STRUCTURAL RELATIONSHIPS AND MAGNETOSTRATIGRAPHY OF THE VOLCANIC SUCCESSION AND THE BREIDDALUR DYKE SWARM IN REYDARFJORDUR, EASTERN ICELAND

by

JOHANN HELGASON

A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy at Dalhousie University, March 25, 1983.

Department of Geology
Dalhousie University
Halifax, Nova Scotia
Canada B3H-3J5

DALHOUSIE UNIVERSITY

FACULTY OF GRADUATE STUDIES

The undersigned hereby certify that they have read and recommended to the Faculty of Graduate Studies for acceptance a thesis entitled "Structural Relationships and Magnetostratigraphy of the Volcanic Succession and the Breiddalur Dyke Swarm in Reydarfjordur, Eastern Iceland."

by Johann Helgason

in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Dated March 18, 1983

External examiner [redacted]

Research Supervisor

Examining Committee

CANADIAN THESES ON MICROFICHE | ***THÈSES CANADIENNES SUR MICROFICHE***

ITHOR/*NOM DE L'AUTEUR* JOHANN HELGASON

ESIS/*TITRE DE LA THÈSE* STRUCTURAL RELATIONSHIPS AND MAGNETOSTRATIGRAPHY OF THE VOLCANIC SUCCESSION AND THE BREIDDALUR DYKE SWARM IN REYDARFJORDUR, EASTERN ICELAND

/*UNIVERSITÉ* DALHOUSIE UNIVERSITY

WHICH THESIS WAS PRESENTED/ *UR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* Ph. D.

EGREE CONFERRED/*ANNÉE D'OBTENTION DE CE DEGRÉ* 1983

IPERVISOR/*NOM DU DIRECTEUR DE THÈSE* Dr. MARCOS ZENTILLI

TÉ March 27th, 1983 SIGNED/*SIGNÉ* [redacted]

ADDRESS/*RÉSIDENCE FIXÉ* GNITANES 2
REYKJAVIK
ICELAND

DALHOUSIE UNIVERSITY

Date March 18th, 1983

Author Johann Helgason

Title STRUCTURAL RELATIONSHIPS AND MAGNETOSTRATIGRAPHY OF THE VOLCANIC SUCCESSION AND THE BREIDDALUR DYKE SWARM IN REYDARFJORDUR, EASTERN ICELAND

Department or School GEOLOGY

Degree Ph.D. Convocation Spring Year 1983

Permission is herewith granted to Dalhousie University to circulate and to have copied for non-commercial purposes, at its discretion, the above title upon the request of individuals or institutions.

[redacted]

Signature of Author

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

igure Page

igure Page

igure | Page

LIST OF TABLES

LIST OF MAPS (FOLDED IN POCKET)

LIST OF STRATIGRAPHIC PROFILES (IN POCKET)

ABSTRACT

The 1.9-km-thick sequence intersected by the IRDP 1978 drill hole at Reydarfjordur, eastern Iceland, is correlated with the westward dipping exposed volcanic succession on the basis of extensive field mapping and paleomagnetic studies. The base of the landward extension of sea floor magnetic anomaly 5 (epoch 9) and other exposed marker formations can also be identified in the core. Field observations, including vertically discontinuous dykes, the lack of lava-feeder relationships, and the measured K-Ar age difference between dykes and the surrounding lavas suggest that, contrary to previous interpretations, dykes of the Breiddalur dyke swarm were intruded by lateral injection from the south. These dykes are considerably younger than, and thus could not have fed, the exposed lava succession in the vicinity of the drill site.

The lowest 450 m of the core may represent lavas related to activity in the Reydarfjordur volcanic center 13.5 km to the east. It is proposed that about 10.3 Ma the Reydarfjordur volcanic center ceased to be active and volcanic activity shifted about 20 km to the west, where the Breiddalur and Thingmuli volcanic centers later developed. The above field observations allow a model for the upper crustal construction of eastern Iceland to be proposed. The model assumes that the lava succession of eastern Iceland was formed in at least three successive volcanic zones that resulted from frequent shifting of the location of greatest volcanism.

Contrary to what is generally assumed, no systematic decrease in magnetic intensity with depth was observed for a 0.9 km thick vertical lava section in Holmatindur, about 13.5 km east of the drill site. This suggests that previous generalizations based on regional studies may have little predictive value when applied to certain specific areas.

ACKNOWLEDGEMENTS

A major part of the field work for this thesis was financed by the Nationl Energy Authority (Iceland). In addition, the author received a Dalhousie University Graduate Fellowship, and the research was financed through grants from the Natural Sciences and Engineering Research Council of Canada to Dr. Marcos Zentilli (A-9036) and Dr. James M. Hall, of Dalhousie University. The above contributions are gratefully acknowledged.

The author is deeply indebted to Dr. Marcos Zentilli for his supervision, continuous guidance and constructive criticism throughout this project. Thanks are due to Dr. James M. Hall for reading this thesis and providing numerous useful comments. The author would like to thank other members of his Supervisory Committee, Drs. Patrick J.C. Ryall, Peter H. Reynolds, and Rebecca P. Jamieson for discussions and critically reading parts of the manuscript. Provocative discussions with Dr. Paul T. Robinson and James M. Mehegan are acknowledged. Thanks to Dr. Peter H. Reynolds and Keith Taylor for providing K-Ar dating analysis.

In particular the author is grateful to Ross Boutilier for advice with computing and Dr. Christopher Beamont for providing generous access to computing facilities. The author is thankful to Charles Walls for valuable assistance with the paleomagnetic work, both in field and laboratory. Field assistance by Daniel Schulz, William Kay, and Dr.

James M. Hall, and laboratory work by Martha Duplisea, Thomas Ward, and Mary Peckenham are deeply acknowledged. Assistance with paleomagnetic sampling and fruitful discussions with Dr. Leo Kristjansson are sincerely appreciated. Drafting of some of the illustrations was done by Douglas Meggison and Janice Aumento-Boyce. Petrographic thin sections were skilfully prepared by Gordon Brown. The author is indebted to Dr. Ingvar B. Fridleifsson of the National Energy Authority in Iceland for organizing, on behalf of NEA, financial assistance for part of the fieldwork. The author would finally like to thank members of the Department of Geology, Dalhousie University and the people of Reydarfjordur, eastern Iceland, for their cooperation and assistance during his stay in these places.

INTRODUCTION

General statement

The position of Iceland in the Mid-Atlantic Ridge makes it one of the few accessible sites to study geological processes that may characterize the very extensive, submarine parts of the World Rift System, where oceanic crust is generated. Deep valleys incised into the Tertiary volcanic province of eastern Iceland provide a sample of the effects of processes now taking place in the active volcanic parts of this oceanic island. The purpose of this thesis is to explain the present structure and stratigraphy of the Reydarfjordur area of eastern Iceland on the basis of extensive field mapping, paleomagnetic studies and limited geochronology. It incorporates information obtained during an international deep-drilling project carried out in 1978 under the auspices of the Icelandic National Energy Authority (NEA) and the Iceland Research Drilling Project (Scientific Party, Iceland Research Drilling Project (henceforth IRDP), 1979a, 1979b, and 1979c). The background, development and results of the IRDP 1978 have been summarized in a dedicated volume of the Journal of Geophysical Research (Fridleifsson and others, 1982; Robinson and others, 1982a). Particular emphasis has been placed on stratigraphic correlation of the exposed succession with that intersected by the drillhole, on the relationships between dykes and lavas, and on a re-evaluation of relevant models for upper crustal generation.

Work done

The author was introduced to the area in 1978 (June-September) when sent as a counterpart from NEA in the IRDP project. In that capacity he was directly involved with on site logistics, core descriptions, drill hole temperature measurements. The writer conducted extensive descriptions of the stratigraphic succession, i.e. lavas, clastic materials and dykes in the area surrounding the drill site and extending west as far as the Thingmuli volcanic center. This study provided the neccessary field stratigraphic control for paleomagnetic sampling of the exposed section to Trollafjall by Dr. J. Hall and others. The discussions at one time or another with various scientists involved with the IRDP, Dr. M. Zentilli among them, and many visitors, inspired the author to follow up this work as a thesis.

The author came to Dalhousie University as a graduate student in September 1978. A thesis proposal was formulated, and in 1979, the author spent about three months in Reydarfjordur. The traverses at Holmatindur and Graenafell (Figure 1.4) were described, measured, and sampled for geochronological, petrological and paleomagnetic studies. The author co-operated with Dr. J.Hall and team in the paleomagnetic sampling across the Breiddalur dyke swarm in Graenafell, north of the IRDP drill site (Figure 1.4). The author paid special attention to the structural relationship between dykes and strata. During the last month of that summer a detailed section across the dyke swarm trend was completed from the Reydarfjordur volcanic center, 14 km east of the drill site, to the Thingmuli volcanic center, west of that locality.

The processing of paleomagnetic data at Dr. J. Hall's laboratory at

Dalhousie University by the author during the winter of 1979-1980 resulted in unexpected complications (apparent magnetic reversals in the stratigraphic succession, where none should have occurred). The preliminary results were presented at the IRDP post drilling meeting in Reykjavik in May 1980. From June to August, the author went back to the field and completed the study of several traverses between the Holmatindur and the drill site. Additional paleomagnetic sampling was carried out, this time with the supervision and equipment of Dr.L. Kristjansson of the Science Institute of the University of Iceland. During that summer, Dr. M. Zentilli visited the area and discussed with the author many of the critical field observations, in particular of dyke units.

Petrographic work, drafting and further processing of paleomagnetic samples cleared the way to evaluate the most likely correlation between the IRDP core and the exposed section to the east, and in April, 1981, the author presented such results and a structural model for the generation of the upper crust at Reydarfjordur (Chapters 1 to 4, and Figure 7.4 in this thesis) at the AGU-sponsored Chapman Conference on the Generation of Oceanic Lithosphere. (Helgason, 1981). The author was encouraged by the respose of the participants to the above model, and this led to the completion of manuscripts for the Journal of Geophysical Research, recently published (Helgason, 1982; Helgason and Zentilli, 1982).

Since 1979, geochronological analyses on 16 samples have been performed by the laboratory of Dr. P. H. Reynolds of Dalhousie University. An attempt to obtain analyses commercially was unsuccessful because of unsuitable analytical precision and control. Both K-Ar and Ar-Ar dating techniques have been applied.

Several other pilot studies were initiated during the course of this project, such as vitrinite reflectance of lignite and a study of pollen and spores from the clastic units at Holmatindur. The reflectance analyses were provided generously by Dr.P. Hacquebard of the Bedford Institute of Oceanography (BIO) but the results were inconclusive. Palynological analysis of the above and other beds was carried out by Dr.P. Mudie, also of BIO and Dr.G. Rouse of the University of British Columbia. The palynological study provides new data on climatic changes during anomaly 5 time (Mudie and Helgason, in press).

Organization of the thesis

This thesis consists of eight inter-related chapters describing different approaches to the geological analysis of the Reydarfjordur area. It has been difficult to organize the chapters as discrete independent parts, because as the study progressed, the knowledge derived from each aspect influenced the interpretation of others. For example, stratigrphic correlation would have been difficult without the supplement of the paleomagnetic investigation, and the latter would have been less useful without a concurrent understanding of the stratigraphy. Therefore, after a brief introduction Chapter 1 gives an outline of previous work, the purpose and scope of the study, and proceeds to describe and interpret the stratigraphy of the Reydarfjordur area integrating the author's work with all available information from other relevant sources. This is followed by the results of the paleomagnetic study of the lava units defined in Chapter 2. Following Chapter 3, a description of field relationships of intrusive dykes, the discussion of their paleomagnetic signatures is presented in Chapter 4. Designed as a test for a developing working hypothesis, a K-Ar geochronological investigation of selected units of lavas and dykes is presented in Chapter 5. Chapter 6 reviews models for the generation of the upper crustal structure of Iceland with particular reference to eastern Iceland. A dynamic rift model for the generation of the upper crustal structure of eastern Iceland, compatible with the available data, is proposed and developed in Chapter 7. Finally, Chapter 8 contains a summary of conclusions and some suggestions for future work.

CHAPTER 1

STRATIGRAPHY

1.1 Background

The geology of Iceland has long attracted scientific interest, especially after 1960 as concepts of plate tectonics developed. However, its anomalous character has repeatedly caused some speculation as to whether plate tectonics in Iceland is analogous to the submarine tectonic activity that takes place at the remaining, but less accessible, North American-Eurasian plate boundary.

With the understanding that diverse tectonic regimes exist in Iceland (e.g. Saemundsson, 1978) it follows that no general model, whether stratigraphic or geophysical can account for the crustal generation of the entire country. Instead, a slightly different model may be needed to describe the generation of each type region. In this thesis the active neovolcanic zone of northeastern Iceland is regarded as one possible model for the generation of Tertiary eastern Iceland, the subject of this study. The 1978 IRDP deep drilling at Reydarfjordur (Figure 1.1) provided a 1919 m vertical section, with 99.7% recovery, in an area of westerly dipping basalt lavas of Upper Miocene age (Scientific Party, 1979a, Fridleifsson and others, 1982) One of the aims of the deep drilling was to provide the necessary structural information

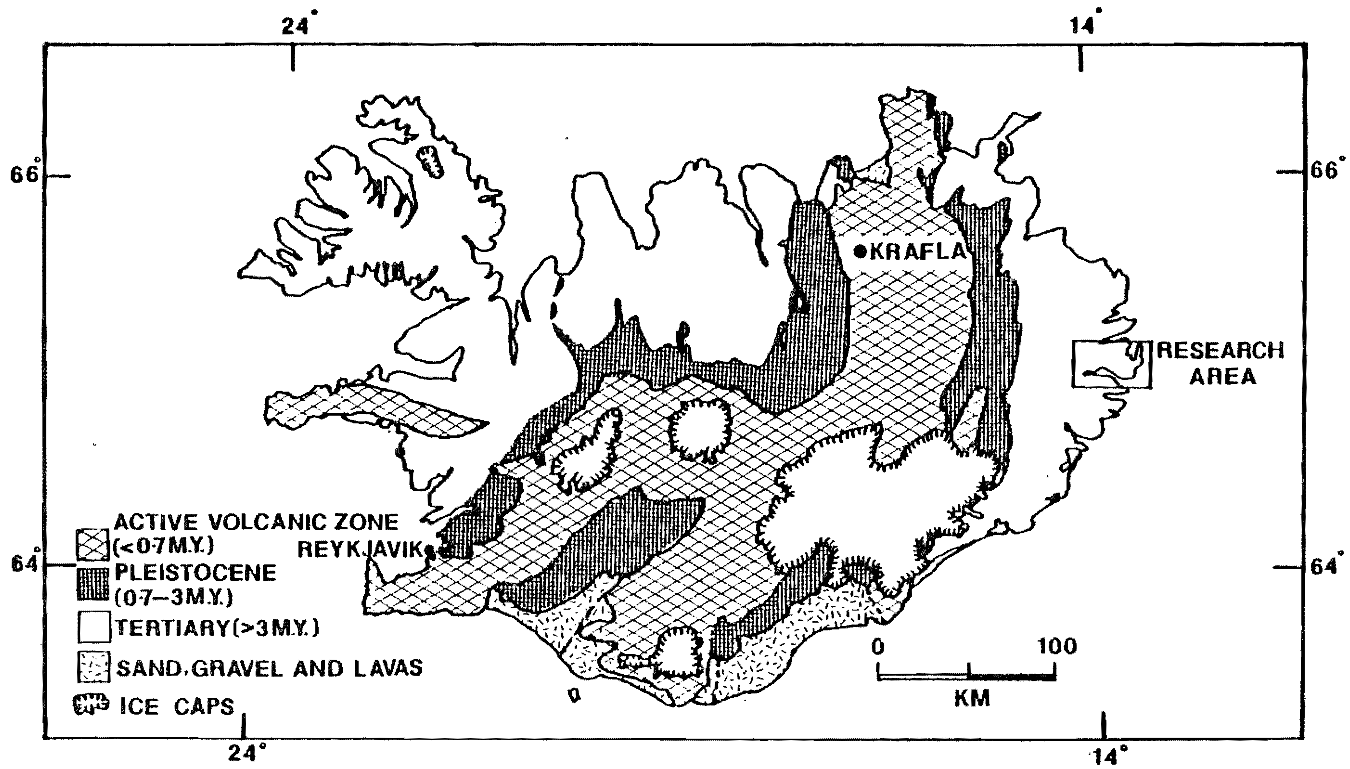


Figure 1.1 Location of the research area relative to the active volcanic zones and Pleistocene-Tertiary formations in Iceland.

on the lower part of layer 2, that portion of the section buried below sea level. In contrast, the upper portion of layer 2 had been fairly well documented. This study contributes stratigraphic information, more detailed than that previously available for the area surrounding the drill site, through mapping at a scale of 1:25,000, as well as detailed investigation of several 200 to 1200-m-thick vertical sections. This permits correlation, often on a unit by unit basis, between profiles in the exposed cliff sections that are more suitable for comparison with the stratigraphic succession of the IRDP core, than the succession shown in the previously available 1:50000 scale maps.

The paleomagnetic investigation of lavas in the same region provides a framework for the local and regional paleomagnetic correlation. One of the main purposes of this thesis was to investigate the relationship between volcanic centers, dyke swarms and the thick basalt lava succession. The stratigraphic information discussed in this thesis poses important restrictions for the possible evolution of eastern Iceland during the Tertiary. Many of the models proposed for this complex problem were based on assumptions and dangerous generalizations, some of which appeared in part contradictory. As a result questions were raised, such as, were the presently exposed dykes the feeders to the presently exposed lavas, as had been suggested (e.g. Walker, 1965). Or alternatively, if the exposed dykes in Reydarfjordur did not feed the surrounding basalt lavas, how would that affect models of crustal generation proposed for eastern Iceland? Furthermore, what did the deep drilling tell about the vertical thickness of the extrusive layer in eastern Iceland?

1.2 Field mapping approach

The mapping procedure was determined by the high degreee of exposures into the cliff stratigraphic succession which are complete in large parts of the area. Individual lava units can thus be traced for several kilometers and exposures in gullies reveal up to 1-km-thick continuous stratigraphic outcrops. Previously available geological maps were utilized and are generally found to be correct with exceptions which are discussed below. In previous studies the lava succession was subdivided into mappable units which eventually were recognized and traced in most of eastern Iceland.

Megascopic features, such as the lack of faults, the continuity of units, down dip thickening of lava formations, and consistent westward tilting of stratigraphic formations had all been fairly well established and could be used as guidelines in the present study. The high relief in Reydarfjordur and the correspondingly small horizontal distance from mountain sides to sea shore poses a problem when transferring stratigraphic data using planar representation. For this reason emphasis was laid on using panoramic photographs and describing numerous vertical traverses into the cliff section, spaced 2-5 km apart. For consistency with the detailed IRDP core descriptions, stratigraphic traverses of the exposed cliff section were generally mapped on a unit basis, as opposed to merely identifying and mapping formations.

The soft tuff beds frequently have a clear topographic expression, if more than about 5 m thick. Repeatedly, the author could walk along such marker tuffs for several kilometers in the dip direction. Aerial photographs, of which there was adequate coverage, were also useful in determining the position of such clastic markers. Although such units are rarely exposed on cliff benches they are generally found exposed where gullies intersect the succession.

Generally, comparison of any two closely spaced vertical sections indicated that they contained similar lithologic successions. As a result of the down dip thickening, however, new lithologic units are occasionally introduced at low stratigraphic levels, which do not extend up dip into the easternmost sections.

Marker formations were correlated by comparison of sections and where neccessary petrographic characteristics were examined microscopically using thin sections.

Confidence was gained in the above method when exactly the same lithologic successions were observed down dip, where they were thicker and better defined. Difficulties arose for example in correlation of the Holmatindur tuff formation (see below), which up dip consists mainly of tuffaceous material, whereas down dip it has been reworked and contains bouldery gravels.

When the continuity and down dip variation of the cliff section had been firmly established an attempt was made to correlate it with the IRDP cored succession. The author divided the IRDP core units into several formations and noticed the overall similar lithologic successions observable in the exposed sections. It was feared that dyke intrusives would be intersected by the core at levels where important marker formations should be found thus preventing or limiting stratigraphic correlation. Although minor intrusions constitute about

40% of the core succession they are sufficiently scattered and the marker formations used in the correlation are sufficiently thick so that dykes generally do not obliterate marker formations. In addition to the lithologic characteristics of core units their paleomagnetic character was compared with that of the exposed area, a method that independently was consistent with the stratigraphic correlation.

The proposed correlation of the IRDP core and the exposed stratigraphic succession is the one favoured by the author after several possibilities had been tested. The author believes that while additional work may contribute a more detailed correlation with the IRDP core, the proposed correlation of main marker formations below justifies the conclusions and implications drawn from this study.

1.3 Previous stratigraphic work

The first geological map of eastern Iceland showed that this region consists of basaltic lavas that are locally interspersed with areas of rhyolites (Thoroddsen, 1901). The acidic rocks in eastern Iceland attracted the most scientific interest and most studies done in this region for the next six decades were related to such rock formations. Thus for example Hawkes and Hawkes (1933) described the Sandfell laccolith in Faskrudsfjordur, Dearnley (1954) described briefly the rhyolitic area in Lodmundarfjordur and Tryggvason and White (1954) described rhyolitic tuffs in eastern Iceland.

Thorough geological investigations in eastern Iceland were carried out by Walker and co-workers for over 10 years, starting in 1955. Their publications, which describe the basic stratigraphic features of the

Tertiary formations, have made a strong impact on geological research in Iceland. In particular the stratigraphic work carried out before the deep drilling project in Reydarfjordur is summarized by Walker (1974). The dissected Tertiary lava succession in eastern Iceland can be conveniently subdivided into three main features: (1) volcanic centers, (2) flood basalt lavas, and (3) swarms of dykes that intrude or constitute feeders for the above. The volcanic centers have typically produced basaltic, intermediate and acidic volcanic rocks.

The mapped lava formations can in most cases be traced for tens of kilometres in the strike direction. Each formation usually thickens downward in the dip direction and causes the overall exposed structure of the lava succession to be lenticular in shape (e.g., Gibson and Piper, 1972). There are few faults with vertical displacements larger than 50 m in the study area (Walker, 1959). Faults with horizontal displacements (strike slip) are typically absent in Reydarfjordur. The difference in inclination of the lava flows from sea level to mountain tops amounts to about 8°, lavas with shallow dip (1°-2°) form the plateau carapace.

Petrological studies were carried out for individual volcanic centers, e.g. Thingmuli (Carmichael, 1964) and the basalt lava succession has similarly been regionally investigated (e.g. Wood, 1976). The stratigraphy of the Reydarfjordur volcanic center, about 25 km east of the IRDP drill site has been described in detail (Gibson, 1963; Gibson and others, 1966).

The magnetostratigraphy of a 9-km-thick Plio-Miocene lava succession in eastern Iceland was originally reported by Dagley and others (1967) but attempts have since been made at correlation with the magnetic polarity time scale (Watkins and Walker, 1977; McDougall and others, 1976; Piper and others, 1977). The major scientific results of the IRDP were collectively published in the Journal of Geophysical Research (in August, 1982) when this thesis was already in an advanced stage of preparation. Unfortunately, it has been impossible to incorporate and give credit to all of the above material. However, an attempt is made to refer to the most relevant aspects of the work of IRDP researchers when appropriate.

1.4 Stratigraphy

1.4.1 Introduction

The fjords represent deep incisions into a high plateau, and cliff sections provide excellent exposures of stratigraphic successions, locally over 1200 m thick. This study provides lithological profiles eastward from the IRDP drill site to the Holmatindur cliff section, and as far as units of intermediate chemical composition ascribed to the Reydarfjordur volcanic center (Figures 1.2, 1.3, 1.4, and 1.5).

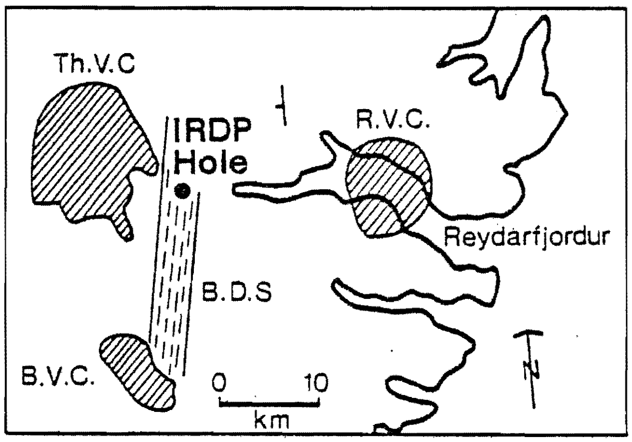


Figure 1.2 Location of the IRDP drill hole with regard to the Breiddalur dyke swarm (B.D.S.) and the surrounding volcanic centers: Th.V.C., Thingmuli volcanic center; B.V.C., Breiddalur volcanic center; R.V.C., Reydarfjordur volcanic center.

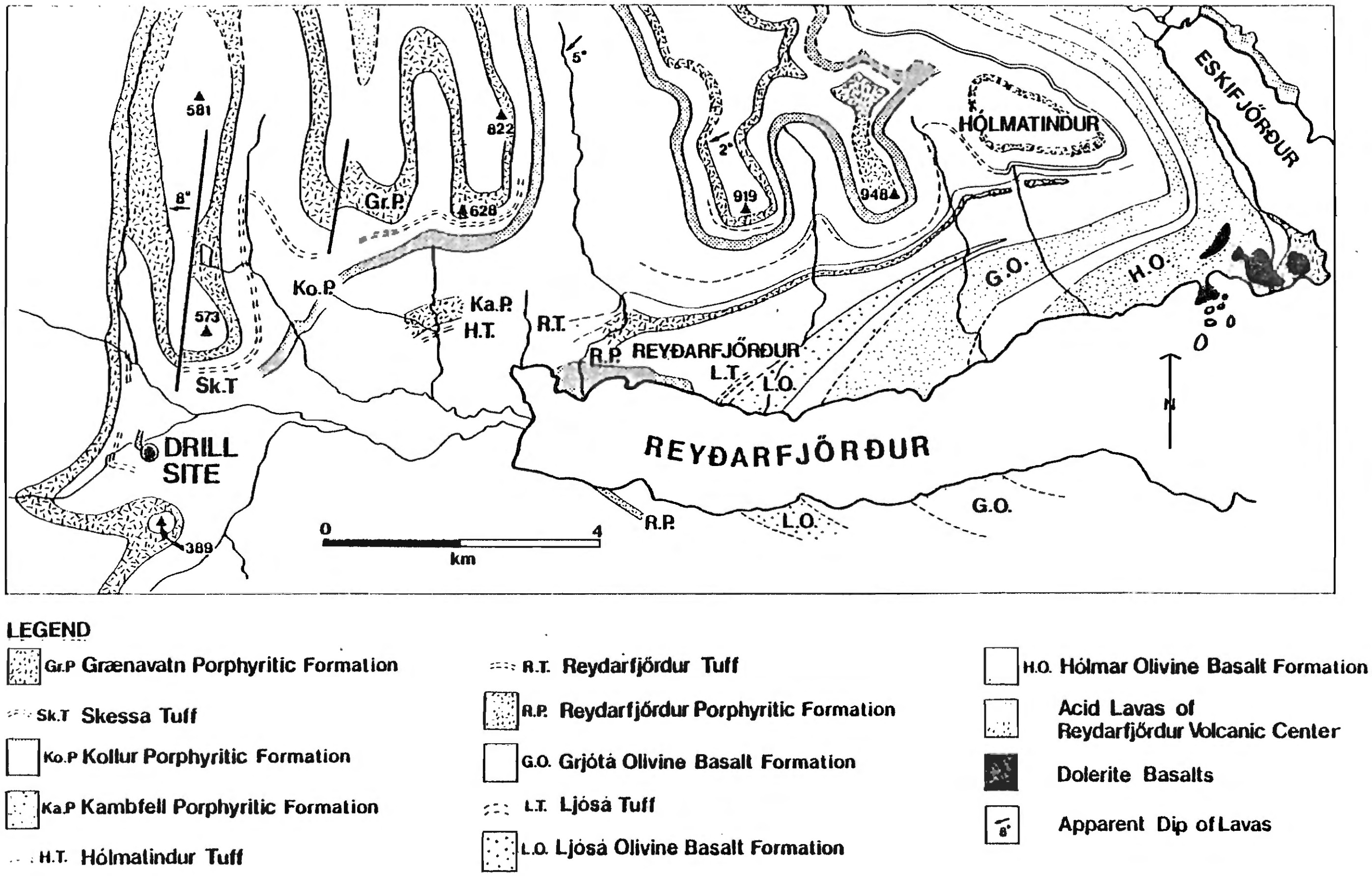


Figure 1.3 Geological map of western Reydarfjordur showing stratigraphic marker formations in the vicinity of the IRDP drill site, modified after Walker (1959).

On the basis of previous work (e.g., Walker, 1959), it could be assumed in this study that the IRDP cored section would incorporate stratigraphic formations that extended up dip, although thinning, into the exposed cliff section, thus allowing a correlation of the core with the surrounding area to the east. The Holmar and Grjota olivine basalt formations, which directly overlie the Reydarfjordur volcanic center (Figure 1.3), were chosen as the oldest units to be considered for this study. Stratigraphically, they lie about 2.0 to 2.5 km above the oldest rocks in the area (not part of this study) that are exposed from Eskifjordur to Gerpir at the head of Reydarfjordur (Figure 2.1). K-Ar dates for these rocks (Moorbath and others, 1968; McDougall and others, 1976) range from 12.7 to 13.3 Ma. All K-Ar dates referred to in this thesis have been modified using currently accepted decay constants (Steiger and Jaeger, 1977). Earlier work established that the Holmar and Grjota formations represent units below a thick, normally magnetized succession of lavas correlated with sea floor anomaly 5, epoch 9 (McDougall and others, 1976). Preliminary paleomagnetic work on the drill core in 1978 by the IRDP Scientific Party showed a thick (over 1 km thick) succession of normally magnetized lavas in the drillcore presumably of anomaly 5 age. This suggested a possible reference for correlating the exposed section with the core.

The main stratigraphic features of the area are shown in Figure 1.3, and the most probable stratigraphic correlation between profiles of the exposed section and the IRDP core, according to the author, is summarized in Figures 1.5 and 1.6. The volcanic and sedimentary formations of the Reydarfjordur area are tabulated in Table 1.1.

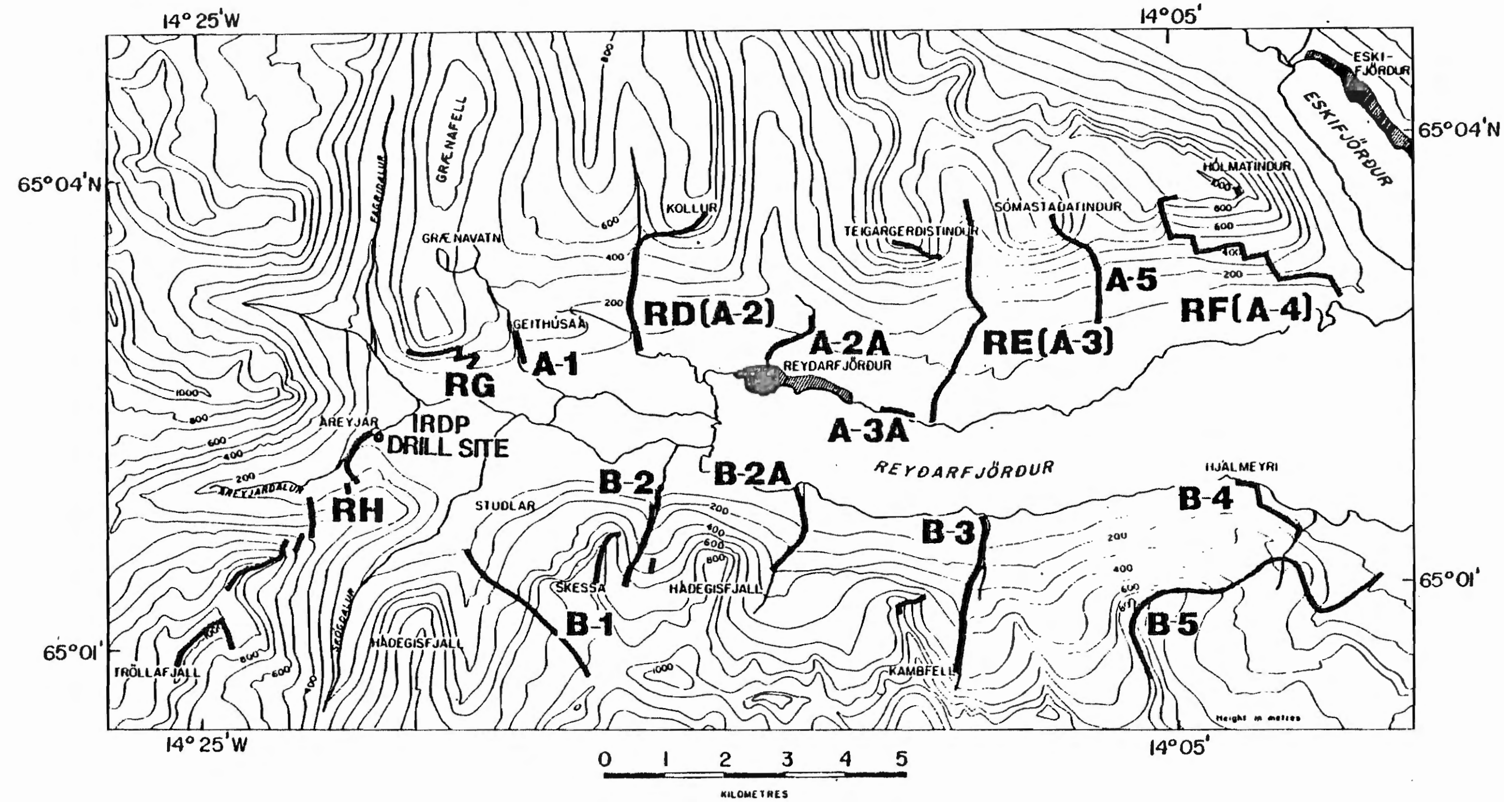


Figure 1.4 Location of stratigraphic sections surrounding the IRDP drill site.

Three types of basalt lavas of tholeiitic composition are distinguished in the field. These are: (1) 'plagioclase porphyritic' lavas, (2) 'olivine phyric' lavas, and (3) 'aphyric' lavas. This distinction has proven most useful, since each lava type is usually represented in several successive lava flows that make up a formation which can easily be traced in the field (Walker, 1963). For the purpose of the present thesis the name 'formation' is used instead of the term 'group' used by previous workers. There is no intention of formally establishing new names for these units, but the term 'formation' is here used to indicate a mappable, rock stratigraphic unit, which can be subdivided into informal members and beds (American Commission on Stratigraphic Nomenclature, 1961; Holland and others, 1978; Hedberg, 1976). The early stratigraphers working in eastern Iceland (e.g. Walker, 1959) informally divided the lava succession into numerous groups and assigned a name to each. Walker (1959) introduced the term 'group' to describe "the tendency of lavas of a particular type to form groups of flows". Thus he was emphasizing the similarities of a lava succession rather than following the usage of the term as now defined by the International Subcommission on Stratigraphic Classification (Hedberg, 1976). Furthermore the unit term 'group' is generally taken to be of a higher rank than the term 'formation' and it would be difficult to divide Walker's 'groups' into 'formations' due to the lithologic homogeneity of lavas in 'groups' as defined by Walker. The 'porphyritic' lavas are plagioclase phyric with phenocryst content usually over 20%. Care should be taken not to regard the field terms as strict equivalents of any petrological classification. However, the 'olivine phyric' lavas contain modal olivine in more than subordinate amounts, are usually olivine normative, and are on petrological grounds, rightfully termed olivine tholeiites (Carmichael, 1964). The 'aphyric' lavas are fine-grained and generally quartz normative and correspond to the petrological term quartz tholeiite. Henceforth, basaltic lavas will be discussed using the field terms 'porphyritic' (i.e., plagioclase phyric), 'olivine basalt' (i.e., olivine phyric), and 'tholeiite' (i.e., aphyric). Generally, lavas are separated by reddish-brown sedimentary units consisting of tuffs, agglomerates, volcaniclastic sediments and, locally, pebble and boulder conglomerates. These units, depending on locality, form about 3-10% of the stratigraphic succession and are here loosely called 'sediments'. Only selected tuff beds used as time markers are described in some detail.

The most distinctive stratigraphic markers, i.e. clastic tuff and porphyritic basalt lava formations, are separated by formations of tholeiite lavas, here informally called Th-1 to Th-6. Most formations (except those indicated with an asterisk in Table 1.1) have been described previously (Walker, 1959; Gibson and others, 1966), although some had not been given specific names before. The detailed mapping undertaken by the writer (see Map 1 folded in pocket) demonstrates that three, not two, olivine basalt formations exist below the Reydarfjordur porphyritic formation on the north side of the fjord near sea level. These are the Ljosa, Grjota, and Holmar formations on Figure 1.3, of which the Ljosa was not recognized in earlier studies. Tholeiite lavas are the most abundant rock type in eastern Iceland. However, both the porphyritic, olivine basalt, and tuff formations are more distincive in the field. Generally, they are much better markers and can be traced for longer distances than the tholeiite formations. Therefore,

Table 1.1 Stratigraphic comparison of correlated formations in the IRDP core and exposed cliff section east of the drill site.

	Cliff Section East of Drill Core			IRDP Core		
Formation	Location (see Figure 3) Altitude, m Thickness, m Unit Number Number of Lavas (Beds) Magnetic Polarity	Lithology (a)	Remarks	Depth Interval, m Thickness, m Unit Interval Lavas/Dykes/Clastics Number of Lava Units Magnetic Polarity	Lithology (b)	Remarks
Kollur porphyritic basalt	Kollur (RD) 379–410 28 RD35–RD38 4 normal	porphyritic basalt lavas with up to 30% (vol) of large (~1–2 cm) plagioclase phenocrysts	available age data: 9.05 ± 0.15 m.y. (unit EF 25; McDougall et al (1976)	Exposed by drill site (c) 17 RH701 and RH704 100%/0.0%/0.0% 2 normal	see cliff section, Kollur (RD)	units RH701 and RH704 are separated by two tholeiite lavas
Tholeiite-5	Kollur (RD) 139–379 216 RD15–RD34 22 normal	fine-grained, aphyric lavas with scoriaceous flow boundaries	formation includes 4-m-thick clastic unit; available age data: 9.33 ± 0.10 m.y. (Unit EF 22; McDougall et al. (1976))	11.70–291.32 (depth) 279.62 1.1–48.2 46.0%/47.4%/6.6% 21 normal	aphyric, fine-grained, holocrystalline basalt lavas with scoriaceous flow boundaries	
Kambfell porphyritic basalt*	Kollur (RD) 114–139 38 RD7–RD12 9 normal	thin and vesicular porphyritic basalt lavas (pl,cpx,ol)	four coarse-grained olivine basalt lavas occur between the Holmatindur tuff and Kambfell porphyritic basalt	291.32–310.80 19.48 49.1–51.2 97.4%/0.0%/2.6% 2 normal	fine- to medium-grained, porphyritic, massive basalt lavas with 20% (vol) plagioclase, sparse clinopyroxene and relics of olivine phenocrysts	below these porphyritic lavas are four coarse-grained, amygdaloydal basalt lavas, units 52.1 to 56.2 at 310.80–344.15 m depth
Holmatindur tuff	Kollur (RD) 58–93 ~30 RD3/2 26 (beds) not studied	upper part is mainly undisturbed pyroclastic tuff whereas lower part consists of reworked volcaniclastic material; for further detail, see text		344.15–409.60 (65.45) 58.1–67.1 2 normal	unit 58.1: finely bedded to massive tuffaceous sediments (18.10 m); unit 67.1: interbedded fine- to coarse-grained sandstone and grit with siltstone and minor tuffaceous material (7.27 m) .	units 58.1 and 67.1 are separated by three lava units
Tholeiite-4	Teigargerdistindur (RE) 360–500 157 RD8–RD19 12 normal	massive, fine-grained, aphyric basalt lavas		409.60–914.88 505.28 70.1–156.1 62.0%/35.6%/2.7% 54 normal	fine- to medium-grained, aphyric, sparsely vesicular basalt lavas	
Reydarfjordur tuff	Teigargerdistindur (RE) ~330 3 + 8 (beds) RE8/7 and RE9/8 2 not studied	clastic material; for detail see text	units RE9/8 and RE8/7 are separated by a tholeiite lava flow	914.88–950.55 35.67 157.1–162.1 0.0%/13.9%/86.1% 4 (beds) normal	Compound ignimbrite with four major flow units; the ignimbrite is underlain by coarse-grained ash layer (unit 163.1, 1.67 m)	separating Reydarfjordur tuff and Reydarfjordur P.B., at 950.50 to 976.63 m are an incomplete basalt lava 0.70 m dyke 22.61 m, and a clastic unit 1.10m
Reydarfjordur porphyritic basalt	Teigargerdistindur (RE) ~345 15 RE7 1 normal	porphyritic, medium-grained massive basalt lava unit with plagioclase, clinopyroxene and olivine phenocrysts; phenocryst content 20%		976.63–1022.60 47.97 167.2–172.1 76.3%/34.1%/0.0% 2 normal	porphyritic basalt lavas with 15–20% plagioclase, 2% clinopyroxene, 1–2% olivine	this formation is intruded by nine minor intrusives
Tholeiite-3	Teigargerdistindur (RE) 180–345 132 RD1–RD6 9 normal	massive, thick, fine-grained aphyric basalt lavas	within this formation a single lava, probably an Icelandite, occurs by sea level on top of Ljosa tuff formation	1022.60–1357.79 335.19 175.1–231.3 56.1%/41.3%/2.6% 25 normal	depth interval 1022.60–1357.79 m in core is correlated with formations Tholeiite-3 and Tholeiite 2. Lithology: 21 units are fine-grained, massive basalt lavas with brecciated and vesicular flow boundaries; four units are gray, fine- to medium-grained, homogeneous aphyric icelandite lavas	
Ljosa tuff*	Teigargerdistindur (RE) 3– ? L.t. ? (beds) not studied	silicic tuff, partly welded	see text for details	not identified as a separate formation in core		
Ljosa olivine basalt*	Teigargerdistindur (RE) 0–100 40 RE0 ~35 normal	coarse-grained olivine phyric basalt lavas		not identified as a separate formation in core		
Tholeiite-2	Holmatindur (RF) 340–358 18 RF48–RF49A 2 normal	fine-grained aphyric basalt lavas with scoriaceous flow boundaries		see core interval by formation Tholeiite-3 above		
Grjota olivine basalt	Holmatindur (RF) 160–325 194 RF30–RF47 22 R(31 m)/N(35 m)/R(128 m)	coarse-grained olivine phyric basalt lavas	available age data: 10.53 ± 0.10 m.y. by correlation with earlier work (unit ED 45; McDougall et al. (1976)	1337.79–1655.40 297.61 232.1–281.1 63.3%/35.9%/0.7% 23 N – R – N	greenish-gray, medium- to coarse-grained, aphyric basalt lavas with mottled texture	polarity: N (1337.79–1445.30), R (1475.30–1577.59), N (1616.48–1655.40)
Tholeiite-1	Holmatindur (RF) 100–165 100 RF16–RF29 3 reversed	fine-grained, aphyric basalt lavas with scoriaceous flow boundaries	distribution probably limited to the Holmar area, i.e., the Reydarfjordur volcanic center	1655.40–1916.35 263.45 283.1–327.2 46.1%/52.4%/1.5% 29 R – N – R	greenish-gray, aphyric, fine-grained, vesicular basalt lavas	polarity: R (1677.33–1698.20), N (1698.20–1861.70), R (1861.70–1919.73)
Holmar olivine basalt	Holmatindur (RF) 50–100 134 RF0–RF15 16 reversed	coarse-grained olivine phyric basalt lavas		not identified as a separate formation in core		

*Formations not previously described.

a) Tuffs and other volcaniclastic material is intercalated between lavas throughout the core and exposed lava sequence

b) Lavas: 54%; minor intrusions: 41%; clastic material: 5% (Robinson et al., this issue)

c) This formation (Kollur) is exposed by the collar of the drillhole at [illegible] m above sea level tholeiite basalt formations (Th-1 to Th-6) are not specifically described here.

The term isochron is used later in this thesis in the same manner as by Walker (1974a). Thus isochrons on geological maps indicate the location of lava formation boundaries that have been mapped over a large area. It should, however, be noted that strictly speaking the upper or lower boundaries of a lava formation may consist of several lavas when viewed in the up dip direction due to thinning out of some lavas away from the zone of lava extrusion. If more than one lava occupy formation boundaries it follows that such boundaries formed over some time interval.

1.4.2 Holmar olivine basalt formation

After acidic volcanism ceased in the Reydarfjordur volcanic center (Figure 1.2), lavas of the Holmar formation were erupted (Holmar group; Walker, (1959)). In the Holmatindur section (Figures 1.4 and 1.5) this formation is 100 m thick and is of particular interest because it contains several volcanic eruptive sites. In the Holmar area, headland between Reydarfjordur and Eskifjordur (Figure 1.3), a major dyke can be observed to be the feeder of a succession of olivine basalt flows. The intrusive-extrusive transitional contact is marked by a scoriaceous unit which contains abundant volcanic bombs. Interfingering and overlying the scoriaceous agglomerate are coarse-grained olivine basalt flows that become thicker to the east of the dyke area. Walker (1960) noted the existence of similar eruptive sites farther north within this formation. These eruptive sites are absent from the overlying formations, whose source, the author contends, now lies hidden below sea level. Eruptive sites such as those in the Holmar formation occur again much higher in the stratigraphic succession in younger rocks erupted from the Thingmuli volcanic center (Figure 1.2).

1.4.3 Grjota olivine basalt formation

This marker formation (Grjota group; Walker 1959), is 190 m thick in the Holmatindur section (Figures 1.3, 1.4, and 1.5) and is separated from the underlying Holmar formation by a 100-m-thick tholeiite formation, Th-1. In the Grjota formation the lavas are generally 2 to 4 m thick with well-defined vesicular tops and bottoms. At four intervals the formation consists of unusually thin lavas, comprising 5-15 units with an average thickness of about 2 m. The Holmar and Grjota formations have very few sedimentary intercalations and none thicker than 1 m. Both these formations are highly zeolitized with mesolite.

1.4.4 Ljosa olivine basalt formation

Probably because of its rapid up dip thinning, the Ljosa formation was not detected in earlier regional studies (e.g., Walker, 1959). At sea level by the Ljosa River, about 2 km east of the town of Reydarfjordur, this formation is approximately 80 m thick and consists of 1 to 3 m thick lavas. In the main gully of the overlying cliff section at Somastadatindur, about 2 km west of Holmatindur (Figure 4), its thickness is reduced to 7 m. The Ljosa lava formation consists predominantly of olivine phyric flow units that are highly zeolitized (mesolite). Thin red sedimentary beds, commonly found intercalated with lavas higher up in the succession are almost totally absent in this formation. At sea level east of the Ljosa formation, on the north side of Reydarfjordur, a 12-m-thick tholeiite lava occurs. This flow is part of tholeiite formation (Th-2) that thins considerably up dip and separates the Grjota and Ljosa olivine basalt formations. In the Holmatindur section (Figure 5) only two fine-grained lavas separate the Ljosa and Grjota formations. In Holmatindur, a 1-m-thick sedimentary bed lies below the Ljosa formation, which here consists of only two lavas, 3 and 4 m thick, respectively.

The introduction of the term Ljosa formation calls for a nomenclature revision. Prior to the present study only the Holmar and Grjota formations had been recognized in the westen part of Reydarfjordur, and both were traced in the strike direction for distances of up to 30 and 20 km, respectively (Walker, 1959). The Holmar formation is well defined in the Holmanes area on the north side of Reydarfjordur. At this locality the Holmar formation is overlain by Th-1, Grjota, Th-2, and Ljosa formations. On the south side of the fjord the Holmar formation is missing, but the Th-1, Grjota, Th-2, and Ljosa formations outcrop on both sides of the fjord as bands about 4 and 5 km east of the head of the town of Reydarfjordur, respectively (Figure 1.3). In previous studies the Grjota and Ljosa formations were misinterpreted as equivalents of the Holmar and Grjota groups, respectively (Walker, 1959; Gibson and others, 1966).

1.4.5 Ljosa tuff

At sea level on the north side of the fjord, lying directly on the Ljosa olivine basalt formation (Figure 1.3), a tuff bed, 7 m thick, is exposed, named here for the first time the "Ljosa tuff." At the locality described above, this tuff has not been mapped previously, and elsewhere in the area this particular stratigraphic level is rarely exposed, although commonly a topographic bench, visible in aerial photographs, indicates its location. This tuff can be subdivided into seven units, from bottom to top:

1. Basaltic lapilli tuff: consisting of vesicular tachylite and lithic fragments, less than 2 mm in size, together with plagioclase phenocrysts in subordinate amounts; thickness, 1 m.

2. Vitric tuff: consolidated ash tuff, unwelded, with sparse plagioclase phenocrysts and pumice fragments. Present are rare felsic and basaltic lithic fragments. Pumice fragments have vesicles that show very slight distortion; thickness; appoximately 3 m.

3. Vitric ash tuff: yellowish, welded, and collapsed pumice lenses. Felsic, subrounded lithic fragments up to about 1 cm in size are

abundant. The bed is sparsely phyric with plagioclase as well as pyroxene phenocrysts; thickness, 0.60 m.

4. Lapilli tuff: aphyric welded tuff, more welded than bed 3. This bed has perlitic cracks and individual pumice fragments clearly show greater distortion; thickness, about 1 m.

5. Crystal tuff: this unit grades into a vitrophyric welded tuff showing evidence of substantial flattening. This bed has about 40% fragments of zoned plagioclase, grains of opaque minerals, clinopyroxene, and rare orthopyroxene phenocrysts. Present in subordinate amounts are both felsic and basaltic lithic fragments. In the matrix are glass shards that are possibly of a different compositon (more mafic) compared with the remaining groundmass which has dusty intergrowths of iron oxides and glass; thickness, about 0.50 m.

6. Vitric tuff: the uppermost tuff bed is sparsely phyric consisting of collapsed pumice (about 10%). The pumice is yellow suggesting an acidic composition. The remainder of this bed consists of dusty intergrowths of iron oxide and glass together with abundant small and angular fragments of plagioclase and opaque grains; thickness, 0.25 m.

7. Soil layer: above the Ljosa tuff proper is a thin (about 0.10 m) red oxidized bed largely composed of minute translucent particles, suggesting a possible soil layer. Sparse plagioclase phenocrysts and dark tachylite fragments are present; thickness, 0.10 m.

The top bed of the Ljosa tuff is here overlain by a tholeiite lava flow of formation Th-3 (Table 1.1). Above the Ljosa tuff horizon in profile RE (Figures 1.3 and 1.5) on the north side of the fjord, several thick, fine-grained lava flows occur. These lavas make up tholeiite lava formation Th-3. At sea level on the north side of the fjord, an icelandite lava is separated from the underlying Ljosa tuff by a single tholeiite lava, whereas on the south side an icelandite lava is resting directly on the tuff. In the latter area this lava is very fine-grained and non-vesicular, shows flow banding, and weathers easily into sharp blocks. Coarse-grained olivine basalt lavas as well as fine-grained tholeiite lavas separate the icelandite bed from the next marker formation higher up in the succession. In the gully by the Ljosa River, two successive individual tholeiite lava flows reach unusual thicknesses of 37 and 42 m, respectively (Figure 1.5).

1.4.6 Reydarfjordur porphyritic basalt formation and Reydarfjordur tuff

The next two overlying marker formations were first described by Walker (1959) and later by Gibson and others (1966). These formations occur close together and are therefore discussed jointly. One consists of porphyritic basalt lavas; the other is a tuff. The Reydarfjordur porphyritic formation and the accompanying tuffs have been mapped over a distance of about 25 km in the strike direction. They extend from the cliff section on the north side of Eskifjordur (Figure 1.3) to Stodvarfjordur in the south (Walker, 1959; Gibson and others, 1966). After a study of the Reydarfjordur tuff over a large area, Gibson and others reached the following conclusion concerning its origin: 'normally the tuff is homogeneous and unbedded, and it is probably the product of an ash-flow, due to a single explosive eruption from an unidentified source'. These two formations may extend well beyond this area, where mapping has not been completed. In Stodvarfjordur, about 20 km south of the drill site, the Reydarfjordur porphyritic formation rests on a 3-m-thick conglomerate that contains boulders up to 0.40 m in size (Gibson and others, 1966). In Reydarfjordur this tuff should be regarded as part of a clastic cycle and can be divided into units which are superimposed on the Reydarfjordur porphyritic formation. Separating units of this cycle are tholeiite basalt lavas that increase in number down dip toward the west. Each tuff unit commonly shows some signs of reworking, probably by a fluviatile process. In the Teigargerdistindur section (RE on Figures 1.4 and 1.5) at an altitute of 350 m, the Reydarfjordur porphyritic formation consists of a single 15-m-thick lava. On top of the Reydarfjordur porphyritic formation rests a poorly exposed reddish tuff bed, approximately 3 m thick. This bed is overlain by a thick tholeiite lava flow (25 m), above which there is a good exposure of an 8-m-thick clastic unit that can be divided into four beds from bottom to top:

1. Very fine-grained (clay size) reworked brown tuff; thickness, 1.40 m.

2. Vitric tuff consisting of light grey glass shards. Present also are fragments (up to 15 cm in size) of petrified trees. This unit is stratified with distinct cross bedding. The sharp angular shape of glass shards indicates no reworking of this tuff after deposition; thickness, 4.50 m.

3. Reworked vitric gray tuff consisting mainly of glass shards. Scattered are lithic fragments and ash grains; thickness, 1.0 m.

4. Vitric tuff, red and oxidized tuff with sparse lithic fragments; thickness, 1.0 m.

Both formations are exposed by the Budara River that runs through the town of Reydarfjordur. Here the Reydarfjordur porphyritic formation occurs at an altitude of 85 m and is approximately 20 m thick. It consists in part of 2-m-thick flow units. The porphyritic lavas are overlain by the Reydarfjordur tuff, which is 6.5 m thick. From bottom to top the tuff is divided into three beds:

1. Fine gray tuff with yellow fine-grained lenses (about 10%): sparsely vitrophyric with rare lithic fragments. This bed is probably reworked; thickness, 2 m.

2. Vitric tuff: consists mainly of glass shards; thickness, 3.5 m.

3. Red oxidized tuff bed; thickness, 1 m.

On top of bed 3 rest three tholeiite lavas, 17 m in total thickness. These lavas are overlain by a tuff unit, at least 4 m thick. This unit is a light brown vitric tuff, consisting of glass shards, strikingly similar to bed 2 in Teigargerdistindur. Part of this unit consists of sparse basalt granules up to 2 cm in size. In thin section the glass shards do not show signs of reworking by water. Above these formations is a succession of tholeiite lavas that make up formation Th-4.

Overlying tholeiite lava formation Th-4 are two marker formations, the Holmatindur tuff (Walker, 1959) and the Kambfjall porphyritic formation. Stratigraphically, they lie close together and their association is strikingly similar to the occurrence of the Reydarfjordur porphyritic formation and its associated Reydarfjordur tuff.

1.4.7 Holmatindur tuff and Kambfjall porphyritic formations

The Kambfjall porphyritic lava formation is here named for the first time. The Holmatindur tuff is the only clastic unit in the entire lower half of the Kollur section (RD). Here it is over 30 m thick, and the lower part consists only of reworked volcaniclastic material that is mainly of sand and silt size. Cross-bedded layers with rounded basalt pebbles up to 35 cm in diameter occur in the lower part. Upward this sedimentary unit grades into an undisturbed pyroclastic tuff. In the Kollur section, four thin lavas, about 25 m in total thickness, separate the Holmatindur tuff and the overlying Kambfjall porphyritic formation.

These four lavas are aphyric and coarse-grained, have amygdaloidal flow boundaries and are strongly zeolitized. Here the Kambfjall porphyritic formation is about 40 m thick and is divided into five flows. The lowest of these is 15 m thick and can be further subdivided into thin flow units, probably formed within a single eruption. The porphyritic lavas thin rapidly up dip and are not observed in Holmatindur (Figure 1.5). In Eyrarfjall the Holmatindur tuff is 35 m thick and excellently exposed. Here it can be divided into at least 27 beds that range in lithology from sandstone intercalated with lignite partings, to airborne tuffaceous units. On top of the Kambfjall porphyritic formation are the Th-5 tholeiite lavas.

1.4.8 Kollur porphyritic formation

Overlying tholeiite lava formation Th-5 is the massive Kollur porphyritic lava formation (Kollur group, Walker (1959)). Clastic beds are found associated with the Kollur porphyritic formation at various localities in the research area. These beds are here regarded as part of a clastic cycle and overlie, underlie, or are intercalated with lavas of the Kollur porphyritic basalt formation. About 25 km north of the drill site, the Kollur formation rests on a 4-m-thick, poorly exposed clastic unit. It consists of a welded tuff with basic and felsic lithic fragments, up to 2 cm in size. Part of this unit can be defined as a crystal tuff. The Kollur porphyritic lava formation is unique for its plagioclase phenocrysts that form up to 50% by volume and are commonly 1-2 cm in size. An outcrop of this formation occurs immediately beside the IRDP drill site where it consists of two lava flows. The porphyritic formation has been traced 14 km eastward (up dip), where it occurs in Holmatindur (Figure 1.3) at an elevation of about 970 m. This formation can be traced over a distance of 60 km in the strike direction. It was mapped in Stodvarfjordur about 25 km southwest of the drill site (Gibson and others, 1966) and the author has traced it to Heidarendi about 35 km north of the drill site. Between the Kollur porphyritic formation and the overlying Graenavatn porphyritic formation are tholeiite lavas of formation Th-6. Intercalated between lavas of this tholeiite formation is the next marker unit, the Skessa tuff.

1.4.9 Skessa tuff

The Skessa tuff, an ignimbrite flow unit, has wide distribution in eastern Iceland and has been described by Walker (1962). Above the drill site the Skessa tuff occurs at an altitude of 100 m, where it is exposed with a thickness of 12 m. In several localities the predominantly rhyolitic ignimbrite contains basaltic glass and pumice fragments (up to 2% by volume; Walker, 1959). The tuff outcrop near the drill site contains an unusual zone with basaltic material in much greater quantity than previously reported (Walker, 1959). Near the drill site the Skessa tuff can be subdivided as follows, from bottom to top:

1. Massive vitric tuff: above about 1 m that is not exposed, the lowest bed is welded and massive in character and does not break up into flakes. Extensive devitrification to quartz and feldspar has taken place. It contains sparse plagioclase phenocrysts and basaltic 'bubbles' or clusters of vesicular basaltic glass; thickness, 2.0 m.

2. Vitric tuff: the next bed consists of a gray to reddish eutaxitic welded tuff that breaks up into flakes. Elongated vesicles in a devitrified matrix are partly or completely filled with laumontite and quartz; thickness, 8.0 m.

3. Tachylitic vitric tuff: shows a transitional contact with the vitric tuff, suggesting synchronous eruption of both zones. The tachylitic bed is dark gray, more mafic than bed 2. It contains basaltic clasts up to 3 cm in size, including medium grained gabbroic fragments. Thin sections reveal abundant basaltic vesicular tachylite fragments and dark glassy shards. Present also are sparse plagioclase phenocrysts in a glassy, partly devitrified groundmass. Walker (1962) noticed elsewhere the abundant basaltic 'bubbles' within the Skessa tuff and suggested that these are the result of mixing of two magma types. However, he did not describe a phase equivalent to the relatively thick basaltic zone reported for this (drillsite) locality. thickness, 1.80 m.

4. Reddish brown bed: this unit is an oxidized bed (probably soil) that is overlain by tholeiite basalt lavas; thickness, 0.35 m.

The ignimbrite eruption of the Skessa tuff, geologically an almost instantaneous phenomenon, is one of the most useful time markers of the region. On the basis of thickness, regional field relationships and petrographic observations, Walker suggested that the Skessa tuff had its source in the Breiddalur volcanic center, about 20 km south of Reydarfjordur (Figure 1.2). He quoted the abundance of spherulites and tridymite as well as the increase in thickness and welding toward the Breiddalur area as evidence for a source now buried below the base of the Breiddalur volcanic center. However, the author has observed abundant spherulites, welding, the presence of basic intercalations, and a thickness of over 12 m in the Skessa tuff near the drill site. The latter thickness is equal to the maximum recognized at Breiddalur by Walker (1962). Therefore, it is suggested that the Skessa tuff may generally thicken down dip to the west, and in addition its source may lie as well in the area now occupied by the Thingmuli volcanic center.

1.4.10 Graenavatn porphyritic formation

Walker (1962) arbitrarily chose the Graenavatn group as the base of the Breiddalur volcanic center. Here called a formation, it has a thickness near the drill site of 90 m and consists partly of very thin (about 2 m) flow units. Two of the 13 lava flows are sparsely phyric, compared with the remainder which are clearly porphyritic. In Graenafell just north of the drill site, Walker (1959) described a dyke feeder of one of the porphyritic lavas. The Graenavatn formation has a very wide distribution. It extends for 80 km in the strike direction, from Berufjordur in the south to Egilsstadir about 25 km north of the drill site (Walker, 1959) and is not seen to thin out but disappears beyond those localities owing to poor exposures. On the basis of reconnaissance work by the author it is suggested that this formation may be down-faulted within a flexured zone (Walker, 1964) located in the Egilsstadir area about 30 km north of the drill site.

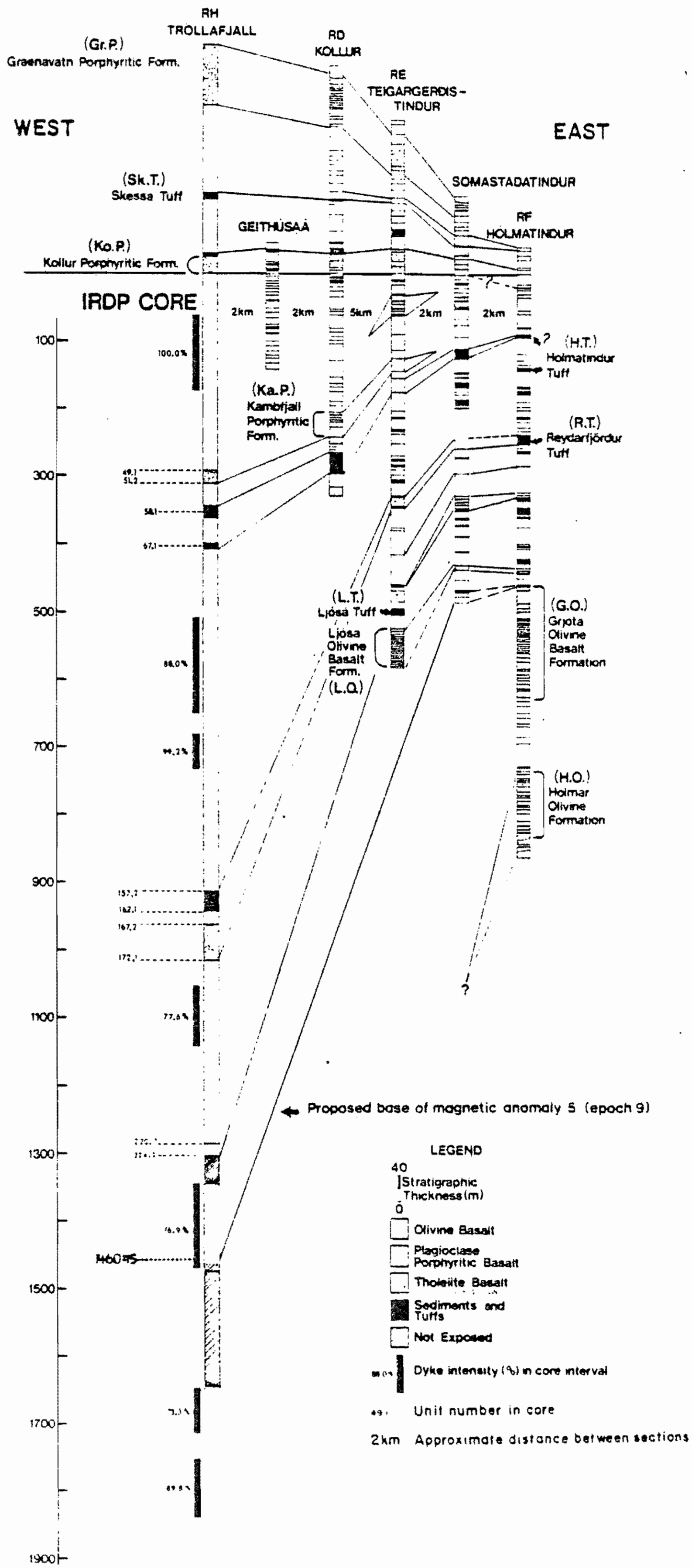
The first exposed andesitic (or intermediate composition) lavas of the Thingmuli volcanic center occur about 700 m stratigraphically above the Graenavatn porphyritic formation. An excellent description of the lava succession above the Graenavatn porphyritic formation is given by Flower and others (1982).

1.5 Correlation with the IRDP core

The present study and earlier work (e.g., Walker, 1963) have demonstrated that lava formations, especially porphyritic basalt lavas, have wide areal distribution and can be readily mapped. Such formations have been traced individually for about 80 km in the strike direction and generally do not thin out but disappear due to lack of exposure. These formations extend at least 15-20 km in the dip direction. Erosion from the plateau surface and lack of exposure below sea level limit further mapping in the dip direction. All the lava formations of the exposed section, including the porphyritic marker formations, thicken down dip, presumably toward their source area at the axis of a paleorift zone.

It should be kept in mind that due to the expected down dip thickening the confidence with which the correlation of the drill core and cliff section is made may seem to decrease with depth into the core. This, however, need not be the case as basalt lava formations are likewise expected to thicken and be better defined in the IRDP core. It would, however, be in accordance with most crustal models to expect differentiated lava units to thin rapidly up dip. It therefore appears that long continuous intervals of intrusive units could obliterate individual lava formations completely. However, as will be discussed below, this does not appear to be the case.

Figure 1.5 The main identified marker formations of the IRDP core correlated with the lava succession to the east (updip) on the north side of the fjord. Approximate distances between the sequences (km) are indicated. The elevation of each sequence has been arranged so as to fit one reference level, i.e. Kollur porphyritic formation, which is exposed immediately beside the drill site at about 60 m above sea level. Note core intervals of high dyke intensity.


RH
TROLLAFJALL
RD
KOLLUR
RE
TEIGARGERDIS-
TINDUR
(Gr.P.)
Graenavatn Porphyritic Form.
WEST
EAST
SOMASTADATINDUR
(Sk.T.)
Skessa Tuff
GEITHUSAA
RF
HOLMATINDUR
(Ko.P.)
Kollur Porphyritic Form.
IRDP CORE
2km
2km
5km
2km
2km
(H.T.)
Holmatindur
Tuff
(Ka.P.)
Kambfjall
Porphyritic
Form.
(R.T.)
Reydarfjördur
Tuff
(L.T.)
Ljósa Tuff
Ljósa
Olivine
Basalt
Form.
(L.O.)
(G.O.)
Grjota
Olivine
Basalt
Formation
(H.O.)
Holmar
Olivine
Formation
100.0%
88.0%
77.6%
Proposed base of magnetic anomaly 5 (epoch 9)
LEGEND
40
Stratigraphic
Thickness (m)
0
Olivine Basalt
Plagioclase
Porphyritic Basalt
Tholeiite Basalt
Sediments and
Tuffs
Not Exposed
Dyke intensity (%) in core interval
Unit number in core
2km Approximate distance between sections
100
300
500
700
900
1100
1300
1500
1700
1900

The entire exposed lava succession between the Thingmuli and Reydarfjordur volcanic centers was deposited on the eastern flank zone(s) of a Tertiary plate boundary. The IRDP core, located on this flank zone, should have the same lithological successions that were identified in the exposed cliff section east of the drill site. With one exception (the Ljosa tuff), no major stratigraphic marker formations are thought to be at levels in the drill hole that have been obliterated by dyke intrusives, making an attempt at correlation feasible.

The proposed correlation of the exposed and cored sections in Reydarfjordur, justified in this and later section of this thesis, is shown on Figure 1.5. It strengthens the proposed correlation that within the cliff section lava formations are still thickening down dip to sea level. Furthermore, the area of lava extrusion is not seen for the lava succession between the Reydarfjordur and Thingmuli volcanic centers. It follows therefore that (a) below sea level there is an unknown distance to the source area, and (b) length of lava formations (in the dip direction) within the cliff section does not exceed the expected half-length of a shield like lava dome (lava lens). As a result it can be argued that there remains little doubt that lava formations should extend into the drillcore as the minimum half-length as defined above is generally 15-20 km in the cliff section. Furthermore, no volcanic bombs or other comparable ejecta were found in the core, as might be indicated by close proximity to the zone of extrusion for these lavas. This does suggest that the zone of lava extrusion for the majority of core lavas is buried to the west of the drill hole. In total 7 horizons of the exposed cliff section, consisting mainly of basalt lavas and tuffs, are correlated into the core.

Kollur porphyritic formation. The first of these is the Kollur porphyritic formation. The collar of the drill hole is located at 60 m above sea level and the Kollur porphyritic formation is exposed immediately beside it, thus forming the upper datum of the correlated cored succession. In Kollur mountain (section RD), approximately 3.5 km east of the drillsite, a total of 22 aphyric tholeiite lavas occur next below the Kollur porphyritic formation. These lavas are a total of 216 m thick and within this formation clastic units amount to a total of 6.5 m. The first plagioclase porphyritic lavas below the Kollur formation in section RD are those of the Kambfjall porphyritic formation that are separated from the Holmatindur tuff by four zeolitized lavas that are 23 m thick. The first porphyritic basalt lavas below the Kollur formation in the drill core occur at 291.32 m depth. All lavas to this depth are aphyric tholeiite lavas but within this interval intrusive units 10.1 and 17.1 extend from 63.14 to 172.29 m, and are well above the next expected marker units. As the aphyric tholeiite lavas below the Kollur formation in section RD are 216 m thick, lavas of this type were expected to extend at least to this depth in the core. Thus the occurrence of aphyric tholeiite lavas to 291.32 m depth is in good agreement with a thicker tholeiite lava formation below the Kollur formation in the core than in the exposed section. If intrusive units in this interval obliterate only aphyric tholeiite lavas this thickening is about 26%. Lavas ot the Kollur lava formation contain usually plagioclase phenochrysts that are up to 2 cm in size. Phenocrysts of this size are not seen within any other basalt lava formtion in western Reydarfjordur. Therefore during mapping of the area lavas with this characteristic proved invariably to belong to the Kollur porphyritic formation.

<u>Kambfjall porphyritic formation and the Holmatindur tuff.</u> Plagioclase porphyritic core units (49.1 to 51.2) at 291.32-310.80 m are correlated with the Kambfjall porphyritic formation. It is stressed, however, that this formation is approximately 38 m thick in the cliff section (in Kollur mountain) whereas it is only about 19 m in the drill core at a stratigraphic level where dykes obliterate neither the overlying nor underlying units. This formation consists of compound flows in the cliff section but is more massive in the core. Sedimentary units at slightly greater depth, 344.15-409.60 m (units 58.1 and 67.1), correspond to the Holmatindur tuff. Clastic unit 58.1 of the core is complete whereas the lower contact of clastic unit 67.1 is the upper chilled margin of dyke unit 70.1 (4.80 m thick) which is underlain by an aphyric tholeiite basalt lava flow. Both in the cored section (unit 58.1) and in the exposed Kollur section (RD) the upper part of the Holmatindur tuff consists of finely bedded to massive tuffaceous sediment whereas the lower part consists of siltstone. In the Kollur section the lower part of the Holmatindur contains in addition sandstone and pebble conglomerate. This lower unit is correlated with the core at a greater depth, i.e. clastic unit 67.1 which contains coarse grained sandstone. In the Kollur cliff section (RD) the Holmatindur tuff is seen only as a single unit whereas it is interpreted to occur as a clastic cycle in the IRDP core. Such clastic cycles are common for ofther marker tuffs in the cliff section. Thus the Holmatindur tuff units in the core, i.e. units 58.1 and 67.1 are interstratified by units 61.1 (basalt lava, 2.05 m), 61.2 (basalt dyke, 17.10 m), 64.1

(basalt lava, 5.30 m), and 65.1 (basalt lava 15.50 m). These four units are 39.95 m thick in total. Consistent with the general down dip thickening of lava formations it is not surprising that basalt lavas were deposited during the formation of the Holmatindur tuff cycle. It should be noted that the thickness of the Holmatindur tuff is over 30 m in the cliff section (RD) but in the core it is thinner or 25.37 m. The different appearance of the Holmatindur tuff in the exposed and cored sections is probably due to (a) initial (syn-depositional) variations of this unit at the time of pyroclastic deposition, i.e. away from the source area, and (b) because of a climatic cooling transition associated with this clastic cycle. To what extent climatic variations affect sediment deposition is not clear. However, based on palynological studies there is little doubt that the occurrence of boulder conglomerates within the Holmatindur tuff is related to increased precipitation and rapid drainage of large watermasses into what is now the up dip direction of western Reydarfjordur (Mudie and Helgason, 1983, in press).

Reydarfjordur tuff and Reydarfjordur porphyritic formation. The next older marker unit in the cliff succession is the Reydarfjordur tuff. This tuff is mappable and can be distinguished from other clastic units in the cliff section because it occurs in close stratigraphic relationship with the Reydarfjordur porphyritic formation. Thus in the cliff area the Reydarfjordur porphyritic lavas are usually interstratified between units of the Reydarfjordur tuff clastic cycle. The compound ignimbrite, consisting of three major flow units at 919.82-950.55 m (units 157.2-162.1), and the associated porphyritic basalt lavas below, i.e., at 973.63-1022.60 m (units 167.2-172.1), are correlated with the exposed section as the well-defined Reydarfjordur tuff and the Reydarfjordur porphyritic basalt formation, respectively (section 1.4.6, above). The proposed correlation of these pophyritic lavas with the Reydarfjordur porphyritic formation suggests a significant thickening of lavas over the core interval 409.60 to 1022.60 m. Corresponding thickness of this stratigraphic level in the cliff section (e.g. RE) is 173.5 m compared with 613 m in the IRDP core. No plagioclase porphyritic lava formations occur in the drill core below the Holmatindur tuff at 409.60 m (unit 67.1) until at 973.63 m (unit 167.2). Within the upper part of this depth interval (i.e. 409.60 to 973.63 m) intrusive units are common and form about 90% over the approximate depth range 510 to 720 m. These intrusive strata occur sufficiently close to the Holmatindur tuff that they are not thought to obliterate the next two markers below, i.e. the Reydarfjordur tuff and Reydarfjordur porphyritic formation. A detailed description of primary features of this ignimbrite cooling unit as observed in the core has been given by Schmincke and others (1982, p. 6447), and Viereck and others (1982) described its secondary mineralogy.

'Intermediate' lava flows of the IRDP core. Several lavas of intermediate composition (SiO_2: 58-60%) occur in the core between units 172.1 and 255.1 at 1022.60-1306.66 m (Flower and others, 1982). One 'intemediate' flow (SiO_2: 58-60%) rests on the Ljosa tuff on the south side of the fjord but, on the north side it is separated from it by a single tholeiite lava. This flow may belong to any of the intermediate core lavas in the interval 1022.60-1306.66 m but it is arbitrary correlated with unit 220.7 at approximately 1287 m depth. The Ljosa tuff, which is 7 m thick in the exposed section near sea level, does not apparently correspond to a particular unit of the core and may be cut by dykes in the cored succession, i.e. in the interval 1022.60 to 1306.66 m. In the exposed section the Ljosa tuff is underlain by the Ljosa olivine basalt formation, which has abundant olivine phenocrysts and is thus exceptionally mafic. Schmincke and others (1982) find the most mafic units in the core to be the olivine basalt lavas at 1306 to 1696 m depth.

Geochemical 'groups'. On the basis of major element geochemical data Flower and others (1982) suggested a threefold division of the cored lava succession. The lowest part of the core, units 224.2 to 326.2 at 1306.75 to 1918.52 form one geochemical group. The middle group consists of units 108.1 to 220.7B at 628.80 to 1306.66 m whereas the upper group, units 86.2 to 991 extends from 507.36 m depth in the core to 1262 m into the cliff section west of the drill site. The lower and upper groups consist predominantly of basaltic lavas while the middle group contains a large proportion of 'intermediate' lavas. This geochemical division is compatible with the exposed cliff section east of the drillhole where the 'intermediate' lavas of the middle group are rare however, probably due to rapid up dip thinning as a result of their low initial viscosity when erupted. It would be desirable as a future study to compare the trace element composition of basalt lavas in the core, especially the aphyric lavas, with those of the exposed succession to the east of the drillsite.

Magnetostratigraphic correlation. Magnetostratigraphic investigation of the exposed cliff section east of the drill site (Chapter 2) clearly demonstrates a long normally magnetized lava succession, which correlates with anomaly 5 (epoch 9). For the core Bleil and others (1982) indicate the existence of a long succession of normally magnetized lavas to depths of 1351.74 m (unit 231.2). Below this depth there is an interval, about 100 m thick (i.e., units 231.3 to 247.2, at 1351.74 to 1445.80 m, which consists of a few lavas but predominantly minor intrusives (69.5%). Lava units that occur within this interval are normally magnetized and are likely to be also part of anomaly 5. Separating lava units 247.2 and 253.1 (1445.80-1475.50 m) is a dyke intrusive. Below this level there is a continuous succession of lavas to a depth of 1586.55 m (corresponding to unit 271.2). The uppermost lava has anomalous magnetic polarity direction, while the others are reversely magnetized. This lava succession consists of at least 10 lava units, thought to mark a reversed magnetic polarity zone below anomaly 5 (Bleil and other, 1982). It is possible that in the core the lower boundary of anomaly 5 lies within the interval 1450-1480 m or at 1465 ± 15 m. It is, of course, equally possible that the lower boundary of anomaly 5 is at a slightly shallower depth, at 1445.80 or even 1351.74 m, as discussed above. Above the proposed lava boundary of anomaly 5 in the core, olivine rich lavas are present (Flower and others, 1982; Schmincke and others, 1982). This is also the case in the exposed section (Chapter 2), where the lower boundary of anomaly 5 is marked by the olivine rich Grjota formation, which in turn is overlain by the Ljosa formation, made up of olivine phyric lavas. The lower boundary of anomaly 5 is believed to have an age of 10.3 Ma (McDougall and others, 1976).

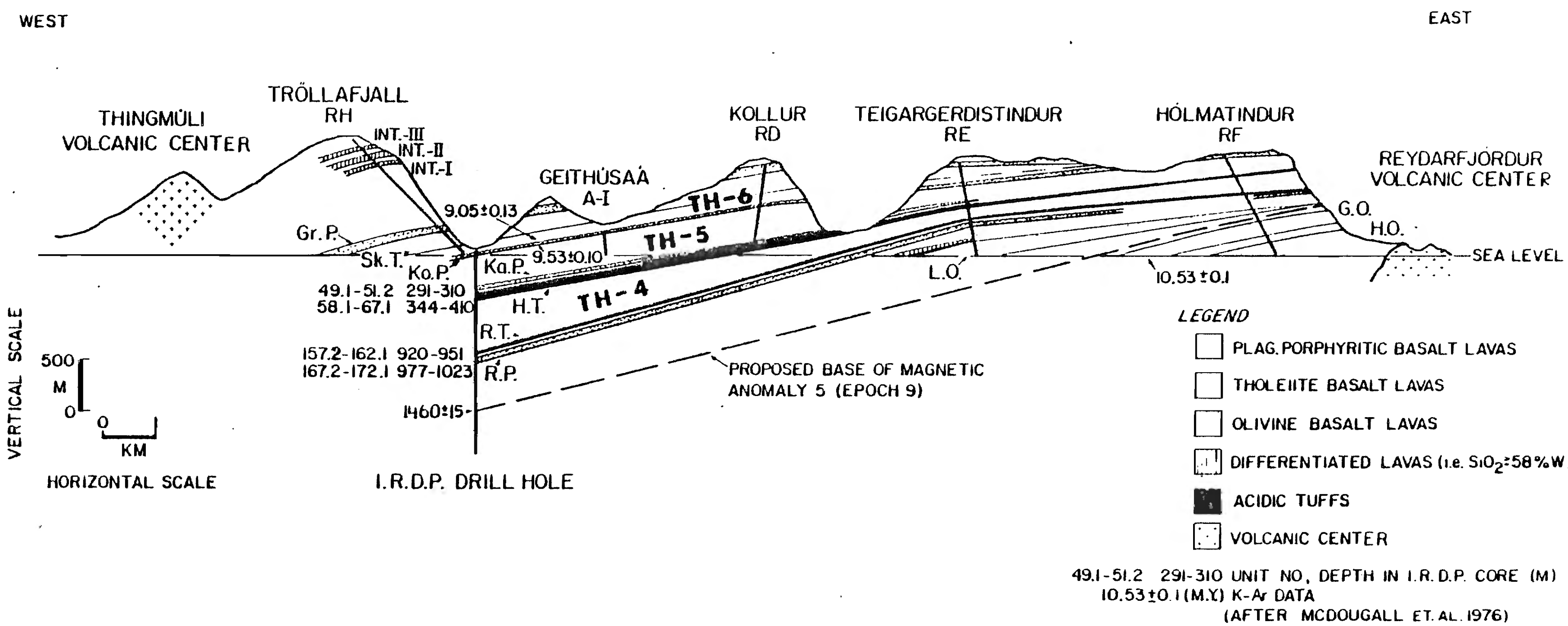
It should be noted that the magnetostratigraphic study provides an independent means of correlating the exposed and cored sections. Based on the thickness of normal lavas 'of anomaly 5 age' in the cored and cliff sections, a substantial thickening is predicted down dip, a feature that is indeed compatible with the proposed lithologic correlation.

1.6 Down dip thickening of lava formations and rates of lava accumulation

1.6.1 Introduction

Inferences about the deeper segments of layer 2 can be made by studying the down dip thickening of lava formations. That lava formations thicken down dip was first pointed out by Walker in 1960. A good example of variable rates of lava accumulation in a vertical section is displayed in Holmatindur (Figure 1.6). The lower part of the Holmatindur section has numerous thin lava flows and very few intercalated sediments. This part of the section is in this study regarded as an example of the deposits in the flanks of a shield volcano with only the flanks exposed. In contrast, the upper part of the section consists of thick lava flows and abundant intercalated sediments, suggesting slower deposition rates for that succession or representing a more distal source. Therefore a more detailed 'tape recording' of the magnetic polarity history is contained in the lower part of the section. As will be shown later (sections 2.4.1 and 2.6, Figures 2.5 and 2.8) the magnetic signature of the lower part of Holmatindur is more uniform than in other sections of the study area, an observation in support of fast accumulation rates for these lavas.

Figure 1.6 Stratigraphic cross section showing the IRDP drill hole relative to the Reydarfjordur volcanic center (east) and the Thingmuli volcanic center (west). Correlated formations of the core are marked according to unit number and the depth interval. The lines connecting known data points have been left as straight lines to avoid bias. Their probable shape is shown on Figure 1.7.


WEST
EAST
THINGMÚLI
VOLCANIC CENTER
TRÖLLAFJALL
RH
INT.-III
INT.-II
INT.-I
GEITHÚSAÁ
A-I
KOLLUR
RD
TEIGARGERDISTINDUR
RE
HÓLMATINDUR
RF
REYDARFJÖRDUR
VOLCANIC CENTER
TH-6
TH-5
TH-4
9.05±0.13
9.53±0.10
Gr. P.
Sk. T.
Ko. P.
Ka. P.
H.T.
R.T.
R.P.
L.O.
G.O.
H.O.
SEA LEVEL
10.53±0.1
49.1-51.2 291-310
58.1-67.1 344-410
157.2-162.1 920-951
167.2-172.1 977-1023
1460±15
PROPOSED BASE OF MAGNETIC
ANOMALY 5 (EPOCH 9)
VERTICAL SCALE
500
M
0
0
KM
HORIZONTAL SCALE
I.R.D.P. DRILL HOLE
LEGEND
PLAG. PORPHYRITIC BASALT LAVAS
THOLEIITE BASALT LAVAS
OLIVINE BASALT LAVAS
DIFFERENTIATED LAVAS (i.e. SiO2≥58%W)
ACIDIC TUFFS
VOLCANIC CENTER
49.1-51.2 291-310 UNIT NO, DEPTH IN I.R.D.P. CORE (M)
10.53±0.1 (M.Y.) K-Ar DATA
(AFTER MCDOUGALL ET. AL. 1976)

One of the many parameters considered in existing models of crustal generation (e.g. Palmason, 1980), is the rate of lava accumulation. In an attempt to quantify this parameter the thickness of units in three tholeiite lava formations was measured in several field localities. The sections lie along the dip direction, from east to west, toward the paleo-rift zone and include the IRDP core (Figure 1.4). The three tholeiite basalt formations are informally termed Th-4, Th-5 and Th-6, as respectively outlined below in sections 1.6.2.1, 1.6.2.2 and 1.6.2.3.

These tholeiite lava formations are shown on stratigraphic diagrams (Profiles 1 and 2, folded inside back cover). They are separated by formations of either olivine or porphyritic basalt lavas, or commonly pyroclastic tuffs, all units that are easily identified in the field. It is assumed here that each tholeiite lava formation is interstratified between two other formations in such a way that boundaries between lava formations essentially mark an isochron. In other words if formations were erupted within a relatively short period with only a minor hiatus separating the lavas. However, once a lava formation of a particular lithology had erupted, a hiatus commonly set in as evidenced by frequent occurrences of sedimentary units at boundaries between lava formations. Assuming isochron boundaries between formations the increase in lava accumulation represented by down dip thickening of formations becomes equivalent to increased <u>rates</u> of lava accumulation. One important aspect of the study on rates of lava accumulation is the scarcity of K-Ar age determinations and the neccessity for high precision on age determinations to detect changes of this parameter. The lavas now exposed in eastern Iceland were deposited at an average rate of one lava in 16,000 years (McDougall and others, 1976) but the best available precision for dated lavas (K-Ar) is about 100,000 to 150,000 years (Watkins and Walker, 1977). The author argues that the actual hiatuses with regard to lava accumulation are poorly defined and can range from perhaps a few years to several hundred thousand years. Considering (a) the precision of dating methods, and (b) the great number of lavas that were erupted over a relatively short period (Table 1.5) it follows that precise rates of lava accumulation are difficult to measure. A problem arises when accounting for down dip thickening of lava formations that is related to ability of lavas to reach distal parts of the volcanic zone. As a result no ideal method exists to compensate for the different rates of lava accumulation obtained from the various elevation levels investigated in the lava succession. It is therefore a risky matter to correlate the measured magnetostratigraphic sections that are obtained from several, often overlapping, stratigraphic profiles with the geomagnetic time scale. Ideally, a prerequisite for doing so is to have knowledge of the thickness of each magnetic chron, both at the measured locality and at the paleorift axis.

1.6.2 Down dip increase in rates of lava accumulation in Reydarfjordur

Tholeiite lava formations (Th-4 to Th-6) forms the basis for a subsequent discussion on the problem of evaluating volcanic production rates in the Tertiary areas of Iceland, section 1.7. Summarized in Tables 1.2, 1.3, and 1.4 are stratigraphic data, relevant to the three tholeiite formations, Th-4, Th-5, and Th-6. Profiles 1 and 2 show in detail the distribution of lava formations Th-4 to Th-6 in various sections of the stratigraphic study on both north and south sides of the fjord.

1.6.2.1 Tholeiite formation, Th-4

Both in Holmatindur and Teigargerdistindur (sections RF and RE, respectively, on the north side of the fjord) a thick succession of tholeiite lavas separates the Reydarfjordur tuff and the overlying marker unit, the Holmatindur tuff (Table 1.2). In the Holmatindur section this formation is 90 m thick (613 to 736 m elevation), but has acquired a thickness of about 500 m in the IRDP cored succession at 409.60 to 914.88 m depth. Thus the rate of lava accumulation is 5-6 times greater at a mean depth of about 660 m below sea-level in the core than in the same lava formation approximately 13.5 km to the east up dip in Holmatindur at a mean elevation of 675 m.

1.6.2.2 Tholeiite formation, Th-5

The stratigraphic succession between the Kambfjall and Kollur porphyritic basalt formations consists of tholeiitic lavas, a formation informally termed Th-5. This formation is well exposed in several vertical cliffs. The formation thickens by a factor of 3 (see Table 1.3), from about 110 m in Holmatindur to about 330 in the core. The increase in the number of lavas for the same interval is from 9 lavas in Holmatindur to 32 lavas in Kollur. In the core, however, only about 22 lava units are observed for this interval due to obliteration by minor intrusives. This typifies the problem of correlating the exposed and

Table 1.2 Stratigraphic parameters for lavas of tholeiite formations Th-4, above the Reydarfjordur porphyritic basalt formation and below the Holmatindur tuff formation.

Section	Profile	Degree of Exposure	Unit Interval	Thickness of Lava Interval (m)	Number of Lavas	Average Lava Thickness (m)	Height/ Depth Interval (m)	Sedimentary Rocks in Unit Interval (%)	Sedimentary Rocks in Unit Interval (m)	Approximate Distance from IRDP Drillsite (Km)
Holmatindur	RF [a]	Complete	66-75	90	9	10	~613-736	8.6	8.5 [b]	13.5
Teigargerdistindur	RE	Complete	8-19	154	12	12.8	~360-528	2.8	4.5	8.0
I.R.D.P. - Core	-	59% [c]	70.1-167.2	519.89 [d] 265.34 [e]	46	5.77	409.60-976.63	8.3	47.14	-

a) the sequence of profiles from the I.R.D.P. drillsite east toward Holmatindur (RF) is approximately perpendicular to the mean lava strike (N2°W). The I.R.D.P. drillsite is at 60 m.a.s.l.

b) fraction of clastic material in core interval (excluding minor intrusives)

c) minor intrusives amount to 41.50% of core interval

d) total thickness in core interval (i.e. complete and incomplete lava units)

e) this value includes only complete lavas in core

Table 1.3 Stratigraphic parameters of units of tholeiite formation Th-5, overlying the Holmatindur tuff formation and below lavas of the Kollur porphyritic formation.

Section	Profile	Degree of Exposure	Unit Interval	Thickness of Lava Interval	Number of Lavas	Average Thickness	Height/Depth Interval	Sedimentary Rocks		Approximate Distance from I.R.D.P. Drill-site
				m		m	m	%	m	km
Holmatindur [a]	RF	Complete	76-84	111	9	12.3	~736-860	4.7	5.5	13.5
Teigargerdistindur	RE	Complete	20-32 [b]	156	13	12.0	~550-695	2.6	4.2	8.0
Kollur	RD	Complete	3-34	277	32	8.7	~ 93-379	2.3	6.5	3.5
Geithusaa	A-1	[c]	1-22	>145	>22	4.8	~ 50-235	4.3	6.5	1.5
I.R.D.P. - core [e]	-	60% [d]	1.1-56.2	>145.78 <332.45	>22	6.8	11.70-344.15	6.24 [f]	10.0	-

a) the lavas in this section are mainly columnar jointed

b) included in the Teigargerdistindur section are 'foreign' olivine basalt lava units (#25-29) that were not found in the other sections downdip

c) only upper part of the lava sequence is above sea level in Geithusaa section

d) minor intrusives amount to 39.9% of this core interval

e) only complete lava units from core are included in this study

f) note that the Holmatindur tuff is not included in this study which significantly lowers the sediment ratio in formation Th-5 cored sections on a unit by unit basis, although lava formations are more easily recognized in the drill core.

1.6.2.3 Tholeiite formation, Th-6

Data concerning formation Th-6 is given in Table 1.4. The lavas above the Kollur formation are all younger than those occurring in the cored IRDP succession but are still important for the study of the three dimensional structure of the lava succession. The tholeiite lava succession between the Kollur and Graenavatn porphyritic formations is well exposed in several vertical outcrops. Over a distance of approximately 8 km from Teigargerdistindur (section RE) to the area above the drill site (section RH) the rates of lava accumulation increase by a factor of about 2, from about 106 to 206 m. The change in elevation for these sections is from about 820 to 150 m.a.s.l. Within this lava interval the increase in the number of lavas down dip is from 11 to 29. The high number of lava flows in formation Th-6 by the drill site might indicate that the volcanic zone from where these lavas flowed is relatively close by, e.g. in the Thingmuli area.

1.6.2.4 Quantitative discussion of down dip thickening of formations

The two-dimensional shape of tholeiite lava formations Th-4 to Th-6 is diagrammatically summarized in Figure 1.7. These lava formations were correlated with the IRDP core, the lowest lava units used for this purpose occur at a depth of about 1000 m. Sections identified in the cored succession are substantially thicker than in the exposed cliff section. The thickness of formations Th-6, Th-5, and Th-4 in sections RE and the IRDP-succession, across an 8 km stretch, increases down dip

Table 1.4 Stratigraphic parameters of units of tholeiite formation Th-6, below the Graenavatn porphyritic formation and overlying the Kollur porphyritic formation.

Section	Profile	Degree of Exposure	Unit Interval	Thickness of Lava Sequence	Number of Lavas	Average Lava Thickness	Height/Depth Interval	Sedimentary Rocks in Unit Interval		Approximate Distance from I.R.D.P. Drill-site
				m		m	m	%	m	
Teigargerdistindur	RF	Complete	37-47	106	11	9.7	740-885	10.7	12.8	8.0 (east)
Kollur	RD	Complete	39-53	180	15	12.0	435-650	7.5	14.6	3.5 (east)
Trollafjall	RH	Complete	720-766	206	29	7.1	65-230	7.8	17.8	< 1 (south)

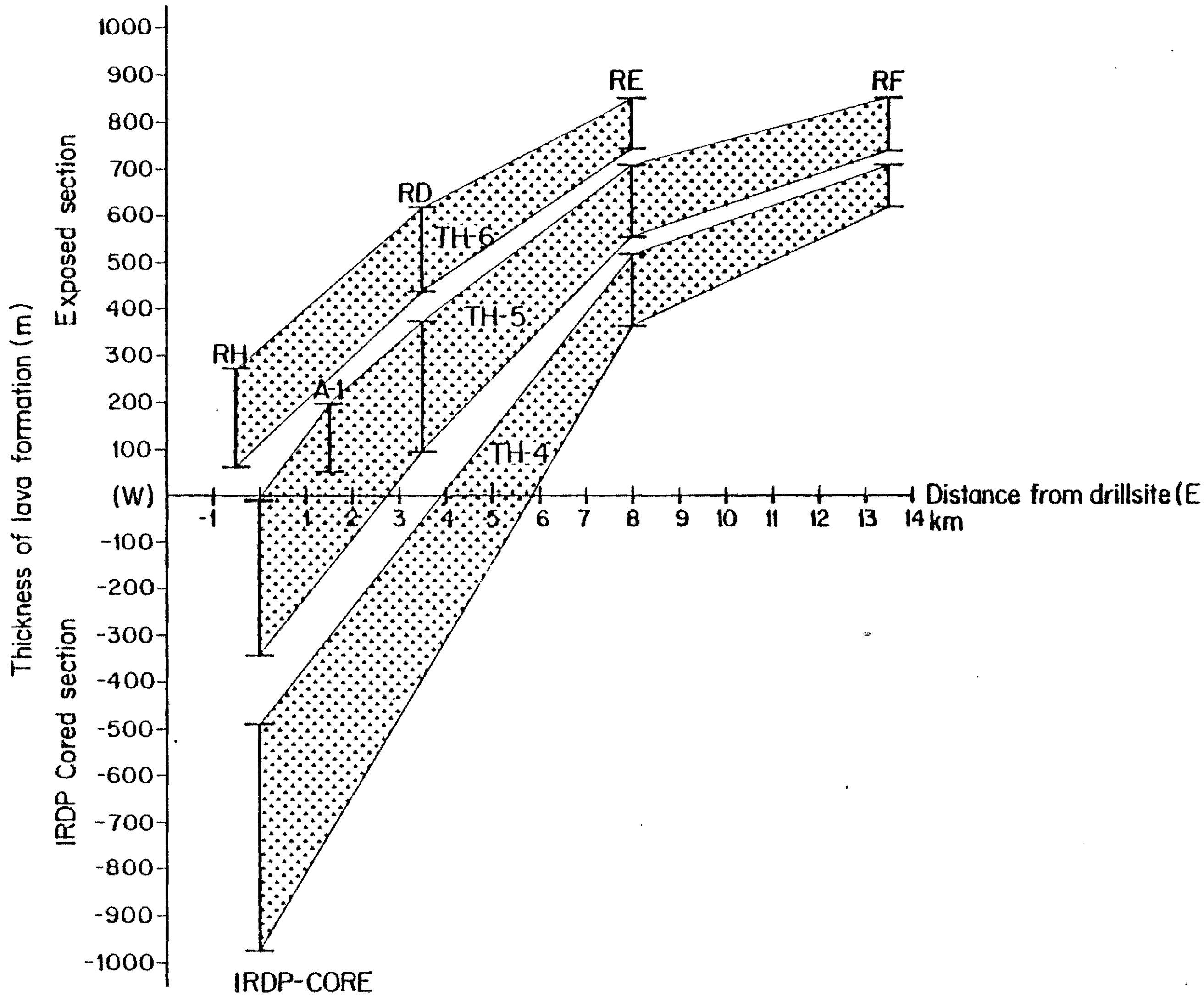


Figure 1.7 Two dimensional shape of lava formations Th-4, Th-5, and Th-6 as measured in sections RF, RE, RD, RH and the IRDP drill core.

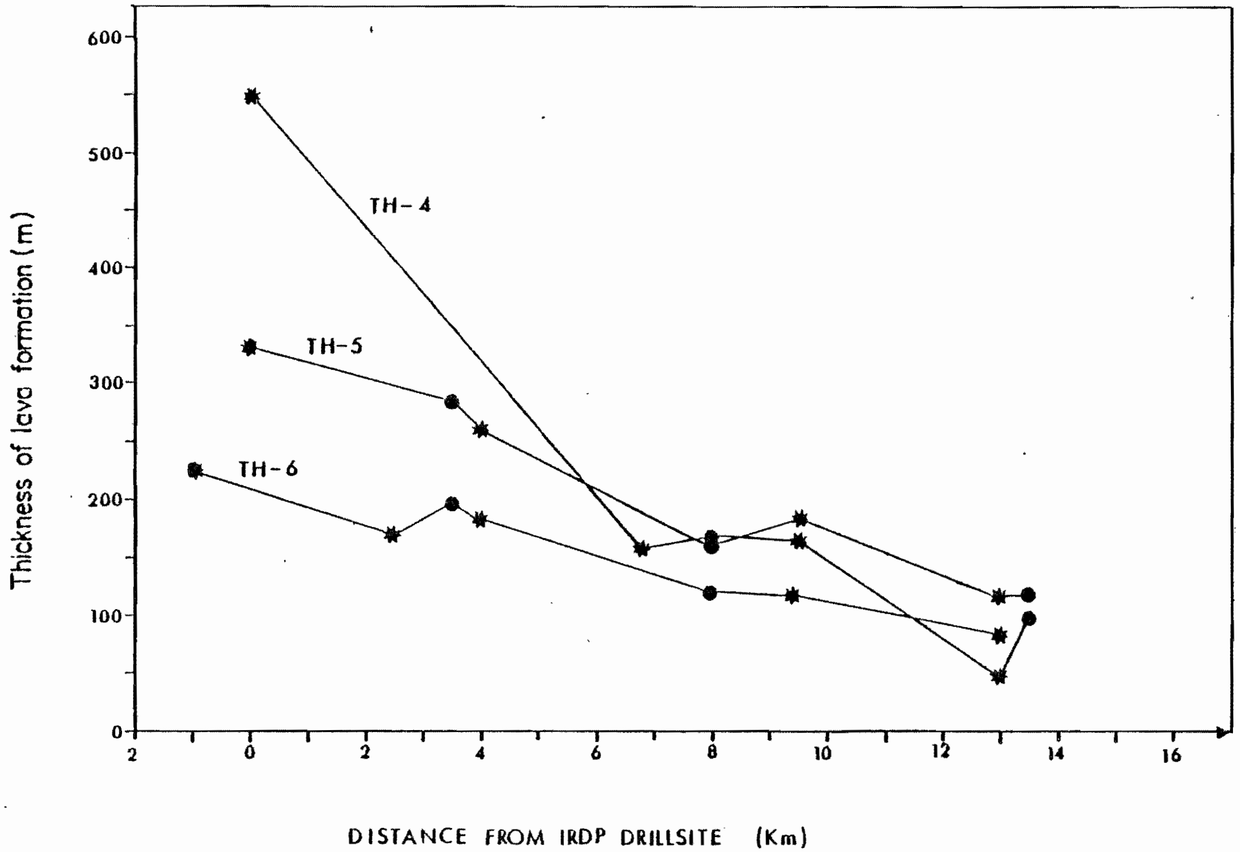


Figure 1.8 Relative thickness of lava formations Th-4, Th-5 and Th-6 as measured from Holmatindur (section RF) toward the IRDP drill site. Asterisks: south side of fjord; dots: north side.

by a factor of about 1.9, 2.1, and 3.4, respectively. Thus the thickness of the lowest of these three formations, Th-4, increases fastest. The relatively greater thickening of formation Th-4 between RE and the drillsite can be accounted for by the increased lateral dimension of this lowest formation. The upper and lower formation boundaries are convex upward. As a result of increased subsidence the arc of these curved surfaces is considerably greater in the lower sections. Worded differently, although the present horizontal distance between section RE and the drillsite is equal for all three formations, Th-4 has been subjected to greater overall subsidence, its lower surface is the most convex upward and therefore it represents a considerably greater surface area of the flanks of a shield like volcano located to the west of the drill site. This is demostrated on Figure 1.8 where the thickness of tholeiite lava formations Th-4 to Th-6, as measured on <u>both</u> sides of the fjord, is plotted against distance from the IRDP the drillsite. Additional explanations for the increased thickness of Th-4 relative to Th-5 and Th-6 could be (a) because the source for these lavas is further eastward, (b) the older lavas had drifted further to the east, or (c) the lavas of formation Th-4 were banking up against a volcanic zone located east of the Thingmuli area (see Chapter 7). Based on the available data, lava formations Th-5 and Th-6 thicken in a very similar manner but lava formation Th-4 thickens considerably faster as was discussed above.

In Figure 1.9a the number of lavas is plotted against distance from drillsite. Generally lavas increase in thickness westward toward the drillsite. This strongly suggests that the paleorift axis of the Tertiary volcanic zone that generated this lava succession is located

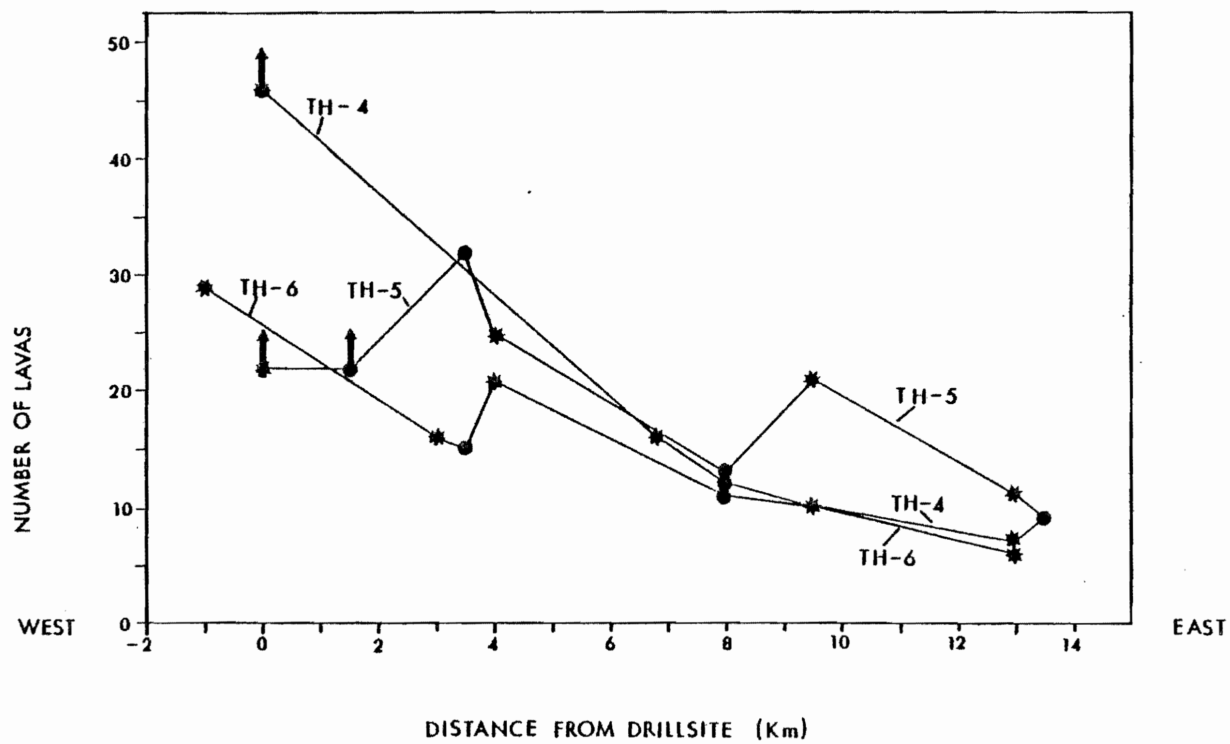


Figure 1.9a Number of lavas in formations Th-4, Th-5, and Th-6. Note that where dyke intrusives occur in the cored IRDP sequence information on the surrounding lava sequence is missing and as a result the number of lavas in formation Th-4 and Th-5 is based on incomplete 'exposure'. Black dots denote values obtained from north side of Reydarfjordur whereas values with asterisks are from the south side.

west of the IRDP drill site.

In Figure 1.9b the mean lava thickness of lavas in formations Th-4 to Th-6 is plotted against distance from the drillsite. The average lava thickness in formation Th-4 is irregular and fluctuates from about 7 to 12 m. Conversely the mean thickness of lavas in formations Th-5 and Th-6 decreases rather regularly from about 12 to 6 m. The variations of the mean lava thickness in formation Th-4 may perhaps be explained by irregularities or relief of the underlying formations, i.e. the Ljosa, Grjota and Holmar olivine basalt formations which are thought to be shieldlike in form and appear to have smaller areal extent than the tholeiite formations.

On Figure 1.10 three best fit exponential curves are presented for the available data (Table 1.6) on the westward thickening of lava formations. These curves are, however, extrapolated 10 km into the area west of the drillsite. By the drillsite these lava formations are a total of 1106 m thick but are predicted with large uncertainty to have a thickness of 1961 m at a distance of 5 km west of the drillsite. The equation that best fits the data is of the form

$$Y = a\ e^{bX}$$

where X is the measured distance perpendicular to the area of lava extrusion as observed in Reydarfjordur; a is the thickness of lava formations at the ridge axis but Y equals the measured thickness in Tertiary regions (i.e. in Reydarfjordur). The rate of change in Y or down dip thickening of lava formations is described by b times Y m/km. For the three formations, Th-6 to Th-4 the value of b is: -0.0722, -0.0772, and -0.1510, respectively. Earlier derived values of b are

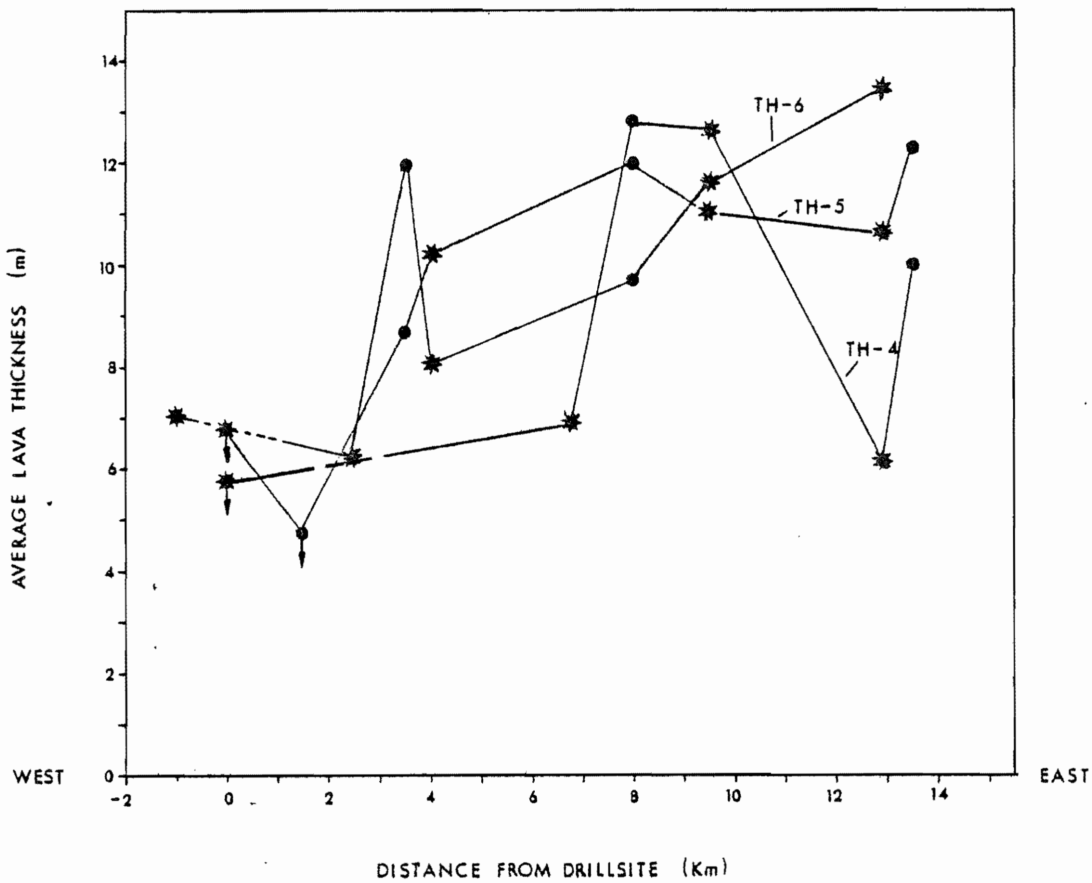


Figure 1.9b Average thickness of lavas in formations Th-4, Th-5, and Th-6 plotted for distance away from the IRDP drill site. Note that values within brackets are based on incomplete exposures. Asterisks: south side; dots: north side.

Figure 1.10 Best fit curves for the thickening of lava formations that form flexural wedges. Based on data from the IRDP drill core (x) and measured stratigraphic sections of the cliff area east of the drill site (Table 1.5). Indicated is the approximate location of the Thingmuli and Reydarfjordur volcanic centers, to where the curves have been extrapolated (dashed line).

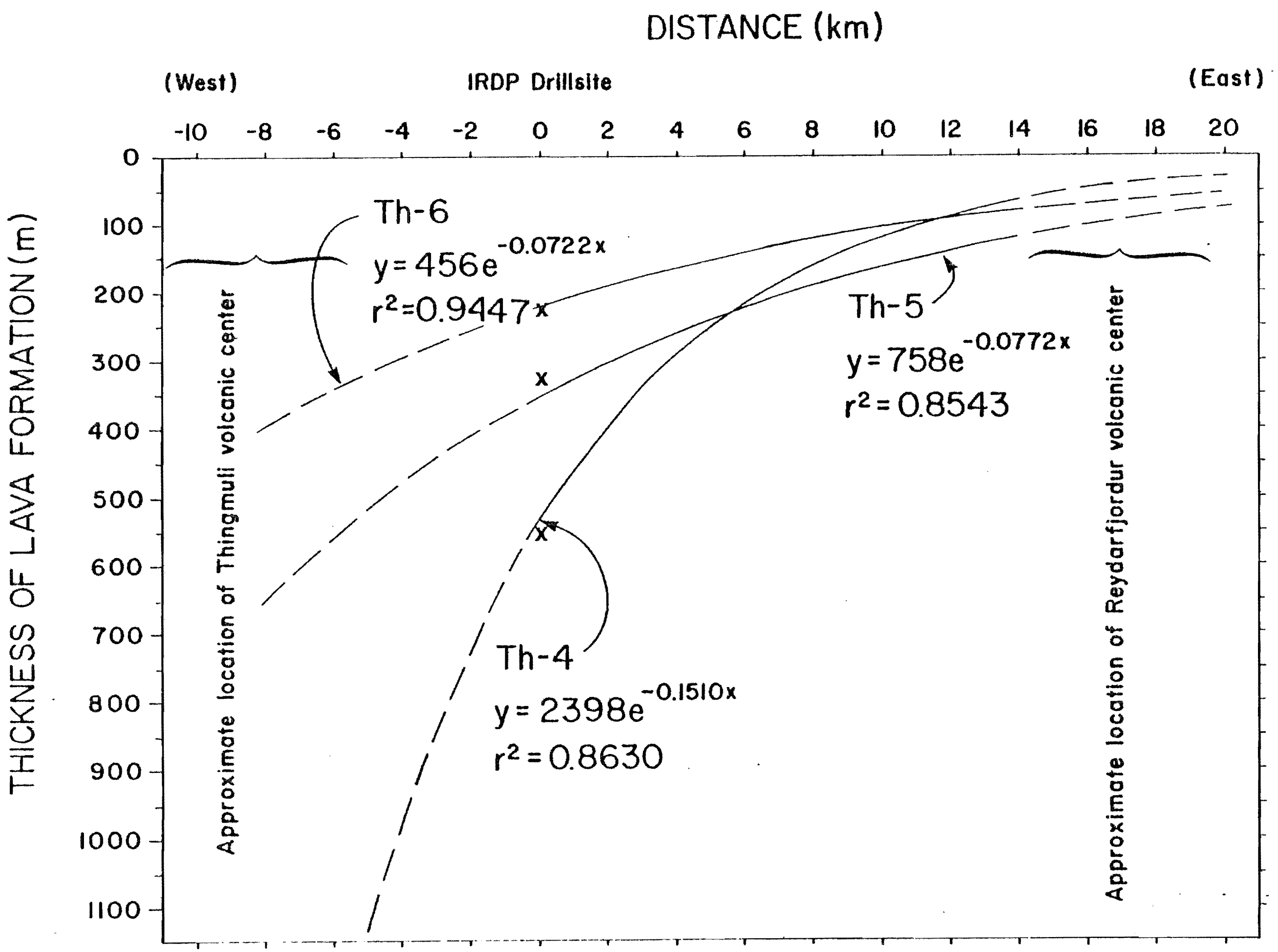

DISTANCE (km)
(West)
IRDP Drillsite
(East)
-10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20
THICKNESS OF LAVA FORMATION (m)
0 100 200 300 400 500 600 700 800 900 1000 1100
Th-6
y = 456e^-0.0722x
r² = 0.9447
Th-5
y = 758e^-0.0772x
r² = 0.8543
Th-4
y = 2398e^-0.1510x
r² = 0.8630
Approximate location of Thingmuli volcanic center
Approximate location of Reydarfjordur volcanic center

Table 1.5 Measured Thickness (m) and distance for lava formations Th-4, Th-5, and Th-6 projected onto a common E-W line relative to the IRDP drill site (distance 0.0 km). These values were used to derive best-fit curves as shown on Figure 1.10.

Th-4		Th-5		Th-6	
distance	thickn.	distance	thickn.	distance	thickn.
0.0	567 (548)*	0.0	332*	-1.0	224*
6.8	157 *	3.5	284	2.5	168 *
8.0	159	4.0	260 *	3.5	195
9.5	163 *	8.0	160	4.0	179 *
13.0	47 *	9.5	238 *	8.0	119
13.5	99	13.0	117 *	9.5	117 *
		13.5	117	13.0	82 *

* Measured values from south side of the fjord, others from north side.

(548) Corrected value for the assumed tilting of lava formation Th-4 in the IRDP core.

Table 1.5 Measured Thickness (m) and distance for lava formations Th-4, Th-5, and Th-6 projected onto a common E-W line relative to the IRDP drill site (distance 0.0 km). These values were used to derive best-fit curves as shown on Figure 1.10.

Th-4		Th-5		Th-6	
distance	thickn.	distance	thickn.	distance	thickn.
0.0	567 (548)*	0.0	332 *	-1.0	224 *
6.8	157 *	3.5	284	2.5	168 *
8.0	159	4.0	260 *	3.5	195
9.5	163 *	8.0	160	4.0	179 *
13.0	47 *	9.5	238 *	8.0	119
13.5	99	13.0	117 *	9.5	117 *
		13.5	117	13.0	82 *

* Measured values from south side of the fjord, others from north side.

(548) Corrected value for the assumed tilting of lava formation Th-4 in the IRDP core.

about -0.1 (Ross and Musset, 1976) where a correction for the flexural wedging shape has not been made. Strictly a correction should be made for formation Th-4, which has been subjected to greater subsidence and as a result its shape is the most concave upward. A correction for this feature toward a straight horizontal line would increase the value of b and result in an almost identical shape for lava formations Th-5 and Th-6. In conclusion it appears that the shape of lava formation Th-4 differs from the two overlying formations, i.e. Th-5 and Th-6, as if the thickness of Th-4 was relatively greater at the ridge axis. Similarly, it appears that the up dip thinning of Th-4 is more rapid than for both lava formations Th-5 and Th-6. Further elaboration of this matter is beyond the scope of this thesis.

1.7 Implications for volcanic production rates in Iceland

Investigated traverses of the stratigraphic succession in different areas may vary in thickness due to factors such as variations in volcanic production, different distances from the source region or erosion.

1.7.1 Estimates of volcanic production and effects of distance to source

Volcanic production rates of submarine mid-ocean ridges are difficult to estimate due to lack of data on the thickness of the extrusive succession of the oceanic crustal layer and the complex tectonic pattern at the spreading ridge axis. In Iceland the volcanic history is well documented for the last eleven hundred years (Thorarinsson, 1967) where the total volcanic production is estimated as 40 km^3. During postglacial times the estimated volcanic production in Iceland amounts to 484 km^3 for the last ten thousand years (Jakobsson, 1972), with a maximum of 123 km^3 just south of middle Iceland over a 65 km length of the volcanic zone.

A quantitative evaluation of rates of volcanic production (volume/time/area) for the Tertiary areas of Iceland has so far remained obscure due to lack of data on the three dimensional structure of the lava succession. Although rough, the most promising way to estimate volcanic production in an extinct Tertiary region in Iceland seems to be to study the rates of lava accumulation (Watkins and Walker, 1977). This method involves assumptions that are not neccessarily valid locally. However, provided that the same assumptions are made everywhere, the method may be a reasonable approximation to distinguish regional differences in rates of lava accumulation. Because of the difficulty of estimating volcanic production in the Tertiary regions of Iceland, rates of lava accumulation may be the best available data to model long term crustal generation. It is of relevance here to remember that most lava formations can be observed to continue their thickening trend down dip, below sea level. As a result it becomes obvious that the exposed lava succession in eastern Iceland represents only a relatively small fraction of the entire extrusive crustal segment. The present study of tholeiite lava formations Th-4 to Th-6 shows that the rate of thickening for these three formations over the same stretch differs. For example the thickness ratio for Th-4, Th-5 and Th-6 between section RE and the drill site are 3.4, 2.1 and 1.9, respectively. The rate of thickening for formation Th-4 is too high to be caused simply by a difference in elevation. Two alternative explanations for the different thicknesses could be that (a) the volcanic production did not remain uniform during the buildup of these formations, or (b) the distance to the eruptive center (fissure swarm) was smaller for formation Th-4 than Th-5 and Th-6.

In their study of the exposed lava succession, Watkins and Walker (1977) calculated apparent rates of lava accumulation for eastern Iceland and found the build-up rate over the time interval 13.4 to 2.3 Ma to range from 2600 to 360 m/m.y. Thus these rates vary by a factor of about 7 when averaged over a one million year interval as shown in Table 1.5.

Watkins and Walker used the zeolite zonation of Walker (1960) to correct for the variable rates of lava accumulation observed by the down dip thickening of the lava succession. The analcime zone was assumed to be parallel to the pre-erosional surface, which in turn is taken to be 600 m above the upper level of the analcime zone. Depending on the relative location of a paleomagnetic section, i.e., above or below the analcime zone, these authors divided its thickness by a factor that was repectively larger or smaller than 1. Applying this adjustment, they found the rate of lava accumulation only to vary by a factor of 4 for the entire build up of eastern Iceland (i.e. during 13.4 and 2.3 Ma) as shown in part B of Table 1.5. This procedure was applied 'to normalize lava thicknesses to that at a fixed distance from the extrusion center' (Watkins and Walker, 1977). The extent to which this normalizing method relates sample locality to distance from the eruptive site is questionable for the following reasons:

Table 1.6 Apparent (A) and corrected (B) rates of volcanic production in eastern Iceland (after Watkins and Walker, 1977).

Episode	Period (m.y.b.p.)	Rate (m/m.y.)	Relative Rate
	A. Uncorrected for downdip thickening		
V-1	13.4 to 7.6	720	2.0
V-2	7.6 to 6.5	2600	7.3
V-3	6.5 to 2.3	360	1.0
	B. Corrected for downdip thickening		
V-1	13.4 to 7.2	560	1.2
V-2	7.2 to 6.4	1900	4.1
V-3	6.4 to 2.3	460	1.0

(a) the reference zone is defined by the occurrence of analcime, a zeolite mineral whose abundance varies greatly from one section to the next (Walker, 1959, and work in progress by the author).

(b) the analcime zone has been shown to fluctuate in thickness and elevation by as much as 500 m in Berufjordur, eastern Iceland (Walker, 1960). This fluctuation cannot be accounted for by different degrees of erosion.

(c) the effects which composition of basaltic host rocks has on the distribution of analcime have not been thoroughly investigated.

(d) as the source region is generally unknown or buried below sea level the validity of this method cannot be tested.

The 'normalizing' method applied by Watkins and Walker (1977) neither accounts for variations in volcanic production nor variations caused by different distances from the extrusive center relative to the IRDP drill site because the location of the extrusive centers for tholeiite lava formations Th-4 to Th-6 remain unknown. Information on the depth of burial of the subaerial lavas coupled with a few measured and derived age determinations has, prior to the IRDP drilling, only been available from the presently exposed section (McDougall and others, 1976). This prompts the question what portion, in a vertical sense, of the total extrusive layer has been investigated? The postulated model in Chapter 7 provides one qualitative answer to this question and several implications that arise from it.

1.7.2. Erosional effects

Despite great variations in local estimates on rates of lava accumulation, it is generally assumed that volcanic production has remained constant during the build up of Iceland (Palmason, 1981). According to accepted models (e.g. Walker, 1965; Gibson and Piper, 1972), variations in rates of lava accumulation between closely spaced traverses would be caused simply by the difference in elevation between the investigated traverses. By applying a normalizing procedure (previous section) the derived rates of lava accumulation were corrected for such effects (Watkins and Walker, 1977). In the present study the up dip part of the exposed lava succession is assumed to represent the flanks of the paleo-rift zone where the lowest rates of lava accumulation occurred. From volume considerations the exposed upper succession is, therefore, of much less importance compared to the more voluminous lava succession below sea levels.

Therefore, the rates of lava accumulation as estimated by Watkins and Walker (1977) must be only minimum values of volcanic production. First, their estimate is affected by the present level of erosion below the original plateau surface in eastern Iceland. Thus if erosion everywhere in eastern Iceland was greater by, for example, one kilometer (or corresponding to a 1 km depth in the IRDP core), the derived volcanic production would have been greater by a factor of at least 2 and probably 4 to 5. Secondly, the geomagnetic traverses (Dagley and others, 1967) were selected to avoid the volcanic centers, i.e., the areas of greatest hydrothermal alteration. Later (1977) Watkins and Walker used these same stratigraphic traverses to derive rates of lava accumulation. By avoiding the volcanic centers, Watkins and Walker (1977) derived rates of lava accumulation for traverses located outside the areas of greatest volcanic production. Therefore, conclusions drawn from paleomagnetic investigations carried out in eastern Iceland may be at fault because considerable uncertainty exists about the length of time of derived magnetic polarity chrons. This uncertainty, caused by the variable thickness of lava successions, does (locally or regionally) affect the length of polarity intervals by at least as much as a factor of 2 to 4.

Similarly, the height to the pre-erosional surface of the lava succession has only been roughly estimated (Walker, 1960). This is because the height of the analcime zeolite is very variable (see above). In conclusion, for eastern Iceland, the exposed lava succession provides a biased, totally inadequate estimate of the volcanic production, because the bulk of each lava formation is located below sea level.

1.7.3 Effects of climatic conditions and shift of the volcanic zone on apparent volcanic production

The style of volcanic accumulation in Iceland is different under subaerial and subglacial or submarine conditions. Any model describing crustal growth in Iceland needs to take into account the onset of cold climate and/or glaciation in a highly active volcanic regime. The earliest lithologic evidence for cool or cold climate in western Iceland has been dated at 4.3 to 4.4 Ma (Johannesson, 1975). A reported age (Ar^{40}/Ar^{39}) for the earliest cold climate formations in eastern Iceland is about 5.5 Ma (Ross and Musset, 1976; Watkins and Walker, 1977). However, new palynological evidence (Mudie and Helgason, in press) indicates an earlier temporary cool climatic transition of about 10°C in the study area as old as 9.8 Ma. The lower rates of lava accumulation observed during volcanic episode V-3 (Table 1.5) could have been caused by local accumulation of lavas within the volcanic zone(s) where eruptions occurred beneath ice caps. Such conditions would presumably prevent or minimize flow of lavas to distal parts beyond the volcanic zones and would have resulted in low observed rates of lava accumulation in eastern Iceland. However, no field evidence in the form of sub-glacial pillowed basalt flows has yet been found in rocks of this age in eastern Iceland.

The effects of large scale (about 100 km, Saemundsson, 1974) and small scale (20-40 km, present study) shifting of the axial rifting zone on rates of lava accumulation may be as effective in changing apparent rates of lava accumulation as a subaerial-subglacial climatic transition. Both onset of glaciation and shifting of the axial rift zone may have significantly affected rates of lava accumulation in eastern Iceland. The effects of shifting the axis of volcanism are discussed in more detail in chapter 7.

In summary, the western Reydarfjordur area consists of two volcanic centers (Figures 1.2 and 1.6), i.e., Reydarfjordur and Thingmuli volcanic centers. The area between these centers is made up of lavas whose source is assumed to be located west of the drill site. It is suggested that a shift in volcanic activity took place from the Reydarfjordur volcanic center to a new rift zone located about 20 km or more to the west. At about 20 km west of the Reydarfjordur volcanic center an axial rift zone was to develop along which the Thingmuli and Breiddalur volcanic centers became active with their associated acidic volcanism. The proposed shift was from 'one line' of volcanic centers in the east to another the Breiddalur-Thingmuli volcanic zone in the west. Based on magnetostratigraphic work (Chapter 2) in Holmatindur and correlations with the geomagnetic time scale, this shift coincides roughly with the lower boundary of anomaly 5 at 10.3 Ma (McDougall and others, 1976).

CHAPTER 2

MAGNETOSTRATIGRAPHY

2.1 Introduction

The paleomagnetic history of the exposed Tertiary basalt lava succession in eastern Iceland has been correlated with the marine as well as onland geomagnetic time scales (Watkins and Walker, 1977). Lavas in the mountainous Reydarfjordur area (Figure 1.3) dip gently (2°-12°) toward the neovolcanic zone west of the research area. The cliff section east of the IRDP drill site, typically 1000 m high, includes lava formations that are intersected at depth below sea level. In accordance with models of crustal generation, the lava formations in the cliff section, although thinner, should generally have the same paleomagnetic signature as the lavas in the cored succession. Lithological and magnetic correlations of the cored and exposed lava successions were regarded as fundamental to an interpretation of the three-dimensional structure of the lava succession. For studying time-dependent variations in the stratigraphic succession it is essential to assign an age to the rock formations. Provided that two objectives are met, the task of dating the IRDP core can clearly benefit from available combined paleomagnetic and K-Ar dating work from the surrounding region. These objectives are: (1) magnetic correlation of lavas east of the drill site with paleomagnetic profiles about 20 km to the north in the strike direction, where lavas had been dated by the K-Ar method (McDougall and others, 1976), and (2) lithological correlation of the exposed lavas east of the drill site with the cored lava succession.

It was anticipated that the present paleomagnetic investigation, substantiated by a detailed stratigraphic study (Chapter 1), would help constrain the three-dimensional structure and mode of formation of a 3.5-km-thick vertical crustal transect. The investigated transect, generated at an accreting plate boundary, extends for about 20 km in the dip direction toward a paleo-rift zone. For this reason a 1-km-thick vertical lava section up dip of the drill-hole was sampled for paleomagnetic studies in Holmatindur in 1979 (section RF, Figure 2.1). However, when correlation was attempted with earlier paleomagnetic work in the region, the paleomagnetic record of the Holmatindur lavas proved unexpectedly complicated. Despite lithological correlation of lavas in Holmataindur and section E, about 20 km north of the drill site (Watkins and Walker, 1977), the study in 1979 indicated contradicting magnetic correlation for these two sections. The Holmatindur section had frequent magnetic reversals whereas section E contained a long succession of normally magnetized lavas that had been correlated with 'seafloor magnetic anomaly 5', epoch 9, henceforth called anomaly 5 (McDougall and others, 1976). Further sampling in the area was essential to solve this conflict, and in 1980, two additional sections were sampled between Holmatindur and the drill site, sections RD (Kollur) and RE (Teigargerdistindur) on Figure 2.1. This disagreement has now been resolved, and the author contends that it is due to the local effects of dykes (see section 2.4.3 below).

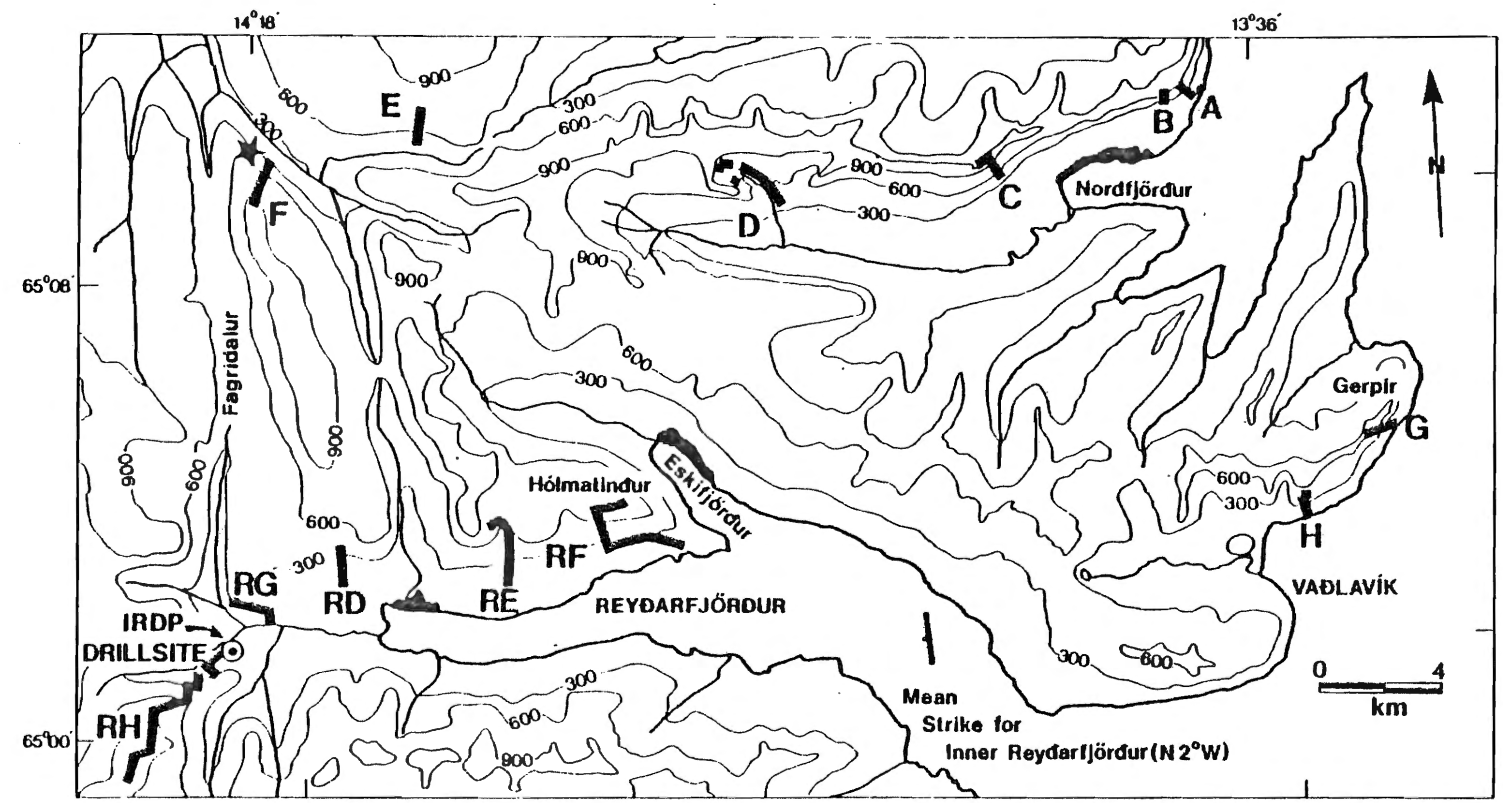


Figure 2.1 Location of investigated profiles in Reydarfjordur: Kollur (RD), Teigargerdistindur (RE), Holmatindur (RF), Graenafell dyke section (RG), Trollafjall lava/dyke section (RH), and previously studied sections in the region (Watkins and Walker, 1977): G, H, A, B, C, D, E, and F. Marked with a star is the location of K/Ar-dating sample: KOP-1.

2.2 Paleomagnetic sampling and laboratory treatment

As stated earlier it was expected that the paleomagnetic section in Holmatindur contained stratigraphic units that would overlap with the IRDP core. One main criterion for selecting sampling sites RD and RE was that they incorporate lava formations that, although thinning, can be seen to extend up dip to the Holmatindur section. Each sampled unit was marked in the field with a painted number. A total of 154 units were sampled in three sections, RD, RE and RF on Figure 2.1. Generally, four minicores, 2.5 cm in diameter, were drilled from each lava with a two-stroke portable drill. The samples were oriented in situ with a Brunton compass using both geographic and sun sightings. Each core was sliced, and approximately 8 cm^3 were used for paleomagnetic studies. Information on stratigraphic sections is provided in Table 2.1. The direction and intensity of natural remanent magnetization (NRM) were measured with a Schonstedt digital spinner magnetometer at Dalhousie University. Applied peak alternating field values during demagnetization ranged from 150 to 250 Oe for sections RD and RE, whereas for section RF the applied field ranged from 25 to 500 Oe in 11 successive steps (i.e. 25, 50, 75, 100, 150, 200, 250, 300, 350, 400 and 500 Oe).

The RF section in Holmatindur was divided into 90 lava units each marked in the field with a painted number. Three intervals of thin flow units occur in the lower part of the section; for each interval only one unit was drilled. Only three segments, each less than 10 m in thickness, are covered with rubble and not exposed in the vertical section. Units 52 through 88 are located in a gully containing a

10-m-thick vertical dyke of reversed polarity (unit RF51D, Table 2.2). A total of five thin lavas, i.e., units 35A, 49A, 54A, 54B, and 88A were not sampled for this paleomagnetic study.

2.3 Paleomagnetic results

2.3.1 Results from section RF (Holmatindur)

Following conventional statistical methods (Fisher, 1953), the minimum scatter was calculated, i.e., α_{95}, for the mean paleomagnetic direction of each unit. Results for section RF (Holmatindur) are presented in Table 2.2. For 20 lava units in section RF, α_{95} indicated low internal consistency; therefore an additional sample was spun. This usually resulted in excellent agreement for three samples of each lava unit. However, samples were rejected if widely removed from the average unit declination and/or inclination. Of the 342 minicores demagnetized from Holmatindur, about 8% were rejected. Of the 90 lava units studied in this section, one unit, RF58, gave very scattered results (not included in Table 2.2). Virtual geomagnetic pole positions (VGP) were calculated from magnetic declination and inclination values. The azimuth of the dip direction in Holmatindur, section RF, is 270° due west, and values in Table 2.3 were used to correct the field data for tilt based on lava dips.

Virtual geomagnetic pole latitudes of lavas in the present study are either close to the geographic poles with clear normal or reversed polarity, latitude greater or equal to $|40°|$, or they are termed transitional, i.e., if latitude less than $|40°|$. Only two lavas have

Table 2.1. Summarized paleomagnetic and stratigraphic information on lava sections sampled in this study

Section*	Formation	Number of Units	Number of Minicores per Unit	Magnetic Polarity
Kollur (RD)	Kollur porphyritic basalt			N
	Tholeiite - 5	35	4	N
	Kambfell porphyritic basalt			N
Teigargerdistindur (RE)	Kollur porphyritic basalt			N
	Tholeiite - 5			N
	Kambfell porphyritic basalt	29	4	N
	Tholeiite - 4			N
	Reydarfjordur porphyritic basalt			N
Holmatindur (RF)	Kollur porphyritic basalt			Mainly normal with
	Tholeiite - 5			eight short
	Tholeiite - 4			reversed
	Tholeiite - 3			polarity
	Ljosa olivine basalt	90	4	zones
	Tholeiite - 2		(or less)	R - N - R
	Grjota olivine basalt			
	Tholeiite - 1			R
	Holmar olivine basalt			R

* See location on Figure 2.1

Table 2.2 Paleomagnetic results for sections RF (Holmatindur), RE (Teigargerdistindur), and RD (Kollur).

Lavas: Section RF, Holmatindur

Unit	N	P	I	D	R	Alfa-95	θ'	ø'
RF1	4	R	-64.6	253.4	3.9925	4.5	-47.8	245.0
RF2	4	R	-58.9	257.6	3.9981	2.3	-40.4	246.9
RF3	4	R	-61.1	252.6	3.9979	2.4	-44.6	249.3
RF4	3(1)	R	-61.2	259.8	2.9731	14.3	-41.7	243.2
RF5	4	R	-59.7	229.4	3.9769	8.0	-53.0	272.8
RF6	4	R	-52.1	225.1	3.9957	3.4	-47.8	283.5
RF7	4	R	-72.9	188.9	3.9267	14.5	-57.7	174.7
RF8	4	R	-67.8	188.8	3.9234	14.8	-75.1	324.0
RF9	3	R	-77.2	196.6	2.9869	10.0	-83.1	243.5
RF10	4	R	-65.3	202.5	3.9059	16.5	-68.6	300.7
RF11	4	R	-72.0	210.4	3.9974	2.7	-73.5	270.6
RF12	4	R	-71.8	218.4	3.9912	4.9	-69.9	262.4
RF13	4	R	-56.7	204.8	3.9161	15.5	-58.7	306.1
RF14	3(1)	R	-67.0	222.2	2.9916	8.0	-63.3	270.5
RF15	4	R	-66.2	216.3	3.9984	2.1	-64.8	279.0
RF16	3(1)	R	-51.7	217.3	2.9654	16.3	-50.3	292.8
RF17	3	R	-52.5	211.9	2.9864	10.2	-52.7	299.1
RF19	4	R	-51.1	229.7	3.9918	4.8	-45.2	279.1
RF20	4	R	-54.5	225.5	3.9182	15.3	-49.7	281.4
RF21	4	R	-62.3	222.7	3.9888	5.6	-58.2	277.2
RF22	3(1)	R	-68.7	191.1	2.9801	12.3	-75.9	317.0
RF23	4	R	-81.0	202.4	3.9953	3.6	-79.1	203.5
RF24	4	R	-78.9	217.7	3.9796	7.6	-75.0	225.5
RF25	4	R	-75.2	225.3	3.9995	1.1	-70.1	243.1
RF26	3	R	-73.4	259.7	2.9957	5.7	-54.8	226.9
RF27	4	R	-73.3	254.3	3.9856	6.3	-56.7	230.5
RF28	3(1)	R	-80.9	246.0	2.9776	13.1	-66.3	209.8
RF29	2(1)	R	-68.9	231.7	1.9963	15.2	-61.4	257.1
RF30	2	R	-65.8	230.4	1.9609	51.0	-58.7	264.0
RF31	2(2)	R(T)	3.8	180.0	1.9998	(3.5)	-23.1	346.0
RF32	4(1)	R(T)	-50.7	304.0	3.9575	11.0	-15.7	213.3
RF33	2(2)	R(T)	-49.9	321.7	1.9935	(20.2)	-10.2	198.8
RF34	4	N(T)	53.0	223.5	3.9069	16.4	14.2	309.7
RF35	3	N	60.3	75.2	2.9876	9.7	42.7	67.8
RF36	4	N	73.9	51.7	3.9895	5.4	66.4	63.7
RF37	4	N	67.7	24.9	3.8979	17.2	70.7	112.2
RF38	3(1)	N(T)	23.2	77.2	2.9961	5.4	16.4	82.5
RF39	4	R(T)	-6.8	130.2	3.9572	11.0	-19.0	39.8
RF40	4	R	-62.4	221.2	3.9940	4.1	-58.9	279.0
RF41	3(1)	R	-62.6	210.0	2.8396	36.4	-62.9	293.9
RF42	4	R	-71.0	211.4	3.9626	10.3	-72.0	273.1
RF43	4	R	-77.8	219.7	3.9842	6.6	-73.9	232.3

Table 2.2 (continued)

RF44	4	R	-51.6	177.2	3.9428	12.8	-57.2	350.4
RF45	4	R	-46.2	195.9	3.9955	3.5	-51.2	323.2
RF46	4	R	-43.0	197.8	3.9768	8.1	-48.4	321.4
RF47	4	R	-68.9	204.9	3.9882	5.7	-72.1	289.1
RF47A	4	N	82.9	170.9	3.9762	8.2	51.2	349.5
RF48	4	N	82.8	260.5	3.9946	3.9	59.5	317.5
RF49	4	N	46.6	313.0	3.9874	5.9	42.7	227.6
RF50	4	N	61.9	78.3	3.9931	4.4	43.0	63.8
RF51	4	N(T)	56.7	79.8	3.9918	4.8	37.5	66.7
RF52	4	R	-78.2	223.9	3.9978	1.9	-72.5	228.6
RF53	3(1)	R	-80.2	199.1	2.9995	1.9	-80.8	207.6
RF54	4	R(T)	-23.7	142.3	3.9526	11.6	-31.4	30.4
RF55	4	N(T)	60.2	93.9	3.9411	12.9	35.0	52.7
RF56	4	N	40.2	4.7	3.9811	7.3	47.8	159.5
RF57	2(2)	R	-79.3	199.3	1.9977	(12.0)	-81.4	217.5
RF59	4	R(T)	-65.2	295.8	3.9689	9.4	-32.7	212.6
RF60	4	N	65.1	53.5	3.9878	5.8	56.7	81.9
RF61	4	N	63.5	65.4	3.9881	5.7	49.9	73.1
RF62	4	N	64.3	58.9	3.9971	2.8	53.5	78.0
RF63	3(1)	N	52.9	23.3	2.9959	5.5	55.4	130.4
RF64	2(2)	N	81.2	230.4	1.9969	(13.9)	51.9	324.4
RF65	4	N	78.8	83.5	3.9977	2.5	59.4	31.8
RF66	3(1)	N	64.7	24.6	2.9937	6.9	67.3	118.2
RF67	3(1)	R	-87.0	212.3	2.9974	4.4	-69.8	175.3
RF68	2(2)	R	-83.7	202.0	1.9987	(9.0)	-75.8	185.2
RF69	2(2)	R	-78.6	189.2	1.9992	(7.0)	-85.2	212.1
RF70	2(2)	R	-67.6	258.0	1.9483	(60.2)	-49.0	237.6
RF71	3(1)	N	69.3	356.0	2.9900	8.7	77.7	177.4
RF72	4	N	76.3	346.6	3.9925	4.5	84.2	253.1
RF73	2(1)	N	59.7	30.8	1.9958	16.2	59.9	115.1
RF74	2(2)	R	-79.2	108.2	1.9695	(45.1)	-63.4	117.0
RF75	4	N	61.7	28.0	3.9880	5.8	62.9	116.9
RF76	2(2)	N	56.8	68.2	1.9927	(21.5)	42.4	76.8
RF77	4	R	-82.8	166.8	3.9974	2.7	-78.4	149.9
RF78	4	N	60.8	43.8	1.9957	16.4	56.2	97.8
RF79	4	R	-81.4	38.0	3.9713	9.0	-50.5	149.8
RF80	4	N	62.3	65.4	3.9933	4.3	48.8	74.3
RF81	3	N(T)	57.6	78.8	2.9747	13.9	38.7	66.9
RF82	4	N(T)	48.0	79.1	3.9155	15.6	30.6	72.3
RF83	3	R	-74.4	244.4	2.9742	14.0	-61.7	233.9
RF84	4	N	76.2	59.0	3.9837	6.7	65.5	51.3
RF85	4	N(T)	43.5	267.8	3.9569	11.0	21.9	269.3
RF86	3(1)	N(T)	37.1	247.8	2.9982	3.7	9.9	284.5
RF87	4	N	69.1	67.6	3.9984	2.1	54.9	63.4
RF88	1	N(T)	41.0	286.7			28.2	251.4
RF89	4	R	-66.1	242.9	3.9884	5.7	-53.7	251.9
RF90	4	N(T)	32.0	285.4	3.9922	4.6	22.2	249.4

Dykes: Section RF, Holmatindur

RF33D	3	R	-62.5	207.8	2.9427	21.1	-63.8	296.4
RF41D	3(1)	N	69.5	7.7	2.8850	30.5	77.6	143.9
RF51D	4	R	-72.1	223.5	3.9963	3.2	-67.9	258.2

Table 2.2 (continued)

Lavas: Section RE, Teigargerdistindur

RE6	4	N	72.7	45.7	3.8518	20.9	67.7	72.3
RE7	4	N	64.6	50.9	3.9822	7.0	57.2	85.0
RE8	4	N	67.5	2.1	3.9924	4.6	75.3	160.6
RE9A	4	N	61.7	33.2	3.9990	1.6	61.1	109.5
RE9	4	N	77.7	32.2	3.9891	5.5	76.8	54.9
RE10	4	N	58.3	33.3	3.9947	3.8	57.6	112.9
RE11	4	N	67.6	30.3	3.9789	7.7	68.6	104.0
RE12	2(2)	N	60.3	12.0	1.9965	(14.8)	65.3	143.8
RE13	4	N	76.2	25.2	3.9986	1.9	79.1	70.7
RE14	3(1)	N	71.0	1.3	2.9953	5.9	80.4	161.3
RE15	4	N	62.0	359.9	3.9903	5.2	68.2	165.9
RE17	4	N	67.4	21.0	3.9990	1.6	71.6	119.1
RE18	4	N	84.1	312.0	3.9967	3.0	70.9	318.4
RE19	4	N	62.3	27.2	3.9972	2.8	63.8	117.3
RE20	4	N	83.3	29.9	3.9969	2.9	75.0	11.8
RE21	4	N	82.4	68.1	3.9972	2.8	66.4	22.6
RE22	4	N	67.7	62.2	3.9942	4.0	55.6	69.9
RE23	4	N	74.4	51.5	3.9969	2.9	66.9	62.0
RE24	4	N	70.5	35.8	3.9838	6.7	69.7	89.1
RE25	4	N	77.1	21.2	3.9955	3.5	81.1	63.6
RE26	4	N	75.4	23.8	3.9953	3.6	79.2	78.8
RE28	4	N	74.4	32.3	3.9955	3.5	74.9	76.3
RE30	4	N	66.3	58.2	3.9937	4.2	55.9	75.5
RE31	4	N	61.7	66.4	3.9907	5.1	47.8	73.9
RE32	4	N(T)	54.1	254.7	3.9958	3.4	25.0	284.7
RE33	4	N(T)	46.4	248.3	3.9975	2.6	16.4	286.7
RE34	4	N	78.4	296.5	3.9947	3.8	65.5	290.5
RE35	1	N(T)	56.9	154.8			14.3	6.2
RE36	4	N(T)	45.7	286.9	3.9437	12.7	31.5	253.0

Table 2.2 (continued)

Lavas: Section RD, Kollur

RD3	4	N	73.9	59.2	3.9942	4.0	63.2	58.5
RD4	4	N	80.7	41.4	3.9956	3.5	73.7	33.1
RD5	4	N	83.6	40.5	3.9986	1.9	72.7	14.2
RD6	4	N	66.1	81.9	3.9809	7.3	45.9	56.3
RD7	4(1)	N(T)	59.1	94.6	3.9980	2.3	33.7	52.7
RD8	4	N	67.3	94.5	3.9941	4.0	42.3	45.8
RD9	3	N	67.6	89.5	2.9965	5.1	44.5	49.0
RD11	4	N	67.8	93.2	3.9888	5.6	43.4	46.2
RD13	4	N	64.1	66.1	3.9974	2.7	50.4	71.5
RD14	4	N	64.8	55.2	3.9914	4.9	55.7	80.5
RD15	4	N	71.5	28.7	3.9735	8.6	73.7	94.5
RD16	4	N	63.8	70.7	3.9954	3.6	48.0	68.0
RD17	3(1)	N	63.2	44.2	2.9810	9.6	58.5	94.1
RD18	4	N	71.3	354.6	3.9909	5.0	80.6	183.9
RD19	3(1)	N	75.3	19.3	2.9878	9.6	81.1	84.0
RD20	3(1)	N	64.6	8.9	2.9896	8.9	70.8	146.9
RD21	4	N	77.0	76.6	3.9354	13.6	59.7	39.9
RD22	4	N	71.9	73.5	3.9744	8.5	55.5	53.8
RD23	4	N	64.2	25.9	3.9735	8.6	66.4	116.6
RD24	4	N	63.7	36.5	3.9863	6.2	62.0	102.6
RD25	4	N	57.4	30.5	3.9987	1.9	57.7	117.4
RD26	4	N	73.0	358.5	3.9278	14.4	83.5	172.6
RD27	4	N	65.3	69.2	3.9938	4.1	50.2	67.4
RD28	4	N	57.5	63.7	2.9902	8.6	45.0	80.3
RD29	4	N	59.7	52.2	3.9955	3.5	51.8	89.5
RD30	4	N(T)	56.3	76.3	3.8182	23.3	38.6	69.7
RD31	4	N(T)	53.3	66.9	3.9654	9.9	39.9	80.3
RD32	4	N	60.5	16.7	3.9884	5.7	64.6	135.6
RD33	4	N	50.8	9.1	3.9522	11.6	56.0	151.8
RD34	4	N(T)	44.1	245.2	3.9801	7.5	13.7	288.6
RD35	4	N	70.4	17.7	3.9809	7.3	76.4	117.2
RD35A	4	N	63.0	28.7	3.9886	5.6	64.1	114.2
RD36	4	N(T)	60.6	157.5	3.9843	6.6	18.0	3.3
RD37	4	N	74.2	98.4	3.9981	2.3	49.4	34.2
RD38	4	N	73.8	50.4	3.9782	7.8	66.8	9.8

NO, unit number; N, number of samples used from each unit; P, magnetic lava polarity, N and R lat > $|40°|$, N (T) and R(T) lat $|10° - 40°|$ (transitional); I, D, tilt corrected magnetic inclination and declination; R, resultant unit vector; α_{95}, radius of a circle with 95% confidence for the mean magnetic direction of each unit; θ' and ϕ', virtual geomagnetic pole positions calculated after tilt corrections.

virtual geomagnetic latitudes less than |10°|. The same divisions have recently been used for the magnetostratigraphy of northern Iceland (Saemundsson and others, 1980). Thus out of the 90 lava units sampled in Holmatindur in 1979, 28 have transitional polarities (31%). Of these, 16 fall on reversal boundaries on the magnetostratigraphic section of Figure 2.5.

2.3.2 Paleomagnetic results from sections RD (Kollur) and RE (Teigargerdistindur)

Paleomagnetic results and statistical data for sections RD and RE are presented in Table 2.2. Units in sections RD and RE were demagnetized using the peak alternating field values: 150, 200 and 250 Oe. If magnetic directions were unstable after demagnetization to 250 Oe, the process was continued to higher values which usually gave stable paleomagnetic directions. Four samples from each unit were demagnetized in sections RD and RE or a total of 256 cores of which all but 2 were considered acceptable after demagnetization. Samples were rejected if stable directions were not attained at 500 Oe. Virtual geomagnetic pole positions (VGP) were calculated after tilt correction, assuming 270° as the azimuth of the dip direction. The field values in Table 2.4 were applied to correct the results for post depositional tilting.

2.4 Discussion of paleomagnetic results

2.4.1 Demagnetization and magnetic intensity

Several lavas and one dyke unit of the Holmatindur section were selected to display the effects of demagnetization under peak

Table 2.3. Tilt corrections for section RF (Holmatindur)

Unit Interval	Elevation, m	Tilt Correction
RF 1-47	40-300	+9°
RF 47A-65	300-600	+6°
RF 66-88	600-900	+3°
RF 89-90	>900	+1.5°

Table 2.4. Tilt corrections for sections RD (Kollur) and RE (Teigargerdistindur)

Unit Interval	Elevation, m	Tilt Correction
RD 3-25	0-300	+9°
RD 26-38	>300-600	+6°
RE 6-23	300-600	+6°
RE 24-36	>600-900	+3°

alternating field conditions on (1) magnetic intensity (Figure 2.2) and (2) magnetic declination and inclination (Figure 2.3). The selected samples show a range of granularity and state of alteration (Table 2.5).

As can be seen from a comparison of Table 2.5 and Figures 2.2 and 2.3, only one of the selected samples, RF1-p3, the lowest exposed lava and the most altered (mesolite grade), seems to have acquired a large soft magnetic component opposing the stable magnetization that is removed during demagnetization. With the exception of RF1-p3, demagnetization affects the magnetic intensity of the selected lava samples similar to demagnetization of fresh oceanic rocks (Fox and Opdyke, 1973). The selected rocks tend to be very stable and demagnetization does not effect magnetic pole positions (VGP) except for lava sample RF32-p3, which shows a trend toward steeper values with increased applied field strength.

An attempt was made to demonstrate the overall vertical variations of remanent magnetic intensity in the Holmatindur section. For this purpose the Holmatindur section, about 0.9 km thick, was divided into nine lava intervals, each consisting of 10 lava units. For each interval the arithmetic mean of the normal remanent magnetization and remanence after 200 Oe a.f. demagnetization were calculated. The results are plotted in Figure 2.4 and tabulated in Table 2.6 together with the standard deviation of the magnetic intensity for each lava interval. Included in Table 2.6 are comparable values for oceanic pillow basalts (after Fox and Opdyke, 1973). Figure 2.4 clearly demonstrates two interesting points, namely; (1) the magnetic intensity of the 0.9-km-thick exposed lava succession does not decrease regularly

Table 2.5. Summarized information on selected samples plotted for magnetic properties (Figures 2.3 and 2.4)

Sample	Field Classification	Grain Size	Mineral Phases*	Alteration State	Stratigraphic Location** m	Natural Remanence J_0 $\times 10^{-4}$ emu/cm^3	Magnetic Polarity
RF 1-p3	olivine tholeiite	medium	pl,ol,px,op, alt	chl, minor ol left	70	1.3	R(T)
RF 32-p3	tholeiite	fine	pl,px,op,alt	specks of chl	317	12.8	R(T)
RF 44-pl	olivine tholeiite	coarse	pl,ol,px,op, alt	clay, ol partly altered	426	11.2	R
RF 62-pl	tholeiite	medium	pl,px,op,alt	fresh, minor clay	665	53.4	N
RF 89-p4	tholeiite	fine	pl,px,op	fresh	980	4.7	R
RF 51D-p4	dyke	coarse	pl,px,op,alt	fresh, minor clay	505	179.1	R

*Phases: pl, plagioclase; ol, olivine; px, pyroxene; op, opaque minerals; alt, secondary alteration minerals; chl, chlorite

**Cumulative thickness above sea level

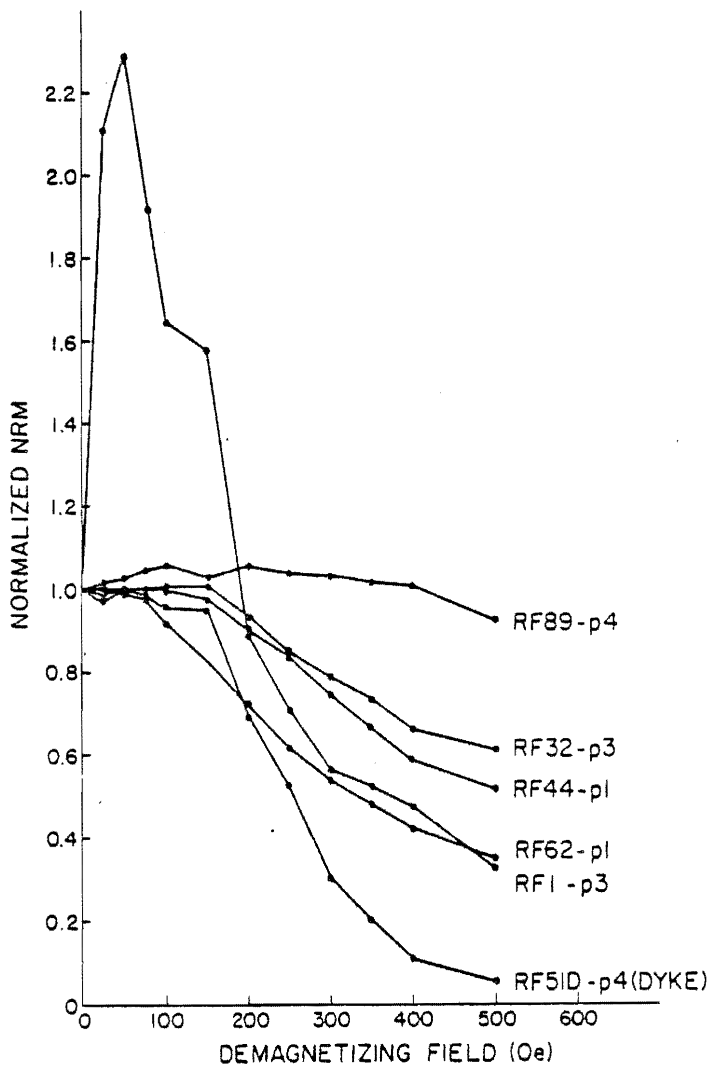


Figure 2.2 Normalized magnetic intensity of selected samples from section RF (Holmatindur) plotted against alternating field strength.

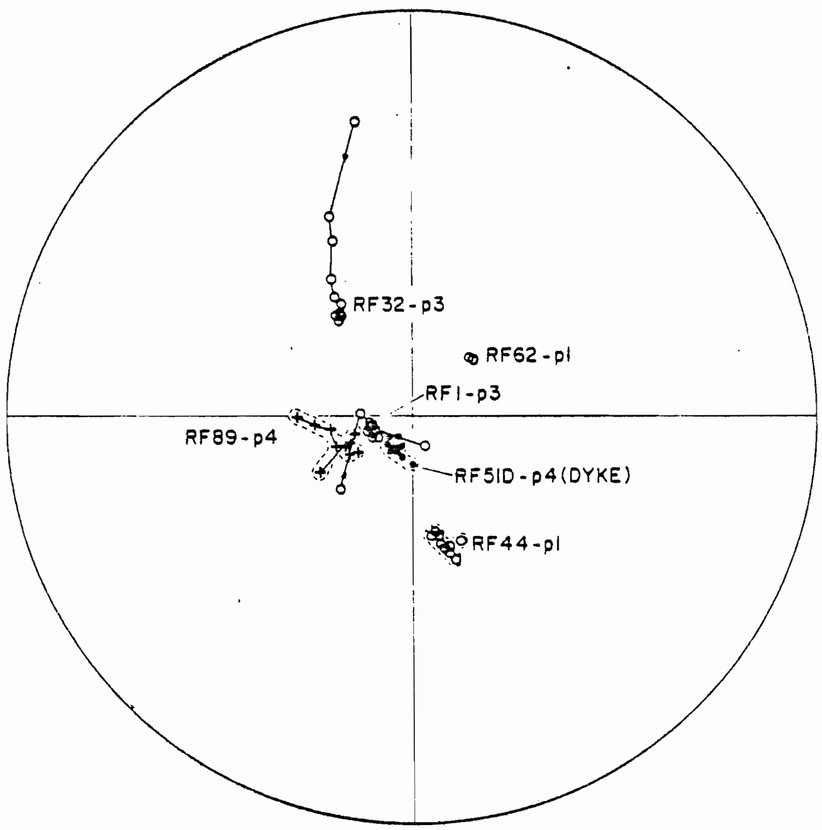


Figure 2.3 Stereographic plot of magnetic inclinations for selected samples from section RF (Holmatindur), showing a trend toward steeper and more stable values with increased demagnetizing field strength.

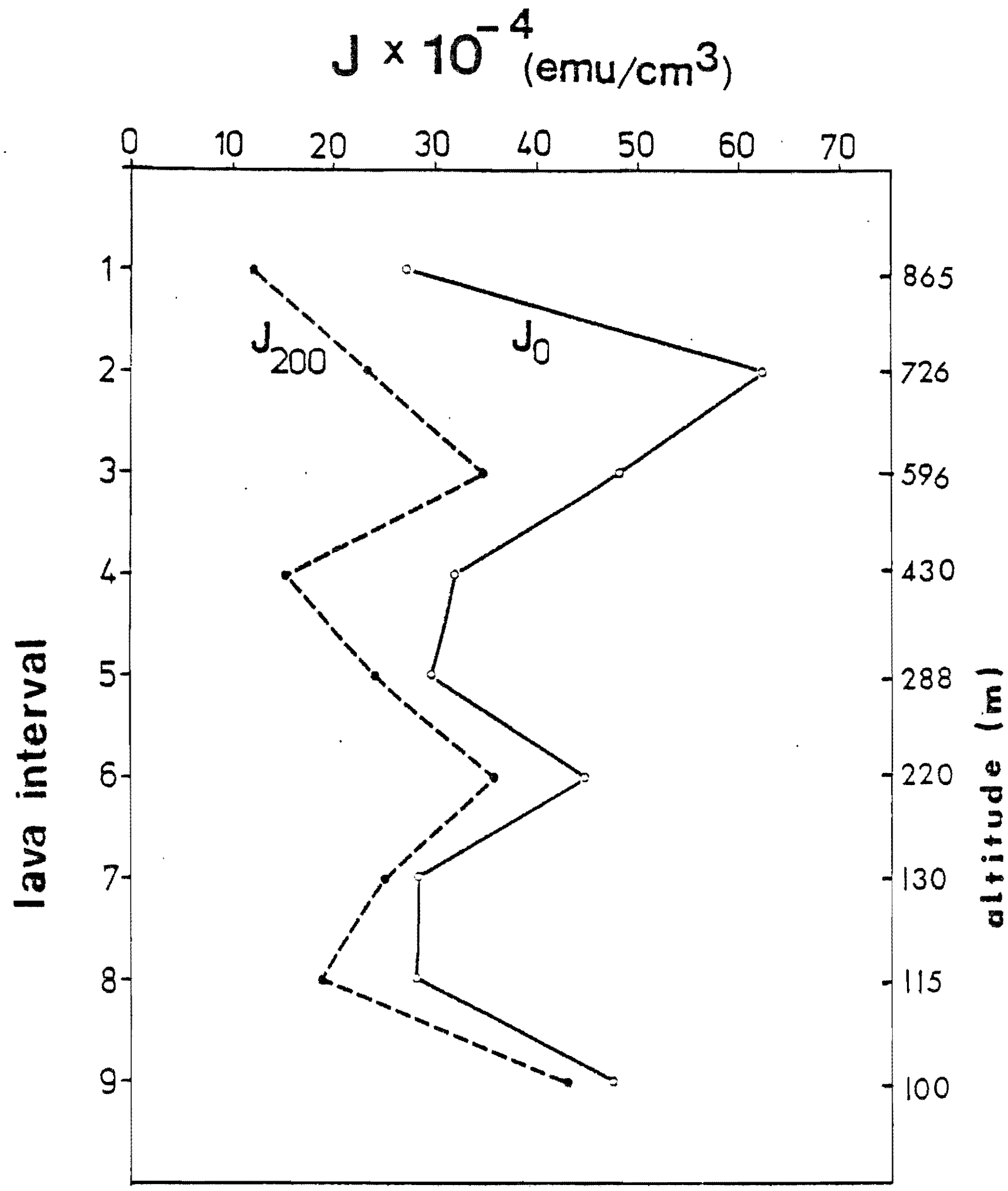


Figure 2.4 Magnetic intensity plotted for lava interval. Each value represents a mean average for 10 lava flows. The two curves show magnetic intensity (J x 10-4 emu/cm3) before and after demagnetization, i.e., at 0 and 200 Oe, respectively.

with depth, and (2) the drawn curves for the magnetic intensity before and after demagnetization become closer with depth in the lava succession. The first observation reflects the heterogeneity of the lava succession with regard to magnetic intensity. The standard deviation for each of the nine lava intervals both before and after 200 Oe demagnetization (Table 2.6) is only slightly lower than the arithmetic mean. This clearly reflects the heterogeneity of the overall exposed lava succession, since intralava variations are usually much smaller. Linear regression analyses for the relationship between magnetic intensity and altitude proved it to be poorly correlated. Thus correlation coefficients (r) of 0.1744 and 0.4393 were obtained before and after demagnetization, respectively and likewise the slopes of the regression line changed from negative (-3.9509) to positive (+2.3639). The second observation indicates that effects of demagnetization on magnetic intensity decrease with depth as if the more altered lower lavas possess more stable magnetic mineral phases. If the nine lava intervals are divided into three separate groups the decrease in magnetic intensity (J_0-J_{200}) from the mountain top to sea level is 48.6, 30.7, and 18.8%, respectively. In their study Fox and Opdyke (1973) (Table 6) show that weathering of submarine pillow basalts drastically reduces their magnetic intensity. Thus they report a NRM value of 147.8 x 10^{-4} emu/cm for fresh rocks but about 31.0 x 10^{-4} emu/cm for all weathered rocks and 4.4 x 10^{-4} emu/cm for metamorphosed basalts. The Holmatindur lavas have average magnetic intensity values of of 38.6 x 10^{-4} and 25.6 x 10^{-4} emu/cm before and after demagnetization, respectively. Both these values are comparable with 31.0 x 10^{-4} emu/cm for weathered oceanic pillow basalts. These results are not consistent

Table 2.6. Comparison of magnetic intensity for nine lava intervals in the Holmatindur section and oceanic pillow basalts (after Fox and Opdyke, 1973)

Holmatindur, Section RF		$J_0 \times 10^{-4}$ emu/cm^3		$J_{200} \times 10^{-4}$ emu/cm^3		$J_0 - J_{200}$	
Lava Interval	Units	Arithmetic Mean	Standard Deviation	Arithmetic Mean	Standard Deviation	Percent Decrease	
1	RF81-90	27.2	19.9	12.1	8.1	55.5	
2	RF71-80	62.6	35.0	23.4	9.6	62.7	8.6
3	RF61-70	48.0	27.8	34.4	21.7	27.6	
4	RF51-60	31.8	32.2	15.3	15.9	52.1	
5	RF42-50	29.6	28.7	23.8	21.0	19.4	30.7
6	RF32-41	44.7	57.2	35.6	51.7	20.5	
7	RF22-31	28.2	17.5	24.2	16.3	14.0	
8	RF11-21	27.7	22.5	18.7	19.0	32.6	18.8
9	RF 1-10	47.5	42.8	42.8	45.0	10.0	
All lavas	RF 1-90	38.6	34.2	25.6	27.6	32.7	

Oceanic Pillow Basalts [Fox and Opdyke, 1973]		$J_0 \times 10^{-4}$ emu/cm^3	
Rock Type	Number of Samples	Arithmetic Mean	
fresh	12	147.8	
slightly weathered	10	37.1	
moderately weathered	18	22.4	31.0
strongly weathered	22	33.4	
metamorphosed	10	4.4	
all basalts	72	47.6	

with earlier work in eastern Iceland.

Watkins and Walker (1977) report how natural remanent magnetization for the exposed basalt lava succession in eastern Iceland decreases linearly with depth below the pre-erosional plateau surface as a result of increased paleotemperature conditions. They derived this relationship from (1) the work on opaque mineralogy in eastern Iceland by Ade-Hall and others (1972) and (2) work by Walker (1960) on zeolite grade alteration. They found that for rocks demagnetized under peak alternating field conditions of 100 to 125 Oe, the magnetic intensity decreased nonlinearly with depth and approached a constant value at sea level, approximately 1500 m below the pre-erosional plateau surface. The present study, however, indicates that magnetic intensity of lavas in the studied section decreases neither to the extent nor in the manner reported by Watkins and Walker (1977). If, indeed, magnetic intensity decreases with depth, the heterogeneity of the lava succession is of such magnitude that it masks a systematic decrease with depth. Furthermore, demagnetization affects magnetic intensity in the upper part of the section to a greater extent than it affects lavas close to sea level. This indicates that hydrothermal alteration is more pronounced lower in the lava succession and that the opaque alteration products are magnetically more stable than the magnetic minerals in the upper part of the lava succession. Here zeolitisation is less pervasive, and only low-temperature zeolites are present (chabazite-thomsonite-stilbite).

2.4.2 Magnetostratigraphy in Reydarfjordur

Stratigraphic correlations between Holmatindur and the surrounding exposed area proved to be straightforward. Lithological successions containing the same stratigraphic formations can be traced for tens of kilometers in the strike direction in eastern Iceland, e.g., the Kollur porphyric formation (Chapter 1, section 1.4.8). However, the paleomagnetic signature of these presumably coeval lavas in the investigated sections surrounding Holmatindur (e.g., Watkins and Walker, 1977) indicated a totally different polarity history. Surrounding Holmatindur a long, normally magnetized lava succession corresponds to 'sea floor' magnetic anomaly 5 (McDougall and others, 1976). The results from the upper part of Holmatindur (Figure 2.5) indicate at least eight short reversed polarity intervals but no long succession of normally magnetized lavas equivalent to anomaly 5. Thus the frequent short polarity intervals in Holmatindur strongly contradicted earlier work in the area that had been coupled with K-Ar dating. Sections RD and RE were sampled in 1980 to shed light on this problem. The results from sections RD (Kollur) and RE (Teigargerdistindur) are presented in Figure 2.6. Here all lavas are normally magnetized. The complete absence of reversely magnetized lavas in both these sections, RD and RE, is in clear disagreement with the Holmatindur lavas. The results from RD and RE agree, however, with three independent studies in the region. These include paleomagnetic work about 20 km to the north (Watkins and Walker, 1977), fluxgate magnetometer results in Teigargerdistindur (Piper and others, 1977), and compass measurements in Holmatindur (Einarsson, 1957).

Figure 2.5 Magnetostratigraphic section for the Holmatindur section based on latitudes of the virtual geomagnetic pole. The stratigraphic sequences on the left side include the main marker formations (abbreviated).

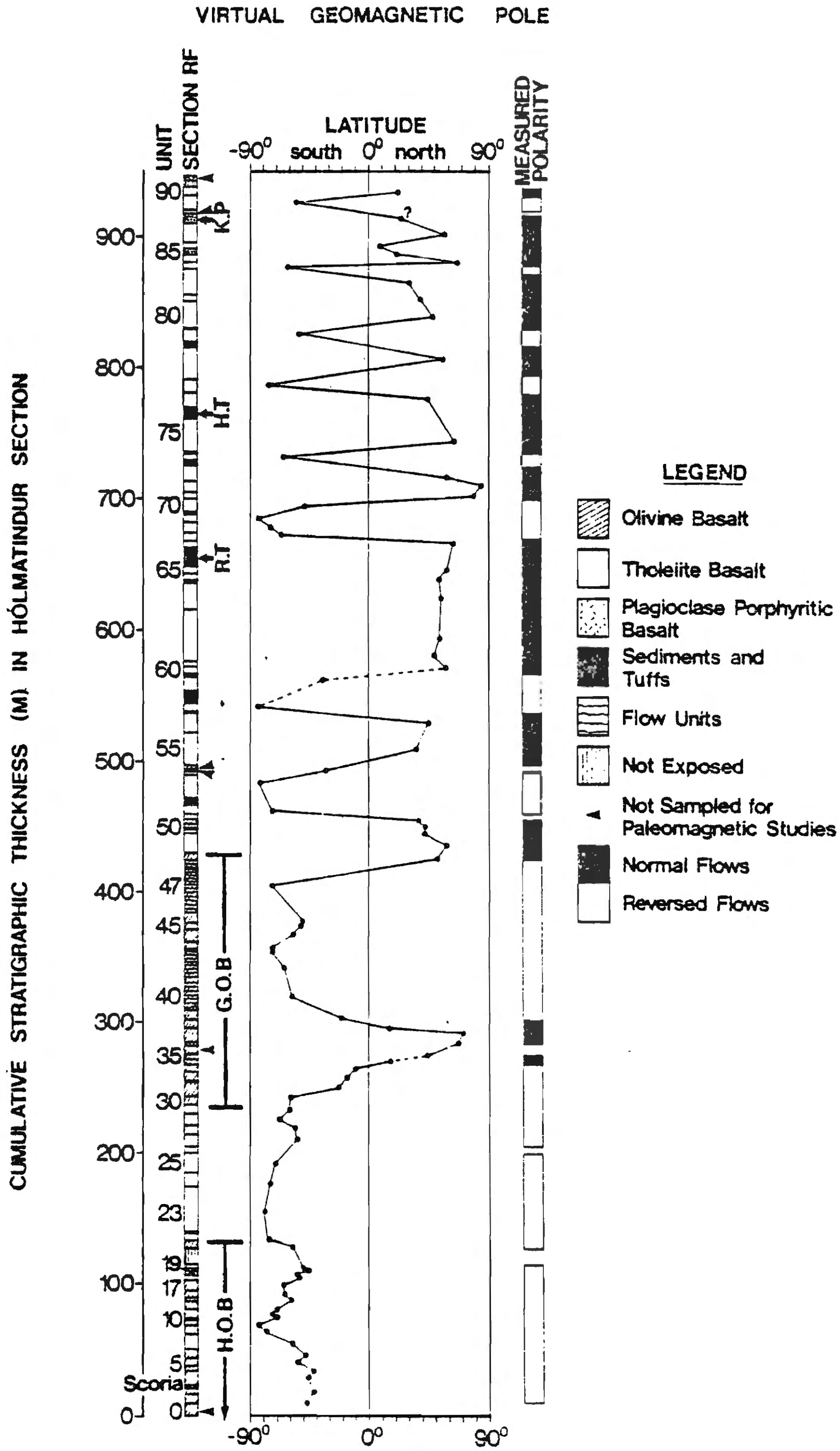
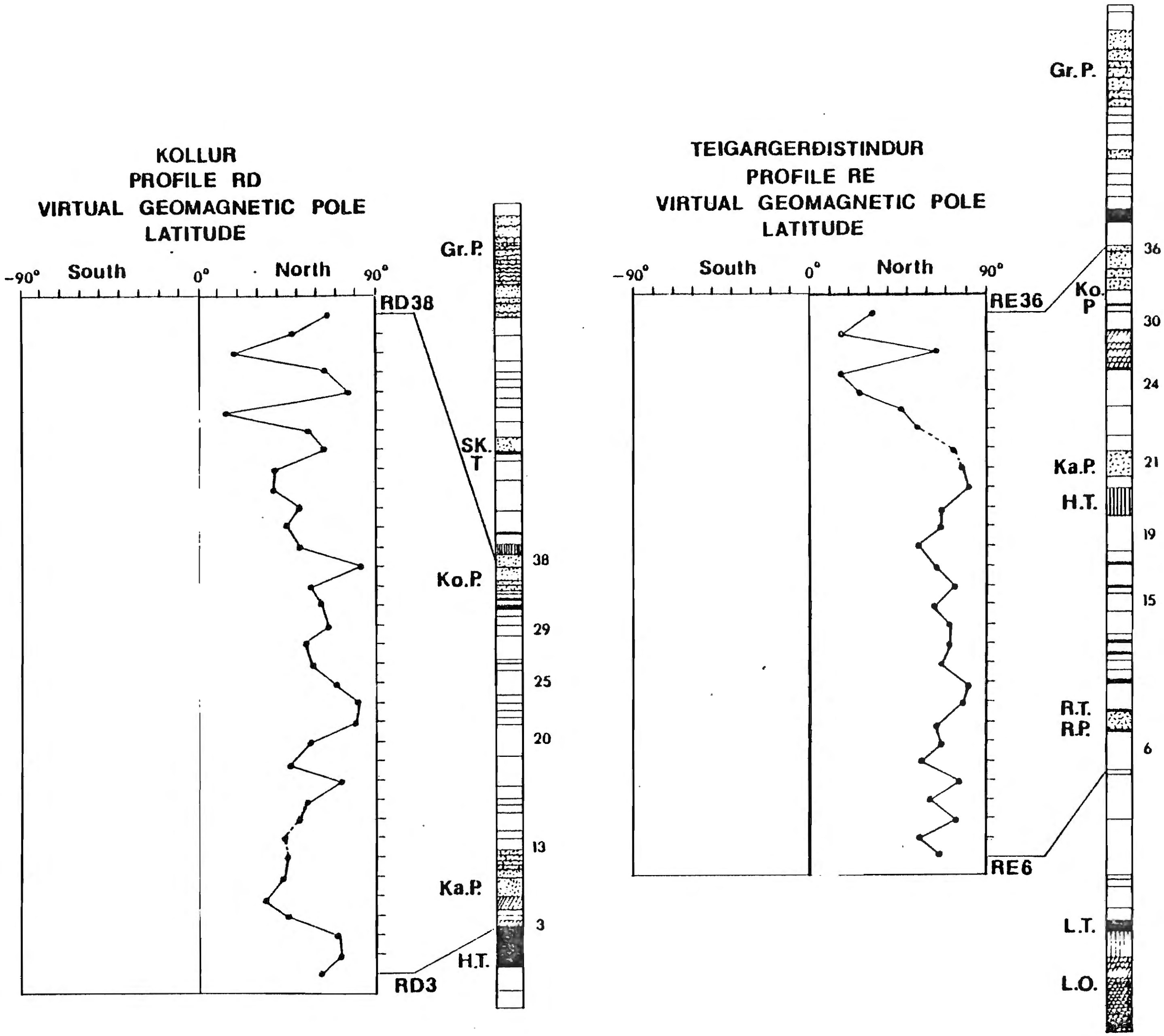

VIRTUAL GEOMAGNETIC POLE
CUMULATIVE STRATIGRAPHIC THICKNESS (M) IN HÓLMATINDUR SECTION
UNIT
SECTION RF
LATITUDE
-90° south 0° north 90°
MEASURED POLARITY
K.P
H.T
R.T
G.O.B
H.O.B
Scoria
-90° 0° 90°
LEGEND
Olivine Basalt
Tholeiite Basalt
Plagioclase Porphyritic Basalt
Sediments and Tuffs
Flow Units
Not Exposed
Not Sampled for Paleomagnetic Studies
Normal Flows
Reversed Flows

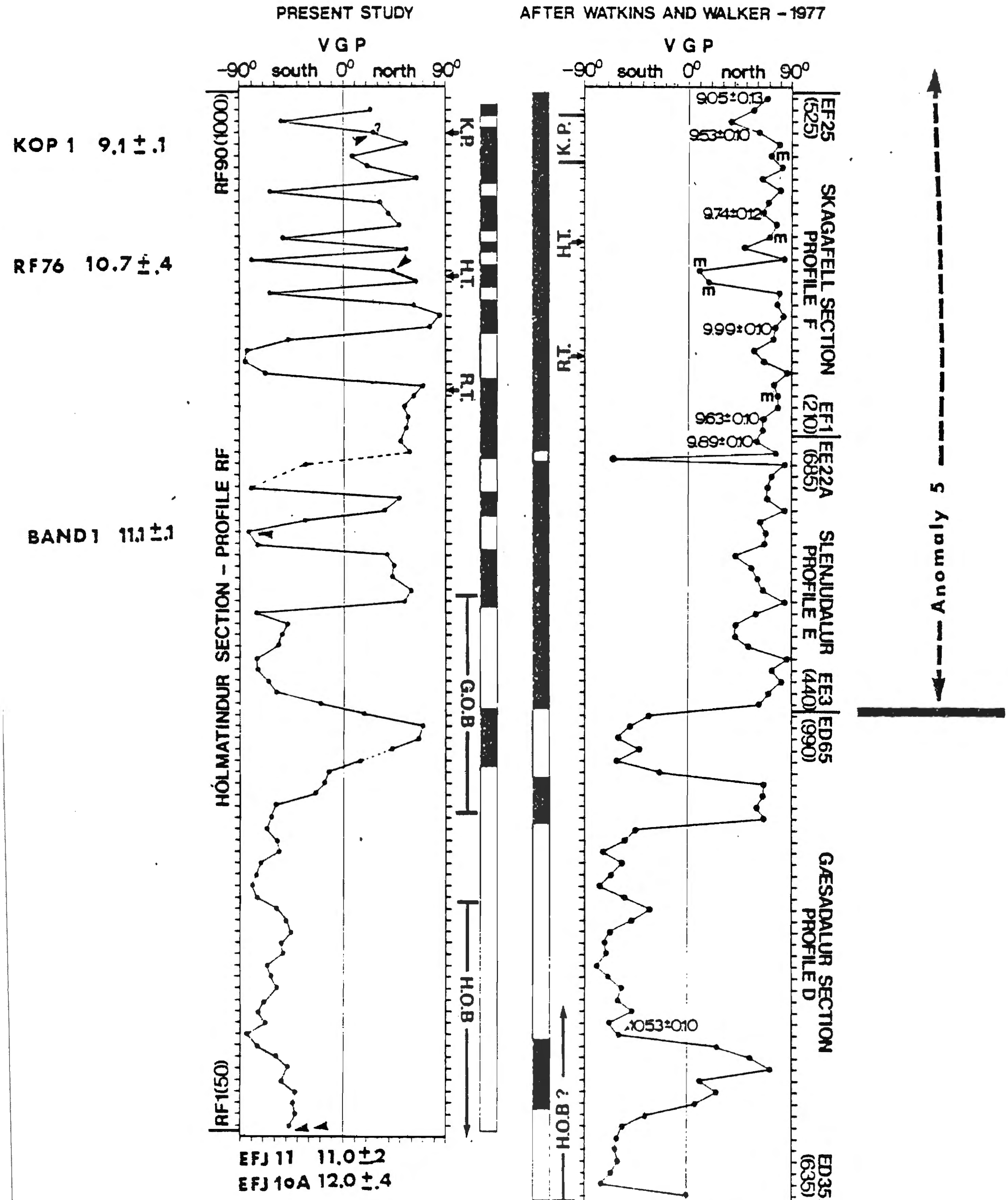
Figure 2.6 Magnetostratigraphic sections for profiles RD (Kollur) and RE (Teigargerdistindur) showing latitudes of the virtual geomagnetic pole values. On the right are stratigraphic profiles indicating the respective units that were sampled for paleomagnetic studies.


KOLLUR
PROFILE RD
VIRTUAL GEOMAGNETIC POLE
LATITUDE
-90°
South
0°
North
90°
RD38
RD3
Gr.P.
SK.T
Ko.P.
Ka.P.
H.T.
38
29
25
20
13
3
TEIGARGERÐISTINDUR
PROFILE RE
VIRTUAL GEOMAGNETIC POLE
LATITUDE
-90°
South
0°
North
90°
RE36
RE6
Gr.P.
Ko.P
Ka.P.
H.T.
R.T.
R.P.
L.T.
L.O.
36
30
24
21
19
15
6

The three sections of this study, RF (Figure 2.5), RD, and RE (Figure 2.6) are correlated stratigraphically and located perpendicular to the strike direction (Figures 1.3 and 2.1). From west to east the sections are correlated so that all of section RD is incorporated up dip in section RE, although here this interval is represented by fewer lava units. This is due to the generally lower 'tape recording' up dip and farther away from a paleovolcanic zone, the extinct ridge axis of which presumably lies buried below sea level west of the IRDP drill hole. Similarly, the entire lava formation of RE is incorporated in RF, but here this lava succession is higher up dip and farther to the east of the assumed paleovolcanic zone. Therefore this lava interval is represented by still fewer lavas in section RF than in RE. As before, the assumption is made that the lavas flowed from west to east; thus lower in the lava succession and closer to the paleovolcanic zone the 'tape recording' was more detailed. From the above it is assumed that if no remagnetization has taken place, all reversals that occur in a high-lying lava section should necessarily be represented down dip in the lower sections as well.

A stratigraphic and paleomagnetic comparison is made on Figure 2.7 between the Holmatindur section and sections D, E, and F of Watkins and Walker (1977). Clearly, despite good stratigraphic correlation of the upper part of these successions they do not correlate paleomagnetically. Since the paleomagnetic results of the present study show reversely magnetized lavas in the upper part of section RF (but neither down dip in section RD nor RE), it is suggested that secondary magnetization took place in section RF during a reversed polarity interval. The lower boundary of anomaly 5 can, however, be deduced in Holmatindur

Figure 2.7 Paleomagnetic and stratigraphic results of the present study in Holmatindur, section RF, are compared with earlier work on coeval lavas from a different locality, i.e., sections D, E, and F on Figure 2.1 Units denoted with m are reported values for the second unit sampled in a sequence of thin flow units. Dashed lines indicate that a lava between the plotted values was not sampled. Question marks denote paleomagnetic values that are less reliable. ED 35 denotes profile ED, unit 35; (635) is the altitude above sea level of unit 35. Also shown are K-Ar age determinations of several samples from McDougall and others (1976).


PRESENT STUDY
AFTER WATKINS AND WALKER - 1977
V G P
-90° south 0° north 90°
KOP 1 9.1 ± .1
RF76 10.7 ± .4
BAND 1 11.1 ± .1
RF90(1000)
HÓLMATINDUR SECTION - PROFILE RF
RF1(50)
EFJ 11 11.0 ± .2
EFJ 10A 12.0 ± .4
K.P.
H.T.
R.T.
G.O.B
H.O.B
H.O.B ?
9.05±0.13
9.53±0.10
9.74±0.12
9.99±0.10
9.63±0.10
9.89±0.10
10.53±0.10
EF25 (525)
SKAGAFELL SECTION PROFILE F
EF1 (210)
EE22A (685)
SLENJUDALUR PROFILE E
EE3 (440)
ED65 (990)
GÆSADALUR SECTION PROFILE D
ED35 (635)
Anomaly 5

between units RF47 and RF47A (Figure 2.7).

2.4.3 Transitional polarity directions and remagnetization of lavas in Holmatindur section

The Holmatindur section is characterized by frequent magnetic reversals and lavas of 'transitional' polarity directions (Figure 2.5). Thus 'transitional' or intermediate polarity directions distinguish the Holmatindur lavas from all other magnetostratigraphic sections in eastern Iceland. As can be seen from Table 2.7, 18% of investigated lavas in Holmatindur have intermediate VGP latitudes. This number increases to 36% if the criteria for intermediate lava polarities are extended to latitude less than |50°|. In Teigargerdistindur, 4 lavas out of 29 (i.e. 13.8%) have intermediate VGP latitudes. In sections D, E, and F a total of 10.3% and 18.1% of lava units have VGP latitudes lower or equal to |40°|and |50°|,respectively.Other sections in the area have a much lower number of intermediate VGP latitudes. Magnetic inclination values have been measured for lava units of the IRDP core, however, VGP values are not available for the core. Only one lava unit out of 152 in the core and one lava unit of the exposed section by the drillsite (RH, Trollafjall) have magnetic inclinations shallower than |40°| (Bleil and others, 1982). The difference between the magnetic inclinations in the core and the exposed section surrounding the drillsite cannot readily be explained. It appears that the criteria for accepting paleomagnetic vectors for the IRDP core were more conservative than in the present study and as a result shallow values, which usually are less well defined, were omitted.

To include shallow magnetic poles, although less well defined, is

Table 2.7 Abundance of intermediate polarity lavas in the province surrounding the Breiddalur dyke swarm.

Location (see Figure 2.1)	Reference Cited	VGP or I≤40° No. Lavas	Percent in Section	
Eastern Iceland	Dagley et al, (1967)	73(2)	6.8	
Trollafjall (RH)	Bleil et al., (1982)	1(2)	0.8	
IRDP-core	Bleil et al., (1982)	1(2)	0.7	
Gaesadalur (D)	Watkins and Walker (1977)	7(1)	16.3	
Slenjudalur (E)	"	1(1)	4.0	10.3 (18.1(3))
Skagafell (F)	"	3(1)	10.7	
Kollur (RD)	Present study	2(1)	5.7	
Teigargerdis-tindur (RE)	Present study	4(1)	13.8	
Holmatindur, (RF)	Present study	16(1)	18.0	(36.0(3))
Holmatindur (RF, lower section only)	Piper et al., (1977)	2(2)	5.0	

(1) Polarity based on VGP-latitude
(2) Polarity based on magnetic inclination value
(3) Lava percentage if criteria are expanded to ≤50°

important as they may indicate when the ambient magnetic field deviated from steep values and in many cases may have reversed. Thus, for example, a single shallow pole in a high lying lava section of normally magnetized lavas may indicate that a true reversal is recorded down dip, where the 'tape recording' of paleomagnetic data is faster or more detailed.

As can be seen from Table 2.2, for the lower part of Holmatindur section (RF1 to RF51), that all the 7 'magnetically transitional' lavas coincide with boundaries of well defined polarity chrons each of which consist of at least 5 lava units. The lower part of Holmatindur does therefore not display an unusual paleomagnetic character and correlates well lithologically and paleomagnetically with the surrounding area.

A closer look at the stratigraphy of the Holmatindur section reveals that the upper lavas, units RF52 to RF87, were all sampled in the same gully, which is cut by a 10-m-thick dyke of reversed polarity, unit RF51D (Table 2.2). No other dyke occurs within 50 m of either side of the gully. Field conditions within the gully did not allow sampling at great distances from the dyke. The distance from the dyke to the first core sampled in a lava was commonly over 10 m, and the minimum was 4 m. This distance was considered ample based on investigations of the effects of intrusives on basaltic host rock (e.g., Ade-Hall and Dagley, 1974). Out of 35 lavas in the gully, 22 are normally magnetized and 13 are reversely magnetized. Four out of seven reversed polarity intervals in this part of Holmatindur are each based on a single lava flow of intermediate VGP latitude. Thus these polarity intervals are of limited definition. In the field season of 1980 fluxgate measurements were conducted within the gully in Holmatindur to help explain the paleomagnetic problem in question. Lavas of 'reversed polarity' were measured at intervals away from the dyke to distances limited by difficult field conditions. A change in polarity toward normal was observed for most of the 'reversed polarity intervals' away from the dyke. It is concluded that the reversely magnetized dyke in the gully may be responsible for the 'reversed events' observed. This would indicate that under certain conditions, remagnetization of lava flows can occur to distances of up to 10 m from a 10-m-thick dyke.

Thus, (1) if the reversed polarity intervals in upper Holmatindur are caused by remagnetization and (2) if before remagnetization these lavas had normal magnetic polarities, it follows that this lava succession would correlate perfectly with the magnetostratigraphy of the surrounding area, i.e., normal lava flows of anomaly 5 age. Second, it follows that the reversely magnetized dyke (RF51D) most likely intruded the upper section after the duration of magnetic anomaly 5, which has the younger age boundary at about 9 Ma. ago, i.e., long after the Holmatindur lava succession was formed. An explanation offered for the remagnetization assumes that before alteration of the lava succession some of the lavas had low Curie points (perhaps 300° C). Upon intrusion of the dyke, during a reversed polarity interval, the magma temperature was high enough to cause the host lavas to reheat above their Curie points and partly or completely remagnetize some of the host lavas to distances of at least 10 m from the dyke.

This explanation is supported by the work of Ade-Hall and others (1971). In their study of magnetic properties of lavas from eastern

Iceland and elsewhere they found that the least altered lavas with no amygdules or those from the chabazite-thomsonite zeolite zones to have both low (100-300° C) and/or high (about 500° C) Curie temperatures. This behavior is also displayed by fresh lavas from the neovolcanic zones in Iceland. The bimodal distribution results from local phase splitting of initially homogeneous magnetic minerals into minerals with low and high Curie point temperatures during magma cooling. Conversely, lavas subjected to a higher degree of zeolite alteration, i.e., mesolite-laumontite zones, only have Curie points greater than about 300° C. Here, as a result of hydrothermal alteration, the lower Curie temperatures have been raised. A study of secondary minerals (zeolites) in the upper part of Holmatindur reveals that only minerals of low alteration grade are present (e.g. zeolite free or chabazite-thomsonite). It is therefore assumed that the dyke in the upper part of Holmatindur was emplaced before pervasive alteration could penetrate the surrounding lava pile and raise their Curie temperatures. Thus the thick intruding dyke may have reheated the host lavas above their Curie points, causing remagnetization and a change of magnetic polarity direction from normal to reverse.

2.5 How continuous is the recording of paleomagnetic data in eastern Iceland?

Magnetostratigraphic studies in Iceland have been based on many assumptions, one of the most important being that volcanism was continuous. With 'continuous' it is meant that the rate of lava accumulation was fast enough so that no major paleomagnetic intervals (chrons) passed unrecorded.

An example of fast rates of lava accumulation is the lower part of the Holmatindur section, i.e. units RF1 to RF30. All these 29 units are reversely magnetized and the magnetic vectors (VGP) cluster around one magnetic pole as has been plotted in Figure 2.8 (upper hemisphere projection; see footnote for details). The stratigraphy of the lower part of Holmatindur is described in some detail in sections 1.4.2 to 1.4.4.

Secondly, it is frequently seen (Watkins and Walker, 1977) that boundaries between well established intervals of normal and reverse magnetic polarities have lava pole positions (VGP) of intermediate values. An example of this behaviour was found by the author in the Holmatindur section, i.e. units RF31 to RF34. As magnetic reversals are thought to occur over short periods the above assumption of 'continuous volcanism' is supported by both these examples.

However, there are features of the magnetostratigraphic sections that, at least locally, seem to oppose the assumption of continuous volcanism. Thus in the region a correlation exists between 'systematic deviations' and lithostratigraphic boundaries of the lava succession. In earlier magnetostratigraphic studies for eastern Iceland, i.e. by Watkins and Walker (1977), the above magnetic reversal-lithostratigraphic relationship was not noted or discussed. Just how drastic or effective were the paleomagnetic or structural changes that occurred during such hiatuses? For how long did they last?

The mean polar value is: VGP-latitude -63.7°, VGP-longitude 262.5°. The α_{95} is 6.4° and the R-value for the 29 units is 27.4682.

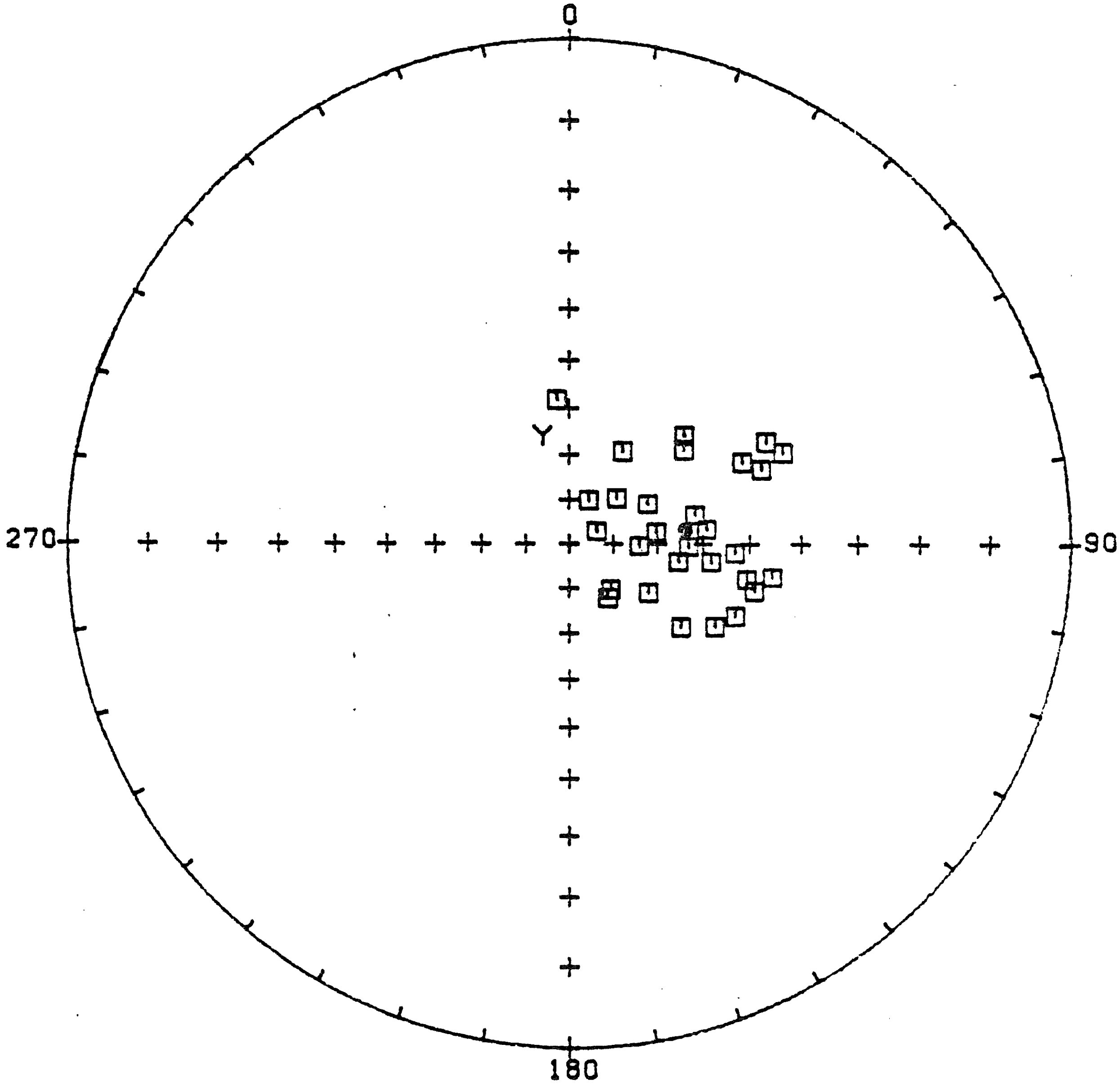


Figure 2.8 Stereographic projection of VGP-values for the lower part of the Holmatindur section, units RF1 to RF30. Solid dot denotes the mean magnetic pole. Note that all these units are reversely magnetized and have after rotation been projected on the upper hemisphere. Location of research area is shown with Y.

Seven examples of this behaviour are given in Table 2.8. The selected examples are taken from the stratigraphic succession in eastern Iceland (Watkins and Walker, 1977) that has an age range of 13.6 to about 10.0 Ma. During this interval a total of 22 well defined reversals occurred of which 7, and probably some others as well, coincided with either a change in lava lithology or stratigraphic occurrences of sedimentary (clastic) units. Thus about every third reversal during this period in eastern Iceland coincided with a stratigraphic hiatus. The fact that 'systematic deviations' coincide with lithostratigraphic boundaries strongly suggests that a considerable time interval elapsed during the hiatus involved. However, few clear examples of polarity reversals coinciding with lithostratigraphic boundaries were observed in western Reydarfjordur because the stratigraphic succession of the present study involves mainly normally magnetized lavas of anomaly 5 age.

One example is seen in the Trollafjall section (RH) where the lower and probably also the upper boundary of the reverse chron on top of anomaly 5 (Bleil and others, 1982) contain clastic beds, i.e. below units RH910, RH923 (and also RH924). Lithostratigraphic boundaries are expected to represent a hiatus in the stratigraphic record greater than those for a period that normally separates two lavas of a uniform lava formation.

2.6 Conclusions

(1) Anomaly 5 age lavas are present in Reydarfjordur, and their lower boundary has been determined with confidence both in the exposed lava succession (this work) and in the IRDP core (Bleil and others, 1982).

(2) Relatively thick dykes can locally remagnetize lavas and produce apparent reversals in a succession where they do not belong. When the available magnetostratigraphic data for eastern Iceland are examined (Watkins and Walker, 1977), some very short polarity intervals are vaguely defined and may possibly be explained by local remagnetization. Thus some reported reversed polarity intervals within anomaly 5 in eastern Iceland (i.e., each of intervals 9a and 9b; Watkins and Walker (1977)) are represented by only one lava unit. The postulated remagnetization of upper Holmatindur may primarily be the result of an unusually thick (10 m) basalt dyke intruding through the lava succession at a high structural level. It should be stressed, however, that in Reydarfjordur the mean dyke thickness is usually 3-4 m and dykes seldom exceed 10 m. Therefore, extensive remagnetization of lavas is considered unlikely.

(3) A reversely magnetized dyke unit (RF51D) extends through the upper part of Holmatindur section where the host lavas form part of anomaly 5 in this area. As reverse chrons within anomaly 5 were of very short duration and none are seen in sections RE and RD to the west it follows that dyke unit RF51D probably intruded the lavas during a longer reverse chron after the termination of anomaly 5. Thus based on field evidence and magnetostratigraphic data the dyke is likely to have intruded the area at least 1 m.y. after the lava succession in Holmatindur was formed, or less than about 9 Ma.

(4) Lava heterogeneity in terms of magnetic intensity of the 0.9 km section in Holmatindur is of such magnitude that no clear decrease is observed with depth. This is in contrast to earlier studies of the

Table 2.8 Stratigraphic occurrences of magnetic reversals coinciding with between lithostratigraphic boundaries (from Watkins and Walker, 1977).

Profile	Unit Boundary	Remarks
A	32/31	Units 32 and 31 are separated by the Bardatangi (clastic) tuff
H	29/28	Lithologic change from aphyric lavas to the Gerpir porphyritic lava formation
G	31A/30A	Lithologic change from plagioclase porphyritic lavas to aphyric lavas
C	55/54	Clastic sediment intercalating aphyric basalt lavas
C	58/57	Same as above
C	60/59	Same as above
D	68/67	Lavas separated by a 6 m thick tuff (clastic) unit

exposed lava succession in eastern Iceland. It is suggested that geochemical variations and/or grain size of magnetic phases play an important role in the magnetic record of the lava succession.

CHAPTER 3

DYKE INTRUSIVES IN REYDARFJORDUR

3.1 Introduction

The first structural models for the generation and lithological composition of what has been termed "seismic layer two" and the boundary between seismic layers two and three in Iceland were proposed shortly after 1960 (Walker 1964; Bodvarsson and Walker, 1964). These models were based on the early work carried out in eastern Iceland (e.g. Walker, 1959, 1960). According to these and some later models (e.g. Palmason, 1973; Piper and others, 1977) dyke intensity was thought to increase linearly with depth and reach a maximum value of 100% at the boundary between seismic layers two and three at a depth of 2-5 km depth. This school of thought interpreted dykes as feeders to the most of lavas presently exposed in the area (Walker, 1960). These models implied that in eastern Iceland dyke age is approximately equal to that of the host lavas and that dykes become consistently younger from east to west due to the westward dipping of the lava succession (Walker, 1965). The role that dykes played in generating the upper crust may have to be re-interpreted as a result of increased knowledge and understanding of the spreading mechanisms in the neovolcanic zones of Iceland (e.g.Bjornsson and others, 1977), deep crustal coring in eastern Iceland (Chapter 1, section 1.5), and deep drilling at various locations in Iceland (Palmason and others, 1979). This chapter offers new insights on the role of dykes in the generation of the crust of the study area.

3.2 The Breiddalur Dyke Swarm

3.2.1 Stratigraphic background

Through geological mapping in Reydarfjordur Walker (1959, 1963) studied the subvertical basaltic dykes and concluded that their intensity varies considerably; some areas are almost devoid of dykes (less than 2%), while elsewhere dyke swarms compose 6% to over 10% of the terrain. Walker defined one such, i.e., the Breiddalur dyke swarm, that crosses the area where the IRDP drill hole is located and can be followed in a north-south direction to the Breiddalur volcanic center.

In the western part of Reydarfjordur the highest intensity of the Breiddalur dyke swarm is generally about 10% (Figure 3.1). The maximum dyke intensity recorded for the Breiddalur dyke swarm (Walker, 1963) is 20% at Stafheidara river (270 m altitude) at about 10 km south of the IRDP drill site as shown on Figure 3.1. Only two inclined dykes (sills or sheets) probably related to the Thingmuli volcanic center, were found within the Breiddalur dyke swarm in Reydarfjordur: they dip to the west at about 45° and are less than 1 m in thickness. West of the drill site the dyke intensity increases, and inclined sheets from the Thingmuli volcanic center become abundant. Conversely, east of the drill site the dyke intensity gradually decreases and is below 1% in the Holmatindur section 13.5 km to the east (Figure 3.1). Fieldwork by the author indicates that not all the dykes of the Breiddalur dyke swarm were

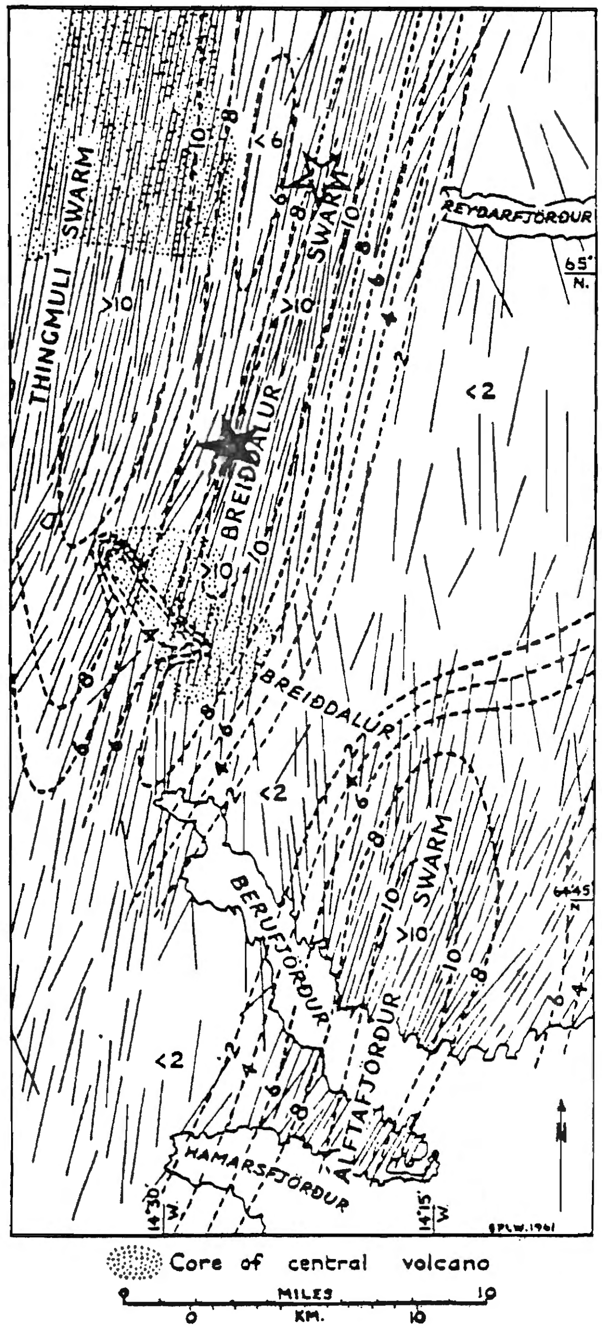


Figure 3.1 Isopleths of the Alftafjordur, Breiddalur and Thingmuli dyke swarms as % dilation by sea level (from Walker, 1963). Only a few dykes are presented to show the predominant trend. Indicated with a solid star is the location of Stafheidara river, where the maximum dyke volume is 20%. The location of the IRDP drill site is shown with an open star.

originated in the Breiddalur volcanic center. At Holmatindur dykes are few, have a more westerly strike and are exposed on the present plateau carapace. Some of the Holmatindur dykes (e.g. RF51D) have reversed magnetization and a northwesterly strike; their source remains unknown. It is possible that they resulted from off-axis dyke injection of less than 9.5 Ma age.

3.2.2 Dyke areas 1 to 4

For the present investigation, the study area of the Breiddalur dyke swarm was divided into four areas as shown on Figure 3.2. Located approximately at the eastern margin of the dyke swarm (area 4) are the youngest lava units of the Reydarfjordur volcanic center. The easternmost dykes that were studied are located at sea level and intersect the Holmar and Grjota olivine basalt formations. These lava formations, described in sections 1.4.2 and 1.4.3, are approximately 10.5 m.y. old. The westernmost dykes of this study are located at about 1200 m altitude in Areyjardalur, about 4 km to the south of the core of Thingmuli volcanic center. Dykes at this locality intrude lavas that are probably derived from the Thingmuli volcanic center. The lava age is here approximately 9 Ma and the dykes are probably part of the Thingmuli dyke swarm. Dyke characteristics for the four areas are quantitatively summarized in Table 3.1. Depending on bedrock exposures, dyke areas were located either on the north or south side of the fjord. The investigated traverses are oriented in an east-west direction, approximately perpendicular to the average dyke strike. In between the four dyke areas are dykes that were neither sampled nor mapped. However, as shown on Figure 3.2, the areas were selected in such a way

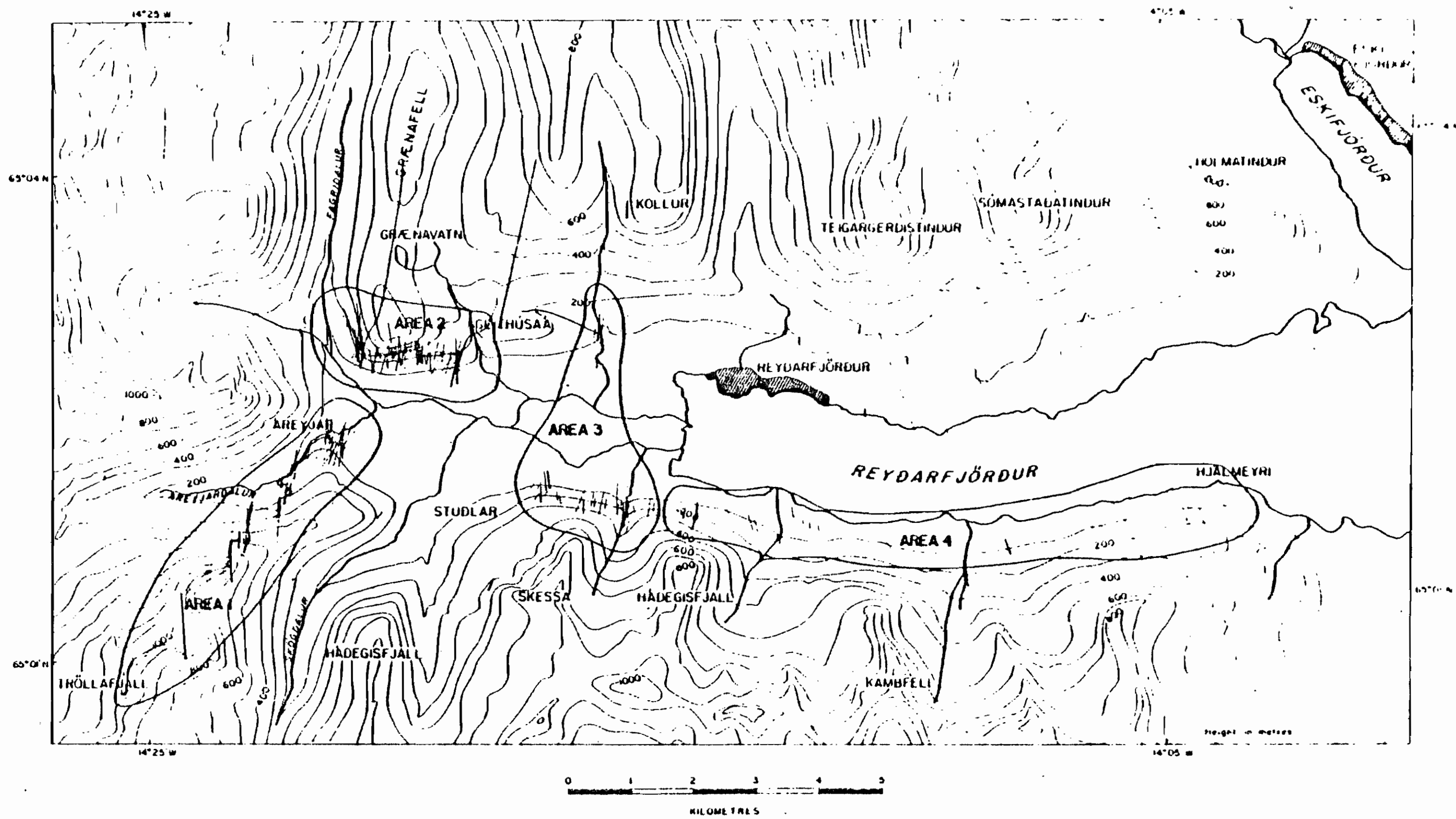


Figure 3.2 Four areas studied for dyke properties that jointly represent continuous outcrops from the Thingmuli- to the Reydarfjordur volcanic center.

Table 3.1 Summarized data on dyke dilation, thickness, and strike for areas 1 to 4.

Area	Dil.	Thickn.	1 STD	No. Units	Strike	1 STD	No. Units
	%	m			°		
1	5.2	3.3	3.3	66	11.0	16.7	64
2	10.0	3.5	2.6	51	2.6	13.3	51
3	3.9	2.8	1.9	29	13.1	18.8	29
4	0.9	3.4	2.3	23	-10.8	15.1	23
All	3.2	3.3	2.8	169	5.8	17.6	167

that they cover a continuous profile from east to west across the Breiddalur dyke swarm in Reydarfjordur. Due to the temporal overlap and structural similarities of the Breiddalur and Thingmuli dyke swarms, no distinction is made between the two in area 1. The study included a total of 174 dykes and for 169 of these the mean thickness is 3.3 m (Table 3.1), ranging from 0.4 to 24 m with a frequency distribution as shown in Figure 3.3. The mean strike for 167 dykes is N5.8°E, ranging from N48°W to N65°E. Frequency distribution for dyke strike is indicated on Figure 3.5. Altitude of measured dykes ranged from zero to 1130 m above sea level. Erosion has commonly been estimated to have reached some 500 m below the mountain carapace (Walker, 1960).

3.3 Dyke section RG in Graenafell (area 2)

The Breiddalur dyke swarm is superbly exposed in Graenafell (section RG) 1.5 km NE of the drill site (Figure 3.8 and Map 2 folded in pocket). Section RG is about 1.75 km long and is roughly perpendicular to the mean dyke strike. A total of 51 dykes were found in section RG with a mean thickness of 3.5 m, indicating Dyke intensity of 10.2%. The mean strike direction of the near-vertical dyke swarm is N3°E for a total of 51 dykes (range N30° W to N31° E). The mean thickness of the dykes as measured is 3.7 m. Based on paleomagnetism, as is shown in the next chapter, section RG is divisible into 5 subgroups (Chapter 4).

3.4 Vertical variations of dyke properties: volume, inclination, and thickness

Walker (1960) studied the vertical variations in dyke intensity and found it to decrease linearly with elevation. He concluded that the linear function for this relationship allows the pre-erosional surface level to be predicted because this level should coincide with the elevation of zero dyke intensity. The author disagrees with the above conclusions of Walker. The deep drilling in Reydarfjordur (Robinson and others, 1982b) demonstrated that dyke intensity in the IRDP drill core remains approximately constant, about 40% in each 500 m interval, to a depth of about 2 km below sea level.

It is appropriate to compare the above observation with a careful study of the Alftafjordur dyke swarm by Olafsson (1977). He measured 95 dykes between 100 and 300 m altitude in Berufjordur, 35 km south of Reydarfjordur. He found their mean dip to be 80°SE while their mean strike was N20°E. Models of crustal generation (e.g. Palmason, 1980) predict that stratigraphic successions in eastern Iceland will, while drifting from the active volcanic zone, be tilted toward west, i.e. toward the area of greatest subsidence in the volcanic zone. The tilting increases with depth and thus dykes, even if intruded late in the history of each region, will be subjected to some westward tilting. The consistent westward dip of the Alftafjordur dyke swarm observed by Olafsson is probablly due to increased burial of this region which, because of the overlying volcanic succession, formed the overlying volcanic succession formed in the Breiddalur-Thingmuli volcanic zone (Chapter 7).

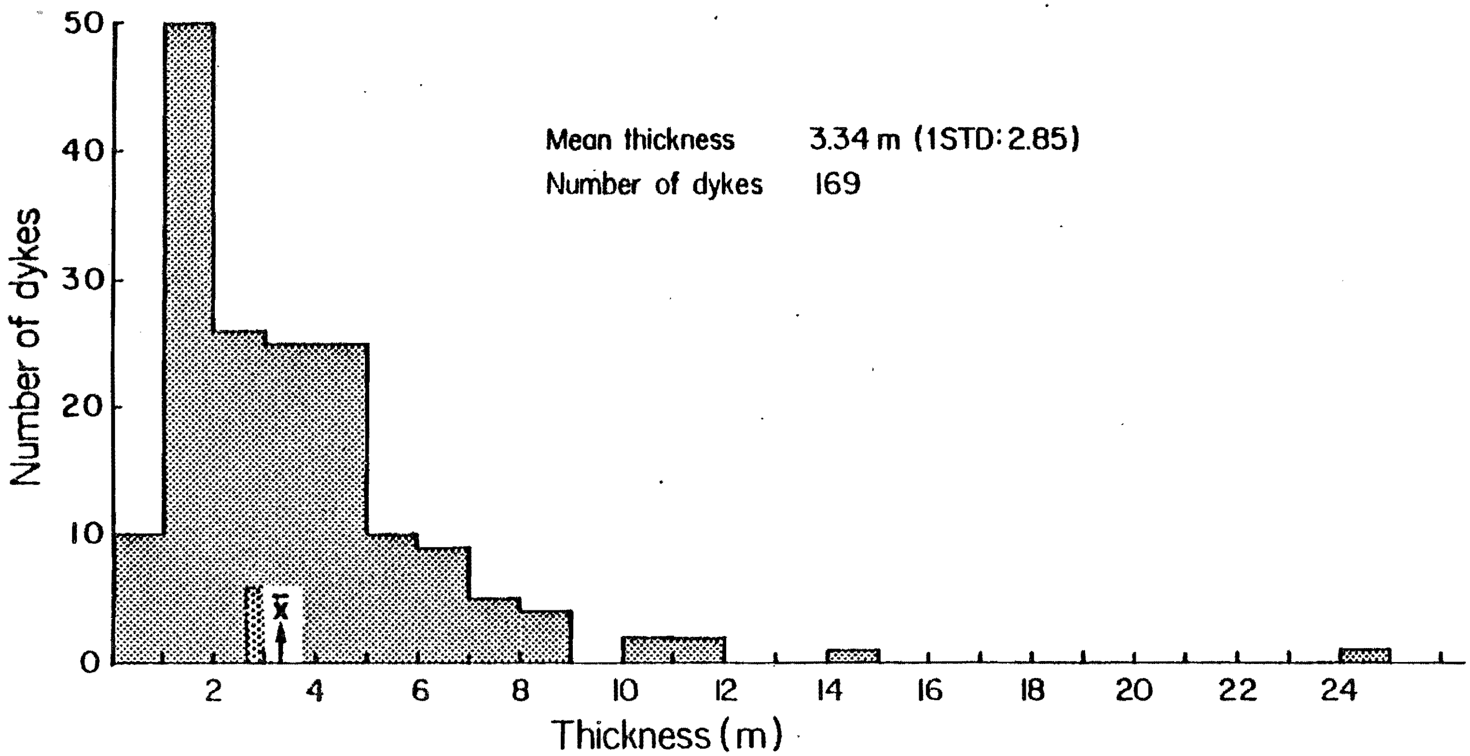


Figure 3.3 Frequency diagram showing the thickness distribution of dykes in areas 1 to 4.

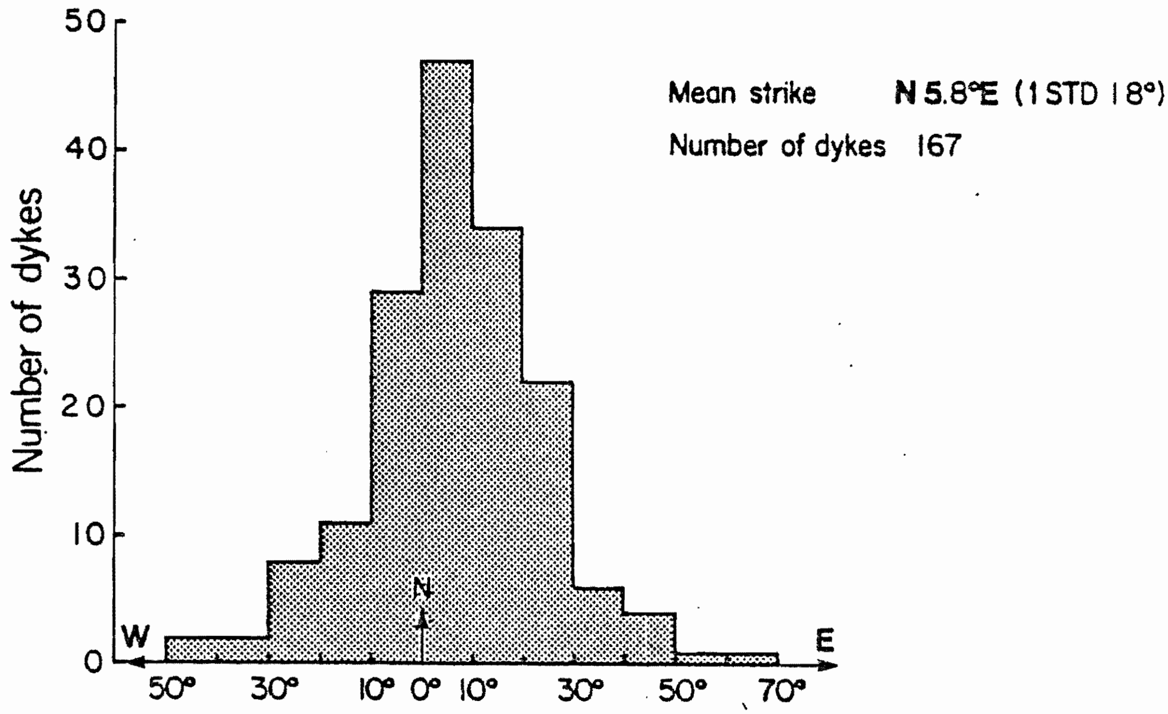


Figure 3.4 Frequency diagram showing dyke strike distribution in areas 1 to 4.

3.5 Southward increase of dyke thickness

The relationship between dyke thickness and elevation was studied by the author for 168 dykes of the Breiddalur-Thingmuli dyke system (Figure 3.6). Excluding a single anomalous dyke (RH939) the maximum dyke thickness decreases with increased elevation. With the same exception, no dykes thicker than 3.5 m occur above the 600 m elevation. Below 600 m elevation a total of 57 dykes out of 157 are thicker than 3.5 m. Thin dykes occur throughout the entire exposed section. Comparison with Olafsson's (1977) data reflects two outstanding differences (Figure 3.7). Mean dyke thickness is considerably greater in Berufjordur than in western Reydarfjordur; this may partly reflect the greater degree of erosion in Berufjordur. In Berufjordur the mean dyke thickness has a tendency to increase from sea level to the 300 m elevation and is only slightly lower at the 600 m contour. The mean thicknesses for the elevation levels are 3.55 (68 units), 3.89 (85), 5.40 (11) and 4.53 m (31), respectively. Clearly, dike thickness in the two swarms differs significantly. Thick dykes are abundant in Berufjordur at an elevation greater of about 600 m (mean thickness 4.53 m) with 16 dykes out of 31 thicker than 3.5 m, whereas only one dyke thicker than 3.5 m occurs at this elevation level in western Reydarfjordur. Note that the data sets (dyke populations) in Berufjordur and western Reydarfjordur are comparable in number. The above differences in dyke thickness for the two areas can be explained in a number of ways. Dyke thickness is most likely a direct function of the stress conditions (both lithostatic and magmatic) and/or spreading of the crust that took place before dyke emplacement. Thus at the time the Breiddalur and the Alftafjordur dyke

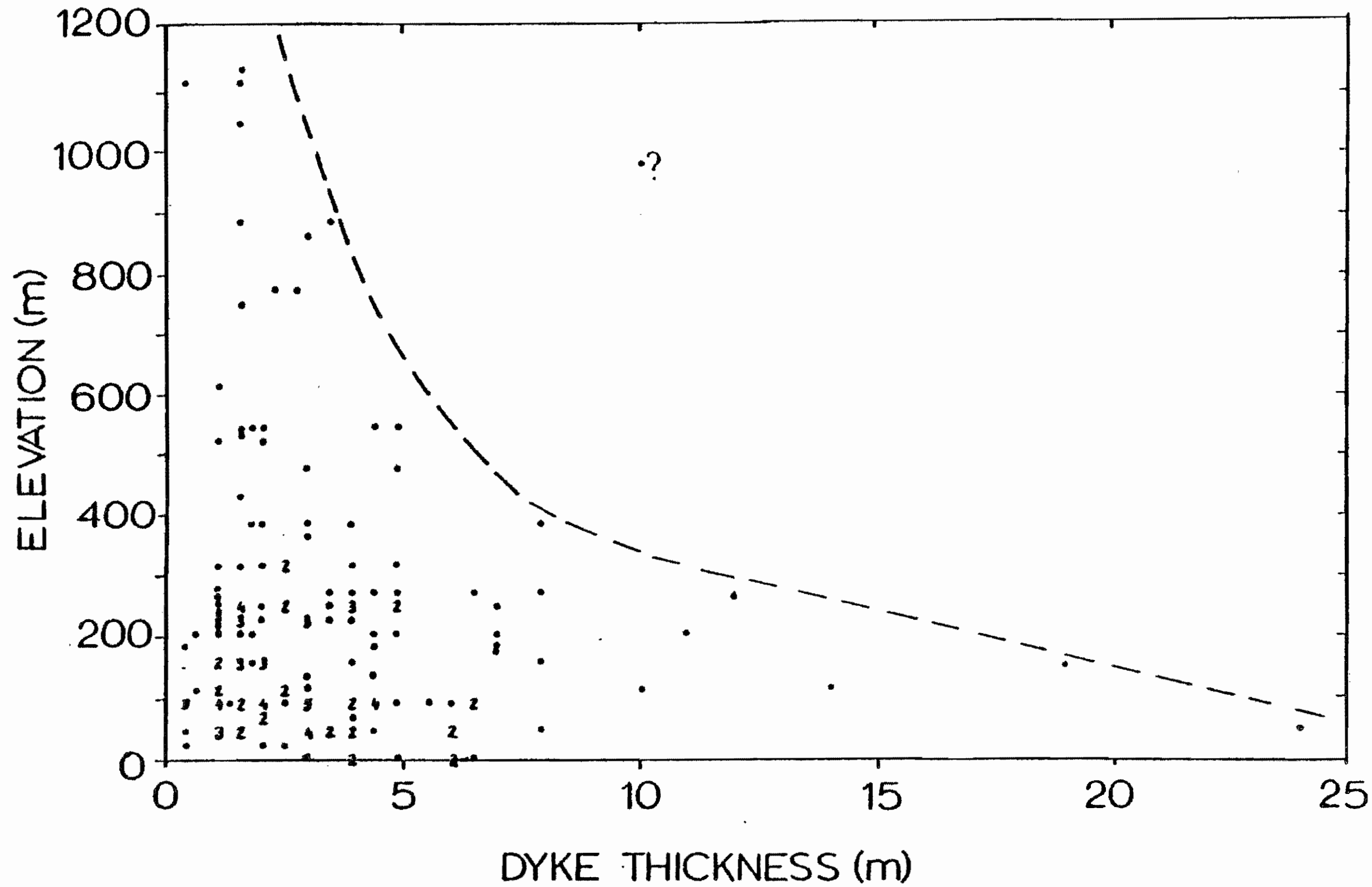


Figure 3.6 The relationship bewteen dyke thickness and elevation. As can be seen maximum dyke thickness decreases clearly with elevation.

swarms were formed it appears that either the spreading rate was greater in the southern part of this region or the spreading of the crust proceeded for longer periods prior to dyke emplacement in Alftafjordur. Whether the higher volcanic production and excess spreading rates proposed for south Iceland (Walker, 1975) had already occurred during the build up of eastern Iceland cannot be verified with the available data. This is difficult, because lava isochrons are approximately parallel for most of eastern Iceland, a feature that would not be expected if spreading rates varied along the strike direction. The actual timing and a quantitative estimate of variations in both volcanic production and spreading rates can only be made when more detailed geological mapping has been carried out in Iceland, parts of which have never been mapped, such as the fjordlands north of the present study area.

3.6 Vertically discontinuous dykes

During the mapping, several examples of upwardly or downwardly terminating dykes were found suggesting that they were intruded laterally. For example Type-A, all in section RD: NV3, NV4, NV4A (about 10 m west of NV4), NV5; Type-B (Hadegisfjall, dyke area 3): R5 (see location on Map 2 in pocket). One has no difficulty in accepting that sills are emplaced by lateral flow of magma, but, somehow, the idea that magma may flow laterally in a vertical dyke tends to produce a skeptical reaction in many geologists. No reference has been found in the literature on Icelandic geology to discontinuous dykes formed as a result of lateral dyke emplacement and in general, dykes in eastern Iceland have been regarded the vertical feeders of exposed lavas in that

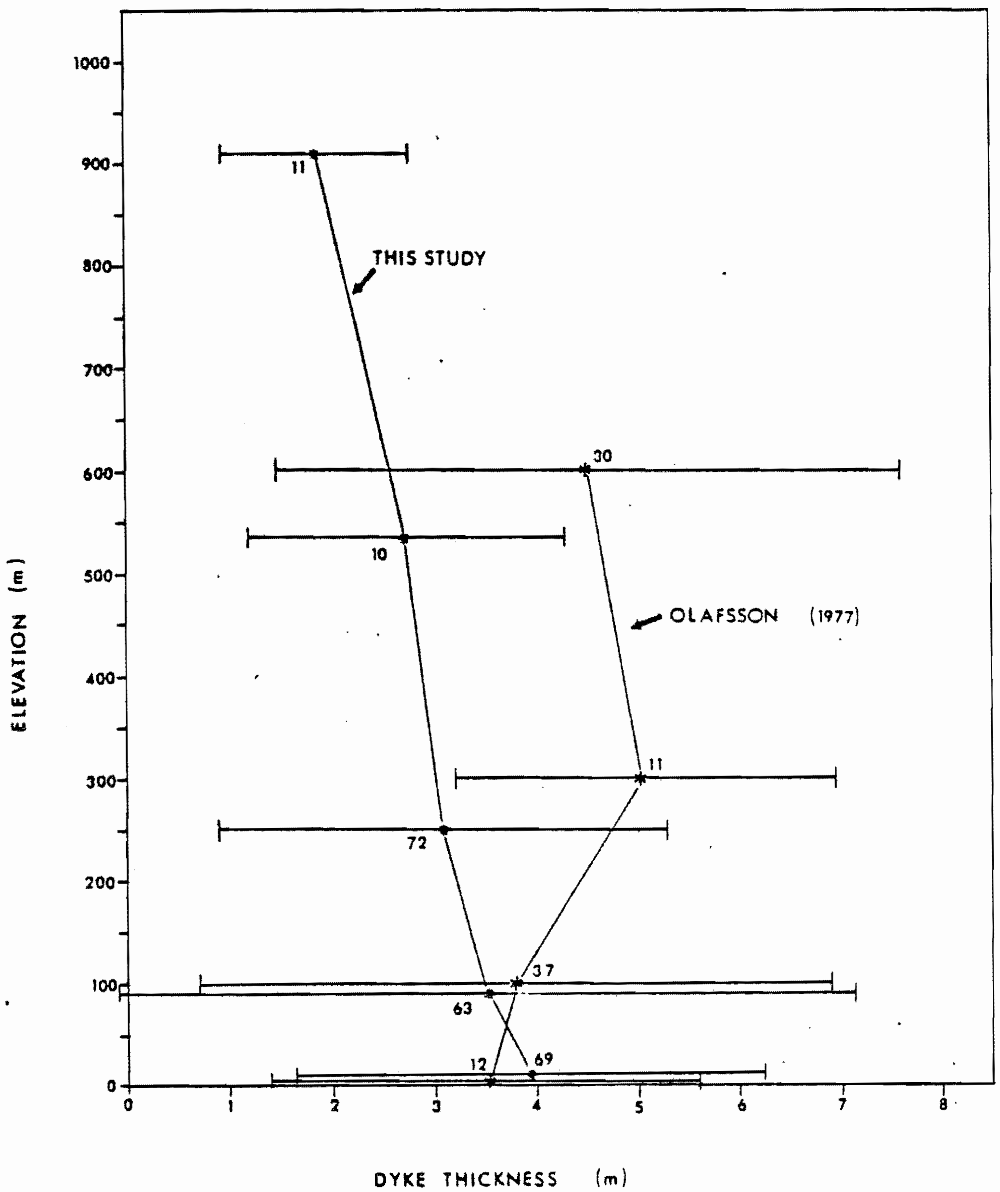


Figure 3.7 Comparison of mean dyke thickness at several (averaged) elevation levels for the Breiddalur and the Alftafjordur dyke swarms. Data for the Alftafjordur dyke swarm from Olafsson (1977).

region. Discontinuous, 'rootless' dykes in Reydarfjordur had been noted by Lomize (1976) and interpreted as being intrusions into old fault planes, i.e. offshoots from vertically intruded dykes. Discontinuous dykes were found by the author to occur under two types of lithologic conditions, i.e., either at lava-sedimentary interfaces (type-A) or between boundaries of basalt lavas (type-B). Type-A, which is most common, occurs at the interface between relatively thick sediments (20-40 m) and basalt lavas (Figures 3.9, 3.10 and 3.11). Note on Figure 3.9 the truncation of sedimentary material below the upper dyke segment. Type-B was found at the interface between two lavas that were separated by a thin (10-20 cm) red bed, Figure 3.12. At the lava-lava interface (type-B) the lower unit is scoraceous whereas the base of the upper unit is dense and non-vesicular. In this case thin dykelets (Figure 3.13) connect the upper and lower parts of the dyke as shown on Figure 3.12. The vertical separation between the two parts is about 1 m, the horizontal displacement being about 4 m.

Exceptionally good exposures are present by the river Njorvadalsa, which has undercut a thick, poorly consolidated unit of the Holmatindur tuff, leaving a vertical dyke (60 cm thick) exposing an unweathered glassy margin of 2 to 4 mm thickness. The glassy dyke wall has a consistent striated pattern similar to horizontal 'slickensides' (Figure 3.14).

The lineations may represent the imprinted fracture pattern of the host rock walls when the fracture opened and the magma congealed on the host rock surface. However, studies indicate (Hodgson, 1961) that basalt fractures do not have regularly flat surfaces that could correspond to the fine (2-3 mm) straight linear pattern observed on the

Figure 3.8 The Graenafell dyke section (RG) yields complete exposures into the Breiddalur dyke swarm. About 1 km south of Graenafell is the IRDP drill site (arrow).

glassy dyke wall (2-3m^2) under consideration. In contrast joint faces commonly show structural features such as plume-like markings and fringe joints.

Likewise these lineations could be slickensides caused by a strike slip fault movement between dyke wall and host rock long after the dyke cooled. This is an unlikely explanation, because displacements in this area are caused by normal tensional faults as opposed to compressional strike slip faults. In fact no strike slip faults have been found in the study area and none are reported for eastern Iceland.

Another hypothesis is that these lineations formed during lateral flow of magma into the host rock.

To test this interpretation 3 samples were collected for thin section studies of (a) slickensides on a normal fault plane, (b) a thin dykelet with a clear glassy margin, and (c) the glassy striated dyke wall (dyke NV5) in question.

(a) Slickensides. A fault plane with about 5 m displacement was sampled by Geithusaa river, cliff section A-1 (Figure 1.4). The fault plane had well preserved slickensides as shown on Figure 3.15. A 2-cm-wide thin section was made of the slickensides that cut across the fault plane. Microscopic examination reveals that the entire thin section is made up of material that has been cataclastically crushed so that no internal primary structure remains (Figure 3.16). This strongly suggests that on normal fault planes considerable material is ground up due to shear.

(b) Dykelet. A dykelet was sampled 'in situ' in the upper part of

Figure 3.9a A discontinuous dyke (NV4) of type-A by the Njorvadalsa river (section RD). The dyke is exposed in a 40-m-thick sediment (Holmatindur tuff). It is noteworthy that the two vertical dyke segments, each about 2 m thick, are displaced horizontally by about 3 m and connected by a thin dykelet, about 30 cm thick. The fine grained dykelet plays only a passive role in connecting the two dykes. Indicated with an arrow is the location of dyke unit NV4A (Figure 3.11) relative to NV4.

Figure 3.9b Same dyke (NV4) as on Figure 3.9a. The figure focuses in particular on the upper dyke portion. Noteworthy is the downward truncation of the sedimentary unit underneath the dyke (scale: backsack).

Figure 3.10 Type-A discontinuous (unit NV5, dyke area 3). Here the dyke is discontinuous (rootless) about 2 m below the lava-sedimentary interface. In this case the vertical dyke is completely cut off at the base. Therefore horizontal as opposed to vertical intrusion more likely explains the mode of dyke emplacement.

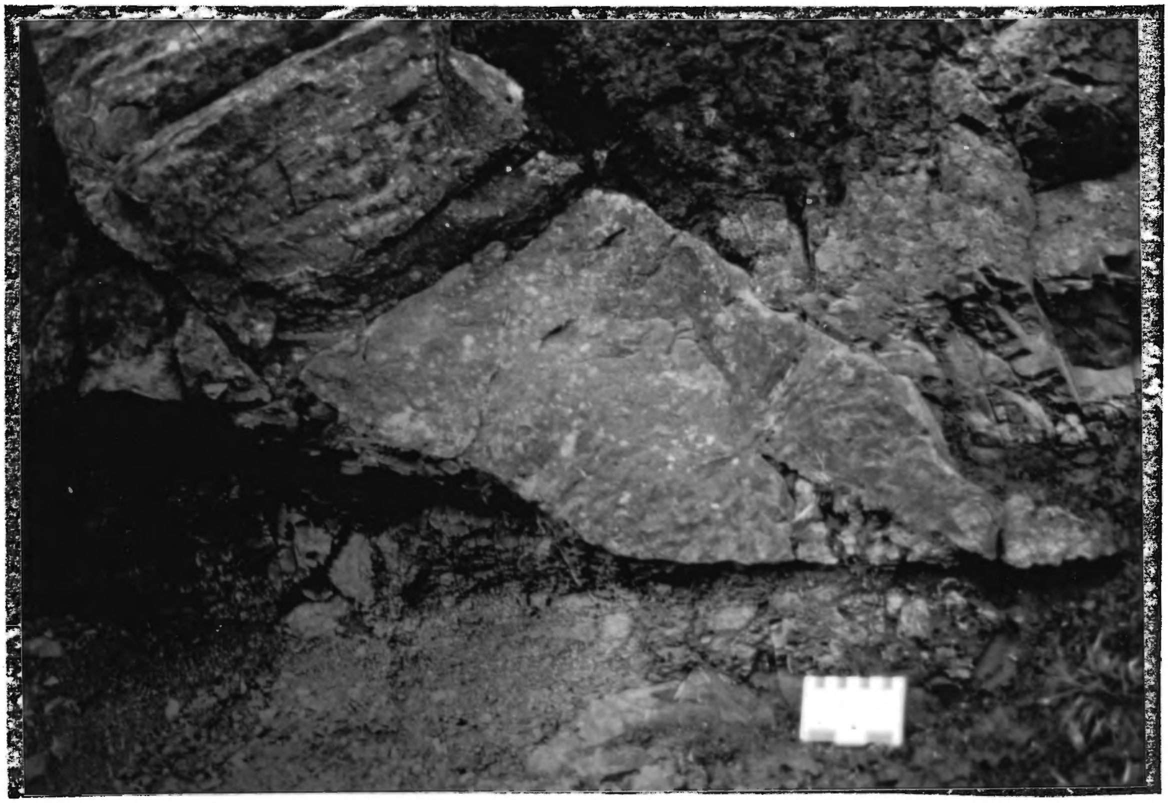


Figure 3.11 Type-A discontinuous dyke (NV4A, dyke area 3). This dyke, only 60 cm thick, is exposed at the intersection of the Holmatindur tuff and the overlying lavas. It is noteworthy that complete discontinuity occurs only 10 cm below the lava-sedimentary interface (scale in cm and inches).

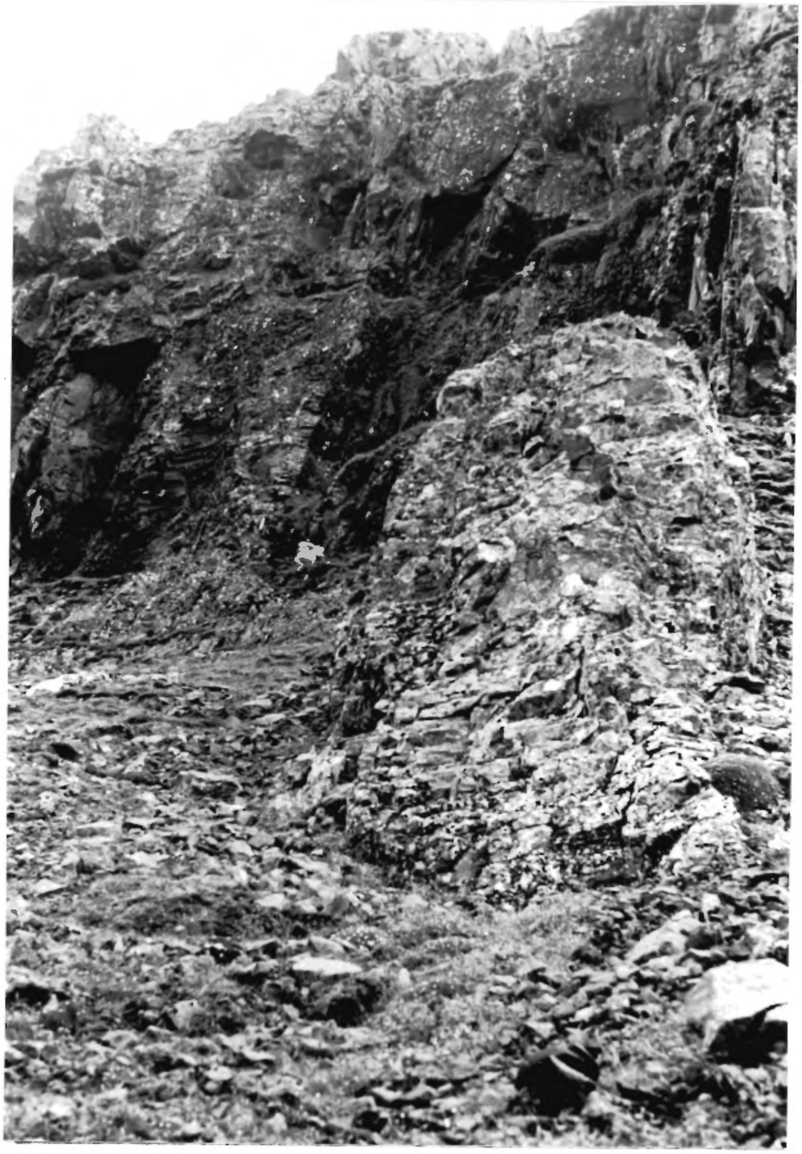


Figure 3.12 Type-B discontinuous dyke (R5, area 3). The discontinuity occurs at a lava-lava interface. Intercalating the two lavas is a thin (5 cm) red clastic bed. However, the lavas differ in that the upper lava consists of a fine grained, dense, nonvesicular lower lava boundary whereas the lower lava is made up of scoriaceous vesicular flow top. The dyke is discontinuous over a vertical distance of about 1 m. Several thin (2-15 cm) veins are exposed over this 5 m interval (see Figure 3.13). The lower dyke segment is offset relative to the upper segment by about 5 m.

Figure 3.13 Thin veins separate the upper and lower seg ments of dyke R5 (area 3). These veins are very fine grained and can clearly not be the channel by which the lower part of dyke R5 transported magma to the upper part.

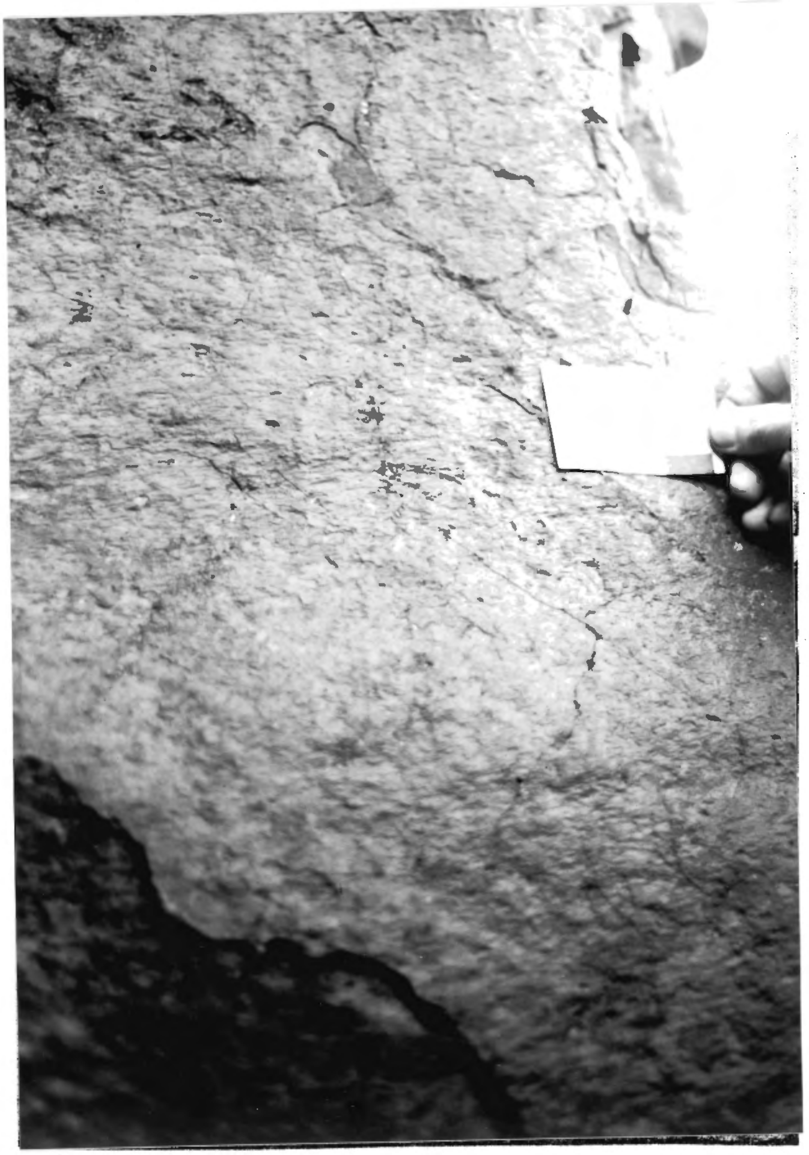


Figure 3.14 Horizontal lineations on a dyke wall. The presence of glass on the wall strongly suggests that the striations are a primary feature formed during dyke emplacement.

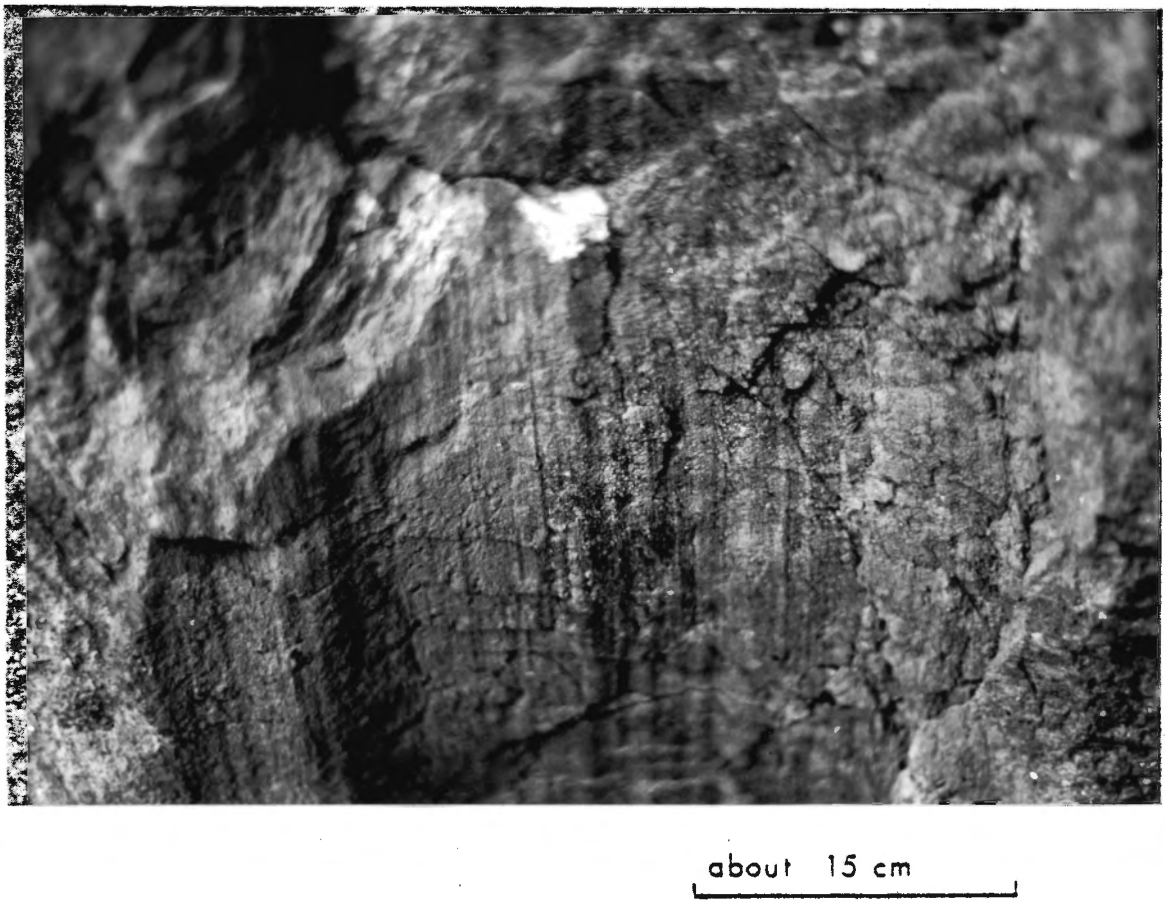


Figure 3.15 Near vertical slickenside on a fault plane in Geithusaa gully with a fault displacement of about 5 m. Note the fine pattern and perfect continuity of striations.

Holmatindur section intruding lava unit RF81. Located at about 830 m elevation the dykelet, 5 cm thick, is probably an offshot from the thick (11 m) dyke nearby, i.e. unit RF51D. The wall surface of this dykelet is highly irregular so that in places plagioclase and olivine phenocrysts protrude from it. The imprint on the dyke wall indicates that the cooling magma adopted the irregular surface of the fracture. The dykelet contains zones with phenocrysts in a glassy groundmass (Figure 3.17). No evidence of shear or deformation is visible, suggesting that in this dykelet, no relative motion between the solidified glass and the host lavas took place.

(c) Glassy striated dyke wall (NV4A). A thin section examination of the dyke margin in question reveals that glass (1-2-mm) is preserved on its very edge (Figure 3.18). From the glassy rim toward the dyke interior the glass gradually changes to a fine- to coarse-grained groundmass. Grinding or crushing of the dyke wall is absent. In the IRDP core there appear numerous examples of dyke-lava contacts where the glassy dyke rim is excellently preserved. The glassy rims are typically 2-3mm wide and their frequent occurrence within the Breiddalur dyke swarm is evidence that the shear stress between the dyke walls and the host lava was not enough to destroy the glassy edge.

The pressure exerted by the intruding magma and its movement, while congealing, may have been great enough to form a linear pattern of striations on the glassy margin. The first step of this mechanism is visualized as the congealing or welding of basalt portion to the fissure wall. At this stage however, the magma is still flowing laterally through the fissure. In turn the newly formed contact is dragged by the

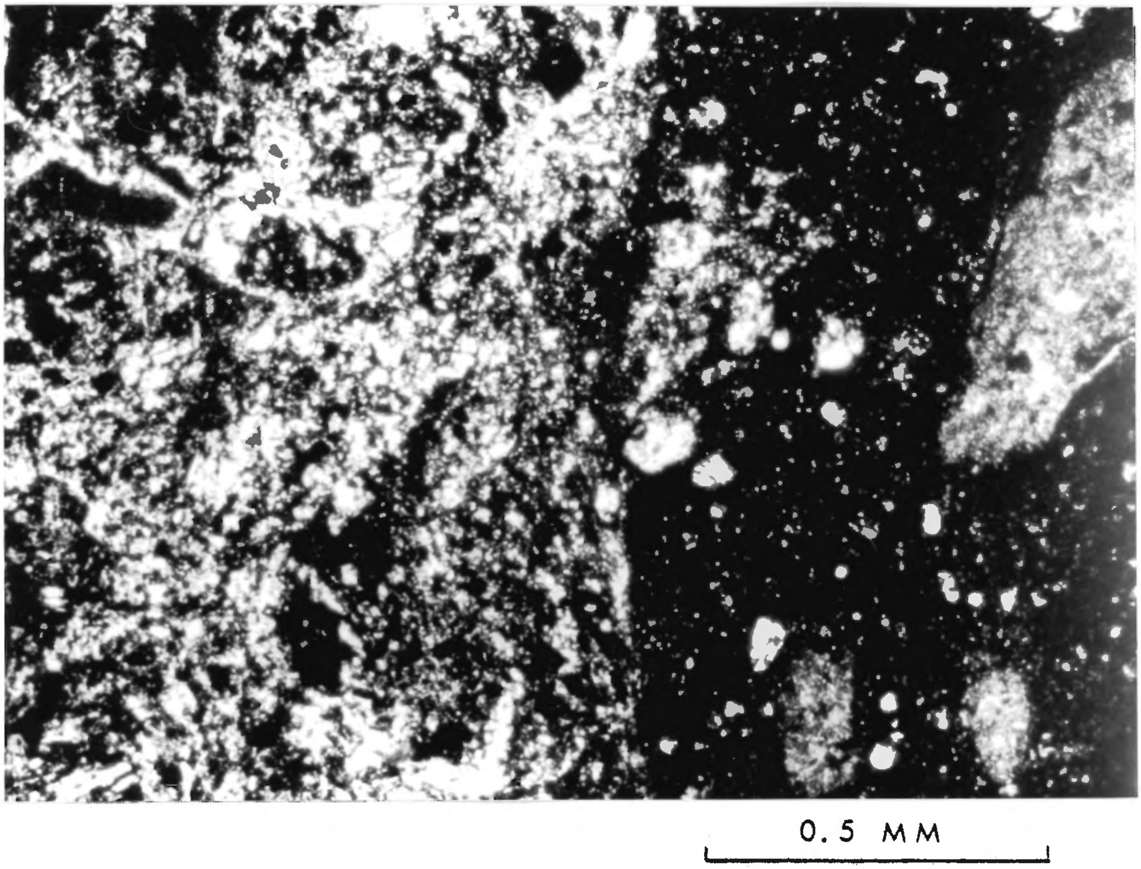


Figure 3.16 Photograph of a slickenside fault plane in a thin section. Note that the primary crystallization pattern of the lava flow has been destroyed by grinding and replaced by subhedral grains of various sizes.

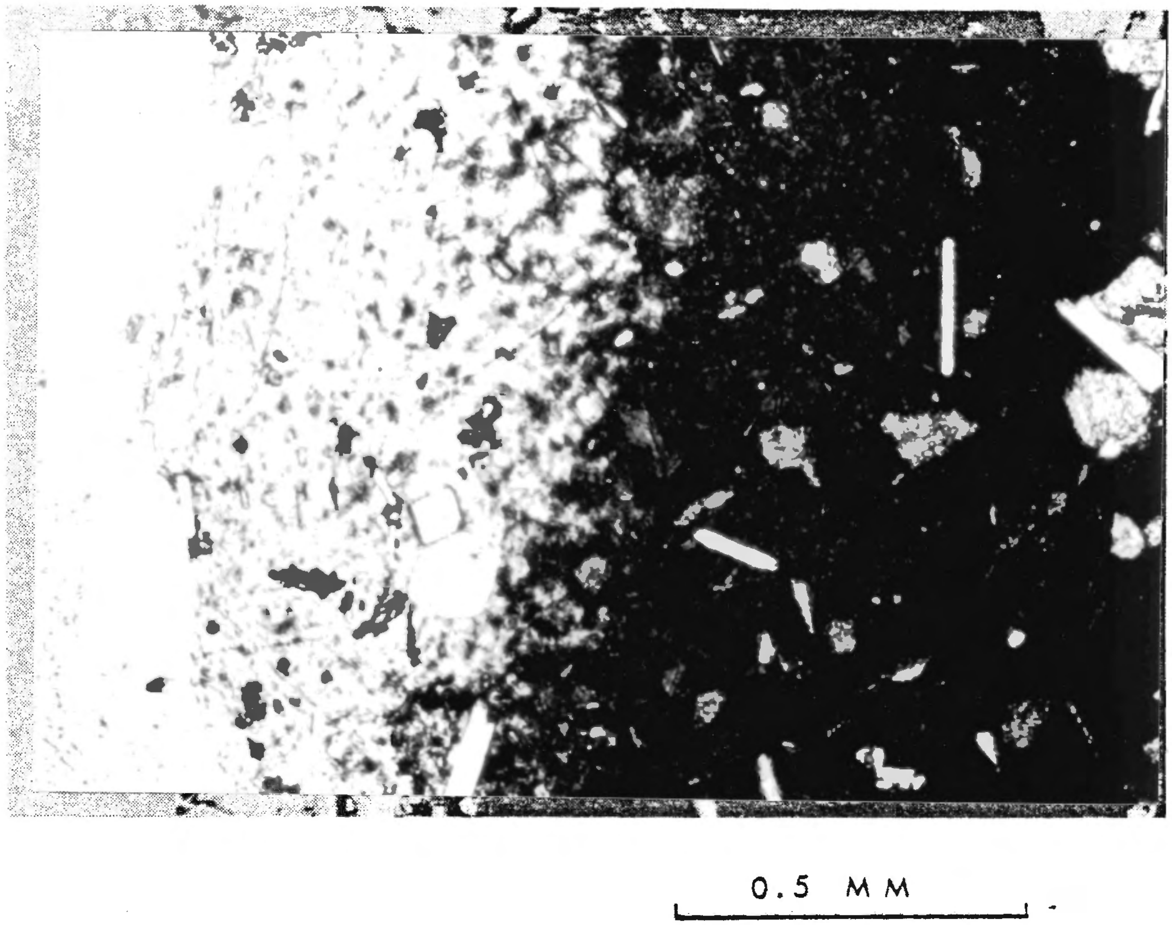


Figure 3.17 A microscopic photograph shows that the edge of a veinlet is made up of fresh glass that grades into a finely crystalline groundmass over an interval of about 0.2 mm.

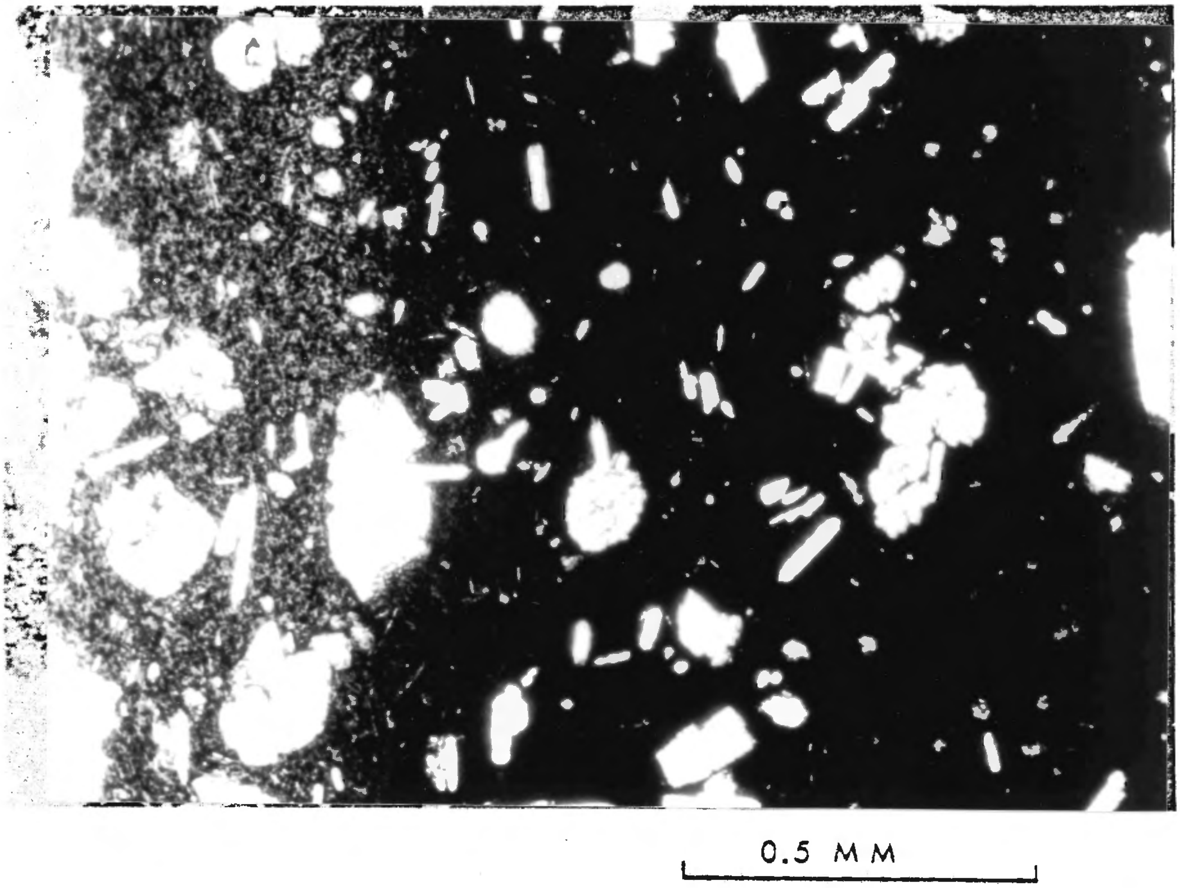


Figure 3.18 Microscopic photograph of a dyke surface (NV4) that contained visible lineations in a hand sample. Here the relative movement of dyke and lava has destroyed part of the margin. However, presence of glass on the margin stronly indicates that hardly any material wasting has taken place or probably less than 1 mm.

dyke which is predominantly fluid. The flow of magma causes these striations to form and their horizontal orientation is thought to correspond to the direction of magma emplacement. Evidently, a deliberate search for this kind of feature would be required to test the validity of this feature as evidence.

3.7 Formation and implications of discontinuous dykes

The current spreading episode in the Krafla volcanic center (Figure 1.1) and its associated fissure swarm in northern Iceland (Bjornsson and others, 1977, 1979) presumably reflect the present-day formation of a dyke swarm similar to those exposed in eastern Iceland. The process occurs by subsurface lateral injection of magma into the fissure swarm that defines the present plate boundary (Einarson and Brandsdottir, 1980; Einarsson, 1978). Thus migration of epicenters along the Krafla fissure swarm away from the magma chamber during deflation events is typically 50 cm/s or less (Einarsson, 1981). As dyke generation surrounding volcanic centers is most commonly the response of magma flow to brittle failure of rocks at the surface of magma chambers, it is important to understand the orientation of the stress field within a volcanic system. A volcanic system is defined here as the magma chamber of a volcanic center <u>and</u> its intrinsic fissure (dyke) swarm. Two large scale processes are thought to determine the distribution of the horizontal compression of the regional stress surrounding magma chambers. These processes are the overall rifting apart of two accreting plates and the influx of magma into a magma chamber, i.e. magmatic pressure. A horizontal tensional stress field is exerted by the east-west accreting plates in the rift zone in Krafla, and a hydrostatic component is exerted by the influx of magma from below into a magma chamber. These two components determine the three dimensional stress field that is thought to be responsible for both the formation of fissures and dyke emplacement.

Fracture formation. The fracture (fissure) formation in the vicinity of volcanic centers starts at depth and propagates away from the magma chamber in an explosive manner. If it is the magmatic pressure at depth that causes the initiation of the fissure a stress gradient exists from the magma-host rock interface away from the chamber. The stress gradient would in part be caused by the decreasing overburden or lithostatic pressure with elevation and/or distance from the magma chamber. For this reason the widening of a fissure, and subsequently the volume of magma emplaced into it, will decrease in all directions away from the magma chamber. Further away from the chamber open 'dry' fissures may exist that could have formed when spreading occurred without simultaneous magma injection from a volcanic center. It has been pointed out (Walker, 1974b) that increased flow of cold groundwater near the surface within the neovolcanic zone causes magma, emplaced at shallow depth to congeal more rapidly than at greater depth. Groundwater flow at shallow levels causing dykes to congeal rapidly in narrow fissures may prevent magma from reaching the surface. A large number of dykes in a dyke swarm may therefore reach minimum (zero) dyke thickness at a shallow crustal level that does not coincide with any "preerosional surface" as had been assumed (Walker, 1974b). The fracturing that is neccessary for dyke formation occurs typically in the top 10 km of the crust (Einarsson, 1981). The confining pressure surrounding the magma chamber, at 3 to 7 km depth, is determined by the lithostatic pressure at this depth interval. Above the magma chamber the geothermal gradient is steep (170°C/km) (Bjornsson and others, 1977), but is probably much lower at the same depth along the fissure swarm away from the volcanic center. The magmatic (hydrostatic) pressure exerted by a periodically inflated magma chamber contributes the neccessary yield stress that overcomes the minimum compressive stress (σ_3) but the magmatic pressure is lower than the confining lithostatic pressure provided by the chamber walls (Einarsson, 1981). Once the fracture has formed, magma enters into it and expands it further. Fractures develop most likely in a direction normal to the minimum horizontal compression of the regional stress (Nakamura, 1977), so that the rocks fail by tension. At a different scale, the formation of fractures in volcanic centres of the Krafla type has analogies with the hydrofracturing of wells (e.g. Haimson, 1974; Hubbert and Willis, 1957). A discussion of the theories of mechanisms of dyke intrusion relevant to the dyke swarms in the study area is beyond the scope of this thesis. However, as a first approximation, the contrasting behaviour of lavas and clastic units during fracturing in response to extensional tectonic regimes and to the (fluid) pressure exerted by the magma is probably related to the contrasting competence (viscosity) of the units. Whereas the more competent lavas fail by brittle failure (i.e. opening of a fracture), intervening water-saturated tuffs and sediments behave as plastic or ductile bodies, stretching or 'pinching' without giving rise to an opening, acting as a continuous seal between lava units.

Dykes intruding relatively thick (10 to 50 m) units of sediments are seen generally to have behaved erratically, displaying abrupt changes in thickness and orientation. In particular, dykes that are less than 50 cm in thickness become discontinuous and randomly oriented entities. It must be indicated, however, that the great majority of thin sedimentary units separating lava flows have yielded brittlely; the behaviour of individual beds must be influenced by the physical properties of the total local lithological package. Obviously, the relationship (ratio) between the thickness of a clastic bed and the width of the dyke-induced fracture imposes limits to the amount of ductile 'pinching' that a bed can attain before fracturing. Also, consideration may have to be given to the rate of strain: materials that behave as ductile bodies at slow rates of strain become brittle when strain occurs at a fast rate.

3.8 Dyke scarcity in western Reydarfjordur

Within the four dyke areas in western Reydarfjordur most of the dykes are located in areas 1 to 3 as shown on Figure 3.2. For the present discussion, and ignoring elevation effects on dyke thickness, all dykes in these three areas are assumed to compose the Breiddalur dyke swarm as it extends into Reydarfjordur. The total dilation in these areas is 442 m (6%) for 136 dykes over a distance of 7400 m. If one assumes further that when this dyke swarm was formed, half spreading rates were equal to present rates in northeastern Iceland or about 1 cm/yr, it follows that the dilation necessary to accommodate these dykes could have occurred over a period of only about 22000 years. Thus in this area there is a notable deficit of dyke intrusives to account for the spreading that must have taken place during the eruption of the host lavas for these dykes which occurred over some 2.5 m.y. Not only did the lava succession in western Reydarfjordur form prior to intrusion of the

Breiddalur dyke swarm, but the dyke swarm appears to have intruded the area over a very brief period. Due to the temporal overlap and general structural similarities between the Thingmuli and Breiddalur volcanic centers, both these centers may be underlain by thick volcanic successions at a depth of about 1 to 2 km. The underlying successions would have originated elsewhere in older volcanic centers now totally buried below sea level (see Chapter 7).

3.9 Summary

Field observations by the author suggest that dykes intruding lavas between the Reydarfjordur and the Thingmuli volcanic centers are laterally emplaced intrusives many of which did not extrude at the surface (Figure 3.19). Dykes that are vertically discontinuous, but appear to have great lateral continuity are incompatible with a general flow of magma in a vertical direction. The well exposed dykes of the Breiddalur dyke swarm are not seen to act as feeders to the lava succession in Reydarfjordur. Eruptive sites in basalt lavas exist only close to the Reydarfjordur and Thingmuli volcanic centers. The estimated age for the youngest eruptive sites near the Reydarfjordur volcanic center is about 10.3 Ma. No eruptive sites in the lava succession between the two volcanic centers were observed by the author, although one such site is reported by Walker (1963) in Graenafell. The lack of identified eruptive sites in an excellently exposed basalt lava succession away from the volcanic centers suggests that the dykes were generally intrusives but not feeders of lavas.

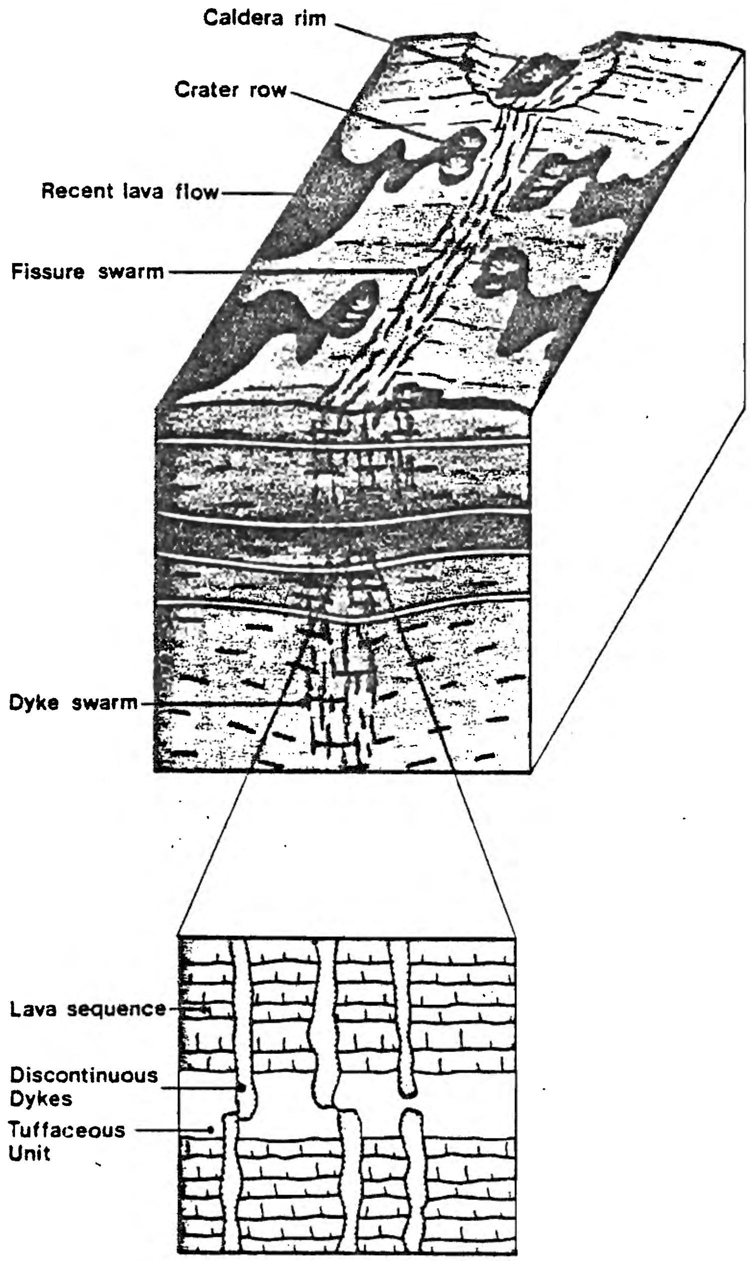


Figure 3.19 Schematic diagram of a volcanic system analogous to the Breiddalur volcanic center and the Breiddalur dyke swarm. The diagram shows a fissure swarm extending from a caldera. At depth a magma chamber feeds fissures with dyke intrusives that become discontinuous at lithostratigraphic boundaries (lava-clastic units). This suggests a lateral as opposed to vertical mode of dyke emplacement and that the source area for most dykes in eastern Iceland are limited to volcanic centers.

3.10 Conclusions

From the above stratigraphic investigation of the Breiddalur dyke swarm the following conclusions are derived:

Field relationships in the Breiddalur dyke swarm strongly suggest that dykes were emplaced laterally, not vertically.

The presence of discrete dyke swarms reflects the localized nature of volcanism similar to the fissure swarm volcanism in the presently active rift zone in northern Iceland.

Exposed dykes of the Breiddalur dyke swarm in western Reydarfjordur were generally not the feeders to the presently exposed lavas but played instead a passive role as minor intrusives. They could have fed lavas higher in the succession, now removed by erosion.

The lava succession between the Reydarfjordur and the Thingmuli volcanic centers formed first, later to be intruded by the Breiddalur dyke swarm. This implies that, where exposed, the Breiddalur dyke swarm is at least 1 m.y. younger than the host lavas. Dykes with a westerly trend that are located in the Holmatindur area, some of which have reverse magnetic polarity, are probably at least 1.5 m.y. younger than the host lavas. The source for these dykes cannot be in the Breiddalur area and remains at present unknown. These dykes may be "off axis" intrusions.

Most of the feeder dykes for the exposed lava section between the Reydarfjordur and the Thingmuli volcanic centers may be hidden below the present sea level west of the IRDP drill hole due to burial caused by lava accumulation.

CHAPTER 4

PALEOMAGNETIC STUDY OF THE BREIDDALUR DYKE SWARM IN GRAENAFELL, SECTION RG.

4.1 Introduction

The paleomagnetic study in Graenafell was completed mainly to test the hypothesis that dykes did not feed the lavas there exposed. The lava magnetostratigraphy in the province is relatively well known (Chapter 2) and for comparison it is important to establish the magnetic pole positions of the dyke swarm. Thus, if the lava and dyke pole positions proved widely dissimilar it could be argued that the dykes did not feed the lava formations of the presently exposed cliff section. If, on the other hand, the dyke-pole positions were similar to those of the lavas the above argument would require further study. If the VGP's of the (supposedly feeder) dykes show small scatter it can be assumed that the VGP's of the lavas also they would feed should also have small scatter. Similarly, if the dyke-VGP's were grouped, the lava-pole positions should have similar grouping.

4.2 Paleomagnetic sampling and laboratory treatment

For the paleomagnetic study a total of 46 dyke units were sampled in Graenafell. The Graenafell section (RG, Figure 1.4) ,is located at

65°04N (latitude), 345°42E (longitude). The field and laboratory techniques for dykes were identical to those for the lavas of section RF in Holmatindur (section 2.2) except that the dykes were sampled at roughly equal intervals across the dyke, avoiding the dyke contacts. In general the average magnetic directions were computed with peak-alternating field values in the range of 100 to 300 Oersteds. During demagnetization a total of 18 out of 160 samples, i.e. 11%, gave meaningless results and were omitted when computing the unit average; this is common practice in paleomagnetic studies of this nature.

4.3 Paleomagnetic results

Summarized in Table 4.1 are results of the paleomagnetic study and information on dyke strike. The results have been corrected for a westward tilt (6°) of the stratigraphic succession using 270° as the azimuth. In the third column of Table 4.1 are shown both the number of accepted samples and those that were rejected (in brackets). Despite rejection of 18 samples a statistically reliable average was obtained for each dyke unit following the criteria of Kristjansson and others (1980). When comparing the mean magnetic properties in their collection they excluded α95-values that exceeded 23.5° (for n:3). In the present study the highest α95 for n:3 and for n:4 are 17.9° and 13.8°, respectively. For seven dykes (out of 46) the unit average was computed from only two sample measurements. These seven units were excluded when calculating the mean α95, which for the remaining 39 units was found to be 9.4° (sd:4.8). For the 6 units that had an 'intermediate VGP-latitude', based on more than two meaningful measurements, the α95 was 14.0°(sd:6.4). The mean α 95 for 33 dyke units with 'steep VGP

Table 4.1 Paleomagnetic results for the Breiddalur dyke swarm in section RG (Graenafell).

UN	SG	ST	N	P	I	D	R	A-95	θ'	ϕ'
RG1	1	N20E	3(1)	R	-73.1	153.0	2.9687	15.6	-75.9	62.1
RG2	2	N13E	2(1)	N	78.9	2.9	1.9971	(13.5)	86.2	2.4
RG3	3	N31E	4	N	70.8	103.6	3.9798	7.6	43.4	35.9
RG4	1	N27E	3(1)	R	-68.0	249.6	2.9950	6.2	-52.9	243.5
RG5	2	N18E	3(1)	N	70.1	327.4	2.9776	13.1	70.5	237.5
RG6	4	N10E	4	N(T)	30.2	26.9	3.9339	13.8	38.0	132.5
RG7	2	N 6E	3(1)	N	81.1	322.0	2.9974	4.5	74.7	301.6
RG8	3	N10W	4	N	78.5	112.7	3.9493	12.1	51.1	19.6
RG9	3	N 3E	4	N	81.7	192.2	3.9764	8.2	49.0	340.8
RG10	1	N 7E	4	R	-61.3	236.9	3.9730	8.8	-51.4	263.4
RG11	2	N 2E	3(1)	N	72.4	24.6	2.9952	6.1	76.1	96.9
RG12	2	N 2E	3(1)	N	63.1	45.3	2.9733	14.4	58.0	93.3
RG13	2	N 7E	3	N	74.4	56.5	2.9772	13.2	64.8	58.8
RG14	3	N 7E	2(2)	N(T)	.8	167.0	1.9935	(20.3)	24.9	355.3
RG15	3	N 4E	4	N(T)	58.6	200.2	3.9699	9.3	15.5	329.9
RG16	2	N10W	4	N	62.3	40.4	3.9958	3.4	59.1	100.0
RG17	2	N13E	3	N	70.4	67.5	2.9969	4.9	56.3	61.0
RG18	1	N14W	4	R	-79.5	166.8	3.9942	4.1	-83.1	124.5
RG19	2	N 9E	4	N	65.5	346.7	3.9873	6.0	71.3	194.9
RG20	5	N14E	3	R(T)	-57.1	290.4	2.9586	17.9	-26.0	221.6
RG21	2	N 3W	3	N	.4	62.2	2.9888	9.3	54.3	72.1
RG22	2	N 6W	4	N	69.4	21.4	3.9957	3.5	73.9	113.7
RG23	2	N14E	3	N	74.2	304.9	2.9980	3.9	65.2	271.6
RG24	2	N 3E	4	N	65.1	64.6	3.9889	5.6	51.9	71.9
RG25	2	N24W	3	N	62.7	8.7	2.9819	11.8	68.6	148.7
RG26	2	N 1W	3	N	63.4	18.2	2.9829	11.4	67.6	130.6
RG27	2	N 0E	3	N	77.2	355.9	2.9967	5.0	88.2	267.5
RG28	3	N 6W	2(1)	N(T)	64.4	135.1	1.9891	(26.4)	26.6	19.1
RG29	2	N 6W	3	N	71.0	34.8	2.9837	11.2	70.7	88.8
RG30	5	N 6W	3	R(T)	-70.4	359.5	2.9968	4.9	-29.5	166.3
RG31	3	N 8W	3	N	80.2	244.1	2.9620	17.2	52.8	317.0
RG32	1	N 0E	3(1)	R	-74.1	211.9	2.9975	4.3	-74.8	259.0
RG33	2	N17E	3	N	62.5	44.5	2.9854	10.6	57.7	94.9
RG34	3	N18W	2(1)	N	81.6	148.4	1.9992	(6.9)	50.2	359.3
RG35	2	N12E	3	N	67.1	41.6	2.9994	2.2	63.7	91.0
RG36	3	N12W	2(2)	N(T)	60.9	98.5	1.9838	(32.3)	34.0	48.5
RG37	2	N12W	3	N	71.2	357.5	2.9956	5.8	80.7	174.1
RG38	2	N 2W	3	N	59.7	354.1	2.9793	12.6	65.3	176.8
RG39	3	N 2W	1	N(T)	57.7	155.7	2.0000	(0.1)	15.1	5.6
RG40	4	N19E	3(1)	N(T)	39.0	44.2	2.9327	23.0	38.4	110.5
RG41	1	N26E	3	R	-74.1	229.2	2.9849	10.7	-67.5	244.8
RG41b	2	N 6E	3	N	69.9	32.2	2.9900	8.7	68.9	90.6
RG42	3	N 3W	1	N(T)	60.6	117.0	2.9701	15.2	27.3	34.6
RG42b	1		2	R	-77.6	186.8	1.9840	(32.0)	-86.9	228.7
RG43	1	N 8W	3(1)	R	-71.6	201.4	2.9805	12.2	-76.5	285.8
RG43b	1		3	R	-77.8	217.8	2.9871	9.9	-74.7	232.9

latitude' was 8.6 (sd:4.0). The mean α 95 values for dykes with shallow and steep VGP are significantly different at the 95% confidence level.

4.4 Interpretation of paleomagnetic results

4.4.1 Relationship between reversely magnetized dykes and lavas in sections RG and RH

The dyke magnetic directions have one outstanding feature, namely, although intruding anomaly 5 age lavas which are normally magnetized, 11 out of 46 dykes (24%) have reverse magnetic signature. To date, four reverse magnetic polarity chrons of very short duration have been postulated for anomaly 5 by studying the ocean floor magnetic anomaly pattern (Heirtzler and others, 1968; Blakely, 1974; La Brecque and others, 1977; Ness and others, 1980). Only two reverse chrons were observed within anomaly 5 in eastern Iceland by Watkins and Walker (1977). Bleil and others (1982) observed a total of four short reverse chrons within anomaly 5 in this region. Stratigraphically, the upper boundary of anomaly 5 is proposed at about 770 m elevation, i.e. units 910 to 916 in section RH (Bleil and others, 1982). It is highly improbable that dykes of the Graenafell section were emplaced during a reverse chron within anomaly 5 because the stratigraphically highest reverse lava chron within anomaly 5 (unit RH775) is located at about 240 m elevation, a level above which most of the dykes are seen to extend (for elevation of dyke units, see footnote), and furthermore if fed by

---

Dykes and lava units above the IRDP hole are numbered from 700 to 991 (section RH). Note however, that on Profile 3 dyke units were omitted and occur as 'missing unit numbers'.

reverse dykes in the Breiddalur dyke swarm the number of reverse lavas in the study area is expected to be at least proportional to the number of reverse dykes. However, reverse polarities are represented by more than one fourth of the dyke population in Graenafell but only 11 (10%) lavas out of 139 in section RH above the drill site.

These dykes are therefore more probably younger than anomaly 5 and could be related to such young lavas that are exposed high up in section RH (Trollafjall), i.e., reverse lava units RH910 to RH916 or interval RH954 to RH963 (Bleil and others, 1982). These reversely magnetized dykes could also be synchronous with some still younger lavas of reverse polarity. It follows that the Breiddalur dyke swarm must at this locality be younger than magnetic anomaly 5, i.e. younger than 9 m.y.

It is appropriate at this point to elaborate further on the dyke/lava paleomagnetic study by Bleil and others (1982) which provides relevant paleomagnetic information on intrusive dyke units in the area southwest of the IRDP drill site (section RH, shown on Figure 2.1). They report declination and inclination values for 33 dyke units. These dykes were sampled at an altitude ranging from 60 to 1130 m. Some of the dyke units at low elevation in the section, studied by Bleil and others, form indeed part of the Breiddalur dyke swarm. It is likely that most dykes in sections RH and RG are of similar age and were produced by the same volcanic zone that consisted of both the Breiddalur and Thingmuli volcanic systems. Eight other units gave either normal (3 units) or reverse (5 units) magnetic polarity, but for these the statistical reliability was too low to permit the calculation of a unit average of the magnetic vectors. The author has calculated the virtual geomagnetic pole values for the 33 dyke units for comparison with units of the dyke study in Graenafell (section RG). The calculated VGP's for dykes in section RH are plotted on Figure 4.1. Most of the values in section RH cluster at high geographic latitudes, although a few dykes have shallow VGP's and are comparable to such dykes in section RG (Figure 4.2). Of the 5 reversely magnetized dykes in section RH only 2 have intermediate values. On the contrary only 2 dykes out of 28 with normal signature fall at intermediate latitudes. Of the 8 dykes for which mean inclination could not be calculated (but gave either N or R magnetic signature), 5 were reversely magnetized and only 3 were normally magnetized. This strongly suggests that the reversely and normally magnetized dykes in section RH behave as if the ambient magnetic field at the time of initial magnetization of reverse dykes was either unstable or unusually weak. The magnetic similarity and stratigraphic setting of reversely magnetized dykes in sections RG and RH appear to be closely related both in a spatial and temporal sense.

4.4.2 Grouping of dykes based on VGP directions

In Figure 4.2 the virtual geomagnetic pole values from Table 4.1 have been plotted. It is clear that the dyke-VGP's have considerable scatter, i.e., their range in latitude is from about 15° to 88°. Although VGP dyke directions of the Breiddalur dyke swarm range in latitude from 15° to 80° a pronounced clustering of VGP values into five groups appears on Figure 4.2. The five groups contain from 2 to 22 dyke units and are termed B1 to B5; have either normal or reverse magnetic polarity. A statistical summary of group properties is given in Table 4.2. It is assumed that the dyke magnetic directions represent the

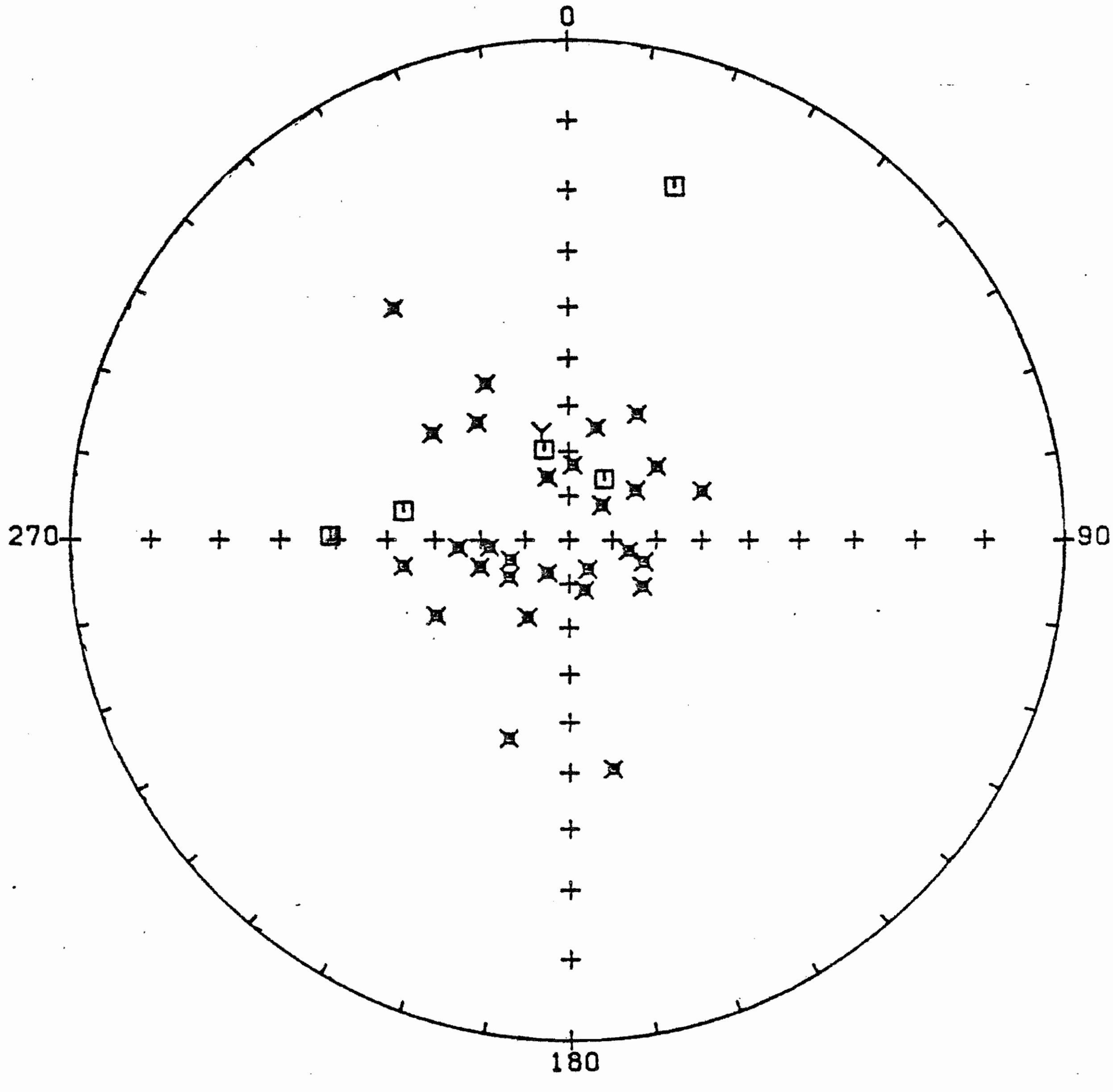


Figure 4.1 Stereographic projections of paleomagnetic dyke vectors (VGP) for section RH (Trollafjall). Based on Bleil and others (1982).

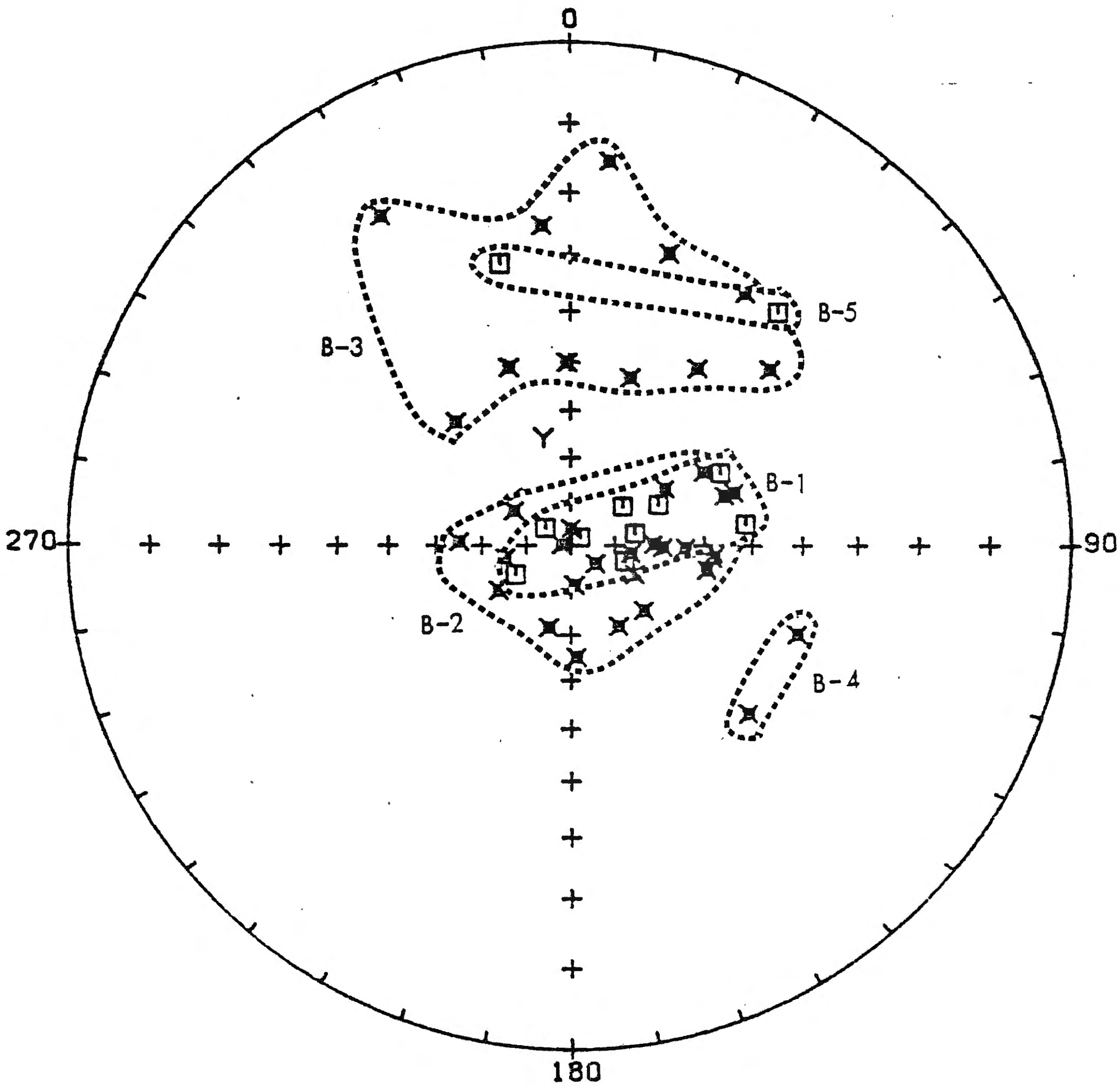


Figure 4.2 Stereographic projection of magnetic pole positions (VGP) for dyke units of the Breiddalur dyke swarm in Graenafell. Normally magnetized dyke units shown with crossed symbols and reverse units with square symbols. Reverse units are upper hemisphere projections.

Table 4.2 Statistical data for paleomagnetic groups B1 to B5 in section RG (Graenafell).

Gr.No.	N	I	D	R	A-95	θ′	Ø′	dm	dp
B1	9	-75.2	212.1	8.8641	6.7	-76.3	251.7	12.3	11.3
B2	22	71.8	23.3	21.5133	4.9	76.7	101.9	8.6	7.6
B3	11	73.5	144.5	10.5911	9.4	30.6	7.1	16.9	15.1
B4	2	34.9	35.1	1.9788	(37.2)	38.7	121.5		
B5	2	-67.6	315.7	1.9266	(74.0)	-30.7	194.4		

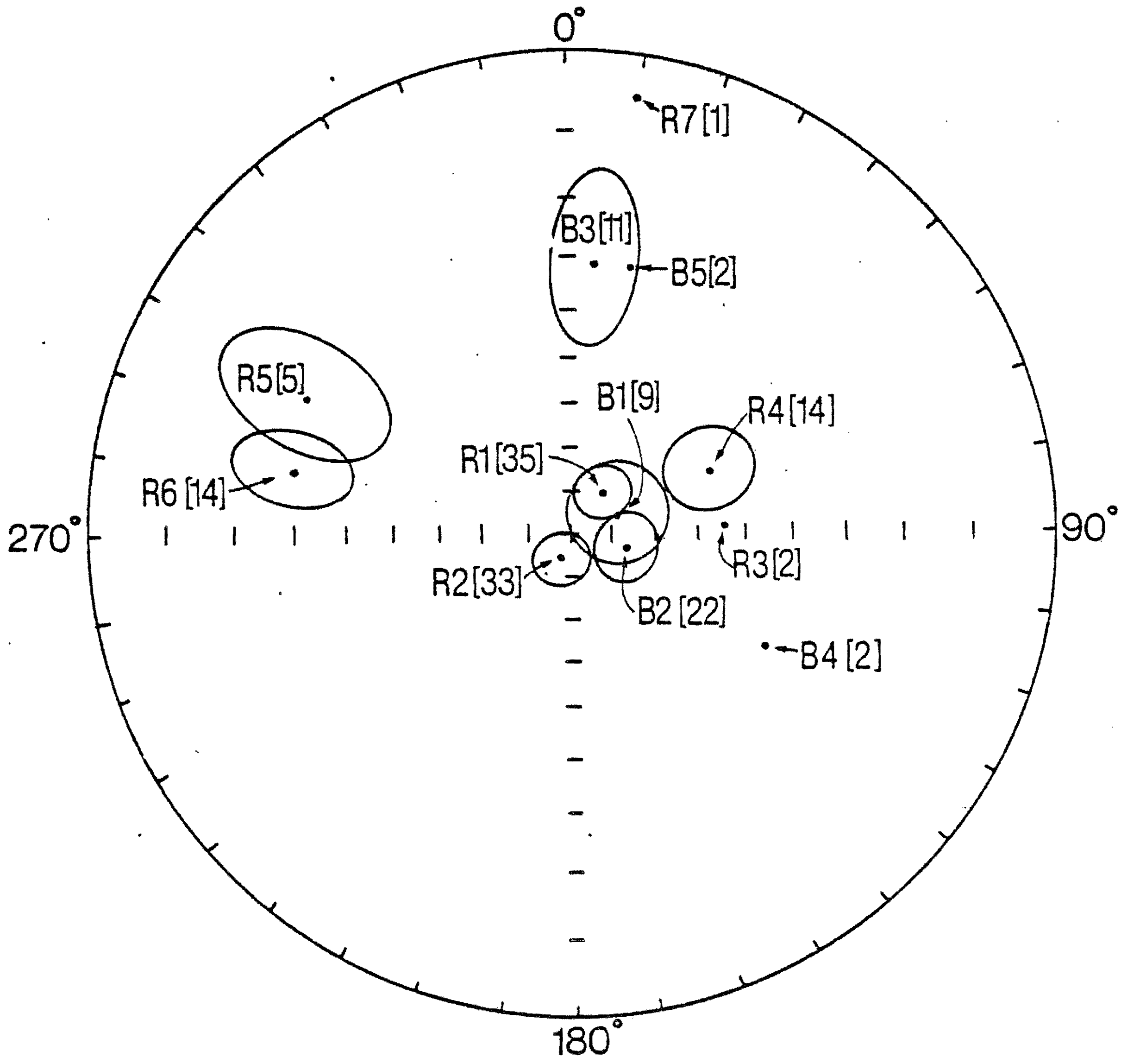


Figure 4.3 Averaged magnetic poles (VGP) for dyke groups of both the Breiddalur and Reydarfjordur dyke swarms, encircled with 95% confidence ovals.

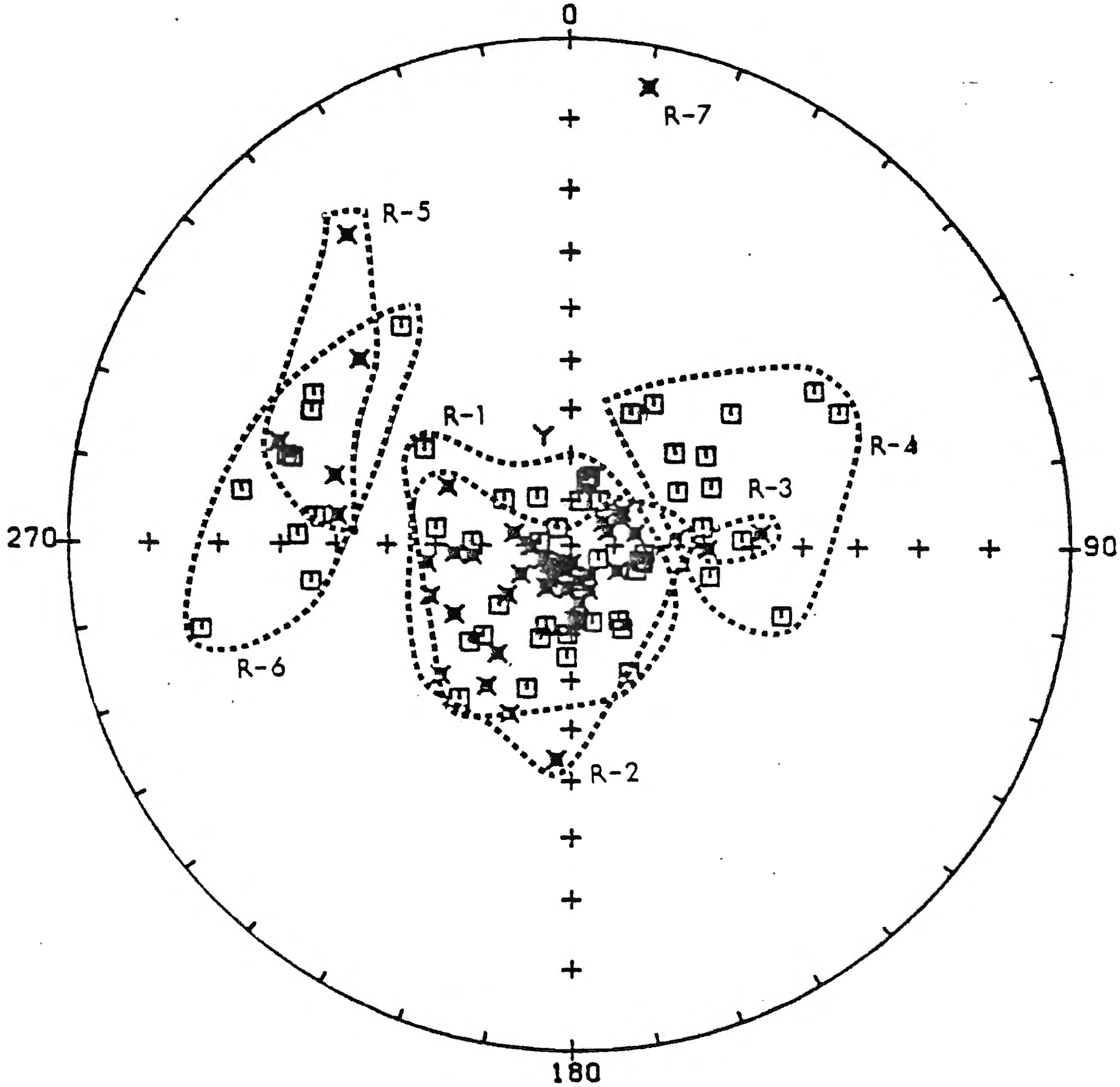


Figure 4.4 Stereographic projection of magnetic pole positions (VGP) for the dyke units of the Reydarfjordur dyke swarm, modified after Piper and others (1977). Crossed symbols normally magnetized dykes and square symbols denote reverse dyke units after upper hemisphere projections.

original cooling TRM. The author calculated virtual geomagnetic poles for other eastern Iceland dykes derived from previously published values of magnetic directions (Piper and others, 1977) and these do indeed cluster. Their work involved a study of the Reydarfjordur dyke swarm located about 25 km east of the Breiddalur dyke swarm. A total of 100 dykes in that study gave meaningful results and their VGP-values are presented on Figure 4.4.

Seven groups were recognized in the Reydarfjordur dyke swarm, termed Rl to R7. The number of dykes in each group ranged from 1 to 35 and the groups were either reversely or normally magnetized. For comparison with the Breiddalur dyke swarm (Table 4.2) group characteristics of the Reydarfjordur dyke swarm are summarized in Table 4.3. Simplistically illustrated on Figure 4.3 are the magnetic poles of dyke groups for both the Breiddalur and Reydarfjourdur dyke swarms with 95% confidence ovals. The selection of dykes into groups for both the Reydarfjordur and Breiddalur dyke swarms was arbitrarily based on clustering of VGP values in each dyke swarm. As can be seen from Figure 4.3 no overlapping of dyke groups is present for these dyke swarms although groups of opposite polarity are of course sometimes dipolar and may represent a stable location of the magnetic pole during one or more magnetic reversals. The grouping behaviour of the Reydarfjordur dyke swarm has not been stressed previously but seems, in the view of the present study, to be a characteristic dyke feature for eastern Iceland. The significance of dyke grouping is probably that dyke injection was episodic and at times coincided with periods when the ambient field had "transitional" signature.

Table 4.3 Statistical data for paleomagnetic groups R1 to R7 of the Reydarfjordur dyke swarm (calculated from Piper et al., 1977).

Gr.No.	N	I	D	R	A-95	θ'	ϕ'	dm	dp
R1	35	71.8	340.8	34.1453	3.9	79.1	42.3	6.9	6.0
R2	33	-72.0	172.2	32.2170	4.0	-82.7	16.6	7.1	6.2
R3	2	61.4	52.7	(1.9954)	(18.6)	53.5	87.8		
R4	14	66.6	245.4	13.6400	6.7	54.2	247.5	11.0	9.1
R5	5	60.7	243.9	4.8802	13.4	28.0	297.7	20.4	15.6
R6	10	-57.4	80.5	9.6520	9.7	-30.9	104.3	14.2	10.4
R7	1	-32.5	334.9			5.1	10.1		

4.4.3 Shallow virtual geomagnetic pole values

Another feature of both the Breiddalur and the Reydarfjordur dyke swarms is the large number of shallow pole positions within the dyke population (Figures 4.2 and 4.4). The number of shallow VGP's ($\leq 40°$) illustrated on Figures 4.2 to 4.4 is anomalously large and can be interpreted in a number of ways, representing either: (a) a large post-depositional tilting of lavas, (b) short time excursions of the earth's magnetic field, i.e., systematic deviations (Lawley, 1970), (c) polarity reversals, or (d) remagnetization (section 4.5). Nowhere outside the stratigraphic complexes of the volcanic centers does the lava succession dip more than 12° and therefore tilting cannot account for the numerous shallow VGP's in the dyke section which was corrected for a tilting of 6°.

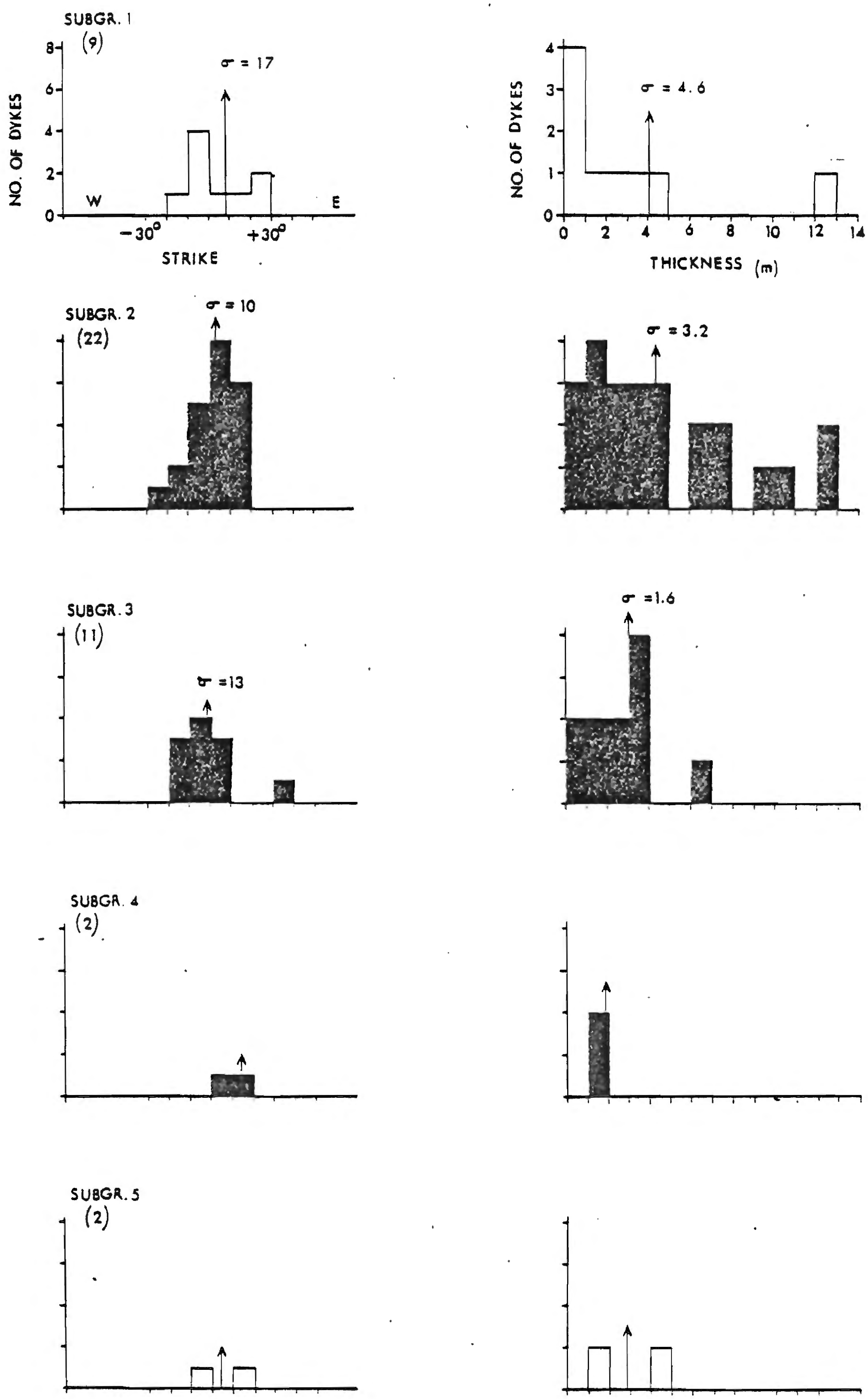
Explanations, (b) and (c), i.e. that the shallow VGP's represent either short time excursions or magnetic reversals are both regarded probable. However, reported paleomagnetic data sets for the lavas in eastern Iceland rarely recorded such magnetic deviations during the period 13 to 3 Ma, a time interval that certainly includes the age range of dykes in both the Breiddalur and the Reydarfjordur dyke swarms. As it is regarded more important for the present study to establish whether the shallow VGP values are primary or secondary (section 4.5) it follows that it is not critical to resolve which explanation, (b) or (c), is correct or more likely. It is interesting to note that for the units studied in both the Breiddalur and Reydarfjordur dyke swarms the proportion of intermediate virtual geomagnetic latitudes is 21% (i.e., 10/46 and 21/100, respectively). Comparable results for dykes have been encountered by other authors elsewhere (Ade-Hall et. al., 1972), i.e. from the Mull regional dyke swarm, where about 27% of the dykes had shallower magnetic inclination than 55°. Only 6.8% (73/1070) of all lavas in eastern Iceland have intermediate magnetic directions (Dagley and others, 1967) and thus in comparison the number of dykes with shallow VGP is anomalously high.

The proportion of lavas in selected sections from eastern Iceland that have either intermediate VGP's or magnetic directions was summarized in Table 2.7. The low number of intermediate values (VGP) for the lava succession emphasizes the overall difference between the lava and dyke paleomagnetism further and suggests that a genetic relationship between the dykes and lavas surrounding both the Breiddalur and Reydarfjordur dyke swarms is absent.

4.4.4 Paleomagnetic subgroups in relation to strike and thickness of dykes

Because the VGP-subgroups differ in terms of magnetic polarity it was thought that each group might have formed over separate non-overlapping periods. During each such period the ambient magnetic field may have differed, been either normal or reverse and given rise to either 'shallow' or 'steep' VGP values. Either dyke strike or thickness might have changed with time as the dyke swarm formed. As a result each subgroup could have had different frequency distribution for dyke strike and thickness. In Figure 4.5 the VGP-subgroups have been compared according to dyke strike and thickness. Only two dyke units occur in subgroups four and five. The strike direction for subgroups two and three (normal magnetic polarity) appears to have well defined means,

Figure 4.5 Comparison of paleomagnetic subgroups in dyke sections RG with regard to dyke strike and dyke thickness distribution of paleomagnetic subgroups.


SUBGR. 1
(9)
σ = 17
σ = 4.6
NO. OF DYKES
W
E
−30°
+30°
STRIKE
THICKNESS (m)
0
2
4
6
8
10
12
14
SUBGR. 2
(22)
σ = 10
σ = 3.2
SUBGR. 3
(11)
σ = 13
σ = 1.6
SUBGR. 4
(2)
SUBGR. 5
(2)

whereas dyke strike in subgroup one (reverse magnetic polarity) is clearly dispersed. Although the ambient magnetic field may have changed with time durint their emplacement, it is concluded that such changes were not accompanied by systematic variations in dyke strike or thickness.

4.5 Curie point measurements of units with shallow VGP values

The presence of both shallow VGP dyke values and reversely magnetized dykes in section RG could possibly be explained by remagnetization in a similar manner as for the lavas in Holmatindur (section 2.4.3). However, this explanation is improbable because stratigraphic conditions in Graenafell (section RG) differ from those in Holmatindur, which lies outside the Breiddalur dyke swarm. The dykes in Graenafell appear to be generally less altered than the host lavas and therefore the author expected that Curie point temperature for dykes could be much lower than for lavas. Therefore dykes might be more easily remagnetized. To resolve this question Curie point measurements were carried out on 10 dyke units in section RG, i.e. five units were selected with shallow ($\leq 40°$) and five with steep ($> 40°$) VGP's. The results for the T_C measurements are shown in Table 4.2 and on frequency histograms in Figure 4.5. Thus the mean Curie point values for shallow and steep dykes are 275°C and 260°C, respectively. The Curie point values for these groups are clearly indistinguishable. It is noteworthy that all these values are low and comparable with much younger dykes, i.e. of either postglacial or Pleistocene age (Becker, 1980). Previous studies of Tertiary dykes in Iceland have generally indicated much higher Curie point values or in the range of 200 to 600°C, with a bimodal

Table 4.4 Results of Curie point measurements of selected samples for dyke section RG (Graenafell) with related paleomagnetic and stratigraphic data.

Sample no.	T_c °C	J_{sat} emu/g 10^{-2}	VGP-lat. °	Thickn. m
RG3	308	2.67	43.4	1.0
RG13	157	3.20	64.8	8.0
RG14	290	3.68	24.9	4.0
RG15	226	2.62	-15.5	2.0
RG17	247	2.52	56.3	1.8
RG21	231	2.29	54.3	2.5
RG28	360	2.67	26.6	6.5
RG30	198	1.48	-29.5	5.0
RG39	300	2.20	15.1	1.5
RG43	360	2.00	-76.5	1.0

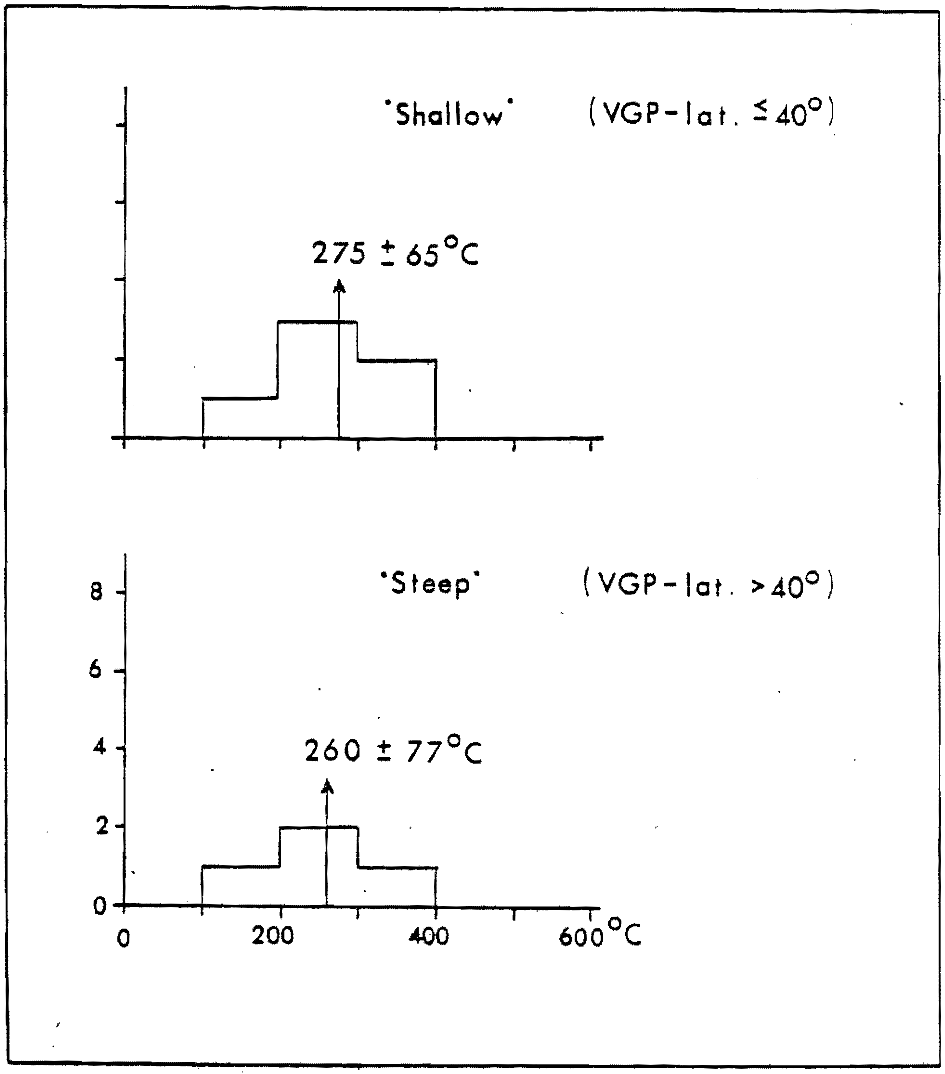


Figure 4.6 Histograms with Curie point temperature (Tc) for 'shallow' and 'steep' VGP-dyke units in section RG (Graenafell).

distribution that has highest populations around 375°C and 525°C respectively (Becker, 1980; Bird and Piper, 1980). The generally low Curie points for dykes with both shallow or steep VGP values in the Breiddalur dyke swarm and the high values obtained for within unit precision of magnetic vectors (Table 4.1) suggests that remagnetization is an improbable explanation for the shallow VGP dyke values. An 11-m-thick dyke intrudes lavas in Holmatindur, whereas in Graenafell a large number of thinner dykes intrude the section. In order to remagnetize each other the dykes in Graenafell would have had to remagnetize the host lavas at this elevation. However, available information does not indicate any remagnetization of lavas in this part of the study area (Bleil and others, 1982). In contrast these lavas are normally magnetized and correlate with sea floor magnetic anomaly 5. It should be stressed that very thick dyke bodies would have had to be uniformly remagnetized as the 'shallow VGP dykes' range in thickness from 1.5 to 6.5 m (10 units, mean: 3.0 + 1.7m) and the 'steep VGP dykes' range in thickness from 1 to 14 m (34 units, mean: 4.1 ± 3.3 m). The author has examined in thin section the opaque mineral phases in 'shallow VGP dykes'. They contain mainly class I and class II titanomagnetite and have a very similar alteration state (and Curie point temperatures) as postglacial or Pleistocene dyke intrusives (Becker, 1980). As a result it is concluded that secondary opaque phases are not present in these dykes in large enough quantities to contain a secondary 'shallow' magnetic component. Besides, if secondary phases were present they would most likely have resulted in higher Curie point temperatures than those measured.

4.6 Discussion of paleomagnetic results

Recent models on fissure swarm generation in Iceland are those of Bjornsson and others, 1977, 1979; Sigurdsson and Sparks, 1978a, 1978b; Einarssson and Brandsdottir, 1978; and Saemundsson, 1978. In general the models, based on volcanic activity in the Krafla area in northeastern Iceland, assume that magma is emplaced laterally into fisure swarms during discrete short episodes.

The emplacement episodes in volcanic systems such as Krafla are separated by longer ones when no dyke injection takes place, but during which the orientation of the ambient magnetic field may change noticeably. The "tape recording" of the ambient magnetic field by cooling dykes occurs frequently but over short periods that are here defined as T_i. These periods are separated by "quiet" periods, T_q, during which no dyke injection takes place. The time portion (T_t) available for "tape recording" of paleomagnetic data is therefore:

$$T_t = 100 \times T_i/(T_i + T_q)$$

For the Krafla volcanic system in northern Iceland T_t is about 2 to 4 % for the past 500 yr. Limited information is available on individual volcanic systems in Iceland but the T_t derived for the Krafla volcanic system appears to be representative and, at least its order of magnitude, comparable with other volcanic systems in the northeastern Iceland rift zone (Gudmundsson and Saemundsson, 1980). No lavas should be extruded above the dyke swarm during periods of no dyke injection.

Therefore knowledge of long term fissure swarm activity and eruptions within the neovolcanic zones can provide an estimate for the maximum T_t

available for recording of paleomagnetic data. In turn the T_t value can be compared with the rate of lava accumulation observed in the magnetostratigraphic sections of the extinct and partly eroded Tertiary provinces. Such a comparison may provide an estimate of how continuously the Tertiary basalt regions record paleomagnetic data, and information on that part of the stratigraphic succession in eastern Iceland that is hidden below sea level.

For the present discussion it is assumed that periods of volcanic extrusions do not overlap and each such event provides a brief reading of the earth's magnetic field, and that that volcanic production has remained similar for the geological history of eastern Iceland. On average there have been 5 eruptions each century in Iceland for the last millenia (Thorarinsson, 1981; Gudmundsson and Saemundsson, 1980). It follows that "tape recording" of paleomagnetic data would persist in a random manner for 5% of the time in all of Iceland. There are close to 25 active volcanic centers in Iceland (Saemundsson, 1978) and if one assumes that their volcanic productivity is homogeneous with regard to volume and area, the "tape recording", (i.e. T_t) for each center would be, on average, only 0.2% or one lava erupted every 500 years. This figure is actually high when compared with the rate of lava accumulation derived for eastern Iceland, which was 16,000 years/flow (Watkins and Walker, 1977). The orders of magnitude provided by these two figures, 500 and 16000 years/flow, may, respectively, represent minimum and maximum estimates of lava deposition rates. The difference between these two figures is most likely explained by different distances from the eruptive source areas, the eastern Iceland section being a "flank" area whereas the active fissure swarms being areas of maximum lava deposition. In conclusion, the T_t for the active volcanic zone in northeastern Iceland is at least ten times (and might be as much as thirty times) greater than in large areas of the Tertiary lava succession now exposed in eastern Iceland.

4.7 Conclusions

It is concluded that, for a significant part (21%) of two dyke swarms in eastern Iceland, shallow magnetic inclinations represent the original remanent magnetization and thus define pole positions at low latitudes. Because such shallow pole positions are much less frequent (7%) in the lava succession surrounding the dyke swarms this further supports a non-genetic relationship between these dykes and the presently exposed lavas in the study area.

CHAPTER 5

K-AR AGE DETERMINATIONS OF LAVAS AND DYKES IN REYDARFJORDUR

5.1 Introduction

The prime objective for employing the K-Ar dating method in the present study was to further investigate the age relationship between lavas and dykes in western Reydarfjordur, in the area between the Thingmuli and Reydarfjordur volcanic centers. Among the most important assumptions of previous models of crustal generation in Iceland is that the presently exposed dykes fed the surrounding lava formations (e.g. Piper and others, 1977). It has generally been stated that the Breiddalur dyke swarm fed lava formations that are presently exposed in the cliff section in Reydarfjordur (e.g. Walker, 1959, 1960, 1964). This assumption implies that the dykes are of the same age or only slightly younger than the bulk of the lavas. However, although searched for, the actual lava-dyke feeding contacts have generally neither been found by the author nor recorded by other workers. Therefore the statistical treatments of the dyke-lava feeding relationships that have been attempted (e.g. Walker, 1964) seem to be of little value. The field observations suggest that the Breiddalur dyke swarm and the host lava succession are not genetically related. It has been assumed that dykes directly feeding lavas are not noticed during geological mapping due to their subtle appearance. Despite field mapping of close to 600 dykes in Reydarfjordur (Walker, 1959) the number of lava-dyke feeding relationships found to date in areas outside the volcanic centers remains well below 10, a number much too low to to have fed the 9-km-thick lava succession in the province.

The entire lava stratigraphy in the study area has been thoroughly established through the correlation of numerous profiles into the exposed cliff section (Chapter 1). Thus there remains no doubt about the relative age of individual lavas that were sampled for K-Ar dating. Furthermore, dykes intrude the lavas in a random fashion and their relative age cannot be assigned as cross cutting relationships between dykes practically do not exist. Nine dyke samples have been dated in this study. They are believed to represent fairly well the dyke population in Reydarfjordur. The working hypothesis considered that the Breiddalur dyke swarm did not feed the exposed lavas, but is considerably younger than them. If the age difference is small the K-Ar dating method may not be precise enough to resolve the age difference of these two lithologic units. The best age determinations on lavas from the Tertiary areas of eastern Iceland have a reproducible precision of about ± 0.15 m.y. for the age range 8 to 12 Ma (McDougall and others, 1976). Thus under optimum conditions an age with a percentage standard deviation less than about 1.5% can be reproduced. Carefully selected samples of both dykes and their host lavas have been dated using identical techniques in the same laboratory, thus making the study internally consistent.

5.2 Previous work

The two first studies that involved K-Ar age determinations on Mio-Pliocene rocks from Iceland were published in 1966 (Gale and others, 1966, McDougall and Wensink, 1966). Before 1966 the oldest exposed rocks in eastern Iceland were thought to be roughly 50-60 m.y. old, i.e. Eo-Paleocene. This high age estimate was based on paleobotanical studies (pollen) of lignite bearing sedimentary units within the basalt lava succession in Gerpir (Pflug, 1959). Gerpir is located about 22 km east of the present research area and represents stratigraphically the oldest exposed units in eastern Iceland. Several other studies, that are relevant to the present investigation and involve dating, either with K-Ar or $^{40}Ar/^{39}Ar$ (hereforth Ar-Ar) techniques, have been made on the Plio-Miocene basalt lavas of eastern Iceland (e.g. Moorbath and others, 1966, McDougall and others, 1976, Ross and Musset, 1976, Watkins and Walker, 1977, Musset and others, 1980). Listed in Appendix I are available results of K-Ar and Ar-Ar datings for eastern Iceland, approximately for the period 8 to 13 Ma after McDougall and others (1976) and Ross and Musset (1976). A summary and critique of the most useful age determinations available for eastern Iceland until 1977 has been given by Watkins and Walker (1977).

The author is not aware of any age determinations on basaltic dyke units that intersect the basalt lava succession of eastern Iceland. However, several major intrusions (especially of acidic composition) in south-eastern Iceland have been dated (Gale and others, 1966). Incorporated in Appendix 1 are all earlier significant age determinations on basaltic lavas from eastern Iceland for the period 8 to 12 Ma. This period is specifically chosen because it represents the volcanic history of the correlated exposed section of the present study with some overlap of older and younger units. Only those age determinations were selected that have an error bar (1 standard deviation) less than or equal to 1 m.y.

5.3 Methods

5.3.1 Field methods

The dated samples, whether dykes or lavas, are representative for the dykes and lavas of the entire study area as shown on the geological map. Samples were taken with a sledge hammer from each unit of the pilot sections in Holmatindur (lavas) and Graenafell (dykes). Apart from the pilot sections samples were collected both from lavas and dykes where the material was non-vesicular, fine grained and exceptionally fresh. From these the best material was selected for K-Ar dating based on thin section examination under a petrographic microscope. Sample localities for the western Reydarfjordur area are shown on Map 1 except the location of sample KOP-1 which is shown on Figure 2.2. The best rock material from the lavas was generally fine grained and non-vesicular. The dykes were coarser grained than the lavas, and also non-vesicular. Surprisingly, they were found to contain glass, either interstitial or segregated, that varied from less than 1% to about 15% by volume. Only the very freshest dykes were dated. Petrographic descriptions are presented in Appendix 2. Units of the pilot sections were marked in the field with a painted number for re-sampling, if this were required.

5.3.2 Laboratory methods

A total of 10 to 30 grams of each sample were crushed to grain sizes of 0.5 to 1.0 mm. The potassium determinations were carried out up to 9 times on separate aliquots (0.2-0.4 grams) using atomic absorption spectrophotometry. A precision of 0.43% to 3.70% (one standard deviation) was obtained with this method. About 6 to 10 grams were used for each argon extraction. The fusion furnace system was heated before argon extraction to a maximum temperature of about 170°C. Before Ar extraction each sample was heated on a hot plate overnight at 102 ± 4°C. A vaccuum pressure of 10^{-6} torr was maintained during argon extraction. ^{38}Ar tracer was prepared on a gas pipette system. The isotopic composition of the extracted argon was determined by isotopic dilution techniques on an AEI MS10 mass spectrometer attached with a small (1800 gauss) permanent magnet. Individual isotopic peaks were focussed by manually changing the accelerating voltage. The base line on either side of each peak was defined carefully, existed, at an adjustment of 120 Volts. For each sample the isotopic ratios were measured 7 times. Isotopic ratios for dykes, i.e. Ar-38/36 and Ar-40/38, were measured with a precentage standard deviation of 0.070 and 0.045, respectively. For lavas these ratios were 0.094 and 0.078, respectively. The ^{40}Ar content of three samples were determined in duplicates as unknowns. Thus the ^{40}Ar content in samples ARD, RG6B and RG3 was measured with a relative precision of 2.95, 1.11 and 0.25 percent, respectively.

5.4 Derivation of stratigraphic height

The dated lava samples were collected at different elevations. Therefore it is neccessary to correct stratigraphic height to one level where stratigraphic thickness is neither affected by the up dip thinning or down dip thickening of lava formations. In other words it is neccessary to correct the stratigraphic position of a sample locality for the effects on lava accumulation caused by distance from the source area. It was shown in chapter 1 that the thickness of a lava formation at sea level and at about 800 m elevation could vary by a factor of five (section 1.6.2.1.). In this study stratigraphic height was derived by combining the IRDP cored section and the overlying exposed lava section in Trollafjall (RH) to construct a master stratigraphic section. The samples collected for dating east of the drillsite were fitted to the master section by stratigraphic correlation (Chapter 1). There are several reasons for choosing this method instead of the one used by Watkins and Walker (1977), outlined in Chapter 1, section 1.7.1. In addition to the arguments presented in there it was regarded particularly difficult to compensate for the different rates of lava accumulation at high elevations in the Holmatindur and Trollafjall cliff sections, respectively. Thus in Holmatindur, rates of lava accumulation were obviously much slower than at low levels in that same section. Such different rates of lava accumulation are probably not present in the Trollafjall section for the same elevation levels. This is because the upper part of Trollafjall section is much closer to the source area (Thingmuli), contains thinner basalt lava flows, some differentiated lavas, and a much smaller proportion of revorked sedimentary material. The lava units in the uppermost part of Trollafjall are thought to have been erupted from the Breiddalur-Thingmuli volcainc zone and are therefore located approximately where rates of lava accumulation attain a maximum. Conversely, the lavas in the top part of the Holmatindur section are located where rates of lava accumulation reach a minimum, i.e. in depositional areas away from the volcanic zone. When samples collected for dating east of the drill site are fitted to the cored section it is assumed that their position coincides roughly with the same lava trajectory. Lava trajectory is the path along which lavas travel from site of initial deposition to final postburial location which for the lowest core units is at least at a 3.5 km distance (vertical) below the pre-erosional lava surface. It should be stressed that, apart form units EFJ10A and EFJ11, the K-Ar dating was done on lavas that erupted in a volcanic zone west of the one that generated the Reydarfjordur volcanic center.

5.5 Results and discussion of K-Ar dating

Dating results for lavas are presented in Table 5.1 and for dykes in Table 5.2. The results for both dykes and lavas have been plotted in Figure 5.1, i.e. stratigraphic height against measured age. The age range for lavas is from 12.0 to 7.9 Ma and in no case does a lava have a greater age, within error limits, than lavas that are stratigraphically younger. A weighted least squares fit method (York, 1969) was used to derive the relationship between lava age and stratigraphic height which is of the form:

$$Y = 17085 - 1497\ X$$

where Y is stratigraphic thickness (m) and X is age (Ma).

Table 5.1 Dating results of the present study for lavas in western Reydarfjordur.

Sample No.	Radiometric Ar40/Tot.Ar40 x 100	Radiometric 40Ar mol/g 10^{-12}	K20 Wt% ± 1 sd.	Age m.y. ± 1 sd.
RH957	4	10.8126	0.946 ±0.02(3)(*)	7.9 ±0.7
RH948	41	29.5604	2.137 ±0.04(4)	9.4 ±0.1
KOP-1	6	4.8790	0.370 ±0.01(3)	9.1 ±0.5
RF76	28	9.5350	0.617 ±0.01(1)	10.7 ±0.4
BAND1	38	26.1270	1.630 ±0.03(4)	11.1 ±0.1
EFJ11	29	19.7742	1.030 ±0.02(4)	11.0 ±0.2
EFJ10A	25	9.2949	0.530 ±0.01(9)	12.0 ±0.4

(*) In brackets are given the number of potassium analyses

Decay constants : $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-10}$ yr; $\lambda_\beta = 4.962 \times 10^{-10}$ yr;

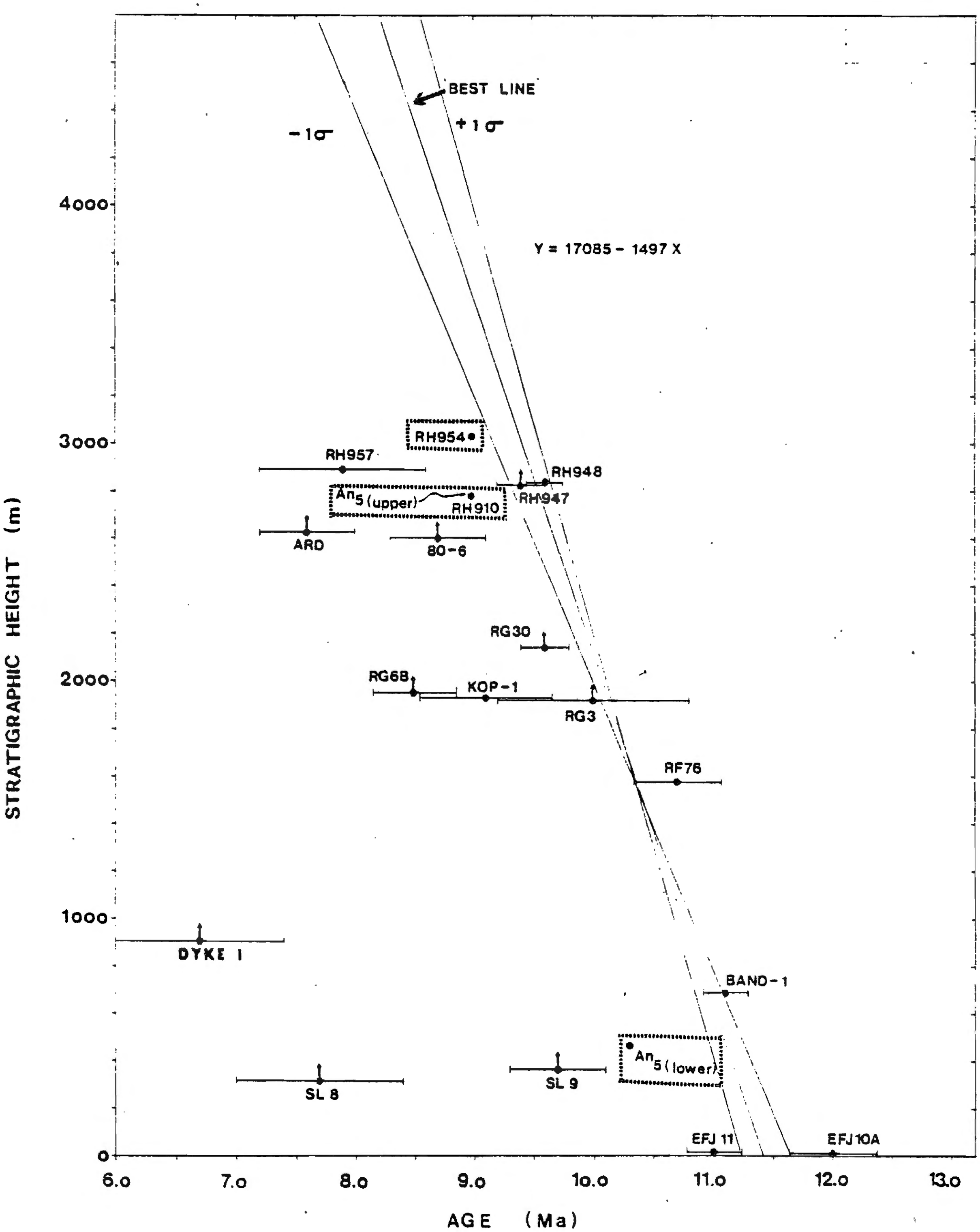
and $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol (after Steiger and Jaeger, 1977)

Table 5.2 Dating results of the present study for dykes intrusives in western Reydarfjordur.

Sample No.	Radiometric Ar40/Tot.Ar40 x 100	Radiometric 40Ar mol/g 10^{-12}	K20 Wt% ± 1 sd	Age m.y. ± 1 sd
ARD	11 13	6.5576 6.9570	0.631 ±0.01(4)(*)	7.2 ±0.3 7.8 +0.5
80-6	17	5.7962	0.462 ±0.02(4)	8.7 ±0.4
RH947	23	9.6608	0.713 ±0.01(3)	9.4 ±0.2
RG30	50	10.2446	0.737 ±0.01(3)	9.6 ±0.2
RG6B	18 18	5.7128 5.8604	0.470 ±0.01(2)	8.4 ±0.4 8.6 +0.3
RG3	8 10	3.8738 3.8538	0.270 ±0.01(6)	9.9 ±0.8 10.1 +0.8
D-1	12	4.8302	0.500 ±0.01(2)	6.7 ±0.7
SL9	20	9.1731	0.652 ±0.02(5)	9.7 ±0.4
SL8	4	2.6087	0.226 ±0.05(5)	7.7 ±0.6

(*) In brackets are the number of potassium analyses

Figure 5.1 K-Ar age dating results for both lavas and dykes (values with arrows) plotted as stratigraphic height (m) against age (Ma). Note that the stratigraphic height of dykes refers to their sampling location. In all cases dykes extend further up into the lava succession by an unknown amount. Included is the upper boundary for 'magnetic anomaly 5' ,unit RH910, as deined by Bleil and others (1982) and the lower boundary as defined by stratigraphic correlation with the work of Watkins and Walker (1977) and McDougall and others (1976). Inserted is also the location of unit RH954 which, rather than unit RH910, may possibly represent the younger boundary for anomaly 5. A 'best' least square fit regression line has been drawn for the lavas and in addition two lines that represent plus and minus one standard error for the slope of the 'best' line.


BEST LINE
-1σ
+1σ
Y = 17085 - 1497 X
RH954
RH957
RH948
RH947
An5 (upper)
RH910
ARD
80-6
RG30
RG68
KOP-1
RG3
RF76
DYKE I
BAND-1
An5 (lower)
SL 8
SL 9
EFJ 11
EFJ 10A
STRATIGRAPHIC HEIGHT (m)
4000
3000
2000
1000
0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
AGE (Ma)

In previous studies of this kind magnetostratigraphic sections were treated as if generated in the same volcanic zone, an erroneous assumption according to this thesis and an assumption that is very difficult to correct for (Chapters 1 and 7). The present study is unique in that a much greater vertical lava succession is available for correlation than in earlier comparable investigations and probably most of the lavas were erupted in the same volcanic zone. It is concluded that the regression line derived above reflects better the true stratigraphic thickness for this Tertiary lava succession than ones where corrections are made based on the relative location of zeolite zones and assuming a stationary plate boundary throughout the geological history of eastern Iceland.

Samples EFJ10A and EFJ11 are collected near sea level on the east side of Holmatindur, from a 50-m-thick lava succession below the pilot section in Holmatindur (RF). The lowest lava units, EFJ10A and EFJ11, have an age of 12.0 (± 0.4) and 11.0 (± 0.2) Ma, respectively. The age difference of these units seems too great considering that unit EFJ11 is directly on top of EFJ10A. In comparison with a great number of K-Ar dates from the Gerpir area (much lower in the stratigraphic succession), which have an age of about 12.5 Ma (Watkins and Walker, 1977; Moorbath and others, 1968) the 12.0 Ma age for sample EFJ11 is probably too high. The weighted mean age (see footnote) of units EFJ10A and EFJ11 is 11.20

The weighted mean age is obtained by first squaring the standard deviation for each dated sample and finding the reciprocal of the squared value. The reciprocal so obtained is multiplied by sample age. The values so found are added up and divided by the sum of all reciprocals.

Ma which might be a more realistic age for the base of Holmatindur section. Of the lava samples selected for dating unit KOP-1 was altered more than others and its age is possibly too low for that reason (see Appendix 2). Units RH948 and RH957 are within the same lava formation yet their K-Ar age is 7.9 (± 0.7)Ma and 9.4 (± 0.1) Ma , respectively. It appears that a weighted mean age for these units, i.e. 9.34 Ma, is more accurate as few units below there occurs a lava interval consisting of reverse units, the lowest of which (RH910) is thought to represent the upper boundary of anomaly 5 (Bleil and others, 1982) and the proposed age for this boundary is 8.98 Ma (Ness and others, 1980).

The dyke age results were inserted on Figure 5.1 at a stratigraphic elevation that coincided with their sampling site. However, this is a minimum elevation, because the dykes extend to higher stratigraphic levels than that at which they were sampled. Therefore the stratigraphic location of dykes on Figure 5.1 is only a reference. It is noteworthy that on Figure 5.1 most of the dykes fall either below the regression line or very close to it. Generally, however, with increased stratigraphic height, i.e. the closer the dyke sample is to the Thingmuli volcanic center, the less the dyke age deviates from the regression line and no dyke unit falls significantly above it. The age difference between lavas and dykes for units SL8 and SL9 is 3.5 and 1.5 m.y., respectively. These two dykes can be traced, however, to an elevation above the sample locality which reduces this age difference by at least 0.4 m.y. Both these dykes occur in the eastern part of the research area and have a more westerly trend (N19°W and N38°W, respectively) than the majority of dykes in western Reydarfjordur. They are probably not related to activity in the Breiddalur volcanic center

(Chapter 3). The weighted mean age of units SL9 and SL8, 9.09 Ma, appears to express better the age of these two closely spaced dykes. Applying this line of thinking it is likely that dykes SL9 and SL8 intruded the area after the termination of magnetic anomaly 5, 8.98 Ma. It has been suggested (section 2.4.3) that a nearby reversely magnetized dyke in Holmatindur (unit RF51D), also intruded the area after the termination of magnetic anomaly 5. Sample SL9 has both higher potassium content and smaller air correction for argon than unit SL8; its age is probably more reliable.

Unit Dykel in Figure 5.1 differs most in age from the host lava formations and is about 4 m.y. younger. This difference is reduced, however, if the dyke is traced into the stratigraphic succession to at least 100 m above the sampling site, where it is still exposed.

Dyke units RG3, RG6B, and RG30 are all clearly within the Breiddalur dyke swarm and their age ranges from 8.5 to 10.0 Ma. They have a K-Ar weighted mean age of 9.36 Ma which appears to be too high. Although the host lavas by the dyke sampling site have the same (derived) age, these dykes are clearly seen to extend to higher stratigraphic levels and thus should give a lower age by at least 0.3 m.y. The author cannot explain the discrepancy, but points out that unit RG6B has K-Ar age of 8.5 Ma, about 1.5 Ma younger than the host lavas. It is possible that, being within the dyke swarm, the samples are more altered, although totally free of zeolites, and altered samples pose a special problem in K-Ar dating (see for example Albertsson and others, 1982). However, to explain why some altered samples yield younger, and some older ages is, unfortunately, beyond the scope of this thesis.

Dyke units ARD, 80-6, and RH947 were sampled high up in Trollafjall section and all give ages similar to the surrounding lavas. Lavas and dykes in this area, less than about 5 km from the core of the Thingmuli volcanic center, were expected to have ages similar to the lavas because, where these dykes were sampled, actual eruptive sites for lavas are common and easily recognized.

5.6 Comparison with previous studies

For several reasons it is delicate to compare the K-Ar dating results of this study with results of other similar studies in this region, either by K-Ar or Ar-Ar dating, that are carried out in different laboratories. When recent results from eastern Iceland, based on the K-Ar technique (McDougall and others, 1976) are compared with results of the Ar-Ar technique (Musset and others, 1980) it becomes clear that the latter gave generally greater rock ages. Thus one sample from stratigraphic section C of Watkins and Walker (1977), lava unit 60, when dated with both techniques gave ages of 11.5 $\pm$ 0.1 Ma and 12.3 $\pm$ 0.5 Ma, respectively. Considering the reported precision of both studies, these ages are significantly different. The contrasting results by these methods may partly be explained by the unlike sampling methods involved. For example, McDougall and others (1976) carefully selected only the freshest material in the field with a sledge hammer whereas Musset and others (1980) dated what was available to them (minicores) sampled with a portable drill, that in part were considerably altered. Further comparison of the work by McDougall and others (1976) and Musset and others (1980) shows that, although some of the samples dated with the Ar-Ar method are <u>stratigraphically</u> much younger than lavas dated with the K-Ar method, their measured ages are similar. This indicates that reported Ar-Ar ages for eastern Iceland are consistently higher than those obtained with the K-Ar technique. Age determinations using the K-Ar method have been preferred in the present study and the results obtained are not compared with those of the Ar-Ar methods (Musset and others, 1980). This decision was made as because the cited analytical precision for the K-Ar method is about four times better than for the Ar-Ar method.

High analytical precision is critical for solving the expected age differences between lavas and dykes in Reydarfjordur. Although the results of K-Ar dating by McDougall and others (1976) are superior in precision to those of the present study the author has chosen not to systematically attempt to compare the two. It is difficult to explain differences between analytical laboratories without cross referencing, and no data on the age of dykes was included in previous studies. The writer feels that in view of the internal consistency of the present geochronological investigation, and of the compatibility of the data with magnetostratigraphic evidence, no such comparison is warranted. The only comparison that the author has used was made in the previous section where the ages of the stratigraphically lowest units by sea level in Holmatindur (EFJ10A and EFJ11) were compared with dates from the Gerpir area, where, in several K-Ar studies, an unusual number of closely spaced lava units had consistently given similar age results in several K-Ar studies.

5.7 Conclusions

On the basis of the dating results, lavas become younger from east to west whereas the dykes are generally younger than the lavas and their age is similar to or less than the age of the youngest lavas in the Thingmuli volcanic center. These lavas were erupted in the Thingmuli-Breiddalur volcanic zone. It follows that dykes could not have fed most of the presently exposed lavas they intrude. It appears that some of the dykes were feeders to lavas that are now generally eroded from the mountain carapace of the present study area.

CHAPTER 6

UPPER CRUSTAL STRUCTURE OF EASTERN ICELAND: REVIEW OF MODELS

6.1 Introduction

The Iceland crust was long regarded as consisting of several layers (e.g. Bath, 1960; Tryggvason and Bath, 1961; Palmason, 1963, 1971). Flovenz (1980) proposed a new interpretation of the crustal structure in Iceland that was based on seismic refraction studies aided by synthetic seismograms. He considers the classical layered model, which divides the Icelandic crust into four layers of increasing P-velocity, as unacceptable. Instead Flovenz proposes a two layered model for Iceland, i.e. upper crust with increasing seismic velocities (P-velocity: 2.0 km/s to 5.0 km/s) and lower crust (Figure 6.1) where seismic velocity is nearly constant (P-velocity: 6.5 km/s). According to this model the upper crust includes layers 0 ,1, and 2 of earlier models (Palmason, 1963) whereas the lower crust corresponds to layer 3. As mentioned earlier this thesis deals only with the upper crustal structure in Iceland.

Regional stratigraphic studies of Tertiary areas in eastern Iceland (e.g. Walker, 1974) have provided fundamental information for models of crustal construction. It has been assumed that these models describe the upper crustal structure in Iceland but, because they are generally

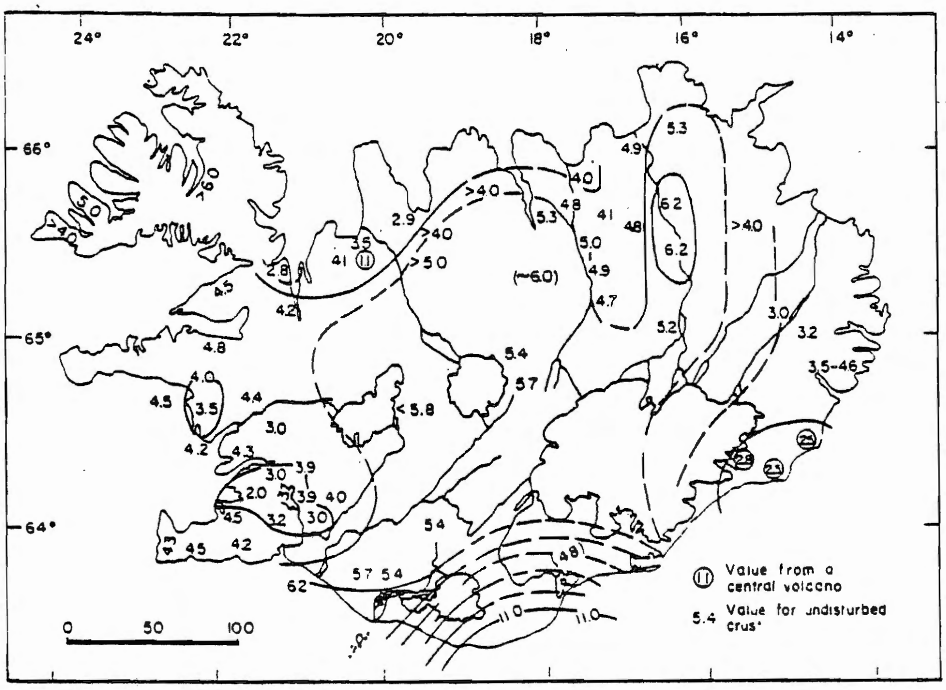


Figure 6.1 From Flovenz (1980): 'depth to the lower crust (layer 3) in Iceland. Seismic velocity is assumed to increase continuously with depth'.

based on the Tertiary stratigraphy of eastern Iceland, an extrapolation to other regions may not be valid. This is due to the various tectonic regimes that exist within the present volcanic zones which may have had their equivalents outside eastern Iceland during the Tertiary.

Previous models of crustal generation in Iceland have been based on a number of important assumptions. If any of these assumptions is not valid, as the author contends, the models need revision. These models assume at least one of the following:

(1) steady state conditions where the volcanic zone was stationary while the plates drifted passively apart (e.g. Bodvarsson and Walker, 1964).

(2) eruption of 'flood basalt lavas' is unrelated to volcanic centers.

(3) a large percentage of exposed dykes fed the presently exposed lava succession.

(4) rates of lava accumulation can be normalized and in turn provide data on temporal variations in volcanic production.

(5) although variable, the production of volcanic material in eastern Iceland was continuous for the period 13 to 2 Ma.

Due to the complexity of plate tectonics in Iceland it is compelling to evaluate, where appropriate, the pertinent crustal construction models in the light of recently advanced information in this field. The first of these models are, however, evaluated with regard to their fundamental value as it is seen now.

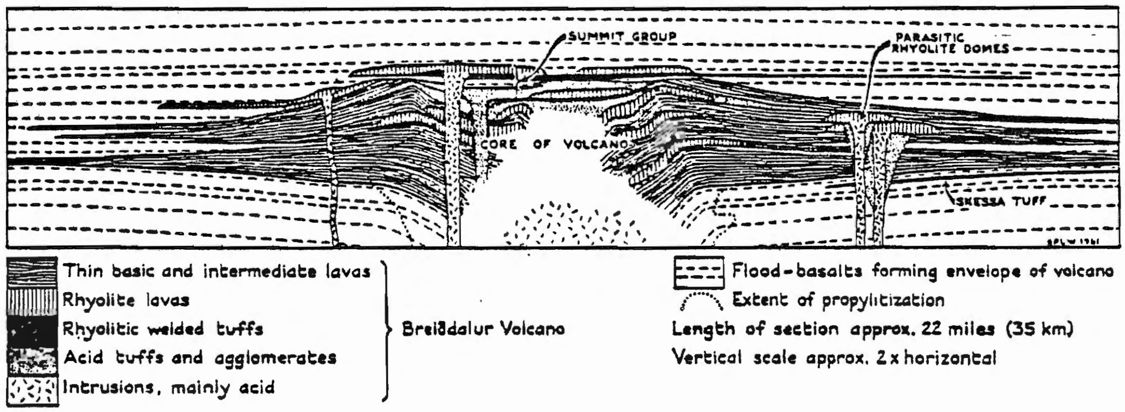


Figure 6.2 From Walker (1963): 'schematic composite section across the Breiddalur volcano and its envelope, summarizing the interpretation of the structure and relationships between the rocks'.

6.2 Review of models

Walker (1959) pointed out that dyke distribution in Reydarfjordur congregates into swarms. He regarded such a 'peculiar' distribution as being against the hypothesis of fissure eruptions, the mechanism which he otherwise accepted as having generated the thick basalt lava succession in eastern Iceland. In later publications Walker (1960, 1963) shows swarms to be a regional phenomenon in eastern Iceland. Walker interprets the dykes as vertical feeders of what he terms 'flood basalt lavas'. According to this reasoning dyke swarms at distances from the volcanic centers did not originate in such centers. Thus at this time the volcanic centers and the surrounding basalt lava succession were regarded as genetically unrelated (Figure 6.2). These early publications by Walker contain field observations and represent the first attempts to model the mechanism that generated the exposed volcanic successsion.

Bodvarsson and Walker (1964) proposed the first in a series of such models for the crustal structure of Iceland which was based on the stratigraphy of eastern Iceland and on seismic refraction studies. They observed that, along a 400 km cross section from eastern to western Iceland, the lava succession becomes consistently younger toward the volcanic zone. They proposed two explanations for this regularity that invoke either a retraction in width of an extensive volcanic zone, or crustal drifting of two plates through dyke injection that amounts to 400 km (Figure 6.3). They favoured the second explanation based on passive crustal spreading. Bodvarsson and Walker (1964) stated that dykes which cross sea level in the Reydarfjordur section have fed the

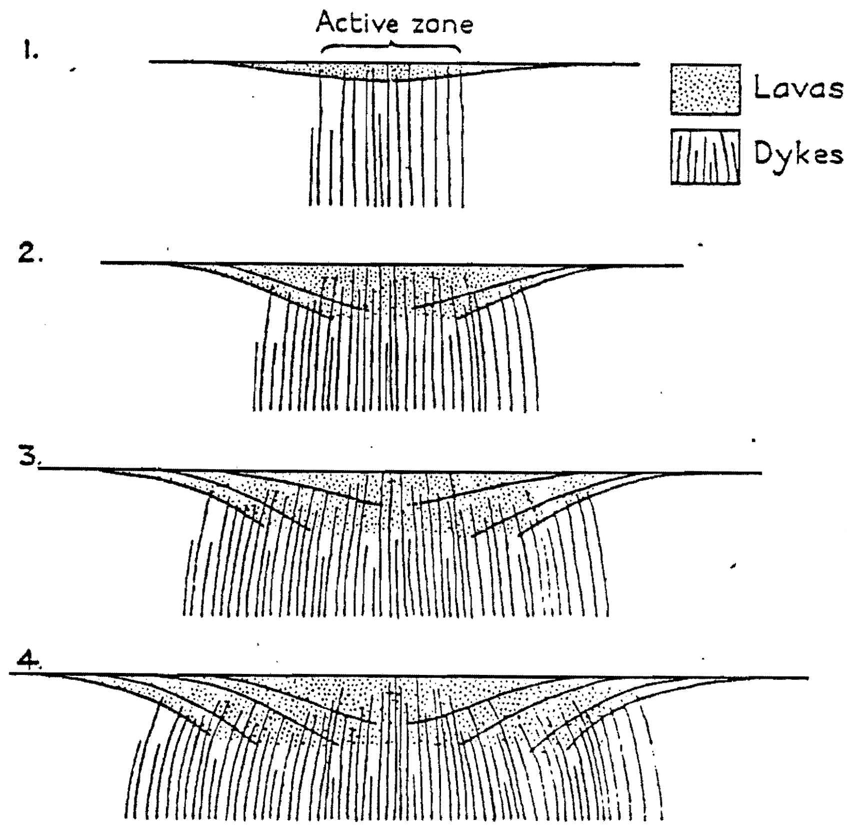


Figure 6.3 From Bodvarsson and Walker (1964): 'four stages of crustal extension by dyke injection'.

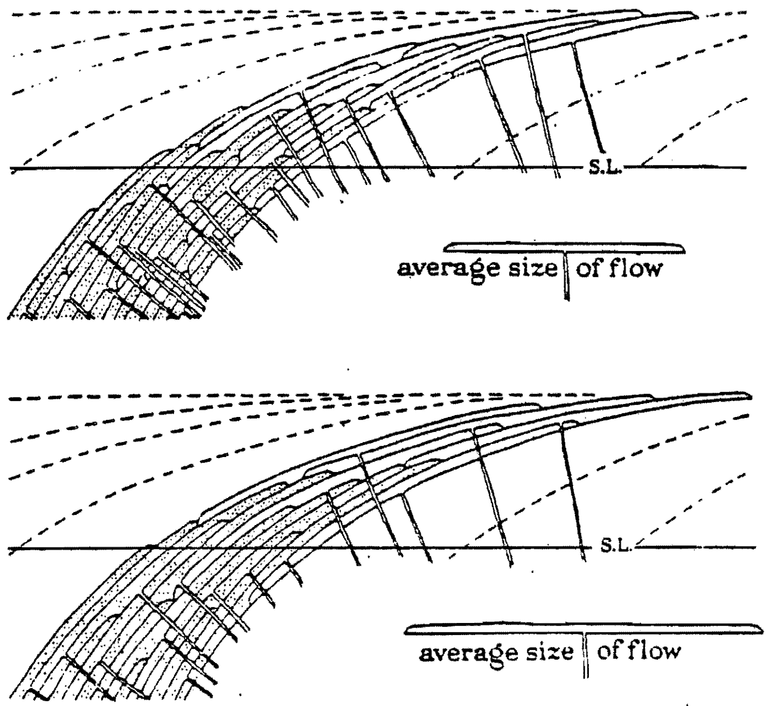


Figure 6.4 Schematic diagram (from Walker, 1965) showing the relationship between basalt lava formations and dykes. Note that all the dykes shown above sea level (s.l.) are feeders to part (20-35%) of a lava formation, the remaining feeders being concealed below sea level.

lavas from the present sea level to an original top averaging about 1500 m elevation. Walker (1960) considered dyke intensity to increase linearly with depth. In a 53 km section across strike along Reydarfjordur the total dyke thickness is about 3 km for 1000 dykes. The present author argues that this value is too low to account for the proposed crustal spreading of eastern Iceland simply through a mechanism of dyke injection. It is clear from stratigraphic considerations, that their model is incompatible with the observed total thickness and distribution of dykes in eastern Iceland.

Walker (1965) extrapolated dyke intensity below sea level and assumed every second exposed lava flow to be fed from a dyke concealed below sea level (Figure 6.4). In the case of Reydarfjordur this means that the total thickness of dykes that produced the exposed cliff section is about 6 km. Walker (1965), referring to the model by Bodvarsson and Walker (1964), argued that the vertical thickness of the extrusive layer has to be about 25 km thick to account for a dilation of 400 km in Iceland since Tertiary times. The author argues that this value is clearly incompatible with volcanic production rates in Iceland as obtained for the last eleven thousand years (Thorarinsson, 1967; Jakobsson, 1972).

Gibson (1966) re-interpreted the crustal structure of eastern Iceland as proposed by Bodvarsson and Walker (1964). Gibson stressed for the first time the importance of dyke swarms in shaping the overall lava succession (Figure 6.5). He stated: 'the lavas were erupted preferably from one particular region for a considerable period of time, after which there was a major change in the pattern of volcanism with

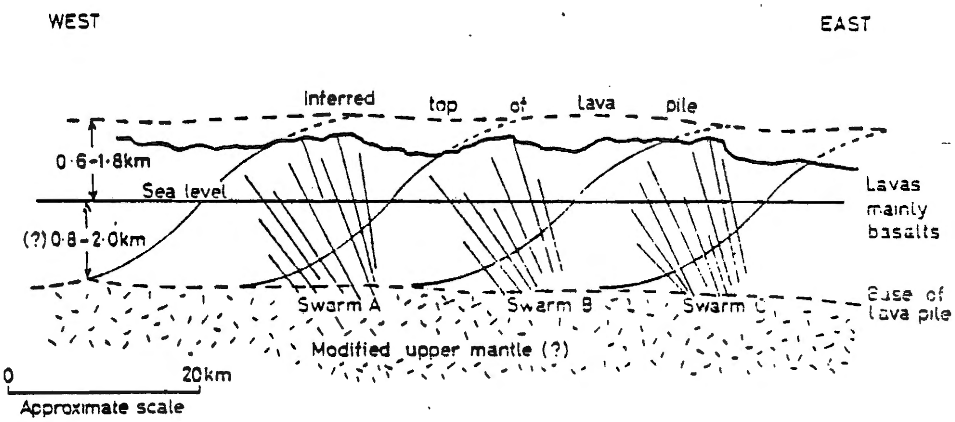


Figure 6.5a From Gibson (1966): 'Simplified diagrammatic cross-section through the lava pile showing the lenticular units each the product of repeated eruptions from a dyke swarm'.

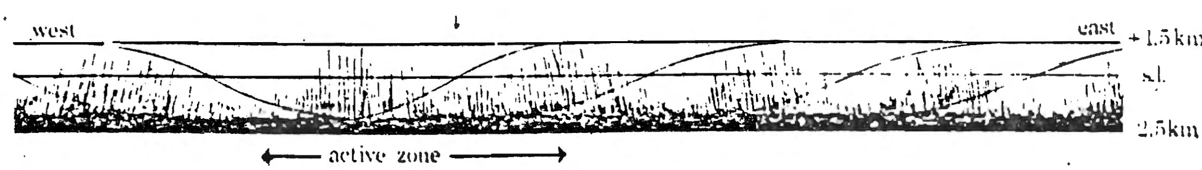


Figure 6.5b From Gibson and Piper (1972, page 149): 'A diagrammatic cross-section through the axial zone in Iceland, illustrating the formation of lenticular units. The section has been drawn for a particular instant in time when the growth of one lense has just been completed on the western side of the active zone. It is suggested that the next lense would grow on the eastern side of the zone and that it would 'drift' the recently formed lense away to the west, deforming it in the process.'

eruptions in a new area further to the west' and 'migration of the swarm to the west would produce a second basalt lens overlying part of the earlier mass'. He regarded the lava succession in eastern Iceland as made up of a succession of such lenses, decreasing steadily in age from east to west. An important part of this model is that it suggests not only an upper pre-erosional level to the lava succession but also the lower boundary below sea level. This model assumes that at least half the succession resides below sea level, otherwise the lava formations would not be thinning everywhere within the exposed section. Gibson concludes that the total vertical thickness of the basalt lava succession in the region is between 2 and 4 km. In this model the estimated thickness of the exposed lava succession is 0.6 to 1.6 km and that below sea level 0.8 to 2.0 km, possibly underlain by a modified upper mantle. Gibson's model is only partly compatible with the one proposed by in the present study (Chapter 7). The model here presented suggest that the lava succession below sea level extends to much greater depths than 0.8-2.0 km.

Sigurdsson (1967) reviewed Gibson's (1966) model and argued that each lens forming on the western slope of an older lens will have an asymmetrical shape across the new dyke (fissure) swarm. The side facing the old fissure swarm (lens) will be much less voluminous than the opposite side. Sigurdsson argues that as a result the thickness of any such concealed lens will be much greater than the corresponding exposed segment. This will result in a much greater thickness of the entire lava succession than proposed by Gibson (1966).

Gibson and Piper (1972) proposed a model for the structure of the Iceland crust (Figure 6.5b) that is essentially an advanced version of an earlier model by Gibson (1966). They regarded the base of the upper crust, which Palmason considers the layer 2/layer 3 boundary, to occur at 2 to 5 km depth below the pre-erosional surface. According to this model the layer2/layer 3 boundary marks the transition from lavas to a layer consisting entirely of intrusive basaltic rocks and is not a metamorphic boundary as was suggested by Palmason (1971).

Palmason (1973) proposed the first theoretical model for the crustal spreading and generation of Iceland applying concepts of plate tectonics. In particular this model describes the two dimensional kinematic evolution of the rifting plate boundary. This model is based on geological observations in eastern Iceland (e.g. Walker, 1965) and the geophysical (seismic) layering as proposed earlier (e.g. Palmason, 1963, 1971). In particular Palmason models the relationship between three parameters: crustal spreading rate (Vd), volcanic production (q) and volcanic zone half width (Xo) as shown in Figure 6.6. The applicability of Palmason's model relies to a large extent on how well it fits the assumed geological conditions within the volcanic zone, namely that: (a) 'the process of crustal generation is a stationary one'; and (b) 'the parameters of the model are independent of time' (Palmason, 1973, page 454).

Let us consider for the present discussion that both above assumptions above are valid; it follows that the model is limited by how accurately the parameters in (b) are known. Accepting the values given by Palmason, the model will accurately determine the crustal layering in

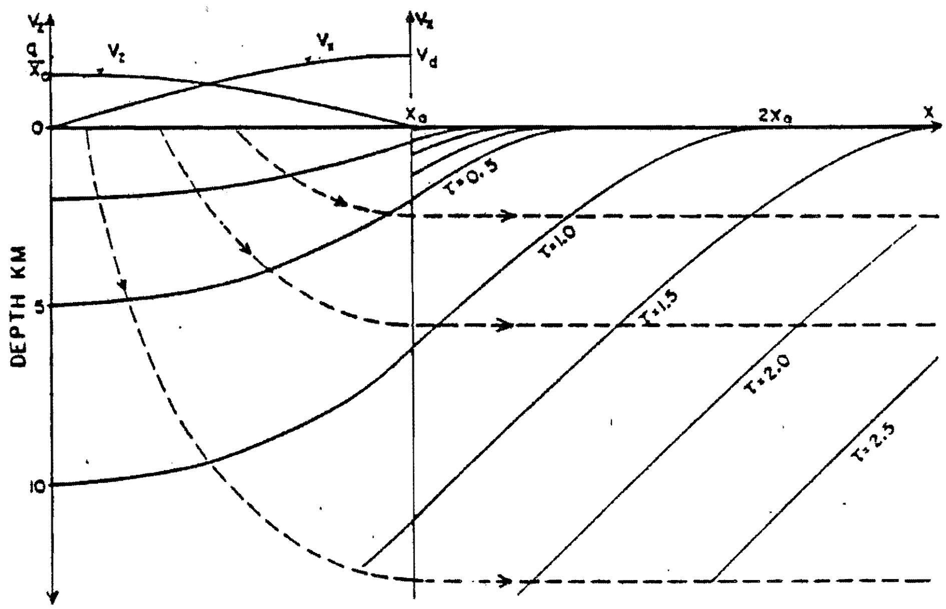


Figure 6.6 From Palmason (1973): Half plate boundary construction with lava isochrons (solid curves), and lava trajectories (dashed curves)

Iceland. Thus inserting observed values for the model parameters a lower boundary for the extrusion layer should uniformly occur at a depth of about 12.5 km (Palmason, 1973, Case II). At this predicted depth the dyke intensity will be about 90%. This conclusion is not in agreement with the earlier model by Gibson and Piper (1972) which assumes that layer 3 is made up of basaltic intrusions at a depth of about 4 km below the pre-erosional surface. However, as pointed out by Palmason and Sigvaldason (1976) this conclusion is logical if assumed that volcanic production in Iceland during the last 16 m.y. is enough to generate an extrusive layer in Iceland that is 7 to 8 km in thickness. Noting that dyke percentage increases with depth, Palmason and Sigvaldason (1976) concluded that the extrusive layer in Iceland, mostly basalt lavas, may cease to be present at a depth of well over 10 km.

The present writer regards it an obvious disadvantage of the model that it neither accounts for the formation of dyke swarms nor for the migration of volcanic activity from one volcanic center to another. According to the model dyke swarms should not be exposed in the Tertiary lava succession. Secondly, the transient nature of the volcanic zones appears to have been so common during the geological history of Iceland that it is rather a rule than the exception.

It should be stressed, however, that Palmason's model is fully compatible with crustal generation at any <u>one stationary</u> boundary. However, because shift of the volcanic zone(s) appears to have occurred frequently it follows that the model applies locally to each volcanic zone and not the entire stratigraphic succession of Iceland.

Daigniers and others (1975) proposed a model for the axial zone evolution of mid-ocean ridges as revealed in the Iceland vòlcanic zone. Their model assumes that tectonic activity in the neovolcanic zone generates three features that indicate crustal spreading, namely: (a) open fissures; (b) emissive fissures; (c) normal faults.

By statistically treating the abundance of these features and assuming (1) constant volcanic production, (2) isostatic equilibrium, and (3) stationary plate boundary, they derive a model for the crustal generation of Iceland that strongly resembles Palmason's model (1973). However, the results of these models differ in that Daignier's assumes a spreading rate of 3 cm/yr compared to Palmason's value of 1 cm/yr. As a result the thickness of the extrusive layer is much smaller in Daignier's model. Consequently it compares well with the model results of Gibson and Piper (1972).

Lomize (1976), in a publication on extensive studies by Soviet scientists in Iceland during the early seventies, proposed a model for the crustal spreading in eastern Iceland. With slight modifications this model is strikingly similar to the models by Gibson (1966) and Gibson and Piper (1972). The model by Lomize assumes a thickness of the extrusive layer no greater than 4.5 to 5 km before erosion. Lomize points out that the dyke swarms in eastern Iceland do not account for but a small amount of spreading, i.e. 2 mm/yr. This value is ten times lower than the observed spreading rate in the neovolcanic zone. Lomize derived the slow spreading rate for eastern Iceland by examining the four dyke swarms exposed in this region, i.e. the Nordfjordur, Reydarfjordur, Breiddalur and Thingmuli dyke swarms. For these swarms the dyke intensity amounts to about 7% of the terrain with dyke intensity about 1.5% for the intervening region between dyke swarms, or 0.6 km and 0.15 km, respectively. Extrapolation to what Lomize regards the base of the extrusive layer (2.5 to 3 km) yields values of about 19-21% and 4-4.5%, respectively (or 1.7 and 0.4 km) for dyke thickness or spreading. Lomize assumes that it took 1 m.y. for each dyke swarm to form and thus concludes that the spreading rate for these four dyke swarms in the Reydarfjordur region was no greater than 2 mm/yr. Lomize explains the discrepancy between this value and the one observed for the neovolcanic zone by assuming that, at any one time during the Tertiary, many dyke swarms were active and spreading in Iceland during the Tertiary was equal to the cumulative spreading of all active dyke swarms.

Piper and others (1977) combined data of lava magnetostratigraphy and dyke magnetization from Reydarfjordur volcanic center to further study in particular the relationship between dykes and the enclosing lava formations. They provided statistically significant paleomagnetic data for 100 dykes of the Reydarfjordur dyke swarm sampled by sea level. Similarly, they either sampled lava flows for paleomagnetic laboratory measurements or measured lava polarities in the field. They correlated stratigraphic marker formations between nearby sections and thus derived a polarity log for correlation with the geomagnetic time scale. They applied dyke paleomagnetic, lithologic character (field classification) and other observations. For example, they indicate that dykes are few in Holmatindur above the Holmar olivine basalt lava formation. They interpreted this as evidence that the dykes are feeders of lavas below the Holmar olivine basalt lava formation. In conclusion they regarded this study as having implications to models for the crustal structure of Iceland. It is useful for the present discussion to briefly review the assumptions in an earlier model by Gibson and Piper (1972). In a reference to this model, Piper and others (1977, page 242) stated: 'the lava succession is built up of lenses of extrusive volcanics each centered on an area of silicic volcanics and each with a life span of the order of 0.5 to 1.0 m.y.' Referring to earlier relevant work and stating the implications of their own, Piper and others (1977, page 242) continue: 'subsequent centers appear to remain intact as they move away from the volcanic zone with new centers generated _en echelon_ with respect to the older ones. This is precisely the situation observed along the present neovolcanic zones (Piper, 1973; Palmason and Saemundsson, 1974; Walker, 1975) where silicic and thermal areas are distributed _en echelon_ at intervals of 30 to 100 km and are also the loci of most of the basaltic volcanism; they appear to be the contemporary analogues of the lenses in the Tertiary lava succession'. This model is in many ways compatible with the present study, with some important exceptions.

Fridleifsson, in 1977, proposed that the base of seismic layer 2 of the upper crust may mark a transition from lavas to basaltic intrusions. The mechanism controlling this transition is, according to Fridleifsson, caused by alteration or metamorphism of basaltic lavas that become less coherent and are easily injected by large basaltic intrusions. Thus Fridleifsson's model regards the lower crust as consisting of basaltic intrusions. He argues that his model is compatible with crustal layering based on seismic velocities and geothermal gradients for the lower crust (layer-3) according to Palmason (1971). The shallow depth to the lower crustal boundary, according to Fridleifsson's model, seems perhaps doubtful; the depth value which Palmason assumes as the base of the extrusive layer using Jakobsson's (1972) estimate of volcanic production in Iceland during the last 11000 years, is probably more accurate.

Palmason, in 1980, proposed a further development of his kinematic model (1973). Palmason states:

'discontinuous processes of lava extrusion, dyke intrusion and tectonic movements are treated as continuous processes representing the average behaviour over a long time. A disadvantage of this point of view is that the details of the volcanic and tectonic processes, such as individual central volcanic complexes, dykes, and faults, are lost in the model. An advantage is, on the other hand that analytical descriptions of the regional movements of crustal material are easily made, as well as calculations of the thermal state of the crust'.

According to the model by Palmason the lava lenses (as defined by Gibson, 1966) would not flatten out at the base of the extrusive layer. In his discussion of the model Palmason states: 'evidence of volcanic and tectonic processes in the central part of the active zone disappears gradually into the deeper part of the distant crust, where it cannot be observed directly. An estimate based on the model indicates that the eastern Iceland visible Tertiary lava succession, some 1300 m thick, was formed outside a 50 to 55 km wide central part of the Tertiary volcanic zone.' In other words Palmason's model assumes that the eastern Iceland lava succession represents an environment outside the volcanic zone where lavas were deposited but not produced. An obvious paradox of the above conclusion is that numerous volcanic centers are exposed in eastern Iceland, thus defining the Tertiary plate boundary. The best exposed example of such a plate boundary are the en echelon oriented Thingmuli and Breiddalur volcanic centers. In general the volcanic centers in eastern Iceland define the active plate boundary at the time when these centers were active. These volcanic centers are exposed at high crustal levels of 1.0 to 1.5 km altitude. These volcanic centers delineated the Tertiary plate boundary at about 9 Ma and have only been slightly buried, perhaps due to a westward migration of the volcanic zone about 7 to 8 m.y. ago.

Musset and others (1980) presented Ar-Ar dating results for eastern Iceland and concluded that within resolution limits 'the spreading has been steady and symmetrical' and that 'in particular neither a large eastward jump nor repetitive westward jumps have occurred'. They further conclude that the 'average half spreading rate for the period 2-12 Ma was 0.78 $\pm$ 0.16 cm/yr'. Because the present study is concerned with some of the basic stratigraphic assumptions applied by Musset and others (1980) and their results conflict greatly with those derived in this thesis, the following paragraph briefly evaluates the stratigraphic assumptions given in their paper. Figure 6.7 is an idealized section of the east Iceland lava pile (from Musset and others, 1980, adapted from Palmason and Saemundsson, 1974) and it clearly demonstrates the overall time-averaged symmetry across the spreading axis on which their calculations of spreading rates were based. Thus they assumed that the spreading rates, rates of lava accumulation, and location of the spreading axis that generated Tertiary eastern Iceland are such that away from the ridge axis the extrusive crustal segment is uniform. As

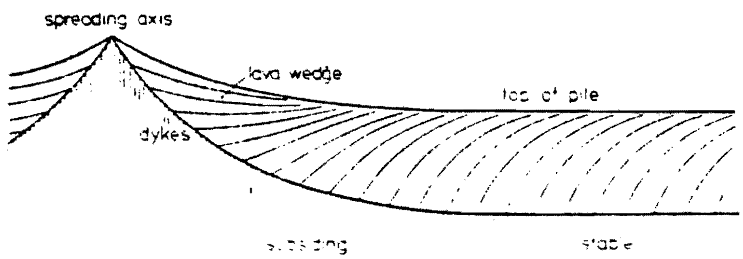


Figure 6.7 From Musset and others (1980), an interpretation of upper crustal structure of eastern Iceland. 'Idealized section of east Icelandic lava pile. Lavas are extruded downhill from fissures within the active zone and spread out to some limit. As spreading proceeds subsidence occurs burying the parts of lavas nearest the axes until finally the pile settles into the form on the right. Vertical scale exaggerated. Adapted from Palmason and Saemundsson (1974).'

such, it can be treated as if all lava lenses were formed at a single spreading axis now located in the active neovolcanic zone of northeastern Iceland. First, this approach ignores an important feature of the spreading mechanism that generated eastern Iceland, i.e. the shifting of the volcanic zones. Secondly, these authors ignore the fact that a substantial volume of lavas lies buried below sea level. These buried lavas may provide data to indicate whether rates of lava accumulation were constant, variable, or abnormal. Third, the author argues that a spreading rate cannot be derived for eastern Iceland at present, because: (1) the location of the spreading centers that generated eastern Iceland are mostly unknown, and (2) the size and frequency of shifting events of the volcanic zone that generated eastern Iceland have not been defined specifically before this thesis (section 7.2). It is therefore not surprising then, if their assumptions are incorrect, that the present spreading axis in northeastern Iceland is 25 km west of where it should be according to their model. Similarly, their method results in unusually low spreading rates for Iceland during the period 2-12 Ma (0.78 ± 0.16 cm/yr).

Christensen and Wilkens (1982) studied the seismic properties, densities, and porosities of 135 samples from the IRDP drillcore in Reydarfjordur. Their results have bearing on the nature of the layer2-layer3 seismic boundary. Thus they found the average seismic velocity for 45 dyke samples to be 6.10 km/s at 1.0 kbar confining pressure, significantly lower than both the average layer 3 velocity of 6.50 km/s as found by Palmason (1971) and the 6.7 km/s for the area surrounding the drillsite that was reported by MacKenzie and others (1982). This is evidence against the hypothesis that the layer 2-layer

3 boundary marks a transition from extrusive to intrusive units. Furthermore, Christensen and Wilkens studied the relationship between downward variations in the mineralogy and seismic velocities of the IRDP core. In particular they found that: 'increasing alteration with depth of Icelandic flows and dykes, which is accompanied by an increase in epidote content could produce the observed compressional refraction velocities for Icelandic layer 3'. Christensen and Wilkens find no support for the lower Icelandic crust to be made up of a sheeted dyke complex of the kind proposed for for eastern Iceland by Walker (1975b). In contrast they agree with earlier interpretations of Palmason (1971) and Flovenz (1980) that the boundary for seismic layer 2-layer 3 represents a metamorphic transition.

6.3 The relationship between Tertiary lava formations and volcanic centers

The most fundamental feature of the lava succession in eastern Iceland are the basalt lava formations, i.e., a succession of lavas (perhaps 10 to 20 units) that have similar petrographic characteristics and are readily mapped in the field. The writer assumes that the lava succession in Reydarfjordur was built up from discrete volcanic centers (fissure swarms) or alternatively from discrete sets of overlapping volcanic centers connected through a line that was oriented approximately along the present strike direction. The strike direction of lavas in eastern Iceland roughly coincides with the gently curved line that connects active volcanic centers in northeastern Iceland. The magma extrusion of a particular lithology (e.g. plagioclase porphyritic lavas) from each such center was great enough, over some fixed time, to construct a homogeneous formation of lavas. After the extrusion of each lava formation a dormant period seems to have followed, judging from the frequent occurrence of sedimentary units separating lava formations. The changes in lava lithology from one lava formation to another are probably related to the long term style of volcanic extrusions and could be explained by:

(a) migration or shifting of the locus of lava extrusion from one volcanic center to another, within the volcanic zones, leaving behind an area removed from lava deposition.

(b) migration of the volcanic zone (to the west) in such a an area was no longer within reach for lava deposition.

(c) periodical renewal of lava productivity after dormancy of a volcanic center.

The author favours the latter, namely that each lava formation is produced by individual volcanic centers that only periodically extrude lavas. This process could occur in such a way that a batch of magma evolves during a dormant interval resulting in changed petrological characteristics. If more than one volcanic center did form a single lava formation, these volcanic centers would contemporaneously have had to produce lavas of identical petrographic character. The known extent of individual lava formations is about 80 km along the volcanic zone (e.g. the Kollur porphyritic lava formation, section 1.4.8) which is a minimum value. Similarly, the author assumes that magma chambers generally did not form simultaneously in all volcanic centers of the volcanic zones although such chambers may occasionally have existed in neighbouring centers. Thus lava homogeneity is unlikely to occur along the entire volcanic zone or outside the depositional regime of each volcanic center.

If it is assumed for the present discussion that plagioclase porphyritic lavas are generated at great depths, say 10 to 20 km, it is likely that such lavas can be simultaneously extruded at the earth's surface within the entire volcanic zone. If, however, this magma was stored in shallow magma chambers before extrusion, say at 3 to 7 km depth, it is quite unlikely that the entire volcanic zone in this region could have produced lava formations of the kind that are presently exposed in eastern Iceland. This is because through processes such as magma mixing (Sparks and others, 1977) or differentiation (Carmichael, 1964), individual volcanic centers would presumably have affected the magma chemistry. This leads to the conclusion that each lava formation in eastern Iceland is an entity that originates from an individual volcanic center.

CHAPTER 7

THE UPPER CRUSTAL STRUCTURE OF EASTERN ICELAND AND A DYNAMIC RIFT MODEL FOR ITS GENERATION

7.1 Introduction

In the present chapter on the upper crustal structure of eastern Iceland the author first re-interprets some earlier important observations. Secondly, a dynamic rift model is presented for the generation of the upper crustal structure of the area. The model is compatible with the data presented in the present study, and it involves a re-interpretation of collected data by other workers in the region.

According to the kinematic model by Palmason (1973, 1980) the volcanic centers should not be exposed outside the volcanic zones, unless erosion exposes units that were buried several kilometres below the surface. Volcanic centers such as Thingmuli that are presently exposed outside the volcanic zone represent a deviation from the predicted behaviour of plate construction according to Palmason's model. With the present dynamic rift model an attempt is made to qualitatively account for the effects of the transient nature of volcanic zones, a mechanism that has not been included in the available theoretical models (e.g. Daignier and others, 1975; Palmason, 1980, 1981). Available qualitative models for eastern Iceland (e.g. Gibson and Piper, 1972) have included migration of the volcanic zone but in a rather simplistic

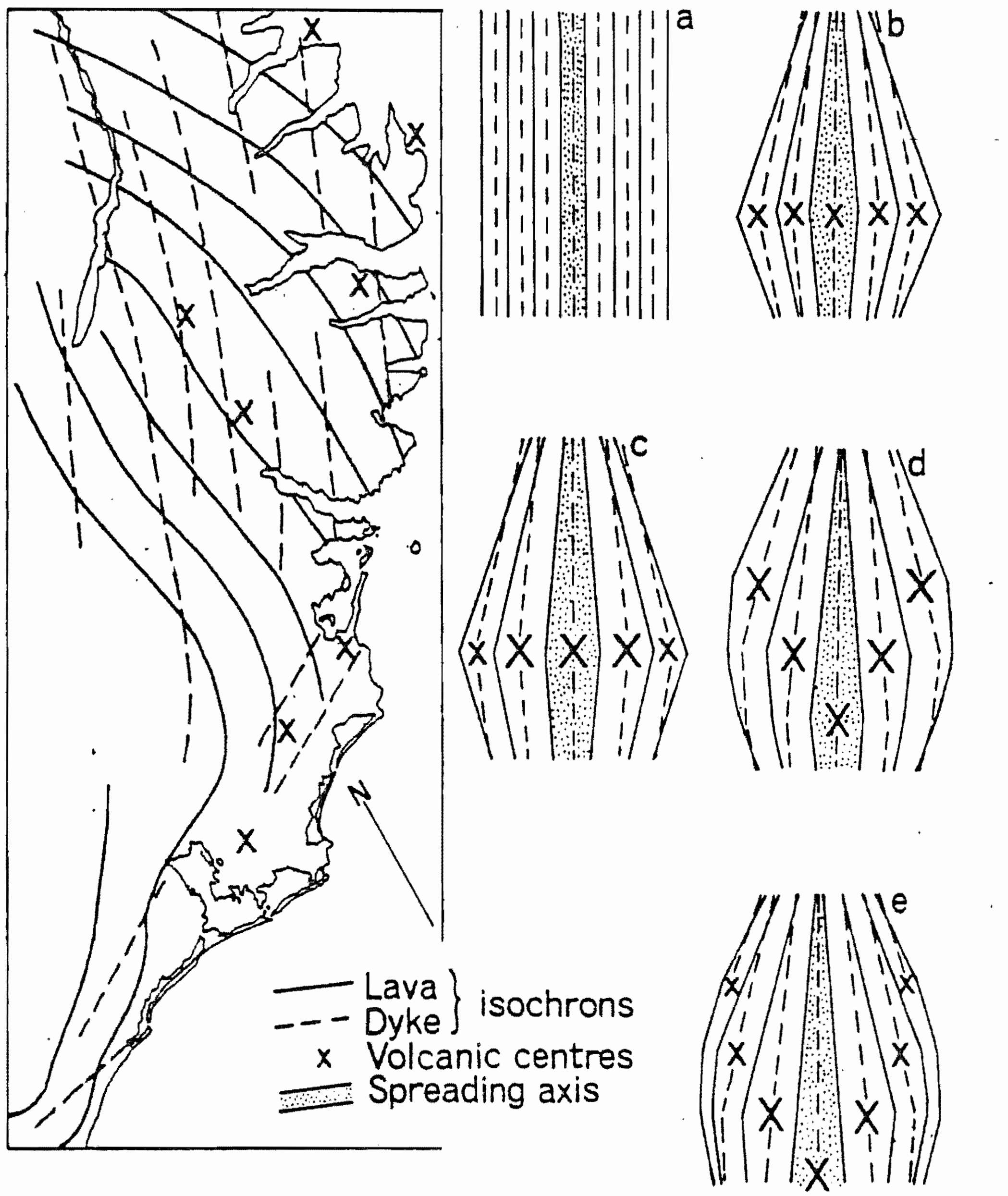


Figure 7.1 From Walker (1974). On the left (Figure 7.1a) are shown lava and dyke isochrons in eastern Iceland that are non-parallel and consistently intersect at an angle of 30° to 60°. To the right (Figure 7.1b) are five situations showing lava and dyke isochrons where one (a) represents parallel isochrons but others (b to e) represent different situations where isochrons intersect (see text). In all situations the plate boundary remains fixed in position.

way, i.e. by assuming that the migration always occurred in a direction from east to west. This is contrary to the present model which assumes that shifts of the volcanic zones, while constructing eastern Iceland, took place either to east or west and that some crustal segments now in the area drifted temporarily westward.

7.2 The large scale construction of eastern Iceland

In his paper on the structure of eastern Iceland Walker (1974a) regards lava and dyke strike directions as equivalents of lava and dyke isochrons. The parallel straight lava isochrons in eastern Iceland occur over a sufficiently large area (about 4000 km^2) and during a large enough time interval (13 to 2 Ma) to allow movements of the volcanic zones during the Tertiary to be detected. Walker suggests four situations or configurations of the volcanic centers with regard to each other to account for the relationship between lava and dyke isochrons (Figure 7.1). The four situations proposed by Walker attempt to explain presently exposed structural features (i.e. lava dyke isochrons) by invoking processes that prevailed during Tertiary plate construction in eastern Iceland. Walker assumes in all these cases that the spreading axis is fixed in position while the plates drift apart. In two of the situations (b) and (c) the spreading rate accelerates with time. In (d) and (e) the locus of greatest volcanism migrates southward. However, situations (d) and (e) differ in that the locus of volcanism in (e) migrates at an accelerating rate whereas in (d) the migration rate is constant. Although Walker favours situation (e) he points out that both situations (d) and (e) most likely simulate the plate boundary conditions that caused the present configuration of volcanic centers in eastern Iceland. In the following it will be argued that the four 'situations' proposed by Walker can probably neither account for the exposed structure of eastern Iceland nor the relationship between lava and dyke isochrons.

Although carefully derived, lava isochrons may not reflect the true conditions that prevaled during the construction of eastern Iceland. This is due to subsequent tectonic events, in particular the Lagarfljot flexured zone norhteast of Reydarfjordur (Figure 7.2), which is almost certainly responsible for the westward change of the lava strike at that locality, as shown on Figure 7.1a.

The author has traced the Kollur porphyritic lava formation (section 1.4.8) northward from Reydarfjordur and found it exposed at about 900 m elevation on Gagnheidi about 25 km north of the IRDP drill site. Southward extrapolation of this outcrop to the Reydarfjordur area gives a strike direction of N20°W. In this same area, which has only been roughly mapped, Walker derived a general lava strike of about N35°W. South of Gagnheidi on the north side of Skagafell there occurs a succession of dip slip faults, each with a downward displacement of about 50 m, usually to the west. This suggests that the Lagarfljot flexured zone is responsible for the abrupt westerly trend of lava strike in this region while dyke strike remains constant. Downfaulting within the Lagarfljot flexured zone is compatible with the observed lowering in elevation of zeolite zones in this area (Walker, 1974, 1975b; Watkins and Walker, 1977). For most of eastern Iceland lava isochrons intersect dyke isochrons at an angle of 30°, dykes having a more easterly strike or approximately N-S. North of Gagnheidi by Lagarfljot river the strike of lavas rapidly becomes more westerly, such that the lava and dyke isochrons form an angle of about 55°. The

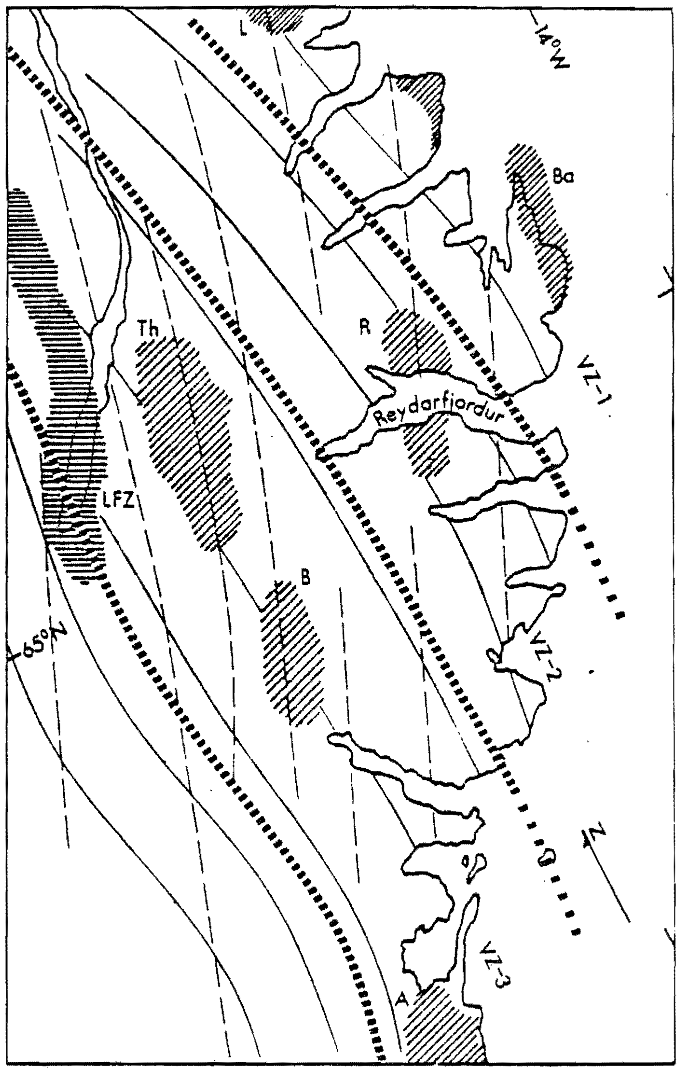


Figure 7.2 Derived volcanic zones for eastern Iceland (modified after Walker, 1974). Volcanic centers within each zone are in close temporal relationship and separated from the other volcanic zones by thick lava sequences which typically represent depositional environments for lavas (distal facies lavas). The heavy broken line separates volcanic zones, i.e. VZ-1 to VZ-3. Location of volcanic centers within these zones are (from north to south): (////) (L) Lodmundarfjordur, (Ba) Bardsnes, (R) Reydarfjordur, (Th) Thingmuli, (B) Breiddalur, (A) Alftafjordur. The Lagarfljot flexure zone (LFZ) is shown on the northwest side of the area (≡). Lava and dyke isochrons are drawn with solid and dashed lines respectively.

orientation of subvertical dyke intrusions is such that normal faulting does not change their strike.

The uniformity of dyke strike is evidence that the regional stress conditions have remained similar during construction of eastern Iceland. This suggests that lava strike was also similar during the Tertiary in eastern Iceland. By assuming that lava and dyke isochrons intersect at a constant angle the strike direction of these dykes, that are of similar age as the lavas, is perhaps a better indicator of the original regional strike direction of both lavas and dykes. Because local faulting within the Lagarfljot flexured zone changes the lava strike, it follows that this change in strike cannot be applied directly to trace the migration of the locus of volcanism elsewhere during the Tertiary. A reconstruction of faults in the lava succession is neccessary in order to derive the true lava strike which in turn can be used to study how (or if) the locus of greatest volcanism migrated with time.

Assuming that downfaulting within the Lagarfljot flexured zone caused the change in lava strike direction it would appear logical to extrapolate lava isochrons in the Reydarfjordur area northward to Lagarfljot. This has been done on Figure 7.2 and as a result lava isochrons remain essentially parallel for entire eastern Iceland and the same applies independently for dyke isochrons. The validity of this correction becomes credible when lava isochrons north of the flexured zone are examined (Figure 6 in Saemundsson, 1980). In that area the lava isochrons are parallel to those of eastern Iceland. Thus in eastern Iceland the true angle between lava and dyke isochrons remains approximately constant at about 30°. This indicates that the mechanism responsible for the buildup of eastern Iceland was generally uniform.

In other words if or when the volcanic zone migrated, this happened uniformly but not in such a manner that a single volcanic center became active to the west or east of others that were about to become extinct. Thus the migration of the volcanic zone occurred simultaneously for a chain of volcanic centers. It appears that neither the distribution of volcanic centers nor the angle between lava and dyke isochrons is caused by the activity of individual volcanic centers as suggested by Walker (1974a) but rather the cumulative stress conditions within a volcanic zone that consisted of several volcanic centers. A systematic increase or decrease in volcanic production at some discrete points along the volcanic zone during the Tertiary would have caused lava isochrons to be non-parallel. The thickening of lava formations close to volcanic centers causes local variations in lava strike due to high volcanic production (e.g. Gibson, 1969), but when removed from these centers lava isochrons remain parallel. At a greater scale the migration of the locus of greatest volcanism would be indicated by non-parallel lava isochrons. As the lava isochrons outside the volcanic centers remain parallel in eastern Iceland, it can be concluded that volcanic production in the volcanic zone during the Tertiary remained uniform along the entire plate boundary that generated this region (see also section 3.5). On the contrary isochrons of lavas that accumulated in western Iceland, approximately during the period 13 to 10 Ma, are clearly non-parallel (Figure 5, in Saemundsson, 1980). Thus it would appear that two different sources of volcanism may have formed the eastern and western fjordlands of Iceland.

With corrected lava isochrons (Figure 7.2) eastern Iceland has been divided into three volcanic zones, VZ-1 to VZ-3. These volcanic zones were active during the period of approximately 13.4 to some 6 Ma. Several sedimentary horizons in eastern Iceland represent a halt in lava deposition. This halt in lava deposition can for example be the result of shifting of one volcanic zone to another or possibly due to climatic cooling (Mudie and Helgason, in press). The derivation of these volcanic zones for eastern Iceland forms the basis for the model presented in section 7.4.

7.3 The active volcanic zone in northeastern Iceland: some constraints

In Figure 7.3 the volcanic zone of northeastern Iceland is shown (modified after Saemundsson, 1979). This area is regarded as a prototype for the volcanic zone that generated eastern Iceland. The strike of each fissure swarm is offset by about 30° obliquely to the east relative to the curvature of the volcanic zone. As can be seen all the volcanic centers are located on the western side of the zone. It can be argued that a shifting of the median zone in this region has occurred. This shifting is at least 20 km and probably as much as 40-50 km. By examining first the width of the area containing recent (less than 3 m.y. old) volcanics in northeastern Iceland and secondly the location of volcanic centers a minimum shift of 20 km is derived.

A line with dotted circles through each volcanic center is taken to arbitrarily define the median line of the presently active volcanic zone. For the last 3 m.y., approximately, volcanic products were distributed roughly across a 130 km wide zone. The present median line appears shifted about 20 km to the west relative to the median line of this 130 km time-averaged volcanic zone. Thus 65% of the area covered with volcanics during the last 3 m.y. is located east of this long term

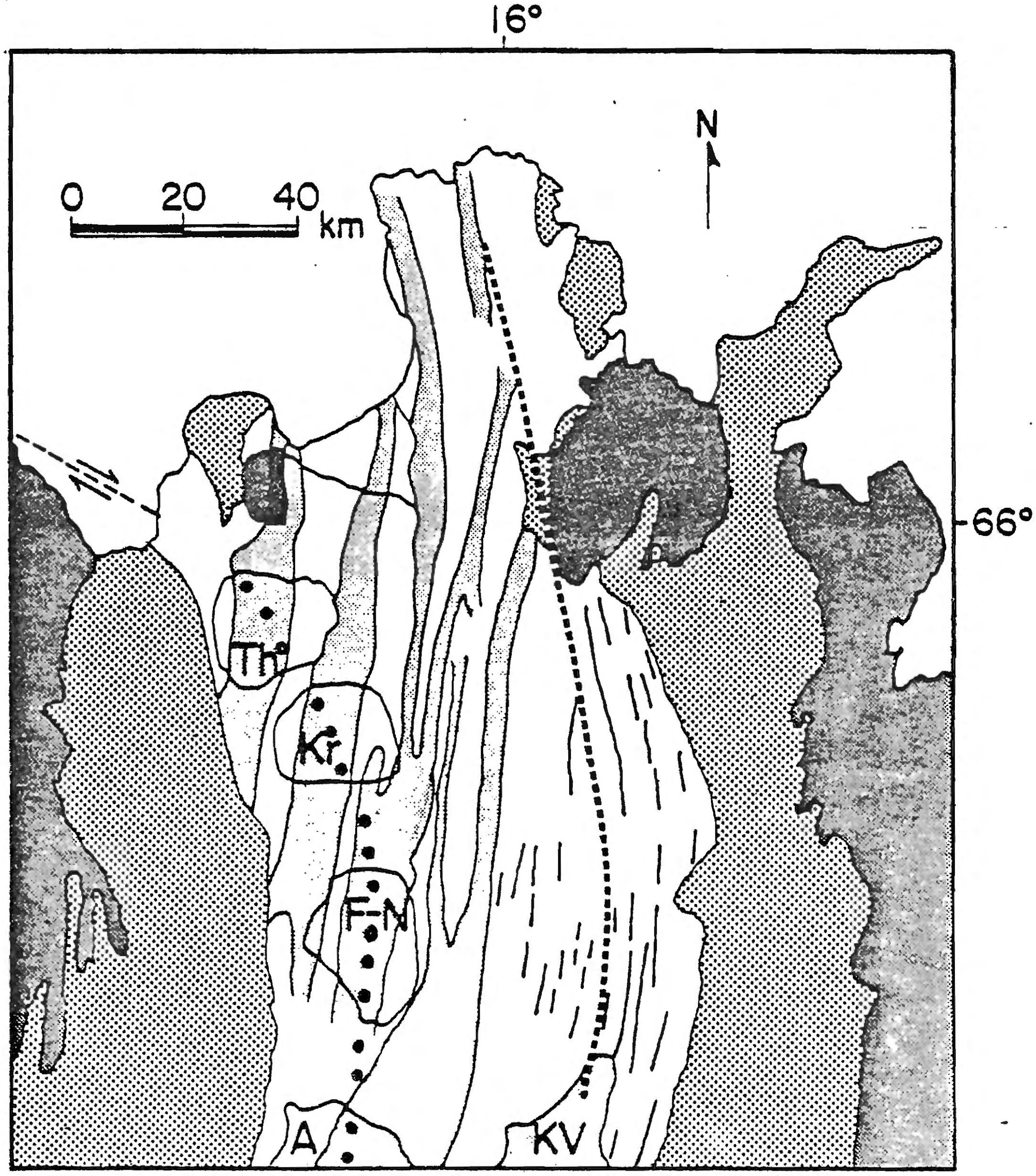


Figure 7.3 The volcanic zone in northeastern Iceland. Modified after Saemundsson (1978) to define constraints of zone transitions.

median line and only 35% to the west of it. Similarly, if inspection is limited only to the area that has been covered with volcanic products during the last 700 thousand years this shifting of the median line is also about 20 km. A more pronounced and a greater shift is seen to have occurred in northeastern Iceland if inspection is focused on where and when volcanism proceeded within this region during the last 700 thousand years.

The volcanic succession that forms the northward continuation of the Kverkfjoll-Snaefell volcanic centers consists mainly of hyaloclastite and tuffaceous sediments and has not been active in postglacial times. Thus the ages of these formations is only roughly known, i.e. to be younger than 700 thousand years and greater than 12,000 years. Walker (1975) considers this area to be volcanically dormant. The author argues that because volcanic centers did not develop within it, because this area may not have been active for several hundred thousand years, and because all spreading in northeastern Iceland occurs along the Theistareykir-Askja median line, it is reasonable to regard it as extinct rather than dormant.

Volcanic material that formed subglacially during the last 700,000 thousand years accumulated close to the eruptive sites and thus clearly indicates the location of the fissure swarms. Using this criterion, Map 3 in pocket, shows the volcanic systems in NE Iceland delineated by the extent of subglacial volcanism. An examination of the map reveals many features that indicate shifting of the locus of volcanism. On the western side are located three volcanic systems, i.e. Theistareykir, Krafla, and Fremri-Namur, all of which are within the presently active spreading zone. The Fremri-Namur fissure swarm probably coincides with fissures extending from the Askja volcanic center farther south. To the east, beyond the Fremri-Namur volcanic system is the direct continuation of the fissure swarm that extends into the Kverkfjoll volcanic center 120 km further south. During the postglacial period the Kverkfjoll volcanic system has not caused volcanic eruptions in this area but has, however, been very active during the last 700 thousand years. That these volcanics originate in a fissure swarm extending from the Kverkfjoll volcanic center, but do not represent a separate fissure swarm, seems likely as no volcanic centers are located in this region that could be the source for these volcanic formations. Because no volcanism occurs in the northern part of the Kverkfjoll volcanic system and active spreading with volcanism takes place in several parallel volcanic systems to the west, it is concluded that the locus of greatest spreading and volcanism has shifted westward over a distance of up to 50 km. Thus the locus of greatest volcanism which coincides with a line through the presently active volcanic centers in northeastern Iceland has shifted 50 km to the west relative to the center of the Kverkfjoll fissure swarm in this region. It is not obvious when this shift took place but it appears to have occurred less than 700 thousand years ago. It is a small scale shift of this order of magnitude, perhaps 20 to 50 km, that the author regards most effective in distributing volcanic material and thus volcanic centers within and outside the time-averaged plate boundary.

7.4 Spatial shift of volcanic activity in Reydarfjordur

The Breiddalur dyke swarm (Figure 1.2) intrudes the presently exposed lavas where eruptive sites are almost totally lacking. Only one eruptive site has been found within the swarm (Walker, 1959), namely, a porphyritic dyke acting as a feeder to a lava of the Graenavatn porphyritic basalt formation in Graenafell, which is about 9.5 m.y. old. For this reason the Breiddalur dyke swarm is assumed not to have fed lavas below the Graenavatn porphyritic formation. The Breiddalur dyke swarm probably fed some lavas above the Graenavatn porphyritic formation that are now eroded from the plateau carapace or possibly exposed high up in Skagafell, about 10 km northeast of the drill site. The area between the Breiddalur dyke swarm and the Reydarfjordur volcanic center (Figure 1.2) is typified by scarcity of dykes, less than about 1% of the basalt terrain. Close to the Reydarfjordur volcanic center in the Holmar olivine basalt formation, at about 50 m elevation in section RF on the north side of the fjord, the author has observed volcanic paleo-eruptive sites. Higher up in Holmatindur, individual lavas are commonly thick and intercalated with sedimentary units. It is suggested that these lavas represent a flank area outside a paleo-rift zone where lavas were deposited but not erupted. Because (1) the eruptive sites for these lava formations are not found exposed to the west of Holmatindur and (2) the formations thicken down dip toward Thingmuli volcanic center, it is assumed that they were erupted from a source now hidden below sea level in the area of the Thingmuli volcanic center. Much higher in the succession, eruptive sites are found again between lavas of the Thingmuli volcanic center.

For the present discussion the most relevant basalt formations of the intervening stratigraphic succession are the plagioclase porphyritic ones, usually with more than about 20% phenocryst content by volume. This is because they are exposed along strike up to 60 km (i.e. the Kollur porphyritic formation) and are most easily recognized in the field. These porphyritic formations can generally be traced up dip for about 15 km. Both these figures, i.e. 60 and 15 km, are minimum values. However, (1) if eruptive sites for the porphyritic lava formations were observed in the field, (2) depending on how frequently such sites are observed, and (3) if the lava formation had reached their maximum thickness and were already thinning 'down dip', it follows that the paleorift axis which generated the lava formations was probably completely exposed. As a result the distance of each lava formation from the point where it reaches maximum thickness, up dip as far as can be traced under the present erosional conditions, represents approximately its its 'half width'. Since these lava formations thicken consistently down dip to sea level and because eruptive sites are generally not seen it follows that extrapolation of lava formations beyond exposure in the down dip direction below sea level is probably at least another 15 km. The eruptive sites, which are not exposed, are assumed to be concealed down dip west of the Reydarfjordur volcanic center. The fact that the thickness of the plagioclase porphyritic formations remains constant in the strike direction suggests that these formations were emanated from fissure swarms of at least 60 km extension.

The following is an alternative explanation to the tectonic setting that may have caused the migration of volcanism coinciding with the end of activity in the Reydarfjordur volcanic center. Thus at the time of the proposed shift volcanism remained within the same volcanic zone which consisted of several fissure swarms. As volcanism ended in one volcanic center it may have resumed in a new fissure system west of the one associated with the Reydarfjordur volcanic center. This explanation is, however, much less favoured and is considered incompatible with the structure of eastern Iceland. In the following this argument is explained in greater detail.

The situation in Reydarfjordur has the Thingmuli volcanic center located directly west of the Reydarfjordur volcanic center (Figure 7.2). The stratigraphic formations of these two centers are separated by the intervening exposed distal facies lava succession (about 1 to 2 km thick) described in section 1.4. As can be seen from stratigraphic profiles from Reydarfjordur (folded in back cover of this thesis), acidic tuffs, welded or unwelded, are common throughout this intervening succession. Acidic explosive volcanism is typical of mature volcanic centers, which form late in the history of fissure swarms (e.g. Saemundsson, 1978). The volcanic centers responsible for the intervening acidic formations were most likely located in younger fissure swarms to the northwest, west or southwest of the Reydarfjordur volcanic center. The location of the Thingmuli, Breiddalur, and Alftafjordur volcanic centers reflects their _en echelon_ arrangement. These volcanic centers are stratigraphically overlapping and lava isochrons passing through this region are parallel. These volcanic centers are separated stratigraphically from the Reydarfjordur volcanic center by a distal facies lava succession. It is therefore concluded that a shift of volcanic activity took place from the Reydarfjordur volcanic zone (VZ-2) to the west where the Thingmuli, Breiddalur and Alftafjordur volcanic centers developed.

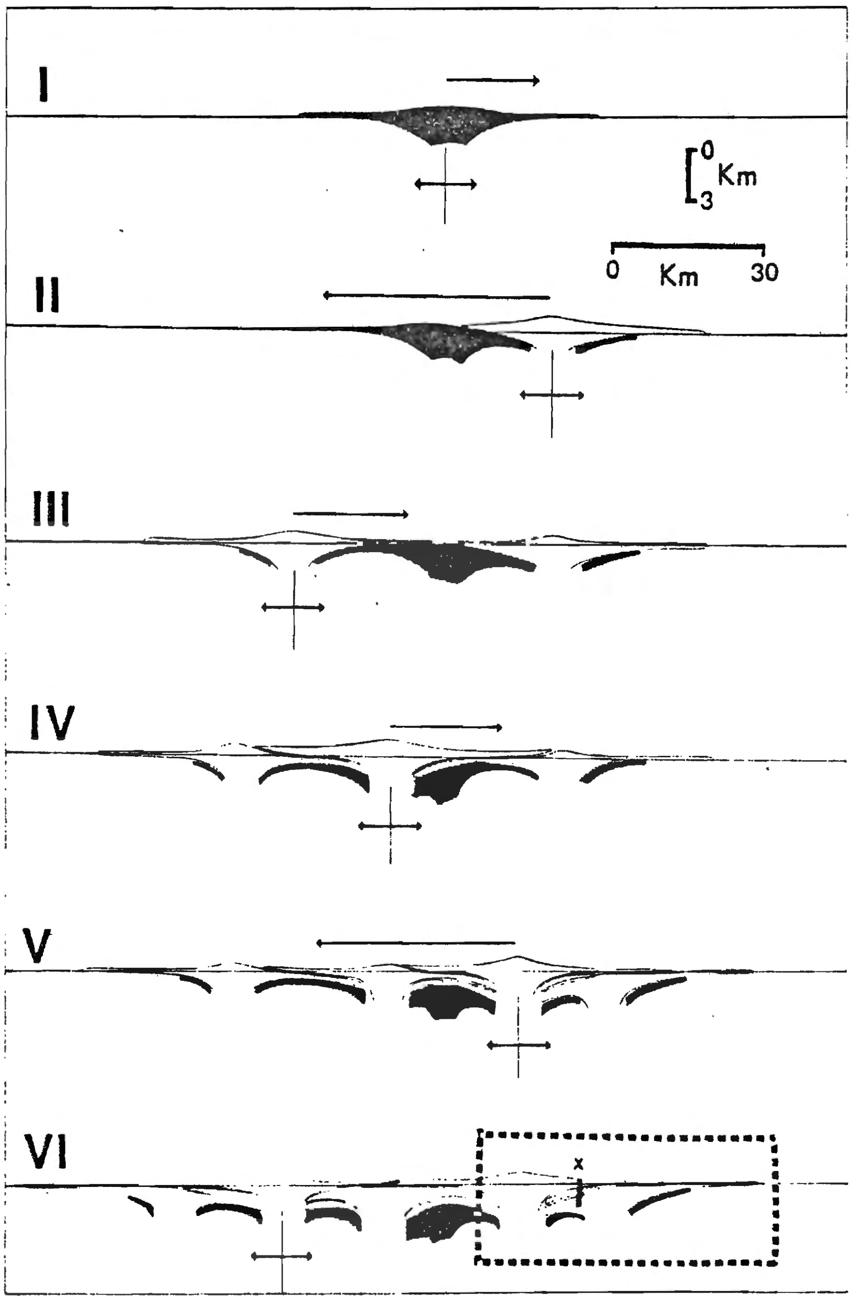
But is this process applicable to the neovolcanic zone? In the neovolcanic zone of northeastern Iceland the fissure swarms are arranged in an _en echelon_ fashion so that a line crossing their locus of highest volcanic activity is gently curved and parallels both the west and east boundaries of the volcanic zone (Figure 7.3). The volcanic centers in the northeast Iceland rift zone do not develop side by side but along the volcanic zone north and south of each other. When a volcanic system has been active for some time the regional stress conditions seem to favour a migration of all the volcanic centers to a new location (zone) as opposed to periodical shifting of individual volcanic systems. Therefore, this process proposed for Reydarfjordur may also apply for the crustal construction of the neovolcanic zone.

7.5 Qualitative model for the dynamic rifting in eastern Iceland

The main factor distinguishing this model from others that describe the upper crustal construction of eastern Iceland is that it assumes small scale shifts, perhaps 20 km, to have occurred at intervals of approximately 1.0 m.y., either to the west or east of the active plate boundary. In section 7.4 it was demonstrated that a shift of the plate boundary took place in Reydarfjordur from the Reydarfjordur volcanic center to the Thingmuli-Breiddalur volcanic centers, i.e. from VZ-2 to VZ-3 (Figure 7.2). Previously a shift occurred from VZ-1 to VZ-2. Earlier models assumed transitions of the plate boundary in eastern Iceland to have on each occasion been from east to west. This would appear in accordance with stratigraphic observations in eastern Iceland. From east to west lavas become successively younger as if the volcanic zone always shifted to the west or the eastern Iceland plate always drifted to the east. It is interesting to note that in discussing the stability of accreting plate boundaries in western Iceland Johannesson (1980) states: 'the active rift zones in Iceland have occasionally shifted and always toward east'. Those that studied the lava stratigraphy of eastern Iceland (e.g. Gibson, 1966) were of the opinion that shifts of the plate boundary always occurred toward west. The author argues that throughout the geological history of Iceland, both in eastern and western Iceland, the volcanic zone(s) shifted periodically either to the west or east in jumps of about 20 to 40 km. As a result there should presently be examples of both westward and eastward shifts of the volcanic zone(s) in eastern Iceland. The same should apply to western Iceland. That previous to this study only a westward shift has been observed in eastern Iceland and vice versa in western Iceland is probably an artifact of high volcanic production and rapid crustal subsidence at the plate boundary. It should be kept in mind that volcanic production in Iceland is such that an extrusive layer to depths of well over 10 km could exist, assuming that the lowest part of the extrusive layer is a mixture of both intrusives and lavas. In their model for eastern Iceland Gibson and Piper (1972) assumed the base of the extrusive layer to be at a much shallower depth or approximately 2.5 km below sea level. The shape and dimension of lava lenses in their model depended highly on the given thickness for the extrusive layer below sea level, i.e. about 2.5 km. Thus a thicker extrusive layer, or 12.5 km, provides the neccessary thickness to incorporate or conceal completely below sea level large extrusive segments only some of which erosion has exposed. An extrusive layer of about 10 km thick is neccessary for Iceland if volcanic production has remained approximately constant for the last 16 m.y.

A model is proposed and schematically presented in Figure 7.4. The approach taken below is to observe the gradual buildup (in two dimensions) of a thick lava succession that can be regarded as a section

Figure 7.4 Proposed dynamic rift model for the upper crustal structure of eastern Iceland. This model assumes that shifting of the volcanic zones occurs frequently, perhaps every 2 m.y. The shifting is to either side of the ridge axis for about 20-40-km in response to changed regional stress conditions. As a result of frequent shifting to either east or west, a thicker extrusive layer is generated than accounted for in previous models. The extrusive layer will thicken until a 'large scale' shift, perhaps 100-200-km transfers lava extrusion to a new area where the same process of crustal construction is initiated. An approximate scale is given in the upper right corner. The delineated area in stage VI resembles the actual stratigraphic conditions by the IRDP drillsite (marked x), which is surrounded by the Thingmuli volcanic center to the west and the Reydarfjordur volcanic center to the east.


I
0
Km
3
0 Km 30
II
III
IV
V
VI
x

across the volcanic zone over a period of about 1.0 m.y. The direction of shift is assumed to be random and to depend on the regional stress conditions of the crust. It follows from this model that different areas close to the volcanic zone where lavas cannot be deposited will be subjected to deposition of thin sediments, either tuffaceous units or volcaniclastic material.

Stage I. A saucer shaped (disc like) lava formation is being built up. The plate boundary does not neccessary represent a volcanic center but preferably the locus where the time-averaged volcanic production has been greatest. In stages 2 to 6 a potential burial history of this formation is simulated. It should be noted that the time averaged distribution of volcanic products depends heavily on the scale at which the shifting of the volcanic zone occurred. The model is made up of 6 stages, where each stage could represent crustal evolution during a period of about 1.0 m.y.

Stage II. Shifting of the plate boundary to the east has occurred and lens II starts forming. As a result the eastern depositional area of lens II is now split up. The shape of lens two will be asymmetrical as the western part is banking up against the ridge of lens II. However, the part of lens II that is isolated east of plate boundary two will probably form an almost continuous succession of depositional type lavas with perhaps a slight unconformity between lenses I and II. The relief of lens I prevents lavas to be deposited on its western side until subsidence of this area is a less dominating factor than the flow of lavas from plate boundary II. Subsidence at plate boundary I will continue for a short time until isostatic equilibrium is reached. Note that the spreading direction of the crustal segment between plate boundaries I and II will gradually revert in direction due to the shifting of the plate boundary.

Stage III. A new shift has occurred to the west of plate boundary I. Volcanism in this zone will be distributed asymmetrically as a result of the relief present in this area. The segment between volcanic zone II and III is likely to undergo faulting and deformation as it is now spreading again in the opposite direction. As the accumulation of lavas is not stationary at one plate boundary but is distributed over a wide area through shifting of the volcanic zones it follows that subsidence of each half lens is greater compared with a situation where lavas accumulate at a stationary plate boundary to periods equivalent to the geological history of Iceland, i.e. about 16 m.y.

Stage IV. An eastward shift has occurred. At this stage lens one has been split up into four segments and is thorougly subsided. However, the distribution of extrusive material across the active plate boundary is highly asymmetrical with a much greater proportion of the extrusive lens on the eastern side.

Stage V. results in a thicker crustal segment with increased deformation of the deeper segments.

Stage VI. After the final shifting of the plate boundary the lens from stage I has been split up into six segments that differ with respect to subsidence, deformation, volume, lithology, petrology and dyke intensity. As a result of this model a crustal structure has been formed that is much more complex and heterogeneous than the one generated by a model that does not account for the shifting of the volcanic zone. Each of the foregoing six stages has involved a small scale shift of the order of 20 to 40 km. Shifts of a larger size

(100-200 km) are envisaged to occur much less frequently or perhaps only 5 to 7 m.y. As a result of such shifts areas where lavas were deposited will be removed from lava deposition or deposition of lavas in such areas will at least be greatly reduced. During such large scale shifts an area of the kind produced in the above model will be sutured to one plate and will from then on probably be permanently attached to the same plate. Thus each of the plates in Iceland will contain crustal segments where volcanic material was asymmetrically distributed with regard to the time averaged plate boundary. In other words the regional deposition of lavas is bound to be highly variable and locally result in drastically reduced rates of lava accumulation or perhaps a complete halt of lava deposition.

7.6 The implications of large scale shifting of the volcanic zones: speculations

An important aspect, although not within the scope of this thesis, is the 'maturity stage' of the present volcanic zones in Iceland. As first suggested by Ward (1971) and later by Saemundsson (1974) a large scale shift (about 150 km) of the volcanic zone, from west to east, occurred in Iceland during the Tertiary causing two volcanic zones to be simultaneously active. As a result the possiblity remains that the present configuration of the volcanic zones may temporarily be anomalous. Thus if two volcanic zones are presently active, i.e. a western volcanic zone that is 'fading out' and an eastern zone 'destined to rule', or vice versa, the number of volcanic centers in Iceland may temporarily be too great. It is therefore possible that on a long term basis the configuration of the volcanic zones was more 'simple' than the present one.

The uniformity of the eastern Iceland lava succession and the configuration of the intrinsic volcanic centers would indicate that during the entire buildup of this region from 13 to 2 Ma the pattern of the volcanic zones was not made complex as a result of either non-accreting volcanic zones, migration of the locus of greatest volcanism, or transform fault belts which are common features of the neovolcanic zones. However, much more field work is needed to test these ideas.

It can finally be speculated what implications the model presented in this chapter may have for the structure of the lower crust in Iceland. It is neccessary first to emphasize that the boundary from the upper to lower crust has, in this thesis, been assumed to represent a metamorphic transition (Christensen and Wilkens, 1982). Strictly, however, this assumption may not apply to the core of volcanic centers. The unusually high heatflow in volcanic centers caused by substantial magma emplacement to shallow crustal depths may elevate the metamorphic boundary compared with the surrounding region. As a result it may be very difficult to destinguish whether the shallow depth to the lower crust in volcanic centers is due to metamorphism or increased dyke percentage. In general, however, the thickness of the extrusive crustal portion is assumed to depend primarily on (1) whether or how often the volcanic zone(s) has shifted in Iceland, (2) the size of each lateral shift, and (3) the duration of volcanism and total volcanic production in each volcanic zone. As the boundary between upper and lower crust appears to be a metamorphic transition it follows that a large part of the lower crust can consist of extrusive material. Thus the lithology and chemical composition of the lower crust will as a result be much more heterogeneous than if it were made up entirely of intrusives.

7.7 Conclusions

(1) Uniformity of volcanism in the Tertiary eastern Iceland: Faulting within the Lagarfljot flexured zone is probably responsible for the westerly trend in lava strike north of Reydarfjordur. By fault adjustment in this area the accumulation of volcanics along the lava strike in eastern Iceland was regionally uniform during the Tertiary.

(2) Comparison of eastern and western Iceland Tertiary lavas: Assuming large scale structural symmetry across each volcanic zone, it appears, based on the parallel and non-parallel lava isochrons in eastern and western Iceland, respectively, that these regions were generated by two different volcanic zones that, at least temporarily, were located far apart, perhaps by 100-200 km.

(3) Recent small scale shift of the volcanic zone in northeastern Iceland: A re-interpretation of the volcanic history of northeastern Iceland suggests that in this area a recent small scale shift, up to 50 km, occurred from the extinct segment of the Kverkfjoll fissure swarm westward to the Theistareikir-Askja median spreading axis. This shift is thought to have taken place less than 700 thousand years ago.

(4) Heterogeneity of crustal properties due to dynamic rifting: Each shifting event of the dynamic rifting model contribute toward diversifying the following crustal properties: plate boundary symmetry, steady state crustal behaviour, subsidence history, deformation, volume distribution of lava lenses, lithology, petrology and dyke intensity.

(5) Thickening of crustal layer 3 due to shifting of the volcanic zone(s): An extrusive layer, thicker than previously assumed, which extends into seismic layer 3 may be present in eastern Iceland. This

thick layer would result from the discrete build up of the lava succession by dyke swarms of more than one volcanic zone.

CHAPTER 8

SUMMARY OF CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

Contrary to most studies of the Tertiary lava succession in Iceland the present one has focused on a basalt lava group intercalated between two exposed volcanic centers. Thus detailed mapping of lava formations in the western Reydarfjordur area and deep crustal coring has made it possible to describe and arrive at a model for the upper crustal construction of this area.

8.1 Summary of conclusions

(1) Stratigraphic correlation: Using the Kollur lava formation as a datum and taking into consideration lateral changes in lithology and thickness, a stratigraphic correlation is proposed for the IRDP core and the exposed section east of the drill site. The Reydarfjordur porphyritic formation is intersected in the core at a depth interval of approximately 975 to 1020 m. Slightly higher in the core, at the approximate depth interval of 920 to 950 m, a thick ignimbrite unit occurs that correlates with the Reydarfjordur tuff of the exposed section. Two sedimentary units, thought to represent a single cycle equivalent to the Holmatindur tuff, occur at approximate depth intervals of 402 to 409 m and 344 to 362 m, respectively. At a slightly shallower depth (about 310 to 290 m), a porphyritic basalt lava formation is intersected, which correlates with the Kambfell formation. On the basis of paleomagnetic studies, the lower boundary of anomaly 5 is encountered

in the drill core at a depth of about 1465 (± 15) m. In Holmatindur, east of the drill site, the lowest exposed lava succession of anomaly 5 age consists of the top part of the Grjota olivine basalt formation. This coincides with a coarse-grained lava succession in the drill core at a depth of about 1475 m that probably extends to about 1655 m depth. The remaining part of the core (i.e., 1655 to 1919 m) has not been correlated with any specific exposed formation; it could have been erupted in the Reydarfjordur volcanic center. This correlation should now be tested or refined using geochemical data for the strata.

(2) Location of Tertiary volcanism in eastern Iceland: The distribution of dykes, the location of eruptive sites and the characteristics of lava flows in the study area suggest a westward shift of volcanic activity, at about 10.3 Ma, from the Reydarfjordur volcanic center to a new rift zone in the region where the Thingmuli and Breiddalur volcanic centers later developed.

(3) Rates of lava accumulation and estimates of Tertiary volcanic production: Watkins and Walker (1977) calculated rates of lava accumulation for the basalt succession in eastern Iceland. Their estimate was for lavas ranging in age from about 13 to 2 Ma. In their study, however, distinction between rates of lava accumulation (m/m.y.) and volcanic production rates (km^3/m.y./length) was not made. Due to lack of information on the three dimensional structure of the lava succession the problem of estimating volcanic production rates for the Tertiary lava succession remains unsolved.

The proposed rates of lava accumulation for the entire lava suceession in eastern Iceland vary by a factor of about 7 (Watkins and Walker, 1977). Down dip thickening of the lava succession affects rates of lava accumulation and must be accounted for. Thus Walker and Watkins normalized the thickness of lava successions to one datum, the top of the analcime zeolite zone. Applying this procedure the derived rates of lava accumulation varied by a factor of only four. Their study does, however, not provide an estimate for true rates of lava accumulation, which may have varied throughout the buildup of eastern Iceland at any one elevation level beacuse the volcanic zone shifted in location. Thus their study neither accounts for the shifting of the axial rift zone nor the onset of cold climate and/or subglacial volcanic conditions on rates of lava deposition. Without considering the influence of cold climate-glacial phenomena and shifting of the paleo-rift zone axis on the mode of volcanic activity, it appears unwarranted to suggest that rates of volcanic production have varied considerably in eastern Iceland since Tertiary times as suggested by Watkins and Walker (1977). On the contrary the lava isochrons for eastern Iceland were parallel during the Tertiary, a feature that at least suggests homogeneous volcanism parallel to the volcanic zones.

(4) Remagnetizaton of anomaly 5 age lavas in Reydarfjordur: Two magnetostratigraphic sections, in Kollur and Teigargerdistindur, clearly establish that their lavas are all normally magnetized and of anomaly 5 age.

Normally magnetized lava formations in these sections become reversely magnetized when traced up dip to Holmatindur. The Holmatindur lava sections contains frequent magnetic reversals that are attributed to a 10-m-thick reversely magnetized dyke, unit RF51D. This 10-m-thick dyke unit may have remagnetized the host lavas up to about 10 m away from the dyke-lava contact. As dyke units of this thickness are few, mean dyke thickness being about 3.5 m, remagnetization by dyke units is regarded uncommon and only to have occurred locally.

(5) Late dyke emplacement in Holmatindur: Dyke unit RF51D in Holmatindur extends through the lava section and is exposed at the mountain carapace. As this unit is reversely magnetized and has intruded through lava successions of anomaly 5 age that further down dip are seen found to be completely of normal magnetic polarity. It is therefore most likely that the dyke intruded the area after termination of anomaly 5 rather than a during this magnetic anomaly. Thus magnetostratigraphic work and field evidence suggest that this 10-m-thick dyke unit intruded the area at least 1 m.y. after the eruption of the lavas that are exposed in Holmatindur. The dyke emplacement most likely took place less than 9 m.y. ago.

(6) Vertical variations in magnetic intensity in Holmatindur lavas: The lavas in Holmatindur are highly heterogeneous in terms of magnetic properties. Thus the magnetic intensity does not decrease regularly with depth as had been suggested previously. Instead it is shown that despite averaging this physical property for 9 lava intervals, each consisting of 10 lava units, no systematic decrease with depth takes place.

(7) Estimates of continuity of paleomagnetic recordings in Icelandic lava flows: An examination of the literature on magnetostratigraphic studies in Iceland suggests that magnetic reversals commonly coincide with lithostratigraphic boundaries. Thus for the period 13.6 to 10.0 Ma there occurred 22 well defined magnetic reversals in eastern Iceland, 7 of which coincided with lithostratigraphic boundaries. This may represent a magnetostratigraphic problem because of the unknown time

interval involved with the formation of sedimentary units at magnetic reversal boundaries.

(8) Laterally emplaced dykes: Examples of discontinuous dykes were found within the Breiddalur dyke swarm. In particular such dykes are found at lava boundaries or within 5 to 40 m thick sedimentary units. Because of how frequent such dyke features are in well exposed sedimentary units it is concluded that lateral emplacement of dykes was the most common intrusion mechanism for the Breiddalur dyke swarm. Lateral dyke emplacement is a mechanism compatible with current dyke magma injection into fissure swarms in the Krafla area in northern Iceland.

(9) The location of Tertiary volcanism in Reydarfjordur: The distribution of dykes into swarms reflects the localized nature of volcanism in Reydarfjordur. Dykes are generally not seen to act as feeders to lavas except within volcanic centers. Lava formations overlying the Reydarfjordur volcanic center, that are older than lavas of the Thingmuli volcanic center were erupted west of the IRDP drill site. Thus K-Ar dating results of this study indicate that to a first approximation the lavas in the Holmatindur area are about 1.5 m.y. older than intruding dykes. Toward west the age difference between lavas and dykes decreases and in lava formations of Thingmuli volcanic center the age difference between lavas and dykes is no longer present. Virtual geomagnetic pole positions of a large portion of dykes in the Graenafell dyke section are shallow (21%). This is in constrast to the surrounding lavas where such shallow values are rare (7%). This leads to the conclusion that dykes and lavas in this area are genetically unrelated. For these reasons a westward shift in the location of

volcanism is proposed, i.e. from the Reydarfjordur volcanic center to the west of the IRDP drill site where later the Thingmuli and Breiddalur volcanic centers developed in a new volcanic zone. This shift is postulated to have occurred at about 10.3 Ma based on K-Ar and magnetostratigrapic data.

(10) Uniform volcanism during the Tertiary in eastern Iceland: It is suggested that the Lagarfljot flexured zone north of the IRDP drill side changed the strike of lavas subsequent to their deposition. This is also supported by the general lowering in elevation of zeolite grade alteration within this zone. In addition several large faults, each about 50 m, with a downward displacement to the west are observed in this area. To the north of the flexured zone lava strike gains a similar strike as to the south of it, suggesting that the flexured zone caused a localized strike variation. The similar lava strike for eastern Iceland indicates that volcanism in eastern Iceland was uniform during the Tertiary and generally devoid of non-accreting volcanic zones, transform fault belts and north-south migration of the locus of greatest volcanism.

(11) Comparison of the Tertiary basalt regions of eastern and western Iceland: When the lava strike directions and lava isochrons for eastern and western Iceland are compared it appears that two distinct volcanic zones generated these two regions. Thus whereas lava isochrons are parallel in eastern Iceland they are clearly non-parallel in western Iceland. It is suggested that the two areas were formed within their own volcano-tectonic regimes and that on a large scale such regional crustal formation may have generated other independent crustal segments.

(12) Recent shift of the volcanic zone in northeastern Iceland: An

examination of active volcanism in the northeastern Iceland indicates that for the last 700 thousand years volcanism has mainly been on the western side of the time-averaged volcanic zone in this region. Activity in the Kverkfjoll fissure swarm extended about 200 km further to the north than it does now. Instead volcanism is displaced about 50 km to the west, i.e. to the Theistareikir-Askja median spreading axis.

(13) Dynamic rift model for the upper crustal construction of eastern Iceland: It is concluded that at least three shifts of the volcanic zone(s) occurred during the crustal construction of eastern Iceland. A dynamic rift model is postulated to account for such shifting and a thicker extrusive crustal layer than has previously been assumed. Continued shifting of volcanism will result in increased burial of extrusive lava formations, but in such a way that in some areas unusually thick crust can be formed. Such a model is compatible with the notion that seismic layer three is a metamorphic boundary but not a transition boundary from intrusive to extrusive volcanic material.

(14) Diversity of crustal properties due to dynamic rifting: It can be speculated that with each new shifting of the volcanic zones a more diversified crust is generated. Thus the following crustal properties may be affected: general symmetry of the plate boundary, steady state crustal conditions, burial mechanisms, isotherms, deformation, crustal melting, crustal metamorphism, dyke intensity, and distribution of lava lenses.

8.2 Suggested future work in a Tertiary area like eastern Iceland

It has sometimes proven difficult to correlate accurately the magnetostratigraphic work that has been carried out in the Tertiary regions of Iceland. Thus, as an example, the corrected total thickness of lava formations of 'anomaly 5 age' in the exposed cliff section in eastern Iceland is about 800 m (Watkins and Walker, 1977). In northern Iceland the total stratigraphic thickness for this period is 1860 m and possibly 2774 m (Saemundsson, 1980). Obviously the rate of lava accumulation was greater in northern Iceland during 'anomaly 5' compared with eastern Iceland. According to earlier models of crustal construction this would indicate greater volcanic production for northern Iceland which need not neccessarily be true. It is suggested that, instead of treating the thick Tertiary lava successions as a genetic entity, emphasis should be laid on knowing in greater detail the paleomagnetic and stratigraphic history of each lava formation. A substantial amount of paleomagnetic information is already available to tackle this problem. This approach is suggested because of the periodical migration of the locus of volcanism during the Tertiary which in turn will cause lava formations, as presently exposed, to have variable thicknesses despite constant volcanic production. This effect of the migration of volcanism has so far not been corrected for in Icelandic magnetostratigraphic studies. Information on this problem might be obtained by studying the relationship between magnetic reversals or changes in magnetic directions that coincide with lithostratigraphic boundaries. The emphasis has been placed on learning the upper and lower age boundaries of paleomagnetic chrons. If such boundaries coincide with lithostratigraphic boundaries it follows that any geomagnetic polarity time scale derived for such a lava succession may be affected depending on the hiatus between formations. This is a problem that needs to be considered when arriving a geomagnetic time scale for the Upper Miocene areas in Iceland. Although not within the scope of this thesis it is suggested that this problem can be partially solved in three ways.

Firstly, the substantial magnetostratigraphic work that has been carried out in eastern Iceland (e.g. Watkins and Walker, 1977), northern Iceland (Saemundsson and others, 1980), and western Iceland (McDougall and others, 1982, in press) will provide the neccessary basis on which a detailed comparison of paleomagnetic chrons in these regions can be made that will determine whether regional hiatuses occur in the stratigraphic succession that cancel out paleomagnetic reversals.

Secondly, an advantage can be taken of the fact that lava formations thicken down dip and if magnetostratigraphic traverses have been selected at high elevations the same formations are thicker down dip and may there collectively contain a greater number of magnetic reversals.

Thirdly, a comparison between magnetostratigraphic sections in western, northern and eastern Iceland will establish whether the rate of lava accumulation, as observed in these provinces, varies to a significant degree, a feature that will affect any geomagnetic time scale derived in Iceland.

Tephrochronological studies of postglacial tephra layers may in the future be a most useful tool to provide knowledge of the total available time for recording of paleomagnetic data (T_t). This is particularly likely as tephra studies have shown that many volcanic systems tend to be chemically distinct over thousands of years in areas where excellent tephra stratigraphic records exists (e.g. Larsen, 1981; Steinthorsson, 1977). Finally, it could be speculated based on the extent of individual lava or sedimentary formations in eastern Iceland that some of the same formations could be found in northern Iceland. Either way it has implications regarding the large scale structure of Iceland.

References

Ade-Hall, J.M., and P. Dagley, The implications for paleomagnetism of the chemical, opaque mineralogical and magnetic porperties of some baked contacts, Geophys. J. R. Astron. Soc., 36(3), 731-736, 1974.

Ade-Hall, J.M., P. Dagley, R.L. Wilson, A. Evans, A. Riding, P.J. Smith, R. Skelhorne, and T. Sloan, A paleomagnetic study of the Mull regional dyke swarm, Geophys. J. R. Astron. Soc., 27, 517-545, 1972.

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., P.J. Hooker, and J.A. Miller, A brief K-Ar age study of the IRDP bore hole, Reydarfjordur, Eastern Iceland, J. Geophys. Res., 87, 6566-6568, 1982.

American Commission on Stratigraphic Nomenclature, Code of stratigraphic nomenclature, Am. Assoc. Petrol. Geol. Bull., 45 (5), 645-660, 1961.

Bath, M., Crustal structure of Iceland, J. Geophys. Res., 65, 1793-1807, 1960.

Becker, H., Magnetic Anomalies (ΔZ) in NE-Iceland and their Interpretation Based on Rock-Magnetic Investigations, J. Geophys., 47, 43-56, 1980.

Bird, C.F., and J.D.A. Piper, Opaque Petrology, Magnetic Polarity and thermomagneteic Properties in the Reydarfjordur Dyke Swarm, Eastern Iceland, Jokull, 30, 34-42, 1980.

Bjornsson, A., K. Saemundsson, P. Einarsson, E. Tryggvason, and K. Gronvold, Current rifting episode in north Iceland, Nature, 266, 318-323, 1977.

Bjornsson, A., G. Johnson, S. Sigurdsson, G. Thorbergsson, and E. Tryggvason, Rifting of the plate boundary in north Iceland 1975-1978, J. Geophys. Res., 84, 3029-3038, 1979.

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

Bleil, U., J.M. Hall, H.P. Johnson, S. Levi, and G. Schonharting, The natural magnetization of a 3 km section of Icelandic crust, J. Geophys. Res., 87, 6569-6590, 1982.

Bodvarsson, G., and G.P.L. Walker, Crustal drift in Iceland, Geophys. J. R. Astron. Soc., 8, 285-300, 1964.

Carmichael, I.S.E., The petrology of Thingmuli, a Tertiary volcano in eastern Iceland, J. Petrol., 5, 435-460, 1964.

Christensen, N.I., R.H. Wilkens, Seismic properties, density and composition of the Icelandic crust near Reydarfjordur, J. Geophys. Res., 87, 6389-6395, 1982.

Dagley, P., R.L. Wilson, J.M. Ade-Hall, G.P.L. Walker, E.S. 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.

Daigniers, M., Courtillot, V., Bayer, R. and P. Tapponnier, A model for the evolution of the axial zone of mid ocean ridges as suggested by Icelandic tectonics, Earth Planet. Sci. Lett., 26, 222-232, 1975.

Dearnley, R., A contribution to the geology of Lodmundarfjordur, Acta. Natur. Island, 1, (9), 1954.

Einarsson, P., S-wave Shadows in the Krafla Caldera in NE-Iceland. Evidence for a Magma Chamber in the Crust, Bull. Volcanol., 41-3, 1978.

Einarsson, P., and B. Brandsdottir, Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE-Iceland, J. Geophys., 47, 160-165, 1980.

Einarsson, T., Der Paleomagnetismus der islandischen Basalte und seine stratigraphische Bedeutung, Neues Jahrb. Geol. Palaontol. Monatsh. 4, 159-175, 1957.

Fisher, R.A., Dispersion on a sphere, Proc. R. Soc. London, Ser. A, 217, 295-305,1953.

Flovenz, O.G., Seismic structure of the Icelandic crust above layer three and the relation between body wave velocity and alteration of the basaltic crust, J. Geophys., 47, 211-220, 1980.

Flower, M.F.J., R.G. Pritchard, G. Brem, J.R. Cann, J. Delaney, R. Emmerman, I.L. Gibson, P.J. Oakley, P.T. Robinson, and H.-U. Schmincke, Chemical Stratigraphy, Iceland Research Drilling Project Reydarfjordur, Eastern Iceland, J. Geophys. Res., 87, 6489-6510, 1982.

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

Fridleifsson, I.B., Distribution of large basaltic intrusions in the Icelandic crust and the nature of the layer 2-layer 3 boundary, Geol. Soc. Am. Bull., 88, 1689-1693, 1977.

Fridleifsson, I.B., I.L. Gibson, J.M. Hall, H.P. Johnson, N.I.

Christensen, H-U. Schmincke, and G. Schonharting, The Iceland Research Drilling Project, J. Geophys. Res., 87, 6359-6361, 1982.

Gale, N.H., S. Moorbath and J. Simons, K-Ar ages of acid intrusive rocks from Iceland, Earth Planet. Sci. Lett., 1, 284-288, 1966. Interscience, New York, 1966.

Gibson, I.L., The crustal structure of eastern Iceland, Geophys. J. R. Astron. Soc., 12, 99-102, 1966.

Gibson, I.L., The Reydarfjordur acid volcanic centre of eastern Iceland, PhD dissertation, Imperial College, pp. 267, 1963.

Gibson, I.L., and J.D.A. Piper, Structure of the Icelandic basalt plateau and the process of drift, Philos. Trans. R. Soc. London, Ser.A, 271, 141-150, 1972.

Gibson, I.L., D.J.J. Kinsman, and G.P.L. Walker, Geology of the Faskrudsfjordur area, eastern Iceland, Visindafelag Isl. Greinar, 2, 1-52, 1966.

Gudmundsson, G., and K. Saemundsson, Statistical analysis of damaging earthquakes and volcanic eruptions in Iceland from 1550 to 1978, J. Geophys., 47, 99-109, 1980.

Hawkes, L., and H.K. Hawkes, The Sandfell laccolith and 'dome of elevation', Q. J. Geol. Soc. London., 89, 379-398, 1933.

Hedberg, H.D. (Editor), International Stratigraphic Guide. A guide to stratigraphic classification, terminology and procedure. John Wiley and Sons, New York, pp. 1-200, 1976.

Helgason, J., Stratigraphy and paleomagnetism of the lava succession surrounding the IRDP drill site, Reydarfjordur, eastern Iceland, Chapman Conference (American Geophysical Union) on the Generation of Oceanic Lithosphere, Warrenton, Va., published abstract, 1982.

Helgason, J., Magnetostratigraphy of the exposed lava section east of the IRDP drill hole in Reydarfjordur, eastern Iceland, J. Geophys. Res., 87, 6396-6404, 1982.

Helgason, J., and M. Zentilli, Stratigraphy and correlation of the region surrounding the IRDP drill hole 1978, Reydarfjordur, eastern Iceland, J. Geophys. Res., 87, 6405-6418, 1982.

Heirtzler, J.R., Dickson, G.O., Herron, E.N., Pitman, W.C., and LePichon, X., Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents, J. Geophys. Res., 73, 2119-2136, 1968.

Holland, C.H., M.G. Audley-Charles, M.G. Bassett, J.W. Cowie, D. Curry, F.J. Fitch, J.M. Hancock, M.R. House, J.K. Ingham, P.E. Kent, N. Morton, W.H.C. Ramsbottom, P.F. Rawson, D.B. Smith, C.J. Stubblefield, H.S. Torrens, Peigi Wallace, and A.W.

Woodland, A guide to stratigraphic procedure, Geol. Sco. Lond. Spec. Rep. No. 10, 1978.

Hodgson, R.A., Classification of structures on joint surfaces, Am. Journ. Sci., 259, 493-502, 1961.

Hubbert, M.K., and D.G. Willis, Mechanics of hydraulic fracturing, Trans. Soc. Petr. Eng. of AIME, 210, 153-168, 1957.

Jakobsson, S.P., Chemistry and distribution pattern of recent basaltic rocks in Iceland. Lithos 5, 365-386, 1972.

Johannesson, H., Evolution of the zones in western Iceland, Natturufraedingurinn, (in Icelandic with an English summary), 50, 13-31,1980.

Johannesson, H., Structure and geochemistry of the Reykjadalur central volcano and the surrounding areas, morthwest Iceland, PhD dissertation, University of Durham, pp. 273, 1975.

Kristjansson, L., and I. McDougall, Some aspects of the late Tertiary geomagnetic field in Iceland, Geophys. J. R. astr. Soc., 68, 273-294, 1982.

LaBreque, J.L., D.V. Kent, and S.L. Conde, Revised magnetic polarity time scale for late Cretaceous and Cenozoic time, Geology, 5, 330-335, 1977.

Larsen, G., Tephrochronology by microprobe glass analysis, In: Tephra Studies, edited by S. Self and R.S.J. Sparks, 95-103, D. Reidel Publishing Company, Dordrecht, 1981.

Lawley, E., The intensity of the geomagnetic field in Iceland during neogene polarity transitions and systematic deviations, Earth Planet. Sci. Lett., 10, 145-149, 1970.

Lomize, M.G., Basalt dykes and spreading of the crust in eastern Iceland, Geotectonics, 10, (2), 115-124, 1976. pp. 46, August, 1977.

MacKenzie, K., J. McClain, J. Orcutt, Constraints on crustal structure in eastern Iceland based on external inversions of refraction data, J. Geophys. Res., 87, 6371-6382, 1982.

McDougall, I., Precision methods of potassium-argon isotopic age determination on young rocks, in Methods and Techniques in Geophysics, vol. 2, edited by S.K. Runcorn, pp. 279-304, Interscience, New York, 1966.

McDougall, I., and H. Wensink, Paleomagnetism and geochronology of the Pliocene-Pleistocene lavas in Iceland, Earth Planet. Sci. Lett., 1, 232-236, 1966.

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

McDougall, I., L. Kristjansson, and K. Saemundsson, Evolution of the northwest peninsula, Iceland, from stratigraphic, paleomagnetic and K-Ar dating studies, Abstract from IAVCEI-IAGC conference, held in Reykjavik, Iceland, 1982 (August).

Moorbath, S., and G.P.L. Walker, Strontium isotope investigations of igneous rocks from Iceland, Nature, 207, 837-840, 1965.

Moorbath, S., H. Sigurdsson, and R. Goodwin, K-Ar ages of the oldest exposed rocks in Iceland, Earth Planet. Sci. Lett., 4, 197-205, 1968.

Mudie, P.J., and J. Helgason, Palynological evidence for climatic cooling in eastern Iceland about 9.8 M.a., Nature, 1983 (in press).

Musset, A.E., J.G. Ross, and I.L. Gibson, 40Ar/39Ar dates of eastern Iceland lavas, Geophys. J.R. astr. Soc., 60, 37-52, 1980.

Ness, G., S. Levi, and Couch, R., Marine magnetic anomaly timescales for the Cenozoic and late Cretaceous: a precis, critique and synthesis, Rev. Geophys. Sp. Phys., 18, 753-770, 1980.

Olafsson, M., The Alftafjordur dyke swarm on the Berufjordur coastline, field mapping and geochemistry. Unpublished dissertation, University of Iceland, 1977.

Palmason, G., Crustal rifting, and related thermomechanical processes in the lithosphere beneath Iceland, Geol. Rundschau, 70, 1, 244-260, 1981.

Palmason, G., A continuum model of crustal generation in Iceland: Kinematic aspects, J. Geophys., 47, 7-18, 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., Crustal structure of Iceland from explosion seismology. Soc. Sci. Isl., 40, 1-187, 1971.

Palmason, G., Seismic refraction investigation of the basalt lavas in northern and eastern Iceland, Jokull, 13, 39-60, 1963.

Palmason, G., and G. Sigvaldason, Iceland - Oceanic or Continental?, in Geodynamics: progress and prospects, edited by C.L. Drake, American Geophysical Union, Washington, D.C., 56-58, 1976.

Palmason, G. and K. Saemundsson, Iceland in relation the the Mid-Atlantic Ridge, Ann. Rev. Earth Planet. Sci., 2, 25-50, 1974.

Palmason, G., S. Arnorsson, I.B. Fridleifsson, H. Kristmannsdottir, K. Saemundsson, V. Stefansson, B. Steingrimsson, J. Tomasson and L. Kristjansson, The Iceland crust: evidence from drillhole data on structure and processes, in Maurice Ewing Series, Deep drilling results in the Atlantic Ocean: ocean crust;, edited by M. Talwani, C.G. Harrison and D.E. Heyes, 2, 43-65, 1979.

Paterson, M.S., Experimental Rock Deformation - The Brittle Field, Springer-Verlag, Berlin, Heidelberg, New York, pp. 1-254, 1978.

Pflug, H.D., Sporenbilder aus Island und ihre stratigraphische Deutung, N. Jb. Geol. Palaont. 107, 141-172, 1959.

Piper, J.D.A., Volcanic history and tectonics of the north Langjokull region, central Iceland, Can. J. Earht Sci., 10, 164-179, 1973.

Piper, J.D.A., M.G. Fowler, and I.L. Gibson, Dyke magnetization, magnetostratigraphy and upper crustal structure in the Reydarfjordur area of eastern Iceland, Tectonophysics, 40, 227-244, 1977.

Robinson, P.T., J.M. Mehegan, I.L. Gibson, and H.-U. Schmincke, Lithology and eruptive structure of the volcanic succession in eastern Iceland, J. Geophys. Res., 87, 6429-6436, 1982a.

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: Synthesis of results and implications for the nature of icelandic and oceanic crust, J. Geophys. Res., 87, 6657-6667, 1982b.

Ross, J.G., and A.E. Musset, 40Ar/39Ar dates for spreading rates in eastern Iceland, Nature, 259, 36-38, 1976.

Saemundsson, K., Outline of the geology of Iceland, Jokull, Special issue, 29, 7-28, 1979.

Saemundsson, K., Fissure swarms and central volcanoes of the neovolcanic zones of Iceland, Geol. Journ., Special issue, 10, 415-432, 1978.

Saemundsson, K., Geological map of north east Iceland, Sheet no. 7, Published by the Icelandic Geodetic Survey and the Museum of Natural History, 1977.

Saemundsson, K., Evolution of the axial rifting zone in Northern Iceland and the Tjornes fracture zone, Geol. Soc. Am. Bull., 85, 495-504, 1974.

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.

Scientific Party, Iceland Research Drilling Project - Reydarfjordur

1978, Detailed core log, volumes I-V, compiled and edited by the scientific staff at the Reydarfjordur drill site and by the technical and secretarial staff, Dept. of Geol., Dalhousie University, Halifax, Nova Scotia, 1979a.

Scientific Party, Iceland Research Drilling Project - Reydarfjordur 1978, Core summaries, compiled by the scientific staff at the Reydarfjordur drill site and edited by P.T. Robinson and H.-U. Schmincke, Univ. of Riverside, California, 1979b.

Scientific Party, Iceland Research Drilling Project, Crust of oceanic affinity in Iceland, edited by I.L. Gibson, Nature, 281, 347-351, 1979c.

Sigurdsson, H., The Icelandic basalt plateau and the question of sial, in: Iceland and Mid-Ocean Ridges, edited by S. Bjornsson, Soc. Sci. Isl., 30, 32-49, 1967.

Sigurdsson, H. and R.S.J. Sparks, Lateral Magma Flow within Rifted Icelandic Crust. Nature, 274, 126-130, 1978a.

Sigurdsson, H. and R.S.J. Sparks, Rifting Episode in North Iceland in 1874-1875 and the Eruptions of Askja and Sveinagja, Bull. Volcanol., 41, (3), 1978b.

Sparks, S.R.J., H. Sigurdsson, and L. Wilson, Magma mixing: a mechanism for triggering acid explosive eruptions, Nature, 267, 315-318, 1977.

Steiger, R.H., and E. Jaeger, Subcommission on geochronology: Convention on the uses of decay constants in geo- and cosmochronology, Earth Planet. Sci. Lett., 36, 359-362, 1977.

Steinthorsson, S., Tephra layers in a drill core from the Vatnajokull ice cap, Jokull, 27, 2-27, 1977.

Thorarinsson, S., Hekla and Katla. The share of acid and intermediate lava and thephra in the volcanic products through the geological history of Iceland, in: Iceland and Mid-Ocean Ridges, edited by S. Bjornsson, Soc. Sci. Isl., 30, 190-197, 1967.

Thorarinsson, S., Jardeldasvaedi a nutima (Postglacial volcanic regions in Iceland), In: Nattura Islands (in icelandic), second edition, Reykjavik, Almenna Bokafelagid, pp. 81-119, 1981.

Thorvaldur, Th., Geological map of Iceland, 1901.

Tryggvason, E., and M. Bath, Upper crustal structure of Iceland, J. Geophys. Res., 66, 1913-1925, 1961.

Tryggvason, Th., and D.E. White, Rhyolite tuffs in lower Tertiary plateau basalts of eastern Iceland, Am. J. Sci., 253, 26-38, 1955.

Walker, G.P.L., Excessive spreading axes and spreading rate in Iceland, Nature, 255, 468-470, 1975a.

Walker, G.P.L., Intrusive sheet swarms and the identity of crustal layer 3 in Iceland. J. Geol. Soc. Lond., 131, 143-161, 1975b.

Walker, G.P.L., The structure of eastern Iceland, in Geodynamics of Iceland and the North-Atlantic Area, edited by L. Kristjansson, pp. 177-188, Holland/U.S.A., 1974a.

Walker, G.P.L., Eruptive mechanisms in Iceland, in Geodynamics of Iceland and the North-Atlantic Area, edited by L. Kristjansson, pp. 189-201, Holland/U.S.A., 1974b.

Walker, G.P.L., Evidence of crustal drift from Icelandic geology, Philos. Trans. R. Soc. London, Ser. A, 258 199-204, 1965.

Walker, G.P.L., Geological investigations in eastern Iceland, Bull. Volcanol., 27, 351-366, 1964.

Walker, G.P.L., The Breiddalur central volcano, eastern Iceland, Q. J. Geol. Soc. London, 119, 23-63, 1963.

Walker, G.P.L., Tertiary welded tuffs in eastern Iceland, Q. J. Geol. Soc. London., 118, 275-293, 1962.

Walker, G.P.L., Zeolite zones and dyke distribution in relation to the structure of the basalts of eastern Iceland, J. Geol., 68, 515-528, 1960.

Walker, G.P.L., Geology of the Reydarfjordur area, eastern Iceland, Q. J. Geol. Soc. London., 114, 367-393, 1959.

Ward, P.L., New interpretation of the geology of Iceland, Geol. Soc. Am. Bull., 82, 2991-3012, 1971.

Watkins, N.D., and G.P.L. Walker, Magnetostratigraphy of eastern Iceland, Am. J. Sci., 277, 513-584, 1977. Holland/U.S.A. 1974.

Wilson, R.L., N.D. Watkins, Tr. Einarsson, Th. Sigurgeirsson, S.E. Haggerty, P.J. Smith, P. Dagley, and A.C. McCormack, Paleomagnetism of ten lava successions from southwestern Iceland, Geophys. J. R. Astron. Soc., 29, 459-471,1972.

Wood, D.A., Spatial and temporal variations in the trace element geochemistry of eastern Iceland flood basalt succession, J. Geophys. Res., 81, 4353-4360, 1976.

York, D., Least squares fitting of a straight line with correlated errors, Earth and Planet. Sci. Lett., 5, 320-324, 1969.

Appendix 1

Previous K-Ar age determinations from the Reydarfjordur area (from McDougall and others, 1976).

Sample No.	Radiometric Ar40/Tot.Ar40 x 100	Radiometric 40Ar mol/g 10^{-12}	K2O Wt%	Age m.y. ± 1 sd	Mean Age m.y. ± 1 sd
EF25	29.1	7.225	0.4643	8.96 +0.12	9.05 +0.13
	30.0	7.383	0.4634	9.16 +0.13	
EF22	75.6	5.824	0.3525	9.47 +0.11	9.53 +0.11
	75.5	5.900	0.3545	9.60 +0.12	
EF16	72.3	9.470	0.5629	9.66 +0.12	9.74 +0.12
	74.8	9.645	0.5651	9.83 +0.12	
EF9	79.8	7.836	0.4549	9.94 +0.12	9.99 +0.10
	63.1	7.913	0.4514	10.04 +0.12	
EF2	39.5	3.036	0.1797	9.66 +0.16	9.63 +0.14
	38.4	3.023	0.1819	9.61 +0.12	
EF22A	37.3	5.158	0.2982	9.95 +0.13	9.89 +0.13
	30.2	5.091	0.2972	9.83 +0.12	
ED45	53.6	3.964	0.2146	10.58 +0.13	10.53 +0.13
	43.0	3.925	0.2161	10.48 +0.13	

* Ages corrected for recent decay constants (after Steiger and Jaeger, 1977).

Appendix 1 (continued)

Ar/Ar datings for lavas surrounding the Reydarfjordur area of eastern Iceland (from Ross and Musset, 1976).

Sample No.	No. of plateau steps	%39Ar on plateau	Mean age I Ma	Mean age II Ma
L33C-1	5	92	8.1	8.19 +0.72
K36A-2	5	86	9.6	9.58 +0.41
K36A-2	6	91	10.2	10.11 +0.27
K36A-1	5	87	10.2	10.18 +0.22
K9-1	4	77	11.6	11.79 +0.40
E14-2	5	55	9.8	9.77 +0.33
E14-2	7	80	12.0	12.30 +0.79
B19-1	6	95	11.6	11.98 +0.78
B19-1	4	80	13.2	13.19 +0.10
G21-1	4	75	12.9	12.92 +0.14

Age-I : Weighted by % 39Ar released in each plateau step.
Age-II: Total argon age, weighted by inverse of variance of each step age.

Appendix 2

Petrographic descriptions of dated samples (K-Ar)

Lavas:

EFJ10A. Eskifjordur, at sea-level on northern side of Holmatindur. Microporphyritic non-vesicular olivine basalt with phenocrysts of olivine, plagioclase (laths about 0.1 mm in width), magnetite and rate pyroxene. Plagioclase laths have fluxion texture. The olivine is altered to clay along edges and fractures whereas other microphenocryst phases are fresh. The groundmass consists of magnetite, pyroxene and some glass (<<1%) that is altered to transparent light green chlorite.

EFJ11. Eskifjordur, sampled from the next lava above EF10A. This sample differs from EF10A in being finer grained and containing a much smaller amount of microphenocrysts. No vesicles present.

Band1. Reydarfjordur by sea-level at Teigargerdisklopp. Very fine grained (basaltic andesite, SiO2 is 58-60%) with rare microphenocrysts of plagioclase and pyroxene. Mesostasis is cryptocrystalline with plagioclase, pyroxene and magnetite that constitute a flow texture. No vesicles present.

RF76. Holmatindur, aphyric tholeiite basalt, fine grained with some 2-3% segregated devitrified glass of colloform texture. Groundmass consists of fresh plagioclase pyroxene and magnetite.

KOP-1. Skagafell, north side. Collected from the base of a lava unit in the Kollur porphyritic formation. The upper part is highly plagioclase porphyritic whereas the base is essentially aphyric. This sample has 10-20% glass in mesostasis that is altered to chlorite. Crystalline phases of the groundmass are plagioclase, pyroxene and magnetite-ilmenite that in places is rimmed with translucent haloes of hematite.

RH948. Trollafjall, andesite from Thingmuli volcanic center. Has microphenocrysts of plagioclase (corroded), pyroxene, and magnetite. Mesostasis consists of plagioclase, pyroxene, magnetite and fresh glass, perhaps 10%.

RH957. Trollafjall, basaltic andesite, fine grained aphyric with irregular patches of green devitrified glass (transparent). Mesostasis consists of plagioclase, pyroxene, and magnetite in addition to scarce, 2-4%, fresh glass.

Dykes:

SL8. Basaltic dyke unit from Slettustrond on south side of Reydarfjordur. Coarse grained, aphyric with plagioclase feldspar and pyroxene in an ophitic textural relationship, titanomagnetite and two kinds of glass: (a) some 6-8% glass, either fresh or devitrified embedded with microlites, (b) about 1% devitrified segregated colloform glass.

SL9. Nonvesicular basalt dyke intrusion. South side of Reydarfjordur on Slettustrond by sea-level. Thin section is heterogeneous and crystallization proceeded either rapidly or slowly. This is clear from fine grained cryptocrystalline mesostasis that forms one half of the thin section as opposed to the other half that consists of coarse grained plagioclase, pyroxene, magnetite and some 2% partly devitrified glass.

Dykel. Very fine grained basaltic unit with some 10% microphenocrysts of plagioclase laths, pyroxene and magnetite embedded in a cryptocrystalline mesostasis with plagioclase, pyroxene, magnetite and minor amounts of fresh glass.

RG3. Graenafell pilot dyke section. Aphyric, fine grained, tholeiite basalt dyke intrusion. Mesostasis consists of plagioclase laths, pyroxene and magnetite in a diabasic textural relationship. Undevitrified glass constitutes some 2-4% of the mesostasis. Segregated specs of glass(<<1%)are altered to green chlorite. Nonvesicular unit.

RG6B. Sampled from the Graenafell dyke section. Medium grained, aphyric, non-vesicular basalt dyke intrusive. Groundmass consists of plagioclase, pyroxene and magnetite in an ophitic textural relationship. Some 10% glass present as fresh intersertal material embedded with opaque microlites and rare (<<1%) segregated glass, altered to chlorite (light green) and chlorophaeite (light brown).

RG30. Graenafell dyke section. Fine grained aphyric non-vesicular tholeiite. Mesostasis consists of plagioclase, pyroxene and magnetite and some 5% partly devitrified glass embedded with minute opaque material.

RH947. Trollafjall cliff section in western Reydarfjordur. Fine grained aphyric tholeiite basalt sill. Mesostasis made up of plagioclase, pyroxene, magnetite and small amount (< 1%) partly devitrified interstitial glass. Segregated colloform glass (about 1%) devitrified to chlorite. Rare spherical vesicles lined with devitrified glass.

ARD. Areydjardalur, western Reydarfjordur. Medium grained aphyric tholeiite basalt dyke intrusive. Plagioclase, pyroxene and magnetite in an ophititc textural relationship. Also some 15% partly crystallized and partly devitrified glass, which, where segregated, is slightly altered to greenish chlorite (<<1%). Nonvesicular unit.

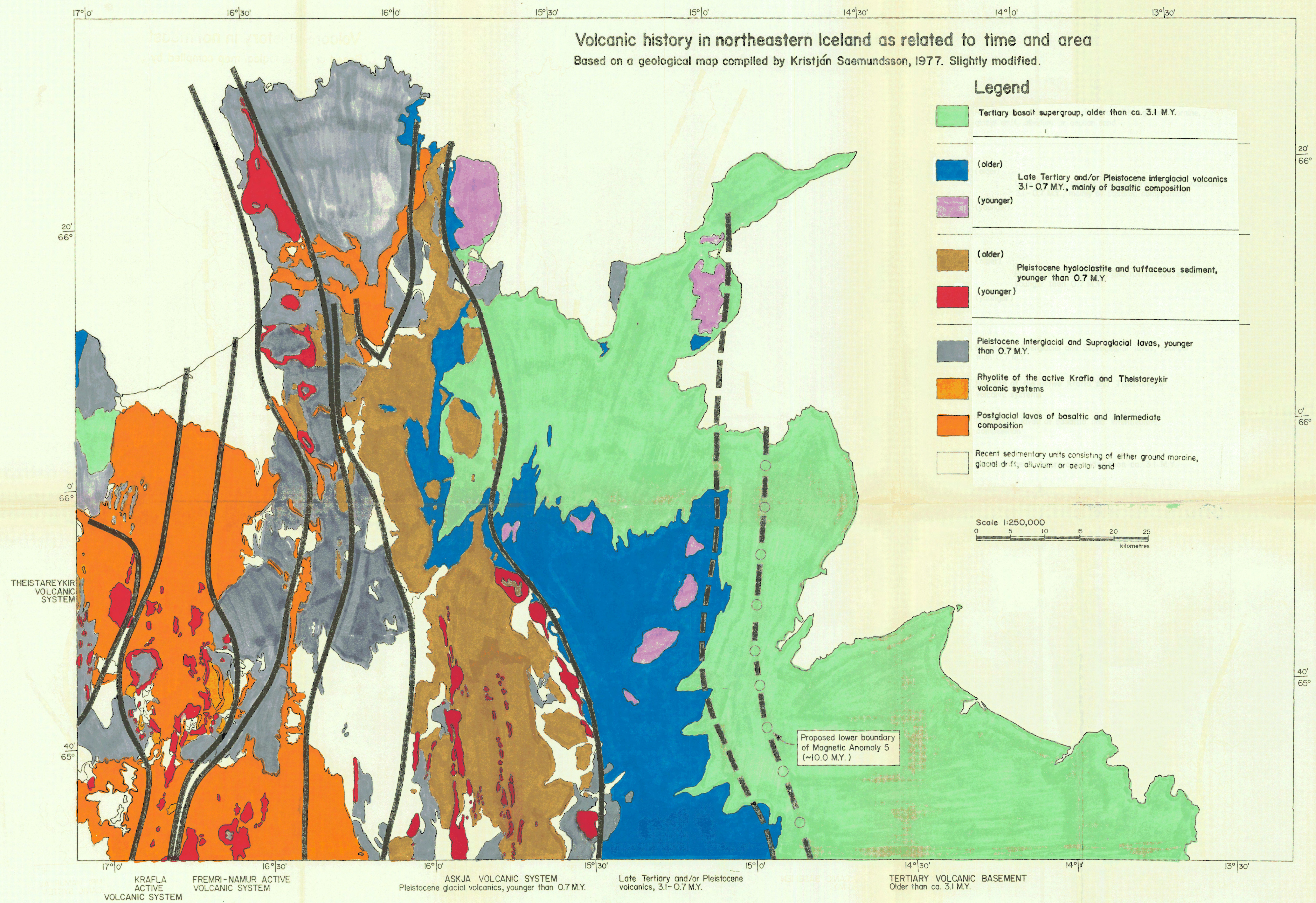
80-6. Areyjardalur, western Reydarfjordur. Aphyric medium grained basalt dyke intrusive. Mesostasis contains plagioclase, pyroxene and magnetite in an ophitic textural relationship. The remainder of the mesostasis is glass, either partly devitrified with opaque microlites (about 5%) or segregated clear glass that is altered to chlorite or chlorophaeite (< 1%).

MAP I.

GEOLOGICAL MAP OF THE AREA SURROUNDING THE I.R.D.P. DRILL SITE, EASTERN ICELAND
(MODIFIED AFTER WALKER, 1959)

MAP II.

MAPPED DYKES IN SELECTED TRAVERSES SURROUNDING THE I.R.D.P. DRILL SITE, REYÐARFJÖRÐUR, EASTERN ICELAND


Volcanic history in northeastern Iceland as related to time and area
Based on a geological map compiled by Kristján Saemundsson, 1977. Slightly modified.
Legend
Tertiary basalt supergroup, older than ca. 3.1 M.Y.
(older)
Late Tertiary and/or Pleistocene interglacial volcanics 3.1 - 0.7 M.Y., mainly of basaltic composition
(younger)
(older)
Pleistocene hyaloclastite and tuffaceous sediment, younger than 0.7 M.Y.
(younger)
Pleistocene Interglacial and Supraglacial lavas, younger than 0.7 M.Y.
Rhyolite of the active Krafla and Theistareykir volcanic systems
Postglacial lavas of basaltic and intermediate composition
Recent sedimentary units consisting of either ground moraine, glacial drift, alluvium or aeolian sand
Scale 1:250,000
0 5 10 15 20 25
kilometres
Proposed lower boundary of Magnetic Anomaly 5 (~10.0 M.Y.)
THEISTAREYKIR VOLCANIC SYSTEM
KRAFLA ACTIVE VOLCANIC SYSTEM
FREMRI-NAMUR ACTIVE VOLCANIC SYSTEM
ASKJA VOLCANIC SYSTEM
Pleistocene glacial volcanics, younger than 0.7 M.Y.
Late Tertiary and/or Pleistocene volcanics, 3.1- 0.7 M.Y.
TERTIARY VOLCANIC BASEMENT
Older than ca. 3.1 M.Y.
17°0'
16°30'
16°0'
15°30'
15°0'
14°30'
14°0'
13°30'
66° 20'
66° 0'
65° 40'

PROFILE I. STRATIGRAPHIC TRAVERSES INTO THE CLIFF SECTION ON THE NORTH SIDE OF REYDARFJORDUR

PROFILE II. **STRATIGRAPHIC TRAVERSES INTO THE CLIFF SECTION ON THE SOUTH SIDE OF REYDARFJORDUR**

PROFILE III.

TROLLAFJALL SECTION (RH)