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HENGILL TRIPLE JUNCTION, SW ICELAND
2. ANOMALOUS EARTHQUAKE FOCAL MECHANISMS AND IMPLICATIONS FOR PROCESS WITHIN THE GEOTHERMAL RESERVOIR AND AT ACCRETIONARY PLATE BOUNDARIES

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Abstract. The Hengill ridge-ridge-transform triple junction is a complex tectonic unit containing two volcanic systems, one active and one extinct, and widespread geothermal resources. The area exhibits continuous, small-magnitude earthquake activity. Good constraint was obtained for the radiation patterns of 178 small earthquakes within the area, of which 50% are non-double couple and are interpreted as resulting from tensile crack formation. These events occurred in the depth range 2-7 km and indicate that at these depths in the area extensional stresses must be prevalent, that outweigh the compressive effect of the overburden. The tensile crack events were mingled with double couple events, and were confined to the high-temperature geothermal area. Outside of this, seismic faulting was almost entirely shear. During a 3-month recording period, tensile crack type events were of low magnitude and accounted for only 2% of the seismic stress release. The fault plane of the shear events was deduced from the orientation of the tensile crack strikes. The continuous small-magnitude seismicity is attributed to the action of circulating groundwater fluids on hot rock at depth which remove heat and cause contraction of the rock, thereby reducing the effective confining stress. This process induces cooling contraction cracks that release thermal and regional stress in a mode that is consistent with the regional stress regime. In close proximity to the accretionary plate boundary, this stress regime is extensional, and some of the fractures formed are tensile cracks. The spatial distribution of the continuous earthquake activity represents a map of the heat source of the geothermal area. In the Hengill area the earthquake locations indicate that the high-temperature geothermal area is fueled by two main distinct heat sources. These are associated with the two volcanoes, and separate geothermal fields that exhibit contrasting reservoir characteristics. Continuous small-magnitude earthquake activity is commonly associated with geothermal areas worldwide, and the results from the Hengill area indicate that they may be used elsewhere as a prospecting tool to gain unique information about the heat source.

1. Introduction

It is widely assumed that all earthquakes occur as a result of shear slip on buried faults and have double couple source mechanisms. Theory predicts that the P wave radiation pattern generated by such movements exhibits equal areas of compression and dilation when projected onto the focal sphere. These areas of compression and dilation may be separated by two orthogonal great circles, one of which represents the fault plane. This theory is widely accepted and used in the routine interpretation of earthquake radiation patterns because the great majority of seismological data and geological observations are consistent with it and it is conceptually attractive.

However, a number of earthquake radiation patterns have been described that cannot be interpreted in terms of a double couple source. The analysis of these events is controversial. Because there are conceptual difficulties with non-double couple sources, and also such events are rare, many authors prefer explanations for them that involve unusual propagation effects or multiple, double couple events. Others have proposed explanations involving source mechanisms other than shear slip on a fault plane.

Robson et al. [1968] described some examples of Japanese earthquakes whose compressional fields project small circles onto the focal sphere. They suggested that such radiation patterns may be generated by extensional failure in fluid-containing rocks and that such events may be triggered where melts occur in the upper mantle. Evison [1963] suggested that they might be generated by rapidly running phase transitions in rock volumes. The compensated linear vector dipole source model has recently been invoked to account for a sequence of large earthquakes at Mammoth Lakes, California [Julian, 1983], and it is suggested that they were generated by dike injection [Aki, 1984; Julian and Sipkin, 1985]. Other workers prefer explanations for these events in terms of propagation effects or multiple events [e.g., Given et al., 1982; Ekstrom, 1983; Wallace et al., 1983].

Several reports have been made of earthquake radiation patterns from the Mid-Atlantic Ridge and its continuation onto Iceland that apparently require nonorthogonal nodal planes [Sykes, 1967, 1970; Klein et al., 1977; Einarsson, 1979]. These events all display reduced dilational fields and could result from sources with an enhanced explosive component. However, because polarity plots from Mid-Atlantic Ridge earthquakes are all lower hemisphere, their radiation patterns may be explained by path effects, e.g., the focusing of downgoing rays through a subcrestal magma chamber [Solomon and Julian, 1974] or interference between P, pP, and sP [Trehu et al., 1981]. Lateral inhomogeneities on a very small scale were invoked by Klein et al. [1977] and Einarsson [1979] to account for

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the upper hemisphere non-double couple radiation patterns of small earthquakes on the Reykjanes Peninsula, Iceland.

A moment density tensor representation is convenient to describe these sources, which appear to involve movements in three dimensions [Aki and Richards, 1980]. Then the principal moments may be expressed in the form:

$$(a, b, c)$$

A volumetric component, i.e., $(a + b + c) \neq 0$, may be difficult to explain because of the large confining pressures at depth in the Earth. Some authors avoid the problem by constraining $(a + b + c) = 0$ in their computations [e.g., Julian, 1983]. The "compensated linear vector dipole" (CLVD) source has principal moments in the ratio (-1, -1, 2), and is a three-dimensional source that conserves volume.

In 1981 an intensive local earthquake study was conducted of the Hengill ridge-ridge-transform triple junction, SW Iceland [Foulger, this issue]. The surface expression of the ridge branches is a fissure swarm that traverses the area from SW to NE and contains the presently active Hengill central volcano. At 7.5 km SE of Hengill lie the eroded roots of the extinct Grensdalur central volcano. The two volcanoes are connected by a transverse tectonic/topographic structure and are encompassed by an extensive high-temperature geothermal area (>200°C in the upper 1000 m) (Figure 1a). Geophysical studies are consistent with twin geothermal systems associated with the two volcanoes. South of 64°N an EW striking zone of destructive historic seismicity represents the transform branch of this triple junction, and contains a low-temperature geothermal area (<150°C in the upper 1000 m).

The area provided an ideal subject for a study of local seismicity, since it exhibits continuous small-magnitude earthquake activity with a constant spatial distribution. In 1981 a temporary, 23-station seismometer network was deployed which recorded 2000 small earthquakes. Well-constrained polarity plots were obtained for 178 events, of which half exhibited radiation patterns of non-double couple type. These focal mechanisms were described in brief by Foulger and Long [1984]. In this paper the focal mechanism solutions are described and discussed in detail, and a complete set of polarity plots presented. They are shown to be related to the mechanism of heat loss from the geothermal system and to have important implications for geothermal prospecting and reservoir process.

2. The Focal Mechanisms

Data

The instrumentation and network configuration is described in detail by Foulger [this issue] and consisted of 23 vertical 1-Hz seismometers and analog tape recording with a 32-Hz upper cutoff frequency. All the events described in this paper were located within the network (Figure 1b); 50% of the events had non-double couple radiation patterns, i.e., the dilational and compressional portions of the focal sphere could not be separated by a pair of orthogonal great circles, whereas the rest permitted highly consistent double couple interpretations. The possibilities were considered that the anomalous radiation patterns were due to instrument malfunction, misidentification of the first P wave arrival, distortion due to propagation path effects, or source complexity. It was possible to rule out the first three factors.

Consistent seismometer response and recording system integrity were indicated by a suite of teleseisms and refraction shots that were recorded throughout the monitoring period. These results were verified by laboratory tests on the equipment both before and after the fieldwork. From this it was concluded that instrument malfunction could not account for the observations. Of the seismograms used to construct the polarity plots, the first P wave cycle was almost invariably impulsive, of relatively high amplitude, and with a dominant frequency of about 10 Hz. Emergent phases were not included in the polarity plots. The seismograms for a typical anomalous event and a double couple event are illustrated in Figure 2. These show little evidence for ambiguity in either the phase or arrival time of the first P wave.

The local and regional refraction shots indicated broad lateral crustal velocity homogeneity to within 10% in the upper few kilometres, and relocation of the local explosions was accurate to within 400 m. This, and the results of a subsequent three-dimensional tomographic inversion performed on the P-wave arrival data [Toomey and Foulger, 1986; Foulger and Toomey, 1986] verified that the crustal model used to locate the earthquakes was reasonably accurate. Relocation of the events using the three dimensional velocity structure resulted in hypocentral adjustments of a few hundred meters only, and therefore mislocation cannot account for the observations. In addition the non-double couple type events were widely distributed over the area and were mixed spatially with double couple events. They thus did not cluster and could not all have undergone the same propagation effects. Their radiation patterns could therefore not be attributed to crustal inhomogeneity on an extremely small scale. The one remaining possibility was that the anomalous radiation patterns observed were generated by events with sources that were not simple shear slip.

For presentation purposes, the data have been divided into 12 groups that are naturally suggested by the epicentral distribution. A selection of events is illustrated in Figure 3, and the rest are presented in a microfiche appendix.[1] Each event is labeled by its origin time. The groups are Klambragil (K) (Figure 3, appendix), Nesjavellir (N), Mosfellsheidi (M), the fissure swarm (F= all events within the fissure swarm excluding Nesjavellir), Svinahlid

[1]Appendix is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document B88-019; $2.50. Payment must accompany order.

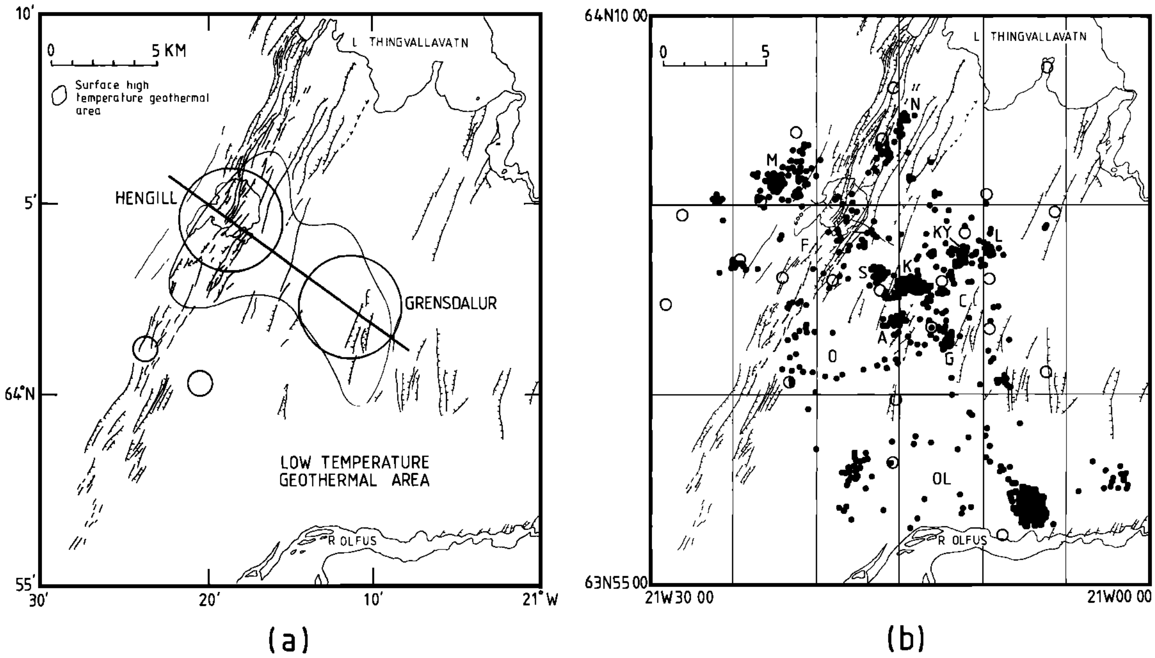

Fig. 1. Maps of the Hengill triple point [adapted from Foulger, this issue]. (a) Tectonic structure. Surface faulting and fissuring, the 600-m contour, and the locations of the double volcanic system and transverse structure are indicated. (b) Local seismicity. Black dots are earthquake epicenters located during a 3-month monitoring period in 1981. Seismometers used to locate the events are shown. Event clusters are identified with letters. See text for key.

(S), Orustuholshraun (O), Astadafjall (A), Kyllisfell (KY), Laxardalur (L), the central cluster (C= all events in the Grensdalur area not included in any other group), Grensdalur (G), and Olfus (OL = all events S of 64°N) (Figures 1b and 7).

Anomalous Events

The radiation patterns of the non-double couple events are dominated by compressional fields that typically occupy 80% of the focal sphere. The dilational fields are correspondingly severely reduced. These observations indicate that the sources that generate these events are volumetric, and that they exhibit a large net explosive component (i.e., "volume increase").

A number of source models were considered to explain these observations. Clearly a double couple model can be ruled out. Some of the radiation patterns are similar to the CLVD, but the majority differ in that volume is not conserved. The tensile crack was finally used as a basis upon which to model the anomalous Hengill events. This is a natural source that theoretically gives an all-compressive P wave radiation pattern [Aki and Richards, 1980] and could thus account for the dominant compressive character of the events. Some additional theory was, however, required to account for the small dilational fields observed.

Foulger and Long [1984] and Foulger [1984a, b] suggest that the events are generated by the formation of tensile cracks in the presence of restricted pore fluid flow. Under these conditions a pore pressure drop would occur in the source volume, generating an implosive pressure pulse that is superimposed on the compressional radiation pattern of the tensile crack. This cancels out and reverses the compressive field in those directions where the amplitude is least, i.e., close to the trace of the crack. The pressure differential is equalized by subsequent aseismic diffusion of the pore fluid. Since the P wave amplitude contours of the tensile crack trace small circles on the focal sphere, the nodal lines of this type of source would be small circles if the implosion were spherical, and elliptical if it were an ellipsoid. Another possible explanation for the sources is that they are tensile cracks with a shear component. In this case the nodal lines would not be simple in shape, and the dilational field would divide up into two discrete parts.

Because of the very large compressional field, in many cases the number of dilations is small and insufficient to constrain the exact shape of the nodal lines. It is therefore not possible to distinguish between the various explanations for the dilational field on polarity grounds alone. The majority of the anomalous polarity plots were consistent with the simplest interpretation, however, i.e., that of a tensile crack and a spherical implosion. These events are interpreted here in that way.

Some additional information may be gleaned from looking at nodal arrivals. These are indicated on the polarity plots where they were observed. In some cases, arrivals that lie very close to the inferred nodal lines are of low amplitude, but in many cases this is not clear. However, the same is true of the shear events and

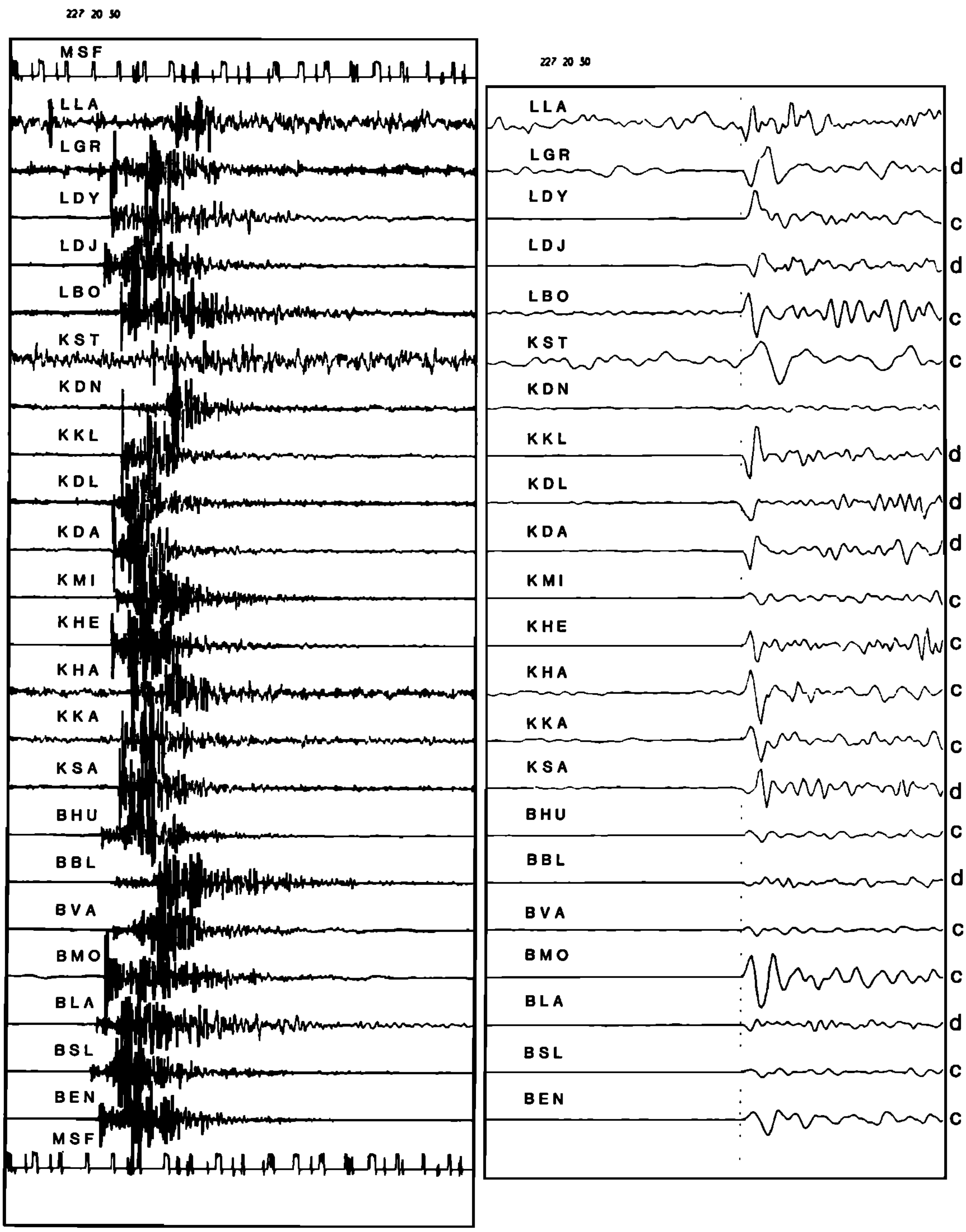

Fig. 2a

Fig. 2. Seismograms for typical events: (a) a shear event (810815 2030, polarity plot, appendix, Figure A2); (b) a tensile crack event (810806 1104, polarity plot, appendix, Figure A5). Labels c and d indicate whether the first break was picked as a compression or a dilatation. In the expanded seismograms, the rms trace amplitudes are normalized and first arrivals are approximately aligned for clarity of presentation.

is probably due in part to crustal inhomogeneity. The interpretation presented here is doubtless over simplistic, and cannot account for a number of events that did not fit a shear interpretation either. These events very likely have both tensile crack and shear components. A rigorous interpretation of the amplitude variation of the arrivals is currently under way [Cordery, 1987; Curran, 1987] and may constrain the shapes of the nodal lines quantitatively, therefore helping to clarify the genesis process of the dilational arrivals.

It may be calculated that for a typical Hengill event with a dilational belt approximately 20° wide, the principal moments of the seismic moment density tensor are

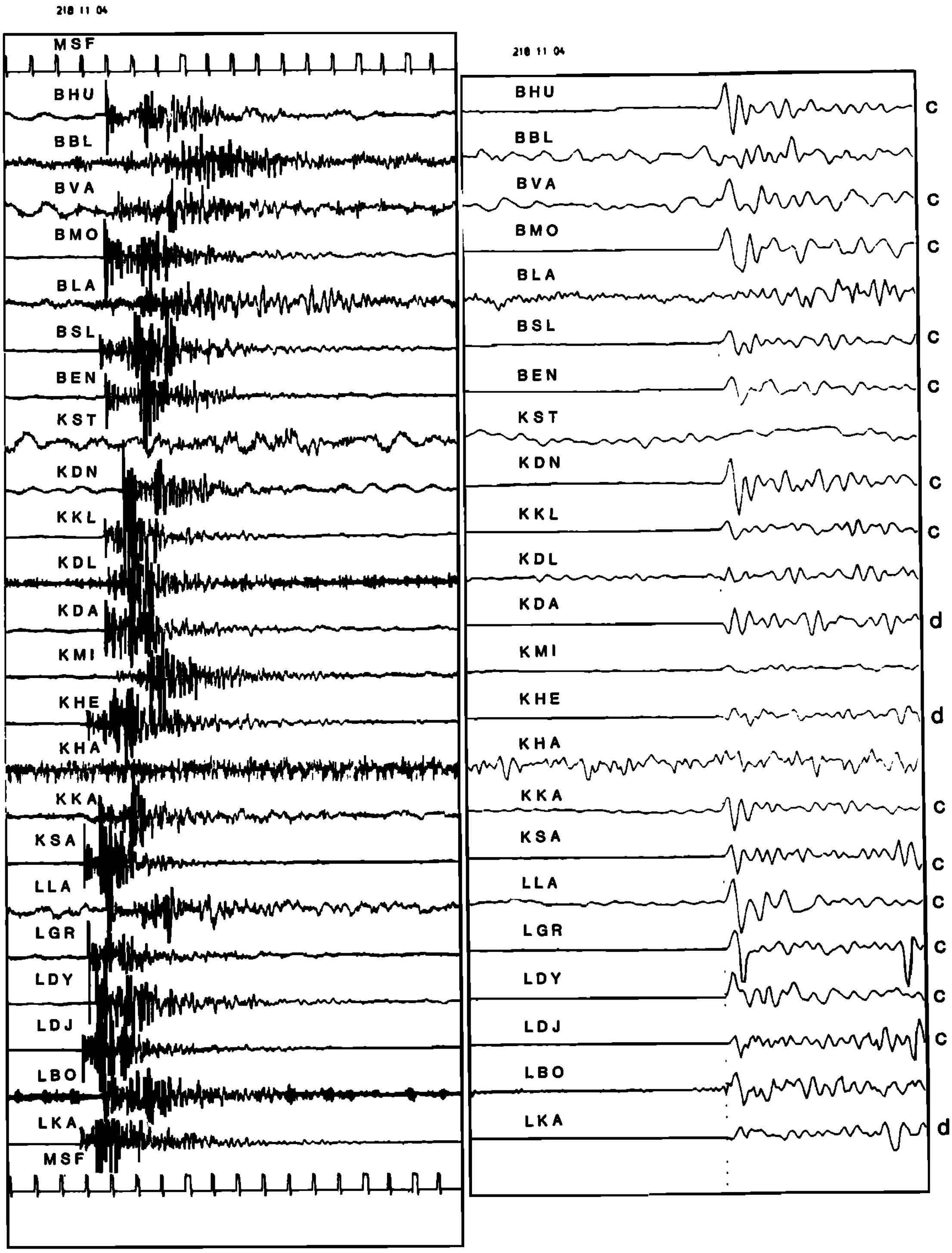

Fig. 2b

approximately [-1, -1, 30] [Foulger and Long, 1984]. It is interesting to compare this with the seismic moment density tensors of other sources of the same genus: tensile crack (approximately), [1, 1, 3]; CLVD (conserves volume), [-1, -1, 2]; and Hengill (typical event), [-1, -1, 30].

The general model described above can satisfactorally account for a large part of the observations, and a theory based on the tensile crack is a reasonable one in an area such as Hengill that contains an accretionary plate boundary and displays features clearly indicative of an extensional stress regime (e.g., dikes, open surface fissures).

In interpreting the individual events, a conservative approach was taken, and where possible, a shear solution was fitted. Where this was not possible, a tensile crack interpretation was attempted, and small circles were fitted to the data. For 80% of the non-double couple events this interpretation was adequate without

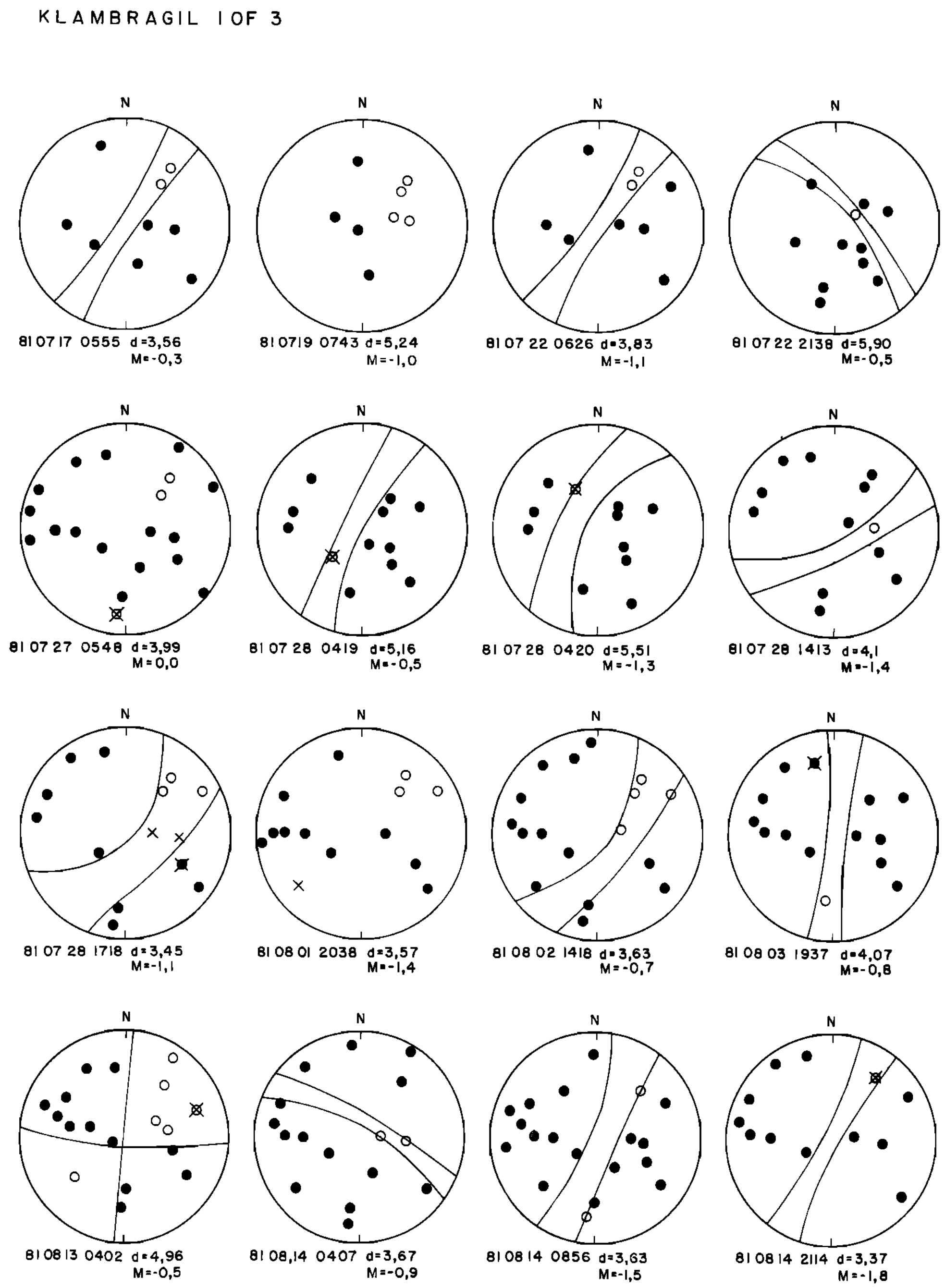

Fig. 3. Polarity plots of a selection of events from the Klambragil cluster. Date and origin time are indicated; d, depth; M, Icelandic local magnitude. Upper hemisphere plots in stereographic projection. Solid circles, compressions; open circles, dilations; crosses, nodal arrivals; and lines, intersections of the nodal surfaces on the focal sphere. In the cases where these lines cross, they are great circles and indicate a double couple solution. Where they are small circles, a tensile crack solution is derived. In the case of events where neither solution could be obtained, no nodal lines are plotted.

violations. Where neither type nor nodal lines could separate the compressional and dilational fields without violations, no nodal lines are drawn.

In addition to displaying the individual solutions in Figure 3 and the appendix, for each epicentral group, a summary diagram is also presented in the form of a stereographic projection (Figure 4). For the tensile crack solutions the planes of the cracks (which dissect the dilational belts) are represented by great circles, whereas for the shear solutions the pressure (P) axes and tension (T) axes are represented by open and solid circles, respectively. The events for which no solution could be obtained are not represented.

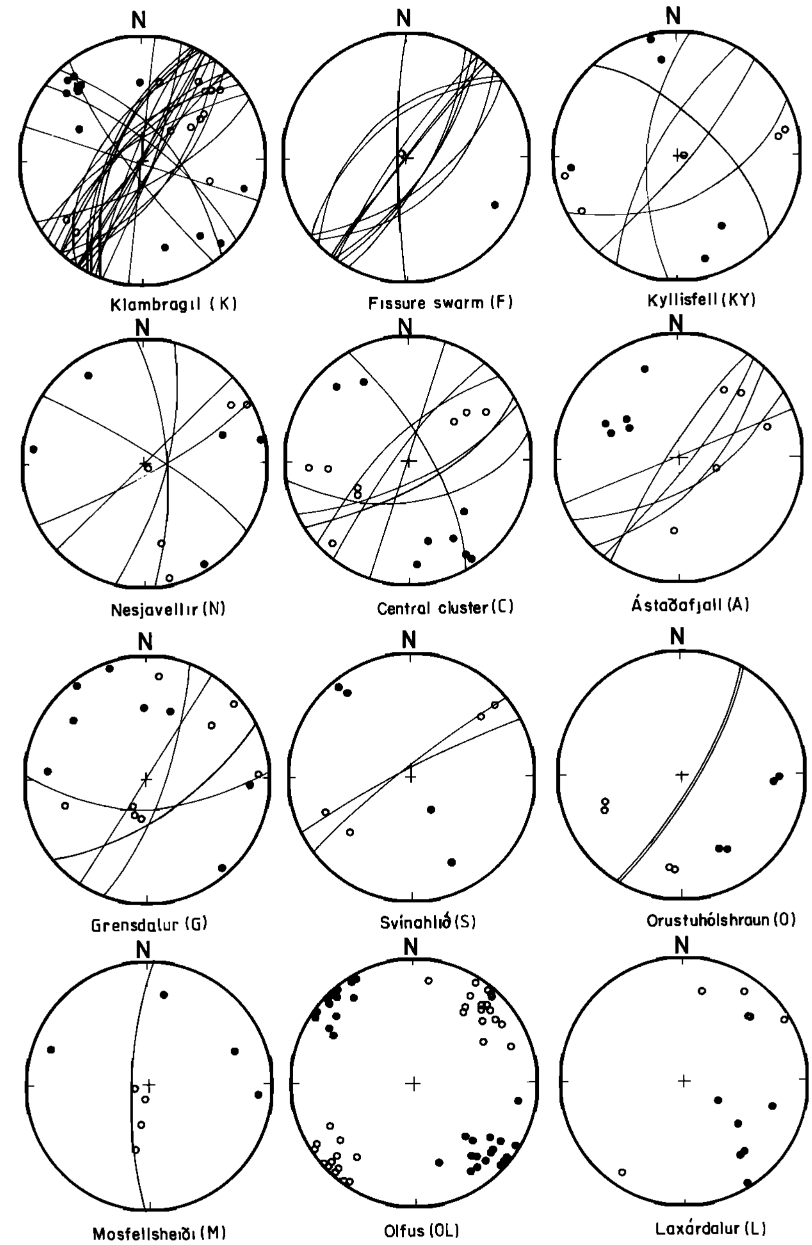

Fig. 4. Stereographic summary diagrams for focal mechanism data groups (see Figure 1b for locations). Open circles, P axes; solid circles, T axes of shear solutions, great circles represent planes of tensile cracks (which dissect the dilational belts of the focal mechanism solutions). Events for which no solution could be obtained are not represented.

Most of the tensile crack events occurred on near-vertical planes (Figure 4). The smallest dip measured was 50°, and the dominant direction of strike was about N35°E. This is also shown in Figure 6, the lower part (c) of which is a smoothed plot of the orientation of crack strikes. In the case of fresh breaks, tensile cracks would form normal to the direction of least compressive stress (i.e., greatest tension). Thus the direction of greatest compressive stress would lie in the crack plane. This implies a direction approximately horizontal N125°E for the least compressive stress (σ_3) in the depth range of the events, i.e., 2-7 km (Figure 8).

The strike and dip of extensional features in the Hengill area indicate an orientation of horizontal N115°E for the least compressive stress at the surface [Foulger, this issue]. It is therefore possible that σ_3 rotates dextrally with depth. Another explanation is that there is a component of shear in some of the tensile crack events, as discussed above. The dilational fields of the shear events that are intermingled with the tensile crack events have a preferred orientation more easterly than those of the tensile cracks (Figure 5b). Thus if the tensile crack events contained a shear component that was consistent with this, it would have the effect of biasing the apparent orientation of σ_3 dextrally.

The width of the dilational belt varies

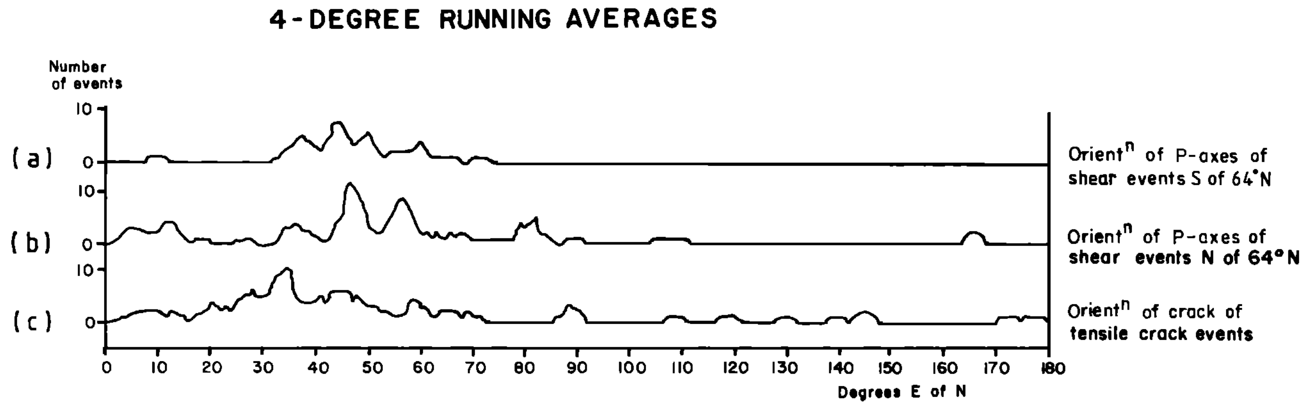

Fig. 5. Smoothed plots of orientation of P axes for (a) shear events located S of 64°N, (b) shear events located N of 64°N, and (c) orientation of the crack planes of the tensile crack events.

somewhat but is never larger than 60°. If generated by a pore pressure drop, the width of the belt would be governed by the magnitude of the pressure drop. This would be dependent on such factors as the type and phase of the pore fluid and the porosity of the rock, that would influence the speed of pore fluid flow.

The implications of the findings described above are far reaching. It is recognized that fissure opening can occur near to the surface where the overburden pressure is zero or small, but such fissuring is not generally considered likely to extend very deep, since at great depth the confining pressure is very large. That such a process is ongoing in the Hengill area, down to depths of 7 km where confining pressures of about 1.5 kbar would be expected, implies the effects of a very strong pore pressure are superimposed onto, and outweigh, the compressional field generated by the overburden.

Shear Events

In Figure 6 the P and T axes of all the shear events are plotted in stereographic projection. In Figures 5b and 5c, smoothed plots of the orientation of the P axes for the events N and S of 64°N, respectively, are shown. The P axes range from horizontal NE or SW through vertical, and the T axes are predominantly NW or SE striking, and near horizontal. Although the P and T axes are not equivalent to the directions of greatest and least compressive stress, they imply an approximately horizontal NW-SE orientation of the direction of least compressive stress, σ_3, and variation from horizontal, approximately NE, to vertical for the direction of greatest compressive stress σ_1.

These solutions indicate faulting which ranges from strike slip on near-vertical NS or EW orientated planes to dip slip on NE orientated planes. The normal movements indicate subsidence and faulting on planes with a similar orientation to fault planes mapped at the surface. These results are very similar to those obtained by Klein et al. [1977] for the Reykjanes Peninsula Zone to the W of the Hengill area.

Spatial and Magnitude Variations in Mechanism

The proportion of double couple to tensile crack solutions was highly variable for the data groups ranging from 90% tensile crack for the fissure swarm group (F), to entirely shear for the Olfus group (OL) (Figure 4). These variations are mapped in Figure 7. A circle is drawn in the neighborhood of each data group, and the proportion of events interpreted as tensile crack is equal to the proportion of the circle filled.

Tensile crack solutions occur preferentially within the high-temperature geothermal area (cf. Figures 1a and 7). In areas which are peripheral to or outside the high-temperature area (data groups M, L, and OL), tensile crack type events are subsidiary or absent. These observations suggest that the tensile crack type events are

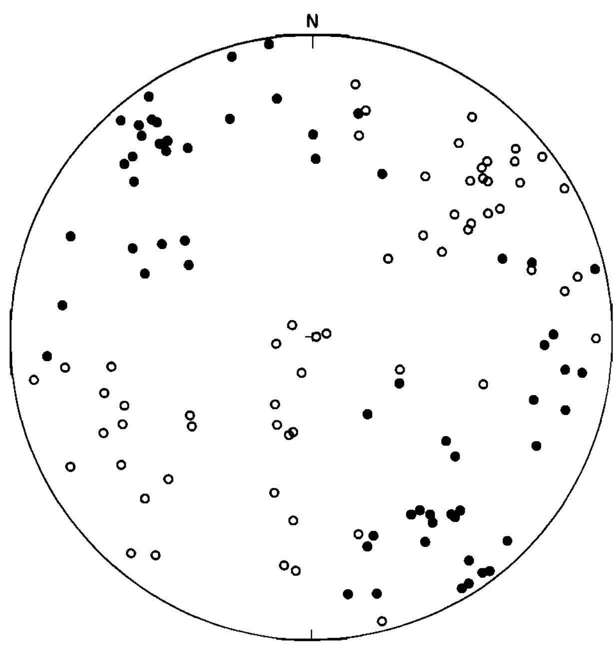

Fig. 6. Stereographic projection of P and T axes of all shear events. Open circles, P axes; solid circles, T axes.

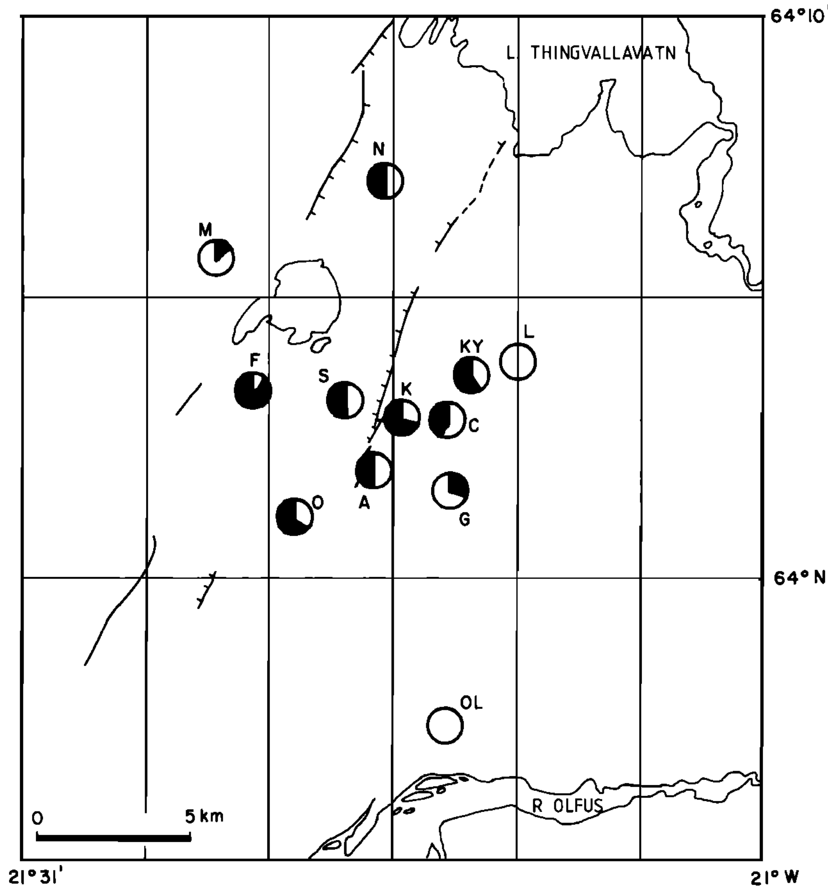

Fig. 7. Spatial variation of event types. The proportion of tensile crack events to total number of solutions obtained is represented as the proportion of the circles shaded for the 12 spatial data groups (cf. Figures 1b and 4).

associated with some deep process beneath the high-temperature geothermal area.

In the case of the shear events, those few that exhibit a large normal component of faulting are also confined to the high-temperature geothermal area (Figure 4). S of 64°N in the transform zone and the low-temperature geothermal area, strike-slip movements dominate. This may be an indication that N of 64°N, the shear seismic activity is influenced by accretionary processes, whereas S of 64°N the stress regime is dominated by the strike-slip tectonics associated with the transform branch of this triple junction.

Figure 8a illustrates the depth distributions for the tensile crack and the double couple data groups. The data are divided into three sets representing different parts of the area. The depth distribution for all areas except Klambragil (K) and Olfus (OL) shows that the two types of events are mixed together, with a very slight tendency for the tensile crack events to occur at greater depths. The depth distribution for the Klambragil (K) cluster is plotted separately. This cluster is a striking feature of the seismicity of the high-temperature geothermal area. It demarcates a small (~1 km^3), shallow volume beneath an area where the most intense surface geothermal activity is observed, and exhibits the highest seismic rate of any part of the area (Figure 4). The depth distributions for the events in this cluster are similar also. The depth distribution of the shear events of Olfus (OL), the low-temperature geothermal area, indicates that stress is released by shear faulting down to slightly greater depths, i.e., 3.5-9 km.

Figure 8b illustrates the magnitude distribution of the tensile crack and shear events for all parts of the area. The shear events occupy the range $-2.0 \leqslant M_{IL} \leqslant 2.2$ and the tensile crack events $-2.0 \leqslant M_{IL} \leqslant 1.4$ (M_{IL} = Icelandic local magnitude [Foulger, this issue]. Thus for the set of events for which solutions were obtained (representing 3 months' recording) the largest shear event was 0.8 magnitude units larger than the largest tensile crack event. For this data set, 98% of the seismic stress release was therefore by shear failure and 2% by tensile crack failure. These observations are in agreement with the hypothesis that tensile crack type events are limited to small magnitudes and thus account for only a very small percentage of the total seismic strain energy release of the Hengill area. However, the recording period of 3 months was too short to provide definite proof of this.

No obvious spatial or magnitude related trend was observed in the width or dip of the tensile crack events.

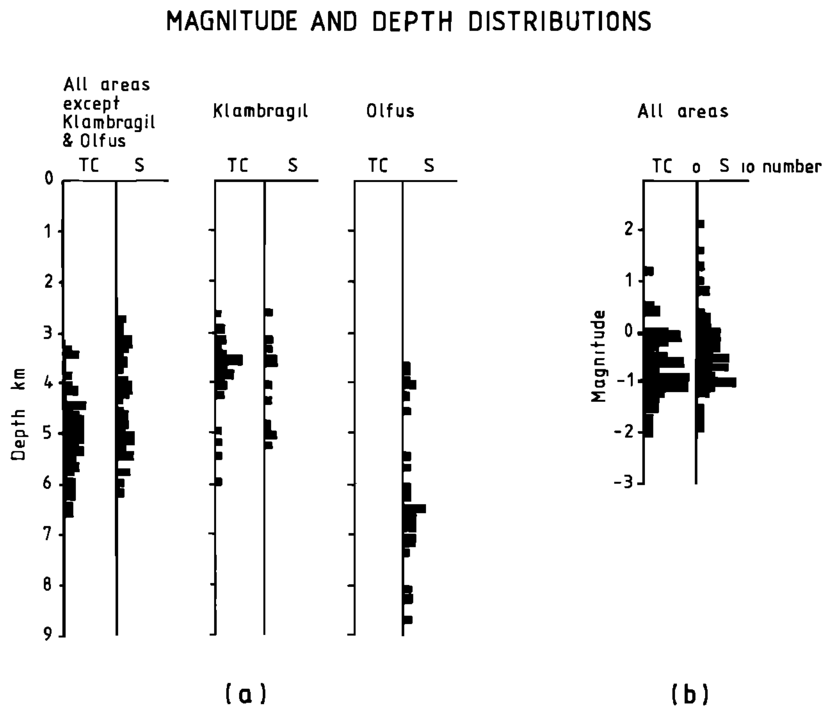

Fig. 8. Depth and magnitude variations for the event types. (a) Depth distributions for three subsets of the data, (b) Magnitude (M_{IL}) distributions of tensile crack and shear events, entire data set.

Implications for Fault Plane Determination for the Shear Events

The shear and tensile crack events are interspersed in the same volume of rock, and also both types of event may occur in a single sequence (e.g., the sequence of 810905 1848 - 810905 2111 in Astadafjall; see appendix). Since the orientation of the principal stresses may be deduced from the tensile crack events, the fault plane for the shear events may be deduced.

The opening of tensile cracks close together results in the buildup of stress in the intermediate rock volume, which is then released by shear failure on a plane connecting the cracks [Hill, 1977] (Figure 9). For tensile cracks forming at the same depth, accompanying shear failure would generate strike-slip earthquakes. For tensile cracks forming at different depths, shear events with a normal component would be generated. Strike-slip shear faulting in the Hengill area preferentially occurs on either NS or EW orientated planes. These two alternatives are illustrated in Figure 9. The release of shear stress on EW orientated vertical planes implies a left-lateral en echelon tensile crack arrangement, and movement on NS orientated vertical planes implies a right-lateral arrangement.

According to McKenzie [1969], for a fresh break in homogeneous rock the direction of greatest compressive stress (σ_1) lies between the P axis of the shear focal mechanism solution and the fault plane (inset, Figure 9). In the case of the shear events, the P axes are preferentially orientated about N45°E, whereas the orientation of the tensile crack events indicates an average of vertical to horizontal about N35°E for σ_1 in the depth range of the events (Figure 5). Thus in the case of the strike-slip shear events, the plane of fracture will be the more northerly striking plane, and a right-lateral tensile crack configuration is implied.

If fracturing of this nature occurred in a zone, the orientation of the entire activated zone would be intermediate between that of the tensile cracks and the shear fault planes (Figure 9). This is observed at the surface in the Hengill area (Figure 1a). The general trend of surface faulting is N25°E, intermediate between the NS striking fault planes deduced for the double couple focal mechanism solutions and the N35°E strike typically exhibited by the tensile crack events.

If it is assumed that this mode of faulting extends into the transform zone S of 64°N, then it implies that faulting there is right-lateral strike slip on NS orientated planes. This is consistent with the strike of surface faults S of 64°N and also with the mode of faulting observed for large destructive earthquakes in the South Iceland Seismic Zone, of which the area S of 64°N forms the westernmost part [Einarsson et al., 1981; Einarsson and Eiriksson, 1982].

To summarize, the mechanism of stress release across the area is consistent with the regional tectonics. N of 64°N, in the high-temperature geothermal area, strong extensional tectonics are associated with the accretionary plate boundary, and tensile crack type failure occurs. S of 64°N, in the low-temperature geothermal area and the transform branch of this triple junction, failure is solely strike slip and consistent with that observed in other parts of the transform.

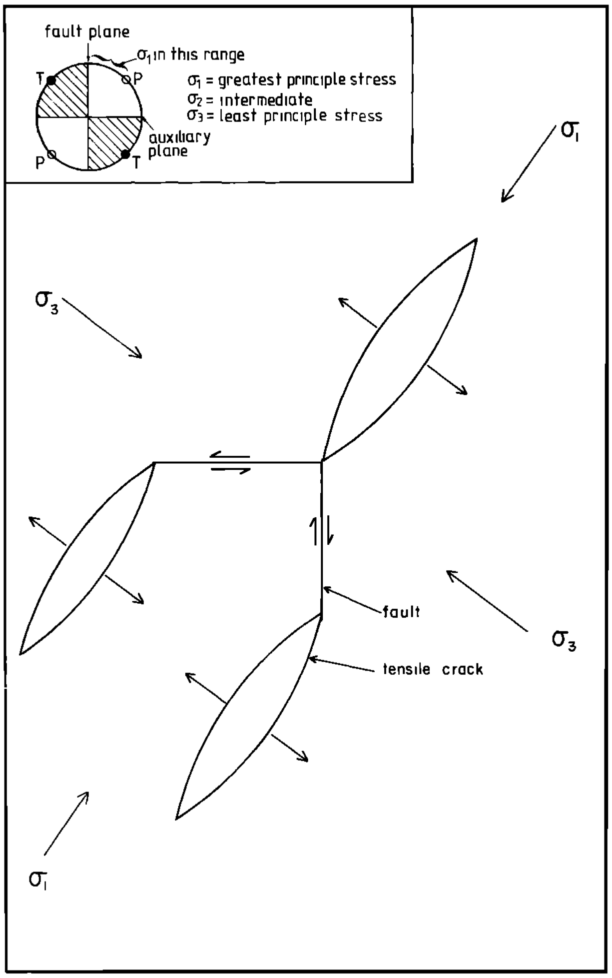

Fig. 9. Schematic diagram of tensile crack opening and accompanying shear seismicity on planes connecting the cracks. Here, σ_1 and σ_3 signify the greatest and least compressive stresses, respectively. Inset shows the relationship between the P and T axes, the fault plane, and the range of possible directions of the greatest compressive stress, for a shear earthquake focal mechanism.

3. Process Within the Geothermal Reservoir

Cooling Rock

It has been proposed that the penetration of water into hot rock is the mechanism by which heat is removed from hot intrusions at depth [Lister, 1974, 1976, 1977, 1980]. Circulating groundwater causes rapid cooling and thermal contraction, and small cracks form, continuously expanding the system of circulation channels and maintaining close contact between the groundwater and a retreating hot rock boundary. This process can account for the very large, long-lived heat losses observed over geothermal areas such as Yellowstone and Grimsvotn, Iceland, which cannot be explained by thermal conduction alone. Also direct observations of the Heimey (Iceland) lava flow indicate that this process is probably occurring there at very shallow depth [Bjornsson et al., 1980]. That continuous small-magnitude seismicity is commonly observed in geothermal areas in general [Ward et al., 1969; Ward and Bjornsson, 1971] is in agreement with the hypothesis that this process may occur seismically. Where focal mechanism studies have been conducted, strain release is generally observed to conform with regional tectonics [Combs and Hadley, 1977; Majer and McEvilly, 1979; Walter and Weaver, 1980].

The seismicity of the Hengill area at low magnitudes is consistent with this picture. It exhibits a persistent day to day temporal distribution, correlates positively with surface heat loss, and the mode of faulting across the area is consistent with the regional tectonics. These facts suggest that this activity is generated by cooling contraction cracking due to circulating groundwater on hot rock at depth [Foulger and Long, 1984].

The natural heat loss of the Hengill high-temperature geothermal area is estimated to be 350 MW [Bodvarsson, 1951]. From this it may be calculated that the total thermal contraction of the heat source beneath the Hengill area is approximately 4.5×10^4 m^3 yr^{-1} [Foulger and Long, 1984]. The approximate volume of the tensile cracks formed seismically can be calculated from their local magnitudes using the relations $\log M_o = 15.1 + 1.7M_L$ [Wyss and Brune, 1968] and $M_o = 2\mu V$ [Foulger and Long, 1984], where M_o is the seismic moment, M_L is local magnitude, μ is the rigidity modulus, and V is the volume of the crack formed. If it is assumed that 98% of the seismic energy release from the high-temperature geothermal field is due to strike-slip shear, and not volumetrically accountable to the problem, then application of these formulas indicate that tensile crack type events of up to about magnitude 6 must occur within the high-temperature geothermal area in order for the contraction predicted by the surface heat loss to be accommodated seismically.

Historical evidence indicates that all large earthquakes ($M_s \geqslant 6$) in the Hengill area occur in the Olfus area, S of 64°N and outside the high-temperature geothermal area. They are probably tectonic events that engineer strain release along the transform branch of the triple point. In that case events within the high-temperature geothermal field may not reach this magnitude [Foulger, this issue]. The largest event observed with a tensile crack mechanism during the 3-month recording period had a magnitude of $M_{IL} = 1.2$, and there is thus no evidence that tensile crack events occur with magnitudes greater than this. It is therefore likely that the seismic rate of the high-temperature geothermal area is insufficient to account for the required contraction rate, and only a very minor part of the volume change resulting from the heat loss occurs seismically.

If only a part of the contraction can be accounted for seismically, then some, possibly most, must proceed aseismically. A possible explanation for this is as follows: as heat is removed by circulating fluids, the rock contracts and tensile stress builds up. When this reaches the breaking strength of the rock, fracturing occurs, forming a tensile crack which provides a new path for the fluids and enables cooling to proceed more quickly. Contraction due to this subsequent cooling is accommodated by aseismic widening of the initial crack and seismic crack propagation (Figure 10). In some cases, crack formation may trigger a seismic sequence, and then a geothermal swarm of events of mixed type may occur.

Hengill High-Temperature Geothermal Area

If the tensile crack type events are attributable to the process of contraction cracking, then their spatial distribution, and that of the associated shear events may be regarded as a map of rapidly cooling volumes of rock that feed surface heat loss, i.e., the geothermal heat source. The seismic rate may be related to the rate of heat loss.

In the case of the Hengill area, earthquake activity is distributed over the whole of the high-temperature geothermal area, and some areas peripheral to it (Figures 1a and 1b). The heat source is therefore not just confined to the presently active Hengill central volcano, but is widespread and likely not monogenetic. Most notable is that the majority of the tensile crack earthquakes lie within the extinct Grensdalur volcanic center. This suggests that the greatest heat loss occurs from that volcanic center. From this it may be deduced that the heat loss over the Grensdalur system is fueled by a vigorous heat source directly below, and not by lateral flow, e.g., from a heat source beneath Hengill. These facts are in accord with the observation that the most intense surface heat loss occurs over the Grensdalur area. Conversely, hot springs and fumaroles are sparse over the Hengill system and so is microearthquake activity.

It is proposed here that two major heat sources feed the high-temperature geothermal area. One heat source is relatively hot and young and is associated with the presently active Hengill volcanic center. The other is cooler and older and is associated with the extinct Grensdalur volcanic center. In Figure 11 a structure for the geothermal area is suggested. The extent of the cores of the heat sources feeding the geothermal reservoir is outlined and based on the tectonic map of the area which was constructed on the results of geological and geophysical work (Figure 1a [Foulger, this issue]). The high-temperature geothermal area may be broadly subdivided into two main fields: the Hengill and the Grensdalur fields, and the hypocentral depth distribution is an indication of the vertical extent of the cooling contraction/heat extraction process.

The Hengill and the Grensdalur fields are associated with heat sources and reservoirs of widely varying age and tectonic history (the Hengill volcano is presently active, whereas the Grensdalur volcano began to dwindle at about -0.7 m.y. and is now extinct [Foulger, this issue]. The properties of the two geothermal fields and their reservoirs are therefore probably different. A possible comparison of the two systems is presented in Table 1. This table suggests why the heat loss and therefore the seismic rate of the two systems contrast so dramatically. The Hengill system is young and the reservoir well sealed by the deposition of minerals from very hot geothermal fluids. The Grensdalur system is mature, cooler, and more deeply eroded.

In addition to this broad structural picture, the detailed seismicity throws light on smaller-scale features within the area. The small volumes demarcated by clusters of activity within the Grensdalur system may be connected to particularly good aquifers that allow efficient heat removal and thus encourage high seismicity (Figure 1b). In particular, the very active Klambragil (K) cluster is associated with the transverse tectonic structure that connects the two volcanoes, which is interpreted by Foulger [this issue] to be a zone of dikes and fissures that also coincides with the thermal migration trail of volcanism within the area. This transverse structure may be a broad aquifer. It continues NW of Hengill in the Mosfellsheidi (M) area, an area that is also seismically active. Although no surface geothermal activity occurs in the Mosfellsheidi area, the seismic data indicate that the reservoir may extend 1 or 2 km to the NW of Hengill along the transverse structure.

A few hot springs and fumaroles do not lie directly above either the Hengill or the Grensdalur heat source, and these may be explained by lateral subsurface flow away from the geothermal field along faults or fissures (Figure 11). Alternatively, if considerably distal, they may be fueled by additional, minor heat sources. (High-temperature geothermal fluids have a very low specific gravity, rise directly to the surface, and cannot travel very far laterally from the heat source.) A third volcanic center may lie to the N of the Grensdalur center, and this may fuel the few hot springs in that area [Arnason et al., 1986].

In some areas, seismic activity is observed, but no surface geothermal displays, e.g., the Nesjavellir (N) and Mosfellsheidi (M) areas. There the seismic evidence pinpoints new areas that may be underlain by heat sources with good permeability at depth.

Hengill Low-Temperature Area (Olfus)

Focal mechanisms from this area indicate right-lateral strike-slip movements on NS striking faults. In that case the area may be dissected at depth by faults with NS trend and not by a single large EW trending fault as might be predicted by simplistic plate tectonic considerations. It would then be expected that the geothermal reservoir would be governed by NS tectonics, which is in agreement with the structural picture that emerges from resistivity investigations in this area [Foulger, this issue].

4. Discussion

Anomalous Earthquake Radiation Patterns

The interpretation of non-double couple earthquake radiation patterns such as those described here and, e.g., the Mammoth Lakes earthquakes [Julian and Sipkin, 1985], in terms of source mechanism is problematical. An infinite number of composite source mechanisms including multiple shear events could be invoked to account for a single set of observations, but many of these are physically impossible. In practice the tensile crack model often presents a conceptually

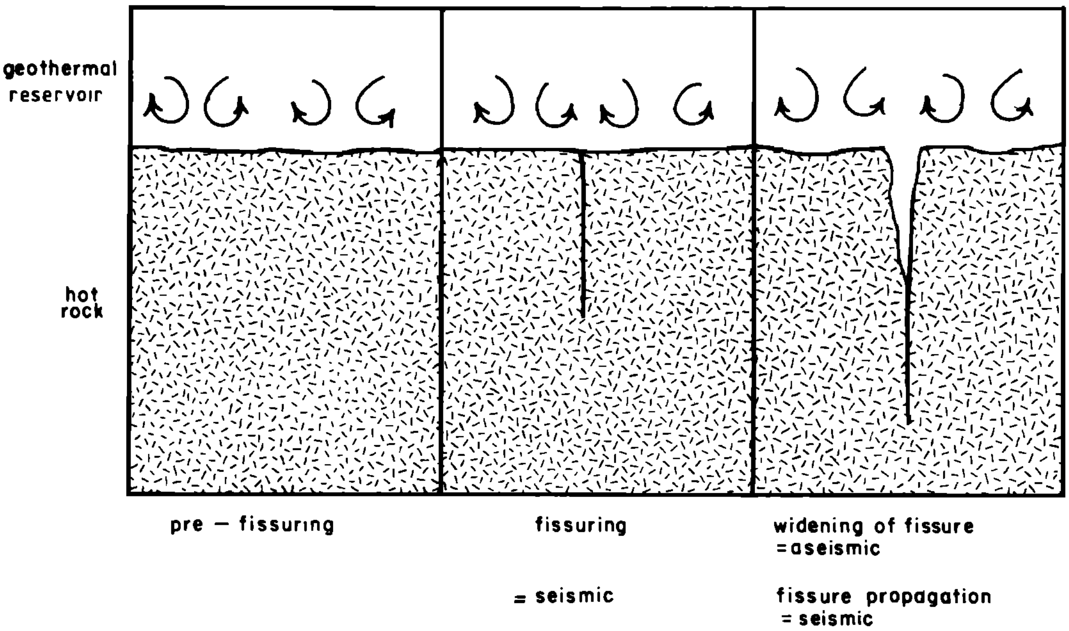

Fig. 10. Schematic illustration of the process of seismic fracture formation, aseismic widening, and seismic fracture propagation in a fluid cooled, hot rock environment.

attractive starting point, but is not without some difficulties. First, the radiation patterns observed rarely match those calculated theoretically for a tensile crack, since in almost all cases a dilational field is observed. Second, it is difficult to accept that tensile cracks can form at depth in the Earth's crust, where confining pressures are 1.5-2 kbar. It is tempting to seek embellishments to the tensile crack theory that can offer solutions to both problems, and recently two have been proposed.

The first proposes that at the instant of fracturing, the crack formed is filled by some fluid under high pressure, e.g., magma. This model was invoked by Julian [1983] and Julian and Sipkin [1985] to explain the radiation patterns of M>6 events at Mammoth Lakes. It accommodates the problem of void creation, but it is disputed whether magma injection could account for the dilational seismic radiation observed. The second model proposes restricted fluid flow at the instant of fracturing, resulting in a sudden pore pressure drop. This model was invoked by Foulger and Long [1984] to account for the Hengill events, and by Aki [1984] to explain the Mammoth Lakes events. It addresses the problem of the dilational field but not the problem of the voids.

The Hengill and the Mammoth Lakes earthquakes are separated by 5-8 magnitude units and are therefore not necessarily generated by the same process. It may then be that both hypotheses are correct in their separate contexts. It is plain, however, that there is room for considerable advance in our understanding of the mechanism that generates these enigmatic radiation patterns, and further observations will be of great value.

Geothermal Seismicity

The continuous small-magnitude seismicity of the Hengill area is associated with hot rock volumes at depth that are cooling and contracting rapidly under the action of circulating groundwater fluids. In the accrectionary environment of Hengill, the extensional stresses induced by this rock contraction reinforce the regional, and it may be that only when the two occur together is the total extensional stress regime strong enough to result in subsurface tensile crack formation. In the proximity of the transform branch of the triple point, S of 64°N, the regional stress regime is horizontal shear, and there the mode of fracture is right-lateral strike slip on N-S striking faults.

As discussed above, the spatial distribution of the "geothermal seismicity" may be looked upon as a map of those volumes of rock that are feeding surface heat loss, i.e., that in mapping this activity we are mapping the heat source of the geothermal area. Imperfect correlation with surface heat loss may indicate lateral flow of the geothermal fluids before they reach the surface. The absence of seismicity need not necessarily imply that the rocks in that volume are not hot, but simply that they are not rapidly cooling down (e.g., beneath the Hengill central volcano).

When compared with other Icelandic high-temperature geothermal areas, the Hengill area is seen to exhibit an anomalously high level of seismicity. This is because of the unusual presence of a double, and therefore anomalously large, high-temperature geothermal area. Also the majority of the seismicity is associated with the extinct and cooling Grensdalur volcano, parallels of which are undocumented. It may be that a very fast cooling rate and correspondingly relatively high level of seismicity are only exhibited by such systems during a certain mature stage of their lifetimes when the conditions of permeability, temperature, and availability of groundwater are right. The level of seismic activity of the presently active Hengill central

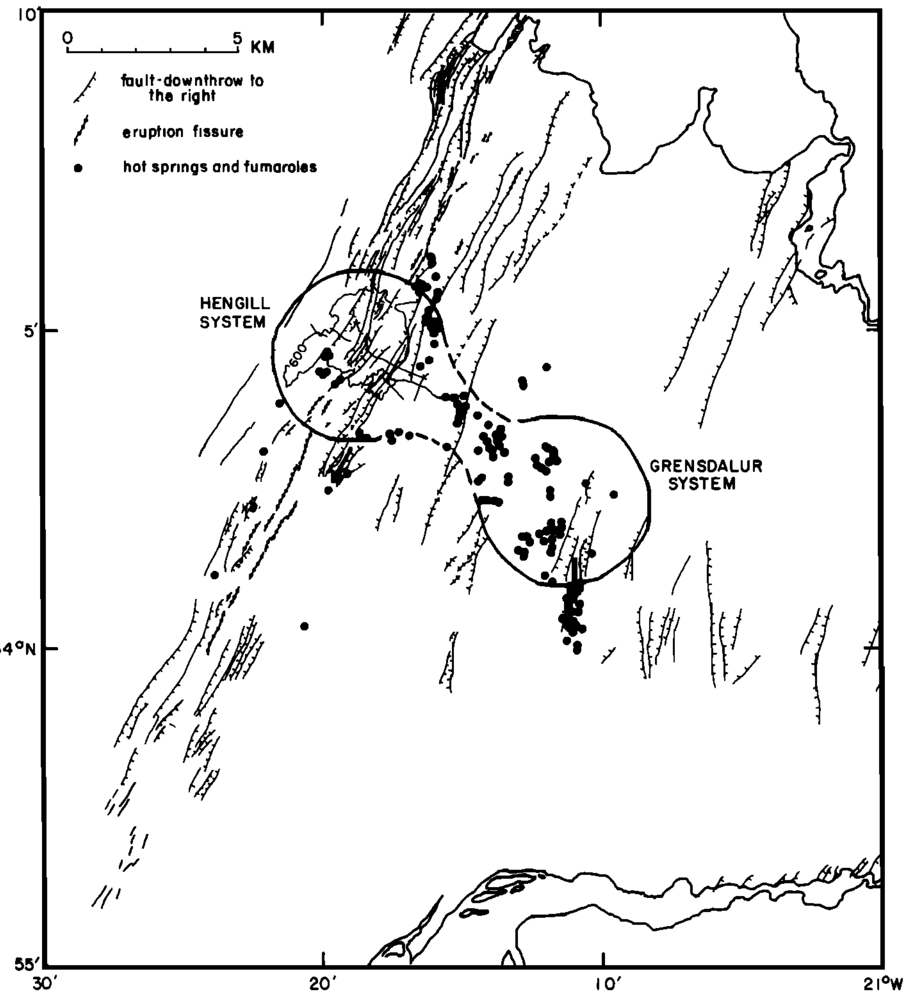

Fig. 11. Gross structure of the high-temperature area. The extents of the cores of the two major heat sources feeding the geothermal fields are outlined, and lateral subsurface flow is indicated by arrows. Subsidiary heat sources may feed the distal surface geothermal displays.

volcano, fissure swarm, geothermal system alone, however, is not anomalous when compared with other similar Icelandic systems [Ward and Bjornsson, 1971]. This implies that the findings from the Hengill area may apply to Icelandic geothermal areas in general, i.e., that the background seismicity associated with other systems may also demarcate their heat sources. This obviously is of great importance to geothermal prospecting and implies that the study of background seismicity is an important exploration tool that can give information about the reservoir that is unobtainable using other geophysical techniques.

The question is also raised as to whether tensile crack type seismicity occurs in other areas. A large proportion of the solutions obtained for events within the Hengill fissure swarm (i.e., on the accretionary plate boundary) were tensile crack type (Figure 7) and many other high-temperature geothermal areas in Iceland also occur along the accretionary plate boundary. It is thus probable that tensile crack type earthquakes occur in similar environments elsewhere. Work done at Reykjanes [Klein et al., 1977] also revealed a few earthquake radiation patterns of a similar type to the Hengill tensile crack events, as has a recent study of Krafla, NE Iceland (G. Foulger, unpublished data, 1988). Similar microearthquake radiation patterns have also been reported from the Mid-Atlantic Ridge [Toomey et al., 1985; D.R. Toomey, personal communication, 1988] suggesting that this process may also be proceeding there.

Along the plate boundary, periodic tectonic episodes also occur, with accompanying seismicity. Where such episodes have been observed, the earthquake source mechanisms exhibit predominantly shear faulting. This seismicity is superimposed onto the continuous, "geothermal" seismicity but displays a contrasting temporal distribution. Sequences such as the September 1972 swarm on Reykjanes [Klein et al., 1977] and the 1975-1984 Krafla earthquake swarms [Brandsdottir and Einarsson, 1979; Einarsson and Brandsdottir, 1980] were sequences of this type. In the case of the activity that could prove useful as a geothermal prospecting tool, however, a continuous temporal distribution would be anticipated that would ensure the successful aquisition of a data set by a relatively short monitoring project.

TABLE 1. Comparison of the Hengill and Grensdalur Geothermal Systems

Hengill system	Grensdalur System
1. Hot, partially molten source	1. Hot, solidified source
2. Magma injections into system during periods of volcanic activity	2. No periodic magma injections; volcano extinct
3. Heat exchange maintained mainly from below by magmatic activity	3. Heat exchange maintained mainly from above by groundwater activity
4. Periodic tectonic rifting episodes forming fissures	4. No periodic rifting episodes
5. Reservoir relatively hot	5. Reservoir relatively cool
6. Well-sealed reservoir	6. Poorly sealed reservoir
7. Thick pile of rock over reservoir	7. Reservoir deeply eroded
8. Small surface heat loss relative to heat content of source	8. Large surface heat loss relative to heat content of source
9. Geothermal swarms and microearthquake activity continuous at a low rate	9. Geothermal swarms and microearthquake activity continuous at a high rate

Small-magnitude, continuous seismicity in geothermal areas outside Iceland often has a temporal distribution that contrasts with the regional, e.g., in the Geysers area [Marks et al., 1978; Majer and McEvilly, 1979; Eberhart-Phillips and Oppenheimer, 1984], the Salton Sea [Gilpin and Lee, 1978] and the Coso Hot Springs [Walter and Weaver, 1980]. Where focal mechanism studies have been conducted, stress release is consistent with the regional tectonics [Foulger, 1982]. Such activity implies continuous small-scale adjustments of crustal equilibrium, and the association of this activity with heat loss is more credible than attributing it to either tectonic or magmatic processes, which are likely to occur in infrequent, intense episodes. Therefore regardless of tectonic regime, a study of geothermal earthquake activity has the potential for profoundly improving our understanding of individual geothermal resources.

Magmatic Processes at Accretionary Plate Boundaries

The accretionary plate boundary in Iceland and the North Atlantic is comprised of discrete segments which are fissure swarms or rift zones, each containing a central volcano [Saemundsson, 1978; Schouten et al., 1985]. The process of crustal accretion by dike injection involves large movements of crustal blocks in the direction of least compressive stress [e.g., Bjornsson et al., 1979]. To date, however, such movements have not been observed seismically. Although some teleseismic focal mechanisms with apparent enhanced explosive components have been reported from the Mid-Atlantic Ridge, these may be explained by propagation or interference effects, and accretionary plate boundaries generally exhibit normal dip-slip shear faulting. In the Krafla area, NE Iceland, dike injection and crustal widening were accompanied by relatively minor seismicity which was not observed teleseismically, and much of the crustal widening was accommodated on preexisting fissures. For example in July 1978, 30 km of the plate boundary rifted, and the crust widened by up to 1 m. Were such large crustal movements associated with a single earthquake, a shock of approximately magnitude 6 would be expected. However, the largest earthquake recorded during the swarm that accompanied this rifting was of magnitude M_{IL} = 4.1 [Bjornsson et al., 1979; Einarsson and Brandsdottir, 1980].

It seems that crustal accretion by dike intrusion is only accompanied by small-magnitude seismicity. A possible explanation may be that intrusion occurs along fissures that are preformed by cumulative small-magnitude cooling-contraction fracturing during inter-episodic periods of volcanic quiescence. These fissures are connected by relatively minor seismic shear movements on planes joining them and are widened aseismically to accommodate the dike volume. In addition, the injection of a dike may take several hours and therefore is not accomplished on the time scale of a single seismic event.

5. Conclusions

1. The radiation patterns of many small-magnitude earthquakes from the Hengill area, SW Iceland, indicate that they have non-double couple source mechanisms. These events are interpreted here as indicating tensile crack formation.
2. The tensile crack type events are intermingled with strike-slip shear events and are confined to the high-temperature geothermal area, whereas the shear seismicity encompasses the low-temperature geothermal area also. The limited data set indicates that the tensile crack events may be confined to lower magnitudes than the shear events. The fault planes of the shear

events may be deduced from the orientation of the tensile cracks.

3. The continuous seismicity is attributed to the process of cooling contraction cracking within the heat source. This process engineers low-level seismic stress release in a mode that is consistent with the regional stress regime. Within the high-temperature geothermal area, close to the accretionary plate boundary, this is extensional N125°E, and tensile cracks form normal to this. Within the low-temperature geothermal area, the regional stress regime associated with the transform zone is horizontal shear, and strike-slip earthquakes occur. Volume considerations indicate that much additional cooling contraction is accommodated aseismically.

4. The spatial distribution of the continuous seismicity demarcates volumes of hot rock that are feeding the geothermal reservoir, and thereby provides a tool to map the heat source of the geothermal area. This indicates that the heat loss is fueled by at least two separate heat sources, associated with the presently active Hengill volcano and the extinct Grensdalur volcano. The two fields associated with these separate heat sources may be expected to exhibit contrasting reservoir properties.

5. These principles may be extended to other geothermal areas along the accretionary plate boundary and within Iceland. They also exhibit continuous seismic activity, some of which will be tensile crack type. The heat sources of these areas may be mapped by accurately locating the background seismicity. Worldwide, the small-magnitude continuous earthquake activity observed in geothermal areas is also related to heat loss, and study of these earthquakes may advance understanding of individual prospects.

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