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A Seismic Crustal Study of the Axial Rift Zone in Southwest Iceland

S.M. Zverev[1], I.V Litvinenko[2], G. Pálmason[3], G.A. Yaroshevskaya[1], and N.N. Osokin[2]

[1] Institute of the Physics of the Earth, Moscow, USSR
[2] Mining Institute, Leningrad, USSR
[3] National Energy Authority, Reykjavík, Iceland

Abstract. Detailed seismic crustal studies by combined reflection and refraction methods were carried out for the first time in the flood basalts and in the active zone of rifting and volcanism of southwestern Iceland. The observations were carried out along two profiles with a total length of 70 km, with 8 shot points, and with a distance between seismographs of 50 m. The flood basalt series flanking the axial rift zone along the profile line ranges in age from 1 7 to 6.0 Ma at the surface. It is characterized by a general increase in seismic wave velocity with depth, and by the presence of high-velocity layers with $V_p = 4.3$–4.7 km/s, connected with denser lava flows interbedded between lower-velocity rocks. The refracting boundaries in the upper part of the section dip towards the axial rift zone at angles of 8°–9°, which is consistent with the dip of the surface lavas. Less dipping refracting boundaries with velocities of 5.2, 6.0, 6.5 km/s, were found at depths of 2–4 km. Within the axial rift zone the refracting boundaries form a slight depression filled with low-velocity formations ($V_p = 2$–3 km/s). Reflecting horizons with an average length of 1–2 km were found. They are on the whole much less regular than in continental regions with sedimentary deposits. They are generally tilted towards the axial rift zone. Steep dipping elements are traceable to a depth of more than 10 km, the dip decreasing with depth in the flood basalt area. In the axial part of the rift the seismic cross-section outlines a volume, where no reflecting horizons could be detected. This indicates relative homogeneity of physical properties and may point to a magmatic chamber, or a region of partial melting underlying the axis of the zone of rifting and volcanism.

Key words: Iceland – Seismic reflection and refraction profile – Axial rift zone – Magma region.

Introduction

The complex geological – geophysical expedition of the USSR Academy of Sciences jointly with the Icelandic National Energy Authority conducted in 1976 a seismic crustal investigation in southwestern Iceland. The purpose was to study in detail the structure of the upper part of the earth's crust along a line transverse to the active zone of rifting and volcanism, crossing the axial zone as well as the adjacent flank area.

The Tertiary and Quaternary flood basalts comprising the flanks of the axial rift zone in Iceland are known to be almost everywhere tilted towards the axis of the zone. This may be viewed as a vast depression in the flood basalts, partly formed by faulting, and filled with younger volcanic formations (Walker, 1960; Bodvarsson and Walker, 1964; Einarsson, 1965, Pálmason, 1973; Pálmason and Saemundsson, 1974; Beloussov and Milanovsky 1977). Little is known, however, about the detailed deeper structure, since seismic refraction studies (Pálmason, 1971) have limited resolving power, and drillholes have penetrated only to about 3 km depth at the present time (Pálmason et al., 1979).

A mechanism of crustal drift and generation, somewhat analogous to the concept of sea-floor spreading, was proposed by Bodvarsson and Walker (1964) to explain the structure of the Tertiary flood basalts in eastern Iceland. The thermo-mechanical aspects of this process are being studied in more detail by one of the authors of the present paper (Pálmason, 1973, 1980). The generation of new crust is assumed to take place in the axial part of the volcanic rift zone by dykes intruded into the crust and by lavas erupted at the surface. The crust is sagging more or less continually under the weight of new material brought to the surface in volcanic eruptions. One of the objectives of the present study was to try to follow by reflection methods some of the dipping Tertiary and Quaternary lava series from their surface exposures to greater depth in the crust. This might contribute to a better understanding of the processes taking place in the active zone of rifting and volcanism.

Location of Profiles, Methods

The choice of a representative seismic profile locality that would cross the flood basalts as well as the active zone of rifting and volcanism in southwestern Iceland was governed largely by the available roads. The line of seismic observations in 1976 is shown in Fig. 1. It consists of two separate profiles. Profile I extends eastwards from a shot point in Borgarfjördur, about 5 km east of the Borgarfjördur anticlinal axis (Fig. 1), and crosses flood basalts of Miocene-Pliocene age, which near the eastern end are replaced by the younger volcanic rocks of the active zone, especially the lava sheets of the shield volcano Skjaldbreidur. Profile II is located within the active zone of rifting and volcanism where the surface rocks are predominantly postglacial lava sheets and interglacial hyaloclastite ridges. The rocks are broken by young fractures with a mainly northeast-southwest direction. This profile crosses the axial part of the active zone of rifting and volcanism in an oblique direction.

The technique of investigation is characterized by the following features. The profiles followed the available roads and were thus not totally straight, which limited the interpretation possibilities somewhat. The shots were fired in the sea (SP 1), in lakes (SP 2–5)

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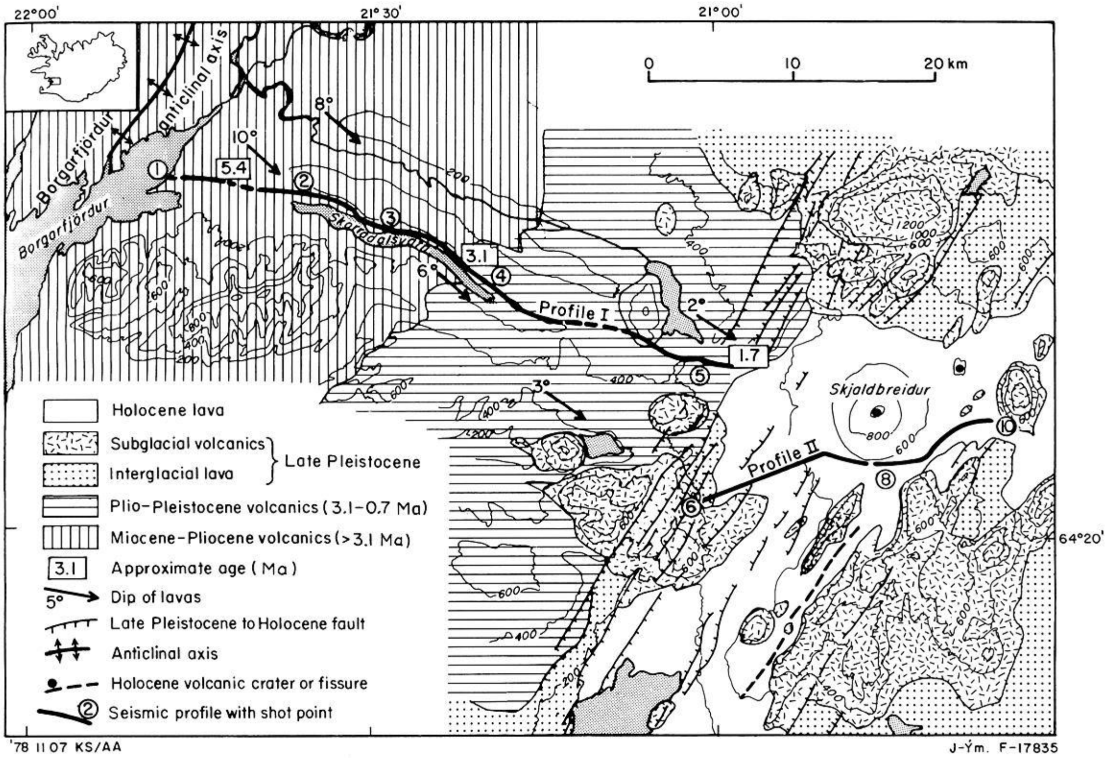


Fig. 1. The location of seismic *Profiles I and II* and the geology of the surrounding area

or in dry pits and cavities of lava flows (SP 8–10). For some of the shot points the charges were limited in size because of proximity to populated areas (SP 1 and especially SP 2–4). The charges for SP 1 were about 150–200 kg, SP 2–4 25 kg, SP 5 50–200 kg, SP 6 150–200 kg, SP 8 250–500 kg, and SP 10 200–400 kg. Shooting conditions were far from optimum in the shallow water basins, open pits, and caves.

Although on the whole the profile measurements were more detailed than in previous seismic investigations in Iceland, they were more of a reconnaissance than a detailed character, if compared with modern seismic exploration surveys. A continuous profiling was used with a distance between the geophones of 50 m. The geophones were usually located on the side of the roads. Two twenty-four channel seismic reflection recording stations of the type SMOV-24 were used. The magnetic tape records were of duration up to 12 or 24 s with a dynamic range of 46 db in the frequency band 5–100 Hz. The geophones had a natural frequency of 10 Hz. The shots were recorded at each recording station from 3 to 6 shot points.

The system of time curves used made it possible to determine twice independently the location of reflecting horizons in the cross-section. At greater depths and on the outermost parts of the profiles the reflecting elements could, however, be traced only for certain ranges of dip. At depths exceeding the length of the time curve only the low-dip boundaries could be traced, while on the outermost parts only the steep ones (Litvinenko, 1971). On Profiles I and II the length of most travel-time curves exceeded 10–15 km. The maximum length reached 45 km, permitting not only the construction of several refracting horizons, but also the identification of reflectors with angles of dip 60°–70° at depths down to 5 km, and at still greater depths of reflectors with lower dip angles.

To identify the useful waves, especially the reflected ones, the field magnetic records were reproduced on special equipment of the types 'Ray' and PSZ-4M. On the record-sections produced, no corrections for elevation, low velocity surface layer, or deviations of the profile from a straight line were introduced, there being insufficient data available for this purpose. In playback the main consideration was given to the frequency filtering of useful signals. In the frequency range above 40 Hz the identification of reflected waves proved to be difficult due to high background noise. At frequencies below 5 Hz the separation of waves was difficult. Experimental tests showed that at distances larger than 15–20 km from the SP the frequency band of 7–14 Hz gave the optimum results and at smaller distances the corresponding frequency band was 10–28 Hz.

The records in the form of conventional seismograms and the above-mentioned record-sections were the basis for the construction of the velocity section, correlating the useful waves and determining the seismic boundaries.

General Features of the Seismic Wave Fields

Examples of wave fields may be seen in the record sections in Figs. 2 and 3. On the whole, the observed picture reveals a complicated medium with little velocity variation. The main features of the wave field are the following:

1. Presence of clear and strong refractions as first arrivals, non-parallel overlapping travel-time curves, difficult separation of waves forming the first arrivals;
2. Short range of observation and little variation in amplitude of later arrivals, lack of dominant reflections;
3. Asymmetry of the travel-time curves of refractions and reflections; in most cases the travel-time minimum of the reflections is displaced from the shot point;
4. Considerable irregularity in the wave field; frequent phases with anomalous velocities join up with the first arrivals and are repeated on reversed and overlapping travel-time curves.

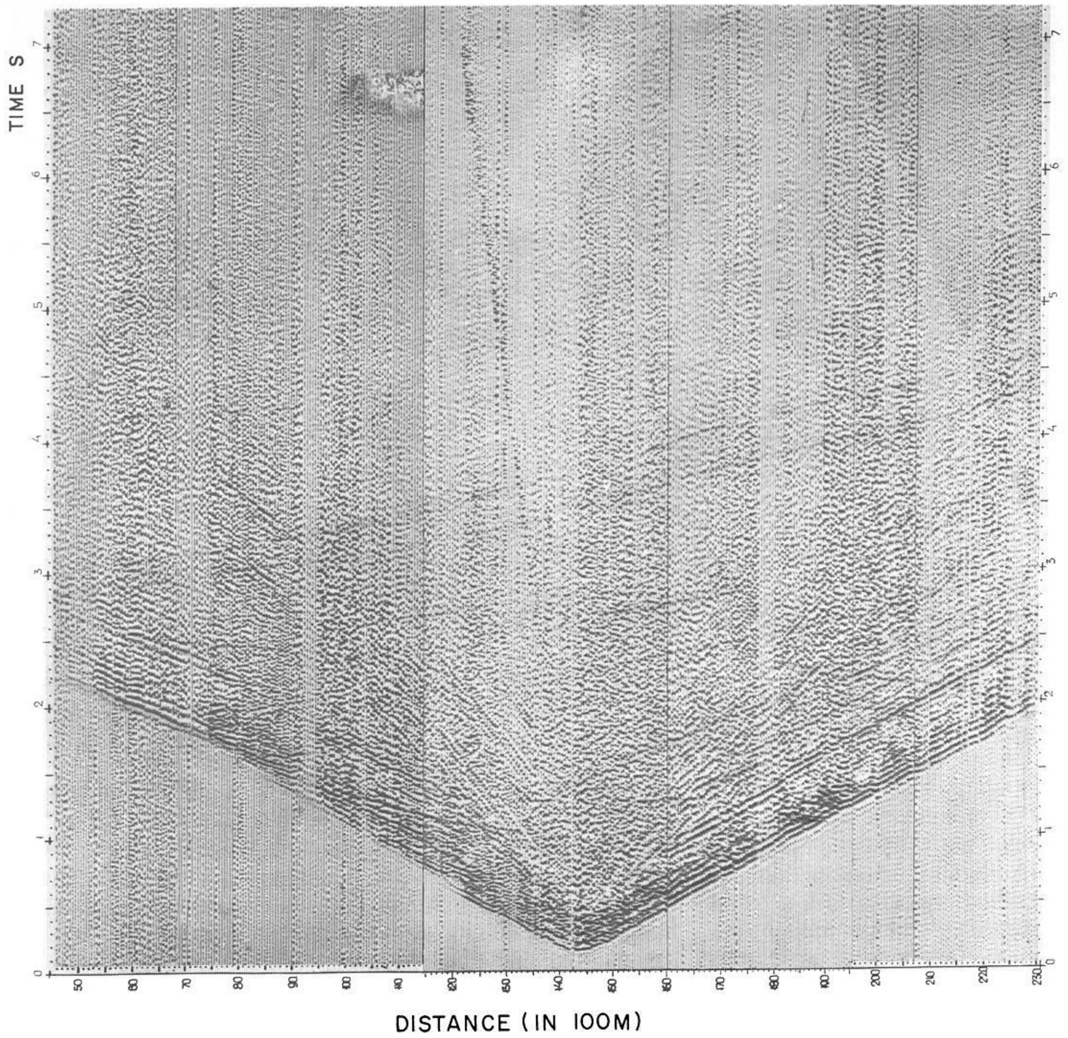


Fig. 2. Record-section in frequency band 9–19 Hz for *SP 3 on Profile I*

Characteristics of Refracted Waves

The refracted waves differ in travel-times and apparent velocities on the two profiles. On Profile I along the flood basalts they are compact oscillations lasting 0.5 s on average (Figs. 2 and 3). Their apparent velocities, V^*, increase from 3 or 4 to 6.5 or 7 km/s (Figs. 4 and 5) in the distance range of 0–40 km. The increase is somewhat gradual indicating the absence of thick layers of constant and strongly contrasting velocities. Overlapping travel-time curves are rarely parallel (Fig. 4) such that distinct wave groups cannot be traced for distances greater than the shot intervals; this means that only refracted and diving waves are observed.

The criteria used in dividing the waves into groups were changes in V^* and wave form. The parameters of the groups are given in Table 1. Small local variations in apparent velocity often make identification difficult. The wave groups P_1 and P_3 are most easily identified. For P_1 a distinct asymmetry with respect to the shot point is found (Fig. 4). To the east V^* gradually increases to 4.4 or 4.6 km/s; the westward branches consist of several high-velocity sections which are highly attenuated. Overlapping travel-time curves terminate at the same locations. This may be explained by a laminated gradient medium with intercalated high-velocity layers. The waves of groups P_2' and P_2'' are traceable over short ranges only and are difficult to distinguish, but their continuation as later arrivals (SP 1, 2, 5; Fig. 4) supports their identification.

A summary of the travel-time curves (Fig. 6) shows that the uppermost part of the section does not change much along the profile. An exception is the area around SP 1 where the travel-times are shorter; the velocities change correspondingly between 2 and 7 km east of SP 1. Generally the travel-times are found to increase from west to east, also for other wave groups, for distances greater than 8 km (Fig. 6); this indicates dip of the refractors toward the neovolcanic zone.

Along Profile II within the active zone of rifting and volcanism, the travel-times are distinctly greater and the near-surface velocities are lower (Figs. 5 and 6). Five different wave groups with velocities from 1.6 to 5.6 km/s are identified (Table 1). The waves with $V^* < 4$ km/s are strongly attenuated and the following ones are separated from the earlier ones by a time interval indicating layers with zero or negative velocity gradients.

Waves propagating in the upper part of the section along Profile I have similar mean apparent velocities as the wave groups P_1'' and P_1''' along Profile II. Waves with lower velocities are absent in Profile I, whereas higher-velocity waves are not found on Profile II; the range of observations is probably too short.

Seismic Cross-Section From Refractions

True and average velocities were determined for the cross-section from the observed refractions with several methods (simplified

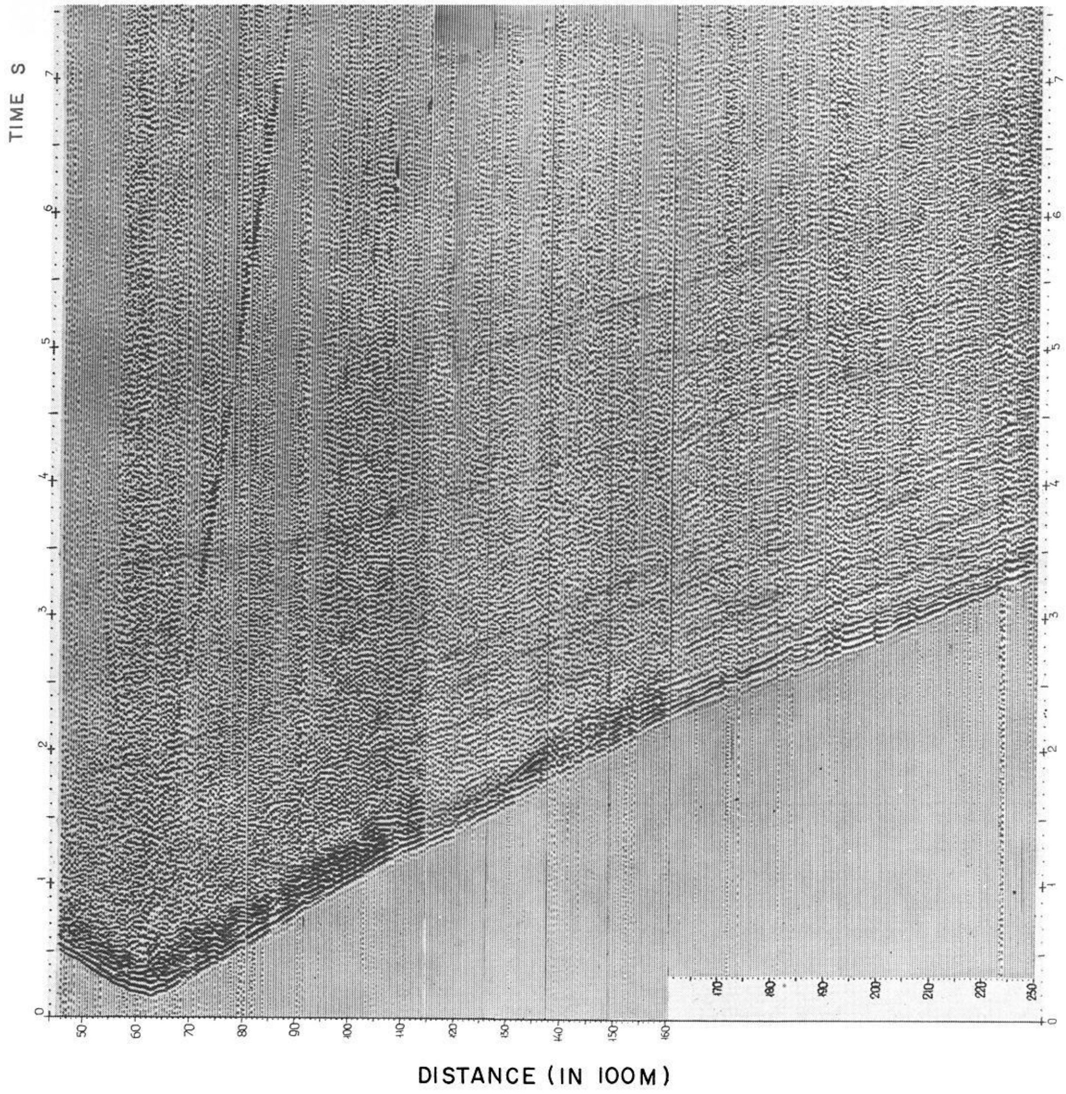


Fig. 3. Record-section in frequency band 9–19 Hz for *SP 2 on Profile I*

Chibisov's (1934) method, intersection-point method, intercept-time method). The average-velocity curves for SP 2–4 of Profile I coincide perfectly (Fig. 7); at SP 5 lower velocities are obtained for 0.5 to 3 km depth; at SP 1 higher values are found. The computed layer velocities agree well with the observed apparent velocities. Owing to less data along Profile II, only one average velocity-depth curve was determined here.

The refractors were computed with various methods. For Profile I, depths and dips were computed with generally known formulae based on apparent velocity V^*, intercept time t_o, average velocity $\bar{V}$, and the values of X and t at both ends of the observation range. The results are given in Table 2. The cross-section (Fig. 8a) shows a complicated structure in the upper part which is considered as a gradient zone. The velocity increases with depth, most strongly in the uppermost 500 m; toward the neovolcanic zone there exist high-velocity intercalations. The boundary velocities are shown in the section (Fig. 8a). The boundaries dip toward the neovolcanic zone with angles of 5°–10° for the flood basalts and 2°–4° at greater depth. At the eastern end of Profile I, the dips slightly decrease.

On Profile II in the neovolcanic zone (Fig. 8b), the boundaries were determined with the intercept-time method and with the time-field method (Riznichenko, 1946). The section has a synclinal structure; the refractors with flood-basalt velocities (4.5–4.7 km/s) regularly dip toward the axis to depths of 3 km, while on Profile I they extend from the surface to about 1.5 km.

Characteristics of the Reflections

Special record-sections were assembled for the identification of reflections (Figs. 2 and 3). Surface waves, shear waves, and diffractions are typical for the sections. Some low-velocity waves join the first phases in certain parts of the profile. Their apparent velocities are practically constant and equal to the velocity of the surface layers (2.5–4 km/s). Diffraction centers seem to occur near the surface usually at fractures, near-surface faults, areas of exposed high-velocity beds, etc.

A large number of wave groups mostly of small intensity are identified in the region where reflections are expected. They can be traced over distances from a few hundred meters to several kilometers. Some have infinite or even negative apparent velocities; they may be reflections from steeply dipping (>45°) boundaries, propagating in a medium with a positive velocity gradient.

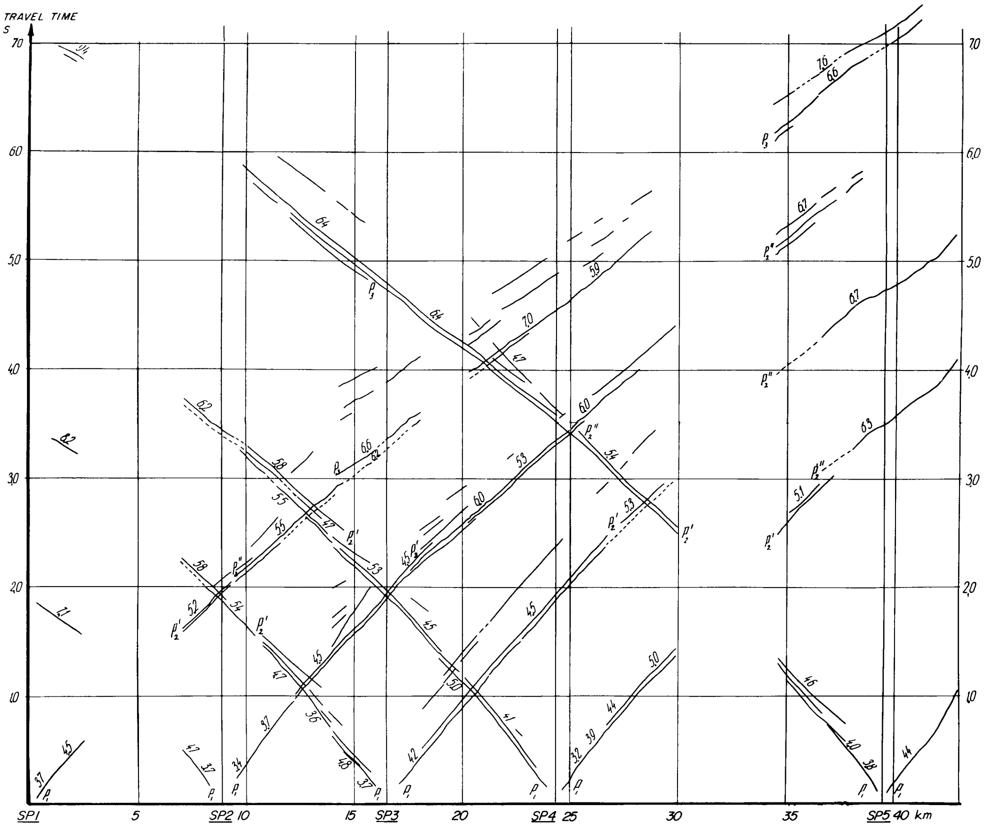


Fig. 4. Travel-time curves of the refracted waves recorded on Profile I

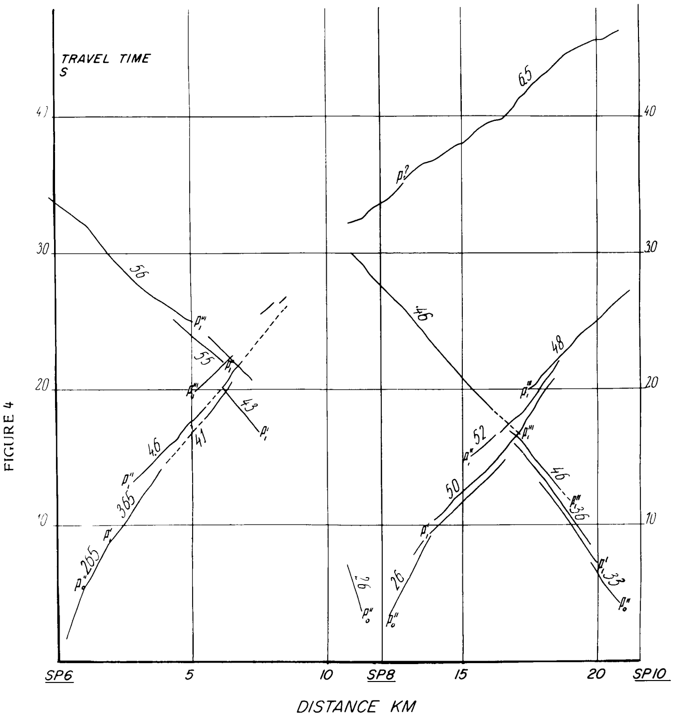


Fig. 5. Travel-time curves of the refracted waves recorded on Profile II

Table 1. Parameters of wave groups

Wave groups	Range of apparent velocities V^* (km/s)	Range of distances (km) for first arrivals
Profile I		
P_1	3.0–4.7	0– 8
P'_2	4.7–5.6	8–12
P''_2	5.6–6.5	12–22
P_3	5.6–7.5	>22
Profile II		
P'_0	1.6–2.0	<1
P''_0	2.6–3.3	1–2
P'_1	3.6–5.0	2–6
P''_1	4.0–5.2	3–7
P'''_1	4.5–5.6	>5

Seismic Cross-Section From Reflections

Correlation of the reflections was carried out in two stages; first, emphasis was placed on tracing correlated waves in reversed sections; second, more intensive phases were identified in unreversed sections. The waves identified in the first stage were the basis for determining the velocity section at greater depth. For that purpose, effective velocities were computed and the corresponding reflecting elements were constructed for all reversed time curves,

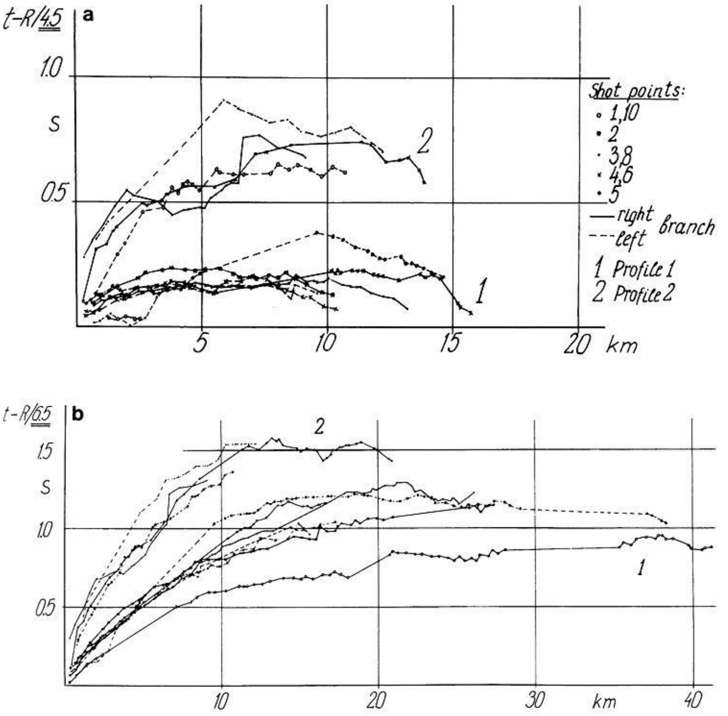


Fig. 6a and b. Travel-times of the first-arrival waves from all shot points on both profiles, with reduction velocities of (**a**) 4.5 km/s and (**b**) 6.5 km/s

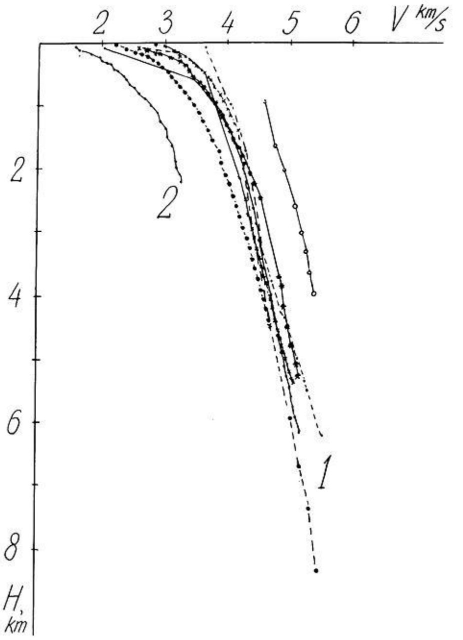


Fig. 7. Average velocities computed from the travel-time curves of refracted waves for different shot points (symbols as in Fig. 6)

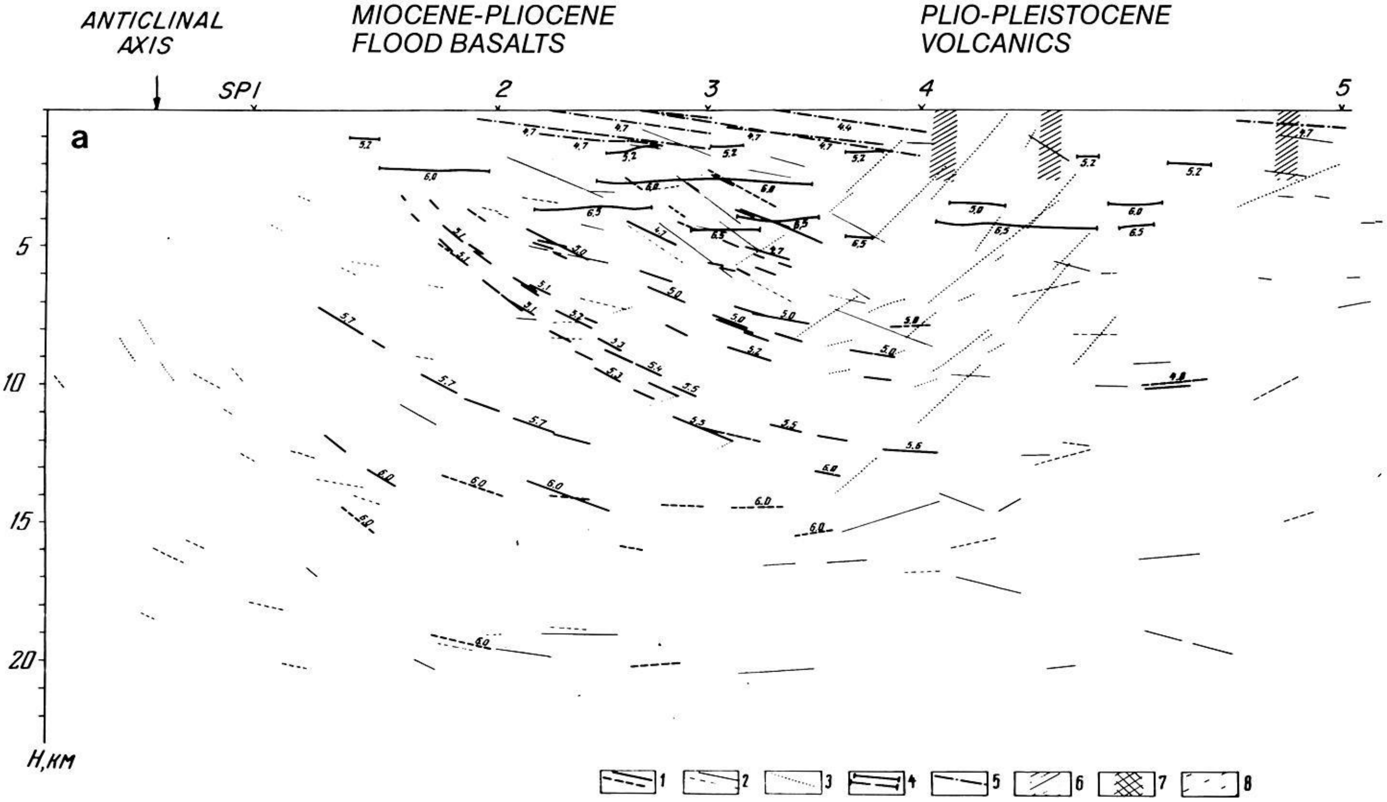
then for the unreversed ones. The velocity section derived from the refractions was also taken into account. The reflectors were constructed by conventional methods with the use of reflection times and average velocities above (given in Fig. 8).

Discussion of the Results

The refraction cross-sections (Fig. 8) are in general agreement with previous models (Pálmason, 1971). The present observations give a more detailed picture. Velocities of 3.7 to 4.7 km/s are typical for the Tertiary flood basalts along Profile I, ranging in age from about 6 to 2 Ma. The highest velocities are found in the region of Borgarfjördur in the west, close to the Borgarfjördur anticlinal axis (Fig. 1). Along lake Skorradalsvatn (SP 2–4) the flood basalts are characterized by a general velocity increase with depth. High-velocity layers representing denser lava flows alternate with lower-velocity layers. The seismic layers dip toward the neovolcanic zone at 8°–9° in agreement with the dip of the surface flood basalts. At a depth of 1.5–2.5 km, seismic boundaries have a more gentle dip of up to 3° or 5°. East of Skorradalsvatn, 4.5–4.7 km/s boundaries have been traced, but with large gaps. This suggests a more complex geological structure, although the data are also more scanty.

In the flood basalt region a boundary was determined with a velocity of 6.5 km/s at a depth of 3–4 km. Such a boundary has been found all over Iceland (Pálmason, 1971). It has been suggested that this boundary in Iceland is related to a change in physical conditions in the crust and to a certain grade of metamorphism.

In the flood basalt area of Profile I, it is possible to identify several definite reflecting horizons which dip toward the active volcanic zone. Usually they can be traced from a depth of about 3–4 km, i.e., deeper than the refractor of 6 to 6.5 km/s. Their dip is steep, up to 30° and even more, at depths of 3 to 7 km. At greater depths the dips decrease to 20° and less. The deepest elements are traced to 16 or 20 km with dips not exceeding 10°. The most prominent reflecting horizon, traced under SP 3 at 11 km depth and under SP 2 at 6 km, may be exposed between Borgarfjördur and Skorradalsvatn, where also a change of velocity is found at the surface. East of Skorradalsvatn (SP 4–5) the reflectors are less regular and considerably less steep; this may indicate a more complicated geological structure, but may also be an artefact of the methods used (end of profile, breaks in observations). Diffracting zones are typical for this part, and reflecting elements have very steep dips indicating fractures and lateral structures.



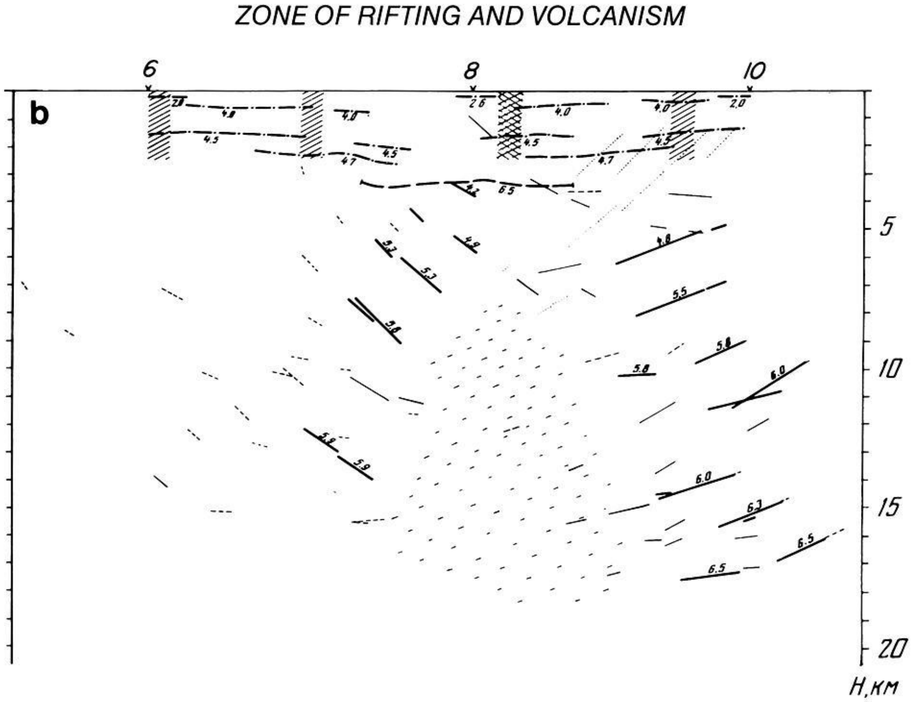


Fig. 8a and b. Seismic cross sections: **a** Profile I and **b** Profile II. *Legend: 1* and *2*: reflecting horizons constructed from the travel-time curves, checked in reversal points (*1*) and from single curves (*2*); the *dotted lines* indicate less reliable data; the *numbers* are computed average velocities in overlying section; *3*: steeply dipping reflectors, in some cases probably laterally displaced from section; *4*: refractors constructed from reversed curves (*solid lines*) or single curves (*dashed lines*); the numbers are boundary velocities; *5*: refractors probably connected with geological horizons; *6* and *7*: fracture zones derived from diffraction points and confirmed by geological observations **non**active (*6*) and active (*7*) in Holocene time; *8*: body with homogeneous seismic property, probably a region of melting temperature

In the active volcanic zone the reflecting horizons dip at steep angles of 25°–30° toward the axis near SP 8. This axial region is slightly displaced eastward from that defined by the refractors.

It may be assumed that the reflectors are boundaries between lava flows and other strata in the basalt series, such as compositional boundaries, fault zones, dykes, intrusive sheets, and metamorphic boundaries. The impedance change across these boundaries gives rise to the reflections. The average elastic properties of the rocks in the cross-section, nevertheless, vary only gradually as the result of compaction caused by pressure, heating, and hydro-

Table 2. Boundary parameters (V_b, ϕ, h) computed from single travel-time curves of refracted waves

Number on travel-time curves	Shot point	Distance on record-section (in 100 m)	Input data for computation		Results			
					$\bar{V}$ km/s	V_b km/s	Dip degrees	h km
1	4	91.5-172.5	$t_0 = 0.25$ s $X_k = 5.4$ km	$V^* = 5.0$ km/s	3.7	4.4	8	0.76
2	3	120.5-133.5	$t_0 = 0.1$ s	$V^* = 4.8$ km/s $V^*_{\text{rev}} = 4.4$ km/s	3.44	4.6	3.5	0.26
3	4	120.5-149.5	$t_0 = 0.49$ s $V^* = 5.3$ km/s	$t_{ip} = 1.31$ s $X_k = 10.3$ km	3.96 4.0	4.7	9-10	1.6
4	3	85.0-103.5	$V^* = 4.7$ km/s $t_{ip} = 0.68$ s	$X_k = 5.75$ km	3.64 3.62	4.3	8	0.8
5	2	131 -148	$V^* = 4.5$ km/s		3.93			
	3	56.5- 73	$V^* = 5.4$ km/s			4.7	7	1.34
6	5	340 -360	$t_0 = 0.23$ s	$V^* = 4.9$ km/s	3.47	4.6 4.7	4 2.5	0.61 0.59

Computation formulas: $t_{ip} = \frac{2 \cdot h \cdot \cos\phi}{\bar{V} \cdot \cos(i \mp \phi)}$; $t_0 = \frac{2 \cdot h \ \cos i}{\bar{V}}$; $V^* = \frac{\bar{V}}{\sin(i \mp \phi)}$

$\tan\phi = \frac{h}{X_k}$; $\sin i = \frac{\bar{V}}{V_b}$

V = Boundary velocity; ϕ = Dip angle; h = Depth

thermal alteration. These processes have a more regional character and lead to more regular refraction than the smaller reflecting elements. The medium containing the reflectors is characterized by velocities of the refracted waves not greater than 7–7.1 km/s, as indicated by the interpretation by G.A. Krasilschikova (personal communication) of a 200 km refraction profile extending our Profiles I and II to the east (W.R. Jacoby, H. Gebrande, and H. Miller, personal communication).

The generalized seismic cross-section of Fig. 8 shows the refracting and the reflecting elements. The faults shown schematically are based on geological data and diffractions. The regular pattern of reflectors in the central part of Profile I (SP 2–4) changes eastward to a complicated zone with more sub-vertical boundaries near the surface and sub-horizontal reflectors at depth.

The axial region of the rift zone is characterized by a depression in the layers with typical flood basalt velocities; the depression is filled with recent low-velocity volcanics. At greater depths reflectors dip steeply toward the axis. In the central part of the active zone, reflecting horizons are absent suggesting homogeneity in physical properties below 8 km depth. This region may be in the state of partial melting or a magma chamber The inclined reflectors on both sides may be intrusive sheets as suggested by Walker (1975) to be important in the lower crust, and as commonly found in the shallow roots of central volcanoes (e.g. Fridleifsson, 1977). The inclined reflectors could also be lavas sagging down above a magma chamber, but it seems unlikely that the deeper reflectors are lavas, since the present rate of volcanism is equivalent to a total lava layer of only some 6–7 km thickness. A similar reasoning may be applied to the deeper reflectors of Profile I along the flood basalts to the west. About 15 km southwest of the suggested magma region was a magneto-telluric station of Hermance and Grillot (1970; 1974); they estimated, on the basis of their observations, that the temperature at 10 km depth should be 800°–1 200° C.

The cross-section of the present study bears a certain resemblance to the crustal structure deduced by Bodvarsson and Walker (1964) on the basis of observations in eastern Iceland. It is also similar to the model of Pálmason (1973, 1980) based on the same data. In particular, these authors predicted the dip of the flood basalts and the presence of a region of partial melting at relatively shallow depth beneath the axial rift zone. These predictions seem to be borne out by the present results.

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