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TECTONIC CHARACTERISTICS OF GEOTHERMAL FIELDS IN SOUTH AMERICA

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The western part of South America shows all the characteristics of plate underthrusting, such as the occurence of great (Magnitude ⩾ 7.7) shallow earthquakes, intermediate and keep focus earthquakes as well as volcanic activity. Several locations in the western part of South America have been examined to determine the tectonic characteristics of locations which show the potential for geothermal energy development. Locations examined include areas which have been already explored as well as other areas not yet investigated. The locations have been examined in terms of the nature and extent of volcanic activity in the area, the distributions of hot springs and/or fumeroles, the amount of rainfall in the area, the configuration of plate boundary, the relationship with rupture zones of great earthquakes, etc. This investigation has identified certain tectonic characteristics which are most favorable to the development of geothermal fields in western South America. It also identifies characteristics which are more or less unfavorable for such development. Favorable tectonic characteristics for geothermal development in South America are compared and contrasted with characteristics of geothermal fields in Japan, the Philippines and Central America in order to identify tectonic characteristics common to all geothermal fields. Since rainfall is much higher in these areas than in many parts of western South America, the study points the extent to which various parameters interact to develop favorable conditions for a geothermal field. The results are then correlated with available heat flow data in these zones.

A parte ocidental da América do Sul mostra todas as características de ''plate underthrusting'' como ocorrênica de sismos rasos com grande magnitude (Magnitude 7,7), sismos com focos intermediários e profundos e atividade vulcânica. Várias localidades da parte oeste da América do Sul têm sido examinadas para se determinar-se as características tectônicas das localidades que mostram potencial para o desenvolvimento de energia geotérmica. As localidades examinadas incluem tanto áreas já exploradas como áreas ainda não investigadas. As localidades foram examinadas em termos de natureza e extensão da atividade vulcânica da área, distribuição de fontes termais e/ou fumarolas, pluviosidade da área, configuração do limite de placa, a relação entre zonas de ruptura de grandes sismos, etc. Esta investigação identificou certas características tectônicas que são as mais favoráveis para o desenvolvimento de campos geotérmicos na parte ocidental da América do Sul. Identificou também as características que são mais ou menos desfavoráveis para o desenvolvimento de tais campos geotérmicos. As características tectônicas favoráveis para o desenvolvimento de campos geotérmicos na América do Sul são comparadas e contrastadas com as características de campos geotérmicos no Japão, Filipinas e América Central com o intuito de identificar as características tectônicas comuns a todos os campos geotérmicos. Uma vez que a pluviosidade é muito maior nessas regiões do que em muitas partes da América do Sul, o estudo analisa até que ponto a interação dos vários parâmetros é importante para o desenvolvimento de condições favoráveis para um campo geotérmico. Os resultados são então correlacionados com os dados disponíveis de fluxo térmico nessas áreas.

(Traduzido pela Revista)

INTRODUCTION

Many of the geothermal fields explored so far occur along spreading ridges or subduction zones, in areas of young tectonism and volcanism, primarily along active plate boundaries (Muffler, 1976). Volcanic areas have higher than average thermal gradient simply because hot magma is rising through the crust. If such an area is also underlain by thick rock segments which are permeable to ground water flow and if ground water circulates freely through them, then there can be transfer of heat from magmatic bodies at depth to shallow crustal depths. Under such conditions, it is possible to economically extract this heat for power generation purposes.

South America forms the eastern boundary of the underthrusting Nazca plate. The western part of South America shows all the characteristics of plate underthrusting, such as the occurrence of shallow great (Magnitude ⩾ 7.7) earthquakes, intermediate and deep focus earthquakes as well as volcanic activity. Fig. 1 shows the plate boundaries, locations of active volcanoes and ruptures zones of great earthquakes. Locations in the vicinity of active volcanoes in South America may therefore be favorable for the exploitation of geothermal energy. Several areas in South America are indeed under investigation (Fig. 2) although the existence of recoverable resources is not yet proven at any of these locations with the exception of El Tatio, Chile. The tectonic characteristics of these areas have been examined in order to understand the favorable conditions under which a geothermal field can develop

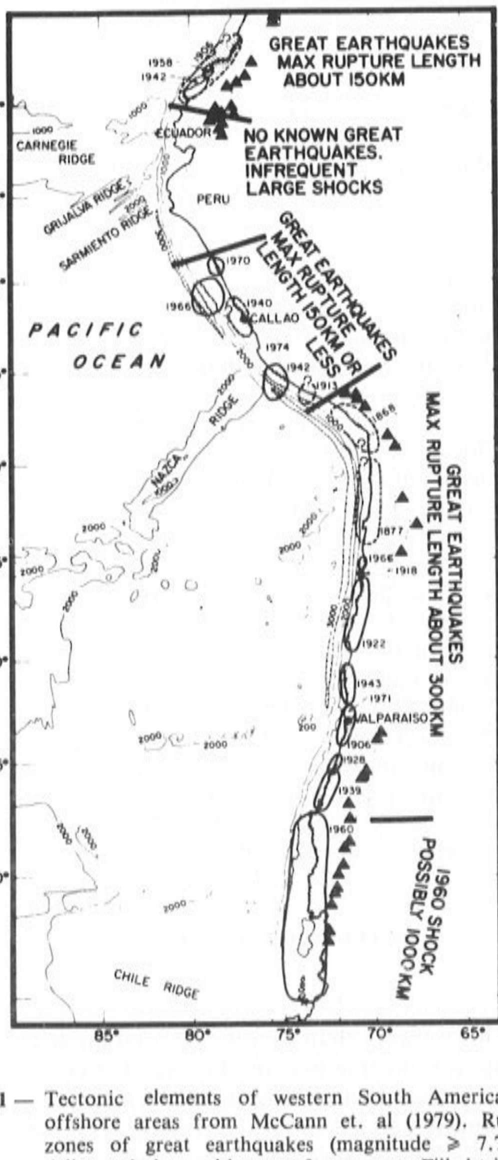

Figure 1 — Tectonic elements of western South America and offshore areas from McCann et. al (1979). Rupture zones of great earthquakes (magnitude ⩾ 7.7) are delineated along with year of occurence. Filled triangles represent active volcanoes.

Figure 2 — Geothermal Projects Underway in South America based on DePippo (1985).

in South America. The tectonic characteristics examined include the nature and extent of volcanic activity in the area, the distribution of hot springs and/or fumeroles, the amount of rainfall in the area, configuration of plate boundary, the relationship with rupture zones of great earthquakes, etc.

Acharya (1982) noted that several of the locations under investigation appear to be situated in transverse zones that segment the South American plate. These transverse zones were identified by Swift & Carr (1974) on the basis of distribution of volcanoes. Acharya (1984a) noted that most of the proven geothermal fields in Japan, Philippines and Indonesia are situated along the extension of zones which terminate the rupture of great earthquakes. These two studies suggest that plate underthrusting does to some extent influence the development of produtive geothermal field in an area. In order to learn more about this influence, Acharya (1985) examined several locations in the Circum-Pacific by the Pattern Recognition Technique. The results obtained in that study are analysed here to identify specific characteristics which are favorable to the development of geothermal field in South America. Characteristics which are unfavorable for such development have also been identified. Finally, tectonic characteristics for South America are compared and contrasted with characteristics for productive geothermal fields in Japan, Philippines, Indonesia and Central America. Before proceeding with this analysis, the status of the geothermal development in various parts of South America is first described, based on information provided in DePippo (1985).

GEOTHERMAL FIELDS IN SOUTH AMERICA

Many areas in western South America have been or are at present explored for the utilization of geothermal energy. Fig. 2 shows the areas which have been explored so far. These are discussed below on a country by country basis.

Argentina

Two areas are being explored. One is Copahue in the western-central Andes Mountains where one well has been drilled. There is some promise for this field. The other area is Jujuy in the far northern area of the country where Argentina borders on Chile and Bolivia.

Studies at Copahue have shown a reservoir temperature of about 230°C. The existing well produced 4.4. kg/s of saturated steam, enough to drive a 2.5 MW condensing turbine. This field may have a power potential in excess of 50 MW.

Bolivia

Seven areas bordering on Chile are considered prospects. They are: Sajama, Valle del Rio Empexa, Salar de la Laguna, Volcan Ollague, Quetena, Laguna Colorada, and Laguna Verde. No deep wells have been drilled yet. Reservoir temperature at some sites may be 240 to 250°C based on shallow wells. By 1990, 30 MW may be installed.

Chile

The main geothermal field in Chile is El Tatio in the Antofagasta province in the far north at an elevation of 4300 m above sea level. Of the seven deep wells drilled, two are productive; the proven power capacity of these wells is about 15.5 MW. Reservoir temperatures is the range 225 to 250°C. Demand for power in this remote part of the country depends on the activity at the Chuquicamata copper mine, the largest in Chile.

Colombia

Four areas are being assessed: Ruiz Volcano (3 zones), Chiles Volcano, Azufral de Tuquerres, and Paipa. Estimated reservoir temperature range from 85 to 271°C based on various geothermometers. A 3 MW pilot plant may be installed by 1990.

Ecuador

Five areas located from Cuenca to Quito and continuing to the Colombian border are being explored. They are: Cuenca-Azogues, Chimborazo, Chalupas, Imbabura-Cayambe, and Tufino-Chiles-Cerro Negro.

Peru

There are numerous areas marked by surface thermal manifestations, the most promising being in the southernmost part of the country. The five areas of most interest are: Chivay, Chachani-Laguna Salinas, Calacoa, Tutupaca, and Challapalca.

Venezuela

Two areas along the northern coastal section appear to hold some potential. They are the Barcelona-Cumana and the El Pilar-Casanay areas. There are no geothermal power plants in Venezuela.

PATTERN RECOGNITION ANALYSIS

Acharya (1985) applied the tecnique of Pattern Recognition to 89 location in the circum Pacific area, including 11 locations in South America. These 11 locations in South America are shown in Figs. 3 and 4. All 89 locations were characterized by responses to 14 questions listed in Table 1. Twenty of these locations (including El Tatio in South America) are situated near productive geothermal fields. The Pattern Recognition algorithm first analyses the responses at these 20 locations and on that basis defines favorable and unfavorable traits. Each trait is a combination of response to any three questions listed in Table 1. It then applies these traits to all 89 locations and identifies locations which have more favorable traits than unfavorable traits. The details of this examination are discussed in Acharya (1985) and will not be repeated. The results obtained for the circum Pacific area are briefly discussed below. The analysis of these results for South America are discussed in the next section.

Traits favorable to the development of a geothermal field in the circum Pacific area are listed in Table 2. The traits so identified help satisfy the two requirements esssential for a geothermal field, namely the presence of a heat source and availability of ground

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 ⩾ 7.7?
10. Is the point near the end of rupture zone of a great (magnitude ⩾ 7.7) earthquake?
11. Is the rainfall near the point < 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 > 0.01/yr?

water. Table 3 lists traits which are not favorable to the development of a geothermal field in the circum Pacific area.

Examination of favorable traits listed in Table 2 suggests that the necessary conditions for development of a geothermal field, namely the occurrence of high crustal temperatures at shallow depth and availability of ground water for heat transfer can arise in a number of ways. In Trait 1, a volcano (dacitic or shyohitic) active in the last 12,000 years provides heat source at depth while the break in lateral continuity of the underthrusting plate may lead to fractured rock in the volcanic zone and, therefore, paths for groundwater movement as well as heat flow. Trait 2 suggests that moderate amount of rainfall, 10-60 in/year, may provide required ground water, while fumeroles and hot springs indicate permeable rock and break in lateral continuity develops paths for flow of heat and water. Trait 3 suggests that volcanoes in a cluster result in high heat flow in an area probably arising from heat flows through the many fracture zones. Trait 9 suggest that a volcano with eruptive rate of more than one a century provides the necessary heat and the break in lateral continuity may provide paths for heat flow. Trait 13 suggests that if volcano has been active in the last 12,000 years then there is enough heat at volcanic depths ($\sim$10 km) that moderate rainfall is not crucial for the development of a geothermal field. Trait 15 indicates that andesitic volcanoes in clusters provide the heat source and the presence of fumeroles/hot springs nearby indicate permeable rock and availability of groundwater. The existence of cluster is sufficient to decrease the need to worry about the rate of activity or whether the volcanoes have been active in the last 12,000 years, for a cluster suggests several vertical fractures for heat and mass transfer. Trait 16, on the other hand, suggests that if the location is not in a volcano cluster but in the vicinity of volcano that has erupted at least once in a century then there is a proximity to a strong heat source and fumeroles and hot springs signify groundwater and permeable rock, all ingredients necessary for the development of a productive geothermal field. Trait 8 indicates that if the rainfall near the point is heavy (> 60 in/year) and fumeroles and hot springs are present, then the dacitic or rhyolitic volcanoes nearby are not the source of heat. Trait 20 indicates that andesitic volcanism and fumeroles and hot springs complete the picture and the location does not have to be near the terminal of rupture zone of a great earthquake. Trait 22 suggests that an active volcano (rate > 1 per century) and fumeroles are sufficient to identify a location as potentially producing and that basaltic volcanism is not the needed source of heat. Trait 24 suggests that fumeroles/hot springs, active volcano, and rupture end of great earthquake provide favorable environment. Trait 25 suggests that the moderate amount of rainfall is not crucial if active volcanoes and fumeroles/hot springs are present. Trait 29 brings together volcano cluster, active volcanism in the cluster, and rupture end to provide the needed heat flow. Trait 32 shows that the location of a point near the beginning of volcano gap provides the surplus heat which can be transferred through moderate (10-60 in/year) amount of rainfall.

Table 2 – Independent Traits for Producing Fields

0 = No 1 = Yes

Trait	Question 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	1	1				1								
2.	1		1									1		
3.	1			1				1						
9.	1									0				1
13.		1					0					0		
15.			1	1			1							
16.			1	0										1
18.			1			0						1		
20.			1				1			0				
22.			1					0						1
24.			1							1				1
25.			1									0		1
29.				1						1				1
32.					1				1			1		

This analysis indicates that six parameters are dominant. These are:

1. Nearness to lateral break in the continuity of the plate margin (Q.1).
2. Nearness to fumeroles or hot springs (Q. 3).
3. Nearness to historically active volcanoes with at least one eruption per century (Q. 14).
4. Point in a volcano cluster (Q. 4).
5. Near volcanoes active in last 12,000 years (Q. 2).
6. Near the beginning of a volcano gap (Q. 5).

In this analysis, nearness implies a distance of about 25-30 kilometers.

Examination by Acharya (1985) showed that no single trait is overwhelmingly common to all producing fields in the Circum-Pacific area. On an average, each trait identifies about six locations, three of which were originally specified as producing locations and three were defined as not near producing locations. This is somewhat surprising in view of an essentially identical tectonic setting (converging plate boundaries). The absence of a few dominating traits suggest that a productive geothermal field can develop from any number of favorable combinations depending on the tectonic and environmental conditions in the area.

Acharya (1985) noted that there are regional differences among the favorable traits reflecting regional differences among the environmental conditions. For example, during the last 200 years, volcanic activity rate was highest in Japan and lowest in New Zealand (computed from data in Simkin et al., 1981). Similarly there is considerable variation in annual rainfall from < 10 in/yr in arid regions of South America to > 100 in/yr in many parts of Asia. It is therefore not surprising that traits differ from region to region. We will therefore analyze the results of Pattern Recognition study to identify traits that are deemed favorable in South America and compare them with favorable traits in Central America, Japan, Philippines and Indonesia.

RESULTS FOR SOUTH AMERICA

The results of this study help identify four areas in South America besides El Tatio as having characteristics favorable to the development of geothermal fields. These four locations near Puchuldiza and Trapa Trapa in Chile, Mt. Ubinas in Peru, and Mt. Cotopaxi in Ecuador (Numbers 2, 5, 10, and 8 in Figs. 3 and 4) were originally designated as not producing geothermal fields but were found in this study to have traits favorable for the development of a geothermal field.

Locations which were originally designated as nonproductive and are shown not to have favorable characteristics are a mixture. Some, such as Solar De Empexa in Bolivia, central Chile, and Juy Juy in Argentina, are situated in nonvolcanic areas (Points 3, 4, and 11). Point 6 in southern Chile is located in volcanic area but not in plate discontinuity. Point 9 in northern Peru is located in a nonvolcanic terrain although it is situated in a zone of some discontinuity. Point 7 in northern Colombia is situated near a volcano but is not near any lateral discontinuity.

All the five locations characterized by Pattern Recognition Technique as productive locations in South America have the following features:

1) All five are near a break in the lateral continuity of the plate margin.
2) All five are near volcanoes that have been active in the last 12,000 years.
3) All five locations are near andesitic volcanoes.
4) All five are near epicenters of shallow earthquakes with magnitude ⩾ 7.7.
5) None of these five locations are near basaltic volcanoes, and
6) Rainfall is not > 60 in/yr near any of these locations.

Furthermore four of these five locations are:

1) Near the end of a rupture zone of a great (magnitude ⩾ 7.7) earthquake and
2) Are situated near volcanoes with activity rate > 0.01/yr.
3) Are not near the beginning of a volcano gap.
4) Are not near dacitic or rhyolitic volcanoes.

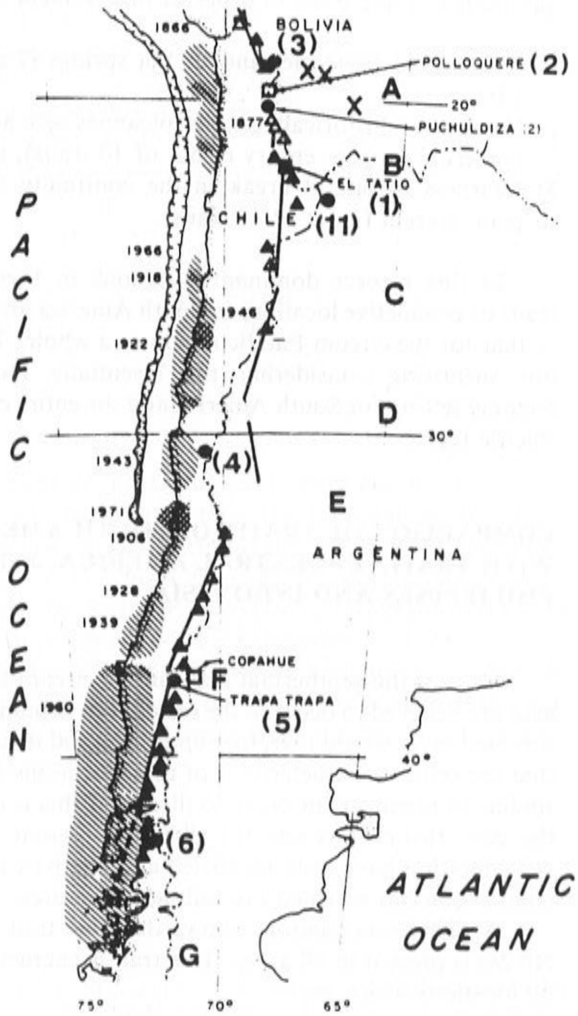

Figure 3 — Locations in western South America below 18°S latitude examined by Pattern Recognition Technique. The locations are shown as filled circles and numbered. Hatched lines show the rupture zones of great earthquakes. Filled triangles represent active volcanoes. Transverse segments A-G as drawn by Swift & Carr (1974). Solid lines between segments represent the orientation of active volcanoes noted by Swift & Carr. X's represent locations with heat flow > 2.5 HFU from Uyeda & Watanabe (1982). Other locations in western South America which have also been explored for examination of geothermal potential are shown as open squares. These locations were not included in this analysis because of their proximity to locations considered in this analysis.

A majority (3) of the five locations are also:

1) Near fumeroles and/or hot springs.
2) Located in areas with rainfall between 10-60 in/yr.
3) Not located in a volcano cluster, and
4) Not located in areas with rainfall < 10 in/yr.

An analysis of traits determined by the Pattern Recognition Technique shows that of the 14 favorable traits identified for the entire circum Pacific area, 10 are present in locations in South America. The dominating questions in these traits in order of involvement are:

1) Nearness to fumeroles and/or hot springs (7 out of 10)
2) Nearness to historically active volcanoes with at least one eruption per century (5 out of 10 traits), and
3) Nearness to lateral break in the continuity of the plate margin (3 out of 10 traits).

In this respect dominant questions in favorable traits of productive locations in South America are same as that for the circum Pacific region as a whole. This is not surprising considering the essentially identical tectonic setting for South America and the entire circum Pacific region.

COMPARISON OF TRAITS OF SOUTH AMERICA WITH TRAITS IN CENTRAL AMERICA, JAPAN, PHILIPPINES AND INDONESIA

Most of the geothermal fields in the circum Pacific area are believed to occur in the tectonic environment of subduction. It would therefore appear logical to assume that thetectonic characteristics of these locations will be similar or identical. In order to discern if this is indeed the case favorable traits for different regions under consideration have been identified and compared. This comparison has revealed the following features:

A. This examinations shows that one trait (Trait Nº 24) is present in all areas. This trait is characterized by locations which are:

1) Near fumeroles or hot springs
2) Near the end of rupture zone of a great earthquake, and
3) Volcanic activity near the point > 0.01/yr.

B. Traits 20 and 29 are present in productive locations in South America, Japan, Philippines and Indonesia but is absent in Central America. This probably arises because geothermal fields in Central America are located in transverse zones defined on the basis of the orientation and geographical distribution of active volcanoes, influenced by changes in the dip of the subducting plate whereas geothermal fields elsewhere are situated in extension of transverse zones defined on the basis of rupture zones of great earthquakes.

C. Traits 2, 3, 16, 18, 24 and 32 are common to South and Central America. Traits 2, 16, 18 and 24 are present in both regions whereas Traits 3 and 32 are absent in both regions. Traits 1, 9, 15, 20, 22 and 29 are present in South America but absent in Central America. Traits 13 and 25 are present in Central America but absent in South America.

Presence of fumeroles or hot springs is common to both areas as a symptom of the favorable environment. It is in combination with either Q. 12 (rainfall between 10-60 in/yr) or Q. 24 (volcanic activity rate > 0.01/yr). Presence of heat indicated by either volcanic activity rate or a break in the continuity of plate boundary. Availability of water is indicated by rainfall between 10-60 in/yr.

D. Of the 14 favorable traits identified, ten are common to both South America and Japan. These traits deal with the presence of heat source at depth. Traits 1, 2, 13, 16, 18, 20, 22, 24, 25 and 29 are common to South America and Japan. Traits 1, 2. 16, 18, 20, 22, 24 and 29 are present in both regions while Traits 13 and 25 are absent in both regions. Traits 9 and 15 are present in South America but absent in Japan whereas Trait 32 and 3 are present in Japan but absent in South America.

E. Eight traits 9, 13, 15, 20, 22, 24, 29 and 32 are common to South America and Philippines. Traits 9, 15, 22, 24 and 29 are all present in both areas. Traits 13 and 32 are absent in both areas. Traits 1, 2, 16 and 18 are present in South America but absent in Philippines. Traits 3 and 25 are present in Philippines but absent in South America.

As in other areas the presence of hot springs and/or fumeroles is an indication of fluid flow and possible presence of a heat source at depth. Rainfall is ambiguous and that is to be expected. Many areas in South America are arid while most areas in Philippines receive very large rainfall. Heat source is indicated by

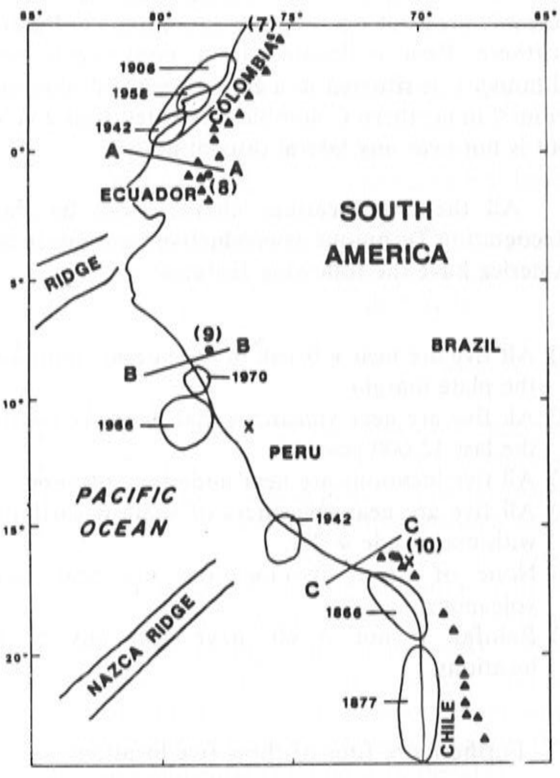

Figure 4 — Locations in western South America north of 18°S latitude examined by Pattern Recognition Technique. The locations are shown as filled circles and numbered. Rupture zones of great earthquakes delineated from McCann et. al (1979) along with major tectonic boundaries A-A, B-B, and C-C. Filled triangles represent active volcanoes. X's represent locations with heat flow > 2.5 HFU from Uyeda & Watanabe (1982).

Question 4, 7 and 14. Questions 1 and 10 probably reflect facility for heat and mass transfer through fractures in the area.

F. Traits 9, 13, 15, 20, 24, 29 and 32 are common to both South America and Indonesia. Traits 9, 15, 20, 24 and 29 are present in both regions. Traits 13 and 32 are absent in both. Traits 1, 2, 16, 18 and 22 are present in South America but absent in Indonesia. Traits 3 and 25 are present in Indonesia but absent in South America.

All traits which define the nonproductive geothermal locations are defined in Table 3. All of these traits are present and characterize all the nonproductive areas in South America identified by the Pattern Recognition Technique.

Acharya (1984a,b) noted that several geothermal fields in Japan are located in areas with high heat flow. Average heat flow measured at a location in any part of the world is about 1.5 HFU (Heat Flow Units) and several locations in Japan near geothermal fields have higher than average heat flow (up to about 3.5 HFU). There are only a few heat flow measurements in western South America and these are listed in Uyeda & Watanabe (1982). Heat flow values ⩾ 2.5 HFU are plotted in Fig. 3 and 4. These locations with high heat flow are all located in zones which segment western South America either on the basis of distribution of rupture zones of great (magnitude ⩾ 7.7) earthquakes or

Table 3 – Independent Traits for Non-Producing Fields

0 = No   1 = Yes

Traits	Questions													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0		0		0									
2		0												
3			0			0				0				
4					0		0	0						
5					0		0							0
6							0				0			0

active volcanoes. Locations in Peru and northern Chile (Fig. 4) are situated near the termination of rupture zones of great earthquakes. For example, three locations in Bolivia (Fig. 4) are situated in the zone defined by Swift & Carr (1974). Available heat flow data in South America are therefore consistent with the suggestion of Acharya (1984a) that heat flow may be higher than average in the transverse zones and this may account for the proximity of geothermal fields to these transverse zones.

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