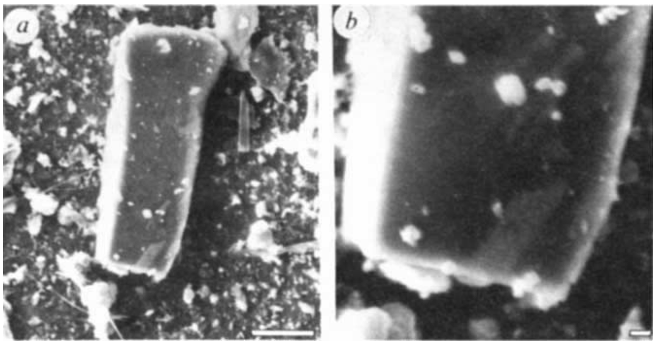

Fig. 3 Particle 34 (CL/ST1). Angular silica particle overgrown with metallic iron. *a*, Silica particle (SEM, secondary mode). *b*, Enlargement of the lower part of *a*. The subparallel overgrowths of metallic iron appear in light grey at the lower and upper right corners. Scale bars: *a*, 10 μm; *b*, 1.0 μm.

fixation of bacterial life in the vicinity of hydrothermal vents, and for its continuation in metalliferous sediments produced through vent activity.

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Anomalous focal mechanisms: tensile crack formation on an accreting plate boundary

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Conventional double-couple solutions do not satisfactorily account for many small magnitude earthquakes in the Hengill geothermal area in the Neovolcanic Zone of Iceland. The far-field radiation pattern is predominantly compressional but a few dilatational arrivals have been recorded. We prefer the interpretation that these events are due to tensile crack formation at a shallow (1–7 km) depth within a cooling intrusive body. Volume considerations indicate that initial fracturing of the rock is seismic but that subsequent widening proceeds aseismically. Other reports of anomalous radiation patterns from earthquakes on the Mid-Atlantic Ridge describe events of a similar type, that is, exhibiting predominantly compressional radiation patterns and a reduced dilatational field[1–4].

In 1981, an intensive 3-month seismic monitoring project was carried out in the Hengill geothermal area of Iceland (Fig. 1). The project was designed using foreknowledge of the spatial distribution of earthquake activity within the area and its ongoing nature[5]. The crustal structure is well constrained by refraction shooting[6,7] and shots fired within the area during the monitoring project confirmed that the crustal model used is accurate to within 5%. In total, 30 seismometers were operated within 14 km of the centre of the network.

About 140 well-constrained focal mechanism solutions were obtainable for small magnitude earthquakes occurring within the network. Conventional double-couple solutions with orthogonal nodal planes cannot be fitted to half of the events. Compressional arrivals dominate the focal sphere and dilatational arrivals of normal amplitude project onto the focal sphere in a narrow zone striking about north-east. Two examples and a composite solution are shown in Fig. 2. The dilatational and compressional portions of the focal sphere may be separated by small circles with typical radii of about 80°. Hence the ratio of the principal seismic moments of these events is approximately: 30 : −1 : −1.

The predominant component of this mechanism is a linear vector dipole (LVD). The sum of the principal moments is significantly greater than zero, indicating a volume increase. In this respect, the source differs fundamentally from the CLVD source recognized by Julian[8].

We propose that this radiation pattern is generated by the formation of a tensile crack in the presence of a pore fluid, and that this type of fissure formation would be expected to occur in the tensile stress regime of an accreting plate boundary.

The Hengill area forms part of the continuation of the Mid Atlantic Ridge (MAR) onto the Icelandic landmass and has been volcanically active for ~700,000 yr (ref. 9). Originally the volcanic centre lay to the north of the village of Hveragerdi but later moved west and now underlies the central volcano Hengill (Fig. 1). The area is occupied by an extensive and complex geothermal field, which is hottest in the immediate vicinity of

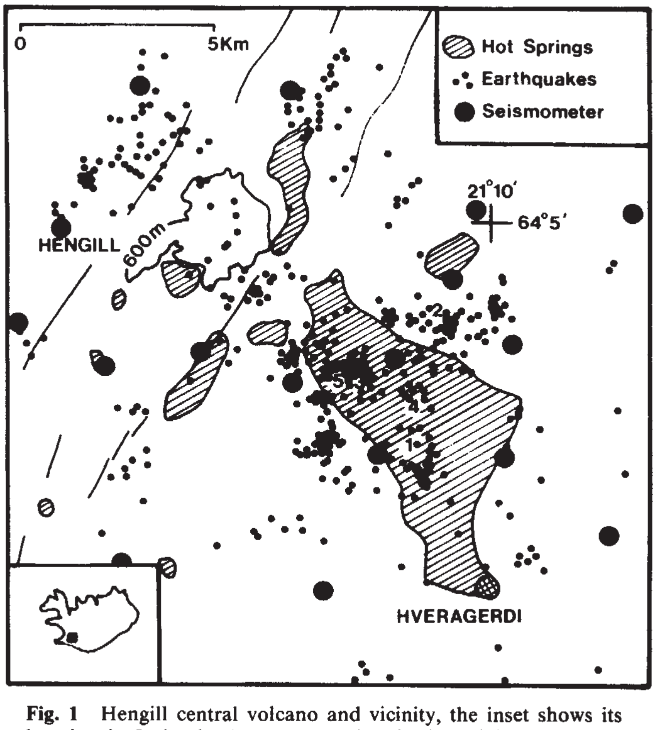

Fig. 1 Hengill central volcano and vicinity, the inset shows its location in Iceland. The map reveals seismic activity during the 3-month recording period, areas of hot springs and outline of fissure swarm transecting the area through Hengill. Of the 30 stations operated, 17 lie within the area shown. 1, 2, Locations of events shown in Fig. 2; 3, 4, 5, locations of events used for composite solution shown in Fig. 2.

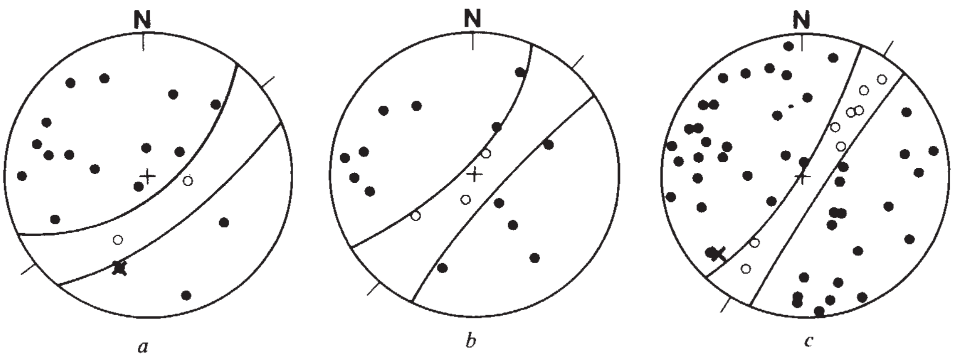

Fig. 2 P-wave first motions from two non-double couple events and one composite solution. Upper hemisphere plots in stereographic projection. ●, Compressions; ○, dilatations; ×, nodal arrivals; curved lines, small circles of radius θ defining nodal lines of tensile crack solution. *a*, Event 1: depth 4.87 km; $M_L = 0.1$; strike N 53° E; dip = 60°, $\theta = 78°$. *b*, Event 2: depth = 4.99 km; $M_L = 0.0$; strike = N 42° E; dip = 80°; $\theta = 76°$. *c*, Composite solution for three events; strike normalized; dip = 80°; $\theta = 80°$.

Hengill. However, most of the hot springs, and hence the greatest heat loss, occur in the vicinity of the original volcanic centre. A fissure swarm striking at N 25° E transects the area, passing through Hengill. The eruption fissures, and vertical, open fissures contained within it, testify to the tensional nature of the stress regime of the area. The direction of least compressive stress is orientated N 65° W, normal to the fissure swarm[10].

Earthquake activity is continuous. The activity rate is 1 magnitude (M_L)0 event per day. The hypocentres of most of the events cluster in a volume beneath the old volcanic site. Hypocentral depths are mostly within the range 1–7 km (Fig. 3). The pore fluid is thus hydrous at shallow depths but may be magmatic deeper down. In such a regime, the most likely cause of continuous seismicity is contraction cracks in the cooling roots of the extinct volcano.

As a result of continuous heat loss from the surface, the rock cools and contracts. This produces a local tensional stress field that is superimposed on the regional. The total stress field is additionally modified by geothermal processes (for example, boiling in the rock), that influence the pore pressure on a very small scale. Where these processes result in an increase in pore pressure thay may trigger fracture formation.

Failure in this predominantly tensile total stress field results in the formation of roughly vertical tensile cracks orientated about NE–SW.

The formation of a planar tensile crack in an isotropic medium would yield an all-compressive far-field radiation pattern of variable amplitude with respect to the orientation of the crack. The largest amplitude is normal to the crack, and the amplitude minimum traces a great circle on the focal sphere where the crack plane projects onto it. The point force equivalent of such a source may be represented by three mutually orthogonal vector linear dipoles with moments in the ratio: $(\lambda + 2\mu) : \lambda : \lambda$, where λ and μ are the Lamé elastic modulii[11]. The seismic moment tensor of the Hengill events can be modelled by combining a tensile crack with a spherically symmetrical implosion:

$$[(\lambda + 2\mu) : \lambda : \lambda] + [-(\lambda + \delta) : -(\lambda + \delta) : -(\lambda + \delta)] = [(2\mu - \delta) : -\delta : -\delta]$$

Fluid flow is a slow process compared with the speed at which a fracture forms so at the moment of fissuring, the volume occupied by the fluid in the immediate vicinity of a fracture increases and causes a local pore pressure drop[12]. This sudden pore pressure drop is omnidirectional and generates the dilatational portion of the radiation pattern.

Decreasing pore pressure limits crack propagation and hence probably limits the size of events. The formation of one fracture causes local changes in the rock medium and stress field, and may trigger a chain reaction. This could explain the 'geothermal swarms' of numerous, very small events observed in many geothermal areas in Iceland.

It is, therefore, a pore pressure drop caused by restricted fluid flow at the moment of fissuring that generates the dilatational part of the radiation field and limits crack growth.

The natural heat loss of the Hengill area is 350 MW (ref. 13). If attributed to a cooling intrusion, the rate of volume contraction may be calculated using the equation:

$$\Delta V = \frac{H\gamma}{C_p \rho}$$

where ΔV is the contraction rate, H is the cooling rate, γ is the coefficient of thermal expansion ($\simeq 16.2 \times 10^{-6}\ K^{-1}$), ρ is the density ($\simeq 3 \times 10^3\ kg\ m^{-3}$) and C_p is the specific heat of basalt at constant pressure ($\simeq 1.3 \times 10^3\ J\ kg^{-1}\ K^{-1}$). Application of this equation to the Hengill area gives a contraction rate of: $\Delta V = 4.5 \times 10^4\ m^3\ yr^{-1}$. An estimate of the total volume of contraction cracks formed seismically may be made and compared with this value. The equations[14,15]:

$$\log M_0 = 15.1 + 1.7 M_L$$

$$\log E = 11.8 + 1.5 M_L$$

give estimates of seismic moment and energy release from local magnitudes (M_L). The ratio of principal seismic moments observed for the Hengill events indicates that δ is small. Therefore, they are predominantly linear vector dipole sources and seismic moment may be approximately related to volume by the equation: $M_0 = 2\mu V$, where V is the volume of the crack. Using these equations, the contraction rate within the seismically active volume is estimated to be two orders of magnitude smaller than that calculated for the cooling intrusion. A similar result is obtained if energy is considered.

These calculations demonstrate that the seismicity may be attributed entirely to a cooling volume and that it is likely that much aseismic widening occurs after the initial fracturing.

There have been other reports of anomalous radiation patterns from the MAR and its continuation onto the Icelandic landmass[1–4]. For these events, dilatational arrivals occupy less than

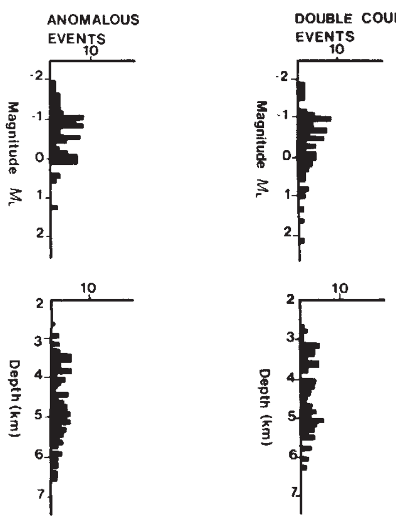

Fig. 3 Magnitudes and depths of events for which good focal mechanism solutions were possible.

half of the focal sphere. Interpreted in terms of source mechanism this also requires a net explosive component. In the case of large, teleseismically recorded events, where lower hemisphere polarity plots are made, explanations for the observed anomalous radiation patterns may readily be found by invoking interference, or path effects where the events are shallow and in areas of active volcanism, where severe crustal inhomogeneity is to be expected[16,17]. However, in the Hengill case we are dealing with shallow earthquakes, upper hemisphere plots and a well constrained crustal structure. Many of the events exhibit extreme non-dipolarity and occur interspersed with double-couple sources. Here it is less easy to explain away the anomalous events as the result of a path effect.

We conclude that the Hengill source mechanism data indicate that at this point on the accreting plate boundary stress is being released by tensile crack formation. These data strongly suggest that such sources can occur in nature in a tensile stress environment. Thus, more credence should be given to the theory that the anomalous radiation patterns reported for MAR earthquakes are due to source effects, particularly an enhanced explosive element leading to volume increase at source, as a result of the crustal accretion process.

Shear source mechanism solutions are commonly fitted to data that are not sufficient to constrain such a solution. The present results suggest that the custom of routinely fitting double-couple solutions to inadequate data should be viewed more critically.

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A complex of copper (II)-montmorillonite with a modified cyclodextrin

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Various classes of compounds, including hydroquinone, urea, cyclodextrin and montmorillonite, can act as host compounds having several types of inclusion spaces, such as three-dimensional cages, parallel channels and layers[1]. Despite the variety of host compounds, however, little attention has been paid to the possible complexation of two or more of different kind host components: all inclusion compounds so far reported[2] use a single component as the host structure. We have now prepared, for the first time, a host compound consisting of two components, one layered and one single channel-like, in which dimers of 1:1 complex of Cu(II) with mono-(6-β-aminoethylamino-6-deoxy)-β-cyclodextrin (CDen) are formed in a stable condition and are closely packed between the silicate layers of montmorillonite, with their opening faces parallel to the interlayer surface. This compound is unique because the cyclodextrin which it takes up as a guest component can also act as host for many substances. In view of the enzymatic function of cyclodextrins, this class of compounds seems promising for use as an immobilized artificial enzyme and in models of membrane enzymes.

Cyclodextrins are cyclic oligosaccharides of D-glucopyranose. The CDen used in this study is a derivative of β-cyclodextrin, in which the 1,2-diaminoethane group is attached to a primary alcohol group on the narrow side of the truncated cone-shaped cyclodextrin molecule. The cyclic dextrins and their derivatives, including CDen, are very useful as micro-encapsulating agents or enzyme models as they stabilize sensitive volatile or toxic substances by encapsulating them, or catalyse various organic reactions in a manner similar to that observed in enzymatic reactions[2,3]. The clay mineral montmorillonite is made up of negatively charged layers with a typical composition of $(Al, Mg)_{2-3}(Si, Al)_4O_{10}(OH)_2$ and interlayer cations compensating the positive charge deficiency of the silicate layers[4]. Due to the layered structure, the clay mineral is capable of intercalating a variety of organic compounds.

CDen was prepared by the method described in ref. 5. The montmorillonite with a chemical composition

$$(Ca_{0.09}Na_{0.16}K_{0.03})(Al_{1.48}Fe_{0.13}Mg_{0.40})[Si_{3.99}Al_{0.01}]O_{10}(OH)_2 \cdot nH_2O$$

(from Tsukinuno mine, Yamagata, Japan) was placed in a 1.0 M $CuCl_2$ solution at 25 °C for 10 days to yield the Cu(II) exchanged form.

The inclusion behaviour of Cu(II)-montmorillonite towards CDen was examined by soaking the Cu(II) exchanged mineral in an aqueous CDen solution and measuring the contents of CDen and Cu(II) in the solid phase as a function of the CDen added[6]. As a result, a complex of Cu(II)-montmorillonite with CDen was found to form as a single phase when the CDen

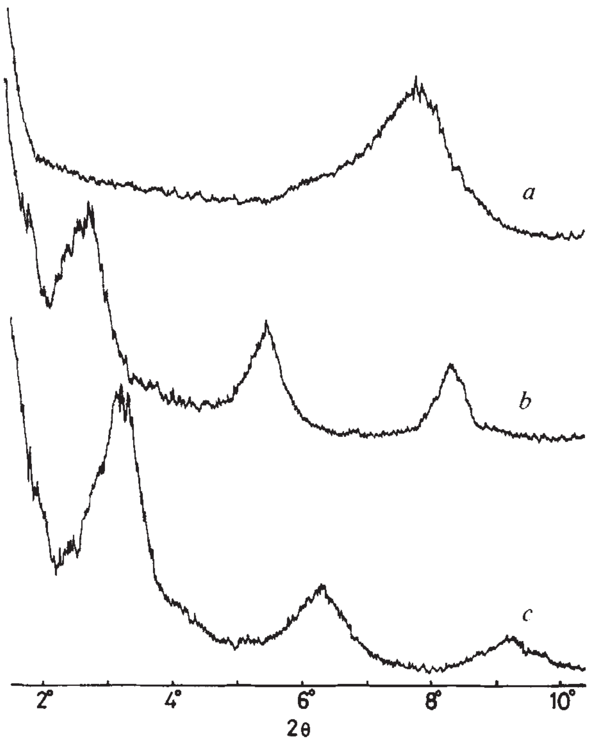

Fig. 1 X-ray powder diffraction patterns of *a*, Cu(II)-montmorillonite and *b*, wetted and *c*, dried forms of CDen–Cu(II)-montmorillonite (Fe*Kα* radiation).