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Implosive earthquakes at the active accretionary plate boundary in northern Iceland

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Non-double-couple earthquake focal mechanisms imply a mode of seismic failure other than simple shear, and movements perpendicular to the fault plane. Reports of such events are rare and it is controversial whether such failure can occur at depth in the Earth. Following reports of such earthquakes from the Hengill and Reykjanes volcanic systems on the accretionary plate boundary in Iceland[1–3], a seismological survey was conducted in the Krafla system, Iceland, to explore whether such earthquakes occur elsewhere along the boundary. Here we report the observation of a mixed suite of focal mechanisms at Krafla, including shear events, explosive tensile-crack events such as were observed at Hengill and Reykjanes, and implosive events. These last represent cavity collapse and constitute an entirely new class of earthquake. The Krafla system had undergone a crustal spreading episode[4–10] during the decade before the observations were made, and our results indicate that immediately after such an episode the accretionary plate boundary is characterized by a heterogeneous stress regime, with shear, extensional and compressional sources in close juxtaposition.

In 1985, the earthquake activity associated with the Krafla volcanic system, on the accretionary plate boundary in Iceland, was investigated with a 30-station, temporary seismometer network (Fig. 1). The impetus for this work came from recent, similar experiments in other parts of the spreading plate boundary in Iceland, where small earthquakes with non-double-couple focal mechanisms were discovered[1-3]. In the Hengill area (inset, Fig. 1), about half of the 178 events studied were of tensile-crack type, and at Reykjanes a few similar events were observed. One of the goals of the Krafla experiment was to test the hypothesis that such events characterize the spreading plate boundary in general.

Very accurate hypocentral locations were obtained for 100 small earthquakes ($-2.0 < M_t < 2.1$, where M_t is the coda duration magnitude, normalized to the surface wave magnitude M_s) in the depth range 1-4 km. 25 focal mechanisms were well constrained by P-wave first motions, of which 17 did not violate a double-couple, shear interpretation, three were non-double-couple, explosive, and fitted a tensile-crack interpretation similar to the Hengill and Reykjanes events[1-3], and five were non-double-couple and predominantly implosive. These latter events represent cavity collapse at depths of up to 3.5 km in the Earth's crust. This study provides further evidence for non-double-couple earthquakes. It also indicates an inhomogeneous stress field—in contrast to those from other volcanic systems on the accretionary plate boundary in Iceland, where relatively homogeneous stress fields were revealed[1-3]—and shows compressional phenomena occurring within a regional extensional environment.

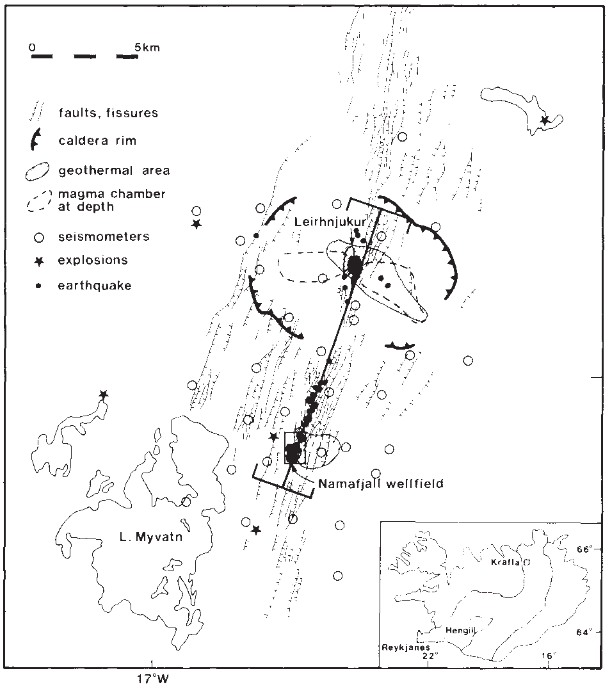

Fig. 1 Tectonic map of the Krafla area, the seismograph network and earthquake epicentres. The outlines of the magma chambers are taken from ref. 4. The bold line corresponds to the section of Fig. 2. Inset shows a map of Iceland. The neovolcanic zone, which marks the locus of the accretionary plate boundary, is shaded, and the locations of the Krafla, Hengill and Reykjanes areas are shown.

The Krafla volcanic system is a segment of the neovolcanic zone in Iceland[11] (Fig. 1). It displays a fissure swarm and a central volcano with a caldera 10×7 km in size, underlain by a molten body in the depth range 3-7 km (ref. 4). Two separate geothermal areas lie within the system (Fig. 1). In 1975 the central volcano became active and triggered a spreading episode. For several years its magma chamber inflated continually at a rate of $\sim 5\ \mathrm{m^3\ s^{-1}}$, and deflated rapidly at intervals of a few months[5-10]. Magma then escaped from the chamber and was intruded along the fissure swarm to form vertical dykes. Up to 8 m of spreading occurred, after which further intrusions could not be accommodated by the altered stress field, and surface magma eruptions occurred[10].

At the time of this experiment, the area was volcanically quiescent, and our aim was to study the continuous seismicity associated with the geothermal areas. The majority of earthquakes were located within these areas (Fig. 1) and activity was continuous on a daily basis. It extended to 4 km depth beneath the Namafjall geothermal area in the south, and 3 km depth beneath the Krafla geothermal area in the north (Fig. 2).

The majority of events beneath the Krafla area directly overlie the intersection of the molten body with the 2-km-wide central part of the fissure swarm where most of the spreading occurred[10]. The events form a zone dipping northerly at an angle of 45°, the surface projection of which lies close to the southern caldera fault (Fig. 2), where minor geothermal activity occurs.

Seismic activity within the Namafjall geothermal area clustered in a narrow 'chimney' 2-4 km deep, directly beneath a producing wellfield (Fig. 2). We conclude that these seismic events are induced by heat mining, and the seismically active volume indicates the extent of the cooling zone[2,3,12,13]. Of 20 well constrained focal mechanisms derived for this volume, 16 were predominantly of strike-slip double-couple type with variable orientations of the P and T axes (Fig. 3), and two were predominantly compressive and of tensile-crack type, similar to those observed at Hengill[2,3] and Reykjanes[1] (I and II, Fig. 4*a*). The crack orientation was NNW, oblique to the orientation of the rift zone. In addition, two focal mechanisms displayed

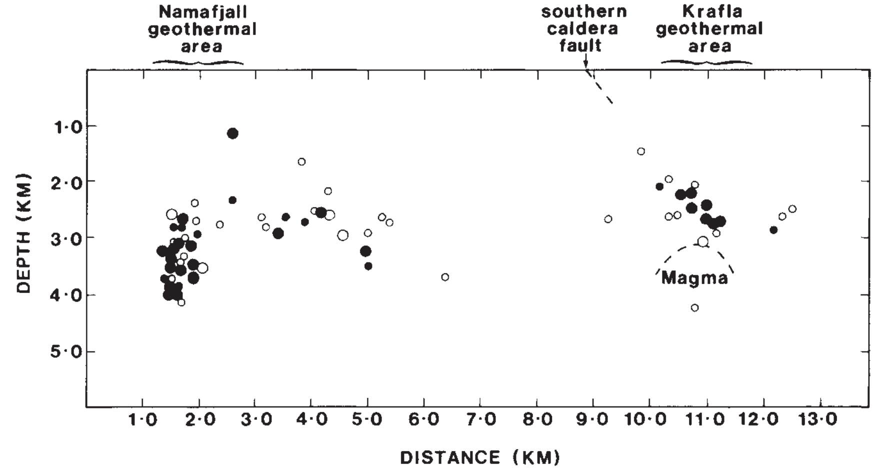

Fig. 2 SSW–NNE cross-section of the region of Fig. 1, showing hypocentral locations.

predominantly dilatational arrivals, and were therefore implosive and indicative of cavity collapse (III and IV, Fig. 4*a*). These results indicate that the seismic volume is deforming chaotically and that the stress field is inhomogenous, in contrast to the Hengill and Reykjanes volcanic systems, where all focal mechanisms were consistent with a uniform extensional stress field.

A third group of events occupy a NNE-trending zone at depths of 2–3.5 km, the locus of recent southerly dyke injections[7]. The four well constrained focal mechanisms obtained for this zone are all non-double-couple, one being of tensile-crack type (III, Fig. 4*b*) and three displaying cavity collapse (I, II and IV, Fig. 4*b*).

Reports of non-double-couple earthquake radiation patterns are rare, so that these data must be examined critically. The P waves were impulsive and did not have the emergent character sometimes observed in volcanic regions, and the seismometer polarities were tested using both explosions and teleseisms. Thus the polarities of the data points presented in Fig. 4 are reliable. Distortion of the ray paths by crustal heterogeneity was ruled out by the refraction-shot data, which showed that the crust is laterally homogeneous to within 5% of the average one-dimensional crustal model used for locating the hypocentres. In addition, the non-double-couple events occurred in the same volume as double-couple events. These factors rule out all explanations, other than non-double-couple source processes, for our observations.

In this spreading environment it is to be expected that the collapsing cavities are cracks orientated parallel to the fissure swarm. The expected radiation pattern of such an event would be omni-dilatational[14]. All events show one or more compressions, however, and in Fig. 4 we show suggested positions for small circular nodal lines that do not violate the data. The seismic moment density tensors of the dilatational events range from $[-1, -1, 0.7]$ to $[-1, -1, 0.3]$. Such sources imply cavity collapse along the edges of the cracks. The event shown in Fig. 4*b*(II) could be fitted only by small circular nodal lines, with the compressive field forming the continuous belt, and such a source represents crack closure. By analogy with source mechanisms that have been proposed to explain the tensile-crack radiation patterns[2,3], the compressive component might be explained by an increase in pore pressure in the crack at the instant of collapse. Such a mechanism would generate small circular nodal lines. An alternative explanation for the compressive field is that it may be generated by a shear component of movement in the source mechanism, in which case the nodal lines would not be small circles.

The non-double-couple events do not exceed magnitudes of $M_t = 0.7$, whereas the double-couple events range in magnitude up to $M_t = 2.1$. The very close correlation of the earthquakes with surface heat loss, and analogies drawn with the Hengill area, are convincing evidence that these events are induced by thermal cracking[2,3,12,13]. The total volumetric component of the earthquakes may be calculated, and compared with the volume contraction resulting from heat loss[2,3]. It is found that the seismic volumetric component is two orders of magnitude smaller than the cooling volumetric component. This result indicates that the majority of the volume contraction resulting from the surface heat loss is accommodated aseismically, a conclusion also reached for the Hengill geothermal area.

The volumetric contraction resulting from surface heat loss reduces the confining stress in the geothermal heat source. In many geothermal areas, this results in continuous, small-magnitude earthquake activity that releases stress in accordance with the regional field[2,3,15–18]. It is to be expected that at the accretionary plate boundary this stress field is uniform and extensional, and that tensile-crack opening occurs[2,3]. This is observed at Hengill[2,3] and Reykjanes[1]. The heterogeneous suite observed at Krafla contrasts with this, probably because of the recent spreading episode, which released the extensional stress field. No such rifting or volcanism is reported for the Hengill and Reykjanes areas for 200 and 700 yr respectively[19,20].

The observations from the Krafla volcanic system provide further evidence that small-magnitude non-double-couple seismic failure characterizes the accretionary plate boundary in

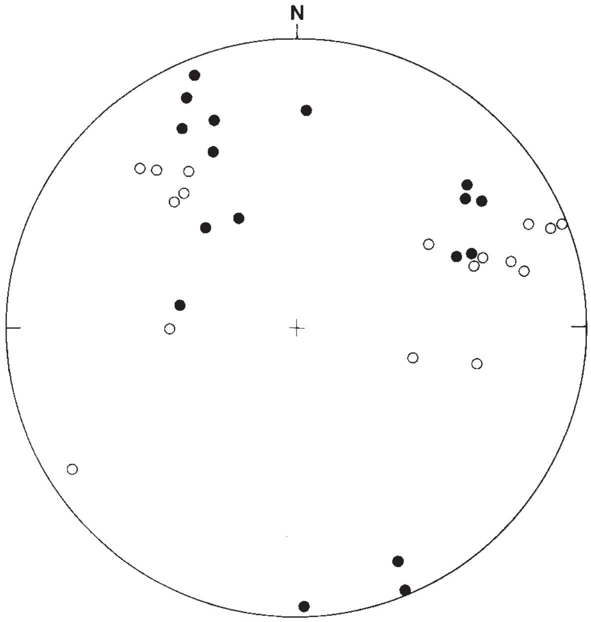

Fig. 3 Stereographic plot of the pressure (○) and tension (●) axes of the double-couple events. These are related to (though not equivalent to) the axes of greatest and least principal stress respectively.

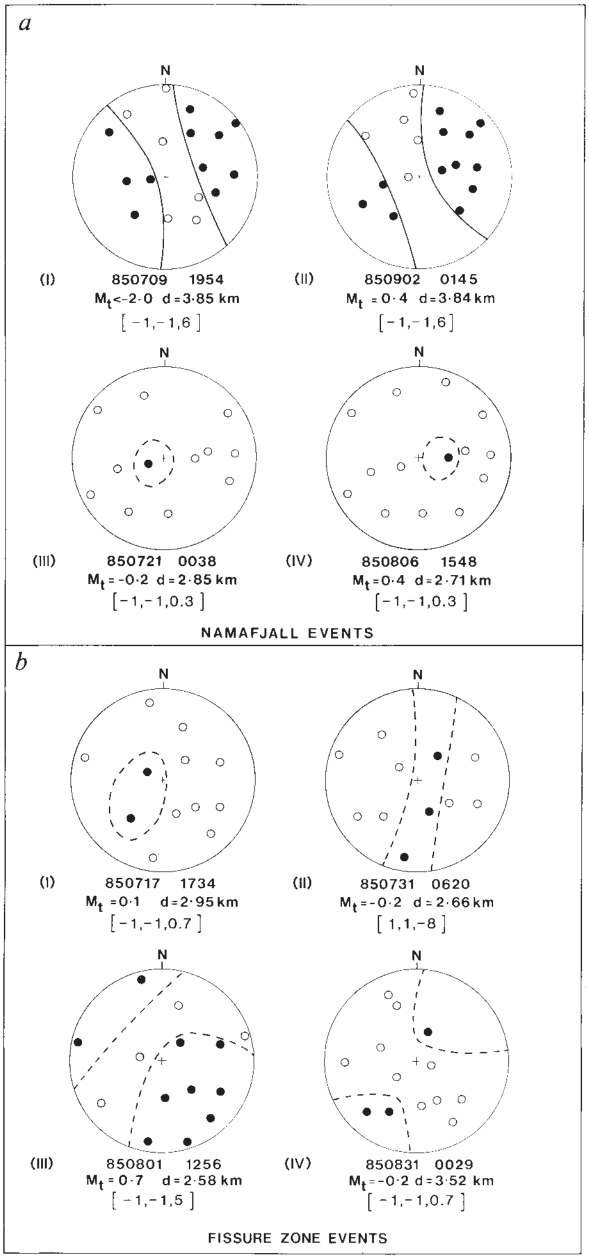

Fig. 4 Non-double-couple focal mechanisms obtained for events beneath the Namafjall geothermal area and along the fissure zone. Filled circles indicate compressions and open circles indicate dilatations. These are upper focal-sphere plots in stereographic projection. Dashed lines are suggested positions of small circular nodal lines. Event captions indicate origin time, local magnitude (M_l), depth (d) and approximate seismic moment density tensor.

Iceland. The Hengill and Reykjanes observations show that an extensional-stress regime may develop during long periods of quiescence between spreading episodes, and that both double-couple and non-double-couple extensional seismic failure occurs. In contrast, the Krafla observations indicate that the immediate post-spreading phase in the accretionary tectonic cycle is characterized by a chaotic stress field, with double-couple events of variable orientation, and both extensional and compressional non-double-couple sources in close juxtaposition.

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Latest Proterozoic plankton from the Amadeus Basin in central Australia

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The plankton of the Proterozoic is preserved mainly as microfossils known as acritarchs, most of which are considered to be cysts of eukaryotic algae. In recent studies of the diversity of Proterozoic and early Palaeozoic acritarchs, a gradual increase in diversity from the Middle into the Late Proterozoic has been shown to be followed by a sharp decrease in diversity in the latest Proterozoic (Ediacarian or Vendian) and then a rise again in the Early Cambrian[1,2]. These observations have been interpreted in terms of the evolutionary diversification of eukaryotic algae and the ecological effects of the pre-Ediacarian glaciation. Occasional discoveries of complex acritarchs in Ediacarian rocks[3–6] have raised some doubts about these interpretations, but more recent work seems to have supported this view[7]. Here we report the discovery of a diverse assemblage of large and morphologically complex acritarchs from the Ediacarian age upper Pertatataka Formation in the Amadeus Basin of central Australia. This, with a recent report of similar fossils from the upper Sinian of China[8], provides a significant new perspective on the history of the plankton. It is now necessary to suggest an earlier radiation, at least in off-shore environments, or to question the reality of the postulated decrease in diversity. In addition, there may well have been an extinction event, late in the Ediacarian. Neither of these phenomena has been recognized previously.

The Amadeus Basin is intracratonic (Fig. 1) and has a sediment fill ranging in age from about 800-900 Myr BP to late Palaeozoic. Dykes in the basement are unconformably overlain by the basal sandstone of the basin and are dated (Rb/Sr on separated minerals) at 897±9 Myr BP providing a maximum age for the sedimentary sequence[9]. The Pertatataka Formation overlies the upper of two Proterozoic glacial sequences and underlies the Arumbera Sandstone which in its lower part contains fossils of the soft-bodied Ediacara fauna (Fig. 2). The upper Arumbera Sandstone contains abundant and diverse trace

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