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Paleomagnetic studies in Skarðsheiði, South-Western Iceland

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# Paleomagnetic studies in Skarðsheiði, South–Western Iceland

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**Abstract** – *We have mapped a well–exposed composite profile through the lava pile in the western part of the Skarðsheiði mountain, and made detailed laboratory measurements of paleomagnetic remanence directions in oriented samples from 92 lava sites from this profile. The lower 55 lavas or so consist of a partially recorded normal–polarity zone, overlain by a thick reverse–polarity zone. The latter which includes a series of porphyritic lavas, was named R5 by Einarsson (1957). The upper part of our profile contains a normal–polarity sequence of about 20 flows (N5 of Einarsson) and a partially recorded reverse zone. Franzson (1978) and others have correlated the R5–N5 boundary with a similar boundary in the Akrafjall mountain and with the transition between the Gilbert and Gauss geomagnetic chrons. We have also sampled 29 lavas in two shorter profiles farther east in Skarðsheiði, at the boundary between the R5 and N5 polarity zones. We confirm the observation of Wilson et al. (1972) and Kristjánsson and Sigurgeirsson (1993) that several lava flows with transitional directions occur at this boundary at the northern side of the mountain. Only a few such flows are found on the south slopes of Skarðsheiði. At least three short geomagnetic excursions are recorded in the R5 zone. The lava flows are good material for paleomagnetic direction measurements, although hydrothermal alteration has affected the lowest part of the composite profile. Their average direction is quite similar to the axial dipole field as expected. Thermomagnetic tests on several samples indicate that they are not very suitable for paleointensity studies.*

## INTRODUCTION

### Geology

The thick sequences of subaerial lava flows (mostly of basalt) and minor sediments, which are exposed above sea level in Iceland, are generally thought to have been erupted in an active zone of rifting and volcanism. This zone which belongs to the Mid–Atlantic rift system, trends roughly from south–west to north–east through the island (Figure 1; see review by Sæmundsson, 1986). The rift activity in the southwest has been suggested to have moved to a new location some tens of km to the east about 15 M.y. ago (Harðarson *et al.*, 1997) and again 5–7 M.y. ago, with a third ridge jump being in progress in the Late Quaternary. Eruptive activity at any time is mostly confined to central–volcano complexes within the volcanic zones. The zones of volcanism are constantly subsiding as a result of the extrusive volcanism, so that the exposed lava pile tilts towards them (Walker, 1959, 1965). In South–Western Iceland this regional dip is of the order of 5–10 degrees to the south–east, decreasing upwards; considerable local variations in dip occur, especially near the central volcanoes. Some regional hydrothermal alteration has occurred in the lava pile, increasing with depth. In the Akrafjall mountain (Figure 1) for instance, an alteration zone characterized by the zeolites mesolite and scolecite is apparent from sea level and up to about 100 m elevation, where it is followed by an analcime zone, a chabazite–thomsonite zone and then from 500 m altitude to the top at 550 m

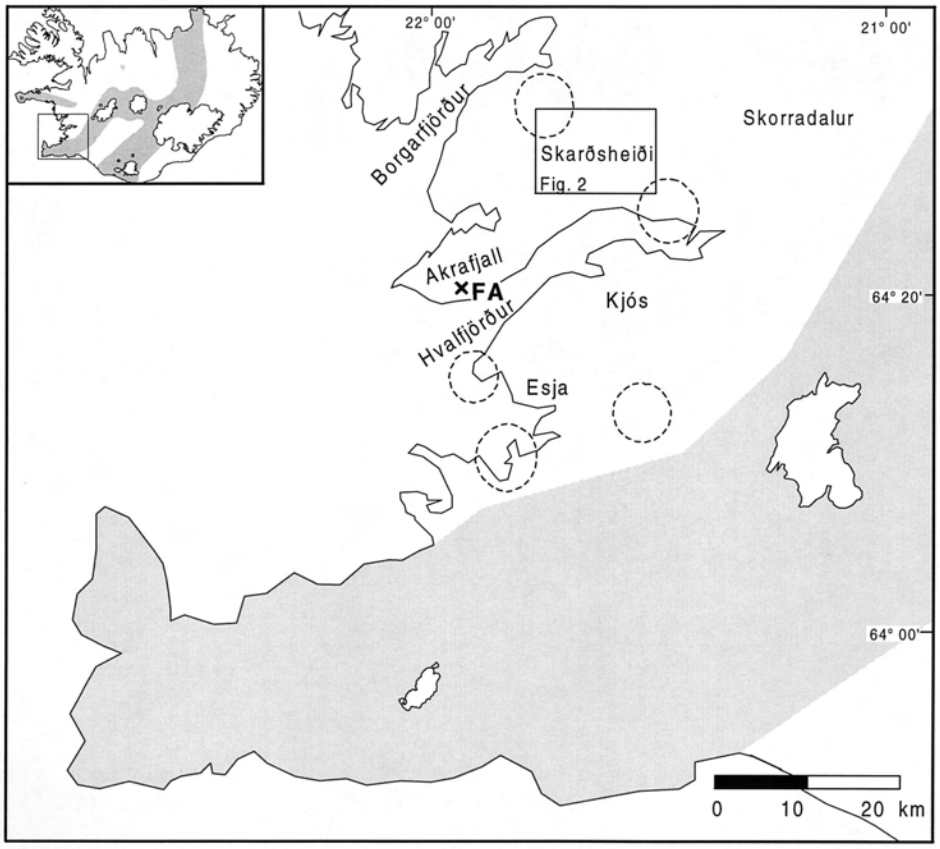

Figure 1. Index map of South–Western Iceland. Circles indicate the approximate positions and sizes of five extinct (Upper Pliocene – Lower Pleistocene) central volcanoes in the vicinity of Skarðsheiði. Stippled region: Western active volcanic zone. – *Lauslegt kort af Suðvesturlandi, þar sem sýndar eru staðsetningar og stærð fimm fornra megineldstöðva í nágrenni Skarðsheiðar. Gosbeltið er skyggt.*

the basalts are zeolite–free. Cores of the central volcanoes and their immediate surroundings have suffered high–temperature alteration, resulting in minerals such as laumontite, calcite, quartz, epidote and chlorites.

The lavas which were erupted before the late Pliocene originally formed a wide plateau but subsequent erosion has left a landscape of fjords, with mountains reaching up to 1000 m above sea level. Typical lava flows in hillside exposures have a mean thickness of 5–10 m and a lateral extent of some km. In the areas of Iceland where Quaternary volcanic formations outcrop at the surface, material erupted under subglacial or subaqueous conditions (hyaloclastite) tends to be dominant. The lateral extent of each unit, as well as the amount of spatial overlap between units, is less than in older areas.

Stratigraphic mapping of the pre–Quaternary lava pile in Iceland has proceeded intermittently, the best–known effort being that of G.P.L. Walker and his students in the fjords of Eastern Iceland in 1955–64 (e.g. Walker, 1959). Many such stratigraphic studies on composite sections in different areas have been accompanied by detailed paleomagnetic measurements on core samples collected from selected sections, and some have included radiometric dating.

## Previous paleomagnetic research

In his pioneering work in South–Western Iceland, Einarsson (1957, 1962) used magnetic remanence–polarity measurements on hand samples in the field to set up a scheme of polarity zones. They were numbered back in time from the present, as N1, R1, N2, R2 and so on. His mapping, however, did not include the delineation of petrographically distinct lava groups as used very successfully by G.P.L. Walker (1959) and later investigators. Unfortunately, Einarsson's regional mapping has not been followed up to sufficient extent: some small areas in South–Western and Western Iceland have been mapped stratigraphically, but the descriptions of many such areas are mostly to be found in student theses and in internal institute reports.

Sigurgeirsson (1957) studied paleomagnetic pole positions in lava flows in South–Western Iceland by laboratory measurements on oriented samples, concentrating on lavas at Einarsson's polarity zone boundaries. His results constituted the first–ever evidence of "intermediate" pole positions in middle and low latitudes. The largest numbers of such intermediate poles were found at the R3–N3 boundary at several sites in the Esja and Kjós areas (Figure 1), which have been subsequently studied by other investigators (Kristjánsson and Sigurgeirsson, 1993; Goguitchaichvili *et al.*, 1999). Another site of several intermediate poles was investigated in the Skorradalur valley east of Borgarfjörður (Figure 1) which Einarsson (1957, Figure 3) and Sigurgeirsson assumed to represent the same polarity boundary as the N4–R3 in Esja and Kjós, see Kristjánsson (1995).

Wilson *et al.* (1972) published polarity results and some diagrams of pole positions from a paleomagnetic study of several profiles through the lava pile of South–Western Iceland, based on Einarsson's mapping. They essentially confirmed his results as regards the polarity of lavas in the profiles. However, no revision of Einarsson's (1957, 1962) polarity zone numbering scheme was attempted, nor a correlation with the time scale of geomagnetic polarity reversals then available in the literature.

Extensive K–Ar dating by McDougall *et al.* (1977) of a composite section in valleys northeast of Borgarfjörður supported correlations previously suggested (e.g., Sæmundsson and Noll, 1974) between polarity zones in the lava pile and the Geomagnetic Polarity Time Scale in the time interval 1.5 to 3.5 M.y. ago, i.e. to below the R5–N5 which was correlated with the Gilbert–Gauss boundary. These correlations also agree fairly well with the polarity mapping by Einarsson (1962) in the Borgarfjörður valleys, where Einarsson's locally designated r5–n5 boundary in his map V may be the upper Mammoth transition rather than the Gilbert–Gauss transition. It corresponds to the zone boundary at NT 10/11 in McDougall *et al.* (1977).

The main comprehensive project of stratigraphic mapping in South–Western Iceland published to date is described in the paper of Kristjánsson *et al.* (1980) in the Esja mountain south of Hvalfjörður and in Akrafjall to the north (Figure 1). This work was based on previous geological studies by Friðleifsson (1973) and Franzson (1978) respectively. Figures 3 and 4 of Kristjánsson *et al.* (1980) indicate that their composite section reaches from the upper part of Einarsson's (1957) R5 zone up to the the lower part of his N2. The paper by Kristjánsson *et al.* (1980) included a K–Ar date of 1.85±0.18 M.y. obtained at the base of N2. It was therefore tentatively concluded that N2 in Esja represents the Olduvai subchron, that the relatively thin N3 zone represents the Reunion, the N4–R3 is the Gauss–Matuyama boundary, and R4 is the Mammoth subchron. The Kaena subchron appears to have been missed by Einarsson but Kristjánsson *et al.* (1980) assigned a thin group of reversely magnetized lavas (EY 7–8) close to sea level south of Hvalfjörður, to this subchron.

The only K–Ar dates published since 1980 on lava flows in SW–Iceland are those quoted by Geirsdóttir (1991) on flows FA 51 and FB 01 in Akrafjall, not far above the base of the R4 zone. Flow FA 51 which is just underneath a conglomerate horizon yielded an age of 3.12±0.23 M.y. whereas FB 01 (in a profile about 4 km north–west of FA, not shown in Figure 1) above that horizon, yielded 2.87±0.23 M.y. These ages do not conflict with the view of Kristjánsson *et al.* (1980) that R4 is the Mammoth subchron but additional, and more accurate, dates in these sections are clearly required.

Kristjánsson and Sigurgeirsson (1993, profile SH) sampled 21 flows at the R5–N5 polarity zone boundary (profile SH, Figure 2) in the Villingadalur corrie in the north–eastern part of Skarðsheiði, close to a site where Wilson *et al.* (1972, profile C) had found several intermediate poles (Dagley and Lawley, 1974, Figure 8). Kristjánsson and Sigurgeirsson (1993, Table 2 and Figure 7) confirmed these early results, finding low–latitude poles (scattered widely around Australia) in flows SH 9–12 and 15–18, separated by two flows with mid–latitude reverse directions.

## NEW STRATIGRAPHIC AND PALEOMAGNETIC MAPPING IN SKARÐSHEIÐI

Given the confirmed presence of at least 8 intermediate virtual poles at the R5–N5 boundary in north-eastern Skarðsheiði, it was of interest to determine if there are also several intermediate poles occurring at other locations of this boundary in Skarðsheiði and/or nearby mountains.

### Stratigraphic mapping in new profiles SI and SJ

*Profile SI*

We wished to map a composite profile up through the various volcanic formations of Skarðsheiði, for paleomagnetic sampling. Suitable locations are however limited, in some parts of the mountain due to scree cover, in others due to steepness or the presence of intrusions, thick rhyolite lavas etc. The location selected is in the south–western part of Skarðsheiði (Figures 2 and 3). At the base of the composite profile, units 1–23 in profile SI are tholeiite lavas exhibiting considerable alteration with infillings of chalcedony (up to fist–size) and calcite. The thick andesite flow SI 28 forms a conspicuous scarp above this part of the profile. Some stratigraphic complications occur beyond this flow, possibly due to a small unconformity or to landscape effects during emplacement. We sampled a tholeiite outcrop numbered 28O above the andesite (contact not seen) and then the flows 28A–F to the northwest. The profile is continued still farther to the northwest, beyond a fault zone, but probably only 10–20 m are missing between the SI 28 series and SI 29. The flows SI 29–47, exposed on the west side of the peak Litlahorn, are largely of feldspar– and olivine–porphyritic composition.

*Profile SJ*

This profile (Figure 3) begins with a few porphyritic flows at a pass about 1 km to the northwest of Litlahorn, between the Skarðshyrna peak and a small peak of acidic composition. Below them, some thin flows may be seen, getting more numerous (in very steep outcrops) to the east. The thick and massive flow SJ 4 is petrographically somewhat similar to the flow SI 44 but their paleomagnetic directions are not identical, so there may be a stratigraphic gap of a few tens of m between SI 47 and SJ 2. According to Franzson (1978) this porphyritic sequence which is reversely magnetized, is also found in the lower part of Akrafjall. However, the top part of this reverse zone in Skarðsheiði (SJ 5–11) includes some tholeiitic basalts (and one fairly thick clastic horizon), whereas corresponding reverse tholeiitic lavas are not seen in Akrafjall. Further mapping and radiometric dating of the exposed lava sequences in the Hvalfjörður area is needed to determine their relation to the extrusive activity of various volcanic centers in South–Western Iceland (see Figure 1). The hydrothermal alteration at this part of the composite section is minor, the zeolite chabazite being noted in several flows.

The profile SJ continues up the western shoulder of the Skarðshyrna peak to flow SJ 24, and includes additional sediment horizons above flows SJ 12 and 14. The sediments are conspicuous (visible from Reykjavík, 35 km away, as a light–brown band in the cliff face) but they seem to be of variable thickness or even absent in some parts of Skarðsheiði. The top part of the profile runs north along the ridge from Skarðshyrna to the Heiðarhorn peak and consists mostly of tholeiites (very fresh at the top) with a thick horizon of conglomerate and other sediment coincident with a polarity change at SJ 33/34. Only a much thinner sediment occurs immediately above the four transitional flows FA 45–48 of the normal to reverse transition in Akrafjall, so that Franzson (1978) correlated the SJ 33/34 sediment with a 4 m thick con-

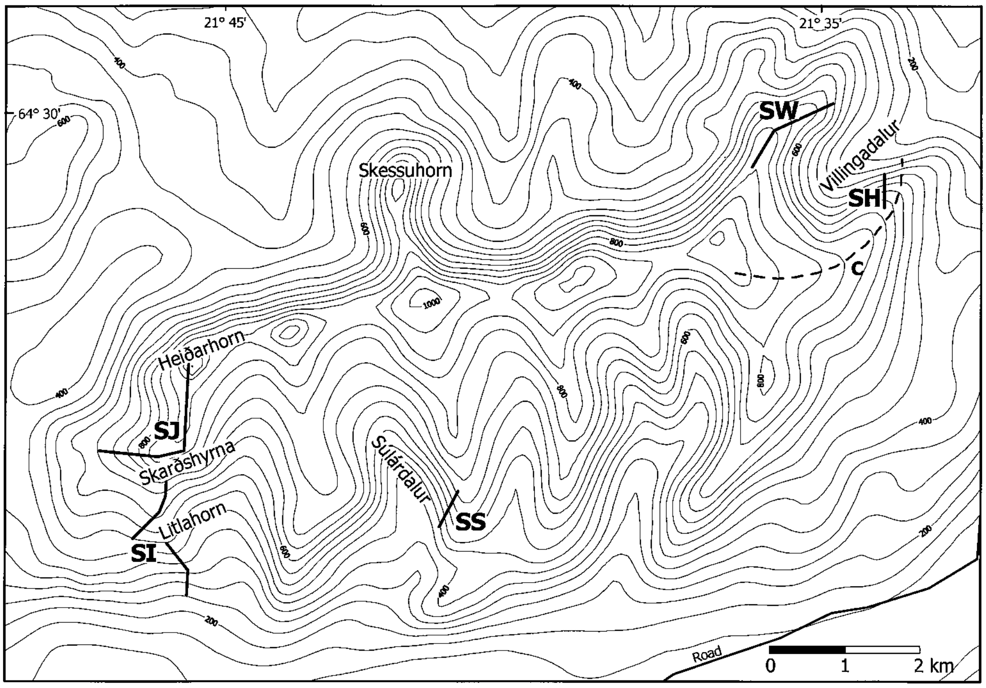

Figure 2. Topographic contours of the Skarðsheiði mountain. Our main paleomagnetic sampling profile is composed of profiles SI (in the hillslope Stóra–Brattatorfa to the Litlahorn peak) and SJ (in Skarðshyrna and the Skarðshyrna–Heiðarhorn ridge), see Figure 3. SS (Figure 5) and SW are short supplementary profiles. The location of profile SH (Kristjánsson and Sigurgeirsson, 1993) as well as the estimated location of the upper part of profile C (Wilson *et al.*, 1972) are also shown. – *Hæðarlínukort af Skarðsheiði, með samsetta sýnasöfnunarsniðinu SI–SJ í Litlahorni, Skarðshyrnu og Heiðarhorni, og styttri sniðum SS og SW. Staðsetning fyrri sýnasöfnunarsniða í Villingadal sést einnig.*

glomerate between FA 51 and 52. Geirsdóttir (1991) referred to the sediment FA 51/52 as "diamictite unit 1", indicating contemporaneous sediment formation in the Akrafjall area and in the Borgarfjörður area some 30 km to the northeast (the NP 319/320 sediment and NT 3/4 sediment, both occurring one or two flows above the base of the Mammoth subchron in the profiles of McDougall *et al.* (1977)). These sediments were for many years considered to herald the onset of cold climate in South–Western Iceland, but the sedimentological analysis of Geirsdóttir (1991) indicates that glacial conditions did not prevail until about 0.5 M.y. later.

## Paleomagnetism – methods

Sampling and measurements followed procedures used in many previous paleomagnetic surveys in Iceland. 2.5 cm cores were collected by a portable drill and oriented with respect to the Sun or by sightings on distant geographical features. Generally, four samples were collected from each unit, spread over a distance of 1 m to several m laterally. Flows SI 24–27 and SJ 1 were thin and crumbly, so that SI 27 and SJ 1 were omitted, and the unit numbered SI 24+ in Table 1 represents two samples from flow 24 and two from 25. Exposures of flow interiors are very good, and not disturbed by block movements, dikes, chemical weathering or other such factors. Remanence measurements

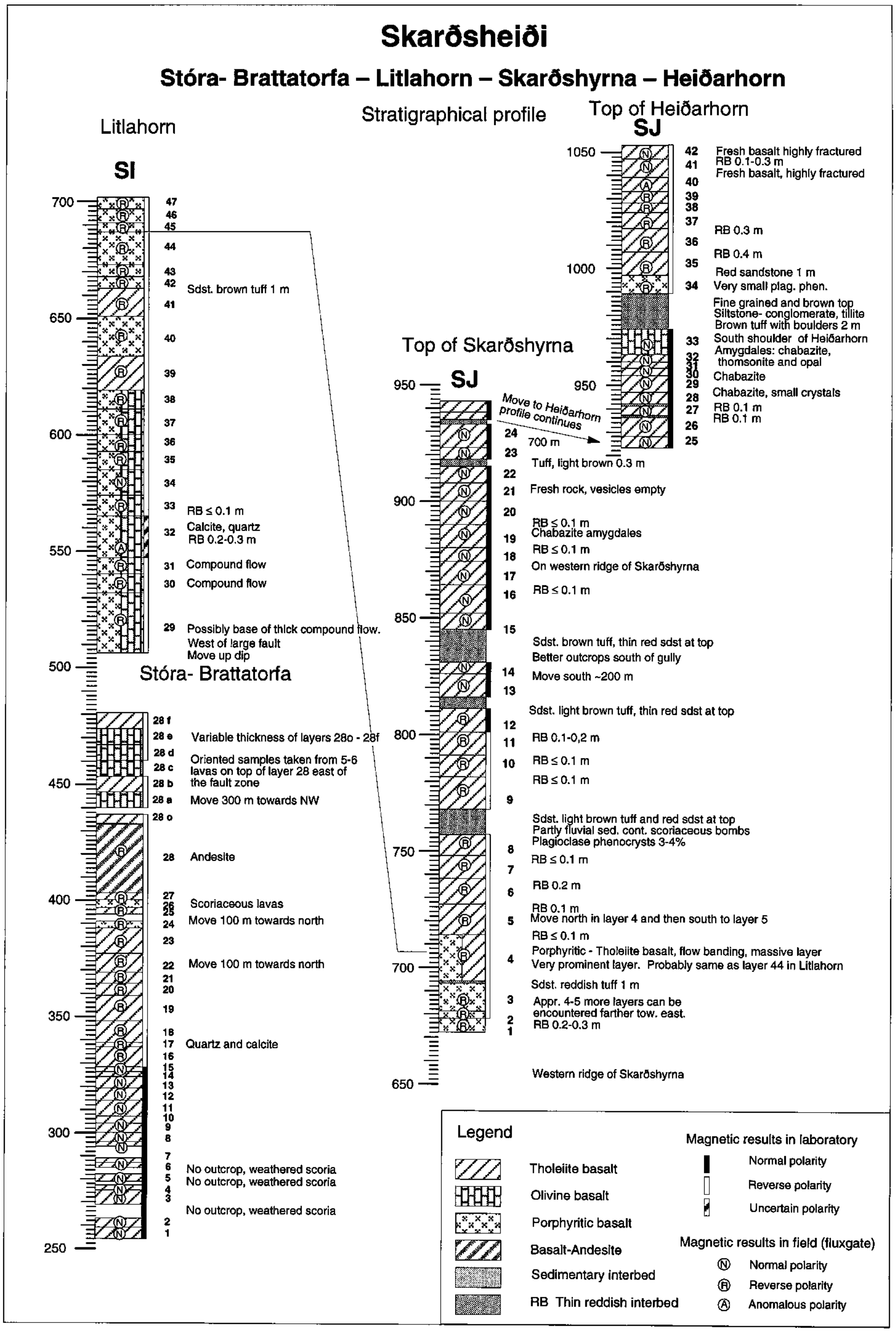

Figure 3. Stratigraphic column for profiles SI and SJ in Skarðsheiði. The thin polarity columns are based on the data of Table 1. – *Jarðlagasnið SI og SJ. Mjóu súlurnar með réttri og öfugri segulstefnu eru byggðar á Töflu 1.*

were made on one specimen from each sample, with an Institut Dr. Förster four–probe static fluxgate magnetometer. The remanence was measured before and after alternating field (AF) demagnetization at 10, 15 and 20 mT peak field in a two–axis tumbler.

Extended demagnetization curves for five typical samples are shown in Figure 4. The directional change between successive steps is shown where it exceeds 1.5°. The 10 mT treatment is generally sufficient to remove all or almost all of the secondary viscous remanence present; the measured remanence direction in a specimen rarely changes more than 3 degrees of arc between the 15 and 20 mT steps. Good to excellent within–unit directional agreement is obtained, as indicated by the 95% confidence radius $\alpha_{95}$ being larger than 9° in only four units. Median destructive fields for the natural remanence are very variable, but they exceed 20 mT in about 60% of the samples from our sampling profiles (including the profiles SS and SW, see below).

Treatment was continued to 25 mT or higher fields for 32 flows from our profiles, in most cases due to minor directional instability of the primary remanence in some of the samples but occasionally due to the presence of lightning–induced remanence. In some samples carrying a weak and soft primary remanence component, anhysteretic and/or rotational remanence may be picked up during AF demagnetization. These samples also have a strong tendency to pick up new viscous remanence immediately after the treatment. This causes fluctuations in the measured remanence directions at strong demagnetization fields (see e.g. sample SI 33–3 in Figure 4) which we have attempted to reduce by performing the treatment twice and averaging the results.

Units where between–sample directional agreement was unsatisfactory, were resampled at a site several m to tens of m from the original sampling site. Altogether about 24 samples were not included in statistical calculations. Table 1 lists the number of samples used from each lava flow, the best paleomagnetic direction for that flow, and its corresponding virtual geomagnetic pole (VGP). The directions have been corrected for tectonic dip (see Appendix). The table also gives the 95% confidence radius for the mean direction of each flow, its mean remanence intensity after 10 mT AF treatment, and its polarity.

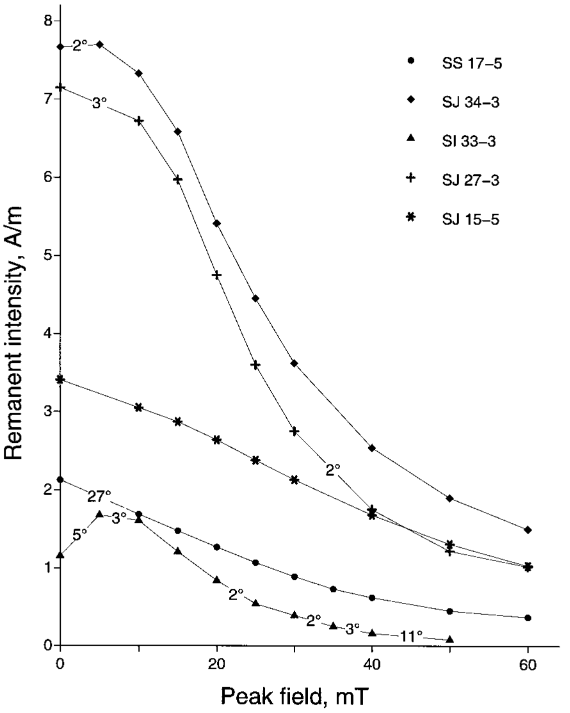

Figure 4. Remanence intensity after AF demagnetization in five samples from Skarðsheiði, including one sample from a transitional flow (SS 17) at the R5–N5 boundary. An increase in intensity at the first step in the reverse flow SI 33 (and also slightly in SJ 34) is due to removal of a viscous overprint of Brunhes age. Directional changes between steps are shown if they exceed 1.5°. – *Niðurstöður riðstraums–afseglunar á fimm sýnum úr Skarðsheiði. Aukning segulmögnunar í tveim sýnum verður þegar nýleg seigjusegulmögnun með „réttri“ stefnu er fjarlægð á undan upprunalegri segulmögnun með „öfugri“ stefnu.*

## Paleomagnetism of profiles SI and SJ – results

In the lower part of profile SI, hydrothermal alteration may have affected the remanence of lavas to a greater extent than in most lava profiles hitherto sampled in Iceland. The average remanence intensity (after 10 mT treatment) is less than 2 A/m in all except one of the flows SI 1–26, as compared to an overall average in lavas of similar or greater age which is about 3.5 A/m. However, these alteration processes do not seem to disturb the remanence directions: the normally magnetized flows SI 1– 14 which exhibit typical secular variation behavior, are followed by two transitional flows and then a thick reverse series. We suggest that SI 1–14 are from the Cochiti subchron, which is not seen in Wilson *et al.*'s (1972) profile C in North–Eastern Skarðsheiði. Much additional work is needed, however, before this polarity zone can possibly be correlated e.g. with the thin zone FA 4–7 in Akrafjall, or with Einarsson's N6 in hills northeast of Skarðsheiði (see Wilson *et al.* 1972, Figure 1).

The remainder of SI as well as the porphyritic bottom part of profile SJ up to SJ 10 forms a single thick reverse–polarity zone. This zone includes three reliably determined excursions of the virtual pole to latitudes of 40° or less, namely at SI 28B, 32 and 47. We then find the transitional flow SJ 11, sampled in two outcrops several tens of m apart which yielded identical directions. Their mean is very similar to the direction in SH 10 but otherwise it was somewhat disappointing to find only a single intermediate direction at this point of the section.

Profile SJ continues in normally magnetized lavas to SJ 33, with only one VGP excursion to mid–latitudes in SJ 24 and 24A. Above the conglomerate bed overlying SJ 33, the profile contains relatively fresh reverse flows (presumably R4, from the Mammoth subchron) up to the top of Heiðarhorn.

The mean field direction in 92 flows from profiles SI and SJ has a declination of 4° and an inclination of +74.4°. It is thus quite close to the central axial dipole direction D = 0°, I = +76.5°. The vector sum R is 87.1, giving an angular standard deviation of 19°. If VGPs are averaged, their mean position is at latitude 87°N, longitude 109°E. The vector sum in this case is 81.7, yielding an angular standard deviation of 27.5°, which is comparable to values found in rocks of similar age elsewhere in Iceland (Kristjánsson, 1995, Figure 4).

## Further mapping and paleomagnetic results at the presumed R5–N5 boundary

### *New profile, SW, in Skarðsheiði*

It was considered possible – although unlikely – that the unusual occurrence of many transitional directions in profile C of Wilson *et al.* (1972) and profile SH of Kristjánsson and Sigurgeirsson (1993) was caused by some disturbance such as localized secondary alteration of the lavas. We therefore sampled lavas west of the Villingadalur corrie, at about 650–740 m altitude (Figure 2) some 1.5–1.8 km northwest of SH. Exposures along the new profile SW are not as good as in SH, and a stratigraphic map of SW has not been prepared. We cored flows numbered SW 10 through 23, except two thin flows SW 12–13. The lavas in profile SW were good material for paleomagnetic direction measurements, only four samples having to be discarded due to lightning effects.

Results are listed in Table 1. A comparison with profile SH shows excellent agreement in paleomagnetic directions between these profiles, for example: SW 10 = SH 4 or 5; SW 11 = SH 7; SW 15 = SH 8 (both sites are also porphyritic); SW 16 = SH 9 (approx.); SW 17 = SH 10; SW 18 and 19 (which may be the same flow) = SH 12; SW 20–23 = SH 13–16. These flows cover most of the R to N transition, but profile SW was not continued farther upwards due to increasing lateral distance between outcrops and the presence of some intrusions.

### *New profile, SS, in South–Eastern Skarðsheiði*

In an attempt to find a R to N transition zone thicker than one flow at the presumed Gilbert–Gauss boundary on the south side of Skarðsheiði, we mapped a new supplementary profile SS (Figures 2 and 5) consisting of 23 flows in the south–eastern part of the mountain, on the eastern slope of the Súlárdalur corrie. The lower part of the exposed lava sequence is largely porphyritic, but tholeiitic flows are more common in the upper part. Profile SS contains at least three sediment beds but further studies are needed before they may be correlated individually with those in SJ and SH. Only flows SS 7–23 were cored for paleomagnetic measurements.

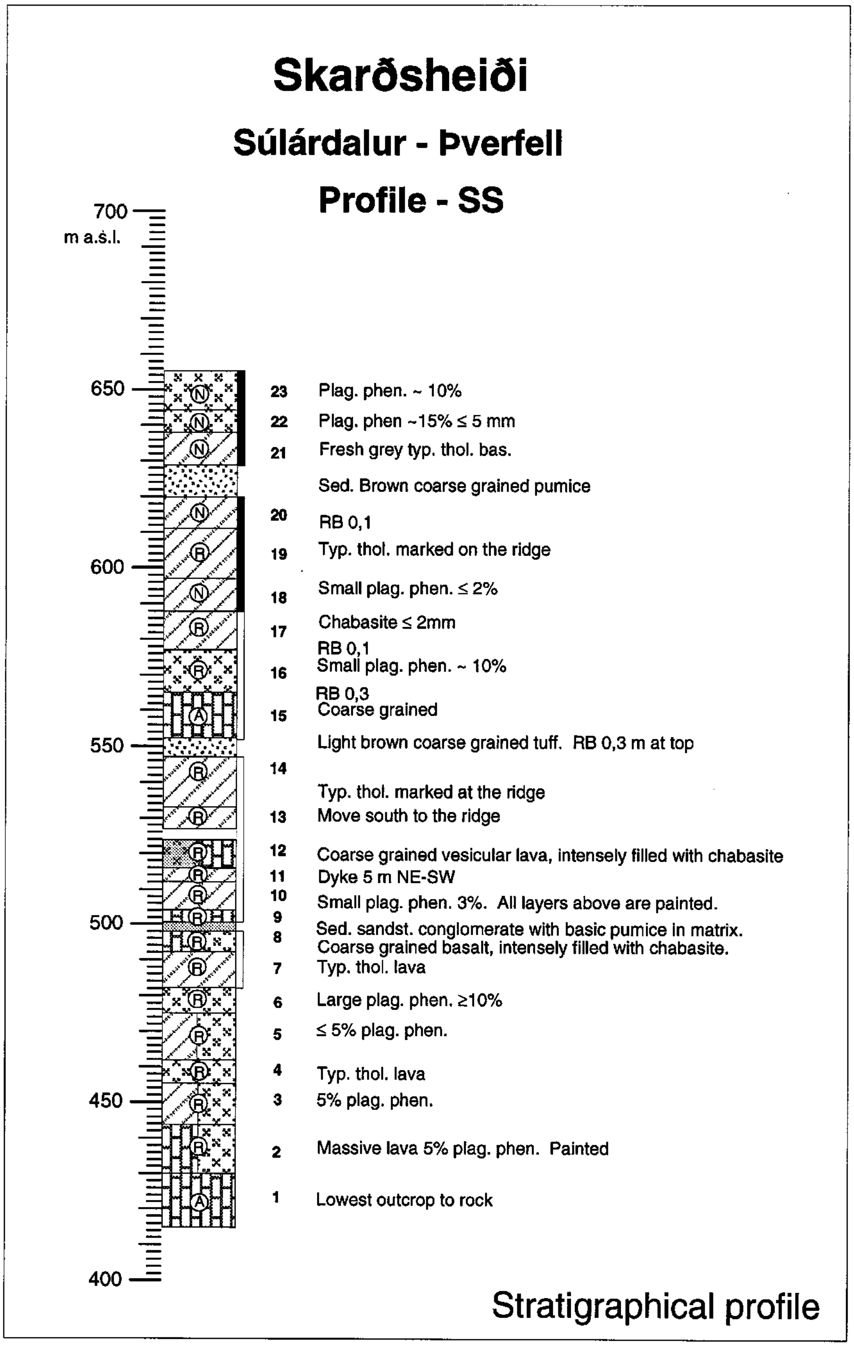

Figure 5. Stratigraphic column for profile SS in Súlárdalur, Skarðsheiði. Legend as in Figure 3. – *Jarðlagasnið SS í Súlárdal.*

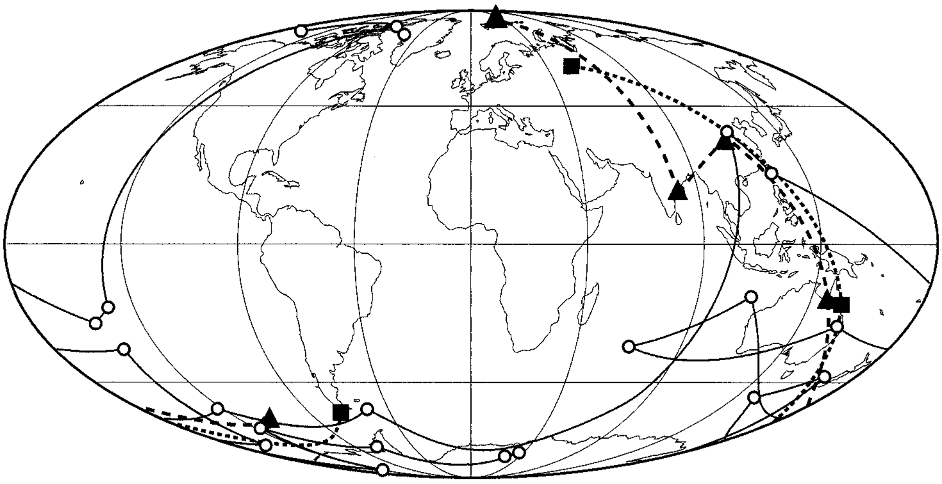

Figure 6. Virtual poles from the R5–N5 transition in profile SH (Kristjánsson and Sigurgeirsson, 1993; open circles) with the poles from flows SJ 10–12 (squares) and SS 16–20 (triangles) added. All transitional poles found in profile SW are very similar to poles from SH. – *Staðsetning sýndarsegulskauta við mót hraunasyrpanna R5 og N5 úr sniðinu SH í Villingadal (Kristjánsson og Sigurgeirsson, 1993) ásamt segulskautum úr hraunlögum í sniðum SJ og SS.*

Flows SS 17,18 and 19 were found to have transitional directions (Table 1; Figure 6). The virtual pole in SS 17 (NE–Australia) is similar to that in SJ 11 and SH 10 while those in SS 18–19 (SE–Asia) are not far from those in SH 15–16. The fact that several intermediate directions are seen in SH and SW, indicates that eruptive activity at the time of the transition was greater in the north–eastern part of the Skarðsheiði mountain than to the south and west. Judging from the results of Wilson *et al.* (1972), the N5 polarity zone is also thicker in their profile C in North–Eastern Skarðsheiði (around 50 flows, some thin) than in our SJ in South–Western Skarðsheiði (22 flows).

### *Search for a possible R5–N5 transitional direction in profile FA in Akrafjall*

Kristjánsson *et al.* (1980) showed that the presumed N5 lavas above a clastic bed between flows 28 and 29 in their profile FA in Akrafjall (Figure 1) have regular normal–polarity directions. Those below that bed have regular reverse–polarity directions, with the possible exception of FA 28 which was quite unstable. We have carried out additional sampling of a few lava flows at this transition, at a locality some 300 m west of the original FA profile. Some of the results are shown at the bottom of Table 1. It appears from these results that no intermediate VGPs occur at this locality. We have used the opportunity to resample the compound flow FA 17, confirming the presence of a low–latitude pole position. This excursion may be of similar age as that in the Skarðsheiði lava flows SI 28B or SI 32.

## Thermomagnetic measurements

In order to ascertain the nature of the carrier of magnetization in the Skarðsheiði lavas, we measured the temperature dependence of the magnetic susceptibility of paleomagnetic cores, at several levels in the lava pile. Measurements were made on 10–gram samples of crushed rock in air, using a Bartington MS2 W/F furnace. Heating to 600°C took about one hour.

Results from four typical samples are shown in Figure 7. The only one whose remanence was unstable during AF demagnetization is SI 29–1; the others exhibited MDF values exceeding 20 mT and minimal direction change during AF treatment. The main

Table 1. Paleomagnetic results from new sampling profiles in Skarðsheiði and three flows in Akrafjall. *N*, number of samples used in calculation of best mean field. *DEC* and *INC*, declination and inclination of best mean field after tectonic tilt correction. *LON* and *LAT*, coordinates of virtual pole corresponding to this direction. *ALF*, 95% confidence angle for the best mean direction degrees, (in brackets if N=2). *J100*, arithmetic average remanence intensity after 10 mT AF treatment (in brackets if affected by lightning), A/m. *POL*, paleomagnetic polarity (N if lat > 0, R if lat < 0, T if the numerical value of lat < 40, E if the numerical value of lat < 10). *– Lava, númer hraunlags, N fjöldi sýna; DEC og INC meðalsegulstefna eftir hallaleiðréttingu; LON og LAT hnit sýndarsegulskauts, ALF óvissa í segulstefnu, J100 meðalstyrkur segulmögnunar, POL er N fyrir „rétta“ segulmögnun, R fyrir „öfuga“, T og E tákna að segulskautið sé nálægt miðbaug.*

Profile SI; BRATTATORFA–LITLAHORN

| *LAVA* | *N* | *DEC* | *INC* | *LON* | *LAT* | *ALF* | *J100* | *POL* |
|---|---|---|---|---|---|---|---|---|
| SI 1 | 6 | 4 | +62 | 150 | +69 | 3 | 1.39 | N |
| SI 2 | 4 | 355 | +60 | 167 | +66 | 8 | 1.61 | N |
| SI 3 | 4 | 4 | +72 | 141 | +82 | 5 | 0.76 | N |
| SI 4 | 4 | 5 | +77 | 51 | +88 | 4 | 1.71 | N |
| SI 5 | 5 | 54 | +74 | 54 | +65 | 4 | 0.63 | N |
| SI 6 | 4 | 80 | +88 | 348 | +65 | 4 | 0.63 | N |
| SI 7 | 4 | 25 | +60 | 114 | +63 | 4 | 1.62 | N |
| SI 8 | 5 | 329 | +73 | 241 | +75 | 9 | 0.52 | N |
| SI 9 | 4 | 338 | +76 | 256 | +80 | 6 | 0.24 | N |
| SI10 | 5 | 66 | +85 | 2 | +67 | 3 | 0.33 | N |
| SI11 | 4 | 334 | +84 | 317 | +75 | 5 | 0.84 | N |
| SI12 | 5 | 261 | +79 | 300 | +55 | 6 | 0.72 | N |
| SI13 | 6 | 308 | +76 | 271 | +68 | 9 | 11.11 | N |
| SI14 | 4 | 284 | +85 | 314 | +65 | 1 | 1.99 | N |
| SI15 | 8 | 149 | -38 | 19 | -42 | 11 | 0.26 | R |
| SI16 | 6 | 83 | +32 | 66 | +18 | 7 | 0.45 | NT |
| SI17 | 5 | 177 | -68 | 347 | -77 | 7 | 0.39 | R |
| SI18 | 4 | 154 | -76 | 73 | -79 | 4 | 0.89 | R |
| SI19 | 4 | 256 | -73 | 221 | -56 | 6 | 0.42 | R |
| SI20 | 4 | 257 | -78 | 210 | -60 | 4 | 0.72 | R |
| SI21 | 4 | 132 | -76 | 86 | -69 | 8 | 0.73 | R |
| SI22 | 5 | 87 | -70 | 101 | -46 | 5 | 0.25 | R |
| SI23 | 4 | 181 | -70 | 334 | -80 | 5 | 0.97 | R |
| SI24+ | 4 | 167 | -85 | 149 | -74 | 14 | 0.48 | R |
| SI26 | 5 | 164 | -56 | 5 | -60 | 7 | 1.60 | R |
| SI28 | 5 | 174 | -46 | 347 | -53 | 2 | 2.26 | R |
| SI28O | 4 | 193 | -67 | 308 | -73 | 6 | 1.13 | R |
| SI28A | 4 | 213 | -70 | 265 | -70 | 8 | 1.93 | R |
| SI28B | 4 | 122 | -48 | 52 | -40 | 2 | 3.12 | RT |
| SI28D | 4 | 177 | -70 | 349 | -79 | 2 | 0.80 | R |
| SI28E | 4 | 202 | -64 | 295 | -68 | 7 | 1.72 | R |
| SI28F | 4 | 223 | -76 | 233 | -72 | 7 | 1.01 | R |
| SI29 | 6 | 155 | -69 | 36 | -73 | 11 | 0.72 | R |
| SI30 | 4 | 235 | -77 | 221 | -68 | 4 | 2.36 | R |
| SI31 | 4 | 146 | -65 | 42 | -65 | 3 | 2.63 | R |
| SI32 | 8 | 84 | -18 | 78 | - 6 | 7 | 0.50 | E |
| SI33 | 4 | 154 | -80 | 112 | -78 | 6 | 3.44 | R |
| SI34 | 4 | 147 | -67 | 44 | -67 | 5 | 4.64 | R |
| SI35 | 4 | 158 | -80 | 111 | -80 | 2 | 3.47 | R |
| SI36 | 4 | 159 | -71 | 38 | -77 | 2 | 5.85 | R |
| SI37 | 4 | 192 | -70 | 303 | -78 | 3 | 4.71 | R |
| SI38 | 4 | 223 | -74 | 240 | -70 | 4 | 3.60 | R |
| SI39 | 4 | 202 | -77 | 237 | -81 | 6 | 8.36 | R |
| SI40 | 5 | 219 | -82 | 197 | -74 | 2 | 16.14 | R |
| SI41 | 4 | 152 | -72 | 50 | -74 | 4 | 5.01 | R |
| SI42 | 4 | 214 | -74 | 247 | -74 | 4 | 2.25 | R |
| SI43 | 4 | 227 | -78 | 222 | -71 | 5 | 3.32 | R |
| SI44 | 5 | 232 | -70 | 246 | -62 | 5 | 3.70 | R |
| SI45 | 4 | 197 | -73 | 277 | -80 | 3 | 3.95 | R |
| SI46 | 4 | 203 | -76 | 246 | -80 | 3 | 1.79 | R |
| SI47 | 4 | 323 | -66 | 185 | -26 | 7 | 0.52 | RT |

Profile SJ; SKARÐSHYRNA–HEIÐARHORN

| *LAVA* | *N* | *DEC* | *INC* | *LON* | *LAT* | *ALF* | *J100* | *POL* |
|---|---|---|---|---|---|---|---|---|
| SJ 2 | 4 | 167 | -42 | 357 | -49 | 3 | 0.87 | R |
| SJ 3 | 4 | 166 | -52 | 1 | -57 | 6 | 5.71 | R |
| SJ 4 | 4 | 179 | -76 | 352 | -89 | 4 | 2.74 | R |
| SJ 5 | 4 | 162 | -69 | 23 | -74 | 5 | 2.73 | R |
| SJ 6 | 4 | 225 | -74 | 239 | -69 | 3 | 2.06 | R |
| SJ 7 | 5 | 263 | -83 | 189 | -63 | 3 | 0.78 | R |
| SJ 8 | 4 | 179 | -79 | 150 | -86 | 6 | 2.31 | R |
| SJ 9 | 4 | 201 | -50 | 307 | -53 | 2 | 1.44 | R |
| SJ10 | 4 | 212 | -56 | 288 | -56 | 3 | 2.65 | R |
| SJ11 | 6 | 14 | -63 | 148 | -19 | 4 | 1.29 | RT |
| SJ12 | 4 | 58 | +70 | 60 | +60 | 7 | 3.30 | R |
| SJ13 | 4 | 59 | +82 | 16 | +68 | 2 | 7.90 | N |
| SJ14 | 4 | 54 | +78 | 37 | +69 | 3 | 3.68 | N |
| SJ15 | 5 | 330 | +78 | 276 | +77 | 3 | 2.46 | N |
| SJ16 | 4 | 314 | +74 | 257 | +69 | 2 | 2.74 | N |
| SJ17 | 4 | 318 | +64 | 229 | +60 | 3 | 3.16 | N |
| SJ18 | 4 | 318 | +62 | 227 | +58 | 4 | 4.18 | N |
| SJ19 | 4 | 32 | +67 | 94 | +67 | 4 | 8.14 | N |
| SJ20 | 4 | 34 | +64 | 96 | +64 | 2 | 7.66 | N |
| SJ21 | 3 | 26 | +62 | 111 | +64 | 12 | 7.03 | N |
| SJ22 | 4 | 14 | +66 | 128 | +72 | 5 | 2.81 | N |
| SJ23 | 4 | 50 | +80 | 26 | +71 | 2 | 6.31 | N |
| SJ24 | 4 | 23 | +38 | 128 | +44 | 4 | 3.48 | N |
| SJ24A | 4 | 35 | +46 | 110 | +47 | 4 | 3.35 | N |
| SJ25 | 4 | 19 | +51 | 129 | +55 | 4 | 3.38 | N |
| SJ26 | 4 | 39 | +88 | 346 | +68 | 2 | 3.86 | N |
| SJ27 | 5 | 334 | +72 | 227 | +75 | 3 | 3.56 | N |
| SJ28 | 4 | 318 | +71 | 245 | +68 | 2 | 2.41 | N |
| SJ29 | 4 | 59 | +74 | 49 | +64 | 5 | 2.71 | N |
| SJ31 | 4 | 56 | +74 | 52 | +64 | 3 | 3.92 | N |
| SJ32 | 4 | 46 | +66 | 79 | +61 | 2 | 2.30 | N |
| SJ33 | 4 | 26 | +79 | 38 | +79 | 2 | 5.74 | N |
| SJ34 | 5 | 180 | -75 | 336 | -87 | 2 | 7.17 | R |
| SJ35 | 5 | 156 | -70 | 38 | -74 | 1 | 4.79 | R |
| SJ36 | 4 | 136 | -72 | 67 | -68 | 3 | 3.30 | R |
| SJ37 | 5 | 146 | -74 | 66 | -74 | 4 | 7.32 | R |
| SJ38 | 4 | 133 | -73 | 75 | -67 | 6 | (34.76) | R |
| SJ39 | 4 | 169 | -65 | 2 | -72 | 3 | 8.88 | R |
| SJ40 | 4 | 235 | -68 | 248 | -59 | 9 | (9.11) | R |
| SJ41 | 4 | 197 | -65 | 302 | -70 | 5 | 3.61 | R |
| SJ42 | 5 | 215 | -72 | 256 | -71 | 7 | (19.87) | R |

Profile FA; AKRAFJALL

| *LAVA* | *N* | *DEC* | *INC* | *LON* | *LAT* | *ALF* | *J100* | *POL* |
|---|---|---|---|---|---|---|---|---|
| FA17W | 3 | 108 | -37 | 61 | -26 | 5 | 0.95 | RT |
| FA28W | 3 | 234 | -80 | 206 | -69 | 3 | 2.51 | R |
| FA29W | 3 | 292 | +71 | 266 | +57 | 13 | 0.79 | N |

Table 1. Continued. – *Framhald.*

| Profile SS; SÚLÁRDALUR–ÞVERFJALL | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *LAVA* | *N* | *DEC* | *INC* | *LON* | *LAT* | *ALF* | *J100* | *POL* |
| SS 7 | 4 | 169 | -64 | 2 | -71 | 1 | 6.64 | R |
| SS 8 | 5 | 213 | -70 | 264 | -71 | 2 | 4.27 | R |
| SS 9 | 5 | 203 | -76 | 240 | -80 | 3 | 5.28 | R |
| SS10 | 5 | 211 | -76 | 238 | -76 | 4 | 4.13 | R |
| SS11 | 5 | 251 | -85 | 183 | -66 | 2 | 4.02 | R |
| SS12 | 5 | 126 | -88 | 150 | -67 | 3 | 5.91 | R |
| SS13 | 6 | 159 | -65 | 21 | -69 | 2 | 4.38 | R |
| SS14 | 5 | 182 | -62 | 330 | -69 | 3 | 3.52 | R |
| SS15 | 5 | 190 | -59 | 321 | -65 | 2 | 6.26 | R |
| SS16 | 5 | 238 | -71 | 239 | -60 | 4 | 2.59 | R |
| SS17 | 10 | 21 | -61 | 142 | -18 | 7 | 1.09 | RT |
| SS18 | 6 | 39 | +28 | 111 | +34 | 4 | 1.20 | NT |
| SS19 | 9 | 71 | +17 | 82 | +16 | 7 | 0.48 | NT |
| SS20 | 5 | 18 | +78 | 35 | +82 | 5 | 2.99 | N |
| SS21 | 5 | 26 | +84 | 359 | +75 | 4 | 4.16 | N |
| SS22 | 4 | 48 | +82 | 19 | +71 | 4 | 4.96 | N |
| SS23 | 4 | 63 | +81 | 21 | +67 | 4 | 2.39 | N |

| Profile SW; DRAGEYRARÖXL, EAST OF VILLINGADALUR | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *LAVA* | *N* | *DEC* | *INC* | *LON* | *LAT* | *ALF* | *J100* | *POL* |
| SW10 | 2 | 221 | -76 | 233 | -72 | (2) | 10.75 | R |
| SW11 | 2 | 30 | -84 | 148 | -54 | (7) | (23.22) | R |
| SW14 | 3 | 149 | -79 | 99 | -77 | 7 | 3.03 | R |
| SW15 | 3 | 209 | -82 | 191 | -76 | 6 | 6.45 | R |
| SW16 | 4 | 318 | -56 | 192 | -16 | 7 | 0.77 | RT |
| SW17 | 4 | 22 | -64 | 142 | -21 | 4 | 1.16 | RT |
| SW18 | 6 | 61 | -38 | 103 | - 8 | 4 | 1.72 | E |
| SW19 | 5 | 71 | -35 | 94 | - 9 | 9 | 0.66 | E |
| SW20 | 5 | 273 | -74 | 210 | -50 | 4 | 1.61 | R |
| SW21 | 7 | 199 | -58 | 306 | -62 | 3 | 2.62 | R |
| SW22 | 6 | 43 | +39 | 104 | +39 | 4 | 1.09 | NT |
| SW23 | 3 | 42 | +10 | 112 | +23 | 6 | (40.70) | NT |

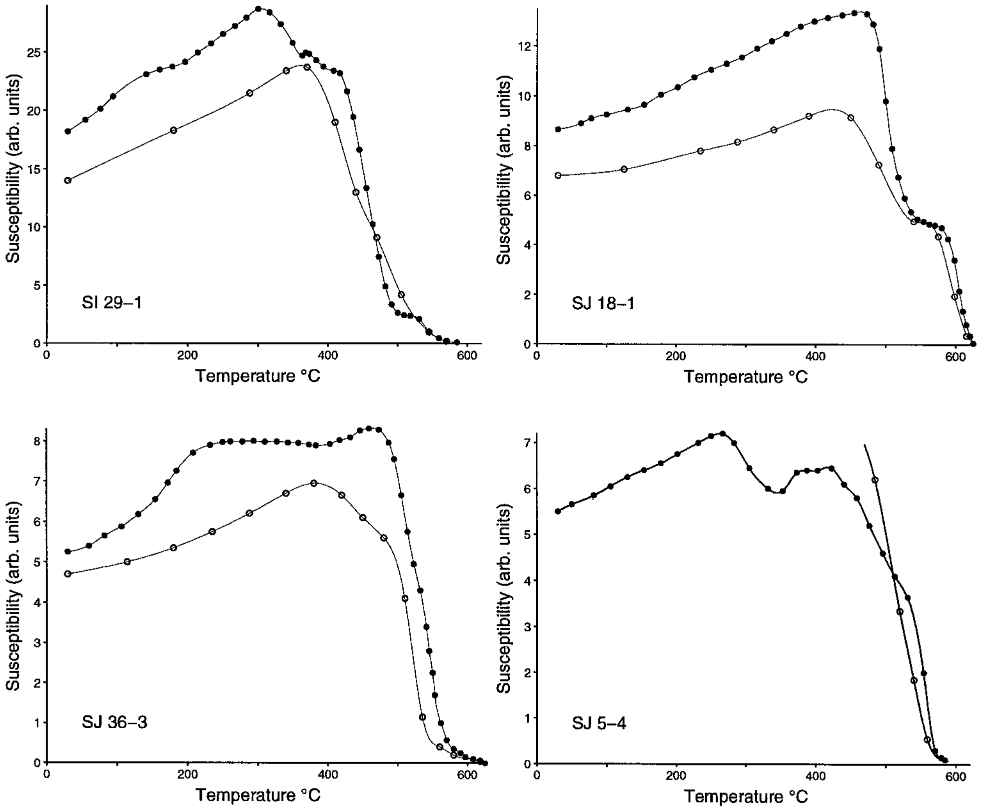

Figure 7. Records of low–field susceptibility variations with temperature, in four samples from Skarðsheiði. Solid dots: heating. – *Breytingar á segulhrifastuðli við upphitun, í fjórum sýnum úr Skarðsheiði.*

characteristic of the curves is a Curie point exceeding 540°C, indicating fairly pure magnetite (oxidized in SJ 18–1). However, in some of the samples one sees that a component with a lower Curie point (350–500°C) is being irreversibly converted (presumably exsolved) on heating. In many lava samples from other Tertiary areas in Iceland which are unstable to AF treatment, the thermomagnetic curves are more complex (L. Kristjánsson, unpublished data) and include components with Curie points below 350°C.

It should be noted that the thermomagnetic behavior of a sample is not decisive when it comes to evaluating whether a particular remanence direction is a reliable indicator of the primary geomagnetic field. The effective titanomagnetite grain size, grain shape and interactions between grains (or lamellae) may be just as important factors in the preservation of the primary remanence through time as the chemical composition of the major magnetic components. Our evaluation of the reliability of the remanence direction in a lava is based mostly on its stability to AF treatment and its consistency between the different samples. The chemical changes which occur during heating in our Skarðsheiði samples (Figure 7) indicate however, that they are not very good material for paleomagnetic field–intensity measurements.

## SUMMARY AND CONCLUSIONS

Skarðsheiði has been considered to belong mostly to the R5 and N5 polarity zones of Einarsson (1957). In his Ph.D. thesis on the area, Franzson (1978) assumed that these zones correspond to the upper Gilbert and lower Gauss chrons respectively. The boundary has in recent years been estimated to be 3.58 M.y. in age (Cande and Kent, 1995). Intermediate geomagnetic poles in several successive flows at this transition were first reported by Wilson *et al.* (1972) in the North–Eastern part of Skarðsheiði. They are shown in diagrams by Wilson *et al.* (1972, Figure 5) and Dagley and Lawley (1974) but the detailed results have not been published. The presence of intermediate poles was confirmed by the more extensive sampling of Kristjánsson and Sigurgeirsson (1993) in their profile SH in Villingadalur.

In this paper we present a composite profile SI/SJ mapped through the exposed succession of South–Western Skarðsheiði, and from a short profile SS farther east. We describe paleomagnetic work on 51 units in SI, 41 in SJ, 17 in SS, and 12 in another short profile SW across Villingadalur from SH. The paleomagnetic work includes extended demagnetization treatment of some samples, and thermomagnetic measurements. The paleomagnetic directions are generally stable and represent the primary thermal remanence of the lavas; this is demonstrated by the excellent within–flow directional agreement after AF cleaning treatment in the laboratory, also in flows where other magnetic properties of the samples vary considerably. Flows yielding low–latitude VGPs have relatively low values of remanence intensity, as well as the most altered flows in the lower part of profile SI (Table 1), but their reliability appears to be quite satisfactory.

Along with the mapping by Franzson (1978) at various locations in Skarðsheiði, our results show that the R5–N5 boundary transects it at altitudes varying between about 500 and 800 m. In the upper part of R5, feldspar–porphyritic lavas are common. The polarity–transition zone becomes thinner towards the south and west. In Skarðsheiði, we have also documented the presence of two subchrons, probably the Cochiti in the lowest accessible exposures (SI 1–14; lower boundary not seen) and the Mammoth at the top (SJ 34–42; upper boundary not seen). Additionally, some major geomagnetic excursions (which may well represent incompletely recorded subchrons) are noted, the main ones being at SI 16 (close to a polarity zone boundary) and 28B, 32, and 47 within R5.

We present a summary of polarity results from Akrafjall and Skarðsheiði where the lowest clearly normal lavas in the N5 polarity zone have been aligned (Figure 8). Also shown are positions of some distinct lava groups and conglomerates which may possibly be correlated. The thickness of the porphyritic series (PF) in profile C is unknown but according to Franzson (1978) it is about 200 m in Skessuhorn (Figure 2). Reversely magnetized compound flows (CP) similar to some of those in Akrafjall are also seen at various localities in Skarðsheiði (Franzson, 1978) but not in our profile SI.

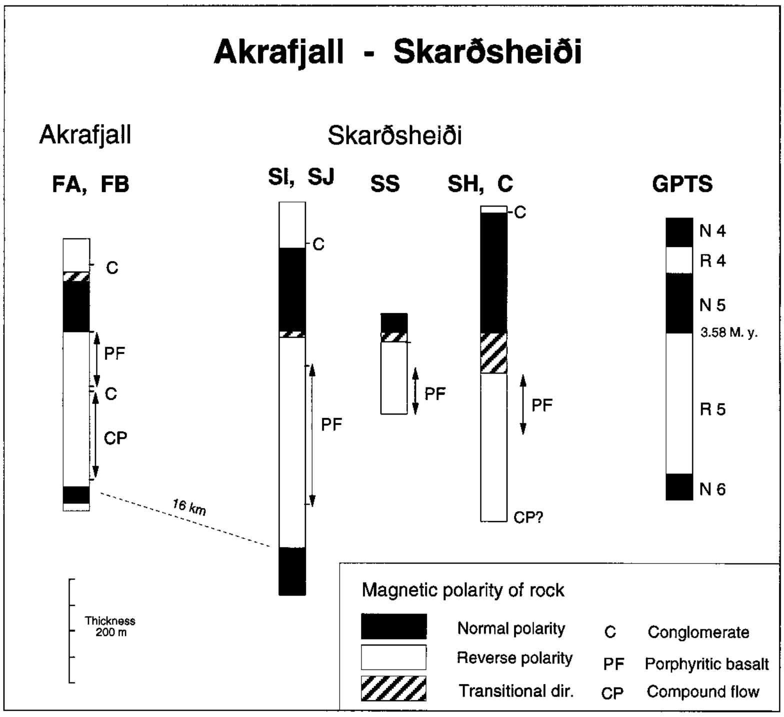

Figure 8. Simplified polarity columns for the Skarðsheiði profiles SI, SJ, SS (present paper), SH (Kristjánsson and Sigurgeirsson, 1993) and C (Wilson *et al.*, 1972), and the Akrafjall profiles FA, FB of Kristjánsson *et al.* (1980), aligned at the onset of the polarity zone N5 of Einarsson (1957). Polarity time scale of Cande and Kent (1995) on the right hand side, including assumed correlations with polarity zones (Franzson 1978, and others). Black is normal polarity. C = conglomerate, PF = mostly porphyritic flows, CP = mostly compound flows. – *Einfaldaðar jarðlagasúlur úr sniðunum SI, SJ og SS (í þessari grein), SH og C (úr eldri greinum) í Skarðsheiði. Til vinstri er sýnd samsvarandi súla úr sniðum FA og FB í Akrafjalli. Til hægri er tímakvarði umsnúninga jarðsegulsviðsins skv. Cande og Kent (1995), með áætlaðri samsvörun segulskeiða við hraunlagasyrpur. Súlurnar eru teiknaðar þannig, að neðstu lög í N5 standast á. C = völuberg, PF = dílabasalt ráðandi, CP = dyngjusyrpur.*

The R5–N5 boundary is also thought to appear in profile FA (Kristjánsson *et al.*, 1980) in Akrafjall, at about 350 m altitude. The stratigraphic column here is in some respects different from that in Skarðsheiði. No transitional flows have been demonstrated at this boundary locality and it has not been dated, but the upper part of R5 is largely composed of feldspar–porphyritic flows as in Skarðsheiði and may thus belong to the same phase of volcanism. These results also support the view of Franzson (1978), Geirsdóttir (1991) and others that conspicuous conglomerate beds at the top of these mountains are essentially contemporaneous. Beds of the same or similar age can also be found in the valleys northeast of Borgarfjörður. The present study and previous detailed mapping in the Hvítársíða area of Borgarfjörður (McDougall *et al.*, 1977) may be built on in further mapping work elsewhere in the Borgarfjörður–Hvalfjörður area.

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## Appendix

Profile positions and tectonic tilt corrections for the profiles. SI (64.4°N, 21.8°W) : 8° for flows 1–10, 7° for flows 11–18, 6° for flows 19–28 and 5° for flows 28O–F, and 4° for flows 29–47. SJ (64.4°N, 21.8°W): 4° for flows 2– 11 and 3° for flows 12–42. SH (64.5°N, 21.5°W): 5° for flows 1–21. SW (64.5°N, 21.6°W): 6° for flows 10–23. SS (64.4°N, 21.7°W): 5° for flows 7– 12, 4.5° for flows 13–18 and 4° for flows 19–23. The down–dip direction is assumed to be south–southeast in SH and SW, southeast in SI, SJ and SS. Errors in the estimates of tectonic tilt vectors may reach 2–3 degrees of arc.

## ÁGRIP

### Bergsegulmælingar á sniðum í Skarðsheiði

Við kortlögðum samsett snið SI/SJ gegnum Skarðsheiði vestanverða. Rannsóknastofumælingar á segulstefnu í borkjarnasýnum voru gerðar á 92 lögum í þessu samsetta sniði, oftast 4 sýnum úr hverju lagi. Neðri 55 lögin í sniðinu eru úr efri hluta hraunlagasyrpu með „rétta“ (N) segulstefnu og þykkri syrpu með „öfuga“ (R) segulstefnu ofan á henni. Sú fyrrnefnda er hugsanlega frá Cochiti–segulskeiðinu, en hún fannst ekki í sniði C (Wilson o.fl. 1972) í Villingadal norðaustantil í Skarðsheiði. Síðarnefndu syrpuna, sem í eru allmörg feldspatdílótt hraun, nefndi Trausti Einarsson (1957) R5. Í efri hluta sniðsins eru um 20 rétt segulmögnuð lög úr N5–syrpu Trausta, og hafa Hjalti Franzson (1978) og aðrir tengt skilin R5–N5 við skilin milli Gilbert og Gauss segulskeiðanna fyrir um 3.6 milljón árum. Í Heiðarhorni er síðan eitt þykkasta setlagið í sniðinu og ofan á því nokkur fersk öfugt segulmögnuð lög sem talin hafa verið frá Mammoth–segulskeiðinu.

Á R5–N5 skilunum í austurhlíð Villingadals höfðu áður fundist a.m.k. 8 hraunlög þar sem sýndarsegulskaut jarðar er á flökti alllangt frá landfræðilegu skautunum. Aðeins eitt slíkt hraun fannst hinsvegar á R5–N5 skilunum í sniði SJ. Við söfnuðum því einnig sýnum úr 29 lögum í tveim öðrum stuttum sniðum, SS í Súlárdal í suðurhlíðum Skarðsheiðar og SW í öxlinni vestan Villingadals, til að kanna nánar útbreiðslu hrauna frá þessu millibilsástandi jarðsegulsviðsins. Í SS gáfu 3 lög á R5–N5 skilunum flöktandi segulskaut, og í sniði SW virðast vera álíka mörg slík hraun og í SH. Ummerki fundust í sniði SI um a.m.k. þrjú stutt tímabil þegar jarðsegulsviðið flökti til innan R5–syrpunnar.

Eins og Hjalti Franzson (1978) og fleiri hafa einnig talið, má að líkindum tengja bæði segulsyrpur hraunlaga eins og R5 og N5, frá Skarðsheiði bæði til Akrafjalls og norðaustur eftir til Borgarfjarðar. Hið sama á við um hraunasyrpur með áberandi bergfræðileg einkenni, og tilteknar setmyndanir. Ekki ná þó öll þessi lög samfellt yfir allt svæðið. Er þörf frekari kortlagningar og aldursgreininga á hraunlagastaflanum við Hvalfjörð og Borgarfjörð, til þess m.a. að tengja uppruna hans við þær megineldstöðvar sem voru virkar á Suðvesturlandi.

Meðal–segulstefna hraunlaganna í Skarðsheiði er svipuð og við mátti búast úr sambærilegum fyrri rannsóknum á Íslandi (t.d. Leó Kristjánsson o.fl. 1980) og sama á við um meðal–flökt segulskautsins. Sérstakar afseglunar–tilraunir með riðstraumi voru gerðar á nokkrum sýnum úr Skarðsheiði. Niðurstöður þeirra tilrauna og gott innbyrðis samræmi segulstefna innan hvers lags staðfesta það, að hraunlögin í Skarðsheiði eru yfirleitt ágætur efniviður til mælinga á segulstefnu. Fáein hraun höfðu orðið fyrir truflunum af völdum eldinga, en ekki mjög til baga. Í neðri hluta sniðs SI virðist jarðhitaummyndun hafa valdið verulegri dofnun hinnar upprunalegu segulmögnunar bergsins, en segulstefnur eru þó vel traustar þar. Hinsvegar benda tilraunir okkar á upphitun nokkurra sýna úr Skarðsheiði ekki til þess að þau séu heppileg til rannsókna á styrk jarðsegulsviðsins þegar hraunin runnu.

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