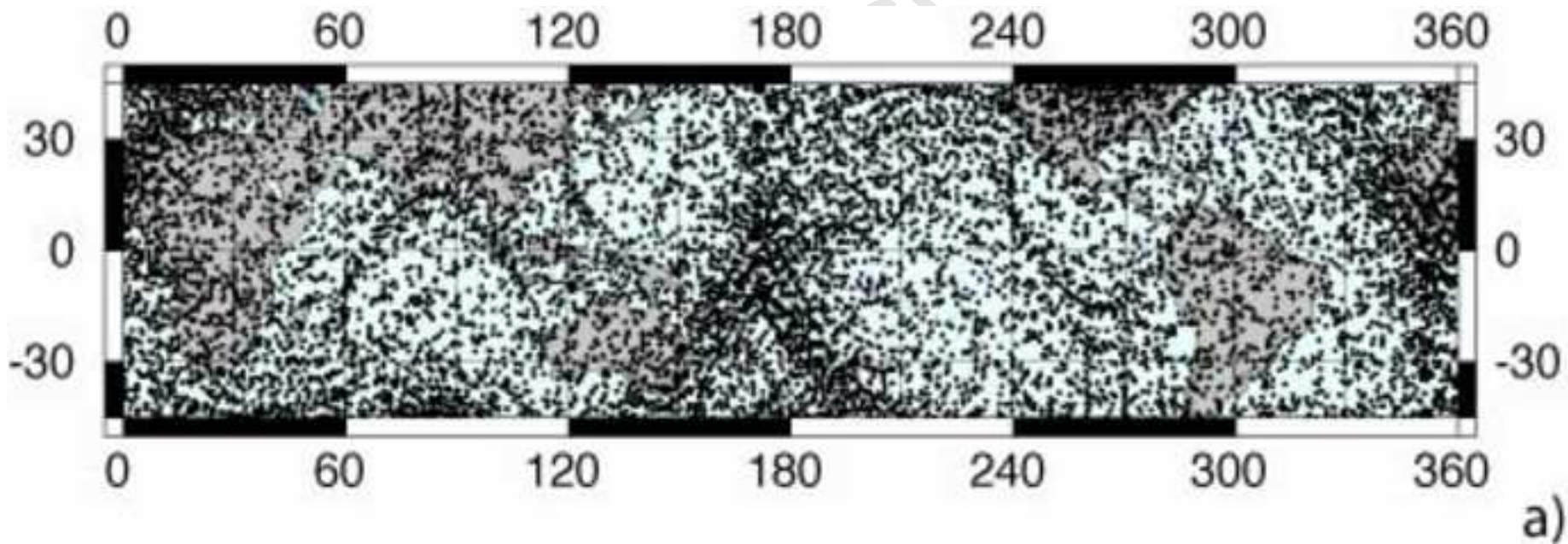


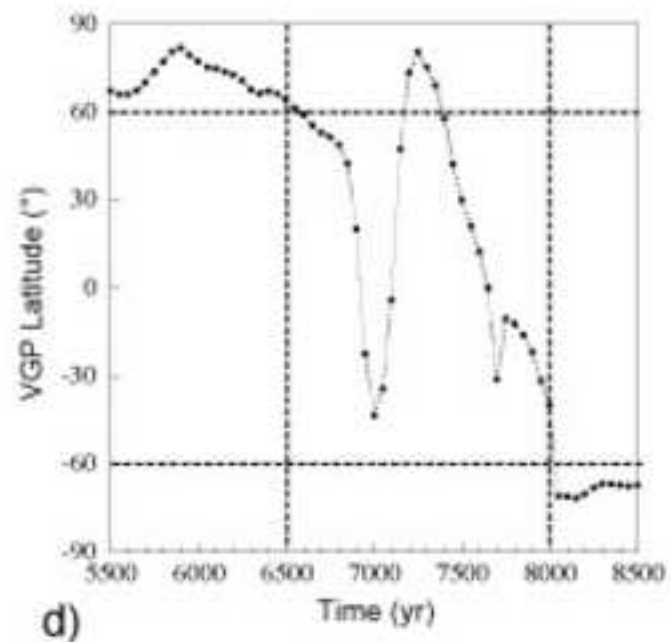
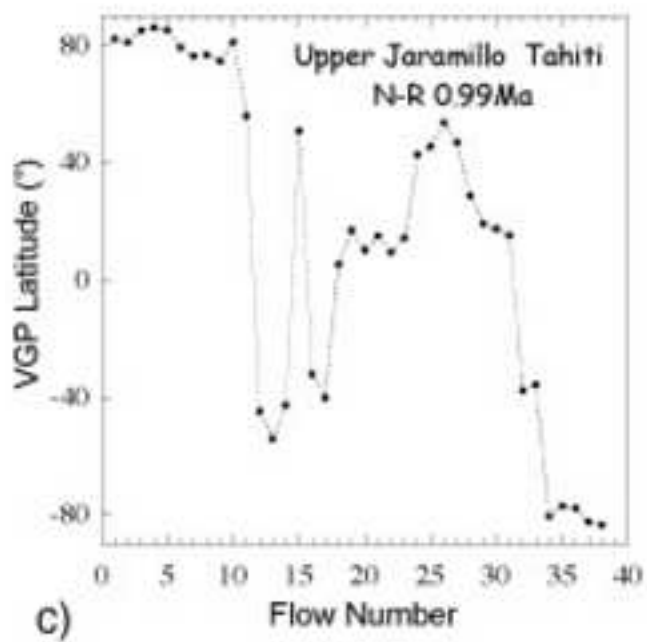
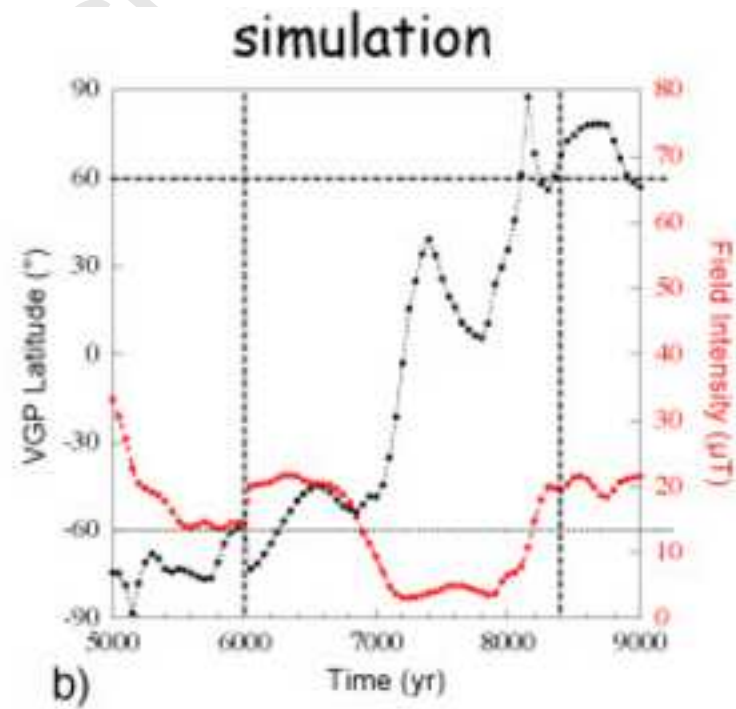
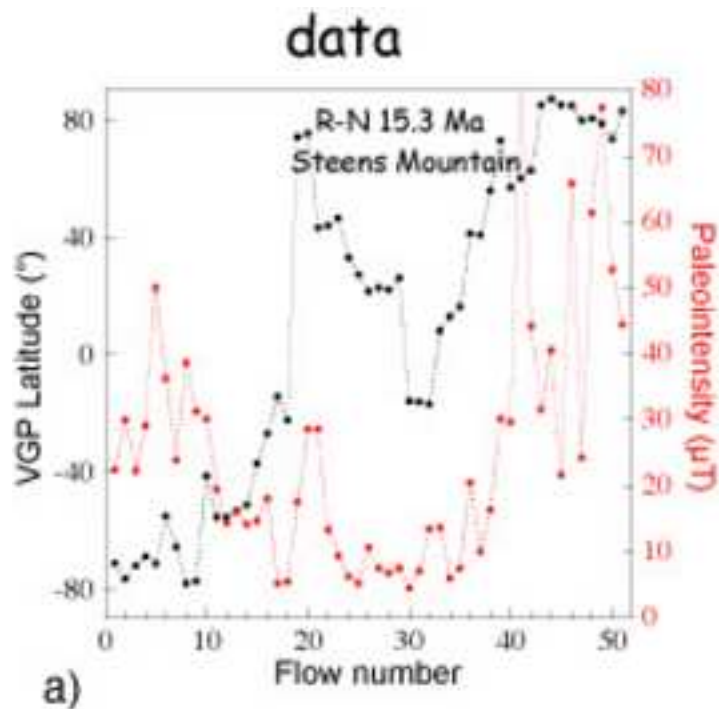
b)

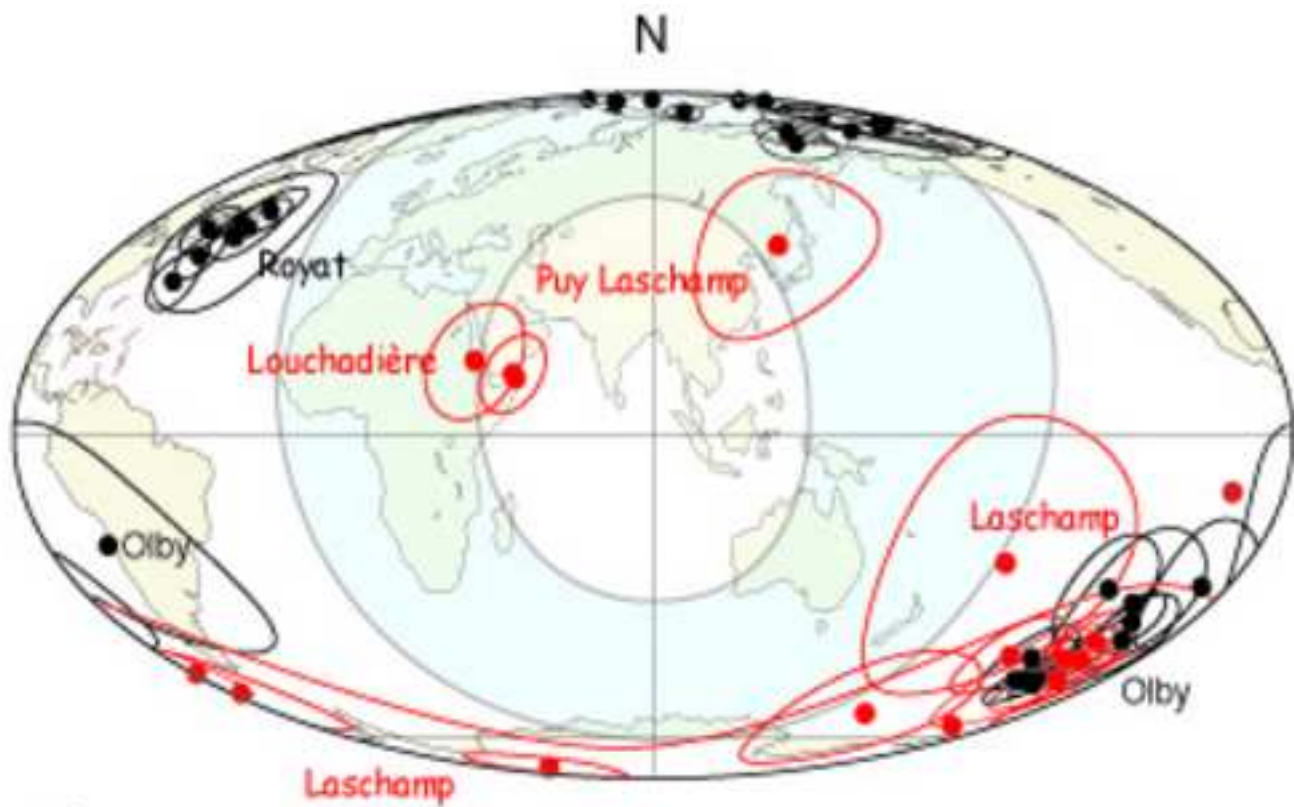


d)

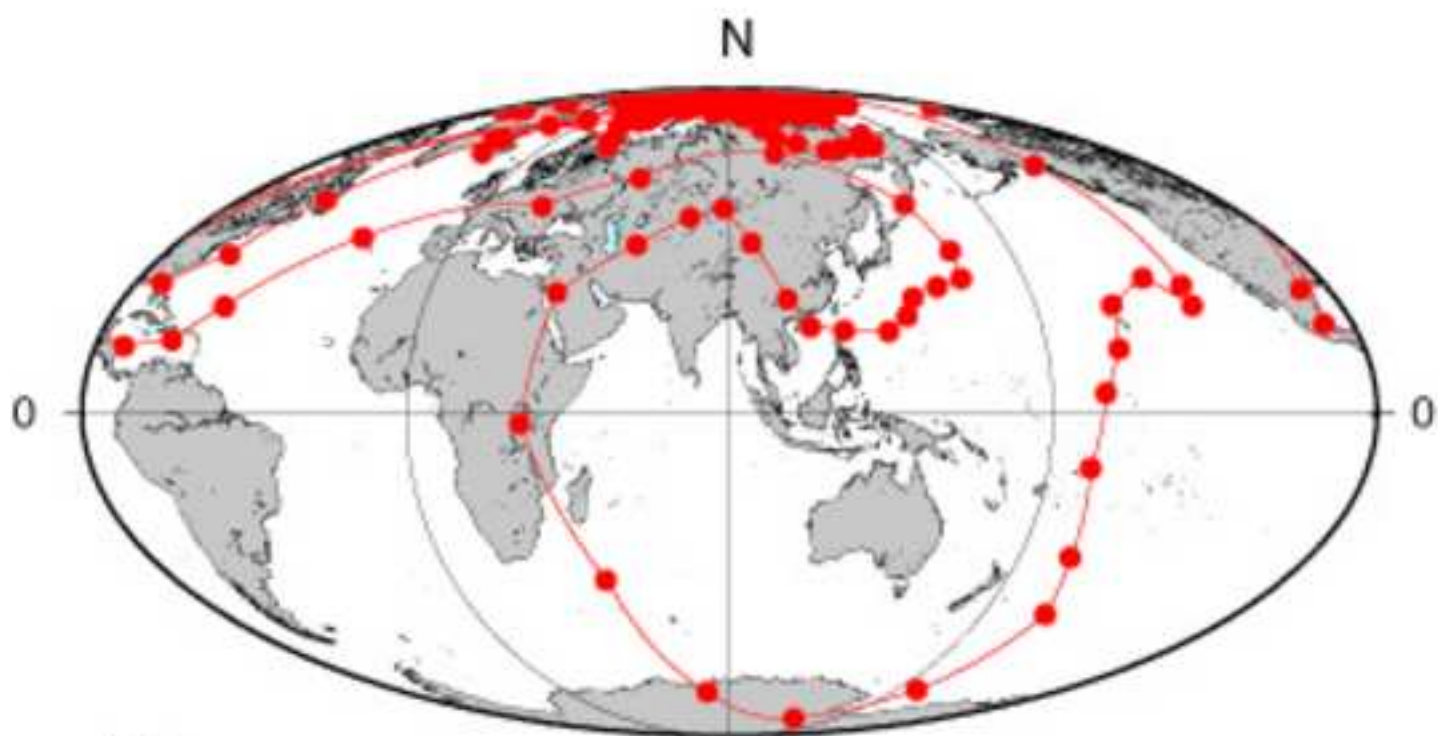








a)



b)

