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Structure and Evolution of the Hengill-Grensdalur Volcanic Complex, Iceland: Geology, Geophysics, and Seismic Tomography

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Recent geological and geophysical research indicates the presence of three volcanic systems in the Hengill-Grensdalur area and progressive westerly migration of the accretionary plate boundary. The Hengill system comprises the active Hengill central volcano and a NNE trending fissure swarm that is the present locus of crustal accretion in the area. Extinct volcanic systems are identified with the mountain Hromundartindur and the Grensdalur area and associated NNE trending zones. The Grensdalur system was formerly the locus of accretion in the area. A widespread geothermal area encompasses the whole area and is fueled by at least three distinct heat sources associated with the three volcanic systems. A tomographic study of the upper 5 km of crust, using local earthquakes, imaged three bodies with velocities up to 15% higher than the average background velocities and volumes of several tens of cubic kilometers. One of these underlies the Grensdalur volcano, and a second underlies the Olkelduhals area within the Hromundartindur system. These are interpreted as intrusions that are the solidified magma reservoirs of their respective volcanic systems and the heat sources of those parts of the geothermal area above them. The third high-velocity body underlies the extinct basalt shield Husmuli, which is not associated with geothermal resources. That body is interpreted as a cold intrusion that is the frozen magma conduit that fed the surface eruptive site. A low-velocity body with a volume of a few cubic kilometers was imaged in the depth range 2-4 km beneath the northern part of the presently active Hengill central volcano. This volume may contain partial melt and represent the heat source, or part of the heat source, fueling the Hengill field. Heat balance calculations show that subsurface magmatism continued in the extinct Grensdalur volcano long after volcanic activity and crustal accretion migrated from it to the Hengill system.

1. Introduction

During the last decade, seismic tomography has been applied extensively to research the three-dimensional structure of the crust and upper mantle on regional and local scales. Since central volcanoes and geothermal areas in particular are associated with extreme lateral crustal and mantle structural inhomogeneities, several of these have been targeted using either teleseisms or local earthquakes [e.g., *Iyer*, 1984].

Of great interest is the possibility of delineating magma chambers or volumes of partial melt within the crust or upper mantle that would be manifest by zones of relatively low-velocity [*Mavko*, 1980]. A number of studies using teleseisms have successfully achieved this, for example, Yellowstone [*Iyer*, 1979], Kilauea [*Ellsworth and Koyanagi*, 1977], Etna [*Sharp et al.*, 1980], Coso [*Reasenberg et al.*, 1980], the Roosevelt Hot Springs [*Robinson and Iyer*, 1981], and the Geysers-Clear Lake area [*Iyer et al.*, 1979; *Oppenheimer and Herkenhoff*, 1981]. In all these cases, low-velocity volumes were imaged, which were interpreted as zones of 5-30% partial melt. These results were in concord with surface geology and also laboratory experiments which show that velocity reductions may exceed 50%. In several other cases, however, no evidence was found for low-velocity bodies using teleseisms, for example, Mount Hood [*Weaver et al*, 1982] and Newberry Volcano [*Stauber et al.*, 1988].

Whereas the long wavelengths of teleseisms limit the image resolution to several kilometers, the higher frequencies of regional or local earthquake or explosive phases enable crustal velocity anomalies to be imaged on the scale of a single kilometer. Again, several central volcanoes and geothermal areas have been targeted using this methodology. *McNutt and Jacob* [1986] imaged the roots of Pavlof Volcano, Alaska, using regional events, and local events were used to study the structures of Mount Hood [*Leaver*, 1984], Kilauea [*Thurber*, 1984], Long Valley [*Kissling et al.*, 1984], the Geysers area [*Eberhart-Phillips*, 1986], and the Coso Hot Springs [*Walck and Clayton*, 1987]. Regional explosions have recently been used to image Newberry Volcano [*Achauer et al.*, 1988], and Medicine Lake Volcano [*Evans and Zucca*, 1988].

It is interesting to note that with the exception of Kilauea and Medicine Lake Volcano, and possibly Newberry Volcano, none of these small-scale studies revealed clearly defined low-velocity bodies that could be identified as crustal level magma chambers. In the cases of Long Valley and the Coso Hot Springs, broad regions of slightly low-velocity were identified that were interpreted as partial melt, but in the cases of Mount Hood and the Geysers, high-velocity volumes were imaged that were interpreted as igneous intrusive bodies. High velocities were also detected beneath the Kilauea rift zones and surrounding the small, low-velocity magma chamber, in the neighborhood of ring fractures at Newberry Volcano and at Medicine Lake Volcano.

A tomographic study of the Hengill-Grensdalur volcanic complex was performed using local earthquakes and adds another case history. In the case of this study, most notable are the three high-velocity bodies imaged, which correlate well with extinct surface eruptive sites. A low-velocity zone underlying the presently active Hengill central volcano and the accretionary plate boundary was observed. However, its volume was small in comparison with the three imaged anomalously high-velocity volumes.

The high-velocity bodies are interpreted as intrusives that represent solidified shallow crustal magma reservoirs or conduits to the surface. Two of these are still hot and fuel geothermal fields at the surface, but the third is not cooling rapidly. The small, low-velocity body beneath the northern part of the presently active Hengill central volcano may represent partial melt. This paper synthesizes recent geological and geophysical work conducted in the area and interprets the results of the tomographic study in the context of other studies.

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2. Synthesis of Previous Work

The Hengill ridge-ridge-transform triple junction is the meeting point of the Reykjanes Peninsula Volcanic Zone, the Western

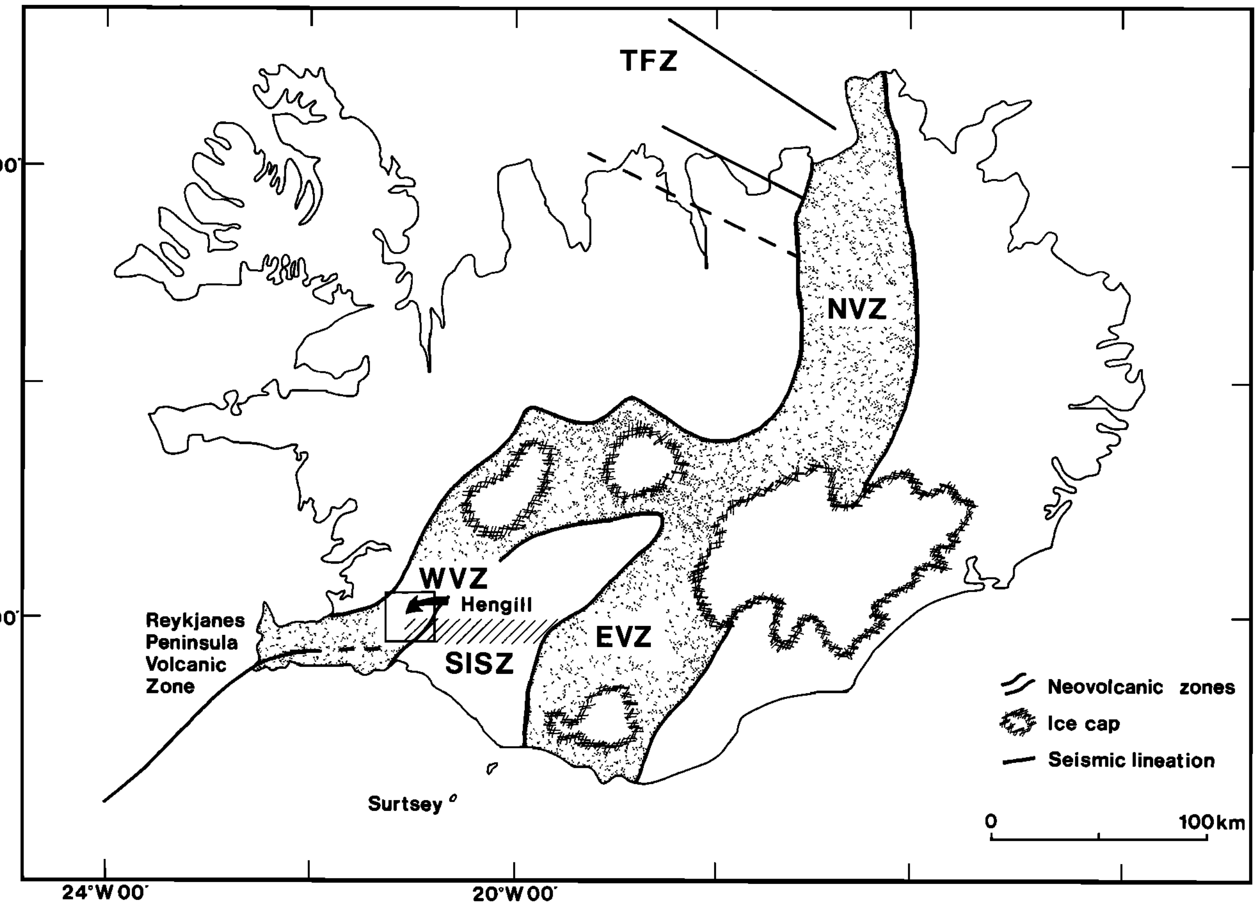

Fig. 1. Regional tectonic map of Iceland. WVZ, Western Volcanic Zone; NVZ, Northern Volcanic Zone; EVZ, Eastern Volcanic Zone; SISZ, South Iceland Seismic Zone; TFZ, Tjornes Fracture Zone. The Hengill-Grensdalur area, shown in detail in Figure 2, is indicated by a box.

Volcanic Zone (WVZ) and the South Iceland Seismic Zone (SISZ), which is considered to be a complicated fracture zone [*Einarsson and Eiriksson*, 1982] (Figure 1). The ridge-ridge-transform configuration is unstable. At present the locus of accretion in south Iceland is progressively being transferred from the WVZ to the Eastern Volcanic Zone (EVZ), the southern tip of which is propagating south at an average rate of 3.5-5 cm yr^{-1} [*Einarsson*, 1988]. The SISZ connects the southern end of the EVZ to the WVZ and is thus also propagating south at the same rate [*Einarsson and Eiriksson*, 1982].

The Hengill triple junction is a distinct structural unit [*Foulger*, 1988*a*]. Within it, the western extremity of the SISZ lies southerly with respect to the zone of accretion, which comprises three volcanic systems (Figure 2). The first, comprising the Grensdalur volcano and an associated NNE trending fissure swarm, was the locus of volcanism and accretion prior to and during the early Bruhnes geomagnetic epoch (approximately -0.7 Ma to present), but subsequently became extinct as volcanism and the locus of crustal accretion migrated northwest. The Grensdalur volcano was later deeply eroded, and its roots are now exposed in sections where intrusions and dykes are observed [*Saemundsson and Arnorsson*, 1971].

The second, the Hengill system, comprises the active Hengill central volcano and a NNE trending fissure swarm that is the present locus of accretion. It has been volcanically active since -0.3 Ma (H. Franzson, unpublished borehole data, 1986) and has produced four postglacial (younger than 10,000 years) lavas [*Saemundsson*, 1967].

A third volcanic system, the Hromundartindur system lies approximately parallel to and between the Hengill and Grensdalur systems [*Arnason et al.*, 1986, 1987]. No mature NNE trending rift/graben developed in association with this system, but a NNE trending eruptive zone is identified at the surface. This system has been volcanically active during the same period as the Hengill system, although no surface eruption has occurred for approximately 10,000 years [*Arnason et al.*, 1987]. It derives its name from the mountain Hromundartindur which is the highest topographic feature of the system and contains intermediate rocks. These rocks may provide evidence for a fractionating crustal magma chamber.

It is probable that since the demise of the Grensdalur system, the majority of volcanism and crustal accretion has occurred within the Hengill system, but minor eruptive activity occurred concurrently within the Hromundartindur system. The latter is now relatively inactive [*Saemundsson*, 1967]. Volcanism within the Hengill system has occurred westerly of late, which is consistent with the continuation of westwards volcanic migration in this area [*Arnason et al.*, 1987].

A secondary tectonic structural trend transverse to the dominant NNE trend of accretionary features within the area has developed in a zone that connects the centers of the Hengill and Grensdalur volcanoes and passes through Olkelduhals (Figure 2). This secondary tectonic structure manifests itself as an elongated topographic high that traverses all three volcanic systems and upon which WNW trending eruptive sites, lines of hot springs and fissures occur. This transverse structural trend may be traced for a distance of 15 km and has developed in response to the radial stress fields associated with the Hengill and Grensdalur central volcanoes, and the trajectory of volcanic migration [*Foulger*, 1988*a*].

An extensive high-temperature geothermal area encompasses the Hengill and Grensdalur central volcanoes, and the whole area displays a continuous background of small-magnitude earthquake activity that correlates spatially with surface heat loss [*Foulger*, 1988*a*]. This activity is known to have been spatially and temporally constant for at least 15 years. Many events have non-double couple radiation patterns with enhanced compressional fields

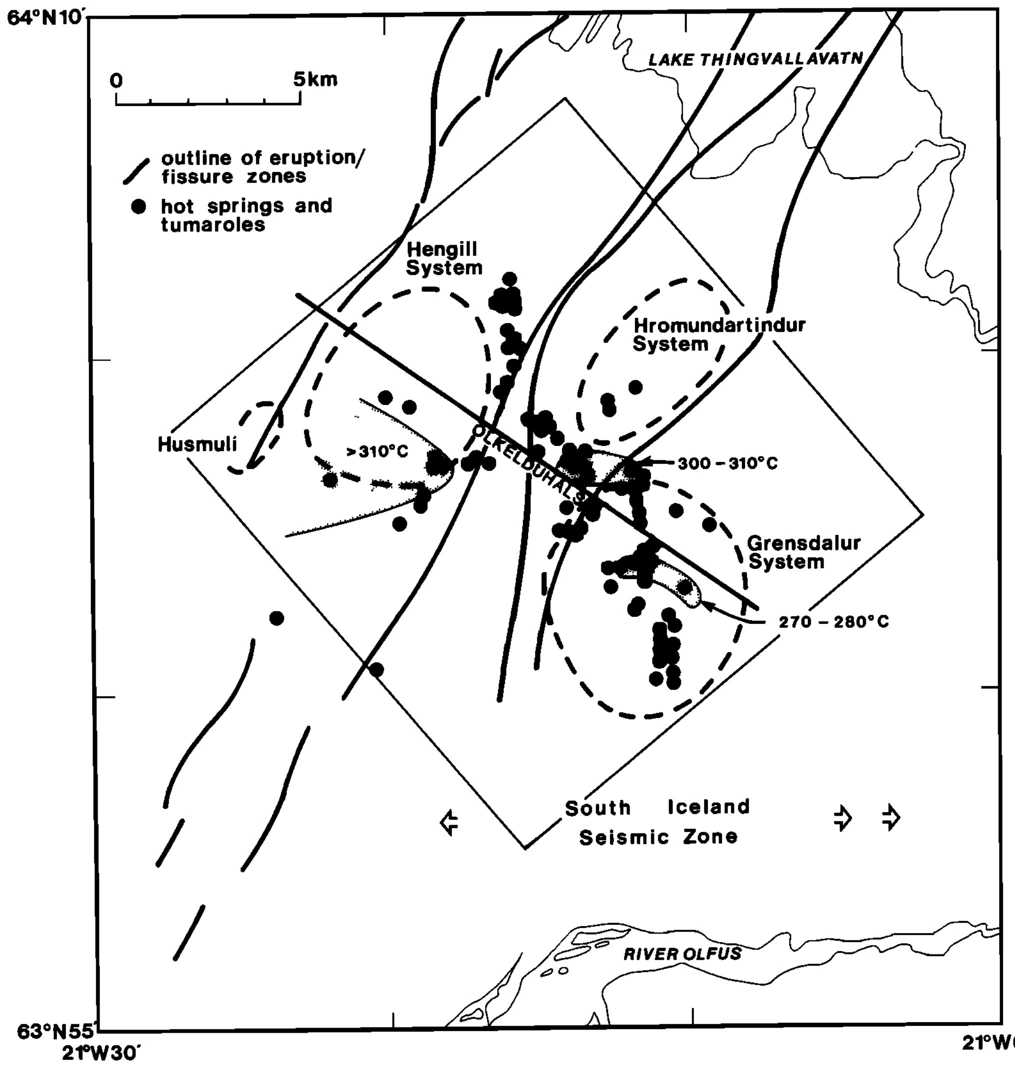

Fig. 2. Schematic tectonic map of the Hengill triple junction. Bold lines indicate the outlines of NNE trending eruption/fissure zones. The four eruptive centers mentioned in the text are outlined by dashed lines and, in the cases of the Hengill and Grensdalur systems, are those central volcanoes. Hot springs and fumaroles are indicated by dots. The line connecting the Hengill and Grensdalur volcanoes indicates the axis of the transverse tectonic structure. Volcanism migrated along this axis subsequent to -0.7 Ma. The three separate geothermal reservoir temperature maxima determined from the geochemistry of fumarole gases are shaded [from *Saemundsson*, 1967; *Torfason et al.*, 1983; *Arnason et al.*, 1986, *Foulger*, 1988*a*].

and were interpreted by *Foulger and Long* [1984] and *Foulger* [1988*b*] as being due to tensile crack formation within the heat source of the geothermal area. These tensile crack events are mixed together with small shear events. This activity occurs in response to the cooling and contraction of the rock under the influence of circulating groundwater fluids, in a tensile stress regime [*Lister*, 1974, 1976, 1977, 1980; *Bjornsson et al.*, 1980]. The spatial distribution of the continuous, small-magnitude earthquakes therefore indicates the extent of the cooling parts of the heat sources, and the seismic rate is related to rate of heat loss [*Foulger*, 1988*b*]. A principal conclusion of *Foulger* [1988*b*] was that the geothermal area is fueled by hot rock underlying both the Hengill and Grensdalur central volcanoes and the transverse tectonic structure between them.

Geochemical studies of fumarole gases detected three separate reservoir temperature maxima (Figure 2) [*Torfason et al.*, 1983]. The hottest underlies the Hengill volcano (>310°C), but this part of the geothermal area only accounts for about one third of the total surface heat loss of the entire area. A second reservoir temperature maximum (300°-310°C) was detected beneath the transverse tectonic structure, in an area known as Olkelduhals, where the most intense geothermal activity within the Hromundartindur system occurs. A third, the coolest, (270°-280°C), was associated with the Grensdalur volcano where widespread geothermal displays also occur.

The results of these various studies are consistent and indicate the presence of two extinct volcanic systems and one active one within the area and a progressive westward migration of the locus of crustal accretion. The extensive geothermal area is fed by at least three distinct heat sources, beneath the Hengill volcano, the Olkelduhals area within the Hromundartindur system, and the Grensdalur area.

3. TELESEISMS

Teleseismic arrival time delays provide evidence for crustal inhomogeneity. During a 3-month period in 1981 a 23-station seismometer network was deployed in the area with station spacings typically 3 km. In addition to a large number of local earthquakes that were used for the tomographic inversion, a suite of 21 teleseisms with clear *P* wave arrivals was recorded. The locations of these events fell broadly into four geographical groups: Europe and western Asia, Japan and the Kuriles, the Caribbean and Atlantic, and the Tonga-Fiji region (Figure 3).

The paucity of data precluded a formal tomographic inversion; therefore analysis of the data was limited to averaging the relative arrival times to give a single delay time for each station. These delay

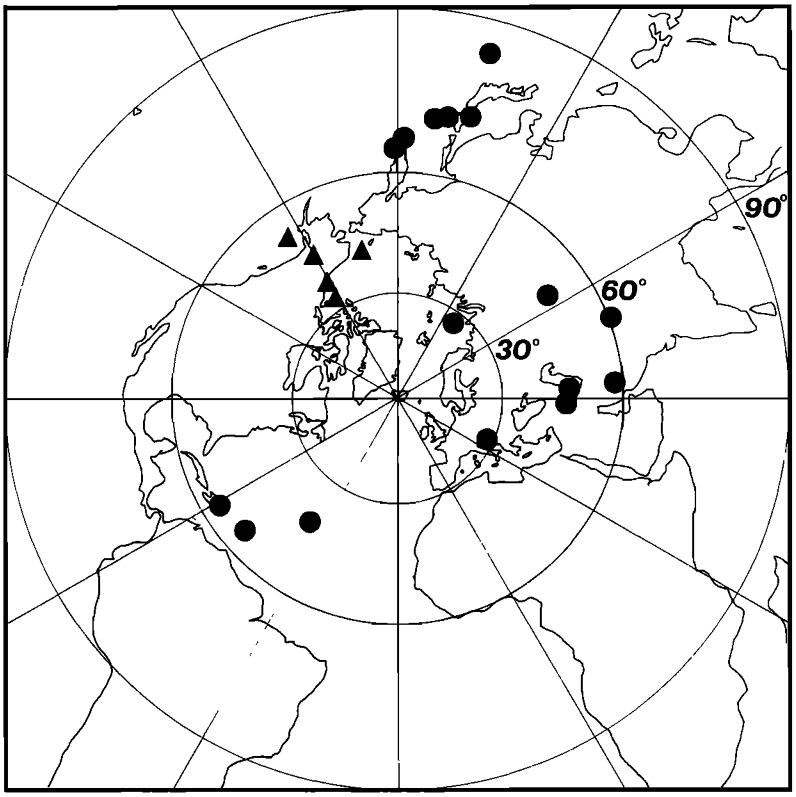

Fig. 3. Locations of events used in the teleseismic analysis, shown on a stereographic projection of world coastlines centered on Iceland. Dots, upper hemisphere epicenters; triangles, lower hemisphere epicenters. (These were in the Tonga-Fiji region).

times were calculated using all the events equally weighted. The average horizontal wave propagation velocity was calculated using the Herrin tables [*Herrin*, 1968]. An arbitrary zero was assigned to station KDN, which was peripheral to the network and the delays calculated are contoured in Figure 4. The angles of incidence of the incoming rays were mostly in the range 27°-15°, the dominant frequency of the *P* waves was 1 Hz, and their wavelength was approximately 6 km. The structures causing the relative delays shown in Figure 4 are therefore on the scale of several kilometers.

This averaging method results in anomalies mostly reflecting shallow crustal features, and not deep structure (H. M. Iyer, personal communication, 1988). They are therefore broadly comparable with the results of the tomographic inversion of local earthquake data described below, which resolved the upper 5 km of crust.

The broad picture that emerges is of positive delays (i.e., relatively low velocities) associated with the active volcano Hengill and negative delays (i.e., relatively high velocities) associated with the Grensdalur and Hromundartindur areas SE and E of Hengill and the Husmuli basalt shield W of Hengill (Figures 2 and 4). This broad pattern of delays remained stable if the data set was narrowed to the best arrivals only, or subdivided into azimuthal groups.

These results indicate lateral crustal inhomogeneity and might be explained by the existence of high-density, high-velocity material underlying the extinct volcanic sites to the west and southeast of Hengill, and relatively low-density, low-velocity material beneath Hengill. This broad structural picture is supported by the results of a detailed gravity survey in the area that shows Bouguer gravity highs in the Grensdalur and Husmuli areas and gravity lows over Hengill and its associated volcanic zone [*Thorbergsson et al.*, 1984].

The shapes of the contoured velocity highs and lows are not well resolved on a scale smaller than a few kilometers since this is the wavelength of the phases used, and events from different azimuths are averaged. The pattern of delays is statistically significant (the standard error of the calculated delays was 0.005 s) and shows a general agreement with the results of the tomographic inversion of local earthquakes interpreted below. The areas of high-velocity coincide very nearly with the surface projections of high-velocity bodies imaged in the tomographic inversion, and the magnitude of the teleseismic relative delays is approximately that which would be expected from the structures imaged by the tomographic inversion (see below).

4. SYNTHESIS OF THE LOCAL TOMOGRAPHY RESULTS WITH THE KNOWN STRUCTURE OF THE AREA

The tomographic inversion of the local earthquake data is described in detail by *Toomey and Foulger* [this issue]. They analyze the effects of model parameterization, quantify resolution of model parameters, and present a three-dimensional perspective plot of crustal heterogeneity. They illustrate the crustal heterogeneity on the basis of $\pm 7\%$ velocity deviation (from the regional one-dimensional model), since this yields the most coherent picture. The volume imaged was a crustal block 14 X 15 km^2 in lateral extent and 5 km in depth. The results of the tomographic study are illustrated here by a series of plan views of normalized velocity perturbations at different depths (Figure 5) and of cross sections orientated parallel to the main structural trends of the area (Figures 6 and 7). Velocity perturbations quoted are relative to the regional one-dimensional model [Foulger, 1988*a*]. The main geological structural elements are superimposed.

A general feature of the results is the clear demarcation between the upper 2 km or so of crust that has velocity gradients of 1.2-1.4 s^{-1} in the approximate interval 3-5.8 km s^{-1} and the crust below this that has much lower velocity gradients (0.2-0.3 s^{-1}) in the approximate interval 5.8-6.4 km s^{-1}. This characteristic of the study volume is apparent throughout the cross sections of Figure 7.

A number of local features were also imaged by the inversion, with lateral variations ranging from +15% to -10% from the original starting model (velocity perturbations of up to 0.45 km s^{-1}). Three of these were high-velocity bodies. One high-velocity body coincides with the extinct Grensdalur central volcano. This body is best illustrated in the plan views of Figures 5*a*-5*c* but can also be seen as an updoming of the velocity contours in the neighborhood

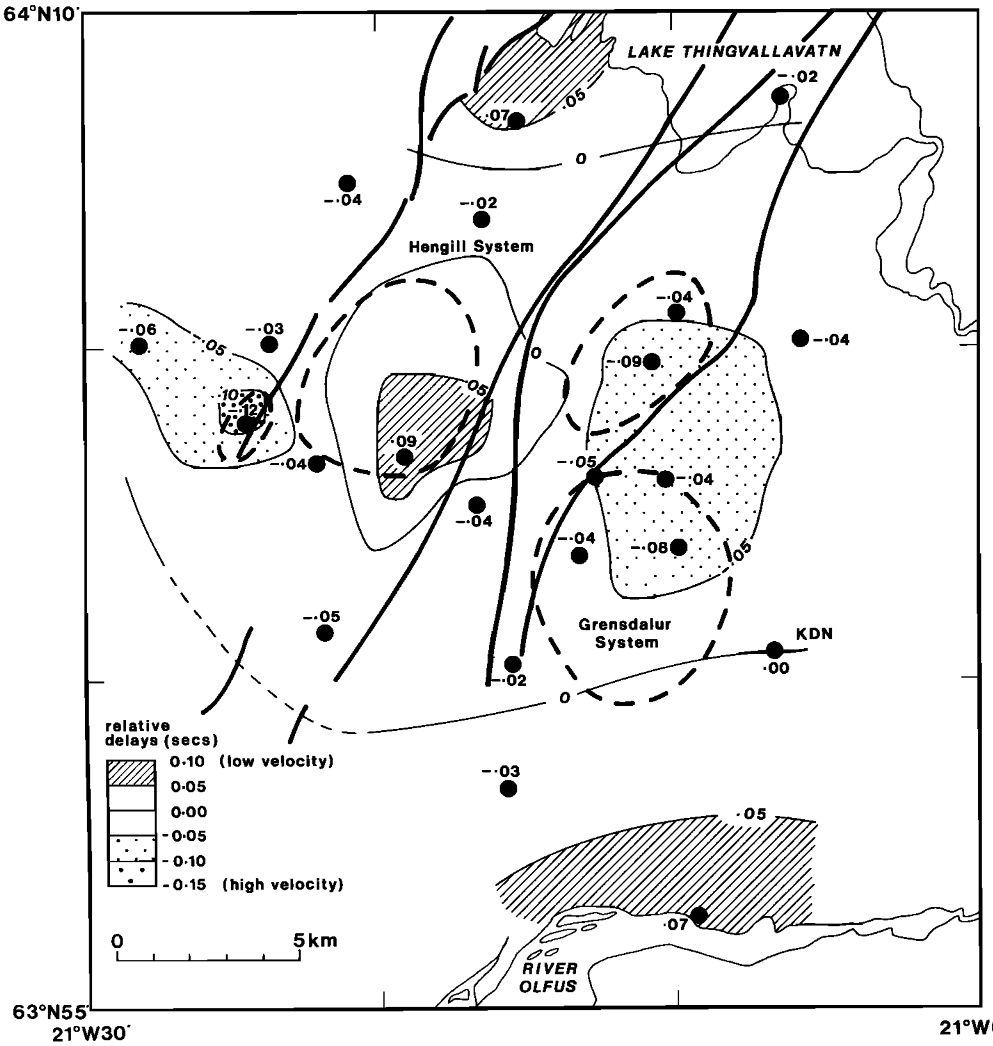

Fig. 4. Contoured average teleseismic P wave delays for 21 events recorded over a 3-month period. Stations are indicated by dots, each annotated with the delay in seconds associated with it. The main tectonic features of the area are also shown (cf Figure 2).

of the Grensdalur volcano in sections AA' and YY' of Figure 7. It extends from the surface to about 3 km depth. Velocities up to 15% higher than the original starting model are constrained in the shallowest levels. The > +7% velocity anomaly has a volume of 40-50 km^3 [*Toomey and Foulger*, this issue, Figure 9].

A second well-defined high-velocity body is imaged to the west of the Hengill central volcano. This body underlies a basalt shield 2-3 km in diameter known as Husmuli (Figures 2, 5, and 7). It has a slightly greater depth extent than that underlying the Grensdalur volcano, and is identifiable in the upper left hand corner of the plan views of Figure 5 and in cross sections WW', XX', and YY' of Figure 7 from the surface down to at least 4 km depth. It is characterized by velocity deviations of up to +15% from the normal (velocity perturbations of up to 0.45 km s^{-1}). It exhibits maximum velocities of about 6.6 km s^{-1} at approximately 3.5 km depth, which is approximately 6% higher than the 6.2 km s^{-1} typical for this depth. It is of narrow lateral extent (1-2 km) compared with its vertical extent (it is identifiable in the cross sections of Figure 5 from 0 to 3 km depth), and therefore forms a conduitlike structure through at least the upper 4 km of the crust (see also Figure 9 of *Toomey and Foulger* [this issue]). The > +7% velocity anomaly has a volume of approximately 15-20 km^3.

The third and best resolved high-velocity body lies approximately midway between the active Hengill central volcano and the extinct Grensdalur volcano and underlies Olkelduhals. It is most clearly illustrated in Figures 5*d*-5*e*, which show plan views at 3 and 4 km depth, and sections CC', DD', XX', and YY' of Figure 7, which are vertical sections passing through it. The body occupies the depth range 2 to at least 4 km but does not extend to the surface. The highest velocities resolved lie at about 3 km depth, below which velocities appear to decrease to normal midcrustal values. This velocity inversion at about 4-5 km depth is not certain, however, given the poor resolution of the model at those depths [*Toomey and Foulger*, this issue]. The body has maximum velocities of over 6.8 km s^{-1}, as compared with typical velocities of about 6.2 km s^{-1} for that depth, which corresponds to a 13% lateral increase in velocity. The > +7% velocity anomaly has a volume of approximately 15 km^3.

Sections EE', XX', YY', and ZZ (Figure 7) illustrate the structure of the presently active Hengill volcano. Beneath its northern and eastern part and extending under the fissure swarm, a small low-velocity body with maximum velocity deviations of approximately -7% is imaged in the depth range 2-4 km. Velocity deviations are greatest at about 3 km depth. This body is best illustrated in section YY' (Figure 7. It does not extend up to the surface, and the < -7% velocity anomaly has a volume of approximately 5 km^3. These low velocities in the presently active accretionary zone contrast sharply with those associated with the flanking high-velocity bodies, and at 3 km depth the lateral velocity gradient is 0.8 s^{-1} which is considerably greater than the typical vertical velocity gradient at this depth. However, it may be seen from Figures 5*a*-5*f* that for the most part average seismic velocities characterize this volcano and the associated NNE trending accretionary plate boundary.

These four bodies represent the best resolved and most coherent

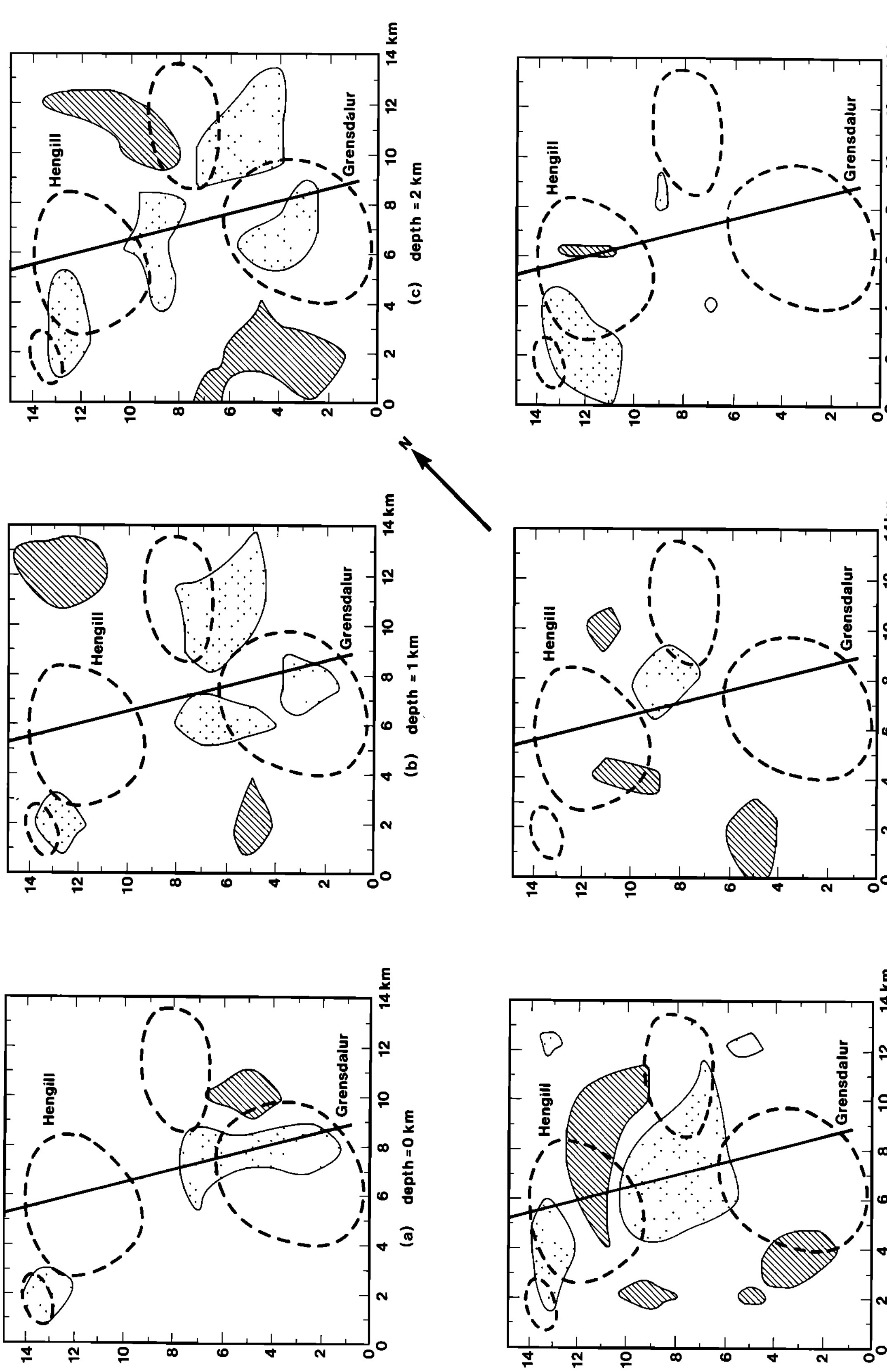

Fig. 5. Horizontal sections of the imaged volume at intervals of 1 km. Areas within which the normalised velocity perturbations are > +0.2 km s-1 (dotted shading, indicating relatively high velocities) and < -0.2 km s-1 (line shading, indicating relatively low velocities) are indicated. The positions of the major volcanological features are superimposed (cf. Figure 2).

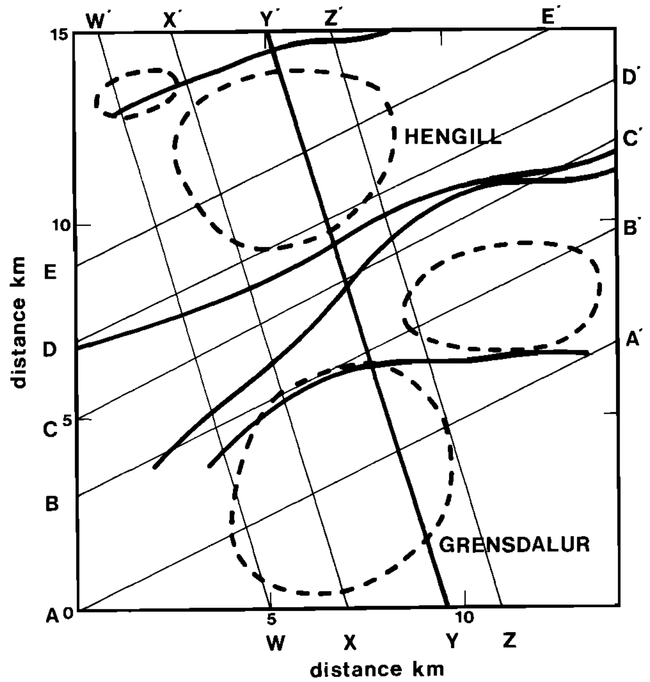

Fig. 6. Schematic diagram showing the lines of the cross sections presented in Figure 7 and the main tectonic features of the study area.

anomalies in the study volume, and those where velocity perturbations exceeded 7% of the average for that depth. A few other anomalies may be distinguished in Figure 5, smaller in both spatial extent and percentage velocity deviation. These are less reliably constrained and are therefore neglected in this discussion.

All accurately located earthquakes that lay within the study volume were relocated using the final three-dimensional velocity structure. In general, hypocentral adjustments were within the 32% error ellipsoids calculated by HYPOINVERSE (ERH, ERZ), which were typically a few hundred meters [*Foulger*, 1988*a*]. No significant systematic trend was discernable in the epicentral relocations but a small systematic shallowing of the hypocentral depths occurred.

Figures 8 and 9 illustrate the distribution of the earthquakes in relation to the main structural features imaged by the tomographic inversion. Figure 8 shows relocated epicenters superimposed on a velocity contour plot at 3 km depth. Figure 9 shows relocated hypocenters superimposed on a velocity contour cross section through the transverse tectonic structure (i.e., section YY' of Figure 7). All earthquakes with epicenters within 1.5 km of the line of section are projected onto Figure 9. The line of this section is indicated in Figure 8.

The greatest concentration of activity is associated with the high-velocity body underlying Olkelduhals and the seismic rate beneath the Grensdalur volcano is lower. The occurrence of earthquakes indicates solid rock, and if it is accepted that the seismicity is related to cooling, then it must be concluded that heat is being mined from these volumes. The earthquakes at the NW end of the section of Figure 9 lie outside the Husmuli body, so there is no seismic evidence that that body represents a cooling volume. The occurrence of some earthquakes within the low-velocity body beneath the Hengill system indicates that that body is at least partly solid and that it is also cooling.

In Figure 10 a schematic summary of the results is presented. The main structural features of the area are drawn, superimposed onto projections of the approximate extents of the anomalous bodies detected by the inversion. It should be borne in mind when examining Figure 10 that the depths and velocity contrasts of the bodies vary.

5. INTERPRETATION

Average One-Dimensional Crustal Structure

It is instructive to compare the general velocity depth structure from the tomographic inversion with those obtained by *Flovenz* [1980], who modelled refraction data for the whole of Iceland using synthetic seismograms (Figure 11). On the basis of his results, *Flovenz* [1980] divides the general Icelandic crust into the upper crust, where velocity increases continuously with depth, and a lower crust, where seismic velocities are constant. He further divides the upper crust into a shallower part, where vertical velocity gradients are large, and a deeper part, commencing at *P* velocities of about 4.0 km s^{-1}, below which the velocity gradient remains constant at about 0.6 s^{-1}. The base of the upper crust is placed at the 6.5 km s^{-1} velocity contour and lies at 5-6 km depth outside the neovolcanic zone. Beneath two extinct central volcanoes it occurred at depths as shallow as 1 km, and this was interpreted as indicating the top of high-velocity "chimneys" through the crust.

In Figure 11 a schematic comparison is made of the generalized crustal structure derived from the tomographic analysis and that of *Flovenz* [1980]. The results of the tomographic study agree qualitatively with the findings of *Flovenz* [1980] but differ in detail as follows: (1) the onset of the deeper upper crust, with constant velocity gradient, which the tomographic analysis indicates at about 2 km depth, occurs at velocities of about 5.4-5.8 km s^{-1}; (2) the velocity gradient in the deeper upper crust is 0.2-0.3 s^{-1}. In broad agreement with the findings of *Flovenz* [1980], the tomographic analysis also resolved velocities of 6.5 km s^{-1} at shallow depth (2.5 km) beneath extinct volcanic sites.

Three-Dimensional Structure

The interpretation of seismic velocity in terms of medium properties is complicated because of the large number of variables involved, such as percentage partial melt, fracture and melt geometry, density, temperature, pressure, phase of the pore fluid, and crystalline structure [*Iyer and Stewart*, 1977; *Iyer*, 1979]. In the absence of independent constraints, it is therefore not possible to interpret *P* wave velocity variations quantitatively or conclusively in terms of one property such as percentage partial melt.

In the case of the Hengill-Grensdalur area, however, a great deal is known about the crustal structure from the application of other research methods. The history of volcanic migration is well understood, petrological evidence exists for a variety of rock types, and where earthquakes are located, brittle failure is known to occur and it may be deduced that solid rock exists. Moreover, the seismically active volumes have been identified as the heat sources of the geothermal area [*Foulger*, 1988*b*].

The *P* wave velocity structure revealed by the tomographic inversion showed good correlation with the volcanic structure of the area. Variations in rock density and partial melt are to be expected throughout volcanic structures. Laboratory experiments demonstrate that high velocities are associated with dense, massive rock and that velocities decrease with increase in percentage partial melt [*Stewart and Peselnick*, 1976; *Peselnick et al.*, 1977]. We offer a qualitative interpretation of the results in terms of these properties that is in agreement with the known structure of the area.

The tomographic inversion clearly resolves three distinct high-velocity bodies in the depth range 0-5 km, and these results are broadly verified by the teleseismic relative delay time study. The bodies are characterized by velocity contrasts of up to 15% from the typical background and vertical extents of 2-4 k, and underlie the extinct Grensdalur central volcano the Husmuli basalt shield and the Olkelduhals area, within the Hromundartindur system. Assuming an average velocity of approximately 4.5 km s^{-1} for the crust, such bodies would be expected to produce teleseismic arrival time anomalies of approximately -0.1 s, which agrees well with the observations (Figure 4).

The body in the vicinity of the Grensdalur volcano extends from the surface, where velocity variations are as high as 15% above the surface average, down to 3 km depth. Surface geological observations indicate that in this area the deeply eroded roots of an extinct volcano are exposed. The Bouguer gravity map shows a positive anomaly [*Thorbergsson et al.*, 1984], and earthquake studies and the geochemistry of fumaroles indicate that a distinct heat source underlies the area. An interpretation qualitatively consistent with all these results is that the high-velocity body imaged is a high-density mass of basic and ultrabasic rocks that is the solidified, exposed magma chamber of the Grensdalur volcano. An alternative explanation is that it is a complex of dykes or intrusive sheets that fed the surface eruptive site. The continuous

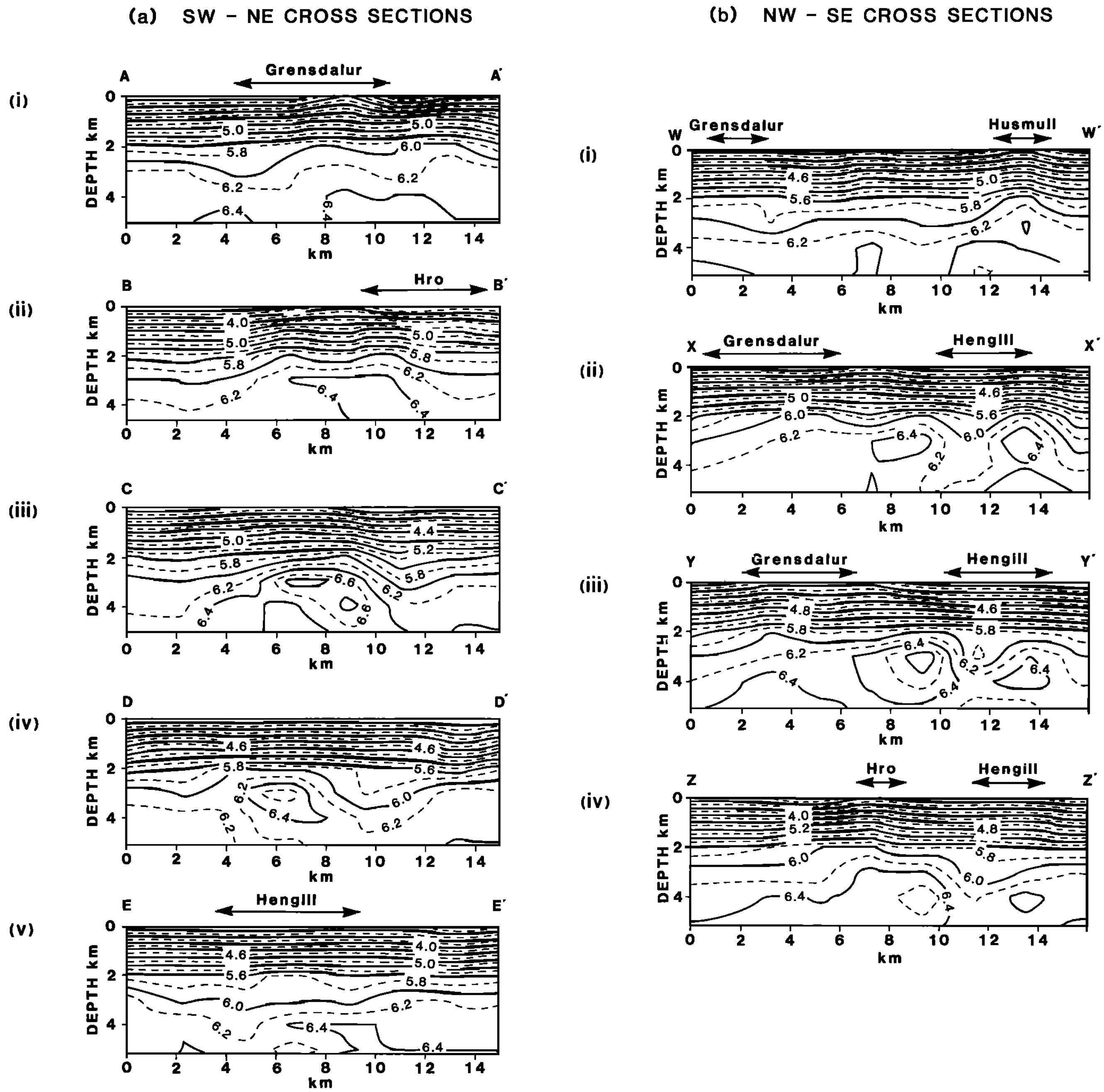

Fig. 7. Vertical cross sections through the imaged volume. (a) Cross sections parallel to the accretionary plate boundary. (b) Cross sections parallel to the transverse structure, and sub-perpendicular to the accretionary plate boundary. Section v in Figure 7a is colinear with the accretionary plate boundary and section iii in Figure 7b bisects the Hengill and Grensdalur volcanoes along the transverse structure. The lines of section are shown in plan view in Figure 6. The positions of the eruptive sites are indicated above those sections that bisect them. Velocities are contoured in km s^{-1}.

small earthquake activity observed in this volume occurs mostly below 2 km depth [*Foulger*, 1988*a*], indicating that heat is being extracted from these depths. The heat source of the Grensdalur geothermal field is therefore identified as the deeper part of the solidified but still hot volcanic core. The paucity of seismicity above 2 km indicates that in this depth range the volcanic core is cooled to the temperature of the reservoir fluids.

The high-velocity body imaged beneath Husmuli forms a very well defined conduitlike structure that curves toward Hengill at depth. [see als, *Toomey and Foulger*, this issue, Figure 9]. The Husmuli basalt shield dates from the beginning of the last glacial, at approximately -0.1 Ma [*Torfason et al.*, 1983], and was a relatively short-lived eruptive site. It has not been deeply eroded like the Grensdalur volcano, exhibits no surface geothermal displays, and is virtually aseismic. The gravity map shows a positive anomaly in this area [*Thorbergsson et al.*, 1984]. It is inferred that this body is a high-density intrusion that is the frozen magma conduit that fed the Husmuli basalt shield, during its period of activity, from a magma source beneath Hengill. Since it is aseismic and no surface heat loss occurs from it, it is concluded that this body is not cooling rapidly. Its age suggests that it is no longer anomalously hot.

The third high-velocity body imaged lies at 2-5 km depth beneath the Olkelduhals area, which is the site of the most intense geothermal activity within the Hromundartindur system. This area contains the only postglacial eruption observed outside the Hengill system [*Saemundsson*, 1967] and forms part of the transverse tectonic structure that represents the migration trajectory of volcanism in the area [*Foulger*, 1988*a*]. Geochemical analyses of the

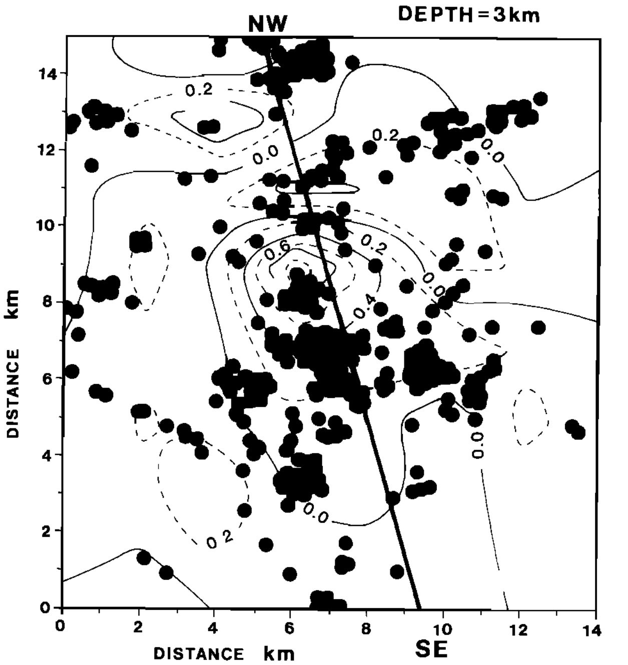

Fig. 8. Horizontal cross section at 3 km depth showing the distribution of the seismicity in relation to the imaged structures. Contours are velocity perturbations in km s^{-1}. Epicenters plotted are all accurately located events within the area, relocated with the three-dimensional velocity model. This section also appears in Figure 5*d*. The line of section of Figure 9 is shown.

fumarole gases indicate that a distinct heat source underlies it [*Torfason et al*, 1983]. The tomographically imaged body generates intense seismic activity (Figures 8 and 9), and a small gravity anomaly high occurs over it [*Thorbergsson et al.*, 1984].

The occurrence of gabbroic inclusions in the single postglacial lava within the Hromundartindur system [*Saemundsson*, 1967] led *Arnason et al.* [1987] to conclude that the shallow crustal magma source of this system was solidifying to gabbro at the time of the eruption (-0.1 Ma). It is concluded that the high-velocity body imaged by the tomographic inversion is that solidified magma source. This result sheds new light on the structure of the Hromundartindur system since it implies that the magma source that fed it underlay the Olkelduhals area and not the mountain Hromundartindur to the northeast.

The seismic activity associated with this body is mostly confined to its southeast perimeter (*Foulger*, 1988*a*, Figures 8 and 9). This suggests that the body may still be cooling from its outer layers by the process of progressive fracture penetration [*Bjornsson et al.*, 1980], and its interior may still be considerably hotter than the 300°-310°C indicated by fumarole geochemistry.

A small low-velocity body was imaged beneath the northern part of the presently active Hengill central volcano. Temperatures in excess of 374°C were drilled at 1 km depth immediately north of Hengill [*Steingrimsson et al.*, 1986], and four postglacial eruptions within the fissure swarm are documented [*Saemundsson*, 1967]. These results provide circumstantial evidence for melt at shallow depth, and the low-velocity body imaged may therefore be the seismic signature of this volume of melt. The location of a few earthquakes within this low-velocity body indicates, however, that the melt may occur as discrete pockets and not a single large chamber. A separate reservoir temperature maximum associated with Hengill has been detected [*Torfason et al*, 1983], implying that a separate heat source fuels this part of the geothermal area. The low-velocity body imaged here may represent that heat source, or part of it.

If the interpretation of this body as the shallow magma source of the active volcano Hengill is correct, it might be expected that its volume would be several tens of cubic kilometers i.e., comparable with that of Icelandic magma chambers identified elsewhere. These include chambers identified geodetically and seismically beneath Krafla, NE Iceland [*Bjornsson et al.*, 1977; *Einarsson*, 1978] by surface mapping in the Tertiary of eastern Iceland [*Walker*, 1974] and here beneath the Grensdalur and Olkelduhals areas. The most likely explanation for the very small size of the low-velocity body beneath Hengill is suggested by the volcanic character of the area. This is distinctive from areas such as Krafla, NE Iceland, where a large intensely molten magma chamber has been positively identified. The Hengill volcano lacks a caldera, so there is no surface evidence for catastrophic magma chamber deflation. Also the Hengill system is not very active volcanically compared with some other systems; its rate of production of surface eruptives is low, as is its eruption frequency (four times during the postglacial period). The Krafla system, in contrast, has a caldera and is much more productive, having erupted about 15 times during postglacial times (K. Saemundsson, personal communication, 1988). One explanation for this relatively low eruptive rate is magma starvation of the Hengill system.

A small magma storage system and low volcanic production rate for the Hengill system would be in keeping with the broad pattern of accretionary evolution in southern Iceland, where volcanism in the Western Volcanic Zone is diminishing in response to increased activity in the Eastern Volcanic Zone.

A teleseismic travel time anomaly of +0.09 s is associated with the active Hengill volcano (Figure 4). This corresponds to a low-velocity body of comparable dimensions and percentage velocity anomaly to the high-velocity bodies discussed above and thus much larger than that resolved by the local earthquake tomography. It may be that the source of this teleseismic delay lies deeper than 5 km, and this may be an indication that a more substantial volume of partial melt underlies Hengill in the lower crust or upper mantle.

An alternative explanation for the relatively small size of the low-velocity body is that the diffraction of seismic energy around its perimeter causes the tomographic image to be artificially small.

Implications for Subsurface Magmatism

The present-day surface heat flux from the Grensdalur system, and the estimated age of the geothermal field, is compared with the amount of heat liberated during solidification and subsequent cooling of the inferred magma chamber. This comparison suggests that the Grensdalur system has been replenished by magma subsequent to the commencement of activity in the Hengill and Hromundartindur systems and probably subsequent to the cessation of surface eruptive activity within it.

The surface heat flux from the geothermal area that encompasses the Hengill, Hromundartindur and Grensdalur systems is approximately 350 MW [*Bodvarsson*, 1951]. Approximately one third of this heat loss (i.e., 120 MW) occurs from the Grensdalur area. The volume (>7% higher than the average) of the high-velocity body imaged below the Grensdalur area is approximately 40 km^3. This is a reasonable value for the volume of the former magma body that fueled this system. The time t taken for this body to cool from 1000°C to 400°C may be calculated using the formula:

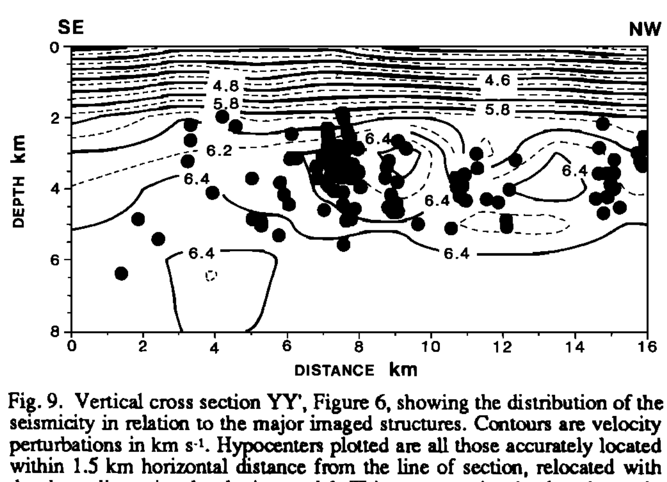

Fig. 9. Vertical cross section YY', Figure 6, showing the distribution of the seismicity in relation to the major imaged structures. Contours are velocity perturbations in km s^{-1}. Hypocenters plotted are all those accurately located within 1.5 km horizontal distance from the line of section, relocated with the three-dimensional velocity model. This cross section is also shown in Figure 7*b*.

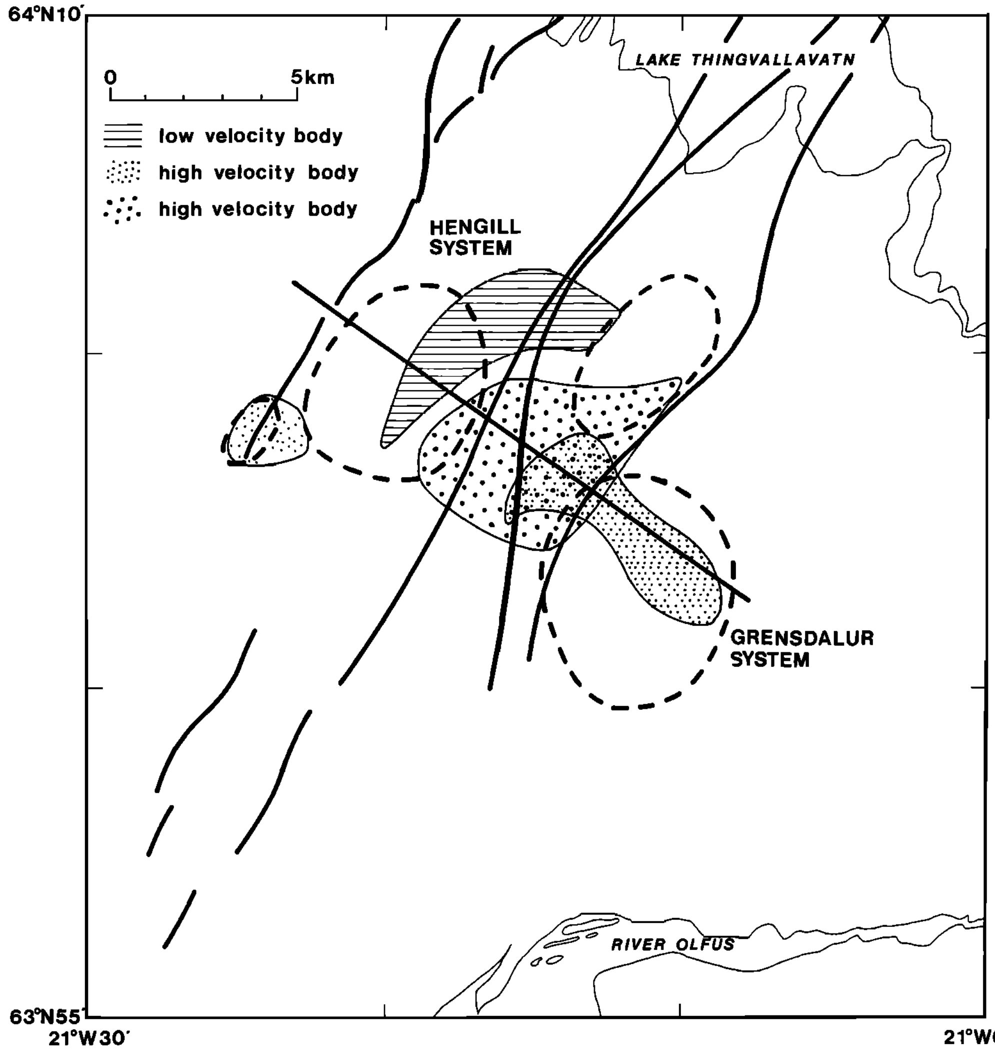

Fig. 10. Schematic map of the main structural features of the area and the approximate extents of the bodies imaged by the tomographic inversion. The areal extents of anomalous velocities are indicated by shading.

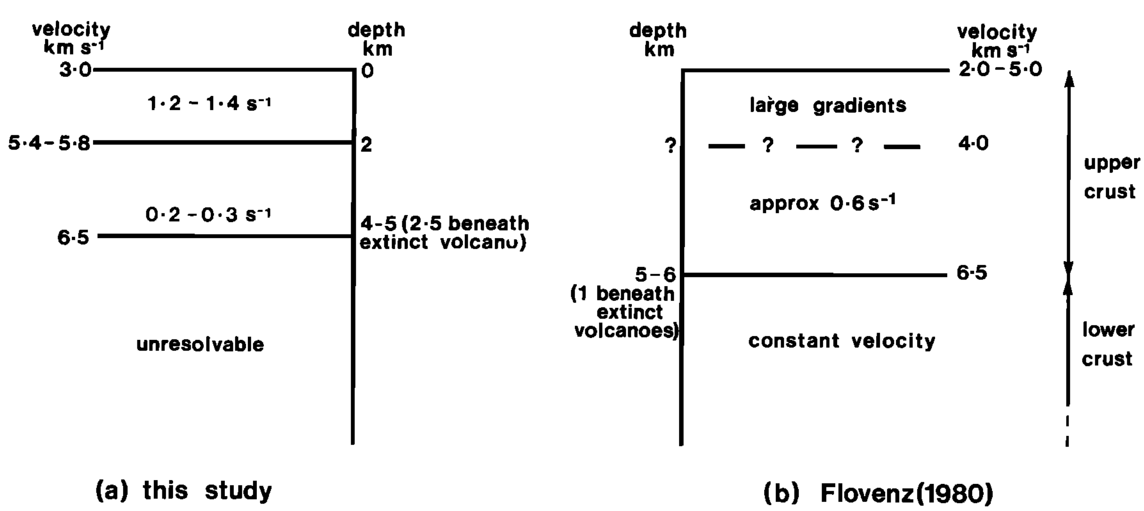

Fig. 11. Comparison of the crustal structure obtained for the Icelandic crust (*a*) from this study, and (*b*) from *Flovenz* [1980], who modelled explosions with synthetic seismograms.

$$t = \frac{V \rho C_p \Delta T}{H_f}$$

where V is the volume of the cooling body (40 km^3), ρ is the density of gabbro (2600 kg m^{-3}), Cp is the specific heat (1.3 x 10^3 J kg^{-1} K^{-1}), ΔT is the temperature drop (600°K), and H_f is the heat flux (120 MW).

Applying this formula, it may be calculated that the imaged body could fuel the geothermal area at its present rate for only approximately 10,000 years. Geological research indicates that thermal activity was previously more extensive than it is today, and therefore cooling would have been even more rapid in the past [*Saemundsson and Arnorsson*, 1971].

The Hengill system has been active since -0.3 Ma [H. Franzson, unpublished data, 1986] which indicates that volcanism began to transfer to the Hengill system from the Grensdalur system at that time. It is clear from the above calculation, however, that in order for the Grensdalur volcano to still be hot enough to fuel its associated high temperature geothermal field, its magma source must have continued to be replenished by subsurface intrusive activity for a long time subsequent to the commencement of activity in the Hengill system.

6. Summary

1. Three principal high-velocity bodies were imaged that correlate spatially with three separate extinct volcanic sites. These bodies are interpreted as dense intrusives that represent solidified shallow crustal magma reservoirs. Two of these bodies, those underlying the Grensdalur and Olkelduhals sites, are still hot and fuel the geothermal fields above them. The third body, underlying Husmuli, is cold.

2. A small low-velocity body, approximately 5 km^3 in volume, was imaged beneath the northern part of the presently active Hengill central volcano and may represent pockets of partial melt with competent rock in between. This body may be the heat source, or part of the heat source, of the geothermal field associated with Hengill.

3. Heat balance calculations indicate that subsurface magmatism must have continued in the Grensdalur system for long after the Hengill system began to evolve.

7. Discussion

This study adds another case history to the small number of tomographic studies that have been performed using local earthquakes to image the small-scale structure of volcanic areas. A somewhat surprising result of the study was that the structure is dominated by several well-defined high-velocity bodies. However, a small (approximately 5 km^3) low-velocity body that may be interpreted as a volume of partial melt was imaged also, beneath the active Hengill central volcano.

This is one of very few positive identifications of a shallow crustal melt accumulation by local scale seismic tomography. It would appear that teleseismic methods more consistently identify clear, large-scale low-velocity anomalies associated with volcanic areas. This suggests that low velocities may be a general characteristic of central volcanoes at depth and on a large scale, but that small shallow chambers of molten material are not a universal feature of active central volcanoes. In the case of volcanoes lacking a shallow magma chamber, volcanic activity may be fed directly from a mantle source.

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