INFLUENCE OF PLATE TECTONICS ON LOCATIONS OF GEOTHERMAL FIELDS

Hemendra Acharya
Stone & Webster Engineering Corporation
Boston, MA 02110 U.S.A.

ABSTRACT

Locations of productive geothermal fields in the circum-Pacific area have been examined in order to identify natural conditions which may have helped in the development of geothermal fields at those locations. Preliminary examination indicates that these locations are (i) near the lateral ends of several plate boundary segments, and (ii) in transverse zones which divide plates into several independent blocks 100-1000 km long. Examination of these locations by Pattern Recognition Technique suggest that these locations are **(iii)** near fumeroles and hot springs and (iv) near historically active volcanoes which erupted at least once in a century. Volcanic rock type and amount of rainfall in the area provide ambiguous results and do not appear to be crucial. Shear heating in these transverse zones may explain the excess heat flow and therefore the development of geothermal fields in these zones. Available heat flow data in Japan support this hypothesis.

INTRODUCTION

A geothermal field includes a source of heat, permeable rock or aquifer, access to groundwater, and the presence of cap rock. A large number of geothermal fields explored so far occur along spreading ridges, subduction zones, interarc basins, and melting anomalies, **i.e.,** in areas of young tectonism and volcanism, primarily along active plate boundaries (Muffler, 1976a). The locations of geothermal fields in the circum-Pacific have been examined in order to identify natural conditions which influenced the occurrence of geothermal fields at these locations.

Volcanic areas in general have greater than average heat flow. Sugimura and Uyeda (1976) note that hot springs (temperature $> 30^{\circ}C$) occur exclusively in the volcanic areas of Japan and many other island arcs. The possibility therefore exists that geothermal fields can occur all along the volcanic arc. Motkya and Moorman (1981) and Acharya (1982a) note, however, that hot springs with temperature $> 90^{\circ}C$ occur in only a few areas of Japan and the Aleutians. This suggests that the presence of magma at depth does not necessarily lead to high temperatures ($> 180^{\circ}C$) at shallow depth (< 2 km), which is necessary to exploit geothermal heat. Figure 1 shows that in Japan the geothermal fields are located at only a few places. Acharya (1982b) observed that, whereas the average heat flow in volcanic areas is about 1.5 HFU, the geothermal fields in California, Mexico, and Italy are situated in areas with heat flow near the surface ≈ 2.5-3.0 HFU. It is therefore likely that only certain special conditions lead to higher temperatures at shallow depth. In order to identify these conditions, I have examined the locations of geothermal fields in terms of the geometry of plate boundaries, effects of volcanism - its nature and rate of activity, and the effect of rainfall as a heat transfer agent. It is hoped that this analysis will help characterize the two factors - (a) presence of a heat source and (b) availability of groundwater, which are essential for the exploitation of geothermal energy in an area.

JAPAN

The tectonics of Japan (Figure 1) is dominated by the underthrusting of the Pacific plate along the Kurile and Japan trenches in the north and the underthrusting of the Philippine Sea plate in the south and west (Sugimura and Uyeda, 1976). Carr et al (1973) examined the morphology of the seismic zones below Japan and found that intermediate and deep focus earthquakes under Japan delineate seismic zones in which there are distinct and abrupt discontinuities that strike transverse to the arc. Sugimura and Uyeda (1976) do not, however, show any discontinuity in the contours of the Benioff zone at 150 km below the surface. Isacks and Barazangi (1977) also disagree with the interpretation of Carr et al (1973). Mogi (1968) has studied the occurrence of large (magnitude $\geq$ 7.0) earthquakes in Japan and has noted that great (magnitude $\geq$ 7.7) earthquakes and their aftershock zones occur in non-overlapping units separated by structural discontinuities in the arc. Figure 1 shows the possible division of Japan into several independent blocks on the basis of rupture zones of great earthquakes and the orientation of the trenches.

Examination of Figure 1 suggests that the geothermal fields in Japan are situated in the inland extension of zones which mark the termination of rupture zones of great earthquakes.

For example, the geothermal field Nigorikawa in Hokkaido is situated near where the Japan trench bends sharply into the Kurile trench (Zone F). The rupture zones of the 1968 and 1952 earthquakes abut along this zone. The Nankai trough bends sharply into the Ryukyu trench (Zone A) in the vicinity of geothermal fields Otake and Hatchobaru in Kyushu. The geothermal fields Matsukawa, Takinoue, and Onuma in Honshu are situated along the extension of Zone E, which separates the rupture zones of the 1968 and 1897-1901 earthquakes. Zone D marks the southern termination of the 1897-1901 earthquakes, and the geothermal field Onikobe is probably situated along the extension of this zone. This zone is approximately drawn, since the rupture zones of the 1897-1901 earthquakes are not well delineated.

It therefore appears that producing geothermal fields in Japan are situated in the extension of zones which mark either (i) a change in the orientation of the trenches or (ii) termination of the rupture zones of great earthquakes.

CENTRAL AMERICA

Central America defines the northeastern boundary of the Cocos plate. Carr (1974) and Stoiber and Carr (1973) have observed that Central American volcanoes do not fall on a continuous line but instead comprise distinct lineaments. Carr (op cit) has therefore subdivided Central America into seven major segments, as shown in Figure 2. The boundaries of the segments occur wherever the chain of active volcanoes is offset or changes strike. The boundary regions are arbitrarily drawn by Carr as about 30 km wide strips centered between the ends of adjacent volcanic lineaments and striking N30°E, about perpendicular to the volcanic

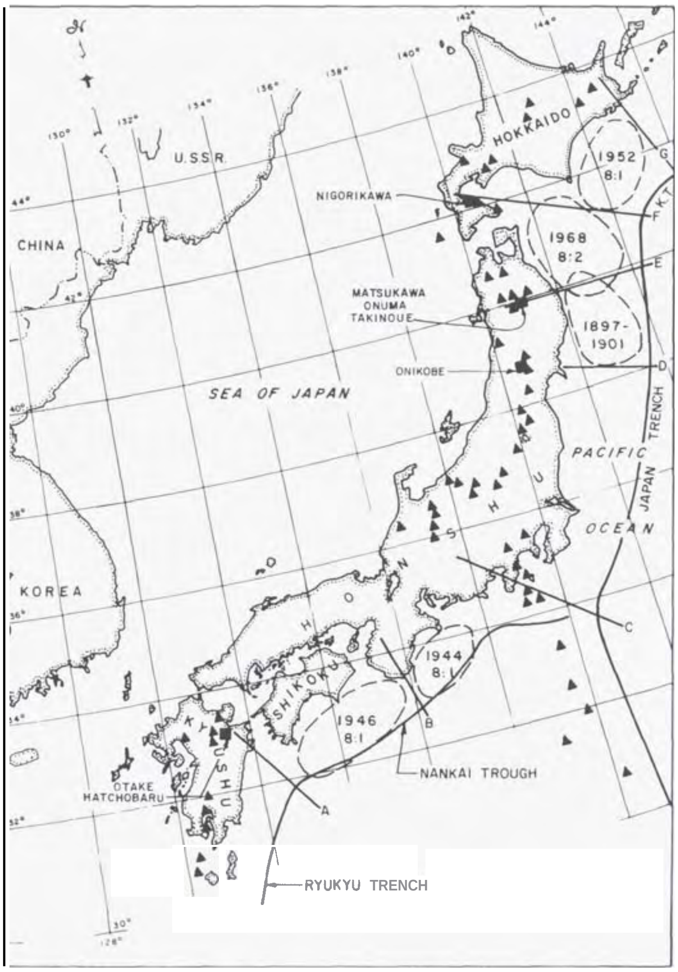

FIGURE 1: Geothermal fields and plate configuration in Japan. Location of geothermal fields (filled squares) from Nakamura (1981). Base map showing volcanoes and plate boundaries from McCann et al (1979). Rupture zones of great earthquakes from Mogi (1968). Transverse zones B, C, D, E, F, and G drawn along termination of rupture zones of great earthquakes. Transverse zones A, C, and F also mark a change in the orientation of the trench system.

chain. In general, these transverse boundary regions are complex and gradational between the adjacent segments.

It is believed that in Central America geothermal energy may replace petroleum for power production by the year 2000. Several geothermal fields have been explored and developed in Central America, and power plants utilizing goethermal energy are in operation in El Salvador and are in a planning stage in Nicaragua, Guatemala, and Costa Rica (Figure 2). It seems clear from Figure 2 that almost all geothermal fields in Central America (operating or planned) are located in or very near the segment boundaries identified by Carr (1974). This suggests that the boundary zones may be areas of higher heat flow. Carr (ibid) also observed that the most unusual types of volcanic eruption in Central America in historic times (Coseguina and Santa Maria - Figure 2) have occurred near the boundary regions.

Potential geothermal fields at Berlin and Chinameca in El Salvador appear to be exceptions to the pattern noted above, i.e., these two potential fields are not situated in or near any transverse zone (Figure 2). It is of course possible that these potential geothermal fields are exceptions. However, an examination of Figure 2 suggests that, based on the distribution of volcanoes and bathymetry, the transverse Zone E drawn by Stoiber and Carr (1973) between El Salvador and Nicaragua can also be drawn passing through Berlin - Chinameca area. Such a transverse zone would also separate the trend of volcanoes in El Salvador from the trend of volcanoes in Nicaragua and explain the locations of geothermal fields in the Berlin - Chinameca area.

This examination of geothermal fields in Japan and Central America suggests that geothermal fields are situated in transverse zones which divide a converging plate boundary into different segments. Acharya (1982 b and c) has noted that many other geothermal fields elsewhere in the circum-Pacific area are also located in similar transverse zones. In divergent areas such as Southern California - Northern Mexico, Acharya (1982 b) finds that the geothermal fields are situated near one end of spreading ridges bounded by transform faults.

Acharya and Spulber (1982) have examined the locations of geothermal fields in the circum-Pacific area by Pattern Recognition Technique in order to identify the effect of other factors, such as volcanism and rainfall, which may influence the location of geothermal fields. The Pattern Recognition Technique has been applied by Gelfand et al (19731, Briggs et al (19771, and Acharya (1981) to characterize the locations of large earthquakes in Central Asia, California, and the Philippines. Acharya and Spulber (1982) applied this technique to 89 locations in the circum-Pacific area with 20

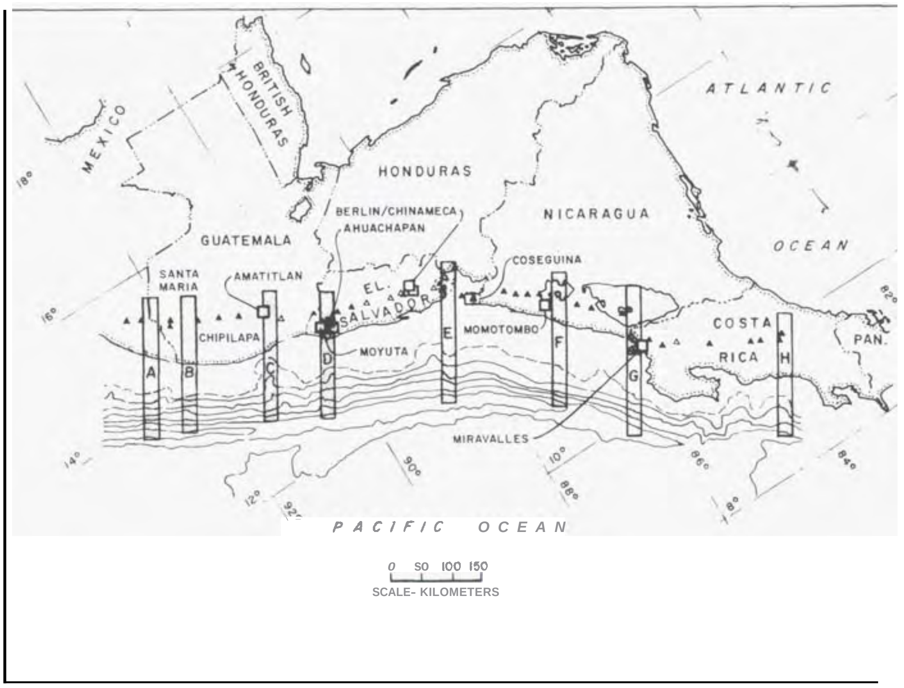

FIGURE 2: Geothermal fields in Central America and plate segmentation. Locations of geothermal fields from Muffler (1976b). Base map showing volcanoes and segmentation of the converging zone from Stoiber and Carr (1973) and Carr (1974). A producing geothermal field is shown by a filled square while a geothermal field under exploration is shown by an open square. Solid triangles are volcanoes with historic eruptions and open triangles are volcanoes with solfatara activity.

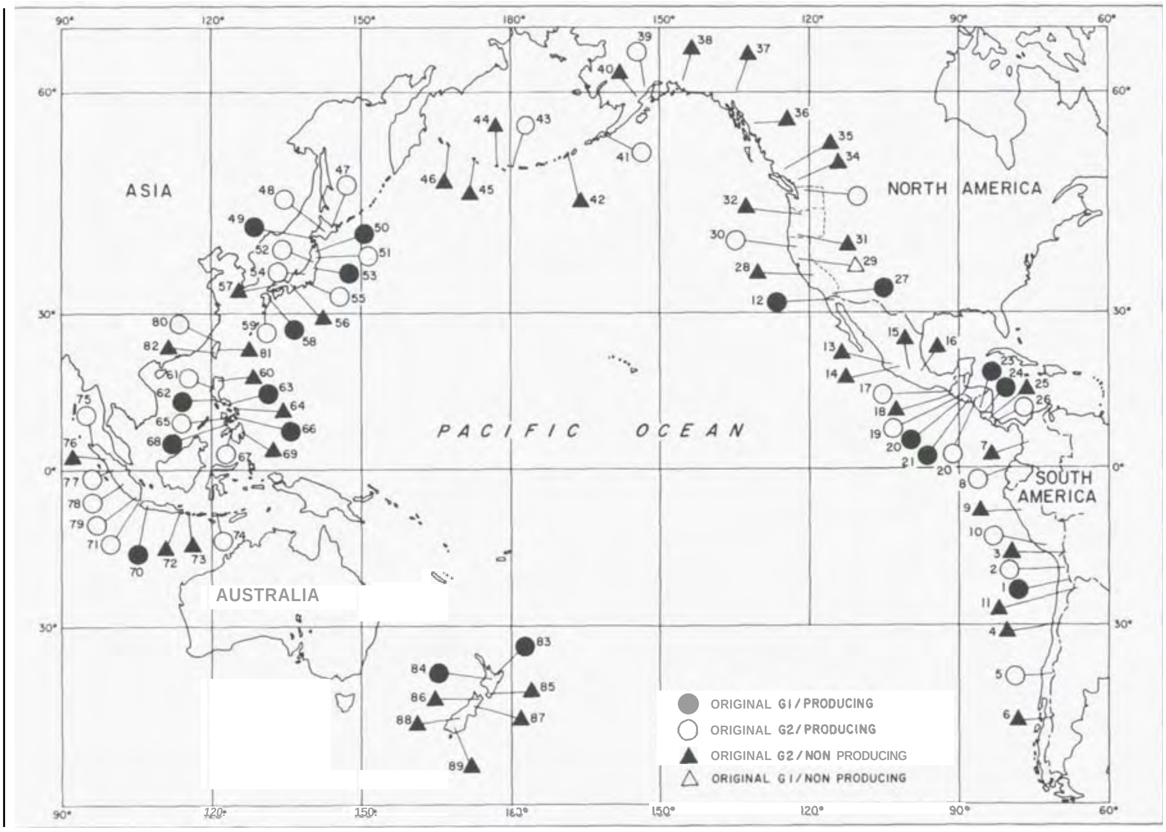

FIGURE 3: Locations in the Circum-Pacific area examined by Pattern Recognition Technique. G1 locations are producing or proven geothermal fields. G2 locations are unexplored or unproven fields.

known producing fields (G1 points) and 69 locations where geothermal energy is not exploited at present (G2 points). These *89* locations were characterized by 14 questions listed in Table 1. Figure 3 shows the locations of these *89* points and the results of this analysis.

Acharya and Spulber (1982) found that, except for the Geysers, all locations originally designated as G1 points were predicted by this technique as producing geothermal fields. Furthermore, *29* locations originally designated as *G2* points were predicted as producing geothermal fields. A number of these locations are being explored at present and may indeed become producing fields in the near future.

DISCUSSION

Transverse zones are broad zones, several miles wide and probably complex, consisting of deep multiple interlacing faults. Transfer of heat from the interior of the earth can be, therefore, greater than average in these zones. Earthquake studies (Kelleher et al 1973) suggest that various segments of the underthrusting plate act as independent blocks in storing elastic strain. Differential shear between these segments can lead to shear heating in these transverse zones, which can lead to higher temperatures at shallow depth.

Available heat flow data (Figure 4) in Japan (Watanabe et al 1977) support this suggestion. The geothermal fields Matsukawa, Takinoue, and Onuma are located in an area with a heat flow of 3.5 HFU. Figure 4 also shows the transverse zones delineated in Figure 1. Heat flow in the islands, along the extension of Zones E, F, G, and H, is $\geq$ 3.5 HFU. These zones mark the termination of rupture zones of great earthquakes. The high heat flow in these zones therefore supports the hypothesis developed above. No heat flow data are available along Zones D and A. Heat flow along Zone C is about 2.0-2.5 HFU. Finally, along Zone B, heat flow is about 1.5-2.0 HFU. There are no volcanoes in this area (Figure 1), and Fitch and Scholz (1971) have suggested that the underthrusting slab has not yet reached depths necessary for the generation of magma. In the absence of magma at depth, the heat flow in Zone B is compatible with heat flow in other transverse zones in Japan. Therefore, it appears that differential movement between two blocks can lead to higher heat flow in these transverse zones.

Vogt (1974) stipulated that rising plumes of magma will be dammed by the transform fault which terminates the plumbing system. Such an arrangement will lead to higher heat flow in the vicinity of the transform fault and may explain the locations of the geothermal fields in Southern California - Northern Mexico area at diverging plate boundaries.

Acharya and Spulber (1982) found that besides nearness to the transverse zones mentioned above, the two factors which influenced the development of a geothermal field in an area are:
(i) nearness to fumeroles or hot springs, and
(ii) nearness to historically active volcanoes with at least one eruption per century. Acharya and Spulber found that volcano clusters are in general favorable to the development of geothermal field in the vicinity, but volcanic rock type and the amount of rainfall are ambiguous in their influence.

The discussion above suggests that the presence of transverse zones and active volcano in an area will lead to higher heat flow and therefore higher temperatures near the surface. If the amount of rainfall in this area is moderate (≈ 10-60 inches/year), then this rainwater percolating through the ground will act as an efficient heat transfer agent. Local geology and structure will influence the locations of fumeroles and hot springs in the area. This plausible model can be used to identify areas in the circum-Pacific for future exploration of geothermal energy.

ACKNOWLEDGEMENTS

I thank S. Spulber for critical review. I thank A. S. Lucks and J. Briedis for review and encouragement and Stone & Webeter Engineering Corporation for support. I thank J. DeSimone for typing the manuscript.

REFERENCES

Acharya, H. K., Analysis of seismicity of Central Luzon by Pattern Recognition, Phys. Earth Planet Int., 24, 53-65, 1981.

Acharya, H. K., Hot Springs, Volcanism and Geothermal Fields in Japan (in preparation), 1982a.

Acharya, H. K., Geothermal Fields and Plate Tectonics (submitted for publication), 1982b.

Acharya, H. K., Geothermal fields and Plate Tectonics in the circum-Pacific, Proceedings third circum-Pacific Energy and Mineral Resources conference, 1982c.

Acharya, H. K., and S. Spulber, Patttern Recognition analysis of locations of geothermal fields in the circum-Pacific area (in preparation), 1982.

Briggs, P., F. Press, and Sh. A. Guberman, Pattern Recognition applied to earthquake epicenters in California and Nevada, Geol. Soc. Am. Bull., 88-173, 1977.

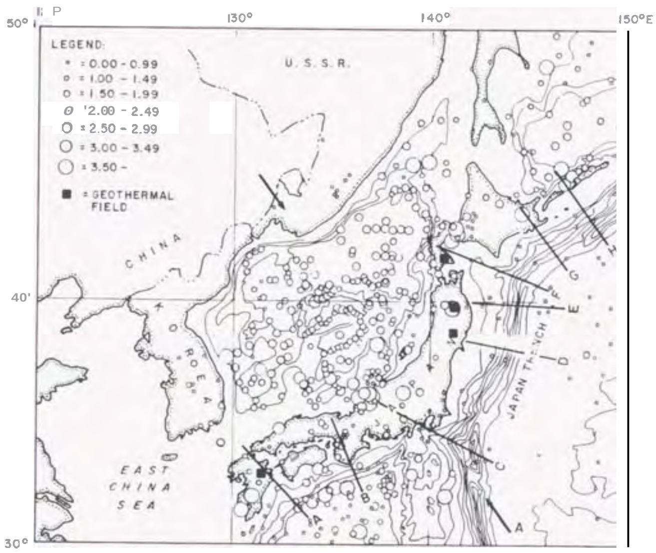

FIGURE 4: Heat flow in Japan and vicinity in relation to the location of geothermal fields and transverse zones. Basic heat flow map from Watanabe et al (1977). Transverse zones A-H mark either a change in the orientation of the trench or the termination of rupture zones of great earthquakes. Note high heat flow of about 3.5 HFU inland along extension of Zones E, F, G, and H.

Carr, M. J., R. E. Stoiber, and C. L. Drake, Discontinuities in the deep seismic zones under the Japanese arcs, Geol. Soc. Am. Bull., 84, 2917-2930, 1973.

Carr, M. J., Tectonics of the Pacific margin of northern Central America, Ph. D. Thesis, Hanover, N. H., Dartmouth College, 121 p., 1974.

Fitch, T., and C. Scholz, Mechanism of underthrusting in southwest Japan: A model of convergent plate interaction, J. Geophys. Res., 76, 7260-7292, 1971.

Gelfand, I. M., Sh. A. Guberman, V. I. Keilis-Borok, and E. J. Ranzman, Recognition of places where strong earthquakes may occur, Comput. Seismol., Acad. Sci. U.S.S.R., 6, 107-133, 1973.

Isacks, B., and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere, in Island Arcs, Deep Sea Trenches and Back Arc Basins, Maurice Ewing Series 1, M. Talwani and W. C. Pitman eds., AGU, 99-114, 1977.

Kelleher, J. A., L. Sykes, and J. Oliver, Possible criteria for predicting earthquake locations and their application to major plate boundaries of Pacific and Caribbean, J. Geophys. Res., 78, 2547-2585, 1973.

Mogi, K., Some features of recent seismic activity in and near Japan, I., Bull. Earthq. Res. Inst., Tokyo Univ., 46, 1225-1236, 1968.

Motkya, R. J., and M. A. Moorman, Reconnaissance of thermal spring sites in Aleutian arc, Atka Island to Becherof Lake, Proc. Geothermal Resources Council, V.5, 111-114, 1981.

Muffler, L. J. P., Tectonic and hydrologic control of the nature and distribution of geothermal resources, Proc. Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, Calif., Vol. 1, 499-508, 1976a.

Muffler, L. J. P., Summary of Section I: Present Status of Resources Development, Proc. Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, Calif, Vol. 1, xxxiii - xliii, 1976b.

Nakamura, H., Development and Utilization of Geothermal Energy in Japan, Geothermal Resources Council Transactions, 5, 33-35, 1981.

Stoiber, R. I.,, and M. J. Carr, Quaternary volcanic and tectonic segmentation of Central America, Bull. Volcanol., 37, 304-325, 1973.

Sugimura, A. and S. Uyeda, Island Arcs, Japan and its environs, Elsevier, New York, 247p., 1976.

Vogt, P. R., Volcano spacing, fractures and thickness of the lithosphere, Earth Planet. Sci. Lett., 21, 235-252, 1974.

Watanabe, T., M. C. Langseth, and R. N. Anderson, Heat flow in back arc basins of the western Pacific in Island Arcs, Deep Sea Trenches and Back Arc Basins, Maurice Ewing Ser., Vol. 1, p. 137-161, American Geophysical Union, Washington, D.C., 1977.

TABLE 1

List of questions used:

1. Is the point near a break in the lateral continuity of the plate margin?
2. Is the point near a volcano that has been active in the last 12,000 years?
3. Is the point near fumeroles and/or hot springs?
4. Is the point in a volcano cluster?
5. Is the point near the beginning of a volcano gap?
6. Is the point near dacitic or rhyolitic volcanism?
7. Is the point near andesitic volcanism?
8. Is the point near basaltic volcanism?
9. Is the point near a shallow earthquake with magnitude $\geqslant$ 7.7?
10. Is the point near the end of rupture zone of a great (magnitude $\geqslant$ 7.7) earthquake?
11. Is the rainfall near the point $\leqslant$ 10 in/yr?
12. Is the rainfall near the point between 10-60 in/yr?
13. Is the rainfall near the point > 60 in/yr?
14. Is the volcanic activity rate near the point > 0.01/yr?