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# Crust of oceanic affinity in Iceland

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*Evidence for subsidence of at least 2 km during crustal formation and the absence of an increase in minor intrusion density with depth in the lower 2 km are the major results of the field study of a 3-km vertical section of Icelandic crust.*



DURING the past six years major efforts have been made to determine the structure, composition and mode of formation of the oceanic crust. Such investigations are, however, severely hampered by the great depth of water in the ocean basins and the difficulty of deep drilling in the basaltic layer of the crust. An alternative approach is to study elevated mid-ocean ridge segments such as Iceland. Although not underlain by typical oceanic crust, Iceland forms a part of the Reykjanes–Kolbeinsey section of the Mid-Atlantic Ridge and contains a record of eruptive processes at a spreading axis. It is also well exposed and easily accessible for study. A detailed investigation of the Icelandic crust should provide important information on the processes of crustal construction, hydrothermal alteration and magmatic evolution of one part of the Mid-Atlantic Ridge.

The first results from a continuously cored, 1,919-m deep borehole drilled in eastern Iceland, forming the lower part of an intensely sampled 3-km section, are reported here. The section is entirely within seismic layer 2. Overall core recovery was 99.7%. Hole diameter was 7.6 cm down to 1,350 m, then 6.0 cm to the bottom.

The structure of eastern Iceland is relatively simple and consists of a thick succession of deeply dissected Neogene flood basalts which dip gently westwards towards and beneath the Neovolcanic zone of North-east Iceland. Walker[1] showed that the lava pile consists of a series of overlapping groups of flows that thin progressively up-dip. Lava dip decreases from 7–10° near sea level to 2–3° near the 1,000-m summit level. The nature of the regional zeolite grade metamorphism suggests that the basalt pile had a finite limit about 1.5 km above sea level where the intensity of dyke injection approached zero and the lavas were horizontal and unzeolitised.

The drill site (lat 65° 01′ N, long 14° 21′ W) is located near sea level, 8 km east of the centre of the Thingmuli central volcano, at the head of Reydarfjordur in a geologically and geophysically well known area[2–6], where crustal dilation by north–south basaltic dykes is 10% (Fig. 1). Final site selection was on the basis of unpublished gravity data (G. Palmason, personal communication) which were used to identify a location within a large area of anomalously high temperature gradient (~80 °C $km^{-1}$ (ref. 7)) where the regional gravity anomaly was of average value.

## Lava stratigraphy

The combined exposed and drill-hole 3-km section consists of subaerial lava flows, with thin intercalated pyroclastic and volcaniclastic sedimentary horizons, all cut by minor intrusions (Fig. 2*a*, *b*). In the drilled sequence minor intrusions comprise 40% of the core and cut out large sections of flow stratigraphy.

Six minor faults with displacements up to 50 m are present in the exposed section and similar faults probably cut the drilled succession, although no obvious stratigraphic repetitions were observed. Regional mapping has indicated the absence of major faults in the area[2].

All thickness values quoted for both the exposed and drilled sequences are vertical thicknesses. The deviation of the hole from the vertical was measured by acid tests at 100-m intervals and was usually much less than the maximum value of 7°.

The observed dip in the cliff section varied from 2° at 1,000 m elevation to 10–14° at sea level. Dips measured in the drill core are scattered but suggest that the observed increase with depth continues until a value of about 20° is reached at about 500 m below sea level, below which little further increase occurs.

Examination of the drill core in the field showed that the flows are predominantly subaerial fine-grained aphyric tholeiitic lavas characterised by reddened rubbly flow tops and massive to weakly flow-banded grey-green interiors, corresponding to the tholeiites and basaltic andesites of Walker[2]. Notable exceptions include a 12-m thick Icelandite flow from 1,083 to 1,095 m (unit 185.5) and a 31-m thick welded ash-flow tuff sequence from 920 to 951 m (units 157.2, 161.1 and 162.1).

It is not possible to correlate the major part of the drill-hole succession with the observed up-dip lava sequences exposed on the north and south sides of Reydarfjordur. This was unexpected in view of the regular nature of the exposed geological structure but several features may explain this situation. First, minor intrusions may cut out some key horizons. Second, an unknown amount of down-dip thickening of the lava units may occur—a simple extrapolation of the rate of thickening observed in the sub-aerial section may not be applicable to the lower part of the section. Third, gradual but large-scale lateral changes in the lava stratigraphy may exist.

Aside from difficulties in making specific correlations between the drill hole and exposed, up-dip sections, a striking general result is the paucity of olivine-bearing basalts in the 3-km crustal section, in contrast with a frequency of occurrence of 23% (ref. 2) in the Reydarfjordur succession as a whole. This paucity of olivine-bearing rocks may relate to the early manifestation of the Thingmuli and Breiddalur centres, which erupted over-saturated basaltic lavas and silicic 'differentiates'.

## Minor intrusions

Steeply dipping north–south basaltic dykes that are approximately normal to the flows are found at all levels in the exposed section. Dyke density increases notably towards sea level reaching a dilation value of 10%, measured over a 1.6-km transect normal to the swarm, through the drill site. In spite of the obvious drawback in sampling near-vertical rock units with a vertical drill hole, the excellent core recovery allows dykes to be identified in the core on the basis of their chilled contacts, their essentially non-vesicular character, and frequently by their large vertical extent. An example of the multiple dykes which occur is the particularly thick complex of dykes between 528 m and 586 m (units 90.1, 90.2, 90.3, 90.4, 91.2, 92.1, 94.1 and 94.2). There is a broad distribution of intrusive contact angles in the core. Over 40% of these contact angles lie between 55° and 75°. The remainder are rather uniformly distributed over all other angles. In total, 98 minor intrusions constitute 40% of the drill core; however, 11 of these, with vertical extent of greater than 20 m, account for over half of this percentage. The seven minor intrusions in the uppermost 400 m of the drill core comprise five isolated examples and one two-component multiple dyke of 110 m vertical extent (units 10.1 and 17.1, 63 to 173 m). Below 400 m the distribution of minor intrusions is markedly non-uniform. Minor intrusions are concentrated in

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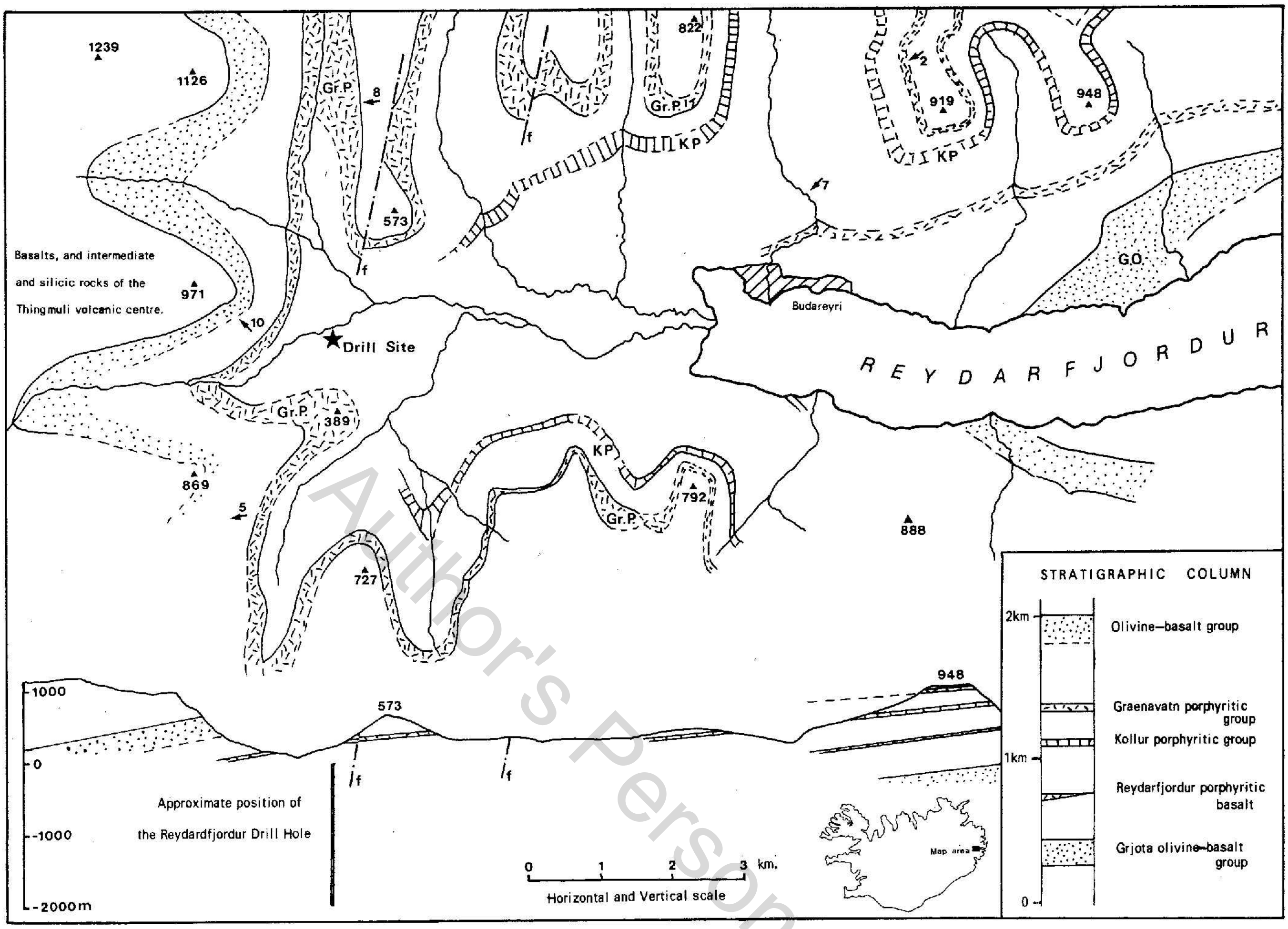


**Fig. 1** Map and section showing the geology in the vicinity of the IRDP Reydarfjordur drill site.

three intervals each of about 300 m vertical extent separated by comparable intervals in which intrusions are generally much less common (Fig. 2*b*).

Preliminary observations suggest that the minor intrusions are generally less altered than the intervening flows. Thin-section studies indicate that at least some of the dykes in the core are olivine bearing and thus may not be directly related to the lavas of the drill core which are mainly olivine free.

Some of the minor intrusions occurring below 400 m in the drill core are almost certainly gently dipping sheets of a type characteristic of the deeper parts of many Icelandic Tertiary and Quaternary volcanic centres. There is no demonstrable increase in the proportion of minor intrusions as a whole with depth in the drill core (0–500 m, 34%; 500–1,000 m, 42%; 1,000–1,500 m, 45%; 1,500–1,919 m, 39%) or in the proportion of thick, apparently steeply dipping dykes.

## Secondary mineralisation

A generally progressive increase of alteration with depth in the section characterises the lavas but is not obvious in the dykes. The topmost flows in the exposed section are unzeolitised. Zeolites appear lower in the exposed section (Fig. 2*a*). In general laumontite is absent in the exposed section, but is found in the Skessa tuff, a silicic ash-flow 100 m above the drill site.

All the flows in the drill core are variably altered, with macroscopic secondary minerals abundantly developed in the brecciated and vesicular flow tops and bottoms. Laumontite is dominant in the upper 1,000 m of the core. A shift from smectite to chlorite dominated assemblages occurs at the 200–300-m depth. Epidote first becomes very common at 1,200 m, where it occurs in both amygdales and veins and in the groundmass of the basalts. From 1,200 m to the bottom of the core at 1,919 m epidote is patchily distributed with alternating rich and deficient sequences. Calcite, various forms of silica and 'celadonite' are common secondary minerals throughout the drill core and various parts of the exposed section. Of particular interest are grossular garnet at dyke contacts at 425 and 1,166 m and anhydrite at 1,055 m.

The alteration pattern of the lavas in the drill core is very similar to that found in other drilled sections in the Tertiary formations of Iceland[7].

Clearly the secondary mineralisation took place at a very much higher temperature than that measured in the hole at present. Based on data from drill holes in the active volcanic zone of Iceland, the lower boundary for the formation of laumontite seems to be about 110 °C and that for epidote about 230 °C (ref. 8). Assuming an original surface 1,500 m above sea level and a linear temperature gradient, the figures suggest the existence of a temperature gradient of close to 85 $^{\circ}C\,km^{-1}$ during the formation of the secondary mineralisation.

## Magnetic properties

Measurements of initial susceptibility and polarity of natural remanence magnetism (NRM) were obtained for the lower 2 km of the section. Susceptibility values were obtained every 50 cm or less, correction being made for the size and cylindrical shape of the core. Although remanence cleaning is necessary to define the polarity succession reliably, natural remanence polarity measurements may be of some value in locating the section with respect to the known time–magnetic polarity sequence.

The most important feature of the susceptibility measurements is a strong and regular overall decrease with depth for the

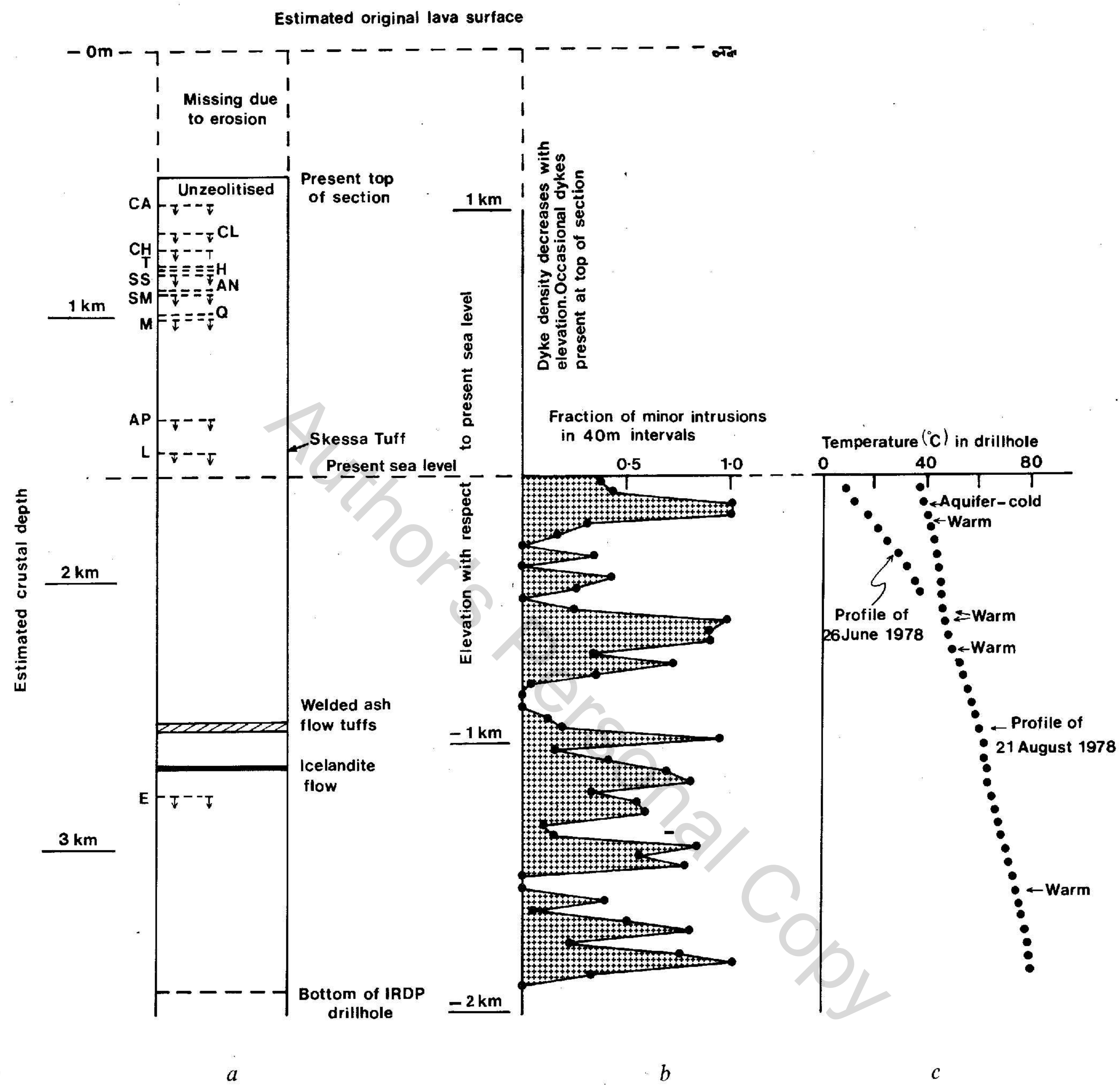




**Fig. 2** Profiles through the 3-km Icelandic crustal section. *a*, Marker horizons and highest occurrence of key secondary minerals are indicated by a dashed line and downward pointing arrows. CA, calcite; CL, clay; CH, chabazite; T, thomsonite; H, heulandite; SS, stilbite; AN, analcite; SM, scolecite–mesolite; Q, quartz; M, mordenite; AP, apophyllite; L, laumontite; and E, epidote. *b*, Fraction of minor intrusions in each 40 m depth interval. *c*, Temperature profiles before and after penetration of the series of artesian warm water aquifers between 517 m and 628 m depth.

flows from a mean value of $40\times10^{-4}$ e.m.u. cm$^{-3}$ for the 0–480-m depth interval to $14\times10^{-4}$ e.m.u. cm$^{-3}$ for the 1,440–1,919-m interval. Linear extrapolation of this trend in mean values for the lavas suggests that susceptibility would reach zero value at 2,600 m below sea level or at just over 4 km beneath the original surface of the lava pile. In contrast, no depth trend in minor intrusion susceptibility occurs, with mean values for 480-m depth intervals varying irregularly from 26 to $31\times10^{-4}$ e.m.u. cm$^{-3}$. Susceptibility typically varies little within minor intrusions, except where fractures or intervals of high permeability occur. In contrast, strong within-unit variation is common for flows, with minima at boundaries and one or two interior maxima. In a general sense, susceptibility variation follows the alteration pattern: the downhole decrease in flow values matches the increase in alteration grade from a laumontite stage to an epidote stage while the minima at flow boundaries correspond to maximum secondary mineral development in these porous regions.

The relatively high average values, and lack of a trend with depth in minor intrusion susceptibility, corresponds with the apparent low alteration state of these units, and may also be indicative of their much younger age. Decomposition of the iron–titanium oxides resulting from zeolite and epidote grade metamorphism is likely to explain reduction of susceptibility in the flows.

Above 1,230 m depth only normal NRM polarity occurs. Reverse NRM polarities, including shallow inclinations, occur mainly within the following depth intervals: 1,445–1,635, 1,690–1,730 and 1,882–1,919 m. Multiple changes of NRM polarity within units have frequently been found in the lower bore-hole section.

At this stage the extended normal polarity zone of the upper half of the core apparently correlates with magnetic anomaly 5 (magnetic epoch 9).

## Geothermal measurements

Temperature profiles in the drill hole were obtained weekly, in each case after a 24-h cessation of drilling. Initial water samples were taken from four levels several days after the termination of drilling, but these showed signs of mixing with drilling fluid and the sampling will be repeated. A temperature profile measured when the well was 445 m deep (Fig. 2*c*) showed an approximately linear thermal gradient of about 80 °C $km^{-1}$. Between 517 m and 628 m a series of prominent artesian aquifers with water at 48 °C were penetrated. These aquifers were tested when the hole was at a depth of 650 m and produced a net flow of 0.8 l $s^{-1}$. Several smaller aquifers were penetrated at greater depths. Flow of water from the prominent aquifers led to a major change in thermal regime in the hole (Fig. 2*c*); the temperature gradient below these aquifers is much lower.

The site was located within an area of anomalously high surface temperature gradient, and results from the drill hole strongly suggest that this anomalous area is the result of shallow regional geothermal flow of water at moderate temperatures.

## Geophysical logging

Extensive geophysical logging of the drill hole was carried out by the Icelandic National Energy Authority with natural $\gamma$-ray, neutron–neutron porosity, $\gamma$–$\gamma$ density, caliper, self-potential, 0.4 m and 1.6 m normal resistivity, temperature, differential temperature, sonic velocity and differential magnetic permeability recorded. In the cased central part of the hole (580–1,350 m) self-potential, resistivity and differential permeability could not be recorded. Sonic velocity was recorded from the surface to 1,350 m depth.

Preliminary results show a very pronounced relationship between the physical and lithological parameters. An example is the high resistivity contrast between the massive centres of lava flows and the brecciated or rubbly margins. Dykes and intrusions are also characterised by high resistivity. Relatively few, but prominent, anomalies in the natural $\gamma$-ray log are recorded. The sequence of welded ash-flow tuffs between 920 and 951 m depth is characterised by high natural radioactivity and low $\gamma$–$\gamma$ density. Thin breccia layers can be identified in the neutron–neutron porosity log as well as in the $\gamma$–$\gamma$ density log.

## Crustal seismology

Two crustal seismic experiments were carried out in association with the drilling project, one by a group from Leningrad and the other by a group from the University of Washington and the Scripps Institution of Oceanography. The results from these experiments are still being interpreted.

## Discussion

Although intensive laboratory studies of the 3-km section are continuing, some important points are already evident. Perhaps the most striking feature is the continuously sub-aerial nature of the lavas implying that at least 2 km of subsidence has occurred. No pillowed basalts were found. The absence of marked erosional features in the exposed upper part of the section suggests that the lavas were erupted in an area of low relief at most a few hundred metres above sea level and the implication is that subsidence probably took place concomitant with the volcanism at a rate of at least 1 km $Myr^{-1}$. Subsidence on this scale is implied in many of the models for crustal growth in Iceland (see ref. 9) and is observed elsewhere where active, volcanic zones occur in areas of oceanic crust[10–12].

The progressive change in the nature of the alteration with depth is also striking. The intensity of metamorphism in the lavas increases gradually, but in detail relatively fresh rocks interfinger with more altered horizons. If the layer 2/layer 3 boundary is fundamentally a metamorphic transition then the present study suggests that such a transition may take place over a distance of the order of 1 km.

The combination of the olivine-bearing nature of some of the minor intrusions, the magnetic properties, and the relative freshness of most of them may imply that they were not feeders for the bulk of the lava succession. The possibility that the dykes are related to the Breiddalur centre[13], 20 km to the south, and that they have been injected laterally northwards in the manner that is presently being observed in the Krafla volcano in north Iceland[14] must be considered.

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