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Detailed paleomagnetic study of two volcanic polarity transitions recorded in eastern Iceland

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Abstract

Two sequences of 45 and 49 individual lava flows respectively have been sampled in eastern Iceland. The two sections range in age from 12.09 to 10.21 Ma as reported by Watkins and Walker [Watkins, N., Walker, G.P.L., 1977. Magnetostratigraphy of eastern Iceland. Am. J. Sci. 277, 513–584.] and are labelled as profiles C and D. Stepwise alternating field (AF) and thermal demagnetizations accompanied by investigations of rock magnetic properties indicate that the magnetization is primarily carried by titanomagnetite. Demagnetization experiments have identified eight and six transitional lavas, respectively, for these profiles. The transitional virtual geomagnetic poles (VGPs) of the (R-N) profile C reversal are located mainly between Patagonia and Antarctica with a tendency of the virtual poles to move towards west coast of South America, subsequently traveling to the northern hemisphere through several discrete steps located in the middle part of South America, then to west Africa and on to central Asia before the poles settle into normal polarity. The second and younger VGP path corresponding to profile D is a path characterized by a reverse-to-normal-to-reverse (R-N-R) motion of the virtual poles. This path is characterized by poles located in west Antarctica, Patagonia and the western and eastern part of South America. The passage from the southern to the northern hemisphere is also through a discrete sets of steps along the southwestern Pacific followed by a rapid motion to the northern Siberian region, continuing to the western equatorial part of South America before moving on to the central region of Asia, followed by a motion to the western Pacific prior to the final move to the eastern part of Antarctica. The data from eastern Iceland based on highly reliable transitional results, as indicated by the demagnetizations and rock magnetic experiments derived from relatively spaced sites and different ages, seem to indicate that the eastern Icelandic high latitude (66°N) profiles studied have several persistent transitional paleofield features that are uniquely observed at those sites particularly when compared to other volcanic records located at lower latitudes. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Iceland; Virtual geomagnetic pole; Paleomagnetism

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1. Introduction

One of the most fundamental questions in Earth sciences is how the Earth's magnetic field is generated and is able to reverse polarity. Today, one of the most important and exciting geophysical experiments being performed is the detailed study of polarity transitions of the geomagnetic record in different types of rock.

During the last few years considerable effort has been devoted to acquisition of detailed records of the short transitional periods during which the field reverses polarity. Most studies focus on sedimentary sequences which have the advantage of providing continuous recordings of field variations. Two unexpected features have emerged from the accumulation of results. Clement (1991), Laj et al. (1991) and Tric et al. (1991) claimed that the virtual geomagnetic poles (VGPs) tend to cluster within the two approximately antipodal longitudinal bands (over the Americas and over east Asia). Valet and Meynadier (1993) observed an asymmetrical pattern of the geomagnetic field intensity characterized by a long-term decrease before the reversals, and a large and sudden recovery after the polarity changes have been completed. Since these features deal with long time constants, they would point to some control of the core dynamo by the mantle.

These two sets of observational data have generated controversy because the spatial and the temporal distribution of the sites is limited, and more fundamentally because they have been obtained from sedimentary records. Records of transitional fields in sediments can be affected by post-depositional reorientations of the magnetic grains which induce artificial directions. It is also possible that the magnetic torque acting on the alignment of the magnetic grains along the field lines may not always be large enough to orient them properly in the presence of low field intensity (Quidelleur et al., 1995). Paleointensity records in sediments can be affected, in turn, by the complicated nature of the magnetization process. In addition, numerous factors can contribute to changes in magnetic concentration, and they must be normalized for paleointensity studies.

Acquisition of multiple records of the same reversal from a broad geographical distribution of sites were usually considered as one of the conditions to test whether those features have a genuine geomagnetic origin. However, several factors can trigger artifacts on a worldwide basis. A good example is the existence of significant groupings of VGP paths ±90° from the site's longitudes which can be caused by smoothing of non-antipodal directions before and after the transition (Langereis et al., 1992; McFadden et al., 1993; Quidelleur and Valet, 1994). Artifacts could also be generated in worldwide records of relative paleointensity as a consequence of the large influence of climatic parameters in the recording processes.

For these reasons, it has become crucial to obtain detailed records from volcanic rocks to shed new light on these phenomena. Prevot and Camps (1993) noticed that the transitional poles obtained from lava flows do not show any preferred geographic locations but rather a uniform distribution of the VGPs in the world. Alternatively, some authors (Hoffman, 1991, 1992) have selected a subset of data and defended the concept that there are clusters of volcanic VGPs which coincide with the preferred bands of longitude. However, these observations regarding the transitional field come mostly from isolated lava flows of various ages and not from long and detailed volcanic sequences. In fact, it is quite surprising that no more than four detailed records of reversals have been obtained so far from volcanic sequences. Only a few studies of reversals from volcanic sequences incorporate detailed records of paleointensity. Among the two most detailed, the one from Steens Mountain (Prevot et al., 1985) (16 Ma old reversal) reveals an asymmetrical evolution of the geomagnetic intensity between the periods encompassing and following the reversal. However, the absence of chronology limits considerably the interpretation of the record. The second record deals with the last reversal and has been obtained from a succession of 69 flows (Quidelleur and Valet, 1996; Valet et al., 1999). Chronology is defined by four dated lava flows, and the results support the concept of asymmetrical variations of the field intensity between the pre- and the post-transitional periods. However, because there is some variability inherent to dating and because the entire polarity interval is not present, it is impossible formally to conclude that this is really the case. The Icelandic records presented here only deal with directional characteristics. However, it is expected in the near future that an attempt will be made to study their absolute paleointensity determinations and other important characteristics of the reversing field.

These data sets show that considerable knowledge about field behavior and more specifically about field reversals will be gained by documenting the field variations across successive reversals rather than to focus exclusively on the transitional period. In other words, what is needed is to study large volcanic sequences uncovered by vegetation and without ambiguity regarding the temporal succession of the flows. In fact, this was not achieved so far because of difficulties in finding adequate sequences for this purpose.

The volcanic sequences from eastern Iceland offer an exceptional (if not unique) opportunity to study the transitional behavior of the geomagnetic field to achieve this goal. All the flows are totally uncovered by vegetation and are uniquely well exposed over large horizontal distances.

The sequence of lava flows in eastern Iceland whose detailed palaeomagnetism was published by Watkins and Walker (1977) records many different reversals over the past 13 Ma. Here we present two transitional records obtained from different volcanic sections and ranging in age from 12.09 to 10.21 Ma. Two of these records originally labelled by Watkins and Walker (1977) as profiles C and D were resampled in order to obtain a more detailed record of their corresponding transitional directions because usually only two samples per lava flow were collected by Watkins and Walker.

2. Geologic setting of profiles C and D

Eastern Iceland, as described by Walker (1960, 1964), contains some 10,000 km^3 of lavas, 90% of which are basalts. The remaining 10% of the rocks are acidic and intermediate in composition. Deeply dissected by glacial erosion, the standard thickness of the pile reaches 7000 m, exposed in vertical outcrops of up to 1000 m and more. A very uniform westward gentle regional dip from 8° at sea level to about 4° at the mountain summits in eastern Iceland is matched by an oppositely directed dip of rocks of the same age in western Iceland. Large faults of more than 100 m of vertical displacement are rare.

The presence of zeolites in the area, distributed in a regular zonal fashion and unrelated to the structure of the volcanic sequence shows that their development was later than to the emplacement of the basalts. It also allows one to calculate the temperature reached by the lava flows on burial after the initial emplacement. The bulk of the area lies in the mesolite zone (Fig. 1), indicative of heating in a range of temperature of 70–90°C, characteristic of low temperature zeolites (Kristmannsdottir, 1978, 1982; Kristmannsdottir and Tomasson, 1978; Palmasson et al., 1979).

The ages of exposed rocks in eastern Iceland have been reported as 12.5 ± 0.2 Ma at the base of the succession, and 11.9 ± 0.3 Ma some 2400 m above the base in the stratigraphic sequence (Moorbath et al., 1968) corresponding to the lowest part of the Upper Miocene. It is seen from this difference of only ca. 0.6 Ma between the base and the top of this 2400-m thick basaltic sequence that volcanism was essentially continuous and rapid. On average, the production rate was 640 m/Ma or one lava flow extruded roughly every 16,000 years. The area of this work, namely, Sections C and D at Neskaupstadur (Walker, 1960, 1964; Watkins and Walker, 1977) is located away from the core of central volcanoes, associated alterations and flexure zones which might introduce some alteration of the results. The exposed section is approximately 650 m at profile C and 750 m at profile D. The average time separating polarity reversals was between 145,000 and 190,000 years (Watkins and Walker, 1977).

3. Field and laboratory methods

Field work for this study was initiated as part of a large project to study polarity transitions recorded in piles of lavas in eastern Iceland (Herrero-Bervera et al., 1996). The Neskaupstadur area where the sampling of profiles C and D took place (see Fig. 1a and b) provides an excellent exposure for such a study, allowing near continuous sampling of eruptive sequences on a flow by flow basis.

Many of the lava flows and particularly those of the pahoehoe type are compound, that is, they are divisible into flow units. Their significance is that

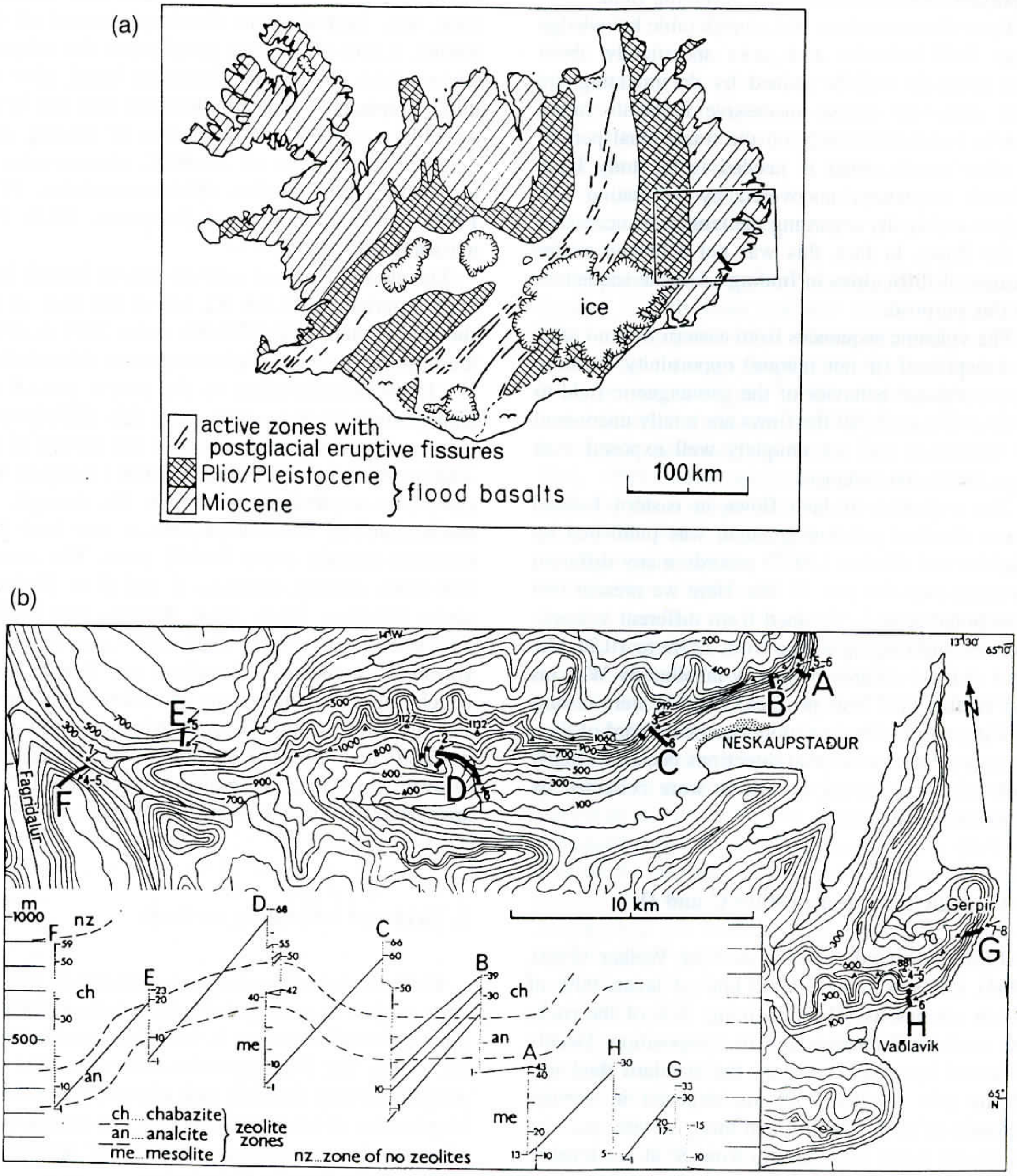
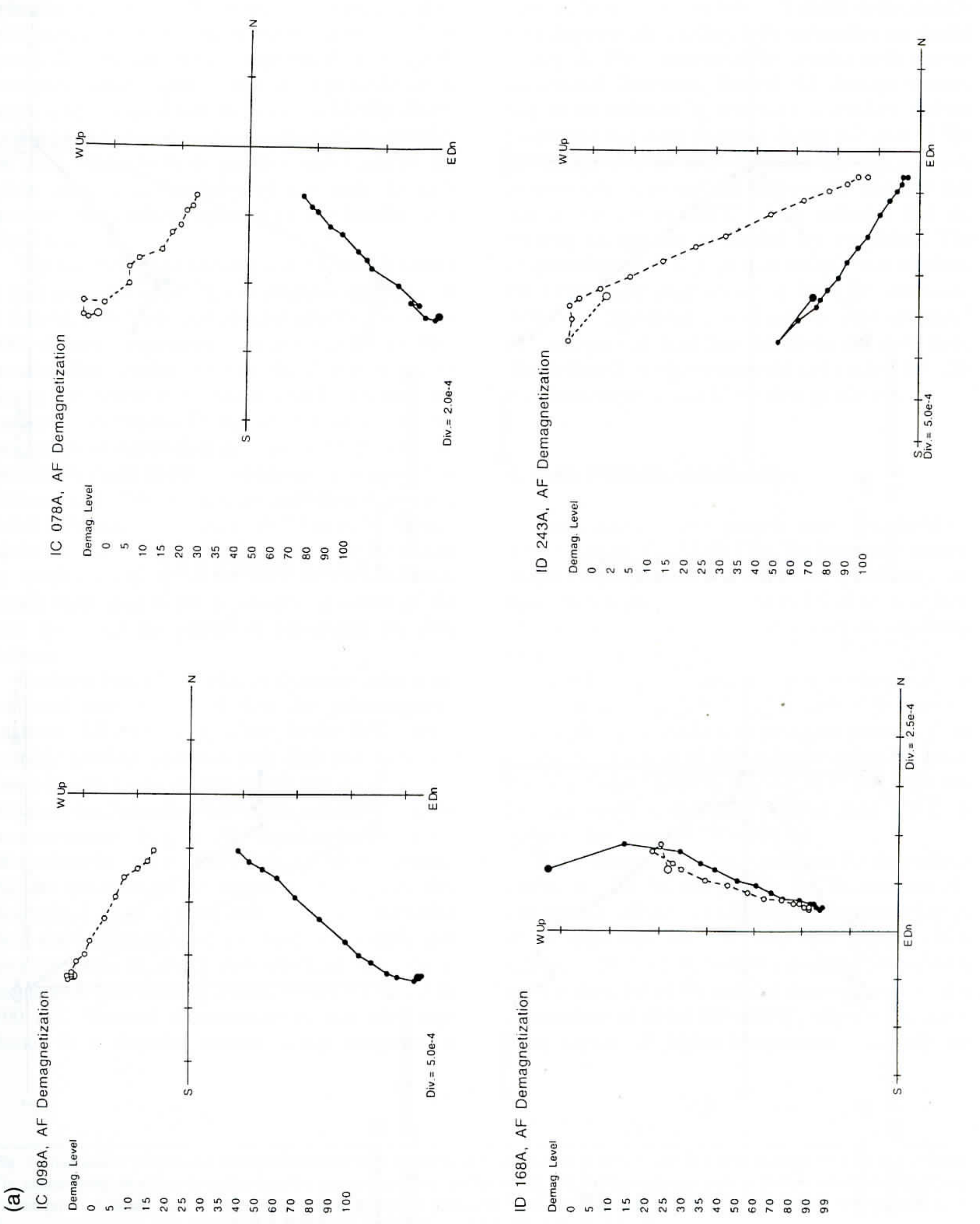


Fig. 1. (a) Map of Iceland showing the location and geologic setting of the area in eastern Iceland that is the subject of this paper. Block corresponds to limits of map showing the location of the profiles studied. (b) Map showing detailed locations, vertical extent, zeolite zones for sections C and D. Each diagram shows between-section correlation lines. Numbers adjacent to vertical sequences are original numbers of each lava, as published by Watkins and Walker (1977). Taken from Watkins and Walker (1977).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IC 098A, AF Demagnetization
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IC 078A, AF Demagnetization
Demag. Level
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ID 168A, AF Demagnetization
Demag. Level
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Div.= 2.5e-4
ID 243A, AF Demagnetization
Demag. Level
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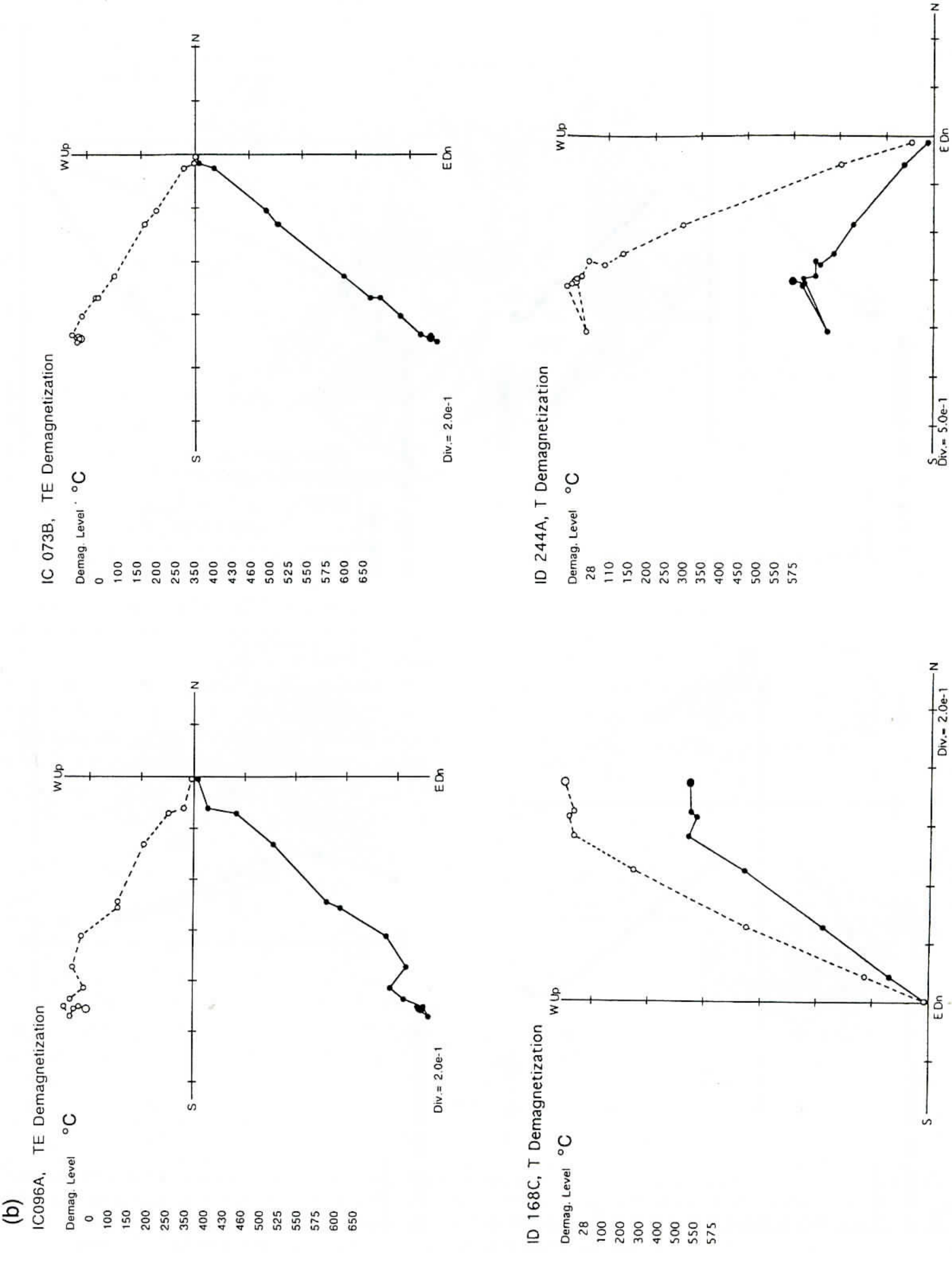
(b)
IC096A, TE Demagnetization
Demag. Level °C
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Div.= 2.0e-1
IC 073B, TE Demagnetization
Demag. Level °C
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ID 168C, T Demagnetization
Demag. Level °C
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ID 244A, T Demagnetization
Demag. Level °C
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whereas separate lava flows may be erupted at intervals commonly of tens to hundreds of thousands of years, all flow units of a compound flow are products of the same eruption and were emplaced over, at most, a few years. Flow units can be ideally distinguished from separate flows because of the absence of boles (red dust beds between units) and of the close lithological similarity of the units to each another. The median thickness of the basaltic lava flows is 5.3 m.

The excellent exposure of profiles C and D allows a near continuous sampling of eruptive sequences on a flow-by-flow basis. Samples for paleomagnetic and rock magnetic experiments were taken from within massive flow interiors to avoid the effects of reheating by subsequent flows which would reset the paleomagnetic directions. Doing so also minimized the possibility of within-flow geochemical variation that potentially could result in erroneous data. Erosional hiatuses and a few sedimentary units were mapped in detail (Watkins and Walker, 1977) in order to constrain any gaps in data. Furthermore, care was taken to avoid resampling of the units, a mistake commonly made due to the anastomosing nature of the lava flows and the effects of topography on flow patterns.

Between 5 and 10 2.5-cm in diameter cores were collected from each lava flow for paleomagnetic analyses. All cores were drilled in the field with a portable gasoline powered rock drill and were oriented in situ using an integrated sun compass and inclinometer. Natural remanent magnetization (NRM) was measured using a 2G Superconducting Rock Magnetometer and a JR5A Spinner Magnetometer. All the specimens were progressively stepwise demagnetized using a three-axis tumbling alternating field (AF) demagnetizer. At least one sample per lava flow was thermally demagnetized. AF experiments were performed in a series of steps from 2.5 to 100 mT. Thermal demagnetization was also conducted in a stepwise manner, using temperatures ranging from 75 up to 650°C. Typical demagnetization diagrams obtained by both techniques are shown in Fig. 2. They correspond to samples with various transitional directions. Overall AF demagnetization was more efficient in removing secondary viscous overprints that were acquired during the past 13 Ma and during storage of the samples. The characteristic components were isolated between 15 and 100 mT and above 300 to 400°C which indicates that the primary component is carried by magnetite. The characteristic direction of each sample was obtained by least-square analyses of at least 10 successive directions. The mean flow directions were calculated by averaging at least five directions per lava flow. The within flow dispersions did not exceed 10°. All the flows were corrected for their gentle tilt.

4. Rock magnetic experiments

Rock magnetic experiments were performed on samples from lavas drilled for the transition studies. Magnetic properties were analyzed to identify the magnetic carriers of the NRM and to determine their characteristic properties as a check on the reliability of the reversal records.

Thermomagnetic analyses were carried out on small amounts of powder from each flow, using a horizontal Curie balance in an argon atmosphere to minimize oxidation of the magnetic minerals. Heating and cooling rates were close to 7–8°C/min and the maximum temperature reached was 700°C in fields of the order of 700–900 mT.

We performed 35 Curie analyses for lavas from profile C and 50 for profile D. Thermomagnetic experiments allows us to distinguish two main groups of samples (see Fig. 3). The first group, which represents 50% of the samples, is characterized by a regular decrease of the induced magnetization until a temperature of about 350–400°C, where transformations appear. At higher temperatures, the only re-

Fig. 2. Diagrams of progressive demagnetization of typical transitional samples for profiles C and D. (a) AF demagnetization of four lavas. The characteristic direction is well defined by univectorial decay to the origin. (b) Thermal demagnetization of the same transitional lavas. Plotted points represent successive positions — in orthogonal projection — of the end point vector. Solid symbols represent projections on the vertical plane and open symbols those on the horizontal plane. Units are in A/m.

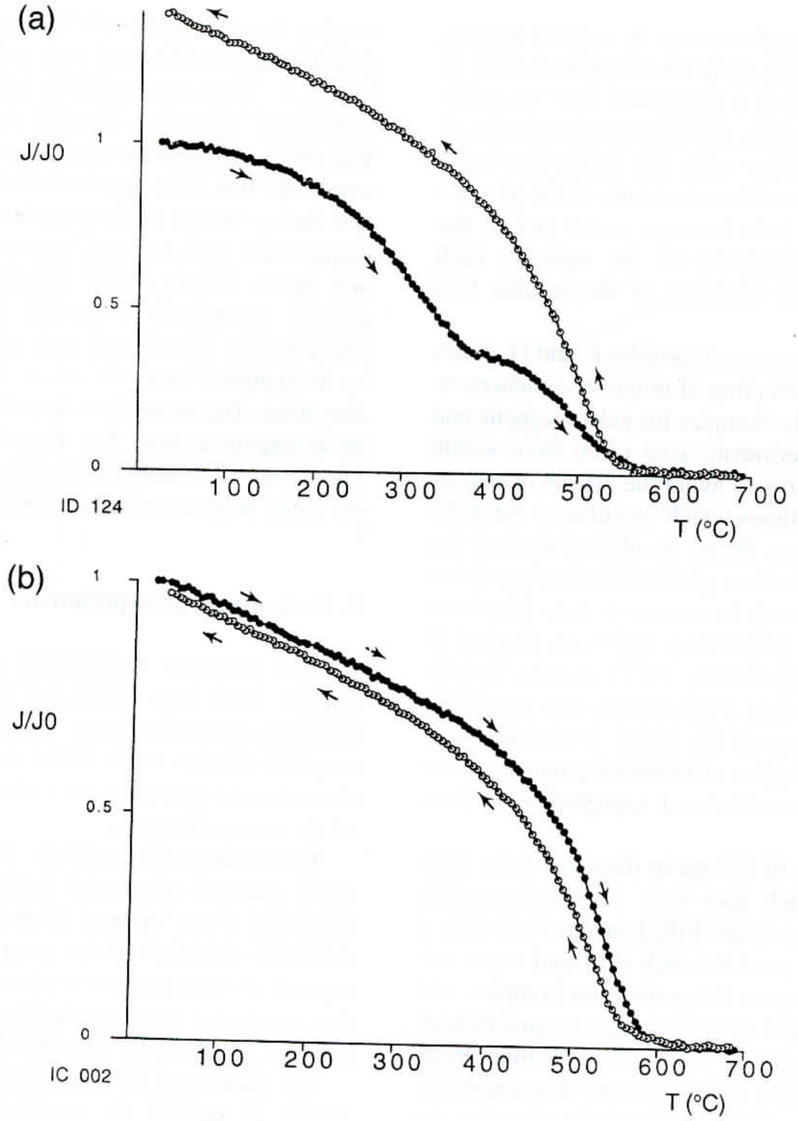

Fig. 3. Representative thermomagnetic analysis plots obtained using a horizontal Curie balance in an argon atmosphere for the lavas of profiles C and D. The two main types of diagrams observed are described in the text.

maining phase is magnetite as shown by the Curie temperature (550–580°C) at the end of the heating cycle (see Fig. 3a). The second group is characterized by a concave-down thermomagnetic curve continuously decreasing to zero with a single Curie temperature close to 580°C typical of low-Ti-content magnetite. In most of the cases for these particular types of curves the heating and the cooling curves are perfectly reversible. Fig. 4 shows that typical transitional samples from both profiles acquire a saturation isothermal remanent magnetization (SIRM) in a strong field, with most of the remanence being gained between 0.5 to 1.0 Tesla after which the curves start to level off. These results also indicate that the dominant magnetic carrier in the samples is magnetite.

Magnetic hysteresis parameters were determined on small chips of rock with an alternating gradient

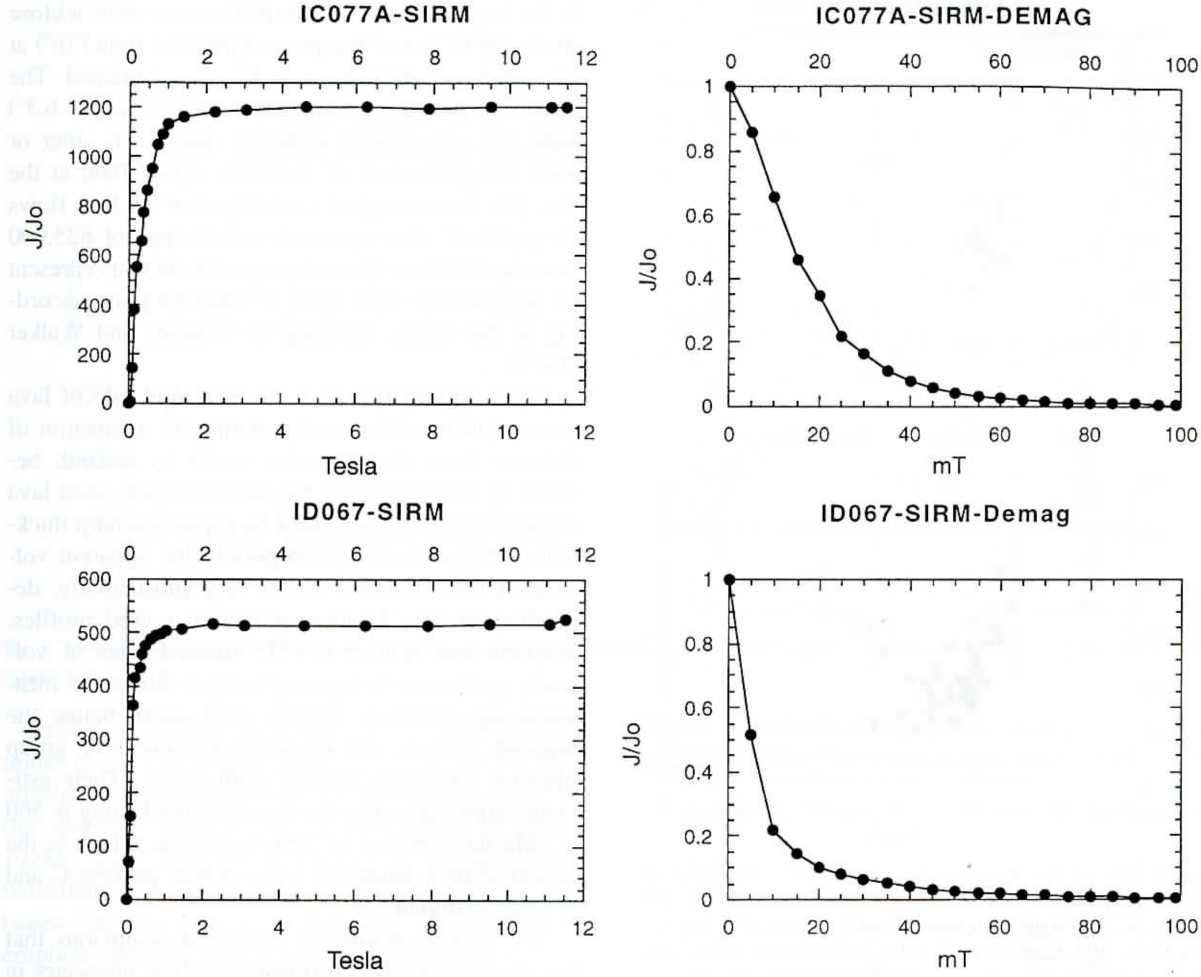

Fig. 4. Typical acquisition SIRM of the transitional samples and their respective demagnetization curves for profiles C and D.

force magnetometer (Micromag). The slope at high fields, which represents the paramagnetic contribution, is calculated automatically using the software provided with the instrument. The saturation remanent magnetization (M_r), the saturation magnetization (M_s), and the coercive force (H_c) were calculated after removal of this component. By applying progressively increasing back fields after saturation, we determine the coercivity of the remanence (H_{cr}) and the S ratio defined as $S = -\mathrm{IRM}(-0.3T)/\mathrm{SIRM}$ (King and Channell, 1991). The results document low values of H_c and H_{cr} and also an S ratio higher than 0.9 for both profiles. This indicates that very large fraction of the NRM is carried by low-coercivity minerals, in agreement with the presence of a high proportion of magnetite. The ratios of the hysteresis parameters plotted as a Day diagram (Day et al., 1977) in Fig. 5 show that the grain size of magnetite is characterized by significant dispersion in the pseudosingle domain range for profile D whereas lower dispersion values in the same range characterizes the samples from profile C. The results indicate that the two populations of the samples studied are within the pseudosingle domain area of the diagram and also that the two different groupings have their sources from two different volcanoes since

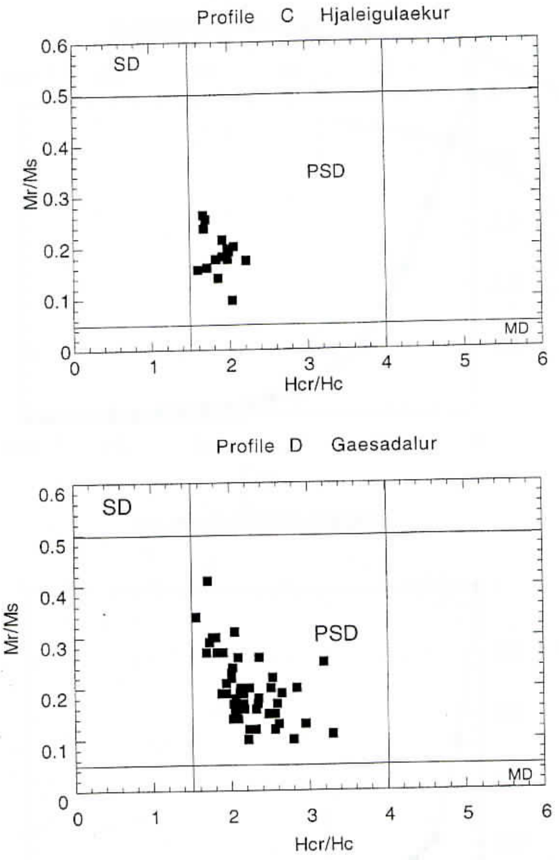

Fig. 5. Plot of the hysteresis parameters, M_{rs}/M_s (ratio of remanent saturation moment M_{rs}, to saturation moment M_s) against H_{cr}/H_c (ratio of remanent coercive force, H_{cr}, to coercive force, H_c). Single domain (SD), multi-domain (MD), after Day et al. (1977). Lavas from profile C and from profile D.

the two groups cluster in relatively different regions of the PSD area (see Fig. 5).

5. Directional results

Fig. 6a represents the magnetostratigraphic plot (declination and inclination) of the measured samples which show a well-defined reversed-to-normal transition (R-N) with an excursion in between the reversed polarity for profile C and a reverse-to-normal-to-reverse (R-N-R) for profile D. The total thickness of the section sampled from the base to the top is approximately 350 and 525 m for profiles C and D, respectively. The sections from their bases up to the beginning of the transition zones show a close similarity to that of the present ambient field (76°) at the site from which the samples were obtained. The observed inclination values ($I = -77.7$; $\alpha_{95} = 6.3°$) were not significantly different from each other or from the inclination of the axial dipole field at the site. We have sampled a minimum of 45 lava flows for profile C that represent a time span of 625,000 years and 49 lava flows from profile D that represent an approximate time span of 940,000 years according to the values reported by Watkins and Walker (1977).

Their argument is that the measured rate of lava accumulation will almost certainly be a function of distance from the extrusion center in Iceland, because as Walker (1964) has demonstrated, most lava sequences are characterized by rapid downdip thickening. Thus for any given period, the apparent volume of lava extruded could vary substantially, depending on the location of the measured profiles. Watkins and Walker (1977) inferred rates of volcanic production in eastern Iceland. Since the measured dip increases linearly with depth below the original surface, the thickness of any lava group likewise increases linearly with depth. Their estimates after correcting for downdip thickening is 560 m/Ma for a period of 13.4 to 7.2 Ma which is the period of time when the lavas of both profiles C and D were extruded.

For polarity transition studies, it is obvious that the need for detailed reversal records is necessary in order to understand the reversal processes generated in the interior of the Earth. Unfortunately, reversal records are very difficult to obtain due to the fact that they occur very quickly on a geological time scale. Although they do require a finite time the directional change typically takes around 4000 to 5000 years which is about 2% of the mean interval between reversals in recent times (e.g., McFadden and Merrill, 1993). In contrast, there is some evidence that changes in intensity associated with polarity transitions may occur over longer intervals, about 10,000 years as an average (e.g., Herrero-Bervera and Runcorn, 1977; Laj, 1989; Herrero-Bervera and Coe, 1999). Thus, it is unrealistic to think that for profiles C and D the duration of polarity transition took place over such a long interval of time as the estimates reported by Watkins and Walker (1977).

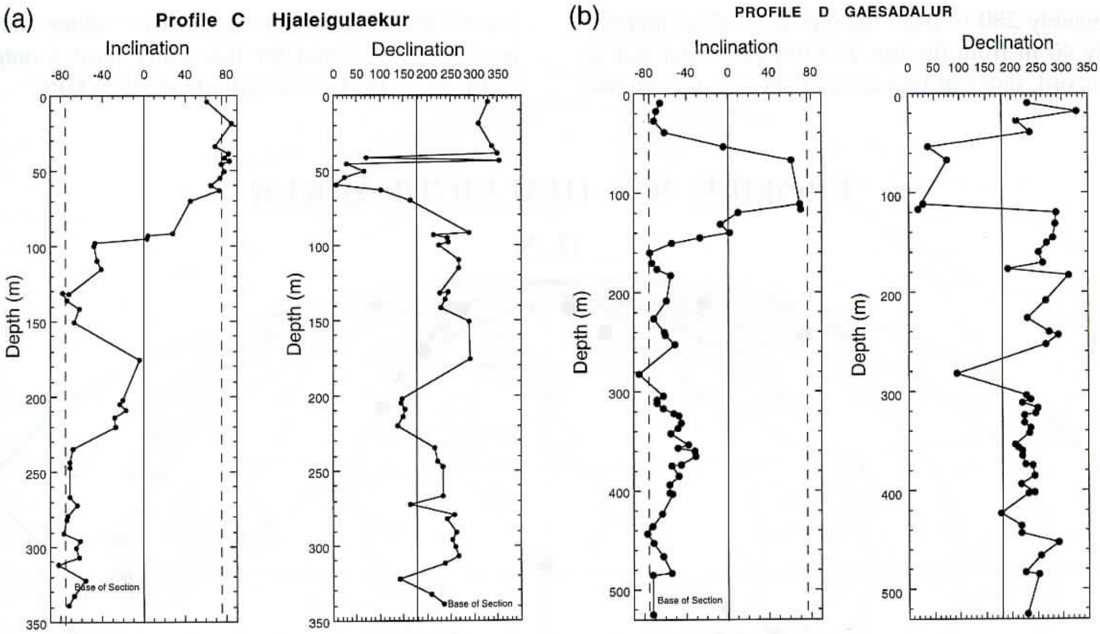

Fig. 6. Stratigraphic plot of inclination and declination: (a) profile C Hjaleigulaekur and (b) profile D Gaesadalur. Dashed lines indicate the expected inclination for the sampling sites.

Profile C is characterized by about eight transitional lavas (16 VGPs from −45° to +45°) and profile D is characterized by six transitional lavas. If the reversals reported so far took place in about 10,000 years then for the Icelandic profiles each transitional lava represents an extrusion rate of between 1000 to 2000 years per flow. These type of eruption rates are very common in Hawaiian volcanoes. For instance, the reversals studied in the Wai'anae volcano are characterized by such fast rates (e.g., Doell and Dalrymple, 1973; Herrero-Bervera and Coe, 1999; Herrero-Bervera and Valet, 1999).

6. VGP data

The declination and inclination results presented in Fig. 6a and b can be converted to VGPs representing the apparent motion of the pole during the 12.09 and 11.47–10.21 Ma polarity transitions at profiles C and D, respectively. Fig. 7 depicts the characteristics of the VGPs in terms of latitude plotted in stratigraphic order. Within the transition of polarity from 60 m down to 130 m, there are eight transitional recordings of the paleofield for profile C. For profile D, the paleofield changes from normal to reverse polarity (N-R). The intermediate lavas start at ap-

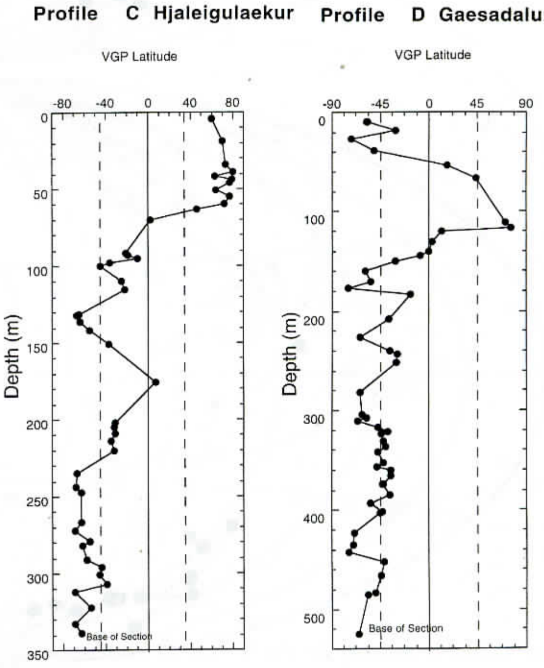

Fig. 7. Plots of the VGP latitude vs. stratigraphic position of the lavas from profiles C and D.

proximately 280 m from the top and end at approximately 40 m from the top. For this particular transition record, one can find at least six true transitional recordings of the paleofield. The values that we consider transitional for this study have a range of −45° to +45° for the latitude of the VGPs.

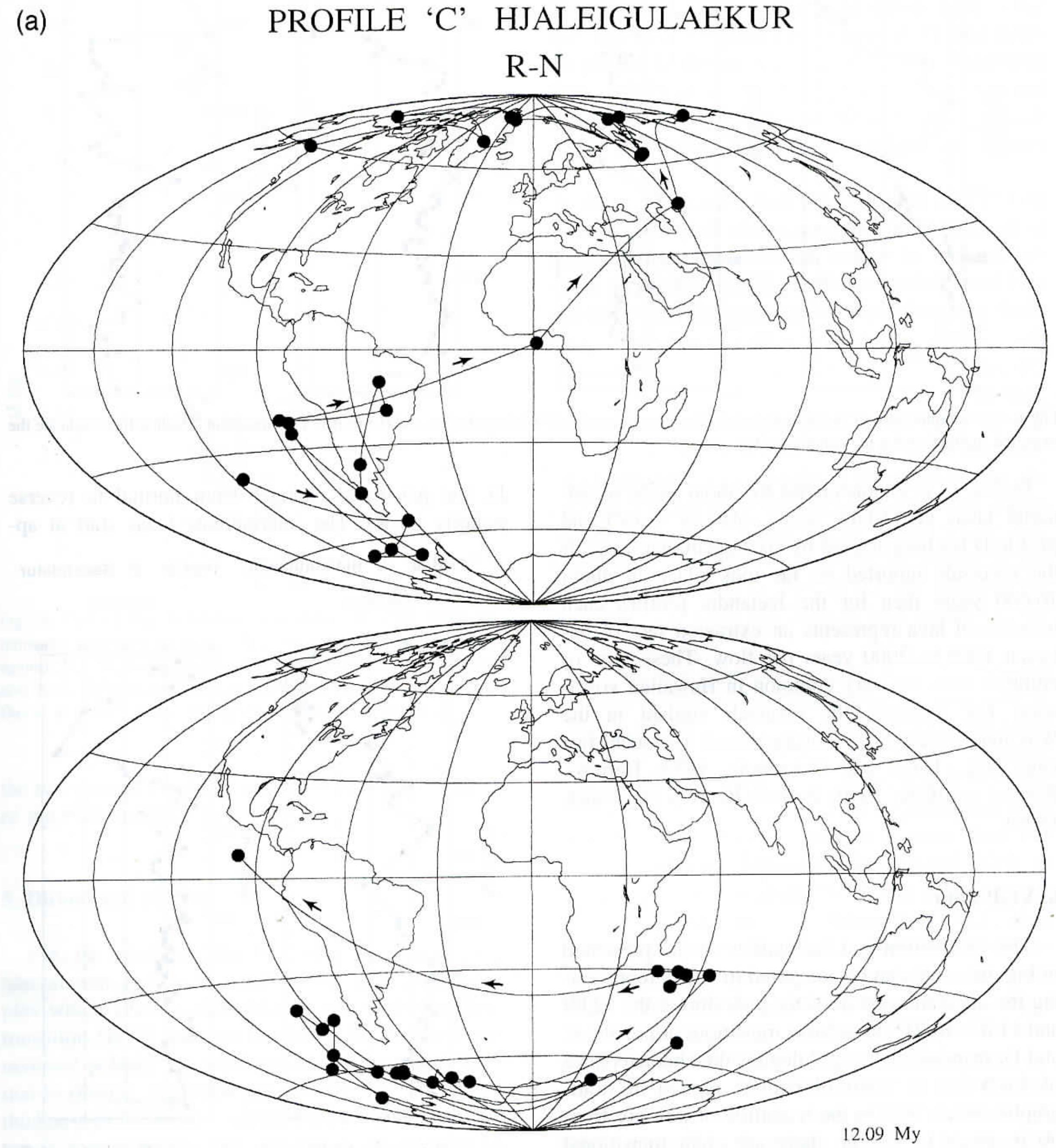

Fig. 8. VGP paths in geographical coordinates of lavas from (a) profile C and (b) profile D recorded in eastern Iceland.

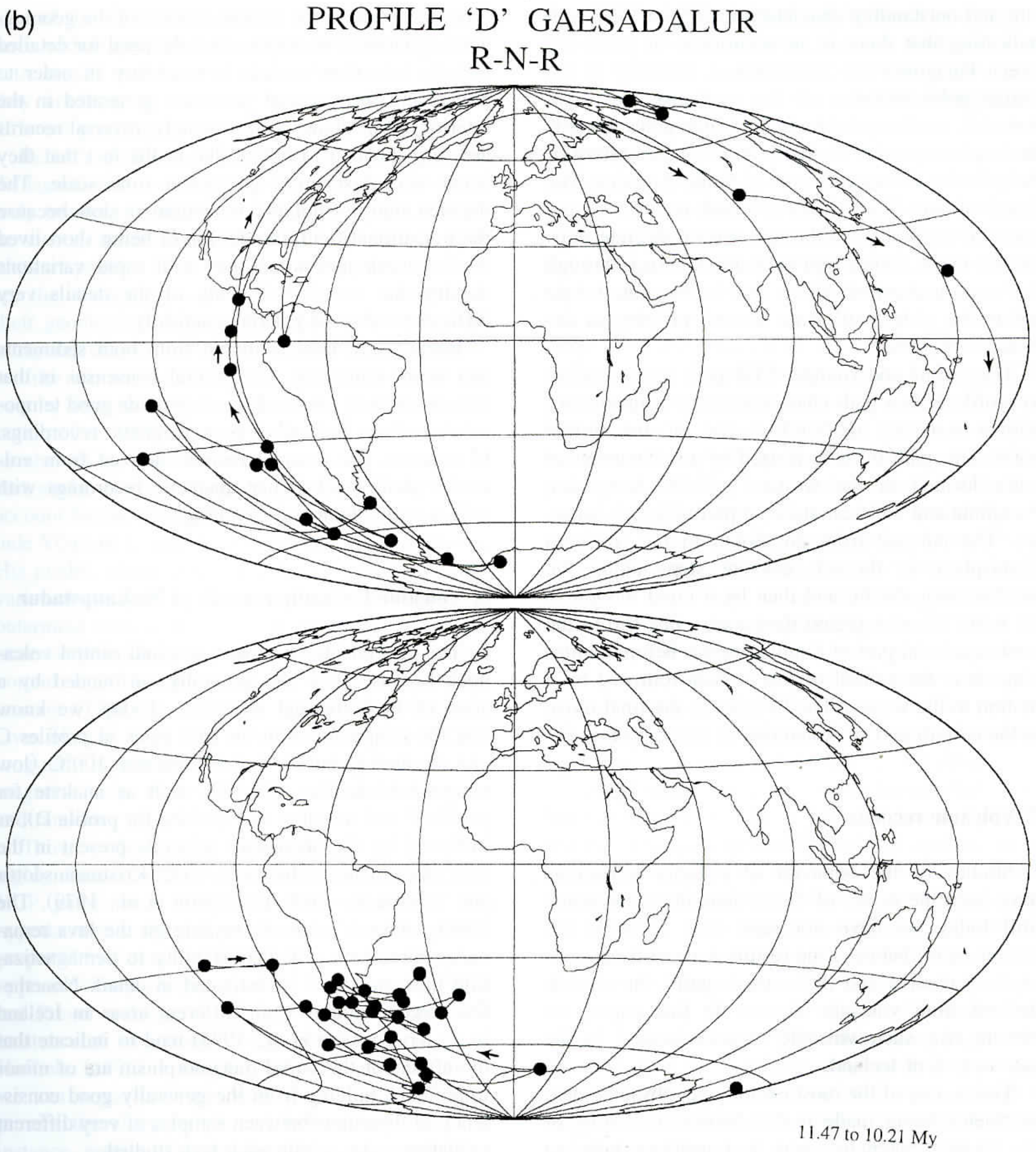

Fig. 8 (continued).

Fig. 8 shows the VGPs of both profiles broken down into two phases in order to visualize the motion of the poles in a clear way. Fig. 8a shows the characteristics of the VGPs of profile C (Hjaleigulaekur). The sense of the reversal is from reversed-to-normal polarity (R-N). One can visualize important and outstanding characteristics of the VGP path indicating that there is an occurrence of poles between Patagonia and Antarctica, a tendency of the virtual poles to move off the west coast of South America, a subsequent motion of such poles towards the southern portion of Africa and a sudden return of the poles to the western part of South America. The travel of the VGPs from reversed polarity to the northern hemisphere is through several discrete steps located in the middle part of South America, through the western coast of Africa then on to central Asia before the poles settle into normal polarity as depicted in Fig. 8a.

The second and younger VGP path corresponding to profile D is a path characterized by a reverse-to-normal-to-reverse (R-N-R) motion of the virtual poles. This path is characterized by a fair number of poles located in the western part of Antarctica, Patagonia and the west and east part of South America. The passage from the South to the Northern Hemisphere is through discrete steps along the southwestern Pacific and then by a rapid motion to the north Siberian region then a very fast trip to the west equatorial part of South America before continuing on to the central region in Asia followed by a motion to the western Pacific prior to the final move to the eastern part of Antarctica as shown in Fig. 8b.

7. Volcanic records

Studies of the behavior of polarity transitions have been the center of discussions in recent years. Still today we have not been able to settle the discrepancies between the results derived from sedimentary records and their counterparts, the records derived from volcanic sources. In this paper, we present two such volcanic records located in the eastern part of Iceland.

Today, one of the most exciting geophysical measurements being made is the detailed recording of the Earth's magnetic field in transitions between polarities. Much of our knowledge of magnetohydrodynamic processes occurring in the Earth's interior has resulted from studies of the geomagnetic field. Much of the current interest in geomagnetic field reversals is concentrated on documenting the detailed field behavior during a polarity reversal in order to constrain the various models of the geomagnetic dynamo. It is obvious that the need for detailed polarity transition records is necessary in order to understand the reversal processes generated in the interior of our planet. Unfortunately, reversal records are very difficult to obtain due to the fact that they occur very fast on a geological time scale. The detailed study of polarity transitions is slow because the transitional field, in addition of being short-lived is also weak and sometimes with rapid variations making the transitional study of the details very difficult to observe paleomagnetically.

Records are now available from both sediments and lavas. Currently, the general consensus is that records derived from sediments provide good temporal recordings but rather poor magnetic recordings. In contrast, the reversal records derived from volcanics yield much better magnetic recordings with only a sparse temporal sampling.

8. Volcanic Icelandic records at Neskaupstadur

The general idea has been to avoid central volcanoes because they are generally surrounded by a zone of hydrothermal alteration. Today, we know that the temperatures in the lava piles of profiles C and D during burial did not exceed 100°C (low temperature zeolites 50–100° such as analcite for profile C and mesolite and analcite for profile D), as indicated by the secondary minerals present in the rock (Kristmannsdottir, 1978, 1982; Kristmannsdottir and Tomasson, 1978; Palmasson et al., 1979). The effects of such moderate heating on the lava remanence directions and their stability to demagnetization have not been investigated in detail. Nonetheless, recent studies from different areas in Iceland (e.g., Kristjansson et al., 1995) tend to indicate that the effects of the burial metamorphism are of minor importance judging from the generally good consistency of directions between samples of very different oxidation states within each lava studied.

One of the main purposes of this paper is to demonstrate how certain key features of the transitional directions of the Icelandic profiles under discussion compare with conclusions drawn from the current work of the transitional directions from records obtained from lower latitudes and to give an idea of the relationship of these important key features with respect to the geodynamo. The paleomagnetic results will be presented in terms of VGPs as they are easy to visualize and compare between different geographical areas.

Reliable paleomagnetic results obtained from the demagnetization experiments and the presence of truly transitional directions (see Figs. 6–8) recorded in several lavas has allowed us to construct VGP plots of profiles C and D. In those figures, we can see the characteristics of the VGP paths in terms of their geometrical distribution. These interesting and intriguing characteristics of the two eastern Icelandic profiles are not new and have been reported in the past by Dodson (1980) when he analyzed the distribution of all VGPs in data sets then available from a number of volcanic locations including Iceland. In that study, Dodson suggested a plausible model to account for the relatively high proportion of low-latitude VGPs in Iceland as compared to other locations. His model, where non-dipole sources of the secular variation are concentrated in polar regions of the outermost core, needs to be tested using additional material from globally distributed sites. Another important set of results is the one obtained by Kristjansson (1995) in which he analyzes about 1000 lavas of ages 7–14 Ma old. Here he found that the long-term distribution of low- and mid-latitude geomagnetic poles of longitude is essentially uniform and random.

Thus, we have to point out that in view of the highly debated and contradicted hypothesis that the VGP paths track along one or both of the two hypothesized antipodal preferred bands of longitude proposed by Laj et al. (1991, 1992, 1993) and by the opposite viewpoint proposed by Valet et al. (1992) and Prevot and Camps (1993) that have brought the existence of long-lived dipolar clusters proposed by Hoffman (1992) or longitudinal bands into question, we can argue that the VGP paths discussed here present the characteristics of both viewpoints. For instance, profile C shows that the traverse from the reversed polarity to the normal polarity of some of the VGPs is through the American continent and some of the VGPs lie on the Asian continent where the 'preferred longitudinal bands' are located. As for the long-lived dipolar VGP clusters or 'patches' hypothesized by Hoffman (1992), profile C shows that only the VGPs located on the South American–South Atlantic–West Antarctica area coincide with one of the VGP clusters proposed by Hoffman. It is interesting to note that in one of the recently published reversal records of the Matuyama–Brunhes boundary derived from igneous rock and sampled in the southern hemisphere by Brown et al. (1994) and Pickens and Brown (1999) the VGPs obtained from such study yielded pole positions that center in Australia. Our contention at this point is that even more important than observing either one of the similarities with respect to the two currently hypothesized ideas about the behavior of the transitional fields is to emphasize the intrinsic characteristics of the VGP paths of the records discussed in this paper. Another set of ideas in terms of the interpretation of the behavior of the VGP paths has been proposed by Valet et al. (1992). These workers saw no statistical evidence for enduring preferred VGP paths. Prevot and Camps (1993) examined volcanic transition records from the past 16 Ma and arrived at the same conclusions as Valet et al. (1992): using various statistical filters, they found no significant long-term patterns in the data.

Regardless of what the currently presented interpretations are of the transitional fields, the importance of our results from eastern Iceland based on highly reliable transitional data as obtained from successful demagnetization of the transitional lavas from profiles C and D — derived from relatively nearby sites characterized by different ages, seem to indicate that at the 66°N latitude there are several persistent transitional features that are uniquely observed at those sites. Additional improvements to the data base may be made by pooling additional studies of Icelandic lavas by normalizing remanence values using (partially demagnetized) anhysteretic remanence magnetization (ARM) and/or samples properties and also by obtaining absolute paleointensity determinations from many individual lavas with a range of VGP latitudes in order to compare them with different sets of lava sequences in the mid and low-latitude locations (Kristjansson, 1999). Recent results from other volcanic records such as the ones derived from the Waianae volcano in O'ahu Hawaii seem to indicate that their transitional VGP paths are not consistent with the current models of polarity transitions but they rather display a unique geometrical geometry not in agreement with the results derived from sediments.

9. Conclusions

The main characteristics that emerge from the study of these two volcanic transitional records located in eastern Iceland, and the comparison with other volcanic records located at lower latitudes can be summarized as follows.

(1) The two volcanic records presented here, namely, profiles C and D, appear to represent two straightforward reversal records.

(2) In our discussion, we emphasize that both AF and thermal demagnetization of each one of the lava flows showing transitional and non-transitional directions successfully removed the secondary magnetizations of low coercivity, isolating a stable univectorial component of magnetization interpretable as records of the transitional paleofield behavior during the two reversals discussed here.

(3) The two reversals records obtained are characterized by 14 $(8+6)$ truly intermediate lavas that recorded the transitional paleofield with a great majority of the transitional VGPs located on the southern hemisphere concentrated in South America (Patagonia), Antarctica and southwest Africa (around Madagascar).

(4) This particular preponderance of the locations of the intermediate VGPs recorded by the two profiles located in eastern Iceland are based on highly reliable transitional data as obtained from successful demagnetization and rock magnetic tests for both profiles derived from relatively close sites (geographically and also in terms of radiogenic ages). They seem to indicate that at the 66°N latitude there are several persistent transitional paleofield features that are uniquely observed at those sites.

(5) It is important to point out that future paleointensity studies of these two profiles will shed some new light on the data presented here particularly in terms of the paleofield characteristics of the two profiles. In any case, the present results show that the paleofield was highly unstable during the transitional periods discussed in this paper. It seems clear that the preferred bands ideas cannot be supported by these data because the physical meaning of the bands suggest that they would persist for the entire transitional period. The fact that they do not show that variable non-dipole components is very significant.

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