Reviewed research article

A reconnaissance study of paleomagnetic directions in the Tjörnes beds, Northern Iceland

Leó Kristjánsson
Institute of Earth Sciences, University of Iceland, Askja, Sturlugötu 7, 107 Reykjavík, email: leo@raunvis.hi.is

Abstract — *Paleomagnetic direction measurements were carried out on core samples collected at 30 sites in sediments and one lava site, on the west coast of the Tjörnes peninsula, Northern Iceland. The sediments are mostly sandstones, more coarse-grained than younger sediments in the peninsula sampled by Eiríksson et al. (1990). The remanence in the present collection also has a lower intensity and stability during alternating field demagnetization. Several sites yield reasonably consistent directions, and both polarities are found. More extensive collections and improved experimental techniques are needed before the reversals can be used in local stratigraphic work.*

HISTORICAL INTRODUCTION

General geology

The fossil-bearing sediments in the Tjörnes peninsula of Northern Iceland are the country's most extensive and best known sediment sequence. These sediments which are largely of shallow marine origin, have been the focus of research by many geologists, paleontologists and other scientists since the mid-eighteenth century. A bibliographic review of this research was published by Eiríksson (1981a), and more recent developments have been summarized e.g. by Eiríksson *et al.* (1990) and Buchardt and Símonarson (2003).

The pioneer geologists Þorvaldur Thoroddsen and Helgi Pjeturss around 1900, Guðmundur G. Bárðarson (1925) and subsequent authors have considered the age of the entire Tjörnes sequence to be Pliocene to Pleistocene. Eiríksson (1981b) divides the sediment sequence into two main parts: the younger one is the Breiðavík Group which contains a number of lava flows and is underlain by a series of lavas named after the small Höskuldsvík inlet. The lower part of the sequence is the Tjörnes beds, which only contains one occurrence of lava flows. It is generally divided into three zones: from top to bottom the *Serripes, Mactra* and *Tapes* zones according to characteristic mollusc fossils.

Various methods have been employed in attempts to obtain definite ages, either absolute or relative, of parts of the sequence. These methods have involved e.g. climate variations, K-Ar radiometric dating of lavas, and faunal changes. An approach used at Tjörnes by Th. Einarsson *et al.* (1967) as well as by several later authors (see Eiríksson, 1981, Buchardt and Símonarson, 2003) was based on correlation of paleomagnetic polarities with a global time scale of geomagnetic reversals. Unfortunately, the polarity time scale of the 1960's and its later versions (derived partially from dated volcanics worldwide and partially from ocean-floor anomaly lineations) have turned out to underestimate the actual number of reversals. Therefore it is becoming increasingly clear that paleomagnetic polarities in sections where only a few reversals occur, are not to be relied on by themselves for long-distance (> 20 km) correlation or age estimates. However, extended polarity patterns and particular smaller-timescale features such as reversal paths can be used for short-distance correlations. Here, new paleomagnetic direction results from sites in the Tjörnes sequence are presented so that they can be of use in future applications of paleomagnetism to stratigraphic work in the peninsula.

Some previous paleomagnetic studies at Tjörnes

These studies have been reviewed by Eiríksson *et al.* (1990) in their paper describing paleomagnetic results from lavas and sediments in the Breiðavík group. The earliest work on the magnetism of the sediments by Dutch investigators in the 1950's and early 1960's, when large specimens ("hand samples") were collected, was only reported in somewhat vague terms and will not be discussed here. Detailed sampling of lavas in Tjörnes for laboratory measurements of remanence directions was first made by Doell (1972). Doell found normal polarity in the lowermost lava above the Tjörnes beds and reverse polarity in the upper one of two pillow lavas in the Skeifá stream within these beds. The other Skeifá flow was unstable.

The only published results known from the Tjörnes sediment beds below the Höskuldsvík lavas are contained in a brief account by Gladenkov and Gurariy (1976, see Figure 3 of Eiríksson, 1981a and Figure 3 of Buchardt and Símonarson, 2003). They seem to have found mostly normal polarities below palagonite tuffs in the topmost (*Serripes*) zone of the sediments but mostly reverse polarities near the base of that zone above the Skeifá lavas. Reverse sediments were also found below lignites in the middle of the *Mactra* zone of the sediments and on both sides of the boundary between the *Mactra* and *Tapes* zones. No information was provided on experimental techniques, the number of samples collected, their stability or within-site agreement. F. Strauch (*written comm.*, 1982) collected 295 oriented cores from sediments in Tjörnes in 1975. Paleomagnetic direction measurements were made on these but apparently never published.

Eiríksson *et al.* (1990) carried out an extensive paleomagnetic study on the sediments and lavas of the Breiðavík Group as well as from a deep borehole on Flatey island 25 km west of Tjörnes. The sediment samples were collected from mudrock, sandstone and tuff. Their remanence vectors turned out to be reasonably easy to measure in the laboratory, even with relatively insensitive equipment. The directions of these vectors were also often quite stable, especially in fine-grained units. At the time, the data were not inspected for evidence of rotational remanence (RRM). This is an axial remanence component which sometimes appears in rock samples during alternating field (AF) demagnetization in tumblers, and increases systematically when the peak field of the treatment is increased (Stephenson, 1980). Upon rechecking of the original data, RRM is not seen to cause any significant error in the direction measurement on most of the samples.

Eiríksson *et al.* (1990, Figure 4) found several reversals in the Breiðavík Group. The sediment sites within that group were of reverse or uncertain magnetic polarity, except two normal-polarity ones (FG 5 and RB 3/3A). Thermomagnetic measurements as well as the magnitude of coercive force in the Breiðavík sediments, demonstrated that the magnetic mineral in the sediments is magnetite. It is considered that the remanence is of thermo-chemical or thermo-viscous origin and introduced during or soon after deposition; this is supported by measurements on a late Quaternary interbasaltic sediment in Reykjavík (Kristjánsson, 2003, site MI S).

THE PRESENT STUDY

Following the relatively successful magnetic measurements in the Breiðavík group, it was decided to attempt sampling at five locations (Figures 1 and 2) in the lower part of the Tjörnes sequence.

Sampling and sample preparation

Core samples were collected from one lava flow in the Skeifá stream, and 30 sites in the sediments, with a portable gasoline-powered drill after removal of weathered material. The four samples (occasionally five or six) taken were distributed over a few meters laterally. Each site is assigned to units in Strauch's (1963) stratigraphic scheme where possible (Table 1, final column). The sediments are soft and fragile, and their grain size is very coarse compared to the Breiðavík sediments sampled by Eiríksson *et al.* (1990). Cores are about 2.4 cm in diameter whereas 2.5 cm cores are normally obtained in low-porosity basalts with the same bits. The orientation scratch is

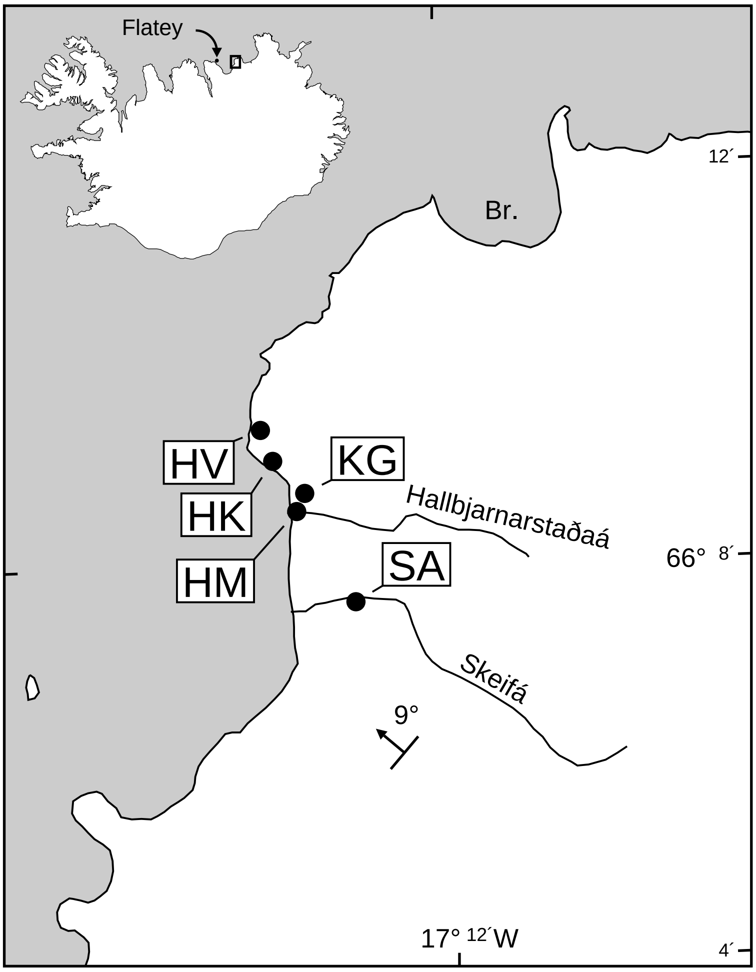

Figure 1. The five sampling localities in Tjörnes. Places mentioned in the text include the Breiðavík inlet (Br.), as well as Kambsgjá, Hallbjarnarstaðakambur and Höskuldsvík which are are small geographical features coinciding approximately with the sites KG, HK and HV respectively.
– Borstaðir í Tjörnes-setlögunum.

less well defined than on basalt cores, reducing the accuracy of laboratory measurements. Many cores broke during orientation and transport, but most could be glued together. All were coated in clear varnish before slicing. One specimen was measured from each sample.

Measurements and data processing

Remanence measurements were made on the natural remanence (NRM), and after AF demagnetization at 10, 15 and 20 mT peak fields with a Molspin demagnetizer. The remanence is much weaker and usually less stable than in typical lavas, the low stability being exhibited either as a directional trend with increasing peak field or as erratic variations at 20 mT. The latter variations were most noticeable in the component along the core direction in each case, reaching up to tens of degrees. The spurious variations appeared in some cases to be due to RRM; similar variations have also been seen in recent work on Miocene sediments from Northwest Iceland (Kristjansson *et al.*, 2003). It should be noted that our demagnetizer has a higher field frequency (172 vs. 69 Hz) and tumbling speed than that used on sediments by Eiríksson *et al.* (1990).

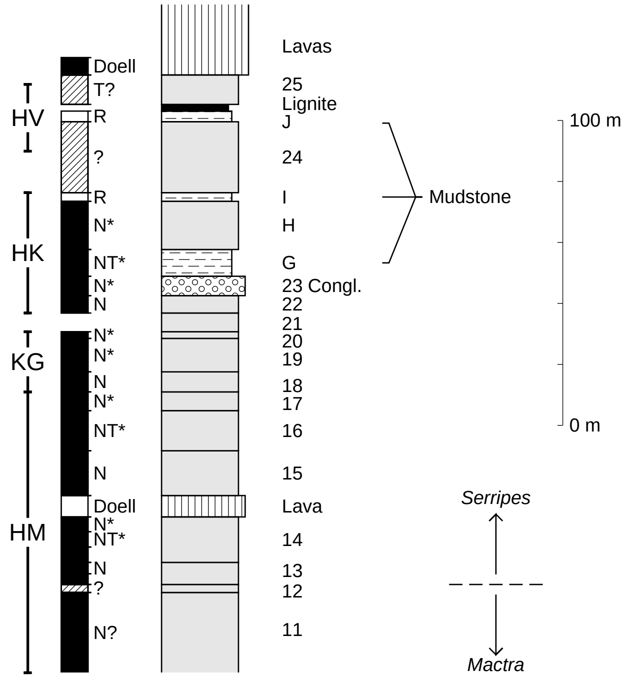

Figure 2. Stratigraphic scheme for the Tjörnes sediments (after Buchardt and Símonarson, 2003), showing the estimated range covered by the present sampling locations. For explanation of stratigraphic units (numbers and capitals) see legend to Table 1. Paleomagnetic polarities (from Table 1 and Doell, 1972: black is normal, white is reverse, hatched is uncertain polarity) are shown for the coastal sites HM, KG, HK and HV. The inland sediment sites in SA are left out as their correlation to individual units of Strauch (1963) is not clear. The polarities given by Gladenkov and Gurariy (1976) are also not included here. – *Áætluð staðsetning sýnasöfnunarinnar innan Tjörneslaganna samkvæmt skiptingu F. Strauchs á lögunum í afmarkaðar einingar. Segulstefnur eru sýndar.*

The irregular direction variations were reduced by repeating the 20 mT treatment and using the mean of the results. About a half of the cores were demagnetized also at 25 mT, and some beyond.

Mean directions for each site were calculated using the "kappa-maximizing" method of Watkins *et al.* (1975): a computer program selects those direction vectors (from the data available after 10, 15, 20 and possibly 25 mT treatment) which yield the longest vector sum. This will in many cases reduce within-site scatter from that obtained at any one of the peak fields. However, there is always a danger that the procedure will select a set of sample directions that are clustered by chance. Values of 95% confidence angles obtained are listed in Table 1; for comparison, representative values for basalt lavas in Iceland are often of the order of 6°. The directions in the table have been corrected for regional tectonic tilt which is estimated to be 9° towards 310° East of true North.

Results

The mean intensity of natural remanence in the sediments is 0.18 A/m, dropping to 0.08 A/m after 10 mT treatment (i.e. J100 in Table 1) and 0.04 A/m after 20 mT. Mean values of J100 for Icelandic lavas are 3–4 A/m and the mean value for "good" samples from the Breiðavík sediments (Eiríksson *et al.*, 1990) is 0.22 A/m. Initial volume susceptibilities, measured in ten samples, were of the order of 0.01–0.015 SI units, about half of those in basalts.

The poor within-site agreement for the lava flow, which is a tholeiite having a crude pillow structure, is disappointing: in case the discordant directions are caused e.g. by regional alteration, it may be expected to affect the sediments even more strongly. Strauch (1963) and Doell (1972) consider two lava flows to be present in Skeifá; our site is presumably the lower flow I 36 which Doell (1972) also found to give unstable or scattered directions. Three of the samples from

Table 1. Mean paleomagnetic directions and intensities in samples from 31 sites in Tjörnes. n = number of samples used in averaging; decl., incl. = declination and inclination of mean field; long., lat. = longitude and latitude of virtual geomagnetic pole; alf = 95% confidence angle for the mean field, degrees; J100 = intensity of remanence after 10 mT AF demagnetization, A/m; pol. = polarity: N = normal, R= reverse, T = transitional. * indicates that alf exceeds 20°. – *Segulstefnur, staðsetning sýndarsegulskauta, og styrkur segulmögnunar á 31 stað í Tjörneslögunum.*

Site	n	decl.	incl.	long.	lat.	alf	J100	pol.	pos.
		SA Skeifá, north of the stream (going down)							
SA 1	6	Four R, two N				>60	0.80	R?	lava
SA 2	4	198	-73	284	-79	14	0.14	R	11 [1)]
SA 3	4	172	-73	12	-81	13	0.08	R	
SA 4	5	219	-75	249	-72	11	0.13	R	
SA 5	6	357	+73	175	+82	22	0.07	N*	
SA 6	4	347	+71	199	+78	13	0.18	N	
SA 7	4	357	+69	171	+76	16	0.07	N	
SA 8	4	Scattered				>60	0.09	?	
SA 9	4	199	-40	319	-45	26	0.12	R*	14
		HM Mouth of the Hallbjarnarstaðaá stream							
HM 1	4	Scattered N/NT				>60	0.11	N?	11/21
HM 2	2	Two N, two R				>60	0.10	?	12/2
HM 3	5	325	+57	215	+55	31	0.08	N*	13/2
HM 4	4	Scattered				>60	0.06	N?	13/4
HM 5	4	7	+66	147	+72	22	0.10	N	14/2
HM 6	4	280	+53	259	+35	46	0.07	NT*	14/6
HM 7	4	319	+49	218	+46	40	0.08	N*	14/8
HM 8	4	359	+70	164	+78	10	0.07	N	15/2
HM 9	4	286	+53	253	+37	30	0.05	NT*	16/2-3
HM10	5	315	+64	234	+59	28	0.08	N*	17/1-2
		KG Kambsgjá gully							
KG 1	5	338	+79	275	+81	5	0.11	N	18/2
KG 2	4	353	+60	175	+65	22	0.04	N*	19/2-3
KG 3	4	Scattered, weak				>60	0.03	?	19/3
KG 4	4	318	+55	223	+51	25	0.11	N*	20 ?
		HK Beach at Hallbjarnarstaðakambur							
HK 1	4	145	+86	352	+59	12	0.14	N	22
HK 2	4	309	+62	239	+54	32	0.05	N*	23
HK 3	4	294	+49	244	+36	43	0.02	NT*	G
HK 4	5	305	+72	261	+63	28	0.04	N*	H
HK 5	5	240	-75	235	-64	7	0.08	R	I
		HV Höskuldsvík inlet							
HV 1	5	Scattered, unstable				>60	0.04	?	24/2
HV 2	5	200	-77	247	-82	17	0.06	R	J/2 ?
HV 3	4	Scattered, weak				>60	0.02	T?	25/2

[1)] Information on the position of samples in Strauch's (1963) stratigraphic scheme for Tjörnes was provided by J. Eiríksson to A.I. Guðmundsson who recorded the sampling positions in L.K.'s field notebook in 1991. Supplementary information on the Skeifá sites SA was provided by J. Eiríksson to L.K. in 2004. In Strauch's notation which is based on previous mapping by G.G. Bárðarson (1925), the main distinct marine sediment units are designated by numbers, from 1 (lowest) to 25 (topmost, below the Höskuldsvík lavas). The present study covers the interval from unit 11 to 25. Terrestrial sediment units are similarly assigned capital letters from A to J by Strauch, and sub-units are indicated by numbers increasing upwards. Strauch (1963) uses the expression "Horisont" for both the units and the sub-units. Strauch's scheme is mostly derived from sections exposed at the coast; he does not indicate in detail how individual layers outcropping inland below the Skeifá lavas fit into it and the situation there is also complicated by faulting (Strauch, 1963, p. 53).

SA 1 give reverse directions similar to Doell's average for his upper site I 37.

Those sediment directions that could be measured with reasonable within-site agreement tend to be of normal polarity. However, the three reverse sites directly underlying the Skeifá lava seem to be quite reliable and the lowest of these is at least 3 m below the lava contact so that the reverse polarity is hardly due to heating by the flow. The reverse polarity of site SA 9 is much less certain, as one sample from there (excluded from Table 1) was normally magnetized.

SUMMARY AND CONCLUSIONS

Remanence measurements from 30 sediment sites and one lava within the Tjörnes beds (Figure 2, Table 1) indicate mostly normal polarities. The quality of the Tjörnes beds for paleomagnetic research is clearly much inferior to the sediments of the Breiðavík group and Flatey. This is likely to be directly or indirectly related to the differences in grain size between the two parts of the Tjörnes sequence. However, at 5 "normal" and 5 "reverse" sites the 95% confidence angles (α_{95}) are less than 20°, and all of these have virtual pole latitudes of 60° and higher. They are considered to give a fairly definite indication of the geomagnetic polarity during the acquisition of the stable remanence component. The sites with α_{95}-values exceeding 20° are not very trustworthy, especially those yielding mid-latitude poles. Reverse polarities found in this study below the Skeifá lava site and by Gladenkov and Gurariy (1976) in overlying sediments, tend to support the conclusion of Doell (1972) that the lava(s) were erupted during a reverse geomagnetic (sub)chron. Evidence for reverse polarities was not found in the coastal sites HM which are supposed to span the same units (Strauch s 11 to 14) as SA; a number of explanations for this disagreement may be suggested. The sites at KG and most of HK are of normal polarity, while the top sampled unit of HK and the one measureable unit in HV are reverse. HV is overlain by the normally magnetized lava flow I 38 of Doell (1972).

Accordingly, there is evidence for at least four geomagnetic reversals having taken place during the deposition of that part of the Tjörnes beds which was sampled: two in the Skeifá profile (not seen in profile HM), one between between Skeifá and Hallbjarnarstaðaá and one south of Höskuldsvík. The polarities in the sediments do not say much about their age, but they are not in conflict with the suggestion of Buchardt and Símonarson (2003) that the beds between the Skeifá and Höskuldsvík lavas were deposited during the Gauss geomagnetic chron (3.58–2.58 Ma ago). Progress in understanding the remanent magnetization of the Tjörnes beds and its use for stratigraphic purposes will clearly require extensive additional sampling as well as major improvements in sampling methods and laboratory techniques.

Acknowledgments

The study was suggested by Jón Eiríksson who selected the sampling sites and provided information on their stratigraphic position. Andrés I. Guðmundsson assisted in the collection of core samples. Haraldur Auðunsson carried out some of the paleomagnetic measurements. The diagrams were made by Geirfinnur Jónsson. The field work was supported by the Science Foundation of Iceland (Vísindasjóður).

ÁGRIP

Segulstefnumælingar á setsýnum frá Tjörnesi

Safnað var sýnum á 30 stöðum í efri hluta setlaga þeirra sem liggja undir Breiðuvíkurlögunum á Tjörnesi. Segulstefnur voru mældar í þeim og að auki í sýnum úr einu hraunlagi. Segulmögnunin reyndist vera mun daufari en í Breiðuvíkursyrpunni og setlögum úr borkjarna í Flatey, og stefna hennar óstöðugri. Þessi munur gæti tengst því að Tjörneslagasýnin eru yfirleitt sandsteinn, mun grófari í kornastærð en hin. Á 10 stöðum fengust sæmilega öruggar segulstefnur (95% óvissumörk undir 20°). Jafnmargar af þeim voru "réttar" og "öfugar", og þær samsvara allar segulskautum á um eða yfir 60° breidd. Virðist líklegt að niðurstöðurnar endurspegli fáeina umsnúninga jarðsegulsviðsins meðan eða fljótlega eftir að lögin voru að myndast. Segulstefnum í sniði niður við sjó (HM) og öðru inni í landi (SA) sem talin eru ná yfir sömu eða jafngamlar setlagasyrpur, ber ekki vel saman. Mun ítarlegri rannsókna er þörf áður en segulstefnumælingar gætu t.d. nýst við tengingar milli sniða eða borhola í þessum setlögum.

REFERENCES

Bárðarson, G.G. 1925. A Stratigraphical Survey of the Pliocene Deposits at Tjörnes in Northern Iceland. *Kgl. Danske Vidensk. Selskab, Biol. Medd.* IV(5), 1-118.

Buchardt, B. and L. Símonarson 2003. Isotope palaeotemperatures from the Tjörnes beds in Iceland: evidence of Pliocene cooling. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 189, 71-95.

Doell, R.R. 1972. Palaeomagnetic studies of Icelandic lava flows. *Geophys. J. Royal astron. Soc.* 26, 459-479.

Einarsson, Th., D.M. Hopkins and R.R. Doell 1967. The stratigraphy of Tjörnes, Northern Iceland, and the history of the Bering Land Bridge. In Hopkins, D.M. (ed.) *The Bering Land Bridge*, 312-325. Stanford University Press, Stanford.

Eiríksson, J. 1981a. Tjörnes, North Iceland: a bibliographic review of the geological research history. *Jökull* 30, 1-20.

Eiríksson, J. 1981b. Lithostratigraphy of the Upper Tjörnes sequence, North Iceland: the Breidavík Group. *Acta Nat. Islandica* 29, 37 pp.

Eiríksson, J., A.I. Gudmundsson, L. Kristjansson and K. Gunnarsson, 1990. Palaeomagnetism of Pliocene-Pleistocene sediments and lava flows on Tjörnes and Flatey, North Iceland. *Boreas* 19, 39-55.

Gladenkov, Y.B. and G.Z. Gurariy 1976. Paleomagnetic characteristics of the Plio-Pleistocene in Iceland (Tjörnes-Peninsula). *Doklady Akad. Nauk* 230, 1173-1175 (in Russian).

Kristjánsson, L. 2003. Paleomagnetic observations on Late Quaternary basalts in Reykjavik and on the Reykjanes peninsula, SW-Iceland. *Jökull* 52, 21-32.

Kristjansson, L., B.S. Hardarson and H. Audunsson 2003. A detailed palaeomagnetic study of the oldest (ca. 15 Myr) lava sequences in Northwest Iceland. *Geophys. J. Internat.* 155, 991-1005.

Stephenson, A. 1980. Rotational remenent magnetization and the torque exerted on a rotating rock in an alternating magnetic field. *Geophys. J. Royal astron. Soc.* 62, 113-132.

Strauch, F. 1963. Zur Geologie von Tjörnes (Nordisland). *Sonderveröff. Geol. Inst. Universität Köln* 8, 129 pp. (in German).

Watkins, N.D., L. Kristjánsson and I. McDougall 1975. A detailed paleomagnetic survey of the type location for the Gilsá geomagnetic polarity event. *Earth planet. Sci. Lett.* 27, 436-444.