Geothermics (1974) - Vol. 3, No. 1

Evidence for Two Possible Relationships between Observable Surface Deformation and Geothermal Activity

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ABSTRACT

During September of 1967 a large increase in the activity of a previously small geothermal field in south-western Iceland was accompanied by an earthquake swarm which lasted eight days.

It is shown here, both from field observations and from the results of precise distance measurements made on a network of permanent benchmarks established soon after the seismic events, that the accompanying surface faulting shows the correct relationships with the local tectonics to be secondary shearing of the type found associated with large strike-slip faults elsewhere in the world.

Vertical angle measurements on the same network of bench-marks are compared with corresponding measurements from the highly productive geothermal field at Wairakei, New Zealand, to show that the Icelandic field deforms more readily to the removal of geothermal fluids than does the New Zealand one.

From this it is suggested that measurements of surface deformation in the immediate vicinity of a producing geothermal field could provide information on the gross permeability of the deep aquifers. and thus suggest how the field would behave under high discharge rates (such as would be encountered during economic exploitation).

In 1967 a programme of investigation into the horizontal crustal extension across Iceland associated with the spreading activity of the mid-Atlantic ridge was begun.

During the course of the first field season, in 1967, a violent earthquake swarm was accompanied by a massive increase in the surface geothermal activity of a previously quite small field at the extreme south-western tip of the Reykjanes peninsula (Figure 1).

The earthquake swarm lasted about eight days, but the increased geothermal activity has continued to the present time.

As a result of these disturbances a small network of permanent trilateration bench-marks was established in the immediate vicinity of the geothermal field, and although the coverage in this area has since been greatly increased, it is the results of vertical angle and precise distance measurements on the original few stations which constitute this report.

Before discussing the results of the measurements however, it is worth-while describing some other observations from this particular field.

A considerable amount of surface fracturing accompanied the 1967 earthquakes, much of which, although too small to be directly visible, was well delineated by the steam which issued through the broken ground. The fractures thus defined were en echelon with individual strikes of almost due north, but forming a zone striking somewhat east of north. Such an arrangement strongly suggests the surface expression of a deeper, left-lateral fault.

The strikes of both the surface fractures and the inferred deeper fault are in marked contrast to the local surface tectonic strike which is N40°-45°E, and expressed by purely extensional features such as large normal faults, open fissures, and eruption lines (Jónsson 1967, Nakamura 1970).

Indeed an overall tectonic extension direction of N45°W-N135°E is strongly expressed by the surface features (Nakamura 1970), by the local sea-floor spreading direction (Heirtzler et al. 1966, Talwani et al. 1971), by fault plane solutions of microearthquakes (Klein et al. 1973), and also by the trilateration results from the parts of the network removed from the geothermal field (Brander 1973).

After the 1967 disturbances the new geothermal area occupied a zone roughly half a kilometre long and a hundred metres wide striking somewhat east of north.

During 1968 a drilling programme was initiated by the National Energy Authority of Iceland to investigate the economic potential of this field. The eight reconnaissance wells drilled as part of the programme penetrated to depths up to 1700 m and all produced hydrothermal discharge at elevated temperatures and pressures.

The spatial distribution of the wells extended beyond that of the surface activity while following roughly the same strike: two of the wells have been left open; one, near the centre of the surface activity, since 1968; the other, five hundred metres north-east of the surface activity, since 1969.

The evidence from the spatial distribution of wells and surface activity suggests that the geothermal field is elongated in a direction somewhat east of north: the evidence from the 1967 faulting suggests that the elongation is a zone of left-lateral strike slip shear, striking at about N30°E.

Two categories of measurements have been made on the trilateration network in the area: precise distance

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measurements with the N.P.L. Mekometer III (FROOME, BRADSELL 1966; FROOME 1971), and vertical angle measurements. The latter were originally made only to provide information for correcting the distance measurements, but it was found that an exceedingly interesting solution to the distance changes was possible if large vertical movements were allowed. It was thus necessary to repeat the vertical survey to ascertain whether such changes had in fact occurred. They had not, but the repeat survey did nonetheless provide some interesting information.

Vertical angles were measured twice, in 1968 and 1973; distance measurements were made at least once, and often twice, per year from early 1968 to 1972.

The vertical angle results show that an area near the geothermal field subsided by 125 mm between 1968 and 1973, and that the resulting depression was bowl-shaped with the maximum subsidence occurring to the south-east of the centre of the surface activity.

The distance measurements show two effects very strongly.

The first is a negative dilatation (decrease of surface area) over a large area (about 2 km by 1 km) elongated somewhat east of north. The minimum dilatation is — 60 ppm (over the four years) and occurs right at the centre of the surface activity.

The second is a large component of shear (reaching as much as 70 ppm near the centre of the field) over all the area of negative dilatation. This shear is associated with an extensional principal strain directed at N85°E, and follows a zone which strikes at N30°E.

Each of these three observations from the distance measurements in the geothermal field is very much at variance with the results obtained from the rest of the network, where dilatation is usually small and positive, shear is low, and the extensional principal strain is directed at N130°E. The measurements from the rest of the network certainly reflect tectonic effects, as was described above.

It has already been shown that the structural observations and fault patterns indicate that the geothermal field is a left-lateral shear zone striking at about N30°E. The distance measurement results show that there is considerable shear in the geothermal region and that it is governed by an extensional principal strain directed at N85°E. The shear directions corresponding to such an extensional direction are N40°E for the left-lateral case, and N130°E for the right-lateral case.

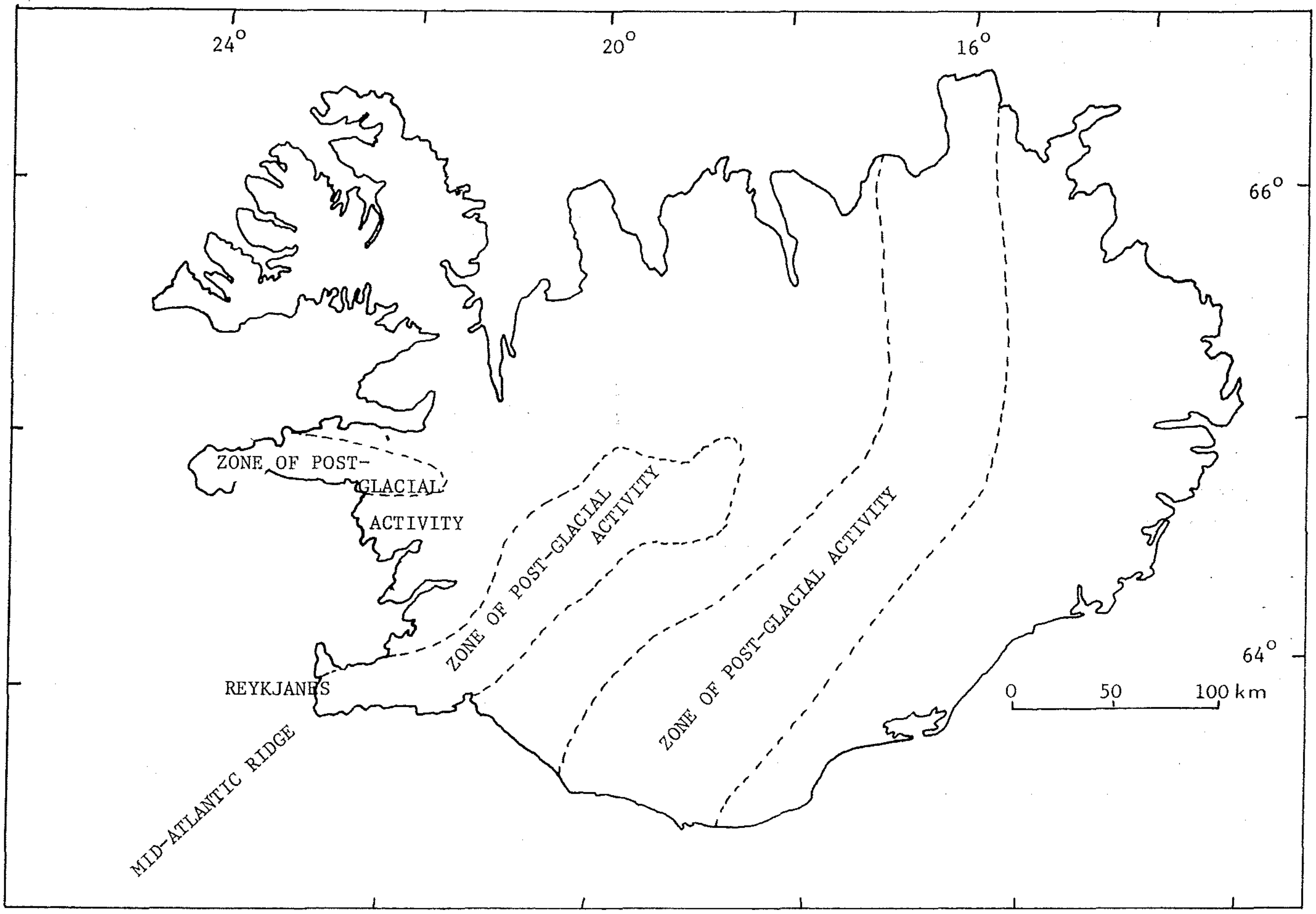

FIG. 1. — *Map of Iceland showing the principal geological features and the position of the trilateration network at Reykjanes.*

The left-lateral case is obviously in very good agreement both in direction and sense of movement with the structural observations, which lends additional weight to the proposal that the geothermal activity occurs on a left-lateral shear zone, striking at about N30°-40°E.

Now it is necessary to consider what relation there is between the overall tectonic activity, governed, as has been observed, by an extensional axis directed at N135°E, and this proposed shear zone which gives rise to the geothermal field.

The actual tectonic role of the Reykjanes peninsula has never been entirely clear. Although it is the topographic continuation of the mid-Atlantic ridge (which is undoubtedly extensional), and does show many obviously extensional characteristics (e.g. the normal faults and eruption lines mentioned earlier), yet it strikes at a different direction (N80°E) from the local ridge (N43°E) and shows a very marked en echelon structure. This peculiar structure, together with the fault plane solutions mentioned above, and the results of the trilateration measurements, lead the present author (Brander 1973) to the conclusion that the Reykjanes peninsula is, now at least, predominantly a left-lateral shear zone, across which there is some crustal extension too, where the rate of movement is between 10 and 20 mm per year, and the direction of movement is about N85°E.

In this case it becomes very easy to explain the observations regarding the geothermal zone in terms of secondary faulting induced by the primary shear movement, completely after the pattern found by Moody and Hill (1956) for secondary features of the San Andreas. Figure 2 shows the relationships between the various primary and secondary directions, in which the angle γ, which relates the direction of secondary extension to the primary shear direction, is zero (a perfectly acceptable value according to Moody and Hill).

Unlike the San Andreas analysis Figure 2 has been drawn from the standpoint of measured strain directions rather than inferred stress directions, so that shear planes are orthogonal and at 45° to the extensional directions.

Thus there is an excellent case for interpreting the observed left-lateral shear zone of the geothermal field as secondary faulting induced by the primary shear of the Reykjanes peninsula.

The author has considered some of the other active geothermal areas of Iceland to see if this relationship can be found there also, but because of the paucity of information it can only be said that on all the southwestern geothermal fields the spatial distribution of wells and surface activity does not conflict with the secondary faulting model.

It might also be mentioned here that in the Taupo volcanic zone of New Zealand the known geothermal fields follow a very well-defined en echelon arrangement strongly indicative of dextral movement in a northeasterly direction; such movement would of course represent the continuation into the North Island of the Alpine fault zone. This suggestion is purely speculative, but might provoke observation.

Returning to the Reykjanes measurements, the second relation between surface deformation and geothermal activity is concerned with the observed vertical subsidence and large negative dilatation.

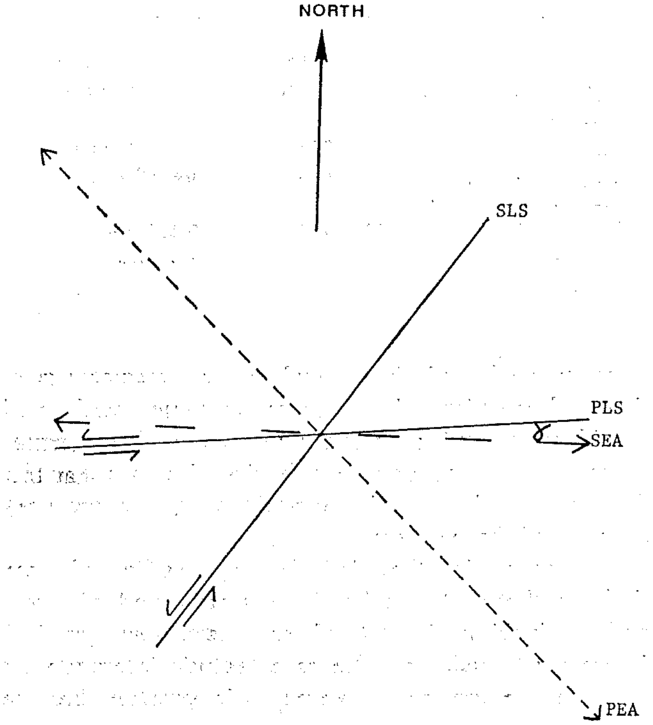

Fig. 2. — *Illustrating the relationship between the primary extensional axis (PEA), the primary left-lateral shear direction (PLS), the secondary extensional axis (SEA), and the secondary left-lateral shear direction (SLS), (adapted from* Moody *and* Hill, *1956). In this particular case the angle = 0.*

Bolton (1973), reporting on thirteen years of exploitation of the Wairakei geothermal field in New Zealand, showed that vertical subsidence had been observed there too, amounting to a total of 3.05 m. Unfortunately though, there are no horizontal measurements from that field.

It is interesting to compare the two fields, Reykjanes and Wairakei, in terms of total and annual rates of mass discharge and vertical subsidence. Table 1 shows the relevant figures (derived from Björnsson et al. 1972, Bolton 1973, Brander 1973).

It can be seen from the table that both the ratios calculated, M.D./V. and H.R./A.S., show that the Reykjanes ground surface deforms more readily than that at Wairakei, by a factor of about one order of magnitude.

It is considered that this difference relates to the ability of the deep producing aquifers to recover from

TABLE 1. — *Illustrating the relationships between the various measured quantities in the two geothermal areas. Data are from* BOLTON *(1973) for Wairakei, and from* BJÖRNSSON ET AL. *(1972) and* BRANDER *(1973) for Reykjanes.*

	Wairakei 1956-68	Reykjanes 1968-73
Total mass discharge (M.D.)	9.6×10^{12} kg	1.4×10^{4} kg
Total maximum vertical subsidence (V.)	3.05 m	0.125 m
M.D. / V.	3.2×10^{12} kg m^{-1}	1.12×10^{11} kg m^{-1}
Current hourly rate of mass discharge (H.R.)	5.4×10^{6} kg h^{-1}	3.6×10^{4} kg h^{-1}
Current maximum annual rate of subsidence (A.S.)	0.39 m a^{-1}	0.025 m a^{-1}
H.R. / A.S.	1.38×10^{7}	1.5×10^{6}

mass removal, and that therefore the parameter relating surface deformation to mass discharge could be of considerable importance in the evaluation of geothermal fields, since the experience at Wairakei shows that the limit to exploitability is determined by the recovery capacity of the aquifers.

In conclusion then, it is felt that the first of these findings, that geothermal activity is associated with secondary faulting, is not of any particular practical interest, although its value as a tectonic interpretation tool may be greater. However, it is possible that the second finding, the ratio of mass discharge to surface deformation, may be of quite considerable use in the evaluation of new geothermal fields.

Acknowledgements

The author wishes to thank Professor F. F. EVISON for some of the information about the Wairakei geothermal field, and also for useful comments.

The Icelandic work was supported by the Natural Environmental Research Council.

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