Stratigraphy and paleomagnetism of a 3-km-thick Miocene lava pile in the Mjoifjördur area, eastern Iceland

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Abstract We have carried out stratigraphic mapping in the Upper Miocene basalt lava pile around the fjords Mjoifjördur and Seydisfjördur, eastern Iceland. The mapping is based on conventional methods including the use of interbasaltic clastic horizons and petrographically distinct lava groups. These units are also used to provide correlations with the Nordfjördur area south of Mjoifjördur. We present a 3-km composite stratigraphic column for the area between Mjoifjördur and Seydisfjördur. The geology of this area shows some differences from the classical model of Walker for the structure of eastern Iceland partly due to the fact that most of Mjoifjördur is not in the vicinity of central volcanoes. Detailed laboratory measurements of remanent magnetization were carried out on oriented core samples from 363 lavas in 10 selected profiles. The local paleomagnetic polarity stratigraphy supports correlations made on the basis of other criteria. Over 20 geomagnetic reversals are recorded in the eastern Iceland lava pile in a period approximately 13–10 Ma ago. The geomagnetic field during this period averages to a central axial dipole field, and its overall statistical properties resemble those obtained in earlier surveys in Iceland.

Key words Paleomagnetism · Stratigraphy · Basalt lavas · Eastern Iceland · Upper Miocene · Geological maps

Introduction

Previous related work on eastern Iceland

In his pioneering studies of the basalt lava pile of eastern Iceland, G. P. L. Walker put forward a new view of the tectonic, volcanic, and geochemical processes shaping the geology of Iceland. According to his model (Walker 1959, 1960; Bödvarsson and Walker 1964; Walker 1974), new crust is continuously generated in an active rift zone which is also subsiding. The activity is concentrated at central volcanoes (Walker 1963), characterized by dyke swarms and other high-level intrusions as well as by acid and intermediate magma production. The lifetime of a central volcano is of the order of 0.5–1 Ma, after which it drifts out of the active zone and is partly buried by younger lavas. Various kinematic and thermal aspects of continuous crustal rifting have been modelled by G. Palmason since 1973 (e.g., Palmason 1981). These models explain many consequences of the rifting process, but the actual situation is complicated by the effects of lateral movements of the rifting activity (Helgason 1985), the presence of a mantle “hot spot”, and variable directions of the rift zone.

The crust above sea level is mostly composed of subhorizontal flood basalts. One of Walker’s (1959) most important discoveries is that certain groups of 2–10 feldspar-porphyrhritic lavas often can be traced over large distances (30 km or more) in eastern Iceland. Extensive groups of olivine-rich basalts also occur, although their boundaries tend to be less distinct. It is likely that each group of lavas was erupted fairly simultaneously on the fissure swarms which are associated with central volcanoes in Iceland; these are known to reach 100 km in length. Walker (1959, 1963) also made use of the presence of widespread volcaniclastic horizons within the lava pile. These mapping methods were later augmented by paleomagnetic measurements on lavas and by K–Ar dating (Dagley et al. 1967). A composite section through the lava pile of eastern Iceland, based on the above work, was published by Watkins...
Volcanism and structure of eastern Iceland

Iceland (Fig. 1) is situated on the mid-Atlantic ridge on the divergent plate boundary between the Eurasian and the North American plates. When the plates drift apart (at a rate of about 1 cm/year in either direction) the gap between them is constantly filled with igneous rocks, both extrusive and intrusive. A zone of rifting and active volcanism crosses Iceland from the Reykjanes peninsula in the southwest to the Myvatn-Skjalfandafloi area in the northeast. This zone follows approximately the region of late Pleistocene (<0.7 Ma) age delineated in Fig. 1.

The present mapping project in the Mjoifjórdur–Seydisfjórdur area has been partly motivated by plans for the construction of road tunnels through the mountains between various communities in eastern Iceland (Haraldsson and Björnsson 1984; Gudmundsson 1992, 1993). Most of the field work presented in this paper took place in 1989–1993.

The present eastern Iceland, once situated on the volcanic zone, has gradually shifted toward east with decreasing volcanic activity. North and east of the Vatnajökull glacier there is a basaltic lava pile including remnants of several central volcanoes (see above, and Figs. 1 and 2) which show vigorous volcanic production accompanied by zones of intense secondary alteration and locally variable tectonic tilts. A flexure zone with sedimentary beds runs approximately N–S along the western border of Fig. 2, but the strata described in the present paper are considerably older than the flexure and not affected by it.

The oldest rocks at the Gerpir promontory on the far eastern coast are estimated to be 13 Ma old, using radiometric data from Watkins and Walker (1977) when recalculated with current K–Ar decay constants. At Lagarfjot the bedrock was formed 6–7 Ma ago. In late Tertiary times the present eastern Iceland can be visualized as a basaltic plateau, with a chain of central volcanoes (rising perhaps hundreds of meters above their
surroundings) extending along the plateau from southwest to northeast (Figs. 1 and 2).

The bedrock outside of central volcanoes consists mainly of basaltic lava flows (80–85%), but acid and intermediate rocks constitute about 10%. Between the basalt lavas there occur thin interbeds of reddish eolian sediment usually indicating warm climate. The amount of such sedimentary rocks of volcanic origin is of the order of 5–10%.

The average accumulation rate of the basalt lava pile mapped previously in eastern Iceland is in the range 700–1000 m/Ma, decreasing with increasing altitude. The average time interval between successive lava flows in any profile is of the order of 10000 years. Due to gradual subsidence of the volcanic zone, the lava pile is tilted 6–12° toward west or southwest near sea level (Walker 1974).

### General geology and tectonics of the Mjoifjördur area

The strata

The geology of the peninsula between Mjoifjördur and Seydisfjördur is to some extent characterized by the absence of central volcanoes. The acid rocks in the extreme east (hatching in Fig. 2) may have been produced by the eroded Bardsnes central volcano (Walker 1963). The location of this volcano is not well known; according to aeromagnetic results its center is approximately 10 km east of Dalatangi (Kristjansson et al. 1989). The basalt lavas are predominantly of three types, classified in the field (Walker 1959) as tholeiite basalts, olivine tholeiite basalts, and porphyritic basalts, but the classification is not always clear-cut. The basalt lavas are generally 8–12 m thick on average, olivine-rich basalts tending to be thinner than others and sometimes forming a series of “flow units” of 3 m thickness or less, erupted in rapid succession.

The lavas are frequently separated by sedimentary interbeds, varying in thickness from several centimeters to a few meters, but occasionally over 50 m. The sediments are mostly made of fine-grained tuffaceous material. Sediments of fluvial origin (such as conglomerates) are rare.

Ages

No new radiometric ages have been obtained in connection with the present study. The oldest rocks are approximately along strike from the Gerpir promontory, which is of 13.0 Ma age as stated above. The youngest lavas sampled by us are in the lower half of the thick normal-polarity zone seen in profiles E, F, and J of Dagley et al. (1967). This normal-polarity zone is likely to correspond to the long interval of predominantly normal geomagnetic polarity associated with the marine magnetic lineation “Anomaly 5”. The lower boundary of this normal zone in eastern Iceland was dated at 10.3 Ma by McDougall et al. (1976). A similar age of 10.5 Ma was found in central northern Iceland (Saemundsson et al. 1980), whereas in the NW peninsula the boundary appears to occur in 11.1-Ma-old lavas (McDougall et al. 1984). The difference has not yet been resolved, but it may be due to effects of regional alteration on the argon isotope ratio in the rocks. The lower boundary of the “Anomaly 5” interval (Chron 5n) is estimated by Cande and Kent (1995) to have an age of 10.9 Ma.

Tectonic tilt

Tectonic tilts in the Mjoifjördur area are toward SW–WSW (225–250°; Fig. 3). These tilts increase toward the west, which is unexpected but may be due to down-sagging in the surroundings of the large Thingmuli central volcano. They are about 5° at sea level on the easternmost promontory of Dalatangi, and 9° at the Mjoafjardara stream. Generally, the tilt decreases by 1–1.5° per 200 m with increasing elevation, and at the top of the mountains at the eastern end of Mjoifjördur it is close to zero. In the outer parts of the Seydisfjördur fjord, the tilt is generally 4–6° toward WSW, but near the town of Seydisfjördur and to the west it is only 2–3° at sea level. Tilt values for all profiles sampled by us are given in Table 1.

Cross section of the lava pile

Rapid erosion in the Quaternary has created numerous fjords and valleys exposing mountainside profiles (Fig. 3) which reach up to 1000 m in thickness. We have mapped 35 such profiles in the area of Fig. 3 (Gudmundsson 1992, 1993). Those ten profiles where we collected palaeomagnetic samples are shown in the figure. Distinct lava groups and sediment beds located during this mapping have been employed for the construction of a simplified east–west geological section (Fig. 4) through the area.

The lava pile in eastern Iceland generally thickens downdip. This can, for example, result in a 50-m-thick series of lavas at 600–900 m altitude above sea level (a.s.l.) having a thickness of 100–200 m at sea level to the west. Although some of our profiles were mapped in the field up to 1000 m altitude, the magnetic polarity stratigraphy is most often based on sampling below 600 m. This should yield comparable rates of lava production between profiles. In the discussion below we have not used the thickness normalization procedure of Watkins and Walker (1977, p. 534).

Faults and dykes

On average there are 4–5 normal faults per kilometer (measured in an E–W direction) in the Mjoifjördur
area according to our preliminary estimate. Most of the faults have a northerly trend, with throws commonly in the range 5–25 m (Gudmundsson 1992, p. 29). Basaltic dykes normally occupy 1–3% of the lava pile near sea level, and their trend is parallel to the strike of the lavas. Just east of our profile TO in Fig. 3 the dyke intensity increases to 4–7%. Another swarm of dykes, to some extent originating in the Breiddalur central volcano (which lies just south of the region of Fig. 2) crosses the Mjoaalfjardara stream in the western part of the mapped area. Most of the dykes are 2–5 m thick. A rose diagram for the dykes shows a dominant N–S trend in the eastern part of Mjoifjôrdur (Gudmundsson 1992), but in the western swarm other trends also occur.

Geothermal alteration

The basalts of eastern Iceland contain widespread secondary minerals such as chalcedony and clay minerals, filling joints and vesicles. Besides, there are zeolites indicating the maximum regional low-temperature hydrothermal alteration. The characteristic zeolites in olivine-rich lavas (Walker 1960) are chabazite/thomsonite, analcime, mesolite/scolecite, and laumontite, in order of increasing temperature. The alteration took place in the lava pile after its emplacement as a whole, but before the main phase of Plio-Pleistocene erosion. The alteration zones are generally horizontal, but they are elevated around the Tertiary volcanic centers. According to an estimate used in Figs. 8 and 13 of Watkins and Walker (1977) the upper boundary of the mesolite–scolecite zone indicates burial temperatures of 140–160 °C. However, Kristmannsdóttir (1982) has inferred from her studies of alteration at geothermal areas in Iceland that the formation of mesolite and scolecite may set in below 100 °C.

In the Mjoifjôrdur area the mesolite–scolecite zone is normally found at the shore and occasionally up to 100–200 m altitude a.s.l. in our profiles. The analcime zone is found in some places in the area up to 500 m a.s.l. The chabazite–thomsonite zone, where most of our paleomagnetic sampling has taken place, reaches up to 800–1000 m a.s.l. In the highest mountains, especially above 800–900 m at the eastern end of Mjoifjôrdur, there are very fresh olivine tholeiite basalts with no amygdale minerals.
Table I. Mean paleomagnetic directions, virtual poles, and remanence intensities measured in lavas from the Mjoifjardr-Seydisfjórdur area.

For continuation of Table I please see the next page.
### Table 1 (Continued)

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**Table continued with data entries.**
Description of individual sampling profiles and correlations

Eastern part

At the Dalatangi promontory there are two successive profiles, DA and DB (Figs. 4 and 5a), covering about 850 m of lavas. In the lower part of the profiles we find three thick acid lavas presumably related to the Bardsnes central volcano east of Mjoifjordur and Nordfjordur. Judging from the strike of the lava pile, acid rock in the Bardsnes peninsula east of Nordfjordur is located at the same stratigraphic level. We therefore expect our profiles DA and DB to be of similar or slightly greater age than profiles G and H (Watkins and Walker 1977) south of the Gerpin promontory.

A thin series of porphyritic lavas can be traced from top of profile DB to the base of profile TO in Mt. Toarfjall (Figs. 4 and 5a). These lavas probably belong to the Gerpin porphyritic group of Walker (1959), which may show cumulate textures and is sometimes accompanied by olivine basalts. Profile TO begins at the shore close to the ruins of Eldleysa farm and continues up a large gully in the mountain. Two prominent lava groups described by Walker (1959) in the Nordfjordur-Reydarfjordur area are most probably represented in this profile. These are the Vikurvatn olivine tholeiites at 520–570 m and the Vindhals porphyritic group at 750–850 m a.s.l. Sampling for palaeomagnetic measurements in this profile only reaches up to 580 m altitude.

Western part and northern extension

Profile MH (Figs. 3, 4, and 5b), located in a stream 1–2 km west of the farm Hesteyri, covers lavas which are stratigraphically equivalent to the upper part of profile TO. However, considerable downdip thickening occurs between the profiles. The above-mentioned Vikurvatn olivine group begins at 40 m a.s.l. On top of the sampled profile at 650 m a.s.l. there are thick sedimentary interbeds which are not well exposed at this locality, but which can be traced over a large area in Mjoifjordur and Seydisfjordur.

Profiles MA and MB at the two Hvita streams can be connected to MH by means of the thick sedimentary beds, found above 200 m altitude in MA. These beds are split by one 10-m-thick lava flow at 930 m in Mt. Toarfjall, but at MB they are split into three parts by 200 m of lavas. Some auxiliary profiles (not shown in Fig. 3) were studied in the field in order to aid in correlation over the 7-km interval between MH and MA and to confirm the presence of downdip thickening of lava groups. In this part of the lava pile there are several intermediate and acid lava flows which are considered to be distal products of the Reydarfjordur central volcano (Walker 1959).

Profile MC in the Mjoafjargar area and the Mjoafjarðarsheiði pass is the topmost profile described in this paper. The sediments mentioned above are not found in this profile, and seem to have been locally displaced or obscured by dykes. The dacite MC 15 may be the same flow as MD 35.

Profiles ST and GK (Fig. 5c) on both sides of the Seydisfjordur fjord have been added in order to provide a more three-dimensional view of the lava pile and to facilitate future mapping farther north. The profile ST is in Mt. Strandartindur just east of Seydisfjordur town. The Vindhals porphyritic group may be represented by lavas at 210–250 m altitude in ST and 350–380 m in GK. The thick sediments at 640–720 m altitude in ST, overlain by the Holmar olivine group, were most useful for correlation with the Mjoafjordur profiles. The profile GK in Mt. Grytukollur contains the same sediments at 590–650 m, also overlain by olivine basalts.

Paleomagnetism

Paleomagnetism has been an important tool for stratigraphic mapping in Iceland since the pioneering work of Jan Hovers and others in the 1950s. The primary remanence vector in the Upper Miocene to Pleistocene
MJOIFJÖRÐUR - SEYÐISFJÖRÐUR
Composite stratigraphic profile in the area between Seyðisfjörður and Mjóifjörður

**STÓRURDARGIL**

- Top of Stórurðargil
- These layers are at same stratigraphic level as layers in Brand at road

**HVIDTA INNRI**

- Western rim of gully
- Almost glassy
- Move into gully
- Dyke swarms parallel to gully below towards west, over dykes

**HVIDTA YTRI**

- Amphibole, stibnite, and merrillite
- Layered, colourless tuff, possibly reflect hot air and water transported
- Sedimentary interbed of colourless layered tuff, possibly reflect hot air and water transported
- Waterfall in top of this layer

**HESTEYRI**

- Profile starts at ruins of whaling station
- Profile starts 0.5 km east of Stóruþargil and goes up eastern flank of gully

**MJOARFJARÐARÁ**

- Prominent very thick lava flows in Stóruþargil
- Rough surface, possibly close to a vent

**MC**

- Profile starts at base of Kiltakjukur
- Profile starts at base of Kiltakjukur
lava pile reverses on average once every 15-20 lavas (Kristjansson and McDougall 1982). The remanence is generally of sufficient intensity that the polarity of up-down oriented hand samples can be estimated by a simple fluxgate magnetometer in the field. The polarity thus found is not entirely reliable due to the presence of Brunhes age viscous remanence (VRM) and other factors. However, careful measurements on 3-4 samples per flow will usually give a consistent polarity which is indicated in Fig. 5 by “N” for normal and “R” for reverse. This parameter aids in the initial correlation between profiles. Lavas where the field measurements did not yield a distinct polarity are marked “A” (for anomalous or ambiguous) in Fig. 5. Occasionally, the viscous overprint has changed the polarity from R to N in all the hand samples.

Sampling and measurements

Four 25-mm cores were generally taken from each flow in the profiles of Fig. 5. The cores are mostly from the bottom 2 m of each flow, distributed over several meters laterally if practicable. We collected cores from the ignimbrite MD 17A, but otherwise no sediments were sampled. The cores were orientated in azimuth by sun compass or geographic sightings using 1:50 000 topographic maps. The natural remanence (NRM) vector was measured in one specimen per sample, and also the remanence left after 10 mT (100 Oe), 15 mT, and 20 mT peak alternating field (AF) treatment. The equipment used was an Institut Dr. Förster four-probe static fluxgate magnetometer and a Molspin AF demagnetizer with a two-axis tumbler. Most or all of the VRM in the specimens has been eliminated by the 10-mT field, and the remanence direction usually changes by 2° or less between the 15 and 20-mT treatments. In cases of apparent instability the 20-mT treatment was repeated immediately and the measurement results were averaged. Alternating fields of 25 mT or more were applied if necessary. Specimen directional results were averaged as unit vectors after each treatment stage, and the average yielding the highest resultant was used in statistical calculations. However, if two successive treatments gave very similar resultant vector lengths, the direction from the higher field was used.

Results from about 20 individual cores were discarded, usually because of magnetic instability, suspected reheating or lightning effects, orientation errors or out-of-place outcrops, etc. Furthermore, all directions from six out of the 363 lavas sampled were rejected due to poor internal agreement. The magnetic results in profile MB were affected by the presence of dykes: of the six rejected lavas, three are in this short profile.

Presentation and discussion of paleomagnetic results

Table 1 lists the best mean direction of remanence in each lava unit after correction for tectonic tilt, and the corresponding virtual geomagnetic pole (VGP). Also given in Table 1 is the 95% confidence angle ($\alpha_{95}$) for the mean field direction, and the arithmetic average remanence intensity for each lava after 10-mT AF treatment. The highest $\alpha_{95}$ value in the list is 21°, and the root-mean-square value of this parameter in the collection is 6°, which is better than in most previous surveys in Iceland. The final column of Table 1 lists the inferred polarity of the primary field. This is used in the construction of polarity columns at the right-hand side of each sampling profile in Fig. 5.

Of the 357 reliable lava directions in Table 1, 154 are of normal polarity, i.e., corresponding to virtual poles with positive latitudes. A total of 203 are of reverse polarity, including three lavas which yield virtual poles within 10° of the equator. Figure 6 is a stereographic projection of the directions of Table 1 on the horizontal plane. It shows that the directions are scattered in azimuth about the central axial dipole directions (±77° inclination) in a fairly random fashion, in agreement with conclusions from other paleomagnetic research in Iceland (Kristjansson and McDougall 1982; section 3.2 of Kristjansson 1995). The mean remanence direction (after inversion of the reverse directions, and exclusion of the one lava with $\alpha_{95}>20°$; cf. rejection criteria in Kristjansson and Johannesson 1989) has a declination of 357° and an inclination of 76.8°. Because the 95% confidence angle for this direction is 2.1°, it is not signif-

![Fig. 5a-c](image1)

![Fig. 5a-c](image2)

![Fig. 6](image3)
icantly different from the field of a central dipole. This is in contrast to some previous studies on lavas in Iceland, especially of 10–15 Ma age (see Table 3 of Kristjansson and McDougall 1982), which tend to yield mean directions with somewhat lower inclinations and positive declinations (“far-sided” and “right-handed” poles). The reasons for these differences are not certain, so it is not yet clear whether the actual long-term Neogene mean field in Iceland is an axial central dipole field. Minor systematic errors in the orientation and marking of cores as well as inadequate correction for tectonic rotations may be among the causes of these variable results.

The angular standard deviation of directions around the above mean is 22° and the angular standard deviation of virtual geomagnetic poles is 31°. These values are similar to those found elsewhere in Iceland (Kristjansson and Johannesson 1989; Kristjansson 1995). In calculating the statistical parameters we use all reliably determined directions from the lava collections, including those (about 20%) which correspond to virtual poles below 50° latitude N or S.

The remanence intensities (J in Table 1) have an arithmetic average of 3.0 A/m, which is similar to, or slightly less than, average results from other Neogene lava collections from Iceland listed by Kristjansson (1984). The effect of burial on the intensity may be estimated by grouping the Mjoifjördur area lavas according to altitude, e. g., 0–200 m, 200–400 m, 400–600 m, and >600 m. The average intensity values in these four groups are 3.1, 2.7, 3.0, and 3.1 A/m, respectively, each with a standard error of about 0.35 A/m. We conclude that burial in the lava pile to as far down as the lower boundary of the chabazite–thomsonite zeolite zone (see above) has very little effect on the primary remanence. A similar result may be seen from Fig. 4 of Kristjansson (1984) for other Icelandic lava collections. However, the outcome of this test may also be affected by spatial and temporal variations in lava composition, and other factors.

The magnetic polarities generally support correlations between profiles inferred from the dip of strata and the petrographic marker series as shown in Figs. 4 and 5. However, it is not to be expected that all details agree in profiles which are several kilometers apart. Due to the episodic character of the volcanism, it is possible that time intervals between successive lava flows may locally be of 0.1 Ma or longer duration so that some short geomagnetic subchrons will not be recorded. For example, a long quiescence of volcanism may have occurred in the eastern part of the Mjoifjördur area during formation of the thick sedimentary interbeds encountered in profile TO (915–945 m altitude), above profile MH, and in the upper parts of profiles ST and GK.

At the top of profile DB and near the bottom of TO the remanence vector displays intermediate directions yielding low-latitude virtual poles from which we estimate that DB 24, 25 may be of the same age as TO 5. A correlation between TO and MH based on dip and strike is supported by the occurrence of a reverse-to-normal transition at TO 54/55 (field measurements only) and MH 18/19. This boundary is also found at ST 16/17 and GK 12/13 in Seydisfjörður, in good agreement with other stratigraphic indicators.

A remarkable single-lava geomagnetic excursion is recorded in the three last-named profiles at a similar (probably identical) stratigraphic level, in flows MH 43, ST 35, and GK 22 (Fig. 6 of Kristjansson 1995). It may have gone undetected in profile TO, because no samples for laboratory magnetic measurements were taken from the uppermost part of this profile, and in profile MA the excursion is probably hidden below sea level.

The polarity remains normal at least up to the thick sediments in profiles TO, MH, and MA. In MB the normal-polarity zone extends a little beyond the lowest sedimentary horizon and in ST beyond two or all three of the sedimentary units. In profile GK north of Seydisfjörður the normal zone ends at the sediment. It should be noted that considerable down-dip thickening of the series between the sediments and the Holmar olivine basalts is taking place from TO/MH/ST/GK to MB/MD. The single-lava normal polarity zone MD 24 may be the same as that recorded in MC 6, 7. Correlations to MB on the basis of magnetic directions are very uncertain due to incomplete core sampling in this profile as well as the disturbing effect of dykes.

Composite section

From the above profiles (excluding MA, ST, and GK, which overlap entirely with other profiles) we have constructed a composite “vertical” section of 3.0 km cumulative thickness. For this composite section we have chosen to use the following flows: DA 1–16, DB 1–25, TO 4–49, MH 3–52, MB 1–12, MD 18–35, and MC 16–56. Figure 7 shows the palaeomagnetic polarities of the composite section in the Mjoifjördur area, with tentative correlations to the time scale of Cande and Kent (1995). Such sections can be very useful for comparison purposes; however, they should not be interpreted in great detail because their appearance is influenced in an arbitrary fashion both by the down-dip thickening and by localized features. Thus, if suitable outcrops had been available, we would have preferred moving the profile locations DA and DB laterally to avoid the three thick acid lava flows of limited horizontal extent. This could have changed considerably the polarity structure of the bottom 500 m of the composite section.
Correlation with the Nordfjordur area

Attempts to establish stratigraphic correlations with the Nordfjordur area south of Mjoifjordur (Fig. 2) can be based both on geology and on geophysical parameters, especially magnetic polarities in the lava pile. Accurate radiometric dating will resolve a number of ambiguities in such correlations if and when it becomes available. In using the magnetic polarities certain shortcomings of previous research in the Nordfjordur area must be kept in mind:

1. The stratigraphic ties between the individual profiles G, H, A, B, C, D, and E (Watkins and Walker 1977) were based on geological criteria only. There is not always sufficient overlap between adjacent profiles to test the degree of agreement of these ties with the pattern of polarities in the lava pile and additional field work is needed to establish the correlations firmly (G. P. L. Walker, pers. commun., 1989).

2. Paleomagnetic sampling in the Nordfjordur area was not complete: in some flows no sample or only a single sample was measured; parts of profiles were unexposed or were close to dykes which may have affected the remanence; faults of undetermined magnitude occur; etc.

3. In the tables published by Watkins and Walker (1977) the directional agreement between the two cores measured in each lava flow is sometimes quite unsatisfactory. These flows are nevertheless used in the above-mentioned paper for the construction of polarity columns which therefore include several spurious one- or two-lava geomagnetic “events.”

A composite section for the Nordfjordur area with a corrected and simplified magnetic polarity column is shown in Fig. 8.

Main stratigraphic correlations of Mjoifjordur-Nordfjordur

The main stratigraphic correlations of Mjoifjordur-Nordfjordur are the following:

1. The acid lavas DA 11, 15 and DB 2 are roughly contemporaneous with the acid and intermediate lavas at the bottom of Watkins and Walker’s profile G, and the acid tuff DB 10/11 may correspond to either of the tuffs G 22/23 or G 31/32. Support of this interpretation from the polarity stratigraphy is not straightforward: in our opinion, the normal-polarity zone at the bottom of profile G is the same as that in our flows DA 12-16, the large difference in thicknesses of these zones being due to localized eruptive activity in the vicinity of the Bardsnes central volcano. The bottom reversely magnetized flows DA 1-11 at Dalatangi all yield similar mid-latitude virtual poles (Table 1), indicating rapid buildup, which is supported by the lack of sedimentary interbeds.

2. Three porphyritic lavas at the top of our profile DB (Fig. 5a) are thought to correspond to the lavas H 29-30, i.e., the Gerpir porphyritic group. The normal low-latitude virtual poles associated with this group in flows DB 24-25 and TO 2-3 may occur in H 28 (unreliable remanence direction) and in the unexposed interval above that lava.

3. Watkins and Walker (1977) correlated flows H 29-30 with A 13-14, across a distance of 15 km. Our own geological observations in the area indicate that H 29-30 should preferably be correlated with the thick porphyritic flow A 30. The normal excursion DB 24-25 might then have a counterpart in A 29-30, but there would be a problem in reconciling the polarities of the lower parts of H and A. Again, this problem is possibly caused by different rates of buildup, profile H being much closer to the Bardsnes and Reydarfjordur volcanoes than profile A.

4. The olivine tholeiite lavas TO 47-49 and MH 2, 5, 9 (Fig. 6b), which we assign to Walker’s Vikurvatn group, are found at the middle of a reverse polarity zone. In Watkins and Walker’s profiles in Nordfjordur these olivine basalts occur around B 30 and C 10, likewise within a reverse zone.

5. Lavas correlated with the Vindhals porphyritic group at TO 59-63 and MH 18-26 are in the bottom part of a long normal-polarity zone with some porphyritic lavas being erupted before the polarity change. In Watkins and Walker’s (1977) profile C this group is found as flows C 32-36, similarly in the lower part of a normal zone. The flow C 25 on the reversal boundary is also highly porphyritic.

6. The thick sediments and tuffs at the top of our profile MH and elsewhere in Mjoifjordur and Seydisfjordur most probably correspond to some or all of the acid tuffs which occur between many of the lavas C 50-60 and at the bottom of profile D in Nordfjordur. It should be kept in mind that this sedimentary sequence with intercalated lavas exhibits a fourfold increase in thickness from profile TO to profiles MB and MD. The single-lava magnetic excursion (MH 43, etc.) in Mjoifjordur and Seydisfjordur has not been located in Nordfjordur, but it may correspond to a stratigraphic level somewhere between flows C 34 and C 50.

7. The Holmar olivine basalts, represented by many of the lavas MC 23-32, are found in D 35-49. In both profiles the lavas envelope a short normal-polarity zone. This is probably also the case with flows GK 46-58 north of Seydisfjordur (Fig. 5c). In profile ST south of that fjord where the Holmar series is unusually thick (at least 250 m of olivine tholeiites) our laboratory measurements only included the lowest 90 m, all reversely magnetized.

8. An olivine basalt group which occurs in some of the lavas MC 42-50 and straddles the lower boundary of the “Anomaly 5” normal zone (at MC 48/50) possibly represents the Gjóta olivine basalts mapped by Walker (1959) in Reydarfjordur. They are also found from lava D 57 upwards, probably well into profile E. The single-flow normal-polarity zone MC
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Fig. 7. Composite polarity stratigraphy of the Mjöifjörður area, also including two profiles in Skjálfandi. The geomagnetic polarity time scale for the period 10.5–14 Ma ago, derived by Cande and Kent (1995) from ocean-ridge anomaly lineations, is shown on the right. Broken lines indicate tentative correlations.
Fig. 8 Composite polarity stratigraphy of profiles G (33 lava flows), H(30), A(43), B(39), C(66), D(68), and E(23) in the Gerpir-Nordjordur-Fagridalur area, based on geological mapping and paleomagnetic measurements (Watkins and Walker 1977). Doubtful or spurious thin polarity zones have been eliminated, and an alternative correlation between profiles H and A is suggested here. Polarity time scale as in Fig. 7.
46 could then correspond to either of the zones D 59-60A or D 66-67.

9. A tuff layer at altitude 750 m between MC 50/51 is presumably the Reydarfjörður tuff. This particular tuff occurs at 360 m altitude between lavas F 62/7 in Watkins and Walker's profile F approximately 6 km to the west, in agreement with the average westerly component of the local tectonic tilt on the way. Very considerable down-dip thickening seems to be present here, because there are only a couple of lavas between the base of the normal zone and the tuff in MC, but over 25 flows in E and F together. This may be due in part to rapid buildup of lavas near the Thingmuli central volcano. We have found lignite just above flow MC 56, which we correlate with the lignite-bearing Holmatindur tuff to the south, also occurring at F 14/15.

**Paleomagnetism**

The lava flows of the Mjoifjörður area carry a stable primary remanent magnetization, the direction of which (Table 1) can be measured accurately after removal of secondary viscous remanence by AF treatment. Within-flow directional agreement is better than in many comparable studies in the Upper Tertiary and Lower Quaternary lava pile in Iceland. We ascribe this to the regional hydrothermal alteration in Mjoifjörður being less than in the areas studied previously. We stress that future paleomagnetic surveys in the lava pile of Iceland should avoid zones of alteration (including dyke swarms) if reliable information on the properties of the geomagnetic field is sought; this is especially important in paleointensity research.

The present study confirms the applicability of paleomagnetic polarity zones for establishing stratigraphies within the lava pile, and it also furnishes examples where geomagnetic subchrons or excursions assist in long-distance correlations. Polarities measured carefully in the field with a hand-held fluxgate magnetometer (Fig. 5) are correct in a large majority of lavas in our Mjoifjörður and Seydisfjörður profiles.

The long-term average direction of remanence in the Mjoifjörður area conforms to that of an axial central dipole. The dispersion of individual lava directions around this average (Fig. 6) is similar to those found previously for other surveys of similar size in Icelandic lavas (Kristjansson and McDougall 1982; Kristjansson and Johansson 1989). In the paleomagnetic literature, low-latitude virtual poles are usually excluded from calculations of dispersion, but there is no physical justification for this practice.

The size of the present Mjoifjörður data collection on its own is insufficient for some statistical studies e.g., regarding the question of overall magnetic differences between lavas of normal and reverse polarities or the question of whether virtual-pole paths during geomagnetic reversals lie preferably in certain longitude intervals. Kristjansson (1995) has combined the present collection with several others from Iceland to study these questions. 

**Ages, rates of emplacement, and polarity zones**

Results of our mapping in Mjoifjörður are summarized in Figs. 4 and 7 where a composite magnetic-polarity column of lavas and sediments of 3 km total thickness has been constructed from the individual profiles. In Fig. 7 we followed the convention of McDougall et al. (1984) in only counting reversals if the VGP position moves 40° beyond the equator. Accordingly, events such as MH 43 (and possible excursions recorded at the top of DB and bottom of TO) are not included. There are 19 reversals of polarity in approximately 210 lavas in our composite section. In the polarity column for the Nordfjörður area as revised by us in Fig. 8, there are 22
reversals in approximately 240 lavas, up to the Holmatindur tuff in profile F. Consequently, a single-polarity zone in these two areas contains on average about 11 lavas. In surveys elsewhere in Iceland (Table 1b of Kristjansson and McDougall 1982) average values of 13–23 lavas per polarity zone were found.

The ages of the ends of our composite section are not certain. At the older end a regression analysis of stratigraphic thickness vs radiometric ages on the profiles C, D, E, and F by McDougall et al. (1976) yields a 12.4-Ma age for the lowest lavas in profile C. However, the lava G 9 in profile G at Gerpir is 12.9 Ma old according to dates published by Watkins and Walker (1977). This implies a relatively rapid buildup in the profiles C, H, A, and B below the base of C, namely 1000 m (see Fig. 8) in 0.5 Ma, which is three times the average rate of emplacement in profiles C through F. Such rapid buildup could be due to the fact that the profiles G and H are on the flanks of both the Bardanes and Reydarfjörður volcanoes.

As for the age of the upper end of our composite section, one conclusion from the downdip thickening between profiles MC and F is that the topmost normal-polarity zone MC 49-56 in our Mjoafjardara profile may cover as much as a half of the “Anomaly 5” normal magnetic interval. The age of MC 56 could be thus in the range from 9.6 Ma according to the dates of McDougall et al. (1976) to 10.4 Ma if the time scale of Cande and Kent (1995) is preferred.

Hence, our composite section may be estimated to cover the time interval from about 13.0–13.2 Ma ago to 9.6-10.4 Ma ago, of length 3.1 ± 0.5 Ma. The number of geomagnetic reversals is then at least 19 in this interval. In addition, we have to allow for reversals which are not recorded in the Mjoafjordur area lava pile (e. g., one normal-polarity zone at the top of profile D in Nordfjordur; see Fig. 8). Furthermore, apparent excursions such as that seen in lava MH 43 probably represent short magnetochrons which were incompletely recorded due to the episodic nature of the extrusive volcanism. This could bring the actual number of geomagnetic reversals in the 3.1-Ma interval to 25, i. e., approximately eight reversals per Ma on average as deduced from other evidence in Iceland by Kristjanson and McDougall (1982).

Correlations with other areas and time scales

We consider the reversely magnetized lavas at the base of our profile DA on the coast at Dalatangi to be the oldest units mapped thus far in eastern Iceland. Judging from the strike of lavas at Dalatangi and north of Seydisfjordur it is possible that still older rocks occur on the promontory north of Lodmundarfjordur (Fig. 2).

Due to the uncertainty in ages mentioned in previous sections, the large variations in eruptive activity between profiles as also mentioned above, and a probable hiatus at the thick sedimentary beds in Mjoafjordur, any correlation of details in our polarity columns with published geomagnetic polarity time scales (Figs. 7 and 8) remains speculative. Furthermore, many short chron (<5·10^4 years) are likely to have been left out in the reconstruction of Neogene polarity time scales from marine anomaly lineations. Correlations with polarity columns from other parts of Iceland are similarly uncertain, except that there is still hope of the thick normal-polarity zone of around 10 Ma age being a useful common reference. Another possibility for long-distance correlation is that the fluctuating remanence directions (representing a period of instability of the geomagnetic field) found in some NW-Iceland lavas by Kristjanson and Johannesson (1989) are contemporaneous with lava flows G 23-30 and H 2-6 or alternatively with those at the top of DB.

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