JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 87, NO. B8, PAGES 6569–6589, AUGUST 10, 1982

The Natural Magnetization of a 3-Kilometer Section of Icelandic Crust

ULRICH BLEIL[1], JAMES M. HALL[2], H. PAUL JOHNSON[3], SHAUL LEVI[4],
AND GUNTHER SCHONHARTING[5]

The magnetization and magnetic properties of samples from a 3 km vertical section of Icelandic crust, the Iceland Research Drilling Project section, are described. The section is located at the head of Reydarfjordur, eastern Iceland at 65°01'N, 14°21'W and extends vertically from about 0.5 km to 3.5 km depth beneath the original surface. The section consists of 1 km of exposed flows with minor dikes and volcaniclastics underlain by a 2-km drill core component consisting of 60% flows and minor volcaniclastics and 40% dikes. The section is largely normally magnetized, corresponding in age and polarity to seafloor spreading anomaly 5 (geomagnetic polarity epoch 9). Flows which accumulated during anomaly 5 time extend vertically for 2145 m in contrast with 1000-m-thick equivalent sections which are exposed updip. This great increase in downdip thickening is consistent with observations elsewhere in eastern Iceland and models for Icelandic crustal formation involving the combination of volcanic activity, subsidence, and spreading. A combination of paleomagnetic and structural evidence is used to provide an age calibration for the section and to predict the local presence of magnetic overprinting in the lower part of the section. This overprinting is probably in part due to the production of secondary magnetite and is developed to a varying extent in epidote bearing flows at below 2.8-km crustal (original) depth. Where moderate secondary magnetite development has occurred, flows frequently show both normal and reverse stable polarities, with the latter being the original. Secondary magnetite development is high where dike density in the epidote bearing flows is also high. Here very strong, well defined, pervasive normal magnetization characterizes the flows, this also being the dominant polarity of the dikes. Magnetic overprinting of this type, imposed shortly after crustal formation, could occur at 800- to 1200-m depth in typical ocean crust and may provide a contribution to the source for the linear magnetic anomaly patterns of the ocean basins. The initial susceptibility of the flows shows the best-defined depth trends over the section. Susceptibility increases with depth to about 2-km crustal depth and then decreases systematically to the bottom of the section. The reason for the initial increase is not known, but the decrease at depth can be explained by transfer of iron from primary oxides to secondary oxides and silicates. The decrease is sufficiently linear to warrant extrapolation to a zero value at 4.3-km crustal depth, or just below the estimated level of onset of greenschist facies metamorphic conditions. In typical oceanic crust the equivalent level is estimated to be at 1.2-km depth. The net magnetization of the section, the combined remanent and induced contributions, when expressed as average values for 500-m depth intervals, is everywhere positive, that is, is in the sense of the present field. Variation in net magnetization is related to the proportions of the normal and reversely magnetized units in each interval.

INTRODUCTION

The magnetization of oceanic crust has, through its expression as linear anomaly patterns, played a major role in our understanding of the formation and evolution of the present ocean basins. Considerable effort has been made, since the first demonstration of the significance of the linear anomaly patterns, to identify the source of the anomaly patterns. Impetus for these investigations has come from the crustal drilling carried out by D.V. *Glomar Challenger* since 1974. The drilling results, which are summarized to date by *Lowrie* [1979], *Hall and Robinson* [1979], and *Johnson* [1979], show that an earlier, simple model of crustal magnetization, in which an approximately 500-m-thick uniformly and highly magnetized lava cap, supposed to overlie the more weakly magnetized remaining part of the crust, may have to be reconsidered at least for slow spreading Atlantic type crust.

Since, for a variety of reasons, it seemed unlikely that *Glomar Challenger* could drill significantly below about 600-m basement depth in normal oceanic crust and it seemed that a vessel capable of deeper penetration would not be available for 5-10 years, we have sought a different approach to the problem of locating the source of anomalies.

A small number of segments of the present and former mid-ocean ridge systems extend above sea level, of which those in Iceland, Afar, and possibly in some ophiolites are the best known and exposed. While we realize that a crustal section above sea level requires either some atypical formational elements or later disruption, these disadvantages appear to be outweighed by the advantage of accessibility to significantly greater depth than is possible at present for more typical ridge segments.

The study reported here is an attempt to delineate natural magnetization from a depth of 0.5 km to a depth of approximately 3.5 km in crust of oceanic affinity in eastern Iceland. Other papers [e.g., *Schonharting and Ghisler*, this issue] describe the rock magnetic and opaque mineralogical properties of the section.

Magnetic anomalies in Iceland [*Serson et al.*, 1968; *Sigurgeirsson*, 1970; *Rutten*, 1975] are less regular than typical linear oceanic anomalies. This is probably explained by the combined action of relatively large discrete movements of the spreading axes, contemporaneous spreading on several axes, the considerable lateral extent of subaerial flows, and the frequent presence of volcanic centers, each with high level intrusions and an associated dike swarm [*Kristjansson*, 1970;

[1]Institut fur Geophysik, Ruhr-Universitat, 4630 Bochum, Federal Republic of Germany.
[2]Department of Geology, Dalhousie University, Halifax, Nova Scotia, B3H 3J5, Canada.
[3]School of Oceanography, University of Washington, Seattle, Washington, 98195.
[4]Geophysics Group, School of Oceanography, Oregon State University, Corvallis, Oregon, 97331.
[5]Institut for Almen Geologi, Oster Voldgade 10, 1350 Copenhagen, Denmark.

Paper number 2B0231.
0148-0227/82/002B-0231$05.00

Piper, 1973; *Angenheister et al.,* 1977; *Schonharting,* 1979; *Becker,* 1980]. In addition, the general absence of pillow basalts and sea water alteration in Icelandic crust may lead to some differences between the magnetic properties of Icelandic and typical ocean ridge basalts. It can be anticipated, however, that many features of the magnetization of Icelandic crust will resemble those of oceanic crust, such as differences between flows and major and minor intrusions, the effects of thermal and chemical alteration by hydrothermal fluids, and remagnetization by dike intrusion.

Eastern Iceland was formed at a subaerial segment of the Mid Atlantic Ridge where the ridge crosses the Greenland-Iceland-Faeroes series of aseismic volcanic rises. The area consists of a 1.0- to 1.5-km-high plateau, now deeply incised by glacial valleys. Basic geological mapping of the area was carried out by G. P. L. Walker and his students in the late 1950's [*Walker,* 1959, 1960] and was followed by a major regional paleomagnetic study with the aim of defining geomagnetic reversal history during much of the Neogene [*Dagley et al.,* 1967; *Watkins and Walker,* 1977]. This paleomagnetic study also provides and age framework for the long sequences of subaerial basalts in the area.

The location (Figure 1) of the section studied, at the head of Reydarfjordur (65°01'N, 14°21'W), directly to the east of the Thingmuli volcanic center, was strongly influenced by the availability of detailed geologic and paleomagnetic data and by deep glacial erosion that allowed the section to be constructed from a 1 km exposed segment (Trollafjall section of Figure 1) underlain by a 2 km continuously cored drill hole segment. The section consists lithologically of subaerially erupted flows, subvertical dikes, and minor volcaniclastics.

Figure 1 shows that a link along strike between sections F and J of Watkins and Walker passes close to the location of our section. Since both F and J contain sequences of flows magnetized during normal polarity epoch 9 (equivalent to seafloor spreading anomaly 5 time), it was anticipated that

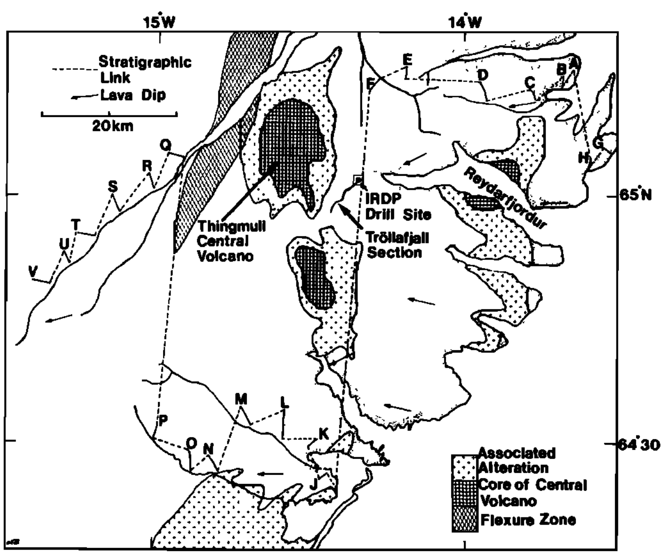

Fig. 1. Location map for the Iceland Research Drilling Project crustal section. Top of exposed part of section (unit 991) is on top of Trollafjall Mountain. Bottom of exposed part of section (unit 700) and top of drill core part of section (unit 1.1) is at drill site. Bottom of drill core part of section is unit 327.2. A through V are profiles sampled for paleomagnetic purposes [Watkins and Walker, 1977]. Seafloor spreading anomaly 5 is represented in sections E, F, and J.

rocks of this age and polarity would also occur in our crustal section. Two significant features of the section are the occurrence of the Skessa tuff, a regional correlation unit, at about 100 m above sea level and dike density equivalent to 10% crustal dilation in the vicinity to the top of the drill hole. The aims of the study can be expressed as a series of questions:

1. How does intensity of remanent and induced magnetization vary with depth in the crust? It was known from the oceans that no significant depth trends occur in the little altered uppermost 600 m and that a similar situation appears to hold for susceptibility and magnetite content in longer sections of Icelandic crust [*Kristjansson and Watkins,* 1977]. However, oceanic greenschist facies metabasalts are very weakly magnetized [*Fox and Opdyke,* 1973], implying that a decrease of magnetization with depth does occur over some interval in oceanic crust.

2. How does the magnetization of the minor intrusions (dikes and sheets) compare with that of the flows? Possible differences in age and degree of alteration could be expected to lead to different directions and intensities of magnetization.

3. What changes occur to polarity intervals recognized in exposed sections as they are traced below sea level? (The lava sequences in the area dip monotonously toward the active zone to the west.) This question bears on the process of accretion in the active zone, and it was already known that the flows occur in groups that thicken downdip.

4. What are the remanence characteristics below the zone where initial cooling magnetization directions are preserved? In popular terminology we are concerned here with nature of the bottom of the 'tape' of the 'tape recorder.'

From earlier work [*e.g.Ade-Hall et al.,* 1971] it seemed likely that the answer to at least some of these questions would depend on the alteration experienced by the rocks composing the section. Early studies [*e.g.Walker,* 1960] showed that on the average, half a kilometer of the original crustal section had been removed by erosion and that the remaining exposed section showed a downward increase in degree of zeolite facies metamorphism. In our section [*Iceland Research Drilling Project,* 1979; *Mehegan et al.,* this issue] and elsewhere in the area, the flows on mountain tops are unzeolitized, whereas at sea level the flows have experienced laumontite zone, zeolite facies metamorphism. The laumontite zone was found to continue to 2.8-km crustal (i.e., original) depth; below this depth, epidote occurs with variable concentration. The greenschist facies proper, as defined by the presence of the assemblage albite-actinolite-chlorite-zoisite-clinozoisite [*Winkler,* 1975, p. 172], does not occur in the drill core, but *Robinson et al.* [this issue] estimate that its onset occurs at 4.1-km crustal depth. From *Palmason et al.* [1979] the onset of laumontite formation, at about 1.5-km crustal depth, corresponds to a temperature of about 110°C, while the onset of abundant epidote at 2.8 km crustal depth corresponds to a temperature of about 260°C. The maximum temperature experienced at the base of the section is estimated to have been 300°C. Present temperatures are well below these values [*Gibson,* 1979].

In addition to an increase in alteration with crustal depth, both lava dip and dike density are seen to increase with depth in the exposed part of the section. However, while dip does show continuous increase with depth in the drill hole, dike density does not. Instead, minor intrusions occur in groups separated by intervals in which they are absent [*Gibson,* 1979].

SAMPLING AND MEASUREMENT

The intention of the sampling program was to obtain at least four completely or semi-oriented samples from each of the 677 cooling units in the crustal section. From experience elsewhere [e.g., *Wilson*, 1970] it was expected that this density of samples per unit would allow well defined stable remanence directions to be obtained after partial alternating field demagnetization. In practice, only 191 of the 309 units in the exposed section and 283 of the 362 units in the drill core were sampled for magnetic studies. Weather, snow cover, and time were the main constraints on sampling the exposed sections during field seasons in 1978 and 1979. Thin or very friable units were left unsampled in the drill core.

Units in the exposed section were sampled using portable diamond drills. Orientation of samples was by solar or geographic sighting except in poor weather conditions where it was necessary to resort to magnetic orientation with a corresponding loss of accuracy. The drill core, representing 99.7% recovery from the drilled section, was sampled transversely with a diamond coring bit held in a machine shop drill press. Measurement pieces about 2 cm thick were sliced from the 2.5-cm-diameter minicores.

Magnetization measurements on the drill core segment were made both in the core laboratory in Iceland shortly after recovery and at the laboratories of the authors. Demagnetization of remanences was carried routinely to a peak field of 500 Oe (50 mT), with higher values where necessary to isolate stable components. Within-sample stable directions were identified visually using directions from an average of four successive demagnetization steps. For units in the exposed section, stable directions were averaged to give within-unit mean directions and the scatter parameter, α_{95}. For units in the drill hole section samples are generally of unknown relative azimuthal orientation, and mean inclinations, with one standard deviation, are quoted.

Initial susceptibility measurements were made using a variety of instruments, including A.C. bridges such as the Geophysical Specialities model MS-3, and the steady field Schonstedt SVM-1 instrument.

THE PALEOMAGNETIC RECORD (TABLE 1, FIGURE 2)

The average directions for extrusives are predominantly of normal polarity. Two stratigraphically short sections of reverse polarity occur near the top of the section. The uppermost section is well defined and consists of the 10 flows 954-963 (550- to 640-m crustal depth). The other section is defined by two flows, 912 and 916, in an area of rather widely spaced sampling, and only approximate boundaries for this section of 810 to 855 m can be drawn. With the exception of units 742, 745 (1475 m), 763 (1390 m), and 775 (1335 m) in the exposed section and 211.1CA, 2830-m depth in the drill core section, normal polarities extend until a depth of 3046 m is reached. Units 742 and 745 are aphyric, low-Mg tholeiite, 763 is a high-Mg tholeiite, and 775 is transitional between low-Mg tholeiite and ferrobasalt [*Flower et al.*, this issue]. Drill core unit 211.1CA is a 4.5 m thick, dark, probably basaltic volcaniclastic (P. T. Robinson and H.-U. Schmincke, unpublished core summaries, 1979). Paleomagnetically, it consists of two distinct units, here denoted by 211.1CA and 211.1CB. The upper reversely magnetized unit, 211.1CA, of between 0.25 and 0.47 m thickness, is well characterized by four samples with stable inclinations of -54°, -55°, -62°, and -34°. The lower normally magnetized unit, 211.1CB, of between 4.02- and 4.23-m thickness, is equally well characterized by six normally magnetized samples with stable inclinations of +72°, +59°, +62°, +77°, +58°, and +77°. The original top of the clastic is not present in the drill core, normally magnetized dike 210.1 being chilled against the unit. At its base the unit is in original stratigraphic contact with normally magnetized flow 211.2.

Reversely magnetized flows appear again below 3075-m depth. However, the paleomagnetism of the extrusives in the 480-m interval from this depth to the bottom of the section at 3520 m cannot be described adequately in terms of the usual normal, reverse, and intermediate classification. The requirement of directional consistency as a criterion for preservation of initial cooling direction is frequently violated in this interval. Fifteen of the fifty-three extrusives in this interval contain both upward and steeply downward inclined stable remanence directions. These are called mixed polarity units and are identified by M in Figure 2. Figure 3 shows in detail an interval containing such units. A combination of reverse and mixed polarity extrusives occupies the depth interval 3075 to 3215 m. Normal and mixed polarity units, with one reverse unit, occupy the interval from 3215 to 3475 or 3490 m, and reverse and mixed polarity units occupy the remaining 30 to 55 m of the interval.

To identify geomagnetic field history recorded in this deepest interval and thereby to date the section, an understanding of mixed polarity magnetization is needed. Mixed polarity units can be divided into those that are visibly adjacent to dikes (253.1, 270.1, 274.6, 285.4, and 298.2, Figure 2) and those that are not in visible contact with dikes (263.2, 276.1, 278.1, 320.1, and 326.1). Olivine tholeiite flow 253.1 is an example of a mixed polarity unit visibly adjacent to a dike (Figure 4). Normal polarity stable inclinations occur in the upper approximately 6 m of the 11.5-m-thick flow, with values close to +75°, similar to the normal inclination of the adjacent 15-m-thick dike 248.1. Over an approximately 2-m-thick central part of the flow, stable inclinations alternate between reverse and normal, while in the lower approximately 4 m of the flow, inclinations are uniformly reversed with values of close to -50°. Partial demagnetization to 1000-Oe peak field shows the presence of one or more soft component and a single hard component in both normal and reverse remanences (Figure 5), while in a single sample, at 1481.98 m, well-developed normal and reverse components are present with the latter being the hardest. Detailed studies of three mixed polarity units not in visible contact with dikes (263.2, 320.1, 326.2) are described by *Schonharting and Ghisler* [this issue]. After both alternating field and thermal demagnetization, all three units show central zones with stable normal magnetization flanked by zones of stable reverse magnetization [*Schonharting and Ghisler*, this issue, Figure 5].

The average paleomagnetic directions for the dikes are also predominantly of normal polarity. In contrast with the extrusives, within-unit internal consistency of stable directions is present throughout the section, there being no convincing instances of mixed polarities. Reversely magnetized dikes are most abundant in the 1500- to 1600-m and 3298- to 3327-m intervals.

TABLE 1a. Paleomagnetic and Magnetic Properties of the IRDP Crustal Section: Exposed Section.

Unit	Elevation, m	Stable Paleomagnetic Direction*, deg			$\bar{J}_{NRM}$ x10[4] cgs	K x10[4] cgs	Q
		$\bar{D}$	$\bar{I}$	α_{95}			
			Extrusives				
990	1120	153	+78	5	83	1.7	99
986	1105	209	+88	4	26	3.3	15
982	1090	013	+72	4	40	11	6.7
978	1080	172	+64	16	41	6.5	13
974	1075	067	+72	10	46	25	4.0
970	1070	007	+71	5	55	9.5	11
966	1060	170	+77	7	24	9.9	4.8
963	1040	107	−80	5	60	17	7.6
961	1030		R		19	27	1.5
960	1025	084	−69	17	16	5.1	6.2
959	1000	314	−65	21	41	5.8	12
958	980		R		4.6	11	0.82
957	975	225	−68	4	14	13	4.1
956	970	240	−56	2	13	31	0.85
955	970	283	−38	13	8.4	5.9	2.8
954	965	212	−69	6	16	4.8	6.5
953	950	348	+65	10	11	7.0	3.3
952	945	028	+79	8	29	5.8	9.4
951	940	114	+81	3	28	11	5.0
950	930	062	+72	20	5.9	15	0.82
949	920	356	+72	5	40	23	3.3
945	900	175	+83	8	23	29	2.4
940	880	178	+65	4	9	7.5	2.6
934	870	052	+70	4	77	20	7.6
929	860	168	+78	8	23	18	2.7
924	810	320	+69	5	21	34	1.2
916	775	109	−67	8	13	24	1.2
910	760	115	−62	13	9.3	26	0.68
907	720	186	+54	4	22	14	3.3
902	730	014	+71	5	43	26	2.4
900	720	034	+74	8	11	4.6	6.0
899	715	057	+81	6	28	10	5.3
898	715		N			23	
897	712	064	+77	4	30	14	4.2
995	700	168	+62	9	34	14	4.8
893	695	032	+79	5	59	34	3.2
890	685	105	+61	12	10	26	0.84
889	680	041	+78	6	29	40	2.3
888C	675	038	+44	10	49	46	2.2
888A	670	023	+45	7	18	34	1.1
886	630	097	+47	6	8.2	23	0.68
884	625	260	+69	8	19	20	1.9
882	618				60	27	4.4
880	608	201	+87	4	30	33	2.0
878	605	239	+76	6	13	12	2.9
875	595	041	+70	5	34	55	1.2
874	590	054	+64	5	36	35	1.9
871	575	350	+61	3	38	35	2.1
869	563	007	+79	11	14	50	0.66
867	553	351	+51	7	23	44	1.0
864	543	011	+77	4	32	27	2.6
863L	530	007	+56	8	27	37	1.4
863J	520	294	+74	4	20	54	0.91
863H	514	043	+70	2	45	33	2.9
857	550	031	+57	6	41	44	1.8
852	550						
850B	545	016	+78	19	48	46	2.8
850A	544	092	+68	17	77	27	5.4
849	542	019	+69	4	48	28	3.4
848	540	021	+67	8	39	25	3.0
847	530	003	+56	16	30	36	1.8
845	520	322	+87	4	29	58	0.96
844	518	199	+83	6	44	33	2.7
843	513	168	+86	5	26	39	1.3
842	512	183	+87	4	33	24	2.7
841	507	181	+85	6	17	25	1.3

Unit	Elevation, m	Stable Paleomagnetic Direction*, deg $\bar{D}$	$\bar{I}$	α_{95}	$\bar{J}_{NRM}$ x10^4 cgs	K x10^4 cgs	Q
			Extrusives (continued)				
839	504			7	10	15	1.2
834	480	037	+57	2			
833	478	349	+59	8	46	37	2.7
832	474	011	+63	7	46	34	2.7
831	470	007	+46	6	23	25	1.8
830	467	001	+68	5	32	24	2.7
829	465	007	+55	4	58	23	4.9
827	457	314	+72	4	39	12	6.5
824	450	019	+85	3	24	38	1.2
822	445	327	+65	6	44	34	2.5
820	435	267	+76	4	50	33	3.2
818	427	000	+72	5	58	12	9.5
816	425	289	+80	2	54	7.8	14
814	415	304	+74	7	32	34	1.8
813	412	003	+81	2	33	50	1.3
812	405	026	+82	3			
811	400	353	+77	6	32	39	1.7
810	400	032	+80	6	20	32	1.2
809	395	012	+79	5	21	38	1.3
808	390	022	+81	4	33	19	3.3
807	385		N		24	47	0.99
806	378	116	+73	14	27	64	0.80
805	370	155	+63	5	26	77	0.70
804	364	148	+61	3	18	32	1.1
803	358	025	+70	10	40	72	1.1
802	355	039	+69	3	38	48	1.8
801	340	021	+59	8	45	75	1.3
800	330	178	+88	5	50	48	2.4
799	318	347	+66	5	35	56	1.3
798	310	343	+70	7	49	70	1.5
797	300	028	+79	6	43	10	0.90
796	290	067	+81	15	34	86	0.80
795	275	337	+83	1	36	45	1.5
794	260	060	+74	8	50	66	2.0
793	250	350	+70	6	29	48	1.2
791B	243	027	+69	3	57	62	2.1
791	240	046	+75	10	62	56	2.6
790	215	006	+68	7	32	29	2.9
786	205	090	+83	7	18	27	1.3
785	200	172	+88	3	70	26	5.2
784	197	059	+89	2	37	36	2.0
782	188	340	+69	6	36	63	1.1
781	177	033	+74	3	39	23	3.3
779	270/170	338	+74	5	20	38	1.1
778	260	276	+85	2	16	17	1.9
777	250	077	+72	3	42	30	2.8
775	240	346	−71	3			
774	235	073	+72	2	23	16	2.9
772	230	003	+61	3	39	30	4.9
771	225	303	+83	1	22	8.8	4.9
768	215/235	197	+74	13	10	4.1	5.1
766	228	224	+83	3	15	47	0.63
765	224	004	+59	4		48	
764	218	278	+85	5	39	60	1.4
763	210		R		10	52	0.39
762	205	303	+81	3	40	95	0.87
760	202	152	+81	10	64	55	2.3
758	198	157	+73	8			
756	188	236	+83	10	26	40	1.3
755	180	303	+87	2	49	56	2.2
754	170		N		40	62	1.3
752	160	246	+80	1	53	37	2.8
750	150	349	+79	9	18	34	1.1
746	138	228	+79	9	36	18	4.2
745	132	163	−88	6	14	69	0.41
742	126		possibly R or I		19	93	0.39
741	120	214	+82	9	14	63	0.46

Unit	Elevation, m	Stable Paleomagnetic Direction*, deg $\bar{D}$	$\bar{I}$	α_{95}	$\bar{J}_{NRM}$ x10⁴ cgs	K x10⁴ cgs	Q
			Extrusives (continued)				
739	108	206	+81	13	11	70	0.30
737	94	333	+64	5	64	49	2.6
734	88		probably N		40		
733	85	010	+84	2	30	63	0.92
729	78	358	+82	5	32	56	1.2
726	75	238	+77	8	28	53	1.1
725	70						
724	67		probably N		26	52	1.2
722	64	051	+70	2	16	63	0.51
720	75		N		23		
704	72	269	+73	6	51	19	5.4
703	67	169	+85	10	24	22	2.1
702	63	324	+71	10	29	18	3.1
701	60	248	+78	2	27	28	2.0
			Dikes				
991	1125	027	+69	2	83	1.7	99
964	1050	059	+69	11	113	3.2	79
846	520	332	+72	6	100	13	17
840	510	080	+84	1	14	20	1.4
838	500	338	+40	4	25	35	1.4
837	500	219	-81	8	34	45	1.4
792	240	088	+79	4	20	32	1.2
791**	240		N		25	87	0.58
788	200	005	+72	3	28	54	1.0
787	200	353	+85	2	47	33	3.3
783	190	358	+28	5	23	47	1.6
776	250		R		12	50	0.5
773	230	026	+79	3	46	33	3.1
769	220	102	-71	6	9.7	27	0.7
767	230	030	+85	3	71	21	9
761	205	214	+82	3	12	25	0.9
759	200	062	+76	4	72	46	3.1
757	190	047	+77	3	272	24	22
751	150	330	-09	4	17	30	1.1
749	120	312	+62	7	15	47	0.6
748	120	330	+74	6	52	61	1.6
747	120		R		21	53	0.8
744	110		no stable direction		18	71	0.5
743	110	173	-88	3	166	37	8.6
740	105	021	+66		38	69	1.1
738	90		R		18	67	0.5
730	85		N		33	56	1.3
727	80	296	+66	7	47	39	2.3
723	70		N		35	41	1.5
721	70	096	-60	8	41	20	4.0
719	70	024	+72	4	162	36	8.8
718	70		R		34	34	1.9
717	70	307	+73	4	41	32	2.8
716	70	248	+83	2	17	58	0.6
715	70	319	+72	2	55	72	1.5
710	70		R		9		
709	70	254	+78	6	22	13	3.4
708	70	001	+69	6	52	20	4.9
707	70	348	+73	6	62	29	4.3
706	70	213	+69	10	23	33	1.4
705	70	340	+66		31		
700	58	319	+75	4	49	24	4.3

*After rotation for tectonic dip (Hall et al., this volume)

**N.B. Also a flow 791.

R, N, I; definite reverse, normal, or intermediate direction of magnetization, respectively, but individual sample directions too scattered to justify averaging.

TABLE 1b. Paleomagnetic and Magnetic Properties of the IRDP Crustal Section: Drill Hole Section

Unit	Depth to Top, m	Thickness, m	Stable Paleomagnetic Inclination, deg $\bar{I}$	s.d.*	$\bar{J}_{NRM}$ x10^4 cgs	K x10^4 cgs	Q
			Extrusives				
4.1	28.21	10.29	+77	4	200	46	12
5.1C and 6.1C	38.50	1.29	+56	13	124		
6.2	41.42	5.68	+63	1	26	89	0.64
7.2	47.26	1.87	+69	6	42	57	1.4
8.3	49.13	1.25	+65	2	71	46	3.0
8.1C	50.38	0.57	+75		32		
8.2	50.95	12.19	+74	2	61	50	2.8
28.1	172.29	4.94	+67	6	126	74	4.0
29.1	177.23	8.87	+68	3	76	53	2.9
31.1	186.10	9.85	+65	4	79	48	3.2
32.1	195.95	3.60	+65	1	128	54	4.7
34.1	207.33	6.87	+71	8	50	56	1.7
35.1	214.20	11.44	+73	5	48	60	2.0
37.1	225.65	11.73	+65	1	50	61	2.1
39.1	237.37	7.73	+77	2	51	48	2.2
41.1	245.10	4.10	+75	4	75	49	3.0
41.2	249.20	9.38	+76	4	35	43	1.9
43.1	258.58	4.10	+71	5	74	37	4.6
44.1	262.68	13.62	+69	2	41	92	0.90
46.1C	276.30	0.30	+82		60		
46.2	276.60	3.11	+72	4	70	23	6.7
47.2	279.86	6.44	N		30	122	0.43
48.1C	286.30	3.60	+71	5	8.2		
51.2	305.48	5.32	+71	12	28	29	1.8
52.1	310.80	8.07	+79	3	40	70	1.1
53.2	319.45	3.08	+79	3	22	82	0.52
54.1C	322.53	4.19	+68	1	22		
55.1	326.72	8.21	+76	4	30	89	0.84
56.1C	334.93	1.87	+87		28		
56.2	336.80	7.35	N		15	91	0.33
58.1C	344.15	18.10	+74	3	9.6		
61.1	362.25	2.05	+80	3	108	54	4.4
64.1	381.40	5.30	+74	1	189	66	5.4
65.1	386.83	15.50	+83	4	11	107	0.20
67.1C	402.33	7.27	+78	1	180		
70.2	414.80	4.13	+73	7	97	60	3.3
73.1	425.90	8.80	+76	2	62	69	1.9
74.1	434.70	9.83	+80	2	46	62	1.8
76.1	444.53	3.37	+73		10	89	0.22
76.2	447.90	5.63	+69	11	23	88	1.0
77.1	453.53	3.78	+52	7	30	11	5.9
79.2	462.10	4.20	+87		19		
80.1	466.90	5.60	+68	6	62	72	1.6
81.1	472.50	6.55	+79	3	19	107	0.39
82.2	480.00	9.05			17	103	0.35
84.1	491.50	11.82	+65	16	12	72	0.31
86.1C	503.32	0.68	+71		25		
86.2	504.00	3.36	+71	1	15	51	0.61
87.3C	509.65	1.60	+79		14		
100.1C	585.82	4.00	+75	8	110		
108.1	628.80	3.87	+81	3	91	47	3.9
112.1	652.70	4.00	+70	10	17	46	0.75
113.1	657.70	1.37	+62	5	8.8	19	1.0
113.2	659.07	5.34	+65	7	22	61	0.40
114.1	664.41	3.07	+69	11	14	32	0.89
114.2	667.48	4.25	+66	9	12	62	0.39
115.1	671.73	11.24	+79	6	23	34	1.6
126.1	733.70	9.38	+71	1	90	54	3.3
127.1C	743.09	0.36	+73		24		
127.2	743.45	7.28	+83	6	17	53	0.64
129.1C	750.73	0.23	+82		147		
129.2	750.90	14.15	+75	6	24	47	0.97
131.1	765.05	4.15	N		12	34	0.67
132.2	769.80	9.76	+68	7	52	79	1.4
133.1C	779.56	0.24	+64		122		
133.2	779.80	4.48	+70	3	56	41	2.6
134.1C	784.28	0.52	+79		18		
134.2	784.80	1.50	+76	2	28	41	1.3

Unit	Depth to Top, m	Thickness, m	Stable Paleomagnetic Inclination, deg $\bar{I}$	s.d.*	$\bar{J}_{NRM}$ x10^4 cgs	K x10^4 cgs	Q
		Extrusives (continued)					
135.1C	786.30	0.30	+36		218		
135.2	786.60	10.50	+60	4	64	55	2.2
136.1	797.10	8.60	+65	3	29	67	0.86
138.1	805.70	16.60	+72	9	11	78	0.25
141.2	823.78	4.72	+65	10	15	52	0.61
142.1C	828.50	0.23	+53		46		
142.2	828.73	8.06	N		11	45	0.49
143.1	836.79	3.41	+55	6	17	48	0.71
144.1	840.20	2.61	+62	2	18	49	0.70
144.2	842.81	6.09	N?		17	60	0.56
145.1	848.90	7.78	+62	0	32	56	1.2
147.1	856.68	3.92	+82	4	25	79	0.64
147.2	860.56	6.72	+78	5	17	67	0.51
148.2	867.50	2.23	+74	3	16	46	0.67
149.1	869.73	3.17	+69	4	36	41	1.6
149.2	872.90	8.22	+69	2	20	54	0.76
151.1	881.12	2.73	+78	4	12	33	0.75
151.2	883.85	8.32	+74	4	15	51	0.62
153.1	892.17	9.13	+70	7	23	73	0.65
154.1	901.30	6.50	+65	6	10	71	0.28
155.1C	907.80	0.87	+64		5.6		
155.2	908.67	5.23	+77	5	24	63	0.75
156.1C	913.90	0.98	+71		14		
157.2, 161.1	919.82	30.73	+70	8	9.3		
and 162.1	ignimbrite cooling unit						
163.1C	950.55	1.67	N		85		
163.2	952.22	0.70	+72	2	40	74	1.0
167.1C	975.53	1.10	+56		48		
167.2, 168.4	976.63	18.25	+63	5	52	36	3.4
and 169.4	probably one unit						
172.1	1005.35	17.25	+69	7	19	47	0.88
176.1	1029.40	7.46	+87	1	15	70	0.39
177.1, 178.2	1036.85	10.89	+74	4	17	49	1.2
and 178.4	probably one unit						
179.1	1048.48	7.62	+72	7	30	68	0.93
and 180.2	probably one unit						
183.1	1071.61	7.29	+70	8	21	39	1.1
and 184.2	probably one unit						
185.5	1082.97	11.49	+70	7	22	43	1.0
187.1	1094.46	1.06	+71	5	40	46	1.6
196.1	1146.73	4.47	+76	8	21	41	0.89
197.1	1151.20	5.70	+66	4	12	12	2.0
198.1	1156.90	7.96	+75	2	26	41	1.2
200.3, 200.5	1165.60	7.25	+68	3	62	58	2.1
200.7 and 200.9	probably one unit						
202.1C	1179.45	2.63	+80	8	62		
202.2	1182.08	11.15	+71	1	27	42	1.3
209.1	1220.33	7.52	+79	4	57	41	2.6
and 210.2	probably one unit						
211.1CA	1230.25	0.35	-52	12	44	21	4.7
211.1CB	1230.60	4.13	+68	9	1.1		
211.2	1234.73	6.57	+61	1	27	27	1.8
213.2, 213.4, 213.6	1241.50	14.27	+69	5	33	38	1.8
214.2 and 214.4	one unit cut by thin dikes						
219.1, 219.3, 219.5	1276.46	6.20	+80	3	60	56	2.3
219.7, 219.9, and 220.2	one unit cut by thin dikes						
220.7	1287.10	19.56	+71	1	23	39	1.2
224.2	1306.75	4.55	+62	6	20	38	0.96
225.1	1311.30	6.25	+68	8	24	33	1.5
228.1	1332.60	2.88	+69	5	25	20	2.7
229.1	1335.48	9.27	+70	1			
231.1C	1348.15	0.30	+80		1.4		
232.1	1348.45	3.29	+75	5	134	55	3.9
243.1	1419.52	10.28	+78	9	26	29	2.4
245.2	1429.95	6.00	+74	2	69	43	3.1
247.2	1442.00	3.80	+77	2	79	23	5.5
253.1	1475.50	11.50	M				
255.1	1487.00	11.00	-62	2	12	16	1.4
257.1C	1498.00	0.30	-49		12		

Unit	Depth to Top, m	Thickness, m	Stable Paleomagnetic Inclination, deg $\bar{I}$	s.d.*	$\bar{J}_{NRM}$ x10^4 cgs	K x10^4 cgs	Q
			Extrusives (continued)				
257.2	1498.30	8.62	-61	1	5.4	14	0.76
258.1	1506.92	3.27	-72	1	4.9	41	0.30
259.1	1510.19	16.11	-68	3	35	22	4.1
261.1	1526.30	8.55	N				
263.1C	1534.85	0.27	-76		0.49		
263.2	1535.12	10.56	M				
264.1	1545.68	10.27	-57	6	1.4	5.9	0.28
266.1	1555.95	4.45	M				
267.1	1560.40	3.38	-62	10	1.7	16	0.23
268.1	1563.78	13.31	R		15	17	1.8
270.1	1577.09	6.31	M				
271.2	1586.00	0.55	+78	1	15	12	2.4
274.6	1601.30	7.58	M				
275.1C	1608.88	0.97	+63		20		
275.2	1609.85	6.63	-68	12	4.8	43	0.37
276.1	1616.48	12.00	M				
278.0C	1628.68	0.10	+58		0.22		
278.1	1628.48	13.47	M		4.3	20	0.34
and 280.1	flow cut by thin dike						
281.1	1642.85	12.55	M				
284.2, 285.2,	1663.20	4.43	+73	6	73	69	2.4
285.4, and 285.6	probably one flow cut by thin dikes						
287.1	1677.33	0.43	+67	4	13	48	0.52
289.1	1691.58	3.62	-77	4	145	38	6.5
290.1	1695.20	1.30	-77	1	99	38	5.2
291.1	1702.10	4.58	+75	1	68	33	3.3
292.1	1706.68	3.00	+73	6	41	42	1.7
294.1	1720.36	0.92	+63	1	4.0	6.6	1.4
294.2	1721.28	13.50	+72	5	69	25	5.3
and 295.3	probably one flow						
296.3	1737.00	0.36	+76		122		
296.4	1737.36	4.73	+74	1	65	42	3.2
298.2	1748.68	5.08	M				
299.1	1753.76	3.56	+79	4	215	61	6.2
and 300.1	probably one unit						
300.2	1757.32	2.19	+80	6	228	48	7.9
300.3	1759.51	1.49	+82		395	95	8.0
303.1	1772.83	1.71	+80	3	66	38	2.8
303.2C	1774.54	0.51	+79		6.3		
303.3	1775.05	0.70	+74		28	62	0.88
304.1	1782.65	5.80	+76	2	27	27	2.0
315.1	1846.51	5.11	+77	1	93	50	3.8
316.1	1853.20	1.52	+88		12	3.4	6.6
317.1C	1854.72	1.49	+77				
317.2	1856.21	6.82	+77	3	34	24	2.7
and 318.1	probably one unit						
319.1	1869.23	7.67	+80	3	33	86	0.74
320.1	1876.90	4.80	M				
321.1	1881.70	1.25	R		7.4	95	0.16
321.2	1882.95	7.74	M		72	85	0.48
323.1	1890.69	9.80	-69	7	8.2	48	0.38
324.1	1900.49	10.04	-70	2	8.4	24	0.70
326.2	1910.62	7.90	M				
327.1C	1918.52	0.33	-77		33		
327.2	1918.85	>0.88	-49		9.3	9.2	1.9
			Dikes				
1.1	11.70	14.47	+78	5	76	38	4.0
5.2	39.37	1.63	+81	4	77	70	2.3
10.1	63.14	40.27	+77	1	37	34	2.2
17.1	103.41	68.88	+69	3	31	19	3.3
33.2	200.83	6.50	+71	4	51	36	29
49.1	291.32	13.66	+73	2	26	23	24
61.2	364.30	17.10	+76	5	54	54	2.0
70.1	409.60	4.80	+77	1	44	58	1.6
72.6	422.05	3.85	+76	3	110	72	2.9
87.2	508.80	0.85	+64	18	18		
87.4	511.25	16.25	N				
90.1	527.50	1.0	N				

Unit	Depth to Top, m	Thickness, m	Stable Paleomagnetic Inclination, deg $\bar{I}$	s.d.*	$\bar{J}_{NRM}$ x10^4 cgs	K x10^4 cgs	Q
			Dikes (continued)				
90.2	528.50	0.58	+63	16	46		
90.4	529.45	3.10	N				
91.2	533.58	7.82	N		61	76	1.5
92 1	541.40	8.60	+73	1	46	18	5.1
94.2	548.70	37.10	+71	2	43	77	1.1
103.2	603.23	25.60	+74	9	28	74	0.71
108.3	633.24	2.86	+74	9	78	31	4.9
109.2	636.60	2.38	+71	2	58	26	4.4
110.1	638.98	3.58	R or I		13	62	0.90
110.2	642.56	7.82	+77	3	45	11	7.7
111.1	650.38	2.32	no stable direction		12	39	0.68
117.2	684.56	0.69	+78	6	89	43	4.4
117.4	685.50	8.62					
119.2	694.50	32.88	+78	2	63	64	2.2
124.1	726.88	6.62	+79	8	66	83	1.5
157.1	914.88	4.94	+62	13	19	41	0.91
163.3	952.92	22.61	N		11	29	0.85
168.1	981.66	0.90	+56	23	11	60	0.34
168.3	982.81	0.59	+65	28	16	57	0.54
169.1	988.14	0.68	+63	3	39	56	1.4
170.1	992.03	13.32	+75	3	15	25	1.2
178.3	1043.04	0.76	+67	1	10	59	0.33
181.1	1056.54	15.08	+72	3	40	78	1.0
184.1	1077.72	0.44	+86	2	20	74	0.57
185.4	1080.23	2.74	+74	2	30	98	0.44
188.1	1096.90	49.83	+66	4	33	51	1.3
200.8	1169.80	0.30	+80	2	140	59	4.5
201.4	1173.87	0.63	-72	4	13	20	1.8
201.6	1174.78	4.67	+80	2	32	66	0.97
204.1	1193.23	27.09	+76	4	35	69	0.99
210.1	1225.80	2.40	+81	3	49	60	1.6
213.3	1242.02	0.20	+73	3	45	99	0.88
215.1	1256.92	20.18	+73	3	45	46	2.0
231.3	1351.74	6.05	+70	10	24	75	0.68
234.3	1366.05	53.47	+70	3	38	27	2.9
246.1	1435.95	5.88	+81	5	44	69	1.3
248.1	1445.80	29.70	+74	4	37	40	2.1
271.1	1583.40	2.60	+71	3	15	12	2.4
271.3	1586.55	14.10	+74	6	42	86	1.1
279.1	1634.80	0.90	+72	3	89	99	1.7
283.1	1655.40	6.85	+81	3	36	43	2.0
284.1	1662.25	0.95	+73	1	61	56	2.1
285.1	1665.50	0.18	+75		62	56	2.2
285.7	1668.12	9.13	+79		52	59	1.7
287.2	1677.76	13.82	+77	9	47	52	1.8
290.2	1696.50	1.50	-78	1	18	66	0.55
290.3	1698.00	4.10	-73	2	8	15	0.86
292.2	1709.68	10.68	+66		16	27	1.1
295.1	1727.08	0.35	-80	2	20	25	1.6
295.2	1727.43	0.67	-76		28	31	1.8
296.1	1735.80	0.90	+81	1	35	68	1.0
297.1	1742.09	4.31	+80	6	79	36	4.4
298.1	1747.40	1.28	+81	2	29	110	0.54
300.4	1761.00	11.83	+82	6	49	83	1.4
303.4	1775.75	6.90	+78	4	38	79	0.93
305.1	1788.45	50.08	+80	6	57	54	2.1
314.1	1838.53	1.17	+75	1	70	46	3.0
314.2	1839.70	1.72	+75	4	31	60	1.0
314.3	1840.42	5.09	+77	11	40	100	0.71
317.3	1859.35	0.80	+85	3	31	100	0.58
318.2	1863.83	5.40	+74	9	59	75	1.5

*Absence of a value for standard deviation indicates only one sample.

R and N; definite reverse and normal direction of magnetization respectively, but individual sample directions too scattered to justify averaging. M; units with mixed polarity containing both upward and steeply downward inclined stable remanence directions.

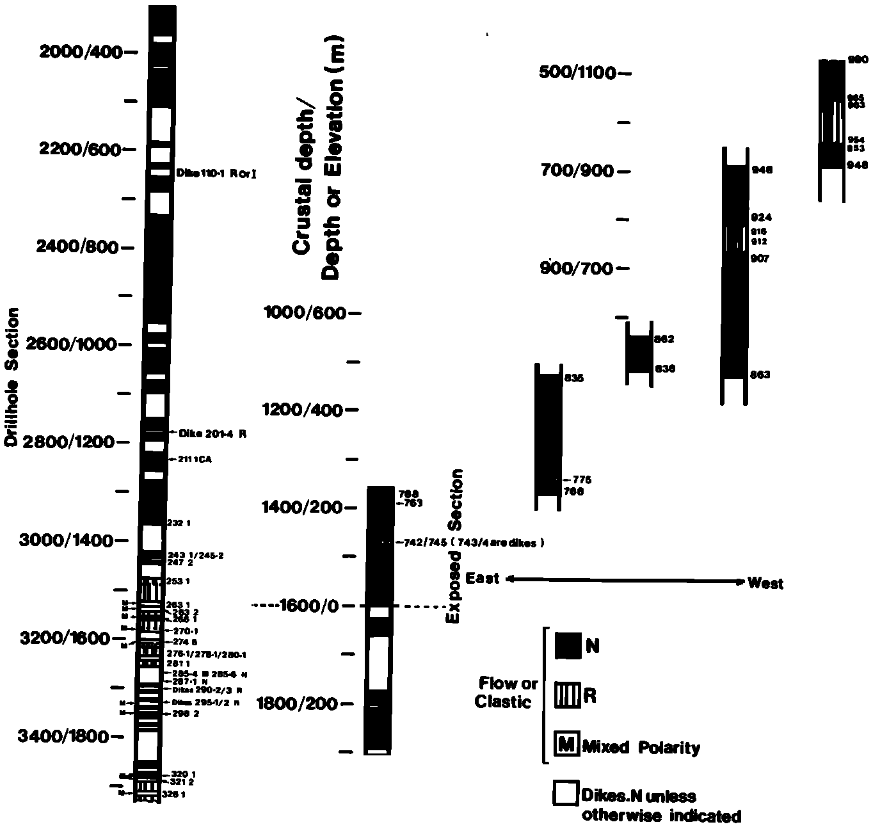

Fig. 2. Polarity profile for the Iceland Research Drilling Project crustal section. Both crustal depths and depths with respect to the drill collar are given. Numbers at the right hand side of the profile are lithologic unit numbers (P. T. Robinson and H.-U. Schmincke, unpublished core summaries, 1979).

THE AGE OF THE CRUSTAL SECTION AND REMAGNETIZATION

These two important topics are considered together, as they are clearly related where the lower part of the section is concerned.

If original magnetic directions are preserved and the eruptive rate was sufficiently high, the age of the section can be obtained by comparison of the polarity sequence with the geomagnetic reversal record. From previous work it was anticipated that extrusives magnetized during the long duration normal anomaly 5 of the seafloor spreading sequence would be present in the crustal section [*Watkins and Walker*, 1977, Figure 2]. The occurrence of an almost entirely normally magnetized interval of over 2-km vertical extent bears out this expectation and indicates an age within the 8- to 11-m.y. period for the section. It will be valuable if the section can be dated more precisely using this approach, and the following well known points on the geomagnetic reversal record can be sought in order to do this: (1) the termination of anomaly 5, (2) the onset of anomaly 5, (3) short reverse events within anomaly 5, and (4) reversals within anomaly 4 and preceding anomaly 5 proper (e.g., 5′ and 5A of *Ness et al.*[1980]).

The termination of anomaly 5. This appears to lie high in the exposed part of the IRDP section. At these shallow crustal levels, limited hydrothermal alteration and high within-unit consistency of stable directions suggest that original cooling polarities are preserved. Two short intervals of reverse polarity occur between 550 and 855 m. The upper at 550-640 m is well defined by 10 successive flows. The lower at 810-855 m is represented by two flows in an area of low sampling density. This interval is probably at least five and may be as many as 16 successive flows in extent. Since the lower of these two reverse intervals has the potential of representing a longer period of time than the events within anomaly 5, the termination of anomaly 5 is provisionally placed at 865 ±15 m crustal depth.

The onset of anomaly 5. Significant sequences of reverse polarity do not occur in the lower part of the exposed section or the upper part of the drill core section, although the possibility that such a section has been cut out by dikes cannot be excluded. Reversely magnetized flows and clastics appear frequently below 3075 m depth. Location of the onset of anomaly 5 is complicated both by the presence of long sections of dikes close to this depth and by the presence of mixed polarity units below 3075 m. The presence of the dikes leads to an uncertainty of 30 m in the location of the onset of reverse polarity flows: these may occur at depths as shallow as 3045 m and certainly do occur below 3075 m. The implication of the presence of mixed polarity flows is more difficult to quantify. The most obvious interpretation of the mixed polarity state is that magnetic overprinting has taken place locally. It is easy to recognize this effect and to allow for it where overprinting is incomplete. If, however, overprinting is complete, a resulting well-defined stable direction might be taken as an original direction. Since overprinting is sometimes associated with the presence of dikes, it may be responsible for the normal polarity of the flows (232.1, 243.1, 245.2, and 247.2) preserved as fragments within the extensive series of dikes directly above

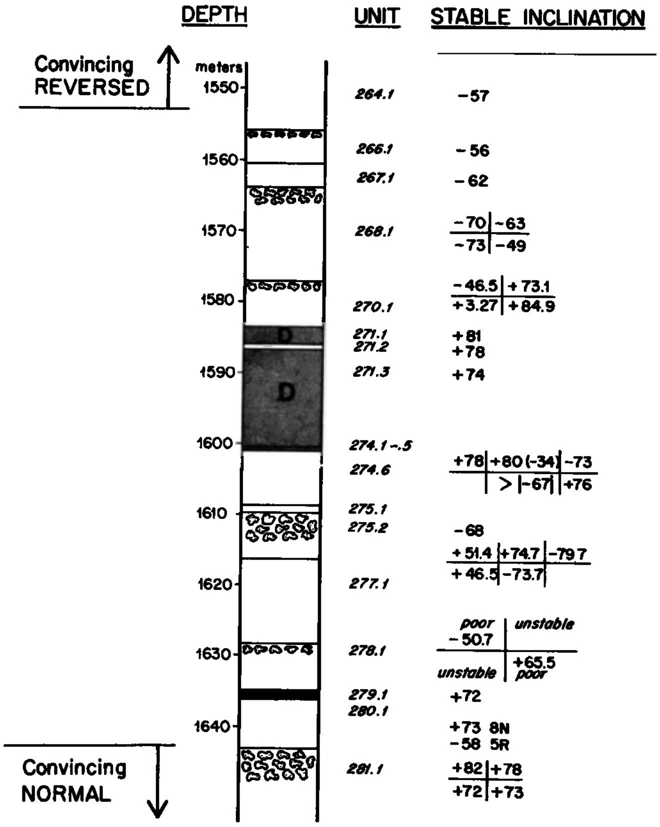

Fig. 3. Detail of paleomagnetic record in the 3150- to 3250-m crustal depth interval (1150- to 1650-m depth in drill hole section) showing dikes (gray, D) and flows with brecciated tops indicated. Average stable paleomagnetic inclinations are shown when well defined. Where mixed polarity flows occur, individual sample stable incinations are given.

3075 m. However, the absence of any indication of mixed polarities in the long series of flows from 2887 to 2952 m together with the clearcut thin reversely magnetized clastic 211.1CA at 2830 m suggest that complete overprinting of originally reversely magnetized flows has not taken place above 2952 m.

Provisisionally, we locate the onset of anomaly 5 between the last appearance of definite normal polarity flows at 2952 m and the first appearance of reverse and mixed polarity flows at 3075 m, i.e. at a depth of 3010 ± 60 m where the uncertainty describes the range of possible depths.

Short reverse events within anomaly 5. All recent compilations of the geomagnetic reversal record show a number of short reverse events within anomaly 5 [*Blakely*,1974; *LaBreque et al.*, 1977; *Ness et al.*, 1980]. Short reverse events are also recorded in sequences of anomaly 5 age elsewhere in Iceland [*Watkins and Walker*, 1977; *Saemundsson et al.*, 1980]. At least four such events are recorded in the IRDP section and others may have been cut out by dikes (Figure 2). Three of these are close together in the 1340- to 1470 m interval. In this interval, two cases of an isolated flow of reverse polarity occur (763 and 775), while a clearly reverse flow is underlain by a flow that is either reverse or intermediate in direction (745, 742) in the third case. No sequence of three closely spaced reverse polarity events is reported from reversal records based on oceanic linear anomaly patterns. However, the relatively long reverse event indicated as separating 5.1 and 5.2 may be a smoothed representation of separate but closely spaced events. Elsewhere in Iceland the upper part of anomaly 5 recorded in the J (Melrakannes) section of *Watkins and Walker* [1977], contains two nearby flows with intermediate directions and the northern Iceland section of *Saemundsson et al.* [1980] contains two nearby short sequences of reverse flows. It is possible that flows 742, 745, 763, and 775 of the IRDP section represents this youngest series of events within anomaly 5, but identification must remain very tentative since all the Icelandic sections record only two events, with the upper probably split, while the geomagnetic record based on oceanic linear magnetic anomaly patterns indicates the presence of four events. A similar ambiguity faces attempts to correlate the reverse event clearly recorded in the upper part of clastic 211.1 (211.1CA) at 2830-m crustal depth. This may be correlative with the event separating 5.4 and 5.5 and the lower event of the other Icelandic sections. None of these correlations are convincing, and it is desirable to formulate an independent approach to the problem, such as described in the following section, before firm correlation is attempted.

Reversals within anomaly 4 and preceding anomaly 5. The IRDP polarity sequence above the level selected as marking the termination of anomaly 5 contains more normal than reverse polarity units and in this respect does not resemble the lower part of the reverse interval that separates anomalies 4 and 5 of the seafloor spreading sequence. For this reason it is advisable to defer an attempt at correlation until other evidence for the age of the upper part of IRDP sequence is described.

A different difficulty faces attempts at correlation in the drillhole sequence below the base of anomaly 5. This is the strong evidence that directional remagnetization has taken place locally, requiring a method of distinguishing original from remagnetization polarities, especially where normally magnetized flows occur in zones containing many normally magnetized dikes. Oxide petrography and rock magnetism can be expected to aid here but in the interim a novel means of separating original and remagnetization polarities can be tested.

Palmason [1980] has modeled crustal construction in eastern Iceland. His model relates the regional tilt of the lava pile with the lava deposition rate (LDR) during crustal

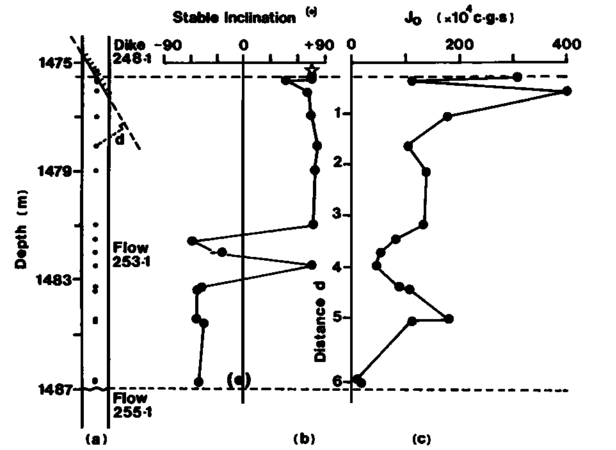

Fig. 4. Internal variation of magnetic properties for mixed polarity flow 253.1 in contact with normal polarity dike 248.1. Inclination of dike contact in Figure 4*a* is measured in the drill core.

formation through the half spreading rate for the area and time. Thus, at distance from the spreading axis,

$$-\left(\frac{dz}{dt}\right)_x \Big/ \left(\frac{dz}{dx}\right)_t = \left(\frac{dx}{dt}\right)_z \qquad (1)$$

where z is vertical distance, x distance from the spreading axis, and t time, or lava deposition rate/lava dip = spreading half rate [*Palmason,* 1980, equation 14). Numerical values for lava dip in the IRDP crustal section are given by *Hall et al.* [this issue], and a spreading half rate of 0.88 cm yr^{-1} for the Reydarfjordur area at 10 m.y. age is obtained from radiometric ages and lava dip measurements [*Hall et al.* this issue, Figure 13]. The term representing lava deposition rate in (1) can be integrated to give either time of accumulation for a particular depth interval:

$$t_{z_1 - z_2} = \int_{z_1}^{z_2} \left(\frac{dt}{dz}\right) dz \qquad (2)$$

or depth interval for a particular time interval:

$$z_{t_1 - t_2} = \int_{t_1}^{t_2} \left(\frac{dz}{dt}\right) dt \qquad (3)$$

Both of these integrations have been carried out numerically for the IRDP crustal section. A first result of the integration in

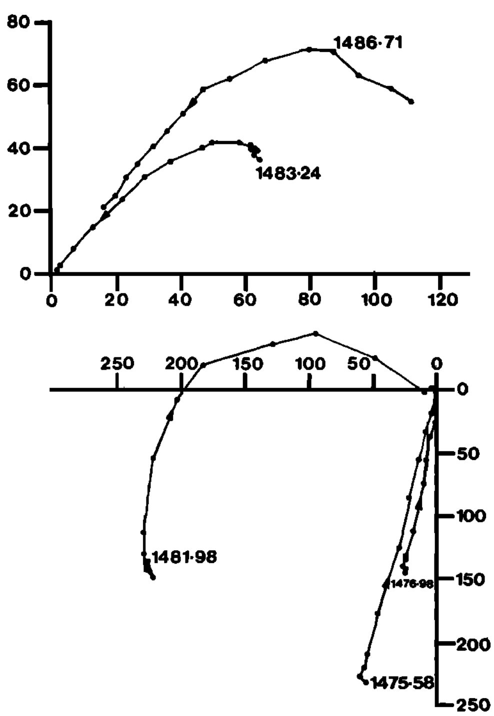

Fig. 5. Alternating field demagnetization behavior of samples from mixed polarity flow 253.1. Plots are of dominant horizontal and vertical components. Units are 10^{-4} emu cm^{-3} Points represent successive demagnetization steps. Samples are identified by depth below drill collar. Note that values for sample at 1481.98 have been reduced by a factor of 2 in order to plot on the same diagram as 1475.58 and 1476.98.

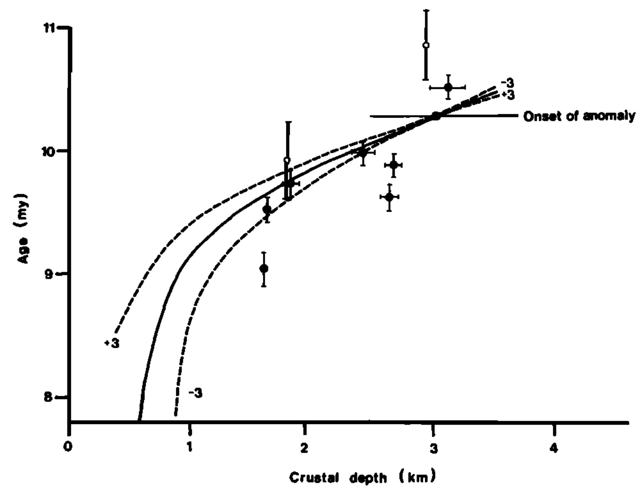

Fig. 6. Age calibration of the Iceland Research Drilling Project crustal section based on variation of regional dip with depth and identification of age at one depth: the onset of seafloor spreading anomaly 5, age 10.30 m.y., depth 3.01 km. Broken curves are for ±3° uncertainties in the regional dip. Solid circles are radiometric ages [*McDougall et al.,* 1976] for units in the Reydarfjordur area that are correlative with units in the IRDP section. Open circles are ages from flows in the drill core [*Albertsson et al.,* this issue]. Vertical error bars are of analytical origin, horizontal error bars represent the uncertainty in correlations.

(2) above is that the 1920 m drill hole part of the section represents a rather shorter time interval, about 0.85 x 10^6 years, than the several million years apparently represented in the exposed section. It will be more useful if absolute age rather than elapsed time can be estimated by this method, and this is possible if the absolute age is known for one point in the section, preferably at depth where LDR was high and a complete reversal record is likely to be present (Figure 6). The onset of anomaly 5 at 3010 ± 60 m, well dated at 10.30 m.y. (*Ness et al.* [1980] and others) satisfies these requirements. The method can be tested by comparing the predicted and observed vertical extent of anomaly 5 in the section. The predicted thickness of anomaly 5 extrusives is 2135 (+245, -185) m (crustal depth interval for absolute age interval 8.98 to 10.30 m.y.), while the observed thickness is 2145 ± 75 m (Figure 2). The uncertainty in the predicted value represents an uncertainty of ±3° in lava dip values, this being a combination of scatter in measured dips and a representative value for the component of original (nontectonic) dip in the direction of the regional dip. This is considered to be sufficiently close agreement to warrant further application of the method. Radioactive ages either for flows from the drill core [*Albertsson et al.,* this issue] or projected into the drill core section from exposed, updip sections [*McDougall et al.,* 1976] follow the trend of age profile of Figure 6 but are scattered beyond the ±3° limits.

Comparison of the predicted and observed magnetostratigraphy of the IRDP section can be attempted using the integration in (3) above (Figure 7). The good agreement for the anomaly 5 interval is apparent, and guidance is obtained in the identification of polarity intervals in other parts of the exposed section. Normal polarity interval 5′ matches the upper part of the normal sequence between 3305 and 3480 m level in the IRDP section. The extension of normal magnetization in the IRDP section below 3400 m is not predicted, and since several thick normally magnetized dikes

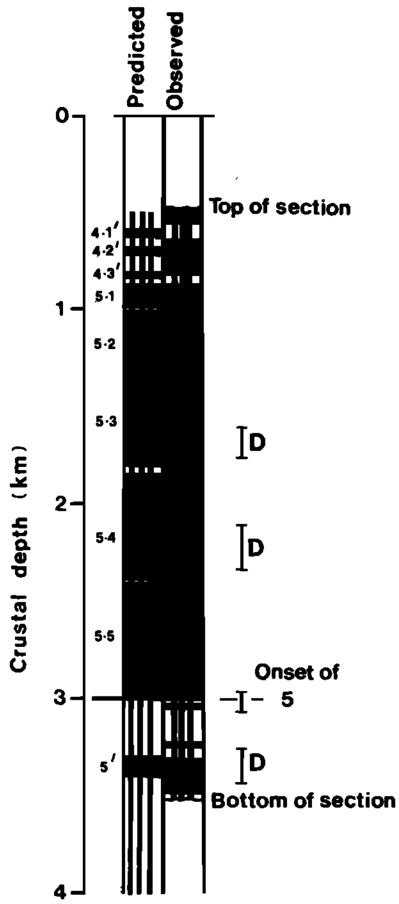

Fig. 7. Predicted and observed polarity profiles for the Iceland Research Drilling Project crustal section. Vertical bars on the left of the figure indicate zones of high dike density in the drill core part of the section.

occur in the 3390 to 3450 m interval, the extrusives in this interval may have been completely remagnetized. A consequence of the high LDR values at the base of the section is that short polarity intervals such as 5', of 0.05 m.y. duration, are represented by thick sequences of lavas. In contrast, at the top of the section, low LDR values result in a compressed polarity record, and if eruptive activity was episodic, some polarity epochs may be unrepresented. For this reason, no correlation with the reversal record above the termination of anomaly 5 is attempted. Further review of the events within anomaly 5 can now be made. The observed reversal at 2830 m depth does not correspond to the level of any predicted event and therefore may not have been recognized in marine magnetic anomaly sequences. The events separating 5.5 and 5.4 and 5.4 and 5.3 are predicted to occur close to intervals of high dike density and may have been cut out by dikes. In contrast with an earlier suggestion, the event separating 5.3 and 5.2 may be identified with the three reverse intervals between 1340 and 1470 m and an age of 9.47 to 9.48 m.y. assigned to this interval. The event separating 5.2 and 5.1 is not seen in the IRDP section.

VARIATION OF NATURAL MAGNETIZATION WITH CRUSTAL DEPTH

Data Reduction. The practical problem is to isolate depth variations of magnetization of an appropriate scale from the many spatial variations that occur. These include within-unit-variations, between-unit variations, variations between groups of units, variations between extrusives and intrusives, variations between the products of volcanic centers and those from fissure eruptions, and variation between material from the different polarity zones and between the exposed and drill core sections. The scales involved range from centimeters or less for within-unit variation to hundreds of meters for certain sequences of units and to kilometers for the exposed and drill core sections. It may not be obvious that differences are to be expected between the exposed and drill core sections since the drill site was not located at an obvious break in the geology of the section. Two differences that are likely to occur, however, are in the relative freshness and the recovery of flow tops in the drill core section.

The sampling and averaging problem was approached as follows. Four subsamples were taken from the more massive parts of cooling units of more than a few tens of centimeters thickness. In addition, for the drillcore section, samples were taken from brecciated flow tops and from the fine grained margins of dikes.

Within-unit average natural remanence and susceptibility were first computed. For the flows in the drill core, values weighted to allow for the relative thicknesses and different magnetic properties of brecciated flow tops and massive interiors were also obtained. At this point ratios of flow top versus interior, and of dike chilled margin versus interior values, were computed for these properties. Large differences between within-unit average values, against which it was difficult to see overall depth trends in properties, were apparent at this stage. Average values with standard errors for 100-m depth intervals were then computed (Figures 8*a* and 8*c*). For the drill core section these were weighted for the relative thicknesses of flow and dike material in each 100-m interval, but in the absence of thickness data this could not be done for the exposed section. Variability of up to a factor of 6 with a length scale of several hundred meters is present in these profiles. Since this scale is comparable with the scale of occurrence of groups of dikes (Figure 8*b*), this level of averaging will be useful in searching for relationships between flow magnetization and dike proximity.

The final stage in averaging was to compute values with standard errors for the massive interiors of units for 500-m intervals (Table 2 and Figure 9). Averages were obtained by weighting contributions from 100-m intervals. This was done on the basis of thicknesses of flow and dike material in each 100-m interval in the drill hole section and relative numbers of flows and dikes in each 100-m interval in the exposed section. For the drill core section 500-m flow averages with appropriate weighting for brecciated flow top contributions were also obtained (Table 2 only).

Results. No depth trend in 500-m average values of natural remanence occurs for either flows or dikes ($\bar{J}_{om}$ columns of Table 2). The one value that stands out, for the 340- to 600-m interval in the dike profile, is based on data from only two units and may not be representative. It is notable that the average natural remanence of flow interiors at 33.1 ± 2.6 x 10^{-4} emu cm^{-3} (simple average of 500-m interval values ± 1 s.e.), is clearly less than the dike remanence at 51.8 ± 22.2 x 10^{-4} or 43.6 ± 2.1 x 10^{-4} if the atypically high value for the 340- to 600-m interval value is omitted. This result is evident in Figure 10, where the flow value exceeds the dike value only in the 1600- to 2100-m interval. This relationship is

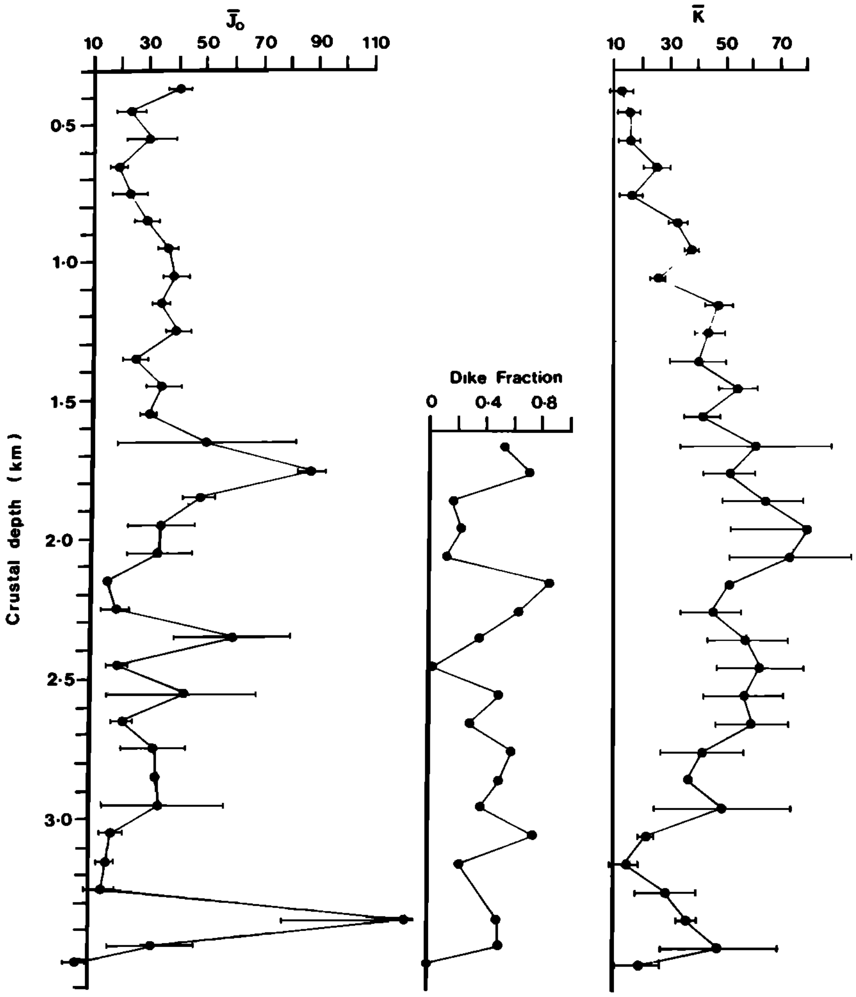

Fig. 8. Weighted average values of natural remanence and initial susceptibility for 100-m depth intervals (8*a* and 8*c*) for the Iceland Research Drilling Project crustal section, together with fraction of dike material in intervals for the drill hole part of the section (8*b*). Uncertainties shown are ± 1 standard error.

maintained even if the higher flow values obtained by weighting the contributions of brecciated flow tops are considered (J_0 of Table 2).

Initial susceptibility ($\bar{K}_{om}$ of Table 2) shows clear and distinctly different depth variations for flows and dikes. The flow variation shows a significant strongly linear increase (r = 0.998) from the top of the section to the 1600- to 2100-m interval, followed by a significant strongly linear (r = 0.990) decrease to the bottom of the sction. The linear expression for decrease in flow susceptibility in the deeper part of the section can be extrapolated to give a zero value at approximately 4300 m beneath the original lava surface or 2700 m below sea level. Allowance for the general difference between the susceptibility of flow brecciated tops and massive interiors leads to insignificant change in the character of the decrease with depth in the drill hole section (r = 0.984; depth for zero susceptibility, 4400 m). In contrast, dike susceptibility shows a weakly defined (r = 0.914) continuous increase with depth from the top of the section.

As a consequence of the lack of depth variation in remanence, weakly defined variation in Q ratio (ratio of remanent to induced magnetization) mirrors the variation in initial susceptibility. For the flows, Q falls from a value of close to 4 at the top of the section to a minimum of almost exactly unity in the 2100- to 2600-m interval and then increases to a value close to 2.5 at the bottom of the section. If the doubtfully representative value for the topmost interval of the dike profile is neglected, Q shows no significant variation with depth.

Before discussing possible explanations for the trends described above it will be useful to consider the net in situ magnetization of the IRDP profile (Table 3). Net magnetization for each 500-m interval is defined as

$$\frac{h_1[\bar{J}_{om} + \bar{K}_{om}F]_{\text{FLOWS}} + h_2[\bar{J}_{om} + \bar{K}_{om}F]_{\text{DIKES}}}{h_1 + h_2}$$

where $\bar{J}_{om}$, $\bar{K}_{om}$ are listed in Table 2, F is the local ambient field (0.52 G), and h_1 and h_2 are either the numbers (in the exposed section) or the net thicknesses (in the drill core section) of flows and dikes sampled in each 500-m interval. Note that the sign of $\bar{J}_{om}$ for the flows and dikes in an interval will depend on the relative abundances or thicknesses of each polarity in the interval. Table 3 shows that all intervals have in situ magnetization in the same sense as the present (normal) geomagnetic field in the area and that no overall depth trend exists. The intensity of net magnetization ranges from +27 to

TABLE 2. Weighted Average Natural Magnetic Properties for 500-m-Depth Intervals in the IRDP Crustal Section

Interval		Flows							Dikes			
Approximate Original Crustal Depth, m	With Respect to Present Sea Level, m	Number of Units	$\bar{J}_{om}$ (1 s.e.)	$\bar{J}_o$ (1 s.e.)	$\bar{K}_{om}$ (1 s.e.)	$\bar{K}_o$ (1 s.e.)	$\bar{Q}_{om}$ (1 s.e.)	$\bar{Q}_o$ (1 s.e.)	Number of Units	$\bar{J}_{om}$ (1 s.e.)	$\bar{K}_{om}$ (1 s.e.)	$\bar{Q}_{om}$ (1 s.e.)
+340 to +600	-1000 to -1260*	24	28.7 (4.0)		15.0 (2.3)		3.68 (+1.27, -0.93)		2	101.0 (12.4)	2.4 (0.7)	80.9 (+47.4, -25.9)
+600 to +1100	-500 to -1000	53	33.1 (2.3)		30.1 (1.7)		2.11 (+0.29, -0.25)		4	43.2 (19.4)	28.4 (7.1)	2.93 (+2.72, -1.64)
+1100 to +1600	0 to -500	57	33.1 (2.9)		45.5 (2.9)		1.40 (+0.18, -0.16)		34	48.3 (18.8)	39.7 (2.9)	2.34 (+0.64, -0.56)
+1600 to +2100	0 to +500	29	48.0 (6.7)	50.4 (6.5)	66.7 (9.6)	55.6 (8.3)	1.38 (+0.47, -0.34)	1.74 (+0.57, -0.42)	9	41.6 (12.0)	31.4 (8.5)	2.55 (+1.95, -1.12)
+2100 to +2600	+500 to +1000	32	28.2 (5.7)	32.7 (4.8)	58.3 (9.6)	48.4 (6.7)	0.93 (+0.41, -0.29)	1.30 (+0.53, -0.33)	20	40.1 (12.3)	47.3 (15.2)	1.67 (+1.51, -0.97)
+2600 to +3100	+1000 to +1500	23	27.8 (5.3)	36.8 (9.8)	41.5 (6.2)	43.7 (7.2)	1.29 (+0.51, -0.38)	1.62 (+0.84, -0.60)	17	36.9 (11.8)	49.3 (14.1)	1.44 (+1.56, -0.68)
+3100 to +3420	+1500 to +1920	40	32.6 (7.2)	31.4 (11.5)	26.3 (4.3)	22.8 (5.7)	2.38 (+1.10, -0.78)	2.65 (+2.17, -1.31)	24	51.2 (19.9)	64.3 (20.0)	1.52 (+1.56, -0.82)

* Negative values are above sea level. Zero is present sea level.
Standard error = s.e..

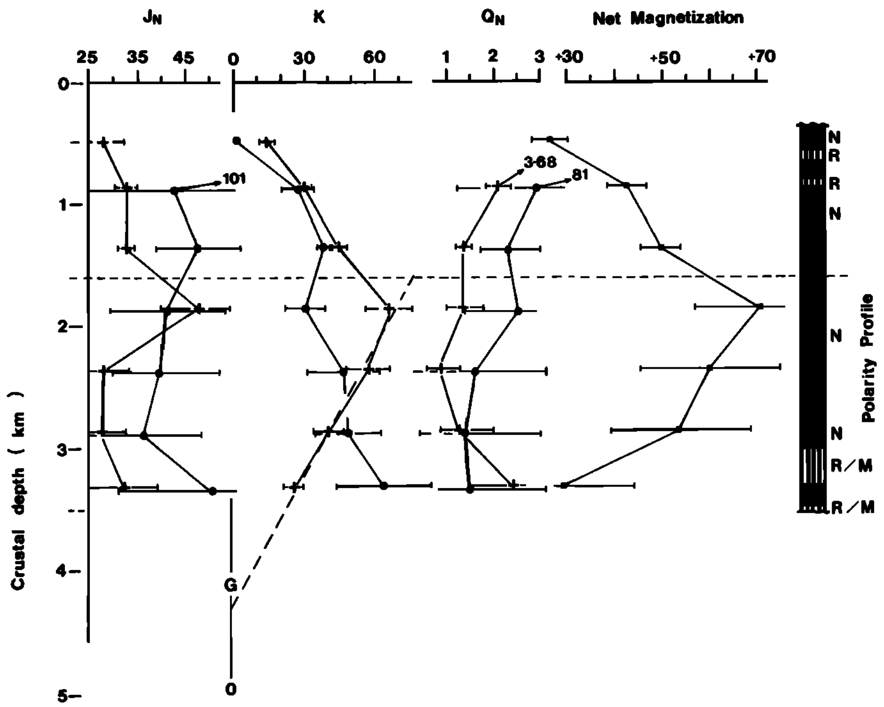

Fig. 9. Variation with depth of natural remanence J_n, initial susceptibility k, Konigsberger ratio Q_n, and net magnetization (remanence and induced magnetization) for the Iceland Research Drilling Project crustal section expressed as weighted averages for 500-m depth intervals: pluses, flow values; dots, dike values. G indicates estimated depth of onset of greenschist facies metamorphic conditions. Horizontal broken line is level of drill collar. Inclined dashed line is the regression line for the four deeper flow susceptibility values.

+71 x 10^{-4} emu cm^{-3} (+2.7 to 7.1 A m^{-1}) Incorporation of viscous magnetization would increase these values in the positive sense. Relatively low values occur where significant sections of reversely magnetized flows occur and relatively high values occur where both flows and dikes are of normal polarity. As a consequence of the high lava deposition rate at the base of the section, low net magnetization values are predicted to occur to at least 4-km crustal depth in the expanded reversely magnetized flow sequence accumulated between anomalies 5.5 and 5′ (Figure 7).

No explanation is given for the increase in susceptibility from the top of the section to about 2-km crustal depth. Primary composition does not show matching variation [*Flower et al.*, this issue]. *Mehegan et al.* [this issue] describe a general increase of zeolite facies alteration with depth in the section, and it is known that natural remanence, which may vary sympathetically with susceptibility, shows a relationship with degree of alteration elsewhere in eastern Iceland [*Wood and Gibson*, 1976]. The sense of the relationship is a decrease in remanence with increased alteration. It is also known that incipient low temperature alteration, marked by the cracking of titanomagnetite grains, results in susceptibility decrease in submarine basalts [*Ryall et al.*, 1977] and similar cracking occurs in the magnetites below about 1-km crustal depth in the IRDP section. Neither of these circumstances is exactly comparable with the situation in the upper part of the IRDP section where susceptibility in subaerial lavas that are altered up to laumontite zone conditions in the zeolite facies is being considered. Explanation of the observed increase with depth for this interval in terms of either primary or secondary effects is still possible and will be attempted after the completion of rock magnetic and opaque mineralogical studies.

The general decrease of susceptibility from below 2-km crustal depth is well defined in the 500-m average values and is also clearly seen in a set of 6135 hand-held susceptibility meter measurements made at 30- to 35-cm intervals along the length of the drill core [*Schonharting and Hall*, this issue]. Secondary alteration continues to increase with depth over this interval [*Mehegan et al.* this issue] with corresponding decomposition of primary oxide minerals (our own observations and *Schonarting and Ghisler* [this issue]), and it is reasonable to account for decrease in susceptibility by these secondary alteration processes. As noted above, extrapolation of the 500-m average values indicates that lava susceptibility should reach zero value at about 4.3-km crustal depth. This is close to the level at which the onset of greenschist facies metamorphism is expected to occur [*Robinson et al.*, this issue]. This result is consistent with reports of iron oxide-free greenschist metabasalts with negligible magnetization [*Fox and Opdyke*, 1973; *Jamieson*, 1979].

Another effect of increased alteration with depth in the deeper part of the section is the change in the ratio of brecciated flow top to massive interior magnetic properties; the former showing more rapid response to alteration through relatively high porosity and permeability (Figure 10 shows this effect for flow susceptibility). At the top of the drill core section, brecciated flow tops clearly have distinctly higher remanence intensity and slightly lower susceptibility than massive interiors. This is consistent with a smaller effective oxide grain size in the rapidly cooled, more oxidized flow tops. With increasing depth there is a continuous change in these relationships such that in the 3100- to 3250-m interval both remanence and susceptibility are very much lower in flow tops than in interiors. The explanation in terms of effective grain

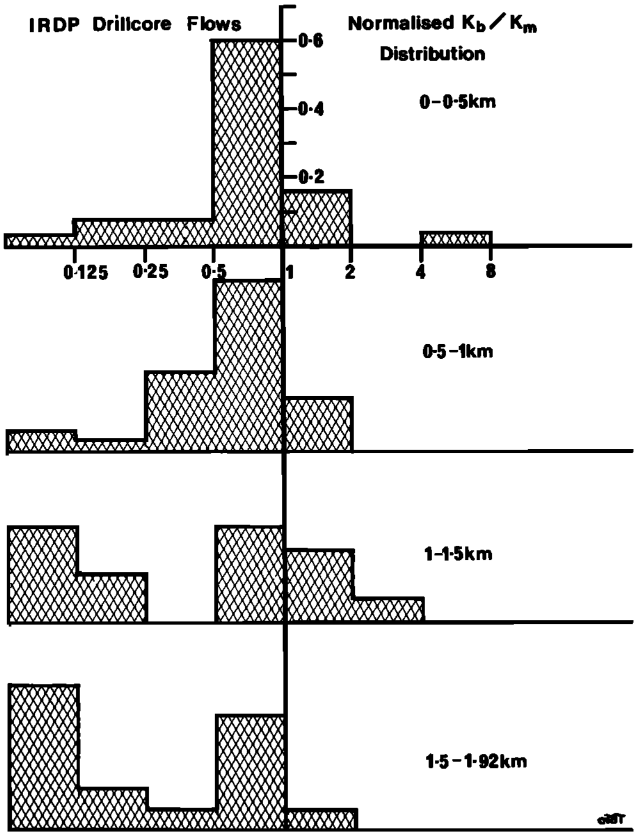

Fig. 10. Variation of the distribution of the ratio of flow top breccia and flow massive interior susceptibility for 500 m depth intervals in the drill core part of the Iceland Research Drilling Project crustal section.

size must be treated with caution at this stage since a comparison of fine-grained dike contacts and massive interiors does not show corresponding remanence and susceptibility relationships. Again, the fitting of separate regression lines to susceptibility for flow tops and interiors shows a more rapid decrease with depth for the latter.

With the broad trend in susceptibility below 2-km depth explained, it will be valuable to examine shorter wavelength variations as seen in the profile for 100-m intervals (Figure 8). The interval from 3300 to 3500 m in which both remanence and susceptibility show strong peaks, is of particular interest. Mismatch of the predicted and observed polarity profiles has already led to the suggestion that remagnetization has taken place over the 3390- to 3450-m interval. Examination of polished sections of flows from this interval suggests an explanation for the high magnetic property values. This is the abundance of secondary magnetite, which at some levels, (for examples, 3298, 3309, 3357, 3360, 3476-3481 m) is either the dominant or the only type of magnetite present. As a working hypothesis, it is proposed that sufficient secondary oxide has been produced through dense dike injection to dominate the remanence and susceptibility of flows in the 3390- to 3450-m interval. The polarity of this secondary magnetite presumably matches the normal polarity of the intruding dikes, and here we have an example of polarity determined by additional magnetization rather than thermal remagnetization in the conventional sense. A similar relationship between high dike density, enhanced remanence, the production of abundant secondary magnetite in epidote bearing lavas, and directional remagnetization has been reported for the Bermuda Seamount by *Rice et al.* [1980].

Application of this model elsewhere in the section suggests that mixed polarity flows are explained by local variation in the ratio of normally magnetized secondary oxides and relic reversely magnetized primary oxides. The model can also be used to test the time of imposition of the polarity of the fragments of normally magnetized flows in the 2958- to 3046-m interval. Doubts about the originality of these polarities led to the designation of a broad uncertainty for the level of onset of anomaly 5 in the section. Figure 8 shows relatively high susceptibility and remanence for flows in this interval but the peaks are not nearly so pronounced as they are between 3300 and 3500 m. Secondary magnetite is reported as occurring at 2630 and 3047 m, close to the limits of this interval. While the evidence for remagnetization of these flows is not so strong as it is for the deeper section, the evidence does appear to justify the caution taken over the question of the time of their magnetization.

DISCUSSION AND CONCLUSIONS

The results of this study bear on three main areas of Icelandic and oceanic geology: crustal formation in a spreading environment, the permanence of directions of magnetization acquired during initial cooling by small volcanic units, and

TABLE 3. Net Magnetization of Crustal Section

Interval	Net Magnetization ± 1 s.e.*, x10^4 emu cm^{-3}	Comments
340 to 600	+27.3±3.8	assumed 13 reversed flows in total of 48 flows in interval
600 to 1100	+43.3±4.1	allowance made for 11 reversed flows in 111 flows in interval
1100 to 1600	+50.4±4.3	allowance made for 4 reverse flows in 57 flows and 8 reverse dikes in 36 dikes in interval
1600 to 2100	+71.3±13.9	all flows and dikes are normal
2100 to 2600	+60.6±14.9	all flows normal, 3.58 m of reverse dikes
2600 to 3100	+54.6±14.8	allowance made for 20.0 m of reverse flows and 0.63 m of reverse dikes
3100 to 3520	+29.9±14.7	allowance made for 110.4 m of reverse flows and 6.72 m of reverse dikes.

* Plus indicates in sense of present field.

variation of magnetization properties with depth in the crust.

Walker [1959, 1960] and others noted the downdip thickening of volcanic groups in eastern Iceland toward the present spreading axis and by invoking concurrent eruptive activity, subsidence, and spreading, *Palmason* [1973, 1980] has constructed models of crustal growth in Iceland that predict the presence of downdip thickening. The contribution of this study, in conjunction with detailed studies of the paleomagnetism and lithology of exposed areas up dip from the IRDP section [*Watkins and Walker*, 1977; *Helgason and Zentilli*, this issue], is to show that thickening continues rapidly beneath the present erosional level and in doing so, to provide numerical values of the parameters involved in modeling crustal growth. The most convincing evidence of downdip thickening is the increase in the thickness of the section of extrusives erupted during the duration of sea floor spreading anomaly 5. At shallow crustal depths to the east of the IRDP section approximately 1000 m of extrusives accumulated during anomaly 5 time, while 2145 m of extrusives represent anomaly 5 at the greater crustal depths of the lower part of the IRDP section.

Measurement of the variation of regional dip in the IRDP section makes it possible to estimate the expected thickness of the anomaly 5 sequence. This estimate, which involves continuous increase of lava deposition rate with depth as the spreading axis is approached, is in close agreement with the obvserved thickness. The success of this combination of paleomagnetic and structural information in modeling crustal growth leads to an age calibration for the IRDP section. This calibration indicates that age varies nonlinearly with depth in the section with rapid variation with depth at the top of the section (6 m.y./km) and slow variation at the base of the section (0.4 m.y./km). It would now be advantageous to apply these methods to the study of more typical mid ocean ridge crests, which are closer to the requirements of Palmason's model in that crustal formation often takes place over a narrow, spatially stable zone.

The successful use of the linear magnetic anomaly patterns of the ocean basins as a means of dating crustal formation requires that some part of oceanic crust be magnetized according to the geomagnetic polarity at the time of crustal formation. The relatively little altered submarine basalts recovered by the Deep Sea Drilling Project show that the magnetization of at least the uppermost 600 m of oceanic crust has retained initial thermoremenence directions, albeit variously rotated by tectonic effects [*Gruver*, 1978]. While deeper, more altered oceanic crust has yet to sampled, basalts altered by zeolite facies metamorphism have been widely studied and it has generally been possible to show that initial thermoremanence directions have been retained [e.g., *Ade-Hall et al.*, 1971]. Characteristically, zeolite facies and less altered basalts have remanences consisting of one or more soft components and a single hard or stable component. It is the direction of the latter that can be demonstrated to have the requirements of magnetization acquired during initial cooling. In contrast, an increasing number of studies of rocks altered to greenschist and higher grades, many from Precambrian terranes, frequently yield by multitechnique analysis the presence of polyphase magnetizations consisting of two or more hard components as well as soft componets [eg., *Roy and Lapointe*, 1976; *Buchan and Dunlop*, 1976; *Palmer et al.*, 1977]. It is generally supposed that one hard component records the direction of initial magnetization while the other or others, which may be dominant, record stages in the thermal or alteration history of the rock. The onset with depth in oceanic crust of more altered rocks with polyphase magnetizations would mark the lower limit of the crustal zone in which original magnetization polarities are preserved, or the bottom surface of the 'tape' of the 'tape recorder.'

An indication of the degree of alteration at which polyphase magnetizations might appear in oceanic crust, and of a mechanism for their occurrence, is obtained from study of the volcanic sequence of the Bermuda Seamount [*Rice et al*, 1980]. Here Paleogene or older pillowed flows altered in epidote-forming conditions, transitional between the zeolite and greenschist facies, are densely intruded by thin lamprophyric sheets. At a distance from sheet concentrations, flows show stable reverse magnetization with relatively low intensities, whereas in zones of high sheet density the flows show extensive strong stable normal magnetization, this also being the polarity of the great majority of the sheets. Saturation magnetization measurements show that there is appreciably more magnetic oxide in the normal flows than in the sheet-rich zones. This fact and the broad spatial occurrence of normal polarities indicate that additional magnetization by the formation of new magnetic material during alteration associated with sheet intrusion rather than conventional thermal remagnetization is the explanation of the normal polarities.

The limitation of the Bermuda result is that the section is not seen in continuity with less or more altered crustal zones. The IRDP section supplies part of this deficiency in that a continuous sequence exists from essentially unaltered material to material altered to a degree that is similar to the Bermuda flows. As has been reported from other parts of Iceland and elsewhere, single stable components that appear to carry original magnetization directions characterize the unaltered and zeolite facies flows, even in zones of high dike density. It is only with the onset of epidote zone conditions at below 2.8-km crustal depth that evidence for overprinting of original magnetization directions appears. This takes the form either of the presence of mixed polarity flows, containing both samples with steeply upward and steeply downward stable inclinations, or of strongly normally magnetized flows in zones containing a high density of normally magnetized dikes. It is suggested that magnetic overprinting in this deeper part of the IRDP section has a similar origin to that deduced for Bermuda. The mixed polarity flows are seen to represent spatial variation in secondary magnetic production such that primary magnetizations are still locally dominant, while the strongly normally magnetized flows represent intense production of secondary magnetite, which everywhere dominates remanences.

It will be necessary to test the supposed polyphase nature of these remanences, perhaps using some of the special methods developed for the study of Precambrian high-grade metamorphic rocks. However, it is already evident that original magnetization directions are generally only preserved to a crustal depth of 2.8 km in the IRDP section.

By combining results from ophiolites and the Deep Sea Drilling Project it is possible to predict that original remanence directions are lost at between 800 and 1200 m depth in ocean crust, within the transition between the extrusive and sheeted dike crustal components [*Rice et al.*, 1980, Figure 14]. In the IRDP section, the magnetic overprinting that has taken place locally below 2.8-km crustal depth is the result of a diking event associated with the Breiddalur volcanic center: These dikes are geochemically associated with the upper of three extrusive groups composing the IRDP section, which were largely accumulated during the latter part of anomaly 5 time [*Gibson et al.*, this issue). This relationship implies that magnetic overprinting took place from 1.0 to 1.5 m.y. after original magnetization. Strong, pervasive magnetic overprinting of this type that takes place rather shortly after original magnetization could provide an addition to extrusives carrying initial cooling magnetization as part of the source for the linear magnetic anomaly patterns of the ocean basins. The geomagnetic reversal history recorded in these two parts of the source layer would be out of phase by a distance that would depend on spreading rate and the delay between formation and dike emplacement into the lower part of the layer.

Much interest has been shown in the variation of magnetic properties other than direction with depth in oceanic crust with the aim of providing additional constraints on the source layer for linear anomalies. Results from DSDP drill holes to 600-m depth in oceanic basement do not show any overall trends with depth [*Harrison*, 1976]. The 3-km IRDP section does show such trends, particularly in lava susceptibility, where the decrease below 2-km crustal depth is sufficiently well defined to extrapolate to a zero value at just over 4-km crustal depth, close to the expected onset of greenschist facies metamorphic conditions. On typical ridge crests greenschist facies metamorphism is expected to occur at below 1.2-km crustal depth [*Rice et al.*, 1980], and magnetization below this depth is likely to be a function of the contribution from any relatively unaltered dikes and, at considerably greater depth, from gabbros. While the arithmetic average remanence intensity of extrusives in the IRDP section, at 33 x 10^{-4} emu cm $^{-3}$ is not significantly different from values for extrusives forming the upper 600 m of oceanic crust, for example, at 37 x 10^{-4} emu cm^{-3} for five DSDP leg 37 sites [*Ryall et al.*, 1977], it will be instructive to look at the reasons for the broad variations about these averages. For the DSDP basalts the range is explained by a combination of variation in grain size and degree of cation deficiency in single phase titanomaghemites. For the IRDP basalts variation is the result of a combination of high-temperature oxidative phase-splitting of titanomagnetites, absorption of iron into silicates, and growth of secondary magnetite. Flow average remanence intensity and susceptibility can be as low as 1.0 and 8.5 x 10^{-4} emu cm^{-3}, respectively, when the effects that reduce magnetization are dominant, for example, in flow 267.1, and as high as 217 and 57.3 x 10^{-4} emu cm^{-3} when secondary magnetite production is dominant, for example, in flow 299.1.

Acknowledgments. We acknowledge the Natural Energy Authority of Iceland, the National Research Council of Iceland and the people Reydarfjordur for making the IRDP experiment possible. The paleomagnetic measurements were shared between paleomagnetic laboratories at Ruhr-Universtat, Bochum, Dalhousie University, the University of Washington, Oregon State University and the University of Copenhagen. We thank the staffs of these laboratories for their patient and painstaking efforts and in particular Samuel Folami of the University of Washington and Charles Walls of Dalhousie University who acted as data coordinator. The figures were prepared by Lata Hall, and the manuscript was typed by Barbara Cossar and David Robinson. We thank all these colleagues. The IRDP experiment was supported by funds from Dalhousie University, NSERC (Canada, grant G063), NERC (U.K), NSF (U.S., grants EAR 78-222764 and EAR 78-11725), ONR (U.S., grant N000-14-78-C-0389), BMFT (FRG, grant ET 4248), DFG (FRG, grant SCHM 250/21), SNF (Denmark, grant 511-101147), and NATO (grant 1652).

REFERENCES

Ade-Hall, J. M., H. C. Palmer, and T. P. Hubbard, The magnetic and opaque petrological response of basalts to regional hydrothermal alteration, *Geophys. J. R.Astron. Soc.*, *24*, 137-174, 1971.

Albertsson, K. J., P. J. Hooker, and J. A. Miller, A brief K-Ar age study of the IRDP borehole, Reydarfjordur, eastern Iceland, *J. Geophys. Res.*, this issue.

Angenheister, G., N. Peterson, and G. Schonharting, Zur Interpretation der Anomalien des Erdmagnetfeldes in Island, *Fortschr. Mineral.*, *54*, 54-92, 1977.

Becker, H., Magnetic anomalies (z) in NE-Iceland and their interpretations based on rock magnetic investigations, *J. Geophys.*, *47*, 43-56, 1980.

Blakely, R. J., Geomagnetic reversals and crustal spreading rates during the Miocene, *J. Geophys. Res.*, *79*, 2979-2985, 1974.

Buchan, K. L., and D. J. Dunlop, Paleomagnetism of the Haliburton intrusions: Superimposed magnetizations, metamorphism and tectonics in the late Precambrian, *J. Geophys. Res.*, *81*, 2951-2990, 1976

Dagley, P., R. L. Wilson, J. M. Ade-Hall, G. P. L. Walker, S. E. Haggerty, T. Sigurgeirsson, N. D. Watkins, P. J. Smith, J. Edwards, and R. L. Grasty, Geomagnetic polarity zones for Icelandic lavas, *Nature*, *216*, 25-29, 1967.

Flower, M. F., G. Brem, J. R. Cann, J. Delaney, R. Emmermann, I. L. Gibson, P. J. Oakley, R. G. Pritchard, P. T. Robinson, and H.-U. Schmincke, Chemical stratigraphy, Iceland Research Drilling Project, Reydarfjordur, eastern Iceland, *J Geophys. Res*, this issue.

Fox, P. J. and N. D. Opdyke, Geology of the oceanic crust: Magnetic properties of oceanic rocks, *J. Geophys. Res.*,*78*, 5139-5154, 1973.

Gibson, I. L., ed., Crust of oceanic affinity in Iceland, *Nature*, *281*, 347-351, 1979.

Gibson, I. L., R. J. Kirkpatrick, R. Emmerman, H.-U. Schmincke, R. G. Pritchard, P. J. Oakley, R. S. Thorpe and G. F. Marriner, The trace element composition of the lavas and dikes from a 3 km vertical section through the lava pile of eastern Iceland, *J. Geophys. Res.*, this issue.

Gruver, N. A, The significance of segregation vesicles to the interpretation of the tectonics of oceanic crust (crust), *EOS, Trans. AGU*, *59*, 1056, 1978.

Hall, J. M., and P. T. Robinson, Deep crustal drilling in the North Atlantic Ocean, *Science*, *204*, 573-586, 1979.

Hall, J. M., C. Walls, and S. L. Hall, On inclined features in the Iceland Research Drilling Project core, *J. Geophys. Res.*, this issue.

Harrison, C. G. A., Magnetization of the oceanic crust, *Geophys. J. R.Astron. Soc.*, *47*, 257-283, 1976.

Helgason, J., and M. Zentilli, Magnetostratigraphy and correlation of the region surrounding the IRDP drillhole 1978, Reydarfjordur, eastern Iceland, *J. Geophys. Res.*, this issue.

Jamieson, R. A., The St. Anthony complex, northwestern Newfoundland: A petrological study of the relationship between a peridotite sheet and its dynamothermal aureole, unpublished Ph.D. thesis, Memorial Univ. of Newfoundland, St. Johns, 1979.

Johnson, H. P., Magnetization of the oceanic crust, *Rev. Geophys. Space Phys.*, *17*, 215-226, 1979.

Kristjansson, L., Paleomagnetism and magnetic surveys in Iceland, *Earth Planet. Sci. Lett.*, *8*, 191-208, 1970.

Kristjansson, L., and N. D. Watkins, Magnetic studies of basalt fragments recovered by deep drilling in Iceland, and the "magnetic layer" concept, *Earth Planet. Sci. Lett.*, *34*, 365-374, 1977.

LaBrecque, J. L., D. V. Kent, and S. C. Cande, Revised magnetic time scale for late Cretaceous and Cenozoic time, *Geology*, *5*, 330-335, 1977.

Lowrie, W., Geomagnetic reversals and ocean crust magnetization in *Deep Drilling Results in the Atlantic Ocean: Oceanic Crust*, edited by. M. Talwani et al., pp. 135-150, AGU, Washington, D. C., 1979.

McDougall, I., N. D. Watkins, G. P. L. Walker, and L. Kristjansson, Potassium argon and paleomagnetic analyses of Icelanic lava flows: Limits on the age of anomaly 5, *J. Geophys. Res.*, *81*, 1505-1512, 1976.

Mehegan, J. M., P. T. Robinson, and J. R. Delaney, Secondary mineralization and hydrothermal alteration in the Reydarfjordur drillcore, eastern Iceland, *J. Geophys. Res.*, this issue.

Ness, G., S. Levi, and R. Couch, Marine magnetic anomaly time scales

for the Cenozoic and Late Cretaceous: A precis, critique, and synthesis, *Rev. Geophys. Space Phys.*, *18*, 753-770, 1980.
Palmason, G., Kinematics and heat flow in a volcanic rift zone, with application to Iceland, *Geophys. J R. Astron. Soc.*, *33*, 451-481, 1973.
Palmason, G., A continum model of crustal generation in Iceland; kinematic aspects, *J. Geophys.*, *47*, 7-18, 1980.
Palmason G., S. Arnosson, I. B. Fridleifsson, H. Kristmannsdottir, K. Saemundsson, V. Stefansson, B. Steingrimsson, and J. Tomasson, The Iceland crust: Evidence from drill hole data on structure and processes, in *Deep Drilling Results in the Atlantic Ocean: Oceanic Crust*, edited by M. Talwani et al., pp. 43-65, AGU, Washington, D. C., 1979.
Palmer, H. C., B. A. Merz, and A. Hayatsu, The Sudbury dikes of the Grenville front region: Paleomagnetism, petrochemistry, and K-Ar age studies, *Can. J Earth Sci.*, *14*, 1867-1887, 1977.
Piper, J. D. A., Interpretation of some magnetic anomalies over Iceland, *Tectonophysics*, *16*, 163-187, 1973.
Rice, P. D., J. M. Hall, and N. D. Opdyke, Deep Drill 1972: A paleomagnetic study of the Bermuda Seamount, *Can. J. Earth Sci.*, *17*, 232-243, 1980.
Robinson, P. T., J. M. Hall, N. I. Christensen, I. L. Gibson, I. B. Fridleifsson, H.-U. Schmincke, and G. Schonharting, The Iceland Research Drilling Project: Syntheses of results and implications for the nature of Icelandic and oceanic crust, *J. Geophys Res*, this issue.
Roy, J. L., and P. L. Lapointe, The paleomagnetism of Huronian red beds and the Nipissing diabase; post-Huronian igneous events and the apparent polar wander path for the interval -2300 Ma to -1500 Ma for Laurentia, *Can J. Earth Sci.*, *13*, 749-773, 1976.
Rutten, K., Two-dimensionality of magnetic anomalies over Iceland and Reykjanes ridge, *Mar Geophys. Res.*, *2*, 243-263, 1975.
Ryall, P. J. C., J. M. Hall, J. Clark, and T. Milligan, Magnetization of oceanic crustal layer 2 - Results and thoughts after DSDP leg 37, *Can J Earth Sci*, *14*, 684-706, 1977.
Saemundsson, K., L. Kristjansson, I. McDougall, and N. D. Watkins, K-Ar dating, geological and paleomagnetic study of a 5 km lava succession in northern Iceland, *J. Geophys. Res.*, *85*, 3628-3646, 1980.
Schonharting, G., Magnetic properties of rocks from the Geitafell gabbro complex, SE-Iceland, *Bull. Geol. Soc. Den.*, *28*, 21-29, 1979.
Schonharting, G., and M. Ghisler, Zones of polarity reversal of stable remanent magnetization within some basaltic flows of the IRDP core, *J. Geophys. Res.*, this issue.
Schonharting, G., and J. M. Hall, A detailed susceptibility log of the IRDP drill core, Reydarfjordur, eastern Iceland, *J. Geophys. Res.*, this issue.
Serson, P. H., W. Hannaford, and G. V. Haines, Magnetic anomalies over Iceland, *Science*, *162*, 355-357, 1968.
Sigurgeirsson, T., Aeromagnetic survey of SW-Iceland, *Sci. Icel.*, *2*, 13, 1970.
Walker, G. P. L., Geology of the Reydarfjordur area, eastern Iceland, *Q. J Geol. Soc. London*, *114*, 367-393, 1959.
Walker, G. P. L., Zeolite zones and dike distribution in relation to the structure of the basalts of eastern Iceland, *J. Geol.*, *68*, 515-527, 1960.
Watkins, N. D., and G. P. L. Walker, Magnetostratigraphy of eastern Iceland, *Am. J. Sci*, *277*, 513-584, 1977.
Wilson, R. L., Paleomagnetic stratigraphy of Tertiary lavas from northern Ireland, *Geophys.J R Astron. Soc.*, *20*, 1-9, 1970.
Winkler, H. G. F., *Petrogenesis of Metamorphic Rocks*, Springer-Verlag, New York, 1975.
Wood,D. A., and I. L. Gibson, The relationship between depth of burial and mean intensity of magnetization for basalts from eastern Iceland, *Geophys. J. R. Astron. Soc*, *46*, 497-498, 1976.

(Received August 21, 1981;
revised December 14, 1981;
accepted February 5, 1982.)