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The Iceland Research Drilling Project: Synthesis of Results and Implications for the Nature of Icelandic and Oceanic Crust

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Study of a 3-km-thick section of Tertiary basalts in eastern Iceland has resulted in the formulation of a model for crustal construction based on accumulation of lava flows on the flanks of large central volcanoes and has led to the development of alteration and physical property profiles in a crustal segment formed at the Mid-Atlantic Ridge. Deep drilling at Reydarfjordur revealed the existence of subaerial lava flows and volcaniclastic rocks to a crustal depth of 3.5 km. Three major stratigraphic units composed largely of basalts are recognized, each characterized by distinctive major and trace element patterns. Each of these units is believed to be the product of a separate episode of mantle melting and fractionation and probably reflects accumulation on the flanks of a central volcano. Extensive fractionation in shallow magma chambers led to intermediate and silicic lavas, which mark the cores of the central volcanic complexes. Dike density does not increase downward below about 1.5-km crustal depth, and the sampled dikes appear to have been intruded laterally along rifts on the flanks of the central volcanoes. Secondary mineral assemblages are dominated by smectite and zeolites near the top of the section and by epidote and quartz near the base. In general, the temperature of alteration increases downward, but the distribution of individual minerals is irregular. Locally, earlier secondary mineral assemblages are overprinted by contact metamorphism along dike margins. The upper surface of greenschist facies metamorphism crops out at the surface in Thingmuli volcano but it lies at an estimated crustal depth of about 4 km in the Reydarfjordur borehole, located only 3 km east of the edge of Thingmuli. Thus, the metamorphic zones clearly crosscut the lava stratigraphy. Physical property profiles correlate well with variations in secondary mineralogy, and the top of layer 3 velocities corresponds closely with the projected upper boundary of amphibolite facies rocks at about 6 km crustal depth. Magnetic susceptibility decreases with depth and is extrapolated to zero at about 4.3-km crustal depth close to the estimated upper limit of greenschist facies metabasalts. A much greater crustal thickness, leading to the emplacement of high level magma chambers within the extrusive part of the crust, is thought to account for many of the differences in crustal structure and evolution between Iceland and the rest of the Mid-Atlantic Ridge.

INTRODUCTION

The Iceland Research Drilling Project was undertaken in 1978 in order to understand better the structure and origin of a crustal segment formed at a constructive plate boundary. Ocean crustal drilling by the Deep Sea Drilling Project had provided much new data on the upper 600 m of basement in the North Atlantic, but it appeared unlikely that lower crustal layers could be sampled by drilling at sea in the near future. Although an anomalous section of ocean crust, Iceland is the only in situ segment of the Mid-Atlantic Ridge that is subaerially exposed. It was anticipated that a detailed study of the upper 3 km of Icelandic crust would shed light on the processes of crustal construction, hydrothermal circulation, and magma evolution taking place elsewhere along submarine sections of the ridge.

A drill site was selected near Reydarfjordur in the Tertiary lava section of eastern Iceland where a 1-km-thick section is exposed in the fjord walls. The geology of the area in relation to the borehole is summarized by *Fridleifsson* [this issue] and *Helgason and Zentilli* [this issue]. In the Reydarfjordur area, the exposed section consists of well-stratified basalt flows interlayered with minor volcaniclastic material. The sequence dips from 2° to 12° westward, toward the present spreading axis, and stratigraphic sequences generally thin updip, suggesting that subsidence took place during crustal construction [*Walker*, 1960; *Palmason*, 1973, 1980]. Three central volcanic complexes, Thingmuli, Reydarfjordur, and Breiddalur, occur in the area (Figure 1), each being characterized by an abundance of silicic lavas and a marked hydrothermal aureole [*Walker*, 1959, 1963; *Carmichael*, 1964]. North to northeast trending dike swarms are focussed on these volcanic centers.

The drill site is located at the head of Reydarfjordur about 3 km east of the edge of Thingmuli in a dike swarm related spatially and compositionally to the Breiddalur center (Figure 1). Seismic refraction studies by *Palmason* [1971] on the west side of Thingmuli volcano suggested that the seismic layer 2-layer 3 boundary at the drill site might be within about 2.5 to 3.0 km of the surface.

The main objectives of the drilling project were (1) to determine the lithology, structure, composition, and alteration history of the section in order to understand better crustal construction processes in Iceland, (2) to determine physical property and logging profiles through the crust for comparison with variations in lithology and alteration intensity determined in the drill core and with seismic refraction profiles (it was considered unlikely that the drill hole would penetrate the

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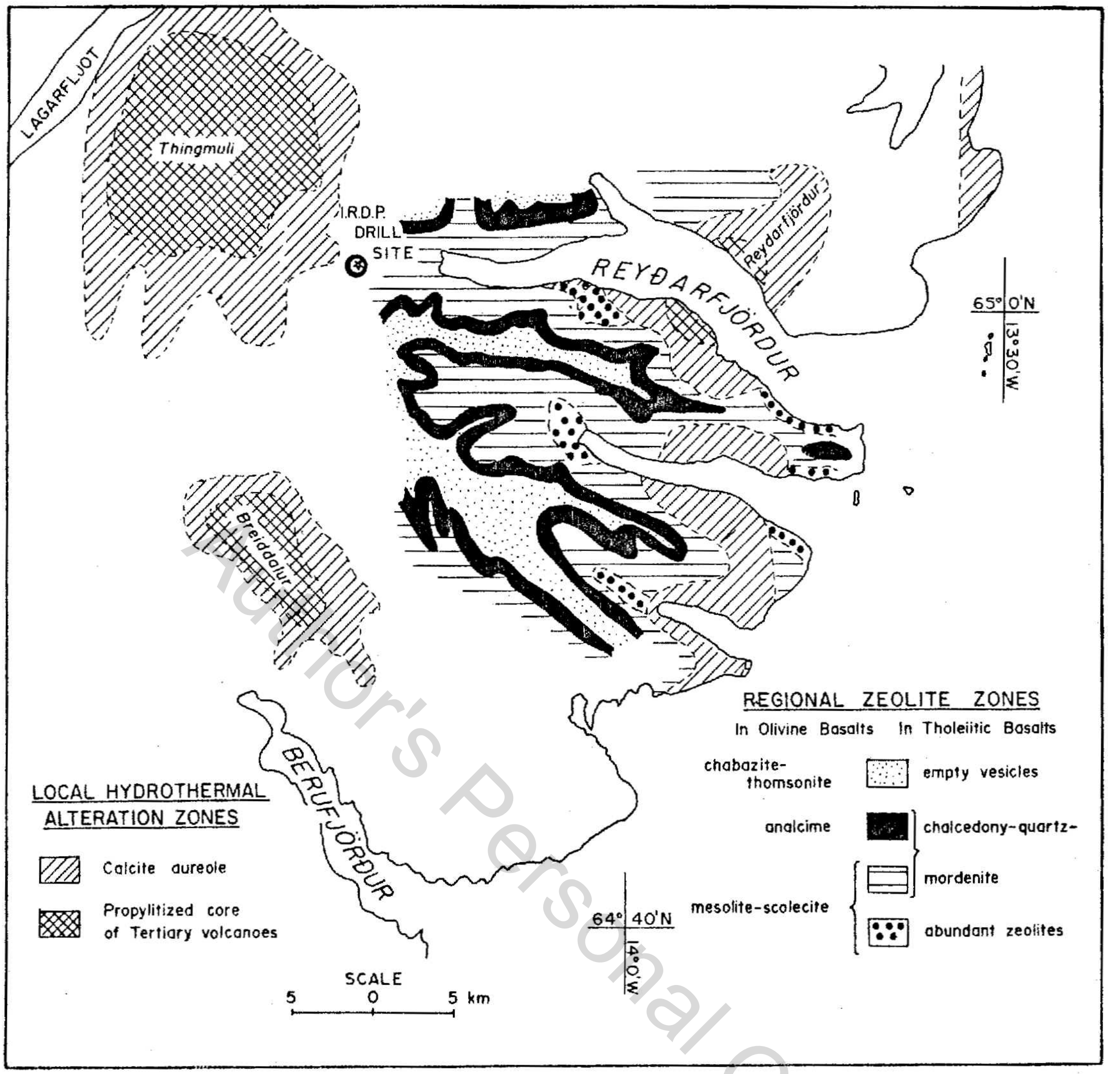

Fig. 1. Index map of the Reydarfjordur area, eastern Iceland, showing regional zeolite zones and locations of central volcanic complexes.

layer 2-layer 3 boundary, but it was expected to give information on crustal properties that would shed some light on the nature of this transition) and (3) to study the nature of a localized heat flow anomaly in the Reydarfjordur area.

Most of these goals have been realized. The borehole penetrated 1919 m into the crust with 99.7% core recovery. The drill core, coupled with samples from the exposed section above the borehole, provides a nearly complete section of the upper 3 km of Icelandic crust. Following *Walker* [1960], we estimate that about 0.5 km of material has been eroded from the top of the lava pile so that the sampled section extends from about 0.5 to 3.5 km in the original crust. In this paper, crustal depth refers to the depth below this original surface.

Numerous studies on these samples have produced a wealth of new data on the nature and origin of Icelandic crust. In this paper, we summarize what we consider to be the most significant results and discuss the application of these findings to Icelandic crust and to ocean crust formed elsewhere along the Mid-Atlantic Ridge.

Significant Results

We view the following to be the major results:

1. The development of a model for crustal construction in eastern Iceland based on the recognition of large scale stratigraphic units in the lava pile having distinctive lithologic and geochemical characteristics, the absence of a downward increase in dike density in the upper 3.5 km of the crust, and the documentation of large scale subsidence of the crust [*Palmason*, 1973, 1980], as indicated by the presence of subaerial lava flows nearly 2 km below sea level. The proposed model suggests accumulation of the lava flows on the flanks of elongate central volcanoes, the cores of which are marked by silicic complexes

2. The sampling of a hydrothermally altered segment of basaltic crust, providing clues to the nature of hydrothermal circulation beneath Iceland and the effects of such alteration on the physical properties and composition of the crust.

3. The establishment of physical property profiles through the crust from downhole logging and sample measurements. The variations in physical properties can be correlated with downhole variations in lithology and alteration mineralogy and with in situ seismic profiles providing predictive models for Icelandic and deep ocean crust.

Crustal Construction Models

All of the sampled basalts in the Reydarfjordur area are chemically evolved and consist largely of low magnesia basalt and ferrobasalt. Within the sampled section, three major geochemical units are recognized on the basis of major and incompatible trace element compositions [*Flower et al.*, this issue; *Gibson et al.*, this issue]. A basal sequence consisting of relatively primitive basalts with low Zr and Sr and high Cr and Ni contents extends from the base of the drill hole to about 1300 m. Interlayered volcaniclastic layers are sparse and are chiefly basaltic in composition [*Schmincke et al.*, this issue]. This sequence is overlain by a 700-m-thick section composed of more fractionated lavas with higher Zr and Sr and lower Cr and Ni contents extending from about 1300 to 600 m in the borehole. The lava flows in this sequence have a much wider range of chemical composition than those of the basal unit. Volcaniclastic units are common only in the lower half of this sequence where both basaltic and relatively thick felsic units are present. The upper 600 m of the borehole and all of the exposed section again comprise more primitive lavas and contain few volcaniclastic units except in the interval between 286 and 410 m in the core [*Schmincke et al.*, this issue].

The drill site is located in a northeast trending dike swarm focussed on the Breiddalur volcanic center. Dike intensity increases with depth in the exposed section to a sea level value of about 10% dilation, and all previous models of Icelandic crust postulated either a linear or more rapid than linear increase in dike density with depth below sea level [*Bodvarsson and Walker*, 1964; *Gibson and Piper*, 1972]. Dike rocks constitute about 41% of the cored material in the Reydarfjordur borehole, but there is no observable downward increase in dike density to a crustal depth of 3.5-km [*Robinson et al.*, this issue]. In the exposed section, some dikes are observed to terminate downward [*Helgason and Zentilli*, this issue]. The sampled dikes in both the drill hole and exposed section are related compositionally only to the upper lava group and appear to have been intruded after the first phase of alteration in the lava pile [*Mehegan et al.*, this issue]. A critical evaluation of the lithologies, thicknesses, and areal extents of individual lava flows indicates that they are distinct from 'flood' or 'plateau' basalts of the Columbia River type but resemble shield basalts of many ocean islands [*Robinson et al.*, this issue].

The above observations suggest that crustal sections in eastern Iceland comprise a series of elongate central volcanoes, each characterized by a broad basaltic apron and a central silicic complex. Several such central volcanic complexes are presently exposed in eastern Iceland (Thingmuli, Breiddalur, and Reydarfjordur), and others are believed to be buried in the lava pile. Similar central volcanoes are also common features in the present day rift zone of Iceland [*Saemundsson*, 1978; *Jakobsson*, 1979], where they are the loci of active volcanism. Here, the fissure swarms and central volcanoes form systems commonly 50 to 100 km long and 10 to 30 km wide.

Each of the macrogeochemical groups in the sampled section at Reydarfjordur [*Gibson et al.*, this issue] is interpreted as the product of one or more of these central volcanoes. The uppermost group is believed to be compositionally related to the Breiddalur and Thingmuli centers. The middle group is compositionally diverse and contains locally abundant felsic volcaniclastic units. These lavas were probably derived from a differentiated central volcanic complex now buried downdip in the lava pile perhaps within 10 km of the drill site [*Schmincke et al.*, this issue]. We interpret the lowest group as part of a volcano that produced relatively primitive basalt flows with little explosive activity. The lavas could have been derived from a fissure system without a distinct volcanic edifice, or they could have accumulated on the flanks of a broad shield. Each of the lava groups is believed to represent outpourings from separate volcanoes rather than multiple pulses from a single source because their distinctive incompatible trace element ratios suggest different mantle sources. [*Gibson et al.*, this issue].

The dikes were emplaced relatively late into the crust and are geochemically unrelated to the lower and middle lava groups in the borehole. On the basis of their relative age, composition, orientation, and lack of downward increase, we postulate that they were intruded laterally along a major rift zone through the Breiddalur volcanic complex [*Gibson*, 1979; *Robinson et al.*, this issue; *Helgason and Zentilli*, this issue]. Such lateral dike emplacement has been demonstrated at Krafla volcano in the present-day rift zone of Iceland [*Bjornsson et al.*, 1979; *Einarsson and Brandsdottir*, 1980], and an analagous process takes place in the East Rift zone of Kilauea volcano in Hawaii [*Swanson et al.*, 1976].

Large scale subsidence of the lava pile in eastern Iceland is clearly demonstrated by the presence of subaerial lava flows 2 km below sea level. Updip thinning of stratigraphic sequences (Figure 2) suggests that much of the subsidence took place during crustal construction [*Palmason*, 1973, 1980]. However, some of the observed thinning could be related to accumulation on the flanks of broad central volcanoes.

We believe that the proposed crustal construction model for eastern Iceland is a function of the crustal thickness, which in turn must be related to the high magma productivity of the Icelandic section of the Mid-Atlantic Ridge. The thick extrusive section in Iceland must inhibit the uprise and eruption of new mantle melts leading to increased opportunities for crystal fractionation in relatively shallow magma chambers. Each major magmatic episode appears to be relatively long-lived, leading to development of thick eruptive piles with characteristic trace element patterns and well-defined dike swarms localized about discrete volcanic centers. In the Quaternary and late Tertiary strata flanking the active volcanic zone of southwest Iceland, similar volcanic systems have persisted from a few hundred thousand to over 2 m.y. [*Fridleifsson*, 1973; *Johannesson*, 1975; *Saemundsson*, 1979]. These major episodes are probably initiated by, or are the result of, jumps in the focus of activity within the spreading axis, with consequent tapping of a different portion or level of mantle material. The scale of these jumps and the time intervals separating them appear to be much larger than comparable features recognized elsewhere along the Mid-Atlantic Ridge.

Extensive crystal fractionation in subvolcanic magma chambers leads to formation of silicic and intermediate magmas [*Carmichael*, 1964; *Wood*, 1978; *Jakobsson*, 1979], which are erupted in the central parts of the volcanoes. Our model predicts that gabbroic rocks should constitute a significant portion of the lower Icelandic crust, and this interpretation is supported by the distribution of large basaltic intrusions in deeply eroded parts of the country [*Fridleifsson*, 1977]. The level at which such gabbroic rocks occur probably varies from place to place. The presence of calderas associated with some active volcanoes in the present-day rift zone and with many of the deeply eroded volcanic centers suggests that magma chambers here occur at a high level, sometimes within 2 km of the surface [*Fridleifsson*, 1977]. Subsidence associated with spreading would carry the solidified portions of such chambers to deeper levels and allow them to be buried beneath later flows to depths of 4 km or more, based on the

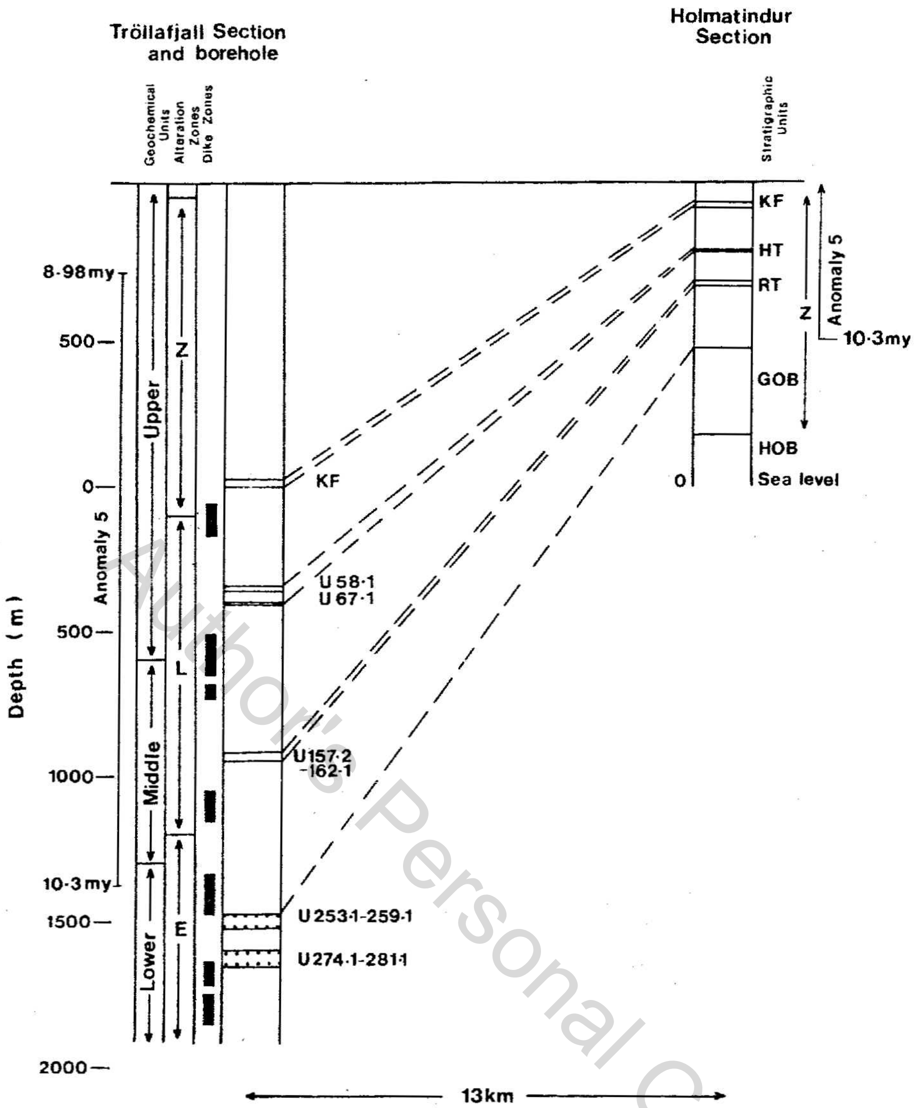

Fig. 2. Correlation of Reydarfjordur borehole section with exposed section at Holmatindur about 13 km to the east (modified after *Helgason and Zentilli* [this issue]). Drilled section divided into upper, middle, and lower geochemical units based largely on trace element data [*Gibson et al.*, this issue]. Alteration zones are Z, zeolite; L, laumontite; E, epidote. Zones of greatest dike density are shown by solid bars. Proposed correlations are based on similarities in lava compositions, major pyroclastic units and paleomagnetic characteristics [see *Helgason and Zentilli*, this issue]. (KF, Kollur Formation; HT, Holmatindur tuff; RT, Reydarfjordur tuff; GOB, Grjota olivine basalt; HOB, Holmar olivine basalt; U58-1 to U281.1, units in the IRDP drill hole).

Reydarfjordur drill hole. However, shallower bodies may underlie some of the central volcanic complexes in eastern Iceland such as Thingmuli, Reydarfjordur, and Breiddalur.

The time span over which the Reydarfjordur crustal section was constructed is difficult to constrain because most of the drilled rocks are too altered to yield reliable K-Ar dates. From K-Ar dating of relatively fresh lava flows from the exposed section, *Watkins and Walker* [1977] estimated an age span from about 13 to 2 m.y. B.P. for the construction of the entire 9-km-thick lava pile in eastern Iceland. The oldest rocks exposed in the Reydarfjordur area have K-Ar dates of 12.4 to 13.0 m.y. [*Moorbath et al.*, 1968; *McDougall et al.*, 1976], but these are stratigraphically well below the base of the drill hole. Based on the stratigraphic relationships proposed in Figure 2, the base of a normally magnetized interval correlated with magnetic anomaly 5 lies about 400 m above the bottom of the drill hole. This datum has an age of about 10.3 m.y. [*McDougall et al.*, 1976] applying the most recent decay constants [*Steiger and Jager*, 1977]. The Kollur porphyritic group lies just above the top of the drill hole and has an age of about 9.5 m.y. [*Helgason*, this issue; *Watkins and Walker*, 1977].

The Reydarfjordur volcanic center lies just below the base of the section correlated with magnetic anomaly 5; hence it is somewhat older than 10.3 m.y. The oldest exposed rocks at the Breiddalur volcanic center are about 9.0 m.y. but activity is believed to have started here as early as 10.3 m.y. B.P. [*Helgason*, this issue]. Field relationships suggest that activity at the Thingmuli center overlapped with the late stages of activity at Breiddalur and probably continued to about 8.5 m.y. B.P. Based on work in progress, the dike swarm penetrated by the Reydarfjordur drill hole, which is related to the Breiddalur center, is about 9.0 m.y. old. [*Helgason and Zentilli*, this issue].

On the basis of dike distribution, location of eruptive centers, and characteristics of the lava flows, *Helgason and Zentilli* [this issue] postulate a westward shift of volcanic activity, at about 10.3 m.y. B.P., from the Reydarfjordur volcanic center to a new rift zone along which the Breiddalur and Thingmuli centers were later constructed.

Hydrothermal Alteration

One of the major reason for undertaking deep drilling in Iceland was to understand better the hydrothermal processes associated with spreading ridges and to determine the effects of alteration on the physical and magnetic properties of the crust. In the present-day rift zone of Iceland, active high-temperature hydrothermal systems are usually associated with central volcanoes, whereas elsewhere there are regional low-grade zeolite zones of alteration with localized high-temperature alteration aureoles associated with extinct central volcanoes [*Palmason et al.*, 1979]. By siting the Reydarfjordur drill hole about 3 km east of the edge of Thingmuli volcano it was hoped to sample both the regional zeolite zones and the hydrothermal system associated with that volcanic complex.

In the exposed section at Reydarfjordur and the upper 100 m of the drill core (to 1.6-km crustal depth), alteration is restricted to the formation of low temperature zeolites, locally accompanied by calcite, quartz, and smectite. Between 100 and 1200 m in the borehole (1.6- to 2.8-km crustal depth), mineral assemblages are dominated by laumontite, chlorite, calcite, and quartz with minor epidote and prehnite in the lower parts. Starting at about 1200 m and extending to the base of the core (2.8- to 3.5-km crustal depth), a higher temperature mineral assemblage composed of abundant epidote, quartz, prehnite, chlorite, and albite prevails. Small amounts of wairakite, pumpellyite, and actinolite are also found in the lower parts of this zone [*Mehegan et al.*, this issue; *Kristmannsdottir*, this issue; *Viereck et al.*, this issue].

A maximum paleotemperature of 100°-120°C is estimated for the upper zeolite zone. In the interval between 100 and 1200 m in the borehole, maximum temperatures of about 230°C were probably reached at the level where epidote becomes abundant [*Palmason et al.*, 1979]. Based on the secondary mineral assemblages, fluid inclusion measurements, and oxygen isotopic data, a maximum bottomhole paleotemperature of about 300°C is estimated [*Mehegan et al.*, this issue; *Hattori and Muehlenbachs*, this issue]. These data suggest an average paleogeothermal gradient of 80°-90°C km^{-1} for the upper 3.5 km of crust. This is significantly higher than the present-day gradients in the regional low temperature geothermal fields, suggesting that the Reydarfjordur borehole is located on the flanks of the ancient high temperature field associated with Thingmuli volcano.

The percent of secondary minerals and the temperature of alteration generally increase with depth, although there are many local fluctuations due to differences in permeability of the lava flows and clastic interbeds and the effects of contact metamorphism adjacent to the dikes. In the lava flows the most complete recrystallization is always in the flow top breccias, and the massive flow centers are often relatively fresh. The dikes are always significantly less altered than the lava flows they cut. This is, in part, due to the massive, impermeable nature of most dikes but probably also reflects emplacement of the dikes after the major stage of alteration in the flows. Contact metamorphism, represented by the formation of andradite garnet, appears to be superimposed on preexisting secondary mineral assemblages [*Mehegan et al.*, this issue].

Following *Mehegan et al.* [this issue], we conclude that the alteration encountered in the Reydarfjordur borehole represents a fossil geothermal system associated with the rift axis along which the Thingmuli volcanic center developed rather than regional, low-grade burial metamorphism. This conclusion is based on the high paleogeothermal gradient, the occurrence of epidote at shallow levels in the crust, and the evidence for passage of large volumes of hot water through the system. Little is known regarding the transition of zeolite zones into deeper high-temperature zones in eastern Iceland because the level of erosion does not extend below the mesolite-scolecite zone. However, drilling in the Tertiary section of northern Iceland also suggests a downward transition from low-temperature zeolite zones into a laumontite zone followed by an epidote zone [*Palmason et al.*, 1979], similar to that observed in the Reydarfjordur borehole. The depth to the epidote isograd in a segment of Icelandic crust appears to be dependent on the proximity of a central volcano, and therefore the depth to this and deeper facies mineral assemblages in Iceland is likely to be highly variable. In most cases, however, the secondary mineral zones appear to cut across the dipping lava flows (Figure 2).

Depth Variations of Physical Properties

Many studies of physical properties reported in this volume find that significant variations with depth occur. Some trends can be related to changes in the original constitution of the crust [*Gibson et al.*, this issue; *Flower et al.*, this issue], whereas others can be related to the relatively continuous increase of secondary alteration with depth [*Mehegan et al.*, this issue; *Viereck et al.*, this issue]. Although no overall change in the ratio of extrusives to intrusives occurs below 1.5-km crustal depth, the lava flows fall into three compositional groups of which the middle group, extending from about 800 to 1300 m below sea level, is relatively evolved geochemically. The increase in secondary alteration with depth is regular and well defined, and using the observed alteration sequence, it is possible to estimate the depth beneath the bottom of the drill hole at which higher-grade metamorphic zones may occur. If physical properties can be estimated for the rocks of these deeper zones, it will be possible to test extrapolations of trends in observed physical properties and perhaps constrain the interpretation of crustal divisions identified from seismic results.

Secondary alteration in the section involves a wide range of mineral species and mineral compositions [*Mehegan et al.*, this issue; *Viereck et al.*, this issue]. To interpret physical properties in terms of secondary mineralization, it is necessary to identify the onset of facies which lead to significant changes in the physical properties of the rocks. It is also valuable to estimate the maximum temperatures reached during alteration, particularly in order to estimate the depth at which higher-grade metamorphic zones are likely to occur. The section at the left-hand side of Figure 3 shows the depth at which significant mineralogical changes occur, and the adjacent temperature profile is based on the temperature of occurrence of these minerals in geothermal wells in Iceland where the phases are in equilibrium with the present physical

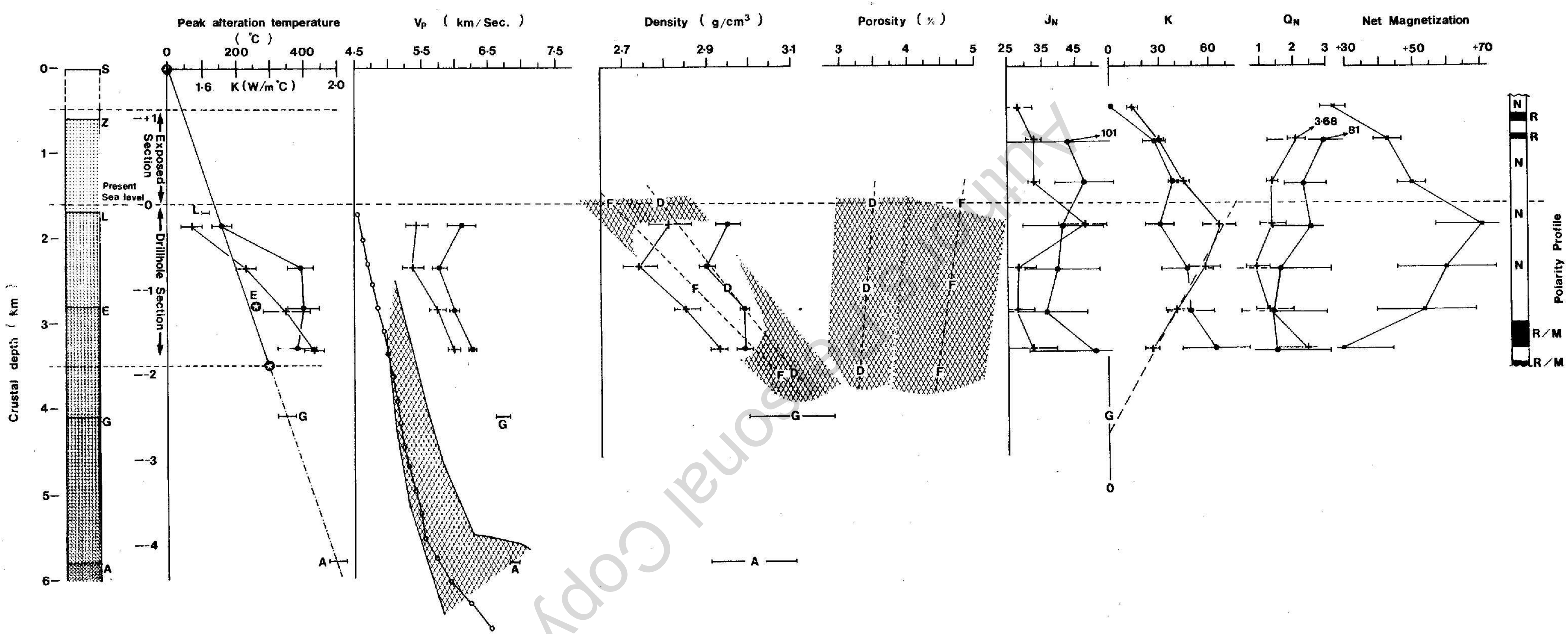

Fig. 3. Variation of secondary alteration, maximum alteration temperature and physical properties with depth in the IRDP crustal section with extrapolations below the base of the section: See text for sources of information. O, temperature; crosses and circles, 500-m-depth interval average values for lavas and dikes, respectively; dashed lines, linear regression trend ±1 s.d. for observed values (F, flows; D, dikes); dot-dash lines, extrapolation of trend below base of section; S, original surface of crustal section (estimated); Z, onset of well developed zeolite facies metamorphism; L, first occurrence of abundant laumontite; E, first occurrence of abundant epidote; G, first occurrence of well-developed greenschist facies metamorphic mineral assemblage (estimated); K, thermal conductivity; J_N, natural remnant magnetisation; K_N, initial susceptability; Q_N, ratio of remanent to induced magnetisation.

TABLE 1. Estimated Physical Properties of Greenschist and Amphibolite Facies Metabasalts

Rock Type	Mineralogical[a] Composition	V_p, km s^{-1}	Density[c], g cm^{-3}	J_N	K	Q_N
Greenschist facies metabasalt	actinolite (0.40), albite (0.25), epidote (0.25), chlorite (0.10)	6-6.8[b]	3.1 (3.0-3.2)	0.1×10^{-4} [d]	0.5×10^{-4} [d]	0.3[d]
Amphibolite facies metabasalt	hornblende (0.55), oligoclase (0.35), quartz (0.05), sphene (0.025), ilmenite (0.025)	6.8-6.9	3.0 (2.9-3.1)		no data	

[a] *Miyashiro* [1973].
[b] *Christensen* [1970].
[c] Mineral densities from Deer et al. [1966]. Values in parentheses corresponds to range of mineral proportions.
[d] From Fox and Opdyke [1973], samples V25-D5-5/10/36, V25-D6-36/71, V25-D9-9/10.

and chemical environments (see previous section of this paper, *Kristmannsdottir* [1975, 1978], and *Palmason et al.* [1979]). Although the temperature-depth profile is likely to have shown local departures from linearity during hydrothermal alteration, it is clear that a broadly linear increase with depth of 80° to 90°C km s^{-1} is indicated by the data. Using the extrapolated temperatures, it is possible to estimate from the known stability fields of metamorphic facies [*Miyashiro*, 1973] that the onset of the greenschist facies will occur at about 4-km crustal depth and that the onset of the amphibolite facies will occur at about 6-km crustal depth. For the purpose of estimating physical properties, approximate mineral proportions and amounts for typical metabasalts are set out in Table 1, together with expected physical properties for these rocks.

Bulk Properties

Measurements of thermal conductivity on 110 samples of flows, dikes, breccias, sediments, and an ignimbrite from the drill hole are reported by *Oxburgh and Agrell* [this issue]. Conductivity increases significantly with depth for both flows and dikes from about 1.6 to 1.9 W m^{-1} °C^{-1} or by 25%. For the flows the increase is close to linear over this interval (1.6- to 3.5-km crustal depth), whereas for the dikes the increase takes place in the upper 800 m (1.6- to 2.4-km crustal depth) below which no further significant change takes place. Oxburgh and Agrell attribute these increases to a combination of the observed reduction in porosity with depth and the replacement of primary minerals by relatively high-conductivity secondary minerals, among which epidote is of particular significance. Thermal conductivity values for high-grade metabasalts are generally unavailable. However, we note that an average value of 2.4 W m^{-1} °C^{-1} for 17 amphibolites (average mafics - hornblende + biotite = 0.54, plagioclase = 0.41, traces of quartz and opaques) [*Drury*, 1980] lies close to the extrapolation of the drill hole trend to 6-km depth.

Information on the velocity structure of the crust in the vicinity of the section is available from direct measurements on rock samples from the drill hole part of the section [*Christensen and Wilkens*, this issue] and from a seismic profile through the drill site [*Mackenzie et al.*, this issue; *Thomson et al.*, this issue]. *Christensen and Wilkens* [this issue] report that compressional velocity V_p is variable within individual flows, with maximum values for massive interiors, but is relatively uniform within dikes. The complete set of 135 samples shows a general increase over the lower kilometer of the section. For the clear identification of broad trends, Figure 3 shows these data expressed as average values for 500-m-depth intervals. For all depth intervals, dike average velocity exceeds the flow value significantly at a level of one standard error. Both dike and flow values are at a minimum in the 500- to 1000-m interval in the drill hole and increase regularly below this level. Christensen and Wilkens suggest that the minima are the result of increased alteration in a high-permeability portion of the section. For the flows an alternative explanation lies in the approximate coincidence of the minimum in average velocity with the evolved group of extrusives that occurs between 800- and 1300-m depth. Christensen and Wilkens attribute the general increase in velocities in the lower part of the drill hole section to increases in epidote content.

The velocities obtained from the seismic experiment are significantly lower, at 4.5 to 5.4 km s^{-1}, than the average velocities from sample measurements at 5.3 to 6.3 km s^{-1}. Continuous increase in seismic velocity from the surface at about 0.3 km s^{-1} over the interval of the drill hole is indicated. This increase continues to 3.0-4.5 km below sea level, where a fairly sharp increase to layer 3 velocities of about 6.7 km s^{-1} occurs.

Following *Schreiber and Fox* [1976] and *Hyndman and Drury* [1976], it is reasonable to attribute the difference between sample and seismic velocities to the influence of partly open fractures, vesicles, and vugs on the latter.

Estimated values of V_p for greenschist and amphibolite facies metabasalts lie close to various extrapolations of the sample measurement velocity data (Figure 3). The value for the amphibolite grade metabasalt (A of Figure 3) is of particular interest since it lies within the top of the layer 3 region in the extremal bounds band of velocity solutions from the seismic experiment and is bracketed by the extrapolations of various linear regression lines fitted to the sample measurements. Lines fitted to sets of all four 500-m averages indicate a value of V_p of about 6.5 km s^{-1} at 5.8-km depth, whereas lines fitted to the three lower average values indicate a value of about 7.5 km s^{-1} at this depth. The fact that the amphibolite metabasalt value lies along a linear extrapolation of the sample measurement data, although velocities determined by the seismic method require a sharp steplike increase to reach this value, suggests that the step marks the existence of a relatively short depth interval over which any remaining open spaces are filled.

Our conclusion that the top of seismic layer 3 in this region correlates with the projected onset of amphibolite facies metamorphism is in agreement with previous studies of the nature of Icelandic layer 3. *Palmason* [1971] and more recently, *Flovenz* [1980], based on extrapolated temperature gradients from borehole data, have concluded that the layer 2 - 3 boundary represents a metamorphic facies boundary. Furthermore, the low Poisson's ratio (0.27) observed for Icelandic layer 3 is consistent with amphibolite facies metamorphism [*Christensen*, 1974]. Poisson's ratio for unmetamorphosed gabbro is much higher, averaging 0.30 at lower crustal pressures and temperatures.

Although, as has been discussed earlier, ophiolite-type spreading models are not applicable to this crustal segment, a metamorphic origin for the layer 2 - layer 3 seismic boundary may well be a universal feature of the oceanic crust. Recent laboratory measurements of the velocity structure of the Bay of Islands ophiolite [*Salisbury and Christensen*, 1978] and the Oman ophiolite [*Christensen and Smewing*, 1981] have shown that the layer 2 - layer 3 boundary coincides with the greenschist facies-amphibolite facies boundary. In the Bay of Islands ophiolite, this boundary occurs within the sheeted dike section, whereas in Oman the transition from dike rocks to high-level gabbro marks the seismic discontinuity and metamorphic boundary.

Density data for the drill hole part of the section are available both from measurements on samples [*Peterson*, 1980; *Christensen and Wilkens*, this issue] and from gamma-gamma logging [*Peterson*, 1980; *Jonsson and Stefansson*, this issue]. The 500-m-depth interval average densities based on the results of Christensen and Wilkens show dikes to be more dense than flows in every interval. The average sample densities show minima in the 500- to 1000-m interval, as do the velocities. Jonsson and Stefansson, using a 400-m sliding window, find minimum bulk and matrix combined flow and dike densities for the same interval. Sample measurements indicate an average density range of 2.74 to 2.93 g cm^{-3} for the flows and 2.90 to 2.99 g cm^{-3} for the dikes, with values in each depth interval significantly different at a level of one standard error. Linear regression of the sample data for the dikes indicates a rate of density increase with depth in the range of 0.04-0.10 g cm^{-3} km^{-1}. The logging data show an increase in combined flow and dike bulk density of about 0.2 g cm^{-3} in the lower part of the hole. The matrix density, calculated from the density and porosity values, also shows variations with depth. The lowest matrix density, 2.9 g cm^{-3}, is found between 700 and 1200 m depth. Above 500-m depth the matrix density is about 3.0 g cm^{-3} and below 1200 m the average matrix density increases, reaching a value of 3.15 g cm^{-3} near the bottom of the hole. The low matrix density in the middle part of the hole is consistent with the more evolved chemical composition of the flows in this interval [*Flower et al.*, this issue; *Gibson et al.*, this issue].

Linear extrapolations of the density data sets are consistent with estimated densities for greenschist facies metabasalts at about 4-km crustal depth but at 3.08 to 3.42 g cm^{-3} at 5.8-km crustal depth are generally in excess of estimated values for amphibolite facies metabasalts. Only extrapolation of the rather scattered average densities for dike samples, at 3.08 g cm^{-3} falls close to the density range for amphibolite grade metabasalt of 2.90 to 3.10 g cm^{-3}. Measured and anticipated densities can be reconciled if either density increases at less than a linear rate with depth below about 4 km or high-density accessory minerals, such as garnet or iron oxides, are sufficiently abundant in the amphibolite grade metabasalt to raise the density appreciably. The former explanation is more likely since the high-density phases are unlikely to be abundant in the relatively low pressure (about 2 kbar) conditions of metamorphism.

Porosity data are available from both sample and neutron-neutron log measurements [*Christensen and Wilkens*, this issue; *Peterson*, 1980; *Jonsson and Stefansson*, this issue]. Flows typically show nonuniform porosity, with highly vesicular (porosity $>$ 10%) margins and massive (porosity $<$ 2%) centers. In contrast, the dikes are relatively uniform with low porosities, comparable to the flow centers. *Jonsson and Stefansson* [this issue] show that porosity measurements on samples are not consistent with density measurements on samples, whereas the logging data on porosity and density are internally consistent. They further show that effective porosity measured on core samples is systematically lower than the total porosity as measured by the logging tools.

Magnetic Properties

Values for natural remanent magnetization (J_N), initial susceptibility (K), Konigsberger Ratio (Q), and net magnetization based on sample measurements are available for the 3.1-km section [*Bleil et al.*, this issue], and these are shown in the form of 500-m-depth interval average values in Figure 3. In addition, measurements of initial susceptibility were made at 10-cm intervals along the length of the drill core using a hand-held magnetometer [*Schonharting and Hall*, this issue]. These 500-m average values were obtained through several steps of data reduction, each involving a weighting process, and for this reason standard errors are not given. Continuous change with depth over the whole section is evident only in dike susceptibility, which increases by a factor of 7, and dike Q ratio, which is a reflection of susceptibility variation in conditions of approximately constant dike remanence. The corresponding decrease in Q ratio is from values of over 3 to approximately unity. A number of other depth trends occur over parts of the section, of which the increase in flow susceptibility from the top of the section (0.5-km crustal depth) to the center of the section (2.0-km crustal depth) followed by a steady decrease to the bottom of the section (3.6-km crustal depth) is best defined. This pattern of depth dependence together with a less clear variation of similar form for flow natural remanence can be interpreted in terms of the combined effects of variation in initial composition and subsequent alteration. For the increase in magnetic properties with depth in the upper half of the section it is necessary to argue that reduction in magnetization resulting from increasing zeolite grade metamorphism, as reported elsewhere in eastern Iceland [*Wood and Gibson,* 1976], was insufficient to compensate for variation in primary lithology with depth. However, observation of the considerable decomposition of primary magnetic oxides in the lower part of the section [*Schonharting and Ghisler,* this issue] strongly supports an alteration-related mechanism for the decrease in magnetic properties over the lower 2 km of the section. The decay in susceptibility is sufficiently regular to warrant extrapolation of a regression line to zero at 4.3-km crustal depth. The less well-confined regression line for natural remanence indicates a zero value at a similar depth of 4.5 km. These depths are only a few hundred meters below the estimated crustal depth of 4.1 km for the onset of well developed greenschist facies metamorphism, and we note that greenschist facies metabasalts are often reported on visual evidence to be oxide free [*Jamieson,* 1979] and to have negligible magnetization compared with less altered basalts [*Fox and Opdyke,* 1973] (Table 1).

Net magnetization (Figure 3) is the vector sum of remanent and induced magnetization. It does not include viscous magnetization, for which information is presently not available. All average values of net magnetization for 500-m-depth intervals are in the sense of the present geomagnetic field, indicated by positive values in Figure 3. The range of values is from 30 to 70 x 10^{-4} emu cm^{-3}. Inclusion of viscous magnetization would offset the profile toward higher positive values. The form of the profile is largely controlled by the distribution of flow remanence polarities (dike remanence polarities are, with rare exceptions, all normal). The presence of sections consisting of reversely magnetized flows and normally magnetized dikes at the top and bottom of the section have the effect of reducing net magnetization in these areas. The form of the net magnetization profile precludes extrapolation to depth.

The Present Physical State of the IRDP Crustal Section

In the previous section, depth trends for physical properties in the IRDP crustal section were compared with trends in primary construction and secondary alteration. Here we summarize information on three properties not included in the previous discussion: present temperatures, heat flow, and present stress field. Present temperatures in the IRDP section are everywhere lower than the maximum temperatures corresponding to the observed alteration [*Gibson,* 1979; *Oxburgh and Agrell,* this issue]. A prime consideration in siting the borehole was the occurrence in this region of anomalously high-temperature gradients of about 80°C km^{-1}, as measured in shallow drill holes, in an area distant from the active zone [*Fridleifsson,* this issue]. A gradient of close to 80°C km^{-1} was encountered in the drill hole to a depth of about 500 m, below which a series of artesian aquifers containing water at 48°C were penetrated.

These aquifers were tested when the drill hole was 650 m deep with the production of a net flow of 0.8 l s^{-1}. Below this depth the temperature gradient was very much reduced [*Gibson,* 1979].

Proper assessment of the thermal structure of the area awaits equilibrium temperatures from the drill hole. However, it is clear that the hole is not in thermal equilibrium. After application of correction for local topography, transient heat flow in the upper part of the hole is of the order of 100 mW m^{-2}, and is about half this value in the lower part of the hole. This variation suggests that thermal relaxation after cessation of hydrothermal circulation in the crust is still incomplete [*Oxburgh and Agrell,* this issue].

Hydrofracturing stress measurements to 600-m depth in the IRDP drill hole [*Haimson and Rummel,* this issue] show that the horizontal principal stresses increase steadily with depth. The comparable, low gradients in σH_{min} and σH_{max} indicate that normal faulting conditions exist below 300-m depth in the drill hole, in accord with the predominant fault style in the area. The mean direction of σH_{max} is N40°E or N50°E, depending on the method of data selection, which is about 30° east of the trend of the nearest fissure swarms. The collected observations are considered to be consistent with a model in which the spreading lithospheric plates are being pulled apart.

CONCLUSIONS

The conclusions to be drawn from the Iceland Research Drilling Project study fall into three areas: (1) the state of knowledge of the original construction of the crust in the vicinity of Reydarfjordur, (2) the subsequent history and present nature of the crust, and (3) applicability of the new information to the oceanic crust.

We now know that in the Reydarfjordur area subaerial basaltic flows, with minor amounts of extrusives of other types and compositions, cut by groups of basaltic dikes, continue to at least 2 km below sea level or to a crustal depth of about 3.5 km. There is no indication of a transition with depth to a sheeted dike complex, as predicted by *Bodvarsson and Walker* [1964] and *Gibson and Piper* [1972]. Lack of increase of dike density with depth may be explained if the dikes in the section were intruded laterally from the Breiddalur volcanic center in the same manner that dikes are being intruded in the active zone of Iceland during the present period of activity at the Krafla volcanic center [*Bjornsson et al.,* 1979; *Einarsson and Brandsdottir,* 1980]. The Krafla and IRDP results raise the important question of the nature of crustal construction at depth in circumstances where dikes are intruded laterally. We favor a model in which a gabbroic layer underlies a layer of flows and dikes, but the IRDP results give little indication of the depth at which such a layer might occur.

The observed large subsidence during crustal formation and the recognition of a method for determining variation in rate of subsidence with depth in the section [*Hall et al.,* this issue] and thus with distance from the axis of the active zone support, in general terms, the models of *Palmason* [1973, 1980] for the formation of Icelandic crust and focus attention on the contemporaneity and matching effects of volcanic extrusion and subsidence during accretion at plate margins. The third major feature of the accretion process is rapid alteration of the newly formed crust, largely through the circulation of heated water. This last feature has left the crustal section with a clear sequence of zones of increasing temperature of alteration with depth, and in contrast with the style of original crustal construction, it is possible to extrapolate the sequence of alteration zones with considerable confidence to about twice the depth of the IRDP section. This extrapolation leads to a number of rather well-constrained predictions which can be tested by further drilling. An example of such a prediction is that the disappearance of magnetization from subsided extrusives corresponds with the absorption of all iron into metamorphic silicates with the onset of greenschist facies metamorphism at close to 4-km crustal depth. Again, it is predicted that the transition to seismic layer 3 in the area corresponds to the top of a zone of amphibolite grade metabasalts at close to 6-km crustal depth, and the physical mechanism responsible for the rise in seismic velocities at this depth is the relatively sharp elimination of remaining porosity in the crust. It is also possible that gabbros or metagabbros, which are likely to be in many respects similar to metabasalts, are present within the 4- to 6-km depth range being considered here.

If careful identification of known differences between Icelandic and normal oceanic crust is made, the results of the IRDP study provide several valuable indications of processes taking place during formation of oceanic crust. While the style of subsidence during crustal formation appears to be very different in Iceland from that farther south on the Mid-Atlantic Ridge, with the former involving regional flexure with little fracturing and the latter appreciably greater disruption [*Gruver,* 1978; *Hall and Robinson,* 1979], subsidence should be taken into account as a generally important component of the accretion processes. Again, while hydrothermal systems in Iceland differ from systems in mid-ocean ridges in having low, near crustal surface pressures and temperatures, and usually in containing low salinity fluids, which will lead to some differences in the secondary mineralogy, the sequence of metamorphic zonation produced at depth by these systems, being largely temperature dependent, is likely to be similar in both environments.

The IRDP results provide additional support for the interpretation that oceanic layer 3 velocities are due to metamorphism. If the top of oceanic layer 3, at about 2-km depth in oceanic crust, marks the onset of amphibolite facies metamorphism, with porosity reduced to zero, the top of the greenschist facies would be expected to occur at depths of 1.5 km or less crustal depth, i.e., at much shallower levels than in eastern Iceland. The relatively shallow estimated depths for high-grade zones must be reconciled with the evidence from DSDP drill holes that oceanic basement in the North Atlantic is essentially unaltered to 600-m depth [*Hall and Robinson,* 1979]. Reconciliation requires a steep temperature increase in the 600-m to about 1-km depth interval in normal oceanic crust. A model for such increase has been proposed by *Rice et al.* [1980]. The essential elements of the model are depression of temperature gradients at shallow crustal depths due to ingress of abundant cold sea water, followed by a sharp increase in gradient due to frequent dike intrusion in a shallow sheeted dike complex. Rice et al. also suggest that crustal magnetization becomes negligible with the onset of greenschist facies metamorphism, and this is also implied by the IRDP results.

It is then possible to predict that the base of the source layer for the linear magnetic anomalies of oceanic basins is at about 1.5-km depth in oceanic crust. This depth is well within the drilling capability of 'Glomar Explorer', so suggesting that the prediction may readily be tested.

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Cometary and Meteorite Swarm Impact on Planetary Surfaces

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The velocity flow fields, energy partitioning, and ejecta distributions resulting from impact of porous (fragmented) icy cometary nuclei with silicate planetary surfaces at speeds from 5 to 45 km/s are different than those resulting from the impact of solid ice or silicate meteorites. The impact of 1 g/cm^3 ice spheres onto an atmosphereless anorthosite planetary surface induces cratering flows that appear similar to those induced by normal density anorthosite meteorite impact. Both of these impactors lead to deep transient crater cavities for final crater diameters less than ~1 to ~10 km and for escape velocities $\lesssim 10^5$ cm/s. Moreover the fraction of internal energy partitioned into the planetary surface at the cratering site is 0.6 for both ice and anorthosite impactors at 15 km/s. As the assumed density of the hypothetical cometary nucleus or fragment cloud from a nucleus decreases to 0.01 g/cm^3, the fraction of the impact energy partitioned into planetary surface internal energy decreases to less than 0.01, and the flow field displays a toroidal behavior in which the apparent source of the flow appears to emanate from a disc or ringlike region rather than from a single point, as in the explosive cratering case. The edges of the crater region are in several cases depressed and flow downward, whereas the center of the crater region is uplifted. Moreover, the resultant postimpact particle velocity flow in some cases indicates the formation of concentric ridges, a central peak, and a distinct absence of a deep transient cavity. In contrast, transient cavities are a ubiquitous feature of nearly all previous hypervelocity impact calculations. The calculations of the flow fields for low density (0.01 g/cm^3) impactors exhibited surface interface (comet-planet) instabilities. These are attributed to both the Rayleigh-Taylor and Helmholtz instability conditions, and we believe that these occur in all flows involving volatile low-density (0.01 g/cm^3) projectiles. It is speculated that these hydrodynamic instabilities can give rise to concentric rings in the inner crater region in large-scale impacts on planetary surfaces, although other mechanisms for their production may also act. The ejecta mass loss versus planetary escape velocity was computed, and these results imply that the critical escape velocity, at which as much material is lost as is being accreted from a planet, ranges from 1.2 to 2.75 km/s for encounter speeds of 5 to 15 km/s, with cometary impactors having a density of 0.01 to 1 g/cm^3. These values compare to 0.83 and 1.5 km/s for silicate impactors, thereby indicating that it is more difficult for volatiles than silicates to be accreted onto objects with escape velocities similar to the Moon, Mercury, and Mars. For objects with escape velocities in the 0.1 to 1 km/s range the accretional efficiency for silicate and various porosity ices are similar, whereas for objects with escape velocities <0.1 km/s the accretional efficiency of icy impactors becomes significantly lower than for silicate impactors.

INTRODUCTION

As our knowledge of planetary surface morphologies has increased to the point where impact cratered terranes have been successively recognized on the Moon [*Shoemaker et al.*, 1970], Mars [*McCaulley et al.*, 1972], Mercury [*Murray et al.*, 1974], Phobos, Deimos [*Veverka and Duxbury*, 1977], Callisto, Ganymede [*Smith et al.*, 1979], Amalthea [*Veverka et al.*, 1981], and, recently, tentatively on Venus [*Campbell et al.*, 1979; *Pettengill et al.*, 1979] the question has been raised repeatedly of how the initial density of impacting objects affects the resulting crater shape as well as the partitioning of energy. In part the motivation for studying the effects of cometary impact on planetary surfaces has come from the suggestion of *Wetherill* [1977], who pointed out the possibility that one half of the terrestrial impact craters could have been produced by retrograde comets, and the repeated suggestions of Roddy and co-workers [*Roddy*, 1968; *Roddy et al.*, 1980] that large flat-floored craters such as that at Flynn Creek, Tennessee, could have been produced by porous, possibly cometary impactors. Finally, numerous studies have suggested that the largest meteoritical phenomenon yet documented by man, the Tunguska explosion, was possibly induced by the interaction of the earth with a comet [*Krinov*, 1966; *Petrov and Stulov*, 1976; *Liu*, 1978]. Although it is likely that some craters on the terrestrial planets are induced by the impact of icy cometary nuclei, it is not clear what the relative role of comets is in producing the observed impact crater population on the earth and other terrestrial planets. Meteoritical element abundance patterns have recently been used to assign different meteorite classes to the projectiles that have produced some 12 large impact craters on the earth [e.g., *Palme et al.*, 1979]. Aside from the active comets, it may be that potential porous impactors exist in the vicinity of the earth in the form of the Apollo asteroids; these may represent devolatized and short-period cometary cores [*Wetherill*, 1976]. This latter class of objects could provide an appreciable fraction of the impactor flux recorded on the surfaces and the Moon

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