JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. B12, PAGES 23,827–23,842, DECEMBER 10, 1994

The Krafla spreading segment, Iceland
2. The accretionary stress cycle and nonshear earthquake focal mechanisms

S. K. Arnott
Shell International Petroleum Company, The Hague, Netherlands

G. R. Foulger[1]
Department of Geological Sciences, University of Durham, Durham, England

Abstract. The continuous geothermal seismicity of the Krafla volcanic system, NE Iceland, was monitored in 1985, immediately following a major spreading episode (Foulger et al., 1989; Arnott, 1990; Arnott and Foulger, this issue). Focal mechanisms of 153 well-located, shallow earthquakes were determined using P wave polarity data. Errors resulting from poorly modeled crustal structure were reduced by calculating hypocentral locations using a three-dimensional crustal model derived from a simultaneous inversion and by deriving takeoff angles and azimuths using three-dimensional ray tracing. The final data are thus of exceptionally high quality. Most of the events display radiation patterns consistent with a double-couple source model. The source orientations exhibit no systematic pattern beneath the Bjarnarflag well field, a little coherence in the Krafla caldera, and a general tendency for the greatest principal stress to be oriented normal to the rift zone in a zone of recent dike injection. Normal, thrust, and strike-slip shear events are mixed together, and five events have radiation patterns inconsistent with a double-couple source model and are attributed to nonshear source processes. Variable non-double-couple events were observed, with implosive and explosive/volume-conserving mechanisms and no clear systematic pattern of type or orientation for the system as a whole, though patterns were discernable in some subsets of events. The nonshear suite, like the shear suite, was therefore in general heterogeneous. The results indicate that a systematic deviatoric stress field was absent in the Krafla spreading segment in 1985, in contrast with the Reykjanes segment in 1977 and the Hengill segment in 1981 (Klein et al., 1977; Foulger, 1988b). The observations are consistent with a model where a strong, systematic deviatoric stress field characterizes the accretionary plate boundary during the interrifting and prerifting phases of the rifting cycle. This systematic stress is partially or wholly released during episodic rifting and spreading episodes, such as that experienced by the Krafla system 1975–1984, and is absent in the immediate postrifting phase of the rifting cycle. Nonshear geothermal earthquakes have been reported from all of the three Icelandic spreading segments studied in detail to date.

Introduction

Ocean bottom seismometer (OBS) studies reveal that continuous, small-magnitude seismicity characterizes the accretionary plate boundary. Deployments of small numbers of instruments for a few days usually report a substantial number of such events [e.g., *Toomey et al.*, 1988]. Little is known about this seismicity, however, in particular, its genesis. The events are small and therefore make a negligible direct contribution to crustal extension. In addition, ocean floor spreading is thought to be an episodic process [e.g., *Björnsson*, 1985], whereas the small-magnitude seismicity appears to be persistent on a daily basis. It is thus probably a consequence of a continuous process in the shallow crust, and thermal activity is a likely candidate.

Detailed information about this seismicity, and in particular focal mechanisms, can provide information

[1]Currently on leave at Branch of Seismology, U.S. Geological Survey, Menlo Park, California

Paper number 94JB00688.
0148-0227/94/94JB-00688$05.00

about their genesis and the stress state of the shallow crust. However, such information must be based on high-quality data from dense networks of reliably calibrated instruments in good geometric configurations. It is not yet possible to deploy such networks on the sea floor. As a result, our knowledge of the seismicity of the oceanic accretionary plate boundary is limited to information from teleseismic recordings of large earthquakes and data from sparse OBS networks. Focal mechanisms for many large teleseismically recorded events are available, but for the continuous small-magnitude events, only a few, poorly constrained mechanisms calculated from OBS networks have been reported.

Until technological advances make possible more ambitious OBS deployments, our ignorance of small-magnitude seismicity at the accretionary plate boundary may be partly redressed by studying the subaerial spreading segments of Iceland, which are also of interest in their own right. Iceland is a large, hotspot-centered subaerial exposure of oceanic crust containing over 20 segments up to 100 km in length. Continuous monitoring by the permanent national seismometer network indicates that earthquakes occur either in occasional sequences associated with magmatic or tectonic activity, or continuously at geothermal areas. Three segments have been studied in sufficient detail to produce reliable focal mechanisms: the Reykjanes, Hengill, and Krafla segments [*Klein et al.*, 1977; *Foulger*, 1988a, b; *Foulger et al.*, 1989; *Arnott*, 1990; *Arnott and Foulger*, this issue] (Figure 1a). At the Reykjanes and Hengill segments, frequent small earthquakes occur in the shallow crust, both tectonic and geothermal. The focal mechanisms indicate consistent failure in response to systematic extensional deviatoric stress fields in keeping with the local tectonics, with the axis of least compressive stress, σ_3, oriented horizontal and parallel to the local extension direction.

A remarkable aspect of both data sets is the occurrence of nonshear radiation patterns for some events. In the Reykjanes study, several events had reduced dilatational fields and were attributed to either small-scale crustal inhomogeneities distorting the ray paths or to nonshear source mechanism components, e.g., tensile cracks [*Klein et al.*, 1977]. In the case of the events from the Hengill segment, 50% of the 178 radiation patterns studied were incompatible with shear faulting, and many resembled those from Reykjanes in having reduced dilatational fields. The Hengill events were closely associated with geothermal heat loss and were attributed to cooling-induced, tensile cracking [*Foulger and Long*, 1984; *Foulger*, 1988b]. The effect of lateral heterogeneity was assessed by tracing rays through a three-dimensional crustal model derived from a simultaneous inversion. This analysis confirmed that path effects cannot account for the observed radiation fields [*Foulger and Julian*, 1993].

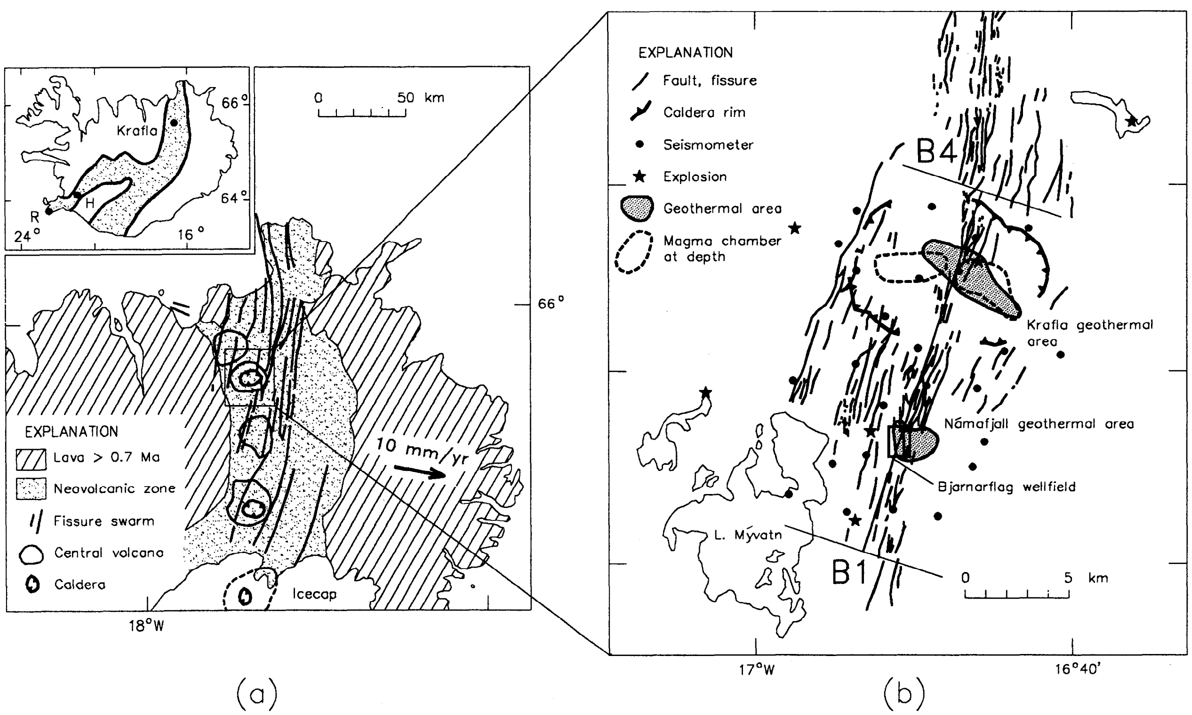

Figure 1. (a) Tectonic map of NE Iceland showing the regional context of the Krafla, Reykjanes (R) and Hengill (H) volcanic systems. The axial rift zone comprises five en echelon volcanic systems of which the Krafla system is one (adapted from *Sæmundsson* [1974] and *Björnsson* [1985]). (b) The temporary seismometer network that monitored the Krafla-Námafjall part of the Krafla volcanic system for 3 months in 1985. The outlines of the magma chamber lobes are taken from *Einarsson* [1978]. Line of cross section shown in Figure 3b is shown.

A detailed study of small-magnitude earthquake activity was conducted in the Krafla volcanic system in 1985, shortly after a major spreading episode [*Arnott*, 1990; *Arnott and Foulger*, this issue]. Despite the fact that this system is one of the most intensively studied in Iceland, very little was known about the earthquake focal mechanisms prior to our investigation. Composite solutions obtained using data from sparse networks had been reported by *Ward et al.* [1969] and *Brandsdóttir and Einarsson* [1979], but such solutions rely heavily on the assumptions of shear slip, orthogonality of the nodal planes and similarity of all the events used. The results must be viewed with particular skepticism, since nonshear earthquakes appear to be common at the accretionary plate boundary in Iceland.

A 28-station temporary seismometer network deployed and operated for 3 months in the Krafla segment recorded several hundred geothermal earthquakes. The experimental setup, data recorded, simultaneous inversion for three-dimensional crustal structure and hypocentral parameters, and the spatial and temporal distribution of the seismicity are described by *Arnott and Foulger* [this issue]. Focal mechanism solutions for 153 events were derived, and these are described here. Distortive path effects were corrected for by tracing rays through the three-dimensional model. In contrast with the results from the Reykjanes and Hengill segments, almost no preference for any mode of failure was detected. Instead, the events appear to have occurred on randomly oriented fault planes, and there is almost no evidence for systematic orientation of the axes of principal stress. A small number of the events have nonshear radiation patterns. Some require an implosive component and others permit volume-conserving or explosive mechanisms, a mixed suite that also suggests the absence of a strong, uniform, deviatoric stress field.

Unlike the Reykjanes and Hengill segments, the Krafla segment was studied immediately after a spreading episode. Our results show that the immediate postrifting phase of the accretionary cycle is characterized by the absence of a strong deviatoric stress field at the plate boundary.

Non-Double-Couple Earthquakes

Recent improvements in the quality of seismic data have brought about a growing body of evidence for nonshear earthquake source processes. For small-magnitude, shallow events, many data are in the form of distributions of P wave polarities where the areas of compressional and dilatational arrivals cannot be separated by orthogonal great circles. Some events require a volumetric source, i.e., a net explosive or implosive component, and the events observed at Reykjanes and Hengill, Iceland, fall into this category. Other studies include those of *Chouet* [1979] and *Shimizu et al.* [1987], who report events interpreted as tensile cracks opening or closing. Apparent implosive events associated with mining have been widely reported, and definitive quantitative evidence for an implosive, isotropic component has been presented [*McGarr*, 1992]. Three large ($M \approx 6$) events beneath in Long Valley, California, have volume-conserving radiation patterns where compressional and dilatational arrivals cannot be separated by orthogonal great circles. These were interpreted as accompanying extensional failure of rock under high fluid pressure during dike intrusion [*Julian*, 1983; *Julian and Sipkin*, 1985].

Caution must be exercised in attributing apparent non-double couple radiation fields to nonshear source processes, since hypocenter mislocation, path effects, phase misidentifications and mistaken instrument polarities may be responsible for the observations. Small earthquakes with reduced dilatational fields from the Reykjanes spreading segment, SW Iceland, were attributed to either focusing by small-scale lateral heterogeneities or tensile cracking [*Klein et al.*, 1977]. Reduced dilatational fields for large events from the Mid-Atlantic Ridge have been attributed to errors in polarity determinations caused by interference between P, pP, and sP phases [*Einarsson*, 1979; *Trehu et al.*, 1981]. Apparent non-double-couple radiation fields from small events on the Mid-Atlantic Ridge were attributed to errors in focal depths or in the assumed velocity model [*Toomey et al.*, 1985]. *Trehu and Solomon* [1983] accounted for nonorthogonality of nodal planes for events at the Orozco Transform by the effects of lateral velocity heterogeneity, and it has been shown that anisotropy in the source medium can have a similar effect [*Kawasaki and Tanimoto*, 1981].

The evidence for nonshear source mechanisms is nevertheless compelling in several studies where alternative explanations for the observed radiation fields have been carefully eliminated. With the exception of the mining events, all reports of shallow non-double-couple earthquakes are from volcanic/geothermal areas, and explanations for the source processes include cavity opening or collapse and dike injections. In the case of volumetric sources at shallow depths, the removal or addition of material in the source volume must occur, and fluid flow is probably involved (magma, steam, water, CO_2). Perturbation of the ambient stress field is a prerequisite to seismicity, and volcanic and geothermal areas at plate boundaries are thus sites where the required ingredients for non-double couple earthquakes are likely to be assembled.

Structure and Tectonics of the Krafla Volcanic System

Structure

The Krafla volcanic system is one of five en echelon systems that comprise the Northern Volcanic Zone of Iceland (Figure 1a). It comprises a swarm of fissures, faults, and dikes about 10 km wide and 100 km long, two high-temperature geothermal areas, and a central volcano with a caldera. The spreading rate is approximately 1.9 cm yr^{-1} [*DeMets et al.*, 1990]. The two high-temperature geothermal areas are both exploited, the

Krafla resource for power generation and the Námafjall resource for heat [e.g., *Ragnars et al.*, 1970; *Stefánsson*, 1981; *Ármannsson et al.*, 1987] (Figure 1b). A magma chamber is known to underlie the Krafla caldera in the depth range 3-7 km from an S wave attenuation study [*Einarsson*, 1978], magnetotelluric soundings [*Beblo and Björnsson*, 1978, 1980; *Beblo et al.*, 1983], seismic reflection work [*Zverev et al.*, 1980], and geodetic modeling [*Björnsson et al.*, 1979].

Continuous, low-level earthquake activity occurs, mostly beneath the two geothermal areas, at a rate of one magnitude 3.2 event per year [*Arnott and Foulger*, this issue]. Spatial correlation suggests that the seismicity is mostly induced by natural geothermal processes but that exploitation may also play a part beneath the Námafjall area. The crustal structure was imaged from the surface down to about 3 km depth by performing a simultaneous inversion for structure and hypocentral parameters using the method of *Thurber* [1983]. Severe lateral inhomogeneity is associated with high-density intrusions around the caldera fault and low-velocity material beneath the two geothermal areas [*Arnott and Foulger*, this issue].

Tectonics

Immediately prior to the study described here, the Krafla system experienced a period of intense tectonism accompanied by several meters of crustal spreading and volcanic eruptions [e.g., *Björnsson et al.*, 1977, 1979; *Björnsson*, 1985; *Einarsson*, 1991]. From 1975, the magma chamber beneath the Krafla caldera continually inflated, with repeated, rapid deflations of up to several tens of centimeters at intervals of a few months. During the deflations, magma flowed out of the chamber to form dikes along the fissure swarm. Several tens of centimeters of local crustal widening usually accompanied these dike injection events and over 15 such episodes occurred. By 1980, 2-9 m of crustal widening had occurred along the center of the fissure swarm, and contraction of the plates on either side out to a few tens of kilometers had occurred in response.

From 1980 the pattern of tectonism changed, and the magma escaping from the chamber erupted onto the surface through fissures north of the Krafla volcano. Evidently, at the start of the spreading episode the minimum compressive stress had been oriented horizontal and normal to the fissure swarm and was low enough that the crust could accommodate up to about 9 m of injected dikes. By 1980, the dike intrusions had raised the compressive stress in the direction normal to the fissure swarm to a level where it could support a column of magma that extended to the surface. Little or no dike intrusion occurred subsequently, and magma escaping from the chamber was erupted onto the surface. Major tectonic activity ceased in late 1984, after a total of about 20 deflation events had occurred.

Assuming a time-averaged spreading rate of 1.9 cm yr^{-1}, the crustal extension that occurred 1975–1984 in the Krafla system accounted for 100–420 years of plate movements. Such episodes clearly must occur infrequently, and the extension rate at this plate boundary between spreading episodes must be much less than the time-averaged rate. Some episodes may not be accompanied by surface eruptions if the magma supply is insufficient for activity to proceed beyond the intrusion phase, but despite this, the episodicity of volcanism may give a rough estimate of the episodicity of spreading. Geological studies suggest a postglacial volcanism recurrence interval of about 300–500 years for the Krafla system [*Thorarinsson*, 1960; *Björnsson et al.*, 1977; *Ármannsson et al.*, 1987]. The last volcanic episode, the "Myvatn Fires," is historically documented. It occurred 1724–1729, about 250 years ago, and may have accompanied dike intrusion and crustal widening similar to that observed 1975–1984 [*Björnsson et al.*, 1977].

The Data

After the cessation of the spreading episode, the local seismicity of the Krafla-Námafjall area was monitored during a 4-month period in 1985 by a 27-station temporary network (Figure 1b) [*Arnott and Foulger*, this issue]. The system was relatively volcanically quiescent at the time, and the seismicity targeted was the continuous, small-magnitude activity that was mostly associated with the two geothermal areas. The stations were deployed at average spacings of about 4 km in a network with a diameter of about 2–3 times the expected hypocentral depths, a configuration expected to yield good data for focal mechanism determination. Six timed explosions were detonated while the network was recording to provide information on seismometer polarities (Figure 1b). In addition, the polarities of the instruments were checked in the laboratory before and after the deployment. The results of these tests were in agreement, and we are therefore confident of the polarity of our instruments [*Arnott*, 1990].

Arrival times and polarities of the first P wave arrivals were measured by hand from paper records (Figure 2). Approximately 500 local events with Icelandic local magnitudes up to $M_{IL} = 2.1$ were located using the program HYPOINVERSE [*Klein*, 1978] and a one-dimensional crustal model (Table 1). A subsequent simultaneous inversion revealed not only substantial three dimensionality but also that the one-dimensional average of the crustal structure differed significantly from the regional model used, which had been derived from seismic refraction data (P. Einarsson, personal communication, 1985, Table 1). Relocation of the earthquakes using the three-dimensional crustal model decreased calculated hypocentral depths by about 1.0 km (or 1/3 of the original depth) in many cases.

The final locations calculated lay in the depth range 0-3 km and are concentrated beneath the Krafla geothermal area, the Bjarnarflag well field within the Námafjall geothermal area (Figure 1b) and along the locus of recent dike injections south of the Krafla volcano (Figure 3) [*Arnott and Foulger*, this issue]. Dur-

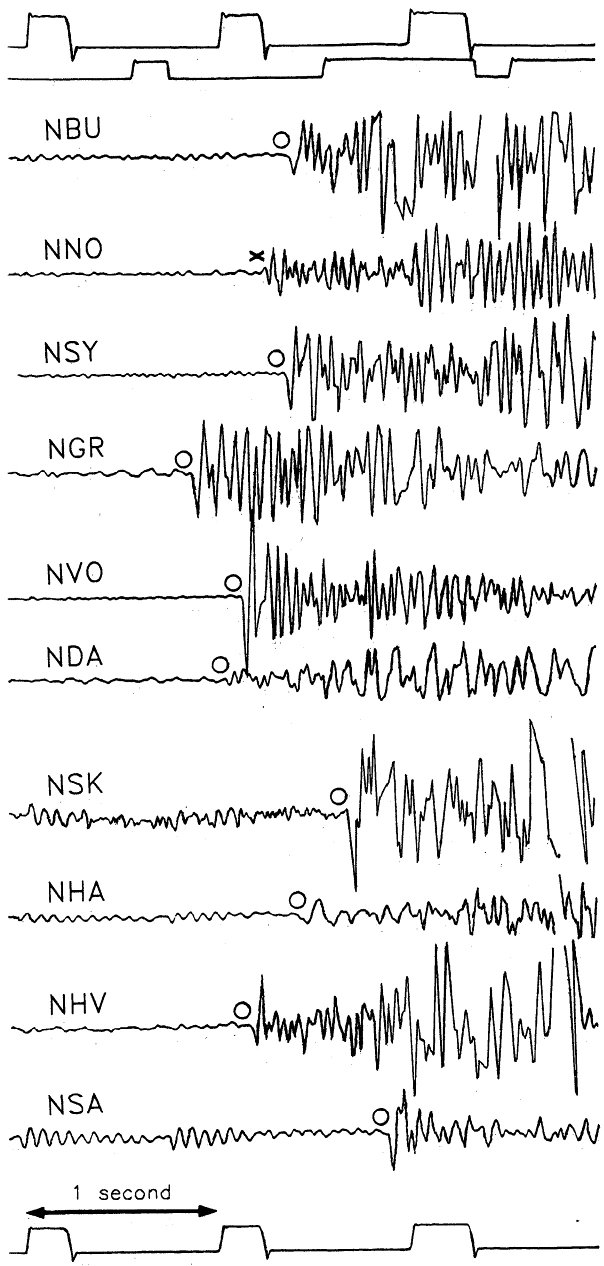

Figure 2. Seismograms of a typical event (event 850806 1548) within the Námafjall geothermal area. Open circles, dilatational polarity; cross, no polarity determination made.

ing the monitoring period, vigorous magmatic activity and associated intensive earthquake activity, such as had occurred during the previous decade, was absent. This, the continuous nature of the activity recorded in our experiment, and its spatial correlation with surface geothermal heat loss suggest that it was induced by geothermal processes. *Arnott and Foulger* [this issue] conclude that the events beneath the Krafla geothermal area are induced dominantly by thermal stresses resulting from natural heat loss and that geothermal mining activities contribute to the seismicity beneath the Bjarnarflag well field by mass and/or heat removal. The events along the zone of recent dike injection resulted from continued postintrusion stress adjustments, and this process may also contribute to the seismicity beneath Bjarnarflag.

Determination of the Focal Mechanisms

Inaccuracies in the crustal model used can result in large errors in calculated ray azimuths and takeoff angles used in constructing the P wave first motion plots that often form the basis for focal mechanism determinations. These errors result from two phenomena. First, significant hypocentral mislocations may result from the use of an incorrect crustal model and lead to calculation of incorrect ray trajectories. Second, the effects of refraction through a substantially laterally inhomogeneous structure may produce significant errors [*Arnott*, 1990; *Foulger and Julian*, 1993].

We determined focal mechanisms for 153 of the best located earthquakes in the Krafla volcanic system by mapping the distribution of P wave first motion polarities on the upper focal hemisphere. Amplitudes and later phases could not be used because our data are not available in digital form. At least nine points constrain each solution, and the average number available is 16. Only impulsive arrivals were used (Figure 2). In order to study the errors introduced by an incorrect crustal model, we initially used the original locations obtained with HYPOINVERSE [*Klein*, 1978] and the one-dimensional, refraction-based crustal structure. Using the results of the simultaneous inversion, we subsequently corrected separately for the effects of hypocentral mislocation and refraction through the refined one-dimensional structure and the three-dimensional crustal structure, following the same proce-

Table 1. Original and Refined One-Dimensional Model Based on Nearby Refraction Shots and Averaging the Results of the Tomographic Study, Repectively

Depth, km	Velocity, km/s
Original Model	
0.00	2.4
0.25	3.8
2.25	5.2
4.50	6.5
10.50	7.0
Refined Model	
0.0	3.00
1.0	3.60
2.0	4.65
3.0	5.60
4.0	5.75
5.0	6.80
6.0	7.00

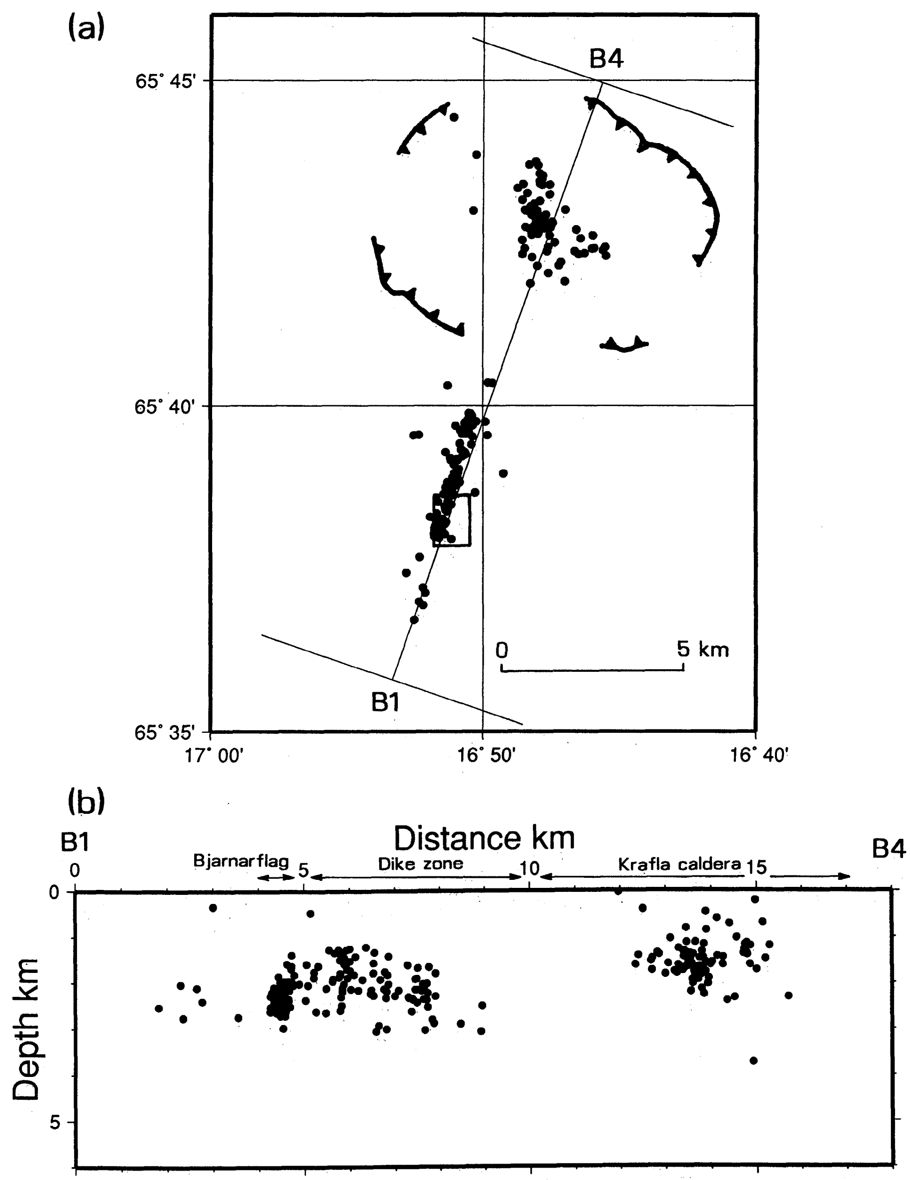

Figure 3. (a) Earthquake epicenters. The Krafla caldera is outlined. Box indicates the position of the Bjarnarflag well field within the Námafjall geothermal area. B1–B4 indicates the line of section of Figure 3b. (b) Earthquake hypocenters. Both figures show the best located events in the area, i.e., those located with ERZ ≤ 0.5 km [*Klein*, 1978].

dures as *Foulger and Julian* [1993]. We determined ray paths using the bending method of *Julian and Gubbins* [1977] in which an a priori ray is perturbed until it satisfies Fermat's principle of stationary time with respect to small path variations. Figure 4 shows the effects of these corrections for a typical well-constrained event from the Námafjall geothermal area.

The effect of changing the original one-dimensional model to the refined one-dimensional model is negligible. Calculated azimuth and takeoff angles generally changed by less than 1° (Figure 4a). Relocation of this event using the three-dimensional crustal model results in a shallowing of the hypocenter from 3.76 km to 2.59 km and a movement of about 300 m in the epicentral position. This adjustment in the event location causes only slight changes in the calculated azimuths, but the takeoff angles change by 0-10° (Figure 4b). Finally, ray tracing was performed through the three-dimensional crustal structure derived by simultaneous inversion, producing more accurate estimates of the ray takeoff directions. The changes introduced by using the three-dimensional model were large and variable (Figure 4c). Changes in ray azimuths were 0–15° and most takeoff angles decreased by 5–20°. A small number of events could not be successfully processed because of nonconvergence of some rays in the ray-tracing process as a result of shadow zones.

The overall effect of all the corrections is to reduce

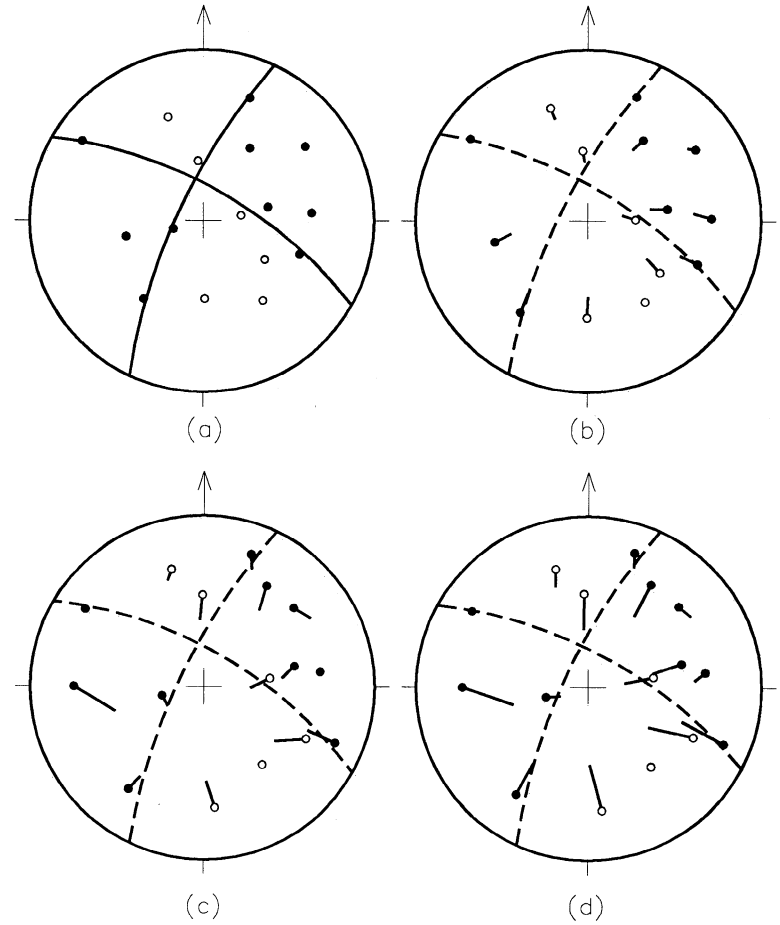

Figure 4. Correction of errors for the polarity plot of event 850709 1954, within the Námafjall geothermal area. Upper hemisphere plots in stereographic projection. Open and solid circles indicate dilatational and compressional first P wave motions; dashed lines indicate the nodal lines for the original interpretation made using the uncorrected data. Lines emanating from the circles indicate how the point moved relative to its location from the original one-dimensional model when the correction was made. (a) The refraction effect of changing the one-dimensional velocity model to the refined one-dimensional model (no discernible point movements). (b) The effect of correcting for the improved hypocentral location calculated using the three-dimensional crustal model. The main change was a shallowing of the hypocentral depth from 3.76 km to 2.59 km. (c) The effect of correcting for the true azimuths and takeoff angles by ray tracing through the three-dimensional crustal structure. (d) The combined effect of the corrections shown in Figures 4a–4c.

takeoff angles by up to 30° and to change azimuths by 0–15° (Figure 4d). Both inaccuracy in the original calculated hypocentral depth and the effect of lateral heterogeneity produce significant errors, and in the case of the event shown in Figure 4 the latter are the more serious.

To assess the impact of these corrections on the results, focal mechanisms were interpreted both before and after corrections were made. Where rays did not converge in the ray tracing procedure, the takeoff angles and azimuths calculated using the best location and one-dimensional crustal model were used. These points are less accurately mapped onto the focal sphere than those that underwent successful ray tracing. Convergence failure was most common for events located within the Krafla caldera, where crustal heterogeneity is greatest [*Arnott and Foulger*, this issue].

The effect of applying corrections to the event shown in Figure 4 was fairly typical for the data set as a whole. In some cases the changes in takeoff angle were larger, occasionally reaching 30°–40°. Takeoff angles were more frequently reduced than increased. Changes in ray azimuths were usually smaller than changes in takeoff angles, being mostly in the range 0–10° but occasionally up to 20°. These changes resulted, in general, in deterioration of focal sphere coverage and focal mechanism constraint.

Results

Introduction

After correcting for errors, a variable suite of focal mechanisms was obtained (Figures 5 and 6) including

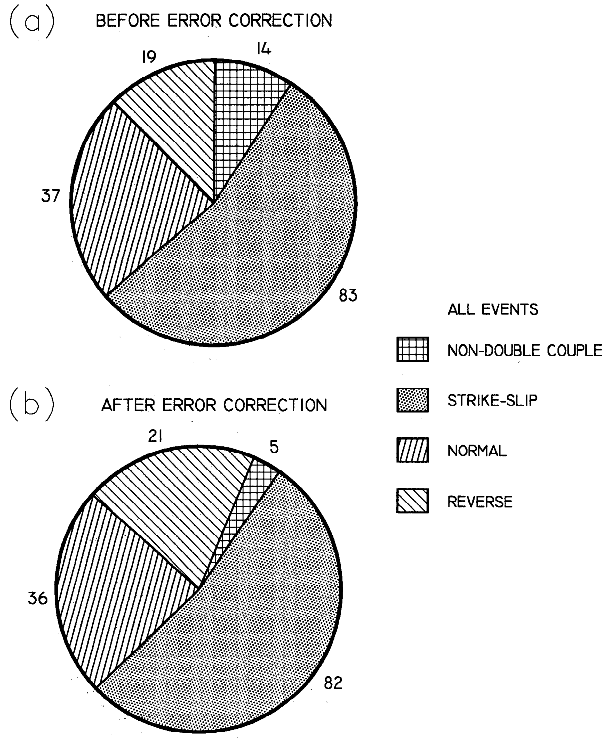

Figure 5. For the whole data set, numbers of events displaying focal mechanisms of various kinds (a) before and (b) after the correction of errors.

strike-slip, normal and thrust double-couple solutions, and explosive, implosive, and volume-conserving non-double-couple solutions. Because of the great care taken to insure the integrity of the polarities, no violations were allowed in the solutions. The events were interpreted conservatively, i.e., wherever possible a double-couple rather than a non-double-couple interpretation was made. Often this was possible only if extreme assumptions were made about areas of the focal sphere devoid of data points. In addition, no downgoing rays were used for non-double-couple solutions, increasing still further the data quality of those solutions. The evidence presented here for the non-double-couple mechanisms is thus the minimum allowed by the data.

The precision to which the positions of the nodal planes were determined is variable. In some cases there is less than 10° uncertainty, whereas in others, up to 30° uncertainty is possible in the case of one or both planes (Figure 7). Any one solution may therefore have considerable error. For this reason we combined the P and T axes of large numbers of mechanisms to infer the stress state of the crust (Figures 8, 9, and 10), thereby reducing the uncertainty in our final conclusions.

Although correcting for errors in the crustal model changed some focal mechanism solutions, the overall pattern of failure remained broadly the same after the corrections were made (Figure 5). The number of events displaying unambiguous non-double-couple radiation fields decreased somewhat because of the reduced focal sphere coverage of the corrected solutions and our conservative interpretive approach. Most of the events could be interpreted as double-couple, with roughly one half having predominately strike-slip mechanisms, a quarter normal, and a quarter thrust. A selection of typical solutions from the Námafjall geothermal area is shown in Figure 7. Five events were interpreted as non-double couple.

Double-Couple Events

Over half the events studied occurred within a volume of approximately 0.15 km^3 beneath the Bjarnarflag well field in the Námafjall geothermal area (Figures 3, 6, and 7). The P and T axes for the events have a quasi-random distribution as do the orientations of the nodal planes (Figure 8). A slight dominance of NNE and ESE striking nodal planes is nonetheless discernible. The sense of motion of these events is irregular. For example, for the events with one nodal plane striking NNE, if it is assumed that these are the fault planes, the sense of slip is approximately evenly distributed between dextral and sinistral motion.

Within the Krafla caldera (Figure 3) a higher proportion of activity was of normal-faulting type than elsewhere (Figure 6). The orientations of the P and T axes vary considerably, though there is some tendency for the P axes to have a preferred orientation of about N70°W and a plunge of about 60° (Figure 9). Similarly, many of the T axes cluster at an azimuth of about N90°E and a plunge of about 35°. The sense of slip for these events, as for the events beneath Bjarnarflag, shows no systematic pattern (sinistral or dextral) for a given choice of fault plane.

The P and T axes of the events beneath the dike zone between the Námafjall and Krafla geothermal areas are the most systematic, though they still show considerable variation (Figures 3, 6, and 10). The P axes are preferentially oriented roughly NW-SE and the orientations of the T axes vary from NNE–SSW through verti-

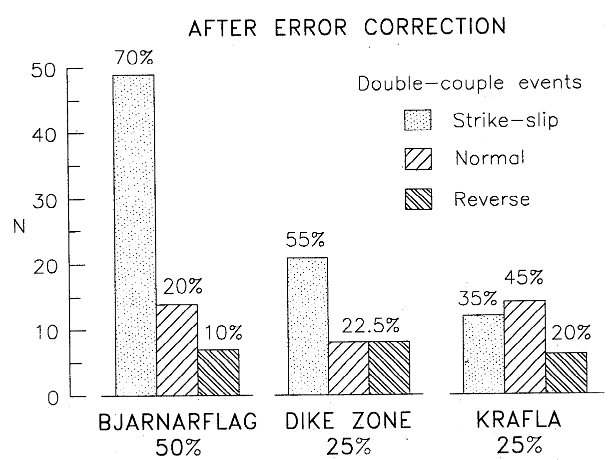

Figure 6. Numbers and percentages of events displaying double couple focal mechanisms of various kinds after the correction of errors, subdivided according to location.

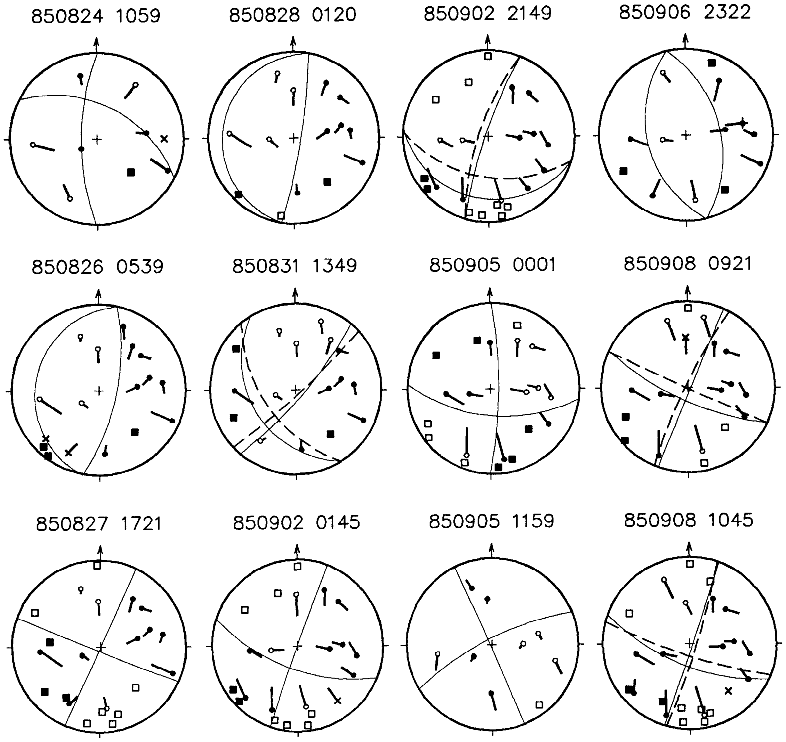

Figure 7. Example polarity plots for events from the Námafjall geothermal area. Upper hemisphere plots in stereographic projection. The solutions were obtained using angles computed by ray tracing through the final three-dimensional velocity model. Solid and open circles, compressional and dilatational arrivals; solid and open squares, compressional and dilatational arrivals that did not converge in the ray tracing process and are indicated in locations on the focal sphere calculated using the refined one-dimensional crustal model. Vectors emanating from the points show the locations of the points before tracing rays, derived using the original, one-dimensional crustal structure and HYPOINVERSE [*Klein*, 1978]. Solid lines indicate nodal lines derived after tracing rays; dashed lines indicate nodal lines derived before tracing rays. No dashed nodal lines are shown if the interpretation did not require change.

cal (Figure 10). The orientations of nodal lines again are highly variable, but, in general, the focal mechanisms imply a sinistral sense of motion if the NNE striking plane is taken to be the fault plane.

Non-double-Couple Events

Prior to correction for errors in the crustal model, 11 of the events studied apparently had non-double-couple radiation patterns. After correction, six of these events could be interpreted as double couple. For the remaining five events, the compressional and dilatational areas on the focal sphere still could not be separated by orthogonal great circles. Since path effects had been corrected and receiver effects eliminated, these events are interpreted as having nonshear source mechanisms (Figure 11).

Candidate moment tensors for each event were calculated using the method of *Julian* [1986], which uses linear programming methods to obtain solutions that are consistent with the data and that maximize or minimize desired linear functions of the moment tensor components. Solutions that maximize and minimize the isotropic component of the mechanisms are shown in Figure 11, superimposed upon the polarity data. It should be borne in mind that these are only examples from the families of solutions that exist for these earthquakes. These extremal solutions are computed subject to the normalization constraint that the sum of the absolute values of the six moment tensor elements equals unity.

One event located in the Námafjall area could be explained as either an explosive, implosive, or volume-conserving event (Figure 11a). Two events, one located beneath the Námafjall area and the other beneath the dike zone (Figures 11b and 11c), allow insignificantly small implosive components only and suggest approximately volume-conserving or explosive failure only. The remaining two events, one located beneath the Námafjall area and the other beneath the Krafla caldera, require large implosive source components (Figures 11d and 11e). The distributions of compressional and dilatational arrivals on the focal sphere is very variable for the five events, and no uniformity of mechanism type is detectable.

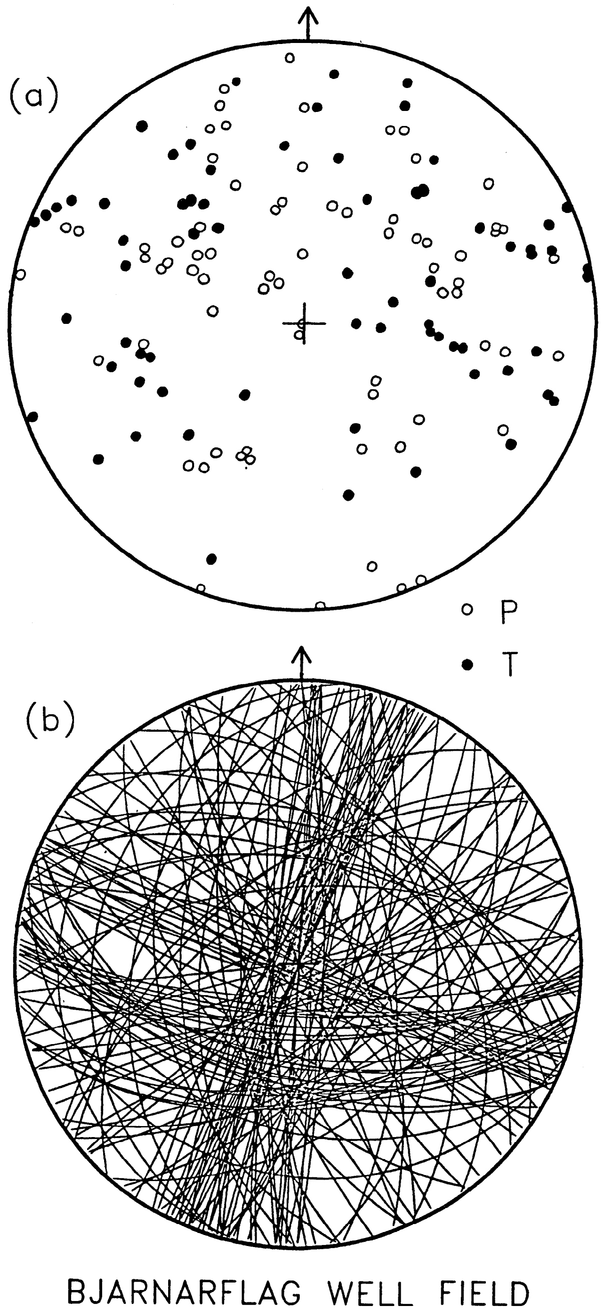

Figure 8. For events beneath the Bjarnarflag well field. (a) P and T axes for all double-couple events. Open circles, P axes; solid circles, T axes. (b) A summary plot of nodal lines for all double-couple events.

Discussion

Stress State of the Crust

It has been argued that the continuous small-magnitude earthquake activity that characterizes geothermal areas along the Icelandic accretionary plate boundary is induced by geothermal processes [*Foulger*, 1988a, b]. The cooling of hot rock at depth and geothermal fluid removal decrease the ambient stress level locally in an isotropic way and induce small-magnitude, continuous seismicity. The mode of failure is governed by the local deviatoric stress. The focal mechanisms of these small earthquakes may therefore be used to infer the orientation and variation of the principal stress axes in the study area.

In the case of double-couple earthquakes, the P and T axes do not correspond exactly to the orientations of the greatest and least compressive stresses, σ_1 and σ_3, but they do nevertheless give an approximate indication [*McKenzie*, 1969]. The events beneath the Bjarnarflag

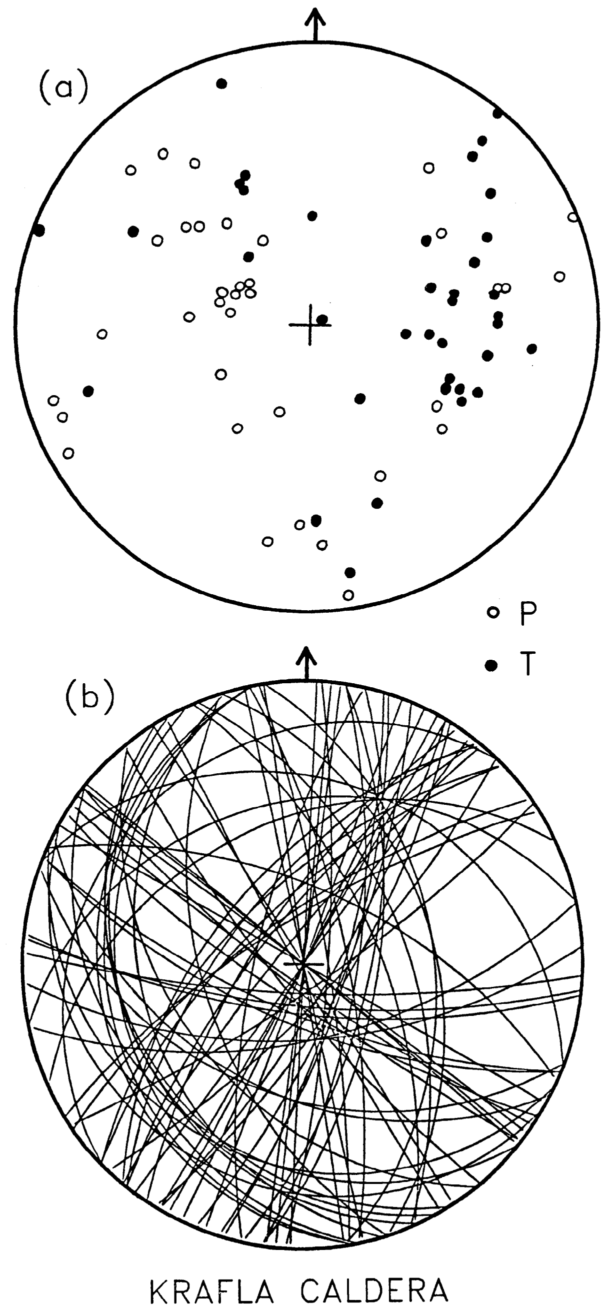

Figure 9. For events in the Krafla caldera. (a) P and T axes for all double couple events. Open circles, P axes; solid circles, T axes. (b) A summary plot of nodal lines for all double-couple events.

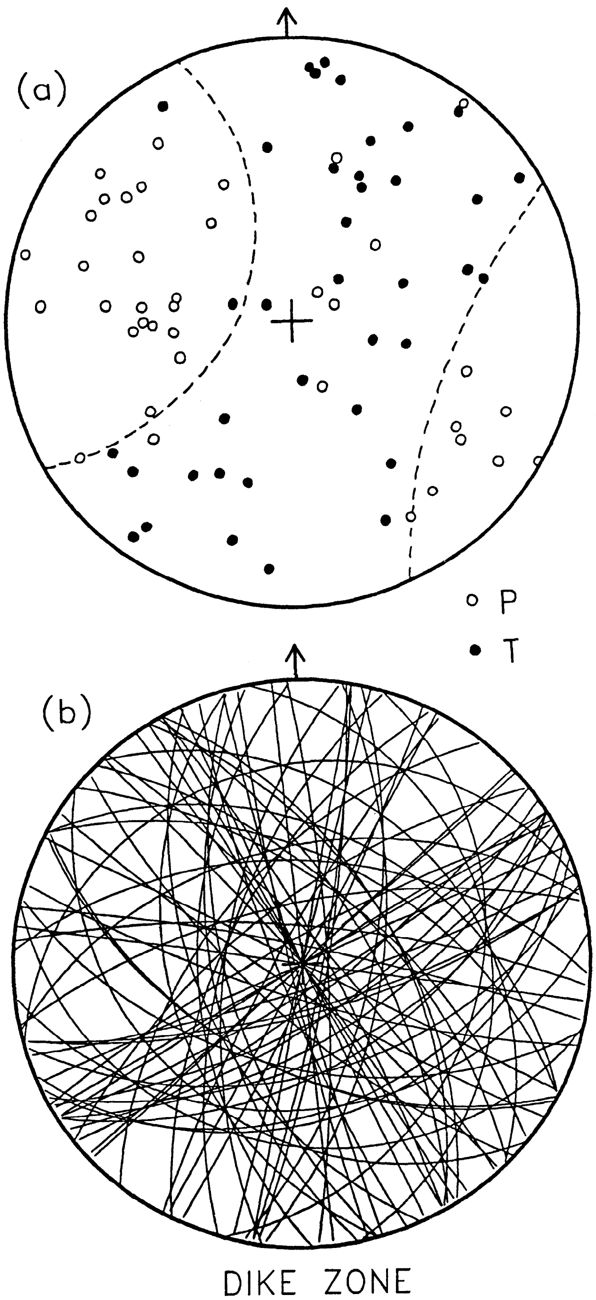

Figure 10. For events in the dike zone. (a) P and T axes for all double-couple events. Open circles, P axes; solid circles, T axes. (b) A summary plot of nodal lines for all double-couple events.

well field within the Námafjall geothermal area suggest that the orientations of σ_1 and σ_3 are highly variable. The events had magnitudes $M_{IL} \leq 2.1$ [*Arnott and Foulger*, this issue], which corresponds to source dimensions of up to a few tens of meters [e.g., *Wyss and Brune*, 1968]. The distribution of P and T axes for events located beneath the Krafla geothermal field suggest a slight preference for σ_1 to trend roughly N70°W with a plunge of about 60°and for σ_3 to trend about N90°E with a plunge of about 35°. In the case of the dike zone, the orientations of the P and T axes for events suggest a general orientation of approximately horizontal and perpendicular to the fissure swarm for σ_1, the greatest compressive stress, and variable from horizontal and parallel to the fissure swarm through to vertical for σ_3, the least compressive stress.

The great variability in the orientation of stress in the Krafla volcanic system suggests that the deviatoric stress field was small and unsystematic at the time of monitoring in 1985. That the orientation of the greatest compressive stress σ_1 is locally parallel to the local tectonic extension direction in the dike zone is an entirely counterintuitive result that contrasts with stress fields reported for other Icelandic spreading segments, derived from focal mechanisms. It is, however, in enigmatic agreement with stress measurements made at shallow depths (a few hundred meters) in boreholes, which generally show the maximum horizontal stress to be parallel to the local inferred extension direction [*Haimson and Rummel*, 1982]. *Klein et al.* [1977] studied 433 events from the Reykjanes spreading segment and found a clear, systematic pattern in the orientation of the P and T axes. They concluded that σ_3 was oriented approximately horizontally and parallel to the inferred spreading direction and that the orientation of σ_1 varied from vertical to horizontal, i.e., normal to the inferred spreading direction. This was intuitive for the tectonic environment. *Foulger* [1988b] analyzed 178 events from the Hengill triple junction and found normal and strike-slip double-couple and explosive non-double-couple focal mechanisms. The data were consistent with a deviatoric stress field with σ_3 oriented horizontally and parallel to the spreading direction. The stress field in the Hengill segment was therefore oriented similarly to that of the Reykjanes segment with respect to the local spreading direction. The results reported here for the Krafla segment are thus anomalous and counterintuitive for the regional tectonic environment.

An explanation for the observations is suggested by the tectonic history of the Krafla segment. The 1975–1985 decade of activity generated numerous dike injection events along the fissure swarm during the first 6 years, after which time, continued magmatism produced mostly volcanic eruptions. It may be concluded that at the commencement of the spreading episode in 1974 the least compressive principal stress was horizontal and normal to the fissure swarm and that after 6 years of dike intrusions the path of least resistance for magma expelled from the magma chamber was flow onto the surface. The principal stresses must therefore have been approximately lithostatic. The earthquakes analyzed here occurred shortly after the end of the spreading episode, and their mode of failure reveals the immediate postspreading stress state of the crust. They show that the average deviatoric stress over the study area was small and that $\sigma_1 \simeq \sigma_2 \simeq \sigma_3$. This conclusion agrees with that drawn from the volcanological observations.

These diverse seismological observations from various Icelandic spreading segments are consistent. It may be concluded that the prespreading stress field in the Krafla system was similar to that observed in the Reykjanes and Hengill segments with respect to the lo-

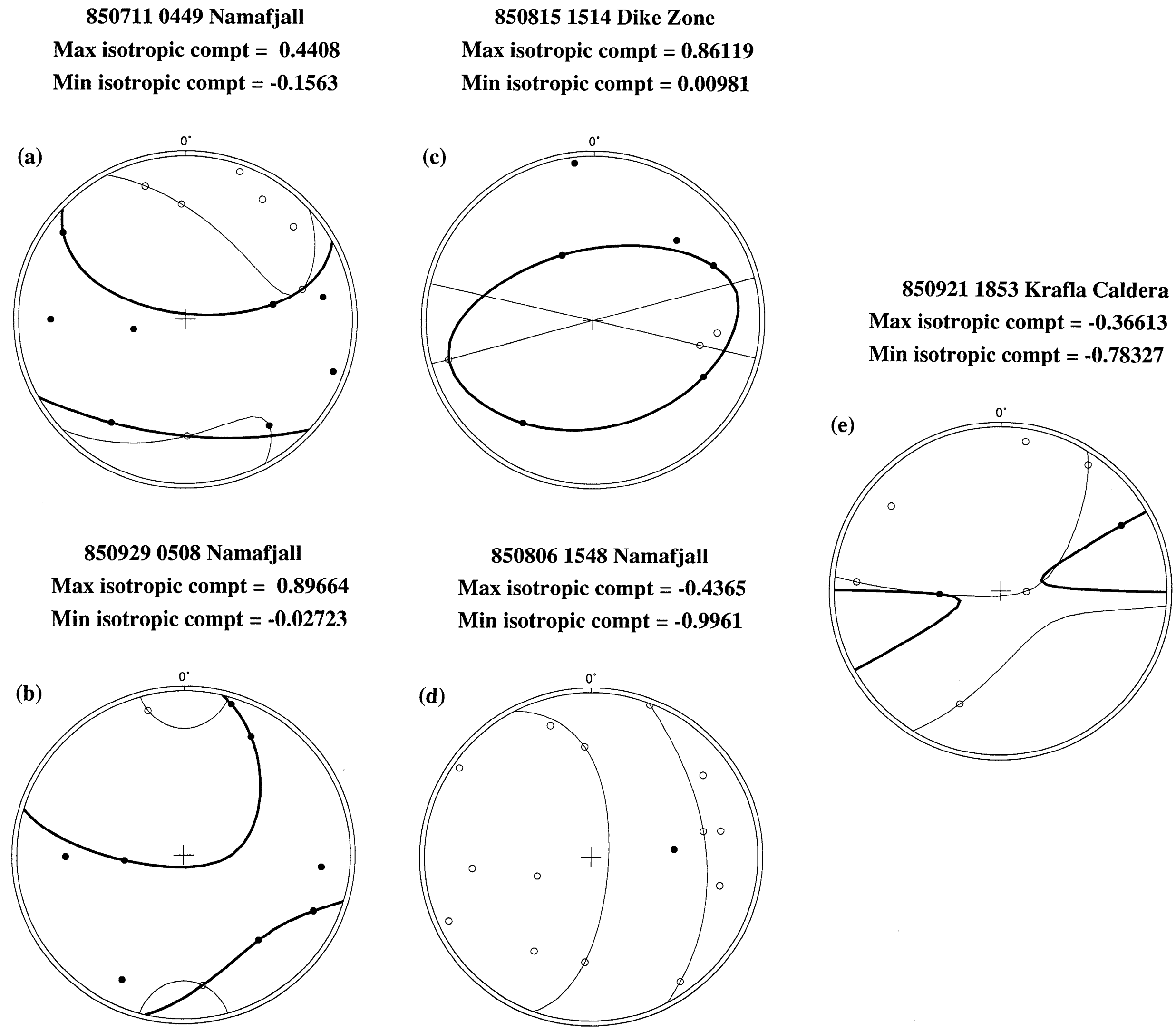

Figure 11. Polarity plots for the events that could not be interpreted as double-couple after the errors were corrected. Solid and open circles, compressional and dilatational arrivals corrected for refraction through the three-dimensional crustal model; circled solid and open circles, arrivals for which ray tracing was unsuccessful. The azimuths and takeoff angles of those points are not corrected for refraction through the three-dimensional crustal model and are less accurately mapped onto the focal sphere. Thin lines, nodal lines of the most explosive solutions; thick lines, nodal lines of the most implosive solutions. Event in Figure 11d has only one compressive arrival and therefore the nodal lines of the most implosive solution are vanishingly small around that point. For each event the origin date and time are indicated along with the magnitude of the maximum and minimum possible isotropic components.

cal spreading direction. Furthermore, the postspreading stress field indicated by both the volcanic behavior and the earthquake focal mechanisms reported here was largely isotropic.

It is possible to make rough estimates of the absolute values of compressive stress after the spreading episode and the stress drop associated with the dike intrusion and thereby to deduce the rough values of the absolute stresses prior to dike intrusion. We may write

$$\sigma_{N(\mathrm{pre})} + \Delta\sigma_{N(\mathrm{diking})} = \sigma_{N(\mathrm{post})}$$

and

$$\sigma_{1(\mathrm{post})} \simeq \sigma_{2(\mathrm{post})} \simeq \sigma_{3(\mathrm{post})} \simeq \sigma_{N(\mathrm{post})} \, ,$$

where for a point at the bottom of the dike complex, $\sigma_{N(\mathrm{pre})}$ and $\sigma_{N(\mathrm{post})}$ are the compressive stresses horizontal and normal to the fissure swarm before and after dike intrusion, $\Delta\sigma_{N(\mathrm{diking})}$ is the change in compressive stress resulting from dike intrusion, and $\sigma_{1-3(\mathrm{post})}$ are the maximum, intermediate, and minimum principal stresses after dike intrusion. Then

$$\sigma_{N(\text{post})} = \rho g z \, ,$$

where ρ is the density of basalt magma ($\approx$2650 kg m^{-3}), g is the acceleration due to gravity (9.81 m s^{-2}), and z is the height of the dike. *Rubin* [1992] estimates the dike bottom to lie at about 8 km depth on the basis of modeling the vertical, codiking deformation field. This equation yields a value of

$$\sigma_{N(\text{post})} \simeq 200 \text{ MPa}.$$

Assuming an elastic whole space, the increase in compressive stress horizontal and normal to an injected vertical dike may be written [e.g., *Pollard et al.*, 1983]

$$\Delta\sigma_{N(\text{diking})} = \frac{\mu h}{(1-\nu)z} \, ,$$

where μ is the shear modulus ($\approx 0.18 \times 10^5$ MPa for the rocks of the Krafla volcanic system [*Rubin*, 1992]), h is the thickness of the dike ($\approx$3 m south of Krafla), and ν is Poisson's ratio ($\approx$0.25). Then

$$\Delta\sigma_{N(\text{diking})} \simeq 10 \text{ MPa},$$

which is also the value of the deviatoric stress prior to dike intrusion, and

$$\sigma_{N(\text{pre})} \simeq 190 \text{ MPa}.$$

The heights of the dikes injected in the Krafla spreading episode are small when compared, for example, with estimates of the heights of dikes in Tertiary Icelandic rocks [*Gudmundsson*, 1983]. This fact gives rise to our exceptionally high estimate ($\approx$10 MPa) for the deviatoric stress. It should be emphasized that this estimate is a rough approximation and ignores substantial sources of error. In particular, the value of the in situ shear modulus is poorly known and may differ greatly from laboratory-measured values. We use a value of 0.18×10^5 MPa, a figure considered to be reasonable for this locality by *Rubin* [1992] and to provide a good fit to local geodetic deformation data from this area. The effect of the free surface would cause the true stress drop to be lower the closer the dike top approaches the surface, which is thought to be about 1 km at this locality. In addition, the depth to the bottom of the dike is rather poorly known, as is the thickness, taken to be 3 m here [*Björnsson et al.*, 1979]. Our reasoning is not dependent on any debatable assuptions about the initial state of stress, however, since this is what we calculate. It is, however, an inescapable conclusion that the 1975–1984 spreading episode in the Krafla system caused unusually large drops in the deviatoric stress of the shallow crust.

The observations from the Reykjanes, Hengill, and Krafla segments suggest that a stress cycle accompanies the episodic spreading cycle at the accretionary plate boundary. Amounts of spreading comparable to the thicknesses of dikes occur infrequently and are separated by quiescent intervals of hundreds of years, during which time the compressional stress horizontal and normal to the fissure swarm decreases. The Reykjanes system had been quiescent for approximately 700 years at the time of monitoring [*Jonsson*, 1983], and the Hengill system had been quiescent for approximately 200 years [*Thoroddsen*, 1899]. Both were thus in interrifting or prerifting stages.

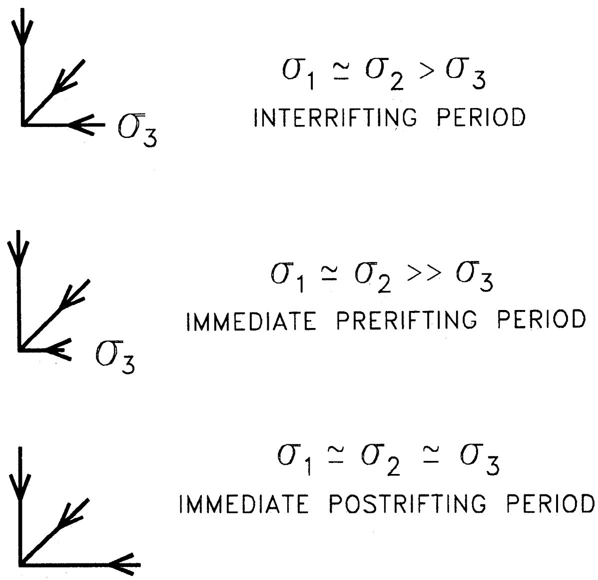

Figure 12. Schematic diagram illustrating the relative magnitudes of the principal axes of stress throughout the spreading cycle. $\sigma_1, \sigma_2, \sigma_3$ indicate the maximum, intermediate, and minimum principal stresses, respectively.

During interrifting and prerifting stages, σ_3 is oriented horizontal and normal to the local fissure swarm, and its magnitude decreases with time (Figure 12). The large ($\approx$10 MPa) deviatoric stress calculated for the Krafla system was presumably built up over the previous 250 year interrifting period. During dike intrusion and spreading, compressive stress parallel to the extension direction increases, and it may equal or even locally exceed the values of the former σ_1 and σ_2. The resulting triaxial stress ellipsoid is close to a sphere (Figure 12) [*Foulger and Long*, 1992]. Stress field modification and crustal deformation are confined to the proximity of the plate boundary only, and expansion of the central part of the rift zone generates compression of the flanks, as was observed geodetically [*Björnsson*, 1985]. The flanks are subsequently redilated by continuing plate motion to which the crust responds by deforming viscoelastically. This process progressively decreases the stress parallel to the spreading direction and commences the new interrifting extensional stress buildup phase [*Björnsson*, 1985; *Foulger et al.*, 1992; *Heki et al.*, 1993].

The Krafla volcanic system clearly demonstrates that radical reorientations of the axes of principal stress may result from major tectonic activity. This example serves to emphasize the time-varying nature of the stress field in active tectonic regions, in contrast with its presumed stability in the plate interiors.

Non-Double-Couple Earthquakes

An apparent non-double-couple earthquake radiation field could be produced by path effects, receiver effects or nonshear source processes. Candidate effects include source mislocation, path complexity, miscalibration of instruments, misidentifications of polarities, and observations in the near field. We corrected for the first two effects and carefully eliminated the possibility of error from the third effect by multiple polarity tests of the instruments. We exercised conservatism to reduce the likelihood of polarity misidentifications and picked only impulsive first arrivals (Figure 2). The seismograms used had first P wave arrivals with dominant frequencies greater than 10 Hz, and the hypocenters were all more than 2 km from the closest recording station. The observations were thus all made in the far field.

Most of the earthquakes recorded were less than 3 km deep. This fact reduces the resolving power of our network, which was designed on the basis of earlier, larger estimates of the depth of seismicity in this area. Even so, a small number of events are well enough constrained that double-couple interpretations can be ruled out, and these represent the minimum evidence for nonshear failure in this area.

A number of source processes have been suggested that could account for non-double-couple radiation patterns. These include simultaneous shear faulting on planes of different orientation, tensile cracking with or without pore fluid pressure drops, dike injection, and simultaneous tensile and shear failure. It is not possible to determine source process unambiguously for a given event based on P wave first motions alone, since a wide range of the sources listed above and combinations of them could generate similar radiation patterns. However, those events that display a volumetric component must involve the seismic opening or closing of cavities and therefore probably the movement of fluids at the source.

The non-double-couple events reported here occurred within the Námafjall and Krafla geothermal areas and the dike zone. The mobile fluids required to enable volumetric seismic failure are thus likely to be high-pressure geothermal water and/or steam. Too few non-double-couple events are unambiguously constrained to deduce any spatial variation in type within the study area.

In Iceland, non-double-couple earthquakes have also been reported from the Reykjanes and Hengill segments [*Klein et al.*, 1977; *Foulger*, 1988b]. In those cases, all the events reported had reduced dilatational areas on the focal sphere and were therefore explosive in type, and tensile crack source models were suggested. Such a mode of fracture is extensional and in keeping with the uniform extensional stress fields that characterize those segments and were revealed by study of the double-couple focal mechanisms. The mode of non-double-couple failure observed in the Krafla segment contrasts with that reported from the Reykjanes and Hengill segments. The earthquakes are of mixed type with no one event requiring an explosive source component, three permitting either explosive or volume-conserving solutions, and two requiring substantially implosive sources. The double-couple seismicity shows that the stress field is highly variable on a small scale and is not strongly deviatoric. The non-double-couple events display no preferred sign or magnitude for the isotropic component and no discernible uniformity of type. They are therefore compatible with the style of accompanying double-couple seismicity in the same way as for other Icelandic spreading segments.

Comparison With Oceanic Spreading Segments

The findings reported here for the Krafla subaerial spreading segment give some hint about processes that may occur in oceanic segments. Swarms of medium-magnitude earthquakes on the mid-ocean ridges have been interpreted as episodic dike intrusion/spreading events (J. Cann, personal communication, 1992). Continuous microearthquake activity has frequently been monitored by OBSs, and non-double-couple mechanisms have been suggested for a few poorly constrained events [e.g., *Toomey et al.*, 1988]. Observations such as these are analogous to those made in the Krafla segment and suggest similarity between Icelandic and oceanic segments.

The deployment of dense seismometer networks for substantial periods and accurate geodetic monitoring of the seafloor may soon be conducted and results from Icelandic segments may be useful in designing marine experiments. The current study suggests that long-term, or occasional, repeated, short-term seismometer network deployments might detect time variations in the stress fields at the plate boundary that could be used to deduce tectonic and magmatic behavior. The hypothesis that small, non-double-couple earthquakes characterize the global accretionary plate boundary should be tested, and good data could provide information on hydrothermal circulation in the shallow, young crust. The present study emphasizes the importance of a well-constrained crustal model to such work.

Conclusions

1. The local crustal structure of the Krafla-Námafjall part of the Krafla volcanic system differs sufficiently from that nearby and is sufficiently heterogeneous that focal mechanisms derived for local earthquakes may be seriously in error if the local model is not used. Accurate hypocentral depths and rigorous accounting of the effects of lateral heterogeneity are essential for the confident identification of non-double-couple radiation patterns.

2. The continuous geothermal earthquake activity occurring within the Krafla system in 1985 comprised mostly events that were consistent with a shear source interpretation, but a small number of events required interpretation involving nonshear source processes.

3. In 1985 the axes of principal stress displayed no systematic orientation beneath the Bjarnarflag well field, little coherence in the Krafla caldera, and a broad

tendency for σ_1 to be oriented normal to the rift zone in the zone of recent dike injection. This resulted in a mixed suite of focal mechanism types, including normal, thrust, and strike-slip shear sources and implosive and explosive/volume-conserving nonshear sources.

4. The rifting cycle at the accretionary plate boundary is accompanied by a stress cycle. During interrifting and prerifting periods a systematic deviatoric stress field is built up, with the minimum principal stress oriented horizontally and parallel to the spreading direction. The deviatoric stresses may be of the order of 10 MPa. During rifting, the deviatoric stress is partly or completely released and in the immediate postrifting phase the systematic deviatoric stress field is reduced, absent, or even reversed locally temporarily.

5. Non-double-couple earthquakes have been reported from all of the three Icelandic spreading segments that have been studied in detail to date. This phenomenon may characterize the accretionary plate boundary in general. The availability of excess, mobile, high-pressure geothermal and magmatic fluids may be the essential ingredient required to enable volumetric, nonshear failure.

Acknowledgments. This project was financed and equipped by the Natural Environment Research Council, the National Energy Authority, Iceland, and the Icelandic Science Fund. Páll Einarsson, Axel Björnsson, Lárus H. Bjarnason, Fred Klein, Bruce Julian, Allan Rubin, and Arthur McGarr made valuable contributions to this project.

References

Ármannsson, H., A., Gudmundsson, and B. S. Steingrimsson, Exploration and development of the Krafla geothermal area, *Jökull, 37*, 13–29, 1987.

Arnott, S. K., A seismic study of the Krafla volcanic system, Iceland, Ph.D. thesis, vii + 283 pp., Univ. of Durham, Durham, England, 1990.

Arnott, S. K., and G. R. Foulger, The Krafla spreading segment, Iceland, 1, Three-dimensional crustal structure and the spatial and temporal distribution of local earthquakes, *J. Geophys. Res.*, this issue.

Beblo, M., and A. Björnsson, Magnetotelluric investigation of the lower crust and upper mantle beneath Iceland, *J. Geophys., 45*, 1–16, 1978.

Beblo, M., and A. Björnsson, A model of electrical resistivity beneath N.E. Iceland, correlation with temperature, *J. Geophys., 47*, 184–190, 1980.

Beblo, M., A. Björnsson, K. Arnason, B. Stein, and P. Wolfgram, Electrical conductivity beneath Iceland–Constraints imposed by magnetotelluric results on temperature, partial melt, crust- and mantle structure, *J. Geophys., 53*, 16–23, 1983.

Björnsson, A., Dynamics of crustal rifting in NE Iceland, *J. Geophys. Res., 90*, 10,151–10,162, 1985.

Björnsson, A., K. Sæmundsson, P. Einarsson, E. Tryggvason, and K. Grönvold, Current rifting episode in North Iceland, *Nature, 266*, 318–323, 1977.

Björnsson, A., G. Johnsen, S. Sigurdsson, G. Thorbergsson, and E. Tryggvason, Rifting of the plate boundary in northern Iceland 1975–1978, *J. Geophys. Res., 84*, 3029–3038, 1979.

Brandsdóttir, B., and P. Einarsson, Seismic activity associated with the September 1977 deflation of the Krafla central volcano in north-eastern Iceland, *J. Volcanol. Geotherm. Res., 6*, 197–212, 1979.

Chouet, B., Sources of seismic events in the cooling lava lake of Kilauea Iki, Hawaii, *J. Geophys. Res., 84*, 2315–2330, 1979.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int., 101*, 425–478, 1990.

Einarsson, P., S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust, *Bull. Volcanol., 41*, 1–9, 1978.

Einarsson, P., Seismicity and earthquake focal mechanisms along the mid-Atlantic plate boundary between Iceland and the Azores, *Tectonophysics, 55*, 127–153, 1979.

Einarsson, P., Earthquakes and present-day tectonism in Iceland, *Tectonophysics, 189*, 261–279, 1991.

Foulger, G. R., The Hengill triple junction, SW Iceland, 1, Tectonic structure and the spatial and temporal distribution of local earthquakes, *J. Geophys. Res., 93*, 13,493-13,506, 1988a.

Foulger, G. R., The Hengill triple junction, SW Iceland, 2, Anomalous focal mechanisms and implications for processes within the geothermal reservoir and at accretionary plate boundaries, *J. Geophys. Res., 93*, 13,507–13,523, 1988b.

Foulger, G. R., and B. R. Julian, Non-double-couple earthquakes at the Hengill-Grensdalur volcanic complex, Iceland: Are they artifacts of crustal heterogeneity?, *Bull. Seismol. Soc. Am., 83*, 38–52, 1993.

Foulger, G.R., and R. E. Long, Anomalous focal mechanisms: Tensile crack formation at an accreting plate boundary, *Nature, 310*, 43–45, 1984.

Foulger, G. R., and R. E. Long, Non-double couple earthquake focal mechanisms and the accretionary tectonic cycle, in *Volcanic Seismology, IAVCEI Proceedings in Volcanology 3*, P. Gasparini, R. Scarpa, and K. Aki, eds., Springer-Verlag, 223–234, 1992.

Foulger, G. R., R. E. Long, P. Einarsson, and A. Björnsson, Implosive earthquakes at the active accretionary plate boundary in northern Iceland, *Nature, 337*, 640–642, 1989.

Foulger, G. R., C.-H. Jahn, G. Seeber, P. Einarsson, B. R. Julian, and K. Heki, Post rifting stress relaxation at the accretionary plate boundary in Iceland, measured using the Global Positioning System, *Nature, 358*, 488–490, 1992.

Gudmundsson, A., Form and dimensions of dykes in eastern Iceland, *Tectonophysics, 95*, 295–307, 1983.

Haimson, B. C., and F. Rummel, Hydrofracturing stress measurements in the Iceland Research Drilling Project drill hole at Reydarfjordur, Iceland, *J. Geophys. Res., 87*, 6631–6649, 1982.

Heki, K., G. R. Foulger, B. R. Julian and C.-H. Jahn, Plate kinematics near divergent boundaries: Geophysical implications of post-tectonic crustal deformation in NE Iceland detected using the Global Positioning System, *J. Geophys. Res., 98*, 14279–14297, 1993.

Jonsson, J., Eldgos á sögulegum tima a Reykjanesskaga (Historic eruptions on the Reykjanes Peninsula), *Náttúrufrædingurinn, 52*, 127–139, 1983.

Julian, B. R., Evidence for dike intrusion earthquake mechanisms near Long Valley caldera, California, *Nature, 303*, 323–325, 1983.

Julian, B. R., Analysis of seismic-source mechanisms by linear-programming methods, *Geophys. J. R. Astron. Soc., 84*, 431–443, 1986.

Julian. B. R., and D. Gubbins, Three-dimensional seismic ray tracing, *J. Geophys., 43*, 95–113, 1977.

Julian, B. R., and S. Sipkin, Earthquake processes in the Long Valley caldera area, California, *J. Geophys. Res., 90*, 11,155–11,169, 1985.

Kawasaki, I., and T. Tanimoto, Radiation patterns of body waves due to seismic dislocation occurring in an anisotropic source medium, *Bull. Seismol. Soc. Am., 71*, 37–50, 1981.

Klein, F. W., Hypocenter location program HYPOINVERSE, *U.S. Geol. Surv. Open File Rep., 78-694*, 1978.

Klein, F. W., P. Einarsson, and M. Wyss, The Reykjanes Peninsula, Iceland, earthquake swarm of September 1972 and its tectonic significance, *J. Geophys. Res., 82*, 865–888, 1977.

McGarr, A., An implosive component in the seismic moment tensor of a mining-induced tremor, *Geophys. Res. Lett., 19*, 1579–1582, 1992.

McKenzie, D. P., Earthquakes and the directions of principal stresses, *Bull. Seismol. Soc. Am., 59*, 591–601, 1969.

Pollard, D. D., P. T. Delaney, W. A. Duffield, E. T. Endo, and A. T. Okamura, Surface deformation in volcanic rift zones, *Tectonophysics, 94*, 541–584, 1983.

Ragnars, K., K. Sæmundsson, S. Benediktsson, and S.S. Einarsson, Development of the Námafjall area, northern Iceland, *Geothermics, Special Issue 2, 2*(1), 925-935, 1970.

Rubin, A. M., Dike-induced faulting and graben subsidence in volcanic rift zones, *J. Geophys. Res., 97*, 1839–1858, 1992.

Sæmundsson, K., Evolution of the axial rifting zone in northern Iceland and the Tjörnes fracture zone, *Geol. Soc. Am. Bull., 85*, 495–504, 1974.

Shimizu, H., S. Ueki, and J. Koyama, A tensile-shear crack model of the mechanism of volcanic earthquakes, *Tectonophysics, 144*, 287–300, 1987.

Stefánsson, V., The Krafla geothermal field, northeast Iceland, in *Geothermal Systems: Principles and Case Histories*, edited by L. Rybach and L.J.P. Muffler, pp. 273-294, John Wiley, New York, 1981.

Thorarinsson, S., *On the Geology and Geophysics of Iceland: Guide to Excursions* 60, International Geological Congress, Reykjavik, 1960.

Thoroddsen, T., Jardskjálftar á sudurlandi (*Earthquakes of Southern Iceland*), Hid Islenzka Bókmenntafelag, Copenhagen, 1899.

Thurber, C. H., Earthquake locations and three-dimensional crustal structure in the Coyote Lake area, central California, *J. Geophys. Res., 88*, 8226–8236, 1983.

Toomey, D. R., S. C. Solomon, G. M. Purdy, and M. H. Murray, Microearthquakes beneath the median valley of the Mid-Atlantic Ridge near 23°N: Hypocenters and focal mechanisms, *J. Geophys. Res., 90*, 5443–5458, 1985.

Toomey, D. R., S. C. Solomon, and G. M. Purdy, Microearthquakes beneath the median valley of the Mid-Atlantic Ridge near 23°N: Tomography and tectonics, *J. Geophys. Res., 93*, 9093–9112, 1988.

Trehu, A .M., and S. C. Solomon, Earthquakes in the Orozco Transform Zone: Seismicity, source mechanisms and tectonics, *J. Geophys. Res., 88*, 8203-8225, 1983.

Trehu, A. M., J. L. Nabelek, and S. C. Solomon, source characterization of two Reykjanes ridge earthquakes: Surface waves and moment tensors; P waveforms and nonorthogonal nodal planes, *J. Geophys. Res., 86*, 1710–1724, 1981.

Ward, P. L, G. Palmason, and C. Drake, Microearthquake survey and the Mid-Atlantic Ridge in Iceland, *J. Geophys. Res., 74*, 665–684, 1969.

Wyss, M., and J.N. Brune, Seismic moment, stress and source dimensions for earthquakes in the California-Nevada region, *J. Geophys. Res., 73*, 4681–4694, 1968.

Zverev, S.M., I.V. Litvinenko, G. Palmason, G.A. Yarashevskaya, N.N. Osokin, and M.A. Akhmetjev, A seismic study of the rift zone in northern Iceland, *J. Geophys., 47*, 191–201, 1980.

S. K. Arnott, Shell International Petroleum Company, Postbus 1, 7760 AA Schoonebeek Beekweg 33, The Hague, Netherlands.

G. R. Foulger, Dept. Geological Sciences, University of Durham, Science Laboratories, South Road, Durham, DH1 3LE, U.K. (email: g.r.foulger@durham.ac.uk)

(Received August 30, 1993; revised March 7, 1994; accepted March 10, 1994.)