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RESOURCES AND DEVELOPMENT PERSPECTIVES OF GEOTHERMAL ENERGY IN CENTRAL AND SOUTH AMERICA

F. BARBERI

University of Pisa, Dept. of Earth Science
Pisa, Italy

R. CATALDI

Enel/National Geothermal Unit
Via Andrea Pisano
56.100 — Pisa, Italy

A. MERLA

Geotermica Italiana
Lungaro Mediceo, 16 — Pisa, Italy

It is widely recognized that a large part of Central America and the whole Andean sector in South America, because of their geodynamic and volcanological conditions, have a very large geothermal potential. However, no systematic attempt has been made so far to quantify this potential, in order to provide an estimate of the reserves which are available in this region for the production of electric energy and for direct applications.
The scope of the present paper is to make a first contribution in this direction.
After a summary of the geological framework of the region, a categorization is made of Central and South America into type A, B and C "provinces" in accordance with a ranking of interest in descending order, depending on the expected quality of their geothermal resources.
For the six type A provinces singled out in the whole region, and for the 15 preferential sectors located in them, a quantitative assessment to 3 km depth is made of the accessible resource bases. Furthermore, for each of the sectors above, the estimation is provided of the "potential reserves," subdivided into two main groups: high temperature reserves ($T > 160°C$), and intermediate-to-low temperature reserves ($T < 160°C$). For the first group, moreover, an estimation is made in terms of electric energy producible and capacity installable.
The results of the estimation indicate that the minimum geothermoelectric potential of Central and South America altogether is of the order of 141-167 GWy_e (gigawatt-years electric), which corresponds to 5600-6700 MW_e for a 25 year production period at a 100% plant capacity factor.
Based on this very attractive, yet conservative, estimate, the present situation of the geothermal exploration in Central and South America is then reviewed, and the possible development targets are discussed in the light of medium- and long-term perspectives.

É um fato conhecido que uma parte considerável da América Central e todo o setor andino da América do Sul tem, devido às suas condições geodinâmicas e vulcanológicas, um potencial geotérmico muito grande. Entretanto, nenhuma tentativa de quantificação sistemática desse potencial foi feita até o momento, com o intuito de fornecer uma estimativa das reservas disponíveis nessa região para produção de energia elétrica e para uso direto. O propósito deste trabalho é dar uma primeira contribuição nesse sentido.
Após um resumo do enquadramento geológico da região, é feita uma classificação para as Américas Central e do Sul em províncias do tipo A, B e C de acordo com um interesse decrescente dependendo da qualidade de suas reservas geotermais.
Para seis províncias do tipo A, individualizadas em toda a região, e para quinze setores preferenciais nelas localizados, foi estabelecida quantitativamente uma profundidade de 3 km para recursos acessíveis. Além disso, para cada um desses setores

acima, é fornecida uma estimativa das "reservas potenciais", subdividida em dois grupos principais: reservas com temperatura elevada (> 160°C) e reservas com temperaturas intermediárias e baixas (< 160°C). Para o primeiro grupo é feita uma estimativa em termos da energia elétrica produtível e da capacidade instalável. Os resultados das estimativas indicam que o potencial geotermoelétrico mínimo das Américas Central e do Sul juntas é da ordem de 141-167 GWa_e (gigawatts-ano de eletricidade), que corresponde a 5600-6700 MW_e para um período de produção de 25 anos com um fator de capacidade das usinas de 100.
Com base nesta estimativa atraente, embora conservadora, a atual situação da exploração geotérmica nas Américas Central e do Sul é revista, e as possíveis áreas para desenvolvimento são discutidas à luz de perspectivas de médio e longo prazo.

(Traduzido pela Revista)

INTRODUCTION

It is generally recognized that the geodynamic, tectonic, volcanologic and hydrogeologic conditions of much of Central America and of the western sector of South America determine as a whole a basic situation that, particularly with respect to the Andean Cordillera, is very favorable for the formation of geothermal fields. Indeed, the research and exploration activities carried out so far in some preferential zones of Central America and of the Andean Cordillera have enabled the discovery of a few areas in which fluid exploitation for the production of electric power is already in progress (Ahua-chápan in El Salvador and Momotombo in Nicaragua)l, or nearing startup (Copahue in Argentina, Miravalles in Costa Rica, and Zuníl in Guatemala).

In addition, numerous other areas of potential interest are already in an advanced stage of prospecting, and in some cases also of exploratory drilling. Among these are Amatitlán in Guatemala, Chipilaga, Berlín and Chinameca in El Salvador, San Jacinto and El Hoyo in Nicaragua, El Valle de Antón in Panama, El Pilar in Venezuela, Ruiz and Chiles in Colombia, Tufiño in Ecuador, Laguna Colorada and Empexa in Bolivia, El Tatio and Puchuldiza in Chile, and Domuyo in Argentina.

For some of these areas, during the pre-feasibility or feasibility studies, assessments were made of the minimum reserves of fluid available for generating electric energy; but systematic estimations of the geothermal potential of Central and South America, aimed at outlining the development perspectives of geothermal energy in the whole region in question, are lacking.

This paper thus proposes to make an initial contribution in this direction. On one hand, it aims at continuing a debate on a subject that is of considerable interest from the methodological and scientific standpoint; on the other hand, this paper is aimed at providing quantitative (yet preliminary) estimates of the minimum geothermal potential of Central and South America, which can bring about a certain stimulation in launching exploration programs in some favorable area of the region.

GEOLOGICAL FRAMEWORK

Because of its intense volcanic activity, the Pacific margin is the privileged geothermal region of Central and South America. This widespread calcalkaline volcanism is related to the subduction of volcanic lithosphere under continental blocks. The subducting oceanic lithosphere belongs to three independent plates (see Fig. 1) which, from north to south, are:

- the Cocos plate, moving northeastwards under the Caribbean plate;
- the Nazca plate, moving eastwards under the continental portion of the South American plate;
- the Antartic plate, moving northeastwards under the southern extremity of the South American plate.

The geometry of the plate boundaries and the convergence motion rate have changed over time, producing changes in the inclination of the subducting slabs, and transversal transcurrent (transform) faulting with transverse break in the volcanic front. Consequently, changes are recorded in the volcanic activity, both in the intensity of the process and in the location of the active front.

In particular, plate tectonics reconstructions suggest that the Central American-Caribbean region, from the Lesser Antilles, Venezuela Basin and the Colombia Basin to the Middle American Trench, acts as an independent plate between the two large North and South American (or Atlantic) plates and is moving eastwards with respect to them.

An impressive front of active volcanoes, running from Guatemala-Mexico to Panama, locally affected by transverse breaks, is the result of the convergence between the Cocos and Caribbean plates. Because of the intense present-day activity, this volcanic belt is the geothermal region of Central America "par excellence", and actually it includes all the productive geothermal fields of the region.

The Andean Cordillera, running for over 8000 km along the Pacific margin of South America, shows important morphological, geological and volcanic longitudinal changes. In particular, present-day volcanic activity is concentrated in three main segments associated to parallel grabens or intercordillera

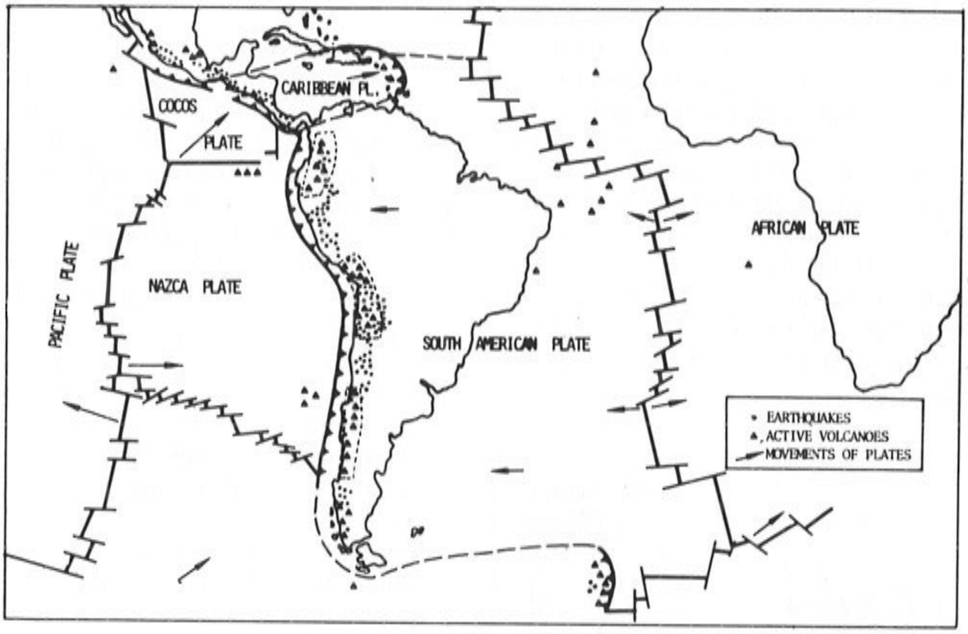

Figure 1 — Plate boundaries in Central and South America. Note that active volcanoes in S. America are concentrated in three sectors whereas seismicity is continuous along plate margins.

depressions: a northern segment (Colombia-Ecuador), a central segment (Peru-Bolivia-northern Chile and Argentina) and a southern segment (Chile-Argentina).

Seismicity is instead continuous along the Pacific margin of all of South America, and it has been suggested that the lack of volcanic activity corresponds to segments where the subducting Benioff zone is shallow-dipping and therefore does not reach, within the asthenosphere, depths suitable for magma generation.

The overall picture is however very complex and characterized by important migration with time of the volcanic front; the northern sector has a very impressive concentration of active volcanoes but lacks the voluminous silicic ignimbrites which are widespread in the central segment. The local subduction of anomalous portions of the oceanic lithosphere, such as the Carnegie Ridge in the northern segment, further complicates the picture, producing offset and transform faulting in the converging continental blocks (i.e. the Guayaquil transcurrent fault bordering the zone of active volcanism of Ecuador to the south).

The three segments of active volcanism are obviously the most attractive geothermal targets in South America; anomalous geothermal gradients, although attenuated, are to be found, however, also in the other segments, due to the occurrence here of Tertiary volcanism.

MAIN GEOTHERMAL PROVINCES OF CENTRAL AND SOUTH AMERICA

A geothermal characterization of South America and Central America can be attempted using the following distinctive criteria:

1. presence of a regional thermal anomaly, proven or possible in the light of the present geodynamic conditions;
2. the magnitude of this anomaly, as it can be estimated from regional geologic considerations, from present subsurface data and from surface evidences, such as active magmatism, temperature estimates based on chemical geothermometers, etc.
3. the existence of regional hydrogeologic conditions "favorable" for the storage and recharge of geothermal fluids.

In a wide part of the studied region both conditions 1 and 2 fulfilled: in fact, the Andean Cordillera and the Central American ranges (and their eastern and western slopes and foothills regions) are the site of active geodynamic processes, recent or active volcanism and magmatism, countless thermal manifestations and, very broadly speaking, favorable hydrogeologic conditions for the presence of exploitable thermal aquifers.

The subsurface thermal anomaly is not uniform throughout these two very large regions. Clear evidences indicate that marked uprisings of the isothermal surfaces occur along a narrow band, roughly corresponding to the axis of the volcanic front of the Andean Cordillera and of Central America, where active volcanism is concentrated.

The remaining, and larges, part of South America, as well as the marginal sectors of Central America, do not present any of the above-mentioned conditions. However, in these sectors, too, and in the easternmost part of South America, exploitable geothermal resources might still be present, in connection with deep-reaching fault systems and/or thick sedimentary basins. Even in a "normal" gradient environment, in fact, the use of low-temperature resources might prove economically attractive in certain cases.

A very general subdivision of the whole region according to the quality of its resources can therefore be traced, and three types of geothermal province can be established (Fig. 2):

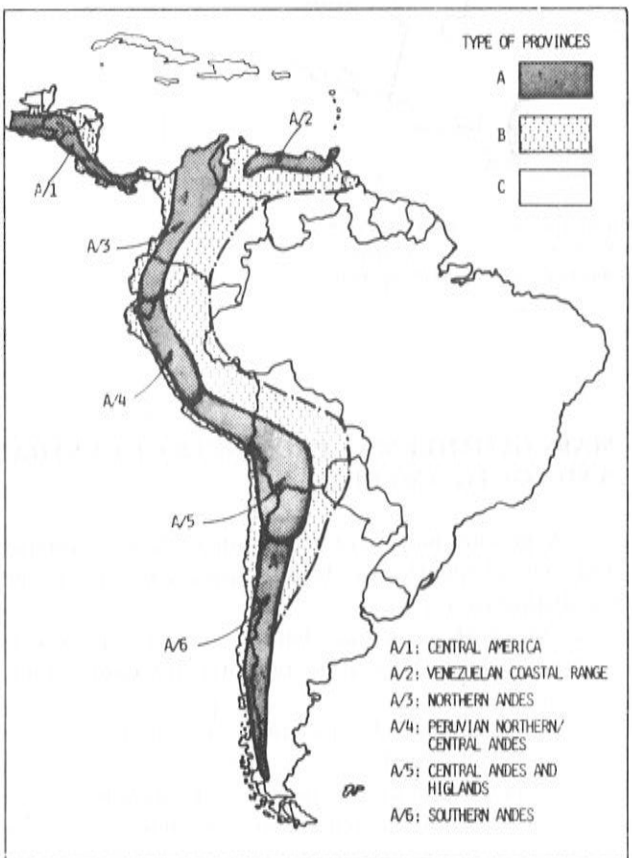

Figure 2 — Geothermal provinces of Central and South America.

Type A Provinces: where the highest anomalous temperatures are expected at relatively shallow depths. Six provinces of this type can be singled out in the whole region considered (see Fig. 2).

Type B Provinces: where marginal effects of the regional thermal anomaly centered in the type A provinces should still exist, associated with favorable hydrogeologic conditions on a regional scale.

Type C Provinces: normal, or below normal, temperature gradients are characteristc of this very large region. The Brazilian shield and Patagonian massif in South America, and other marginal sectors of South and Central America, are included in this type of province.

Preferential Sectors of the Type A Provinces

Given the objective of this paper, interest has been concentrated on those portions or sectors of the type A provinces, which seem to present the most favorable geothermal conditions, that is, the highest concentration, within the 3000 m depth limit, of exploitable geothermal resources. Such "preferential sectors" (see Fig. 3) have been established on the basis of the following considerations:

— known existence of geothermal fields (under development or exploitation);
— presence of prospect areas already identified on the basis of systematic reconnaissance surveys and pre-feasibility studies;
— thermometric estimates based on geochemical thermometers indicating anomalous temperature values;
— presence of widespread active volcanism or of important, although isolated, active volcanic centers;
— reasonable extrapolations of the above conditions on regional geologic grouds.

Each sector is intended as a geological-morphological-geothermal unit characterized by homogeneous overall conditions.

Central America. Four preferential sectors have been identified within this type A geothermal province (Fig. 3a) Three sectors (A/1-1, A/1-2 and A/1-4) coincide with the active or recent volcanic ranges, and constitute a narrow band roughly parallel to the Pacific coast. A fourth sector (A/1-3), including parts of Honduras, Nicaragua and Guatemala, although devoid of important recent volcanic activity, is certainly still affected by the regional thermal anomaly and by local enhancements of this anomaly due to extensional tectonics and deeply fractured intrusions.

Venezuelan Coastal Ranges. Only one major preferential sector is thought to be present within this province (Fig. 3b). It is located along the regional transcurrent fault system controlling the Caribbean coast of South America, where, in places, extensional conditions and the formation of geothermal systems may be determined by the geometry of the two bordering plates.

Northern Andes. Three sectors have been singled out in this province (Fig. 3b), two of which of very great geothermal interest, because of the impressive concentration of active volcanism (A/3-2 and A/3-3). The southern Colombian Andes and the Ecuadoran Andes (A/3-3) show quite favorable hydrogeologic conditions in several zones (thick Tertiary volcanic sequences overlying the crystalline basement), contrary to what happens in the Central Andes (A/3-2), where Quaternary volcanoes directly overlie the basement.

The A/3-1 sector (merida and Western Colombian Andes), although clearly less important as a whole, presents localized favorable situations of probable geothermal interest.

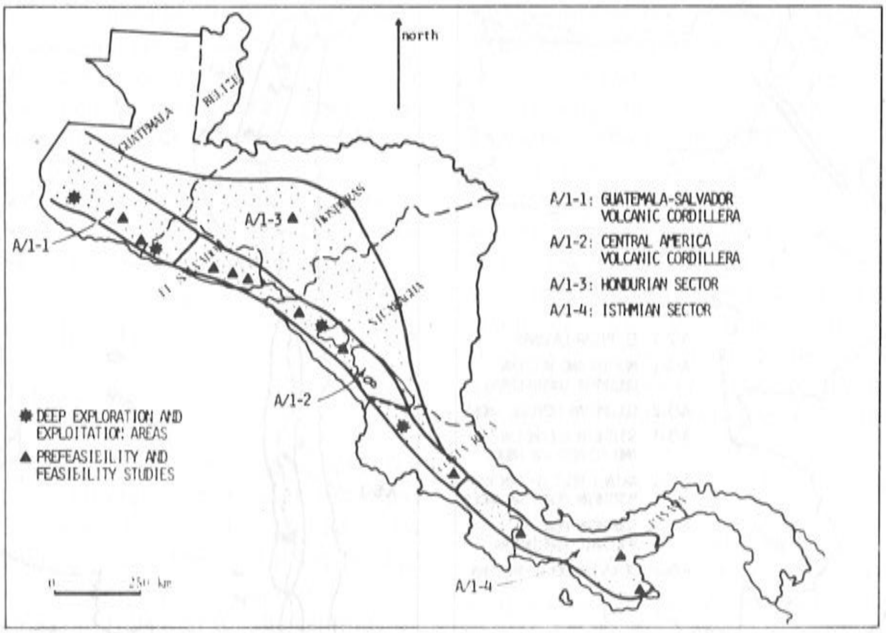

Figure 3a —Preferential sectors within the type "A" geothermal provinces in Central America.

Central and Northern Peruvian Andes. Deep-reaching vertical fault systems and the presence of large intrusive bodies characterize this area, where only one preferential sector (A/4-1) has been established (Fig. 3b). Geothermal resources related to fluid uprising along faults are concentrated in tectonically controlled narrow bands.

Central Andes and Highlands. This very large province, mostly constituted of volcanic rocks, shows a very important concentration of active/recent volcanic activity and widespread fossil or active thermal manifestations. The thermal anomaly is intensive throughout the area and is enhanced locally by magmatic feeding systems of active volcanoes. Four preferential sectors have been recognized (Fig. 3c), mostly on a geographic-morphological basis, given the rather homogeneous geologic character of this province.

Southern Andes. In the Chilean-Argentinian Andes, active geothermal systems, whose existence has already been proved, are preferentially located along the axial belt and in coincidence with the discontinuous recent volcanic centers. Two narrow N-S trending preferential sectors have been defined within this province (Fig. 3c).

METHODOLOGICAL APPROACH FOLLOWED FOR THE RESOURCE ASSESSMENT

The general approach followed for the assessment of the geothermal potential of the region at hand is the "volume method", as described by Muffler & Cataldi (1978). Given the size of the territory considered, however, and taking into account the great variability of local factors, it was necessary to resort to adaptations and simplifications of the above method in order to enable homogeneous estimates.

Geothermal Provinces and Depths Considered

Bearing in mind the large-scale geological characteristics of the various zones, the region in question was subdivided into "provinces," referred to as type A, type B or type C in accordance with a ranking of geothermal interest in descending order. The average estimation depth was set at 3000 m.

The reason this depth was chosen is twofold: firstly, because it is the value normally considered for this kind of estimate; secondly, because in some areas already explored by drilling (i.e. Momotombo in Nicaragua and Berlín in El Salvador) there are evidences of fluid production from layers located below 2000 m. On the other hand, permeable (and hence possible production) layers are likely to exist within 3 km depth in most geothermal areas of the region under consideration.

For reasons of prudence, only the provinces of type A were considered for the estimate; in any case, they are the ones that offer the most immediate perspectives for the discovery of resources to be utilized for practical purposes.

The exclusion from the calculation of the provinces of types B and C, as well as other conservative hypotheses introduced in the calculations (see following paragraphs), thus offers the advantage of obtaining minimum but practically certain estimated values of the resources and reserves for the whole region considered.

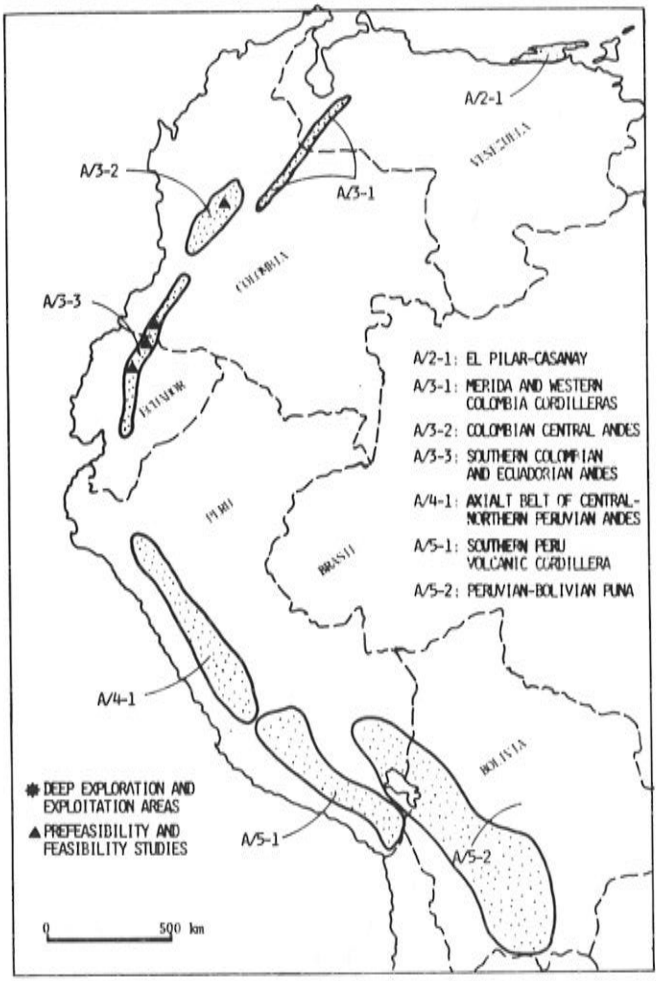

Figure 3b —Preferential sectors within the type "A" geothermal provinces in South America.

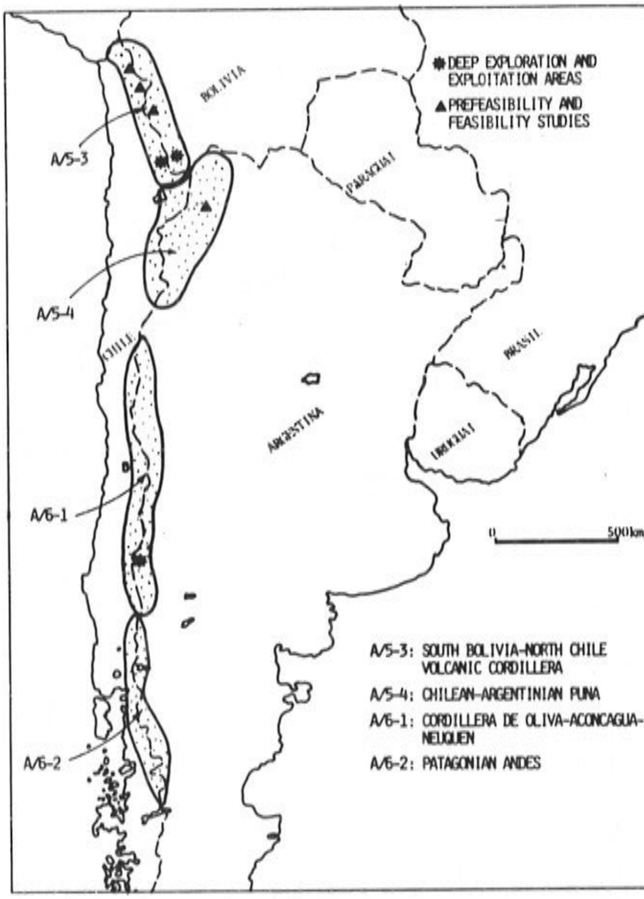

Figure 3c —Preferential sectors within type "A" geothermal provinces in South America.

Calculation of the "Accessible Resource Bases"[1] of the Type A Provinces

For each province, the "Accessible Resource Bases" (ARBs) were calculated on the basis of the equation:

$$H = C_v \cdot V \cdot (T_m - T_o) \quad (1)$$

where H is the heat in place (i.e. the ARBs) to a depth of 3 km, C_v is the specific volumetric heat of the rock plus water in the volume V of crust considered, T_m is the average temperature of the volume V, and T_o is the average annual ambient temperature in the zone.

The temperature T_m was established by assuming, for each province, a value of the temperature gradient, ranging between 70 and 100°C/km, held to be significant, on the average, for the whole area.

[1] By "Accessible Resource Base" is intended all the thermal energy contained in the crust of a certain area down to a chosen depth (in our case 3 km), with reference to the average annual temperature of the area itself (Muffler & Cataldi, 1978).

Calculation of the ARBs for the Preferential Sectors of the Type A Provinces

Since the whole area of every province of type A cannot correspond to a zone of potential interest for geothermal development, "preferential" sectors (where the temperature gradient may reach values of more than 100°C/km) have been singled out. Furthermore, as these sectors include absorption areas, active volcanoes, inaccessible zones, etc., an effort was made to evaluate, for each sector, the aggregate surface area likely to correspond to production areas.

Then, with a view to a separate assessment of the high-temperature resources and of the intermediate-to-low temperature ones, the value of 160°C was set as the thermal level dividing the two groups. This value, indeed, is the temperature level below which (except in particular cases, for example, the Yang Ba Jing field in Tibet — China) the production of electric power by water-dominated systems is no longer economically profitable. In other words, only fluids at T > 160°C were considered utilizable for the production of electric energy.

For the expected production areas of each preferential sector, taking into account the relative temperature gradient (established on the basis of direct data, if available, or considerations of a geological nature), the depth of the 160°C isothermal surface was them determined by hypothesizing, for the sake of simplicity, that the temperature increase occurs from ground level rather than from the "neutral point." This point is in fact generally located at shallow depth, from a few meters to several dozen.

We then proceeded separately to the calculation of the ARBs for the portions of volume at $T > 160°C$ and at $T < 160°C$ by using the following equations:

$$H^h = C_v \cdot V^h \cdot (T_m^h - T_o) \qquad (2a)$$

$$H^l = C_v \cdot V^l \cdot (T_m^l - T_o) \qquad (2b)$$

where h stands for "high temperature" and ℓ stands for "intermediate-to-low temperature." It will be noted that the specific volumetric heat C_v is assumed to be independent of the temperature. The symbols H, V, T_m and T_o have the same meaning as in equation (1).

The conceptual model followed for the estimate of the ARBs in the preferential sectors of the type A provinces is illustrated in Fig. 4.

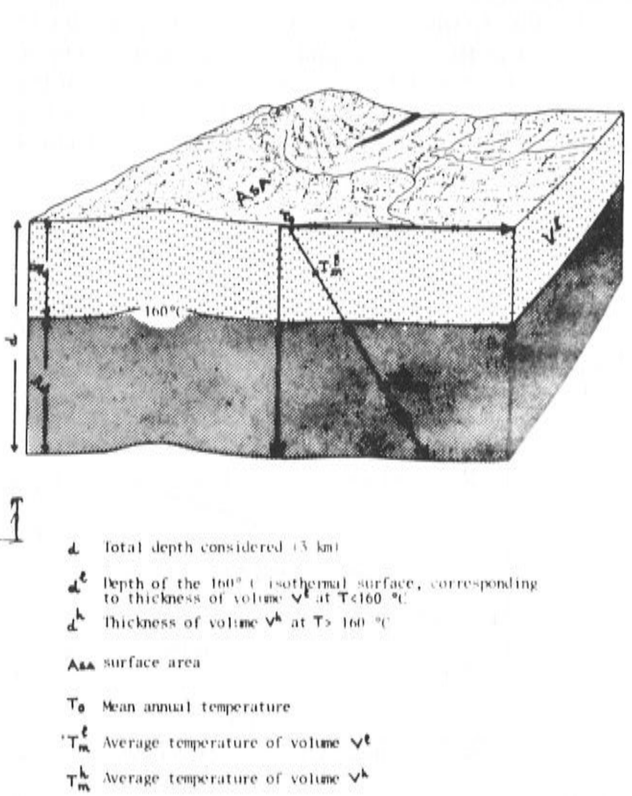

Figure 4 — Conceptual model followed to estimate the intermediate-to-low temperature, and the high temperature "accessible resource base" in the preferential sectors of the type "A" geothermal provinces in Central and Southern America

[2] It should be noted that this is a conservative value. Indeed, some authors, such as Nathenson & Muffler (1975), consider values of around 50% for cases like these.

Calculation of the "Potential Reserves" in the Preferential Sectors of the Type A Provinces

Bearing in mind the relatively large size of the expected production areas in each sector, and the general purpose of this paper, for the estimate of the extractable energy it was considered advisable to adopt a more simplified method than the one suggested by Muffler & Cataldi (1978). That is, it was decided to skip the intermediate step of calculating the "extractable resources" and to estimate directly the "potential reserves" of the various sectors considered by directly applying a recovery factor to the total of the heat in place. This concept is expressed by the general equation:

$$\bar{H} = R \cdot H \qquad (3)$$

where $\bar{H}$ is the extractable energy, H is the heat in place, and R is the recovery factor. The latter was established as described below, separately for the potential reserves at high (> 160°C) and intermediate-to-low temperatures (< 160°C).

In the meaning in which it is used in this paper, the term "potential reserves" thus indicates the thermal energy that is estimated to be extractable in a certain zone within the established depth, leaving aside considerations of an economic nature and any possibilities of water recharge or heat resupply from lower depths.

The recovery factor was established as follows.

— *For the high-temperature potential reserves,* it was first hypothesized that the fraction of porous and permeable reservoir (that is, directly accessible to drill-holes under natural or unstimulated conditions) is approximately one-third (30-35%)[2] of the total volume at $T > 160°C$. Then, on the basis of analogies with the results of similar estimates in well-studied geothermal regions (i.e. Cataldi et al., 1978; U.S.G.S., 1978; U.S.G.S., 1982), and also using other, indirect considerations that take into account the effective porosity, temperature and enthalpy of the fluids, it was further hypothesized that the energy extractable from the fraction of reservoir accessible to the drill-holes may range between 2.5 and 5‰ of the total heat contained therein.

In practice, as a result of the two hypotheses made (30-35% of volume accessible to drill-holes, and 2.5-5‰ of energy extractable from this volume fraction), we have assumed that the recovery factor R^h relative to the whole volume V^h having $T > 160°C$ may vary between 0.75 and 1.5‰.

Thus, by applying equation (3) and taking into account the value of H^h obtained with equation (2a), $\bar{H}^h$, the energy extractable from the volume V^h, proves to be:

$$\bar{H}^h = (0.75 - 1.5‰) \cdot H^h = (0.75 - 1.5‰) \cdot C_v \cdot V^h \cdot (T^h_m - T_o) \quad (3a)$$

For the various sectors considered, the criterion with which the value R^h is set in the range of 0.75 — 1.5‰ is obviously in large part subjective. In practice, however, remaining in this range, but taking into account the different geologic conditions, we assigned the highest values (1.4 — 1.5 ‰) to those sectors in which the 160°C isothermal surface is found at shallower depth, the sector itself is located in correspondence to very active tectonic belts and the effective porosity is consequently higher. On the contrary, the lowest values (≤ 1 ‰) were assigned to those sectors in which, due to scarcity of information, or deeper location of the 160°C isothermal surface, we preferred to remain on the most prudent possible side.

— *For the intermediate-to-low temperature potential reserves,* it was first hypothesized that only fluids from very shallow reservoirs, at T < 160°C, are amenable for direct applications. This, too, is a simplication made for reasons of prudence. In principle, also fluids from reservoirs at T < 160°C could in fact be utilized for direct applications.

Then, supposing that all the reservoirs are of the water-dominated type, independently of every possibility of better heat extraction through natural processes of recharging or sweeping by means of artificial loops between nearby wells, it was assumed that the porous and permeable portion of reservoir (as in the case of volumes at T > 160°C) is around one-third of the volume V^l; however, a value double that assumed for the high-temperature reserves was hypothesized for the recovery factor R^l. This was in consideration of the fact that at shallower depths the fracturation conditions are generally more accentuated everywhere, the degree of compaction of the rocks is lower, and therefore, the porosity is higher with respect to the one existing at greater depths.

Hence, by applying equation (3) and taking into account the value of H^l obtained with equation (2b), $\bar{H}^l$, the energy extratable from the volume V^l, turns out to be:

$$\bar{H}^{-l} = (1.5 - 3‰) \cdot H^l = (1.5 - 3‰) \cdot C_v \cdot V^l \cdot (T^l_m - T_o) \quad (3b)$$

Calculation of the Producible Eletric Energy (E) and the Installable Capacity (C)

First of all it was assumed that all the volume V^h at temperatures > 160°C are part of water-dominated systems and that the fluidis producing according to a process of intergranular flow, with flashing at wellhead. Thus, letting e = f(T) be the conversion factor of the thermal energy into eletric energy, two possible transformation cycles were considered: the single-flash type, and the dual-flash type. The relative values of e = f(T) were obtained by means of the two curves illustrated in Fig. 5.

The eletric energy (E) producible in each of the sectors considered was then obtained using the general equation

$$E = e \cdot \bar{H}^h \quad (4)$$

where $\bar{H}^{-h}$ is the high-temperature potential reserve calculated by means of equation (3a).

In particular, for the two conversion cycles considered (and hence for the two different values of e), the equations are:

$$E_1 = e \cdot \bar{H}^h \quad (4a)$$

$$E_2 = e_2 \cdot \bar{H}^h \quad (4b)$$

In conclusion, the eletric energy producible in the expected production areas of each preferential sector was estimated for two different scenarios that provide for conditions of heat energy transformation as a function of two different utilization technologies of the fluid produced.

Finally, to obtain the eletric capacity installable in the two cases (that is, C_1 and C_2), the value of eletric energy obtained with the equations (4a) and (4b) for the two scenarios above was hypothesized as being distributed uniformly over a span of 25 years, and with a 100% plant capacity factor.

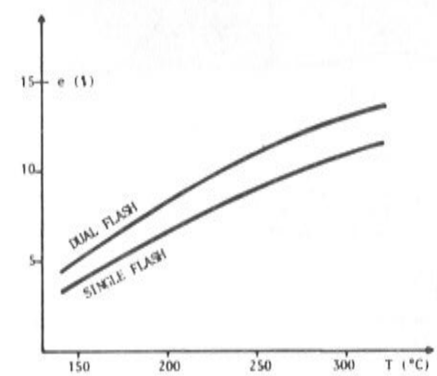

Figure 5 — Electricity conversion factor (e) as a function of temperature of reservoir fluid.
This factor is the ratio (expressed in percent) of electricity generated to the enthalpy of the fluid at the indicated temperature (relative to a reference enthalpy of 15°C saturated water).
The upper curve refers to a "dual flash" power plant, and the lower curve to a "single flash" power plant.
For both type of plant a condensing temperature of 50°C, and a global machinery efficiency have been considered.

APPROXIMATION LIMITS OF DATA USED AND RESULTS OBTAINED

Accessible Resource Bases

The basic data utilized for the estimation of the ARBs of the type A provinces and of the preferential sectors of these provinces are shown in Tables 1 and 2.

With regard to the values used and to the respective limits of approximation, the following considerations can be made.

- The density of the rocks (δ) and the mean specific heat (ϱ) of rock plus water were drawn, for the relative lithotypes, from the bibliography, and can both be held to be approximate to within ±5%. Taking this into account, and also some uncertainty in the evaluation of the deep lithotypes, the values of the specific volumetric heat (C_v) can be considered as approximate to within ±10%.
- The surface area and the total volume of the various provinces considered can be held to be reasonably accurate within the limits of available information.

  For the expected production areas of each preferential sector, however, we are unable to say by how much the approximation limits of the surface area are. Nonetheless, we can say that we have always tried to remain on the conservative side.
- The mean annual temperature of the various provinces or of the different preferential sectors, established on the basis of belts of mean latitude and altitude, was obtained from bibliographical data. The values chosen for each province or sector considered are approximate to within a couple of degrees and must therefore be regarded as reasonably accurate.
- The value of the temperature gradient (G) chosen for each province or expected production area of the preferential sectors is derived (when possible) from temperature measurements made in deep wells, or is based on temperature estimates of chemical geothermometers associated with reasonable hypotheses of reservoir depth. When this was not possible, the value of the gradient was established on the basis of hydrogeological, volcanological and tectonic considerations, and on analogies with known, comparable zones.

  For the sake of simplicity, furthermore, it was assumed that the temperature gradient is linear with depth within the 3 km considered in the estimate. In conclusion, although with some uncertainty in a few cases, it is thought that the gradient values used have an approximation of ±10%.
- This approximation of the temperature gradient affects to a nearly equal extent the approximation of the temperature values T_m^l and T_m^h of the volumes V^l and V^h: however, it may generate in

Table 1 – Data used and results of calculation of the "accessible resource base" to 3 km depth of the type a geothermal provinces in central and south america

NUMBER AND DENOMINATION OF PROVINCE	δ	ρ	Cv	Apa	V	Gpa	T_o	T_m	$T_m - T_o$	ARB TOTAL		ARB PER UNIT AREA
	$\frac{g}{cm^3}$	$\frac{cal}{g\ °C}$	$\frac{cal}{cm^3\ °C}$	$km^2 . 10^3$	$km^3 . 10^3$	$\frac{°C}{km}$	°C	°C	°C	$cal . 10^{21}$	$GWy_t . 10^6_*$	GWy_t/km^2
CENTRAL AMERICA:												
A/1: Central America	2.4	0.24	0.58	50	150	100	20	170	150	13.05	1.73	34.5
SOUTH AMERICA:												
A/2: Venezuelan Coastal Range	2.6	0.22	0.57	40	120	70	25	130	105	7.18	0.95	23.7
A/3: Northern Andes	2.5	0.23	0.57	300	900	80	20	140	120	61.56	8.14	27.1
A/4: Peruvian Northern Central Andes	2.4	0.23	0.55	170	510	70	15	120	105	29.45	3.90	22.9
A/5: Central Andes and Highlands	2.5	0.24	0.60	600	1800	90	15	150	135	145.80	19.29	32.1
A/6: Southern Andes	2.6	0.22	0.57	300	900	70	15	120	105	53.86	7.12	23.7
TOTAL SOUTH AMERICA	–	–	–	1410	4230	–	–	–	–	297.85	39.4	27.9
GRAND TOTAL	–	–	–	1460	4380	–	–	–	–	311	41	28.1

Symbols and Equation of Table 1

δ = Rock density
ρ = Average specific heat of rock plus water
Cv = δ .   = Volumetric specific heat
Apa = Surface area of the type A provinces
V = Total volume
Gpa = Average temperature gradient
T_o = Mean annual temperature
T_m = (d/2 . Apa) → T_o = Average temperature of volume V
ARB = C_v . V . (Tm – To) = Accessible Ressource Base (i.e. heat in place)
* GWy_t = gigawatt-year (thermal) = 10^9 watt-year (thermal) = $7.56 . 10^{15}$ cal

Table 2 – Data used and results of calculations of the "accessible resource base" to 3 km depth of the type a geothermal sectors in Central and South America.

NUMBER AND DENOMINATION OF SECTOR	δ	ρ	Cv	Asa	Gsa	To	d^{ℓ}	d^h	V^{ℓ}	V^h	T_m^{ℓ}	T_m^h	$T_m^{\ell} - T_o$	$T_m^h - T_o$	H^{ℓ} TOTAL		H^{ℓ} PER UNIT AREA	H^h TOTAL		H^h PER UNIT AREA
	$\frac{g}{cm^3}$	$\frac{cal}{g\ ^\circ C}$	$\frac{cal}{cm^3\ ^\circ C}$	km^2	$\frac{^\circ C}{km}$	°C	km	km	km^3	km^3	°C	°C	°C	°C	$cal . 10^{18}$	$GWy_t . 10^8$	$\frac{GWy_t}{km^2}$	$cal . 10^{18}$	$GWy_t . 10^3$	$\frac{GWy_t}{km^2}$
CENTRAL AMERICA:																				
A/1-1: Guatemala-Salvador Volcanic Cordillera	2.4	0.23	0.55	2.200	150	20	0.93	2.07	2.046	4.554	90	315	70	295	78.8	10.4	4.7	738.9		
A/1-2: Central America Volcanic Cordillera	2.3	0.24	0.55	2.500	150	20	0.93	2.07	2.325	5.175	90	315	70	295	89.5	11.8	4.7	839.6	111.1	44.4
A/1-3: Hondurian Sector	2.5	0.23	0.58	600	100	20	1.40	1.60	840	960	90	240	70	220	34.1	4.5	7.5	122.5	16.2	27
A/1-4: Isthmian Sector	2.5	0.24	0.60	800	120	25	1.12	1.88	896	1.504	92	272	67	247	36.	4.8	6.	222.9	29.5	36.9
TOTAL CENTRAL AMERICA	–	–	–	6.100	–	–	–	–	6.107	12.193	–	–	–	–	238.4	31.5	5.2	1.923.9	254.5	41.7
SOUTH AMERICA:																				
A/2-1: El Pilar-Casanay	2.7	0.21	0.57	800	120	25	1.12	1.88	896	1.504	92	272	67	247	34.2	4.5	5.6	211.7	28.	35.
A/3-1: Merida and Western Colombia Cordilleras	2.6	0.23	0.60	600	110	20	1.27	1.73	762	1.038	90	255	70	235	32.	4.2	7.	146.4	19.4	32.3
A/3-2: Colombian Central Andes	2.6	0.21	0.55	1.500	130	15	1.11	1.89	1.665	2.835	87	282	72	267	65.9	8.7	5.8	416.3	55.1	36.7
A/3-3: South Colombian and Ecuadoran Andes	2.5	0.23	0.58	3.800	140	15	1.04	1.96	3.952	7.448	88	298	73	283	167.3	22.1	5.8	1.222.5	161.7	42.6
A/4-1: Axial Belt of Central-Northern Peruvian Andes	2.6	0.22	0.57	800	110	15	1.32	1.68	1.056	1.344	88	253	73	238	43.9	5.8	7.2	182.3	24.1	30.1
A/5-1: Southern Peru Vulcanic Cordilleras	2.6	0.22	0.57	1.600	140	15	1.04	1.96	1.664	3.136	88	298	73	283	69.2	9.2	5.7	505.9	66.9	41.8
A/5-2: Peruvian-Bolivian Puna	2.6	0.23	0.60	2.000	120	10	1.25	1.75	2.500	3.500	85	265	75	255	112.5	14.9	7.4	535.5	70.8	35.4
A/5-3: South Bolivia-North Chile Volcan Cordill.	2.5	0.23	0.58	2.000	150	10	1.	2.	2.000	4.000	85	310	75	300	87.	11.5	5.8	696.	92.1	46.
A/5-4: Chilean-Argentinian Puna	2.6	0.22	0.57	1.600	140	15	1.04	1.96	1.664	3.136	88	298	73	283	69.2	9.2	5.7	505.9	66.9	41.8

Table 2 – continuation. . .

NUMBER AND DENOMINATION OF SECTOR	δ	ρ	Cv	Asa	Gsa	To	d^{ℓ}	d^h	V^{ℓ}	V^h	T_m^{ℓ}	T_m^h	$T_m^{\ell} - T_o$	$T_m^h - T_o$	H^{ℓ} TOTAL	H^{ℓ} TOTAL	H^{ℓ} PER UNIT AREA	H^h TOTAL	H^h TOTAL	H^h PER UNIT AREA
	$\frac{g}{cm^3}$	$\frac{cal}{g\ °C}$	$\frac{cal}{cm^3\ °C}$	km^2	$\frac{°C}{km}$	°C	km	km	km^3	km^3	°C	°C	°C	°C	$cal \cdot 10^{18}$	$GWy_t \cdot 10^8$	$\frac{GWy_t}{km^2}$	$cal \cdot 10^{18}$	$GWy_t \cdot 10^3$	$\frac{GWy_t}{km^2}$
A/6-1: Cordillera de Oliva-Aconcagua-Neuquen	2.5	0.22	0.55	1.500	150	15	0.97	2.03	1.455	3.045	88	313	73	298	58.4	7.7	5.1	499.1	66.	44.
A/6-2: Patagonian Andes	2.6	0.22	0.57	1.000	140	10	1.07	1.93	1.070	1.930	85	295	75	285	45.7	6.	6.	313.5	41.5	41.5
TOTAL SOUTH-AMERICA	–	–	–	17.200	–	–	–	–	18.684	32.916	–	–	–	–	785.3	103.8	6.	5.235.1	692.5	40.3
GRAND TOTAL	–	–	–	23.300	–	–	–	–	24.791	45.109	–	–	–	–	1.023.7	135.3	5.8	7.159.	947.	40.6
															100 . 10^9 PET			700 . 10^9 PET		

Symbols and Equations Table 2

δ = Rock density
ρ = Average specific heat of rock plus water
Cv = δ . ρ = Volumetric specific heat
Asa = Surface area of type a sectors
Gsa = Average temperature gradient
T_o = Mean annual temperature
d = Total depth (3 km)
d^{ℓ} = (160 °C – T_o)/Gsa = depth of the 160 °C isothermal surface
d^h – d – d^{ℓ} = Thickness of volume V^h at T > 160 °C

V^{ℓ} = Asa . d^{δ} = Volume at T < 160 °C
V^h = Asa . d^h = Volume at T > 160°C
$T_m^{\ell} = (d^{\ell}/2 \cdot Gsa) + T_o$ = Average temperature of volume V^{ℓ}
$T_m^h = (d^h/2 + d^{\ell})\,Gsa + T_o$ = Average temperature of volume V^h
$H^{\ell} = Cv \cdot V^{\ell} \cdot (T_m^{\ell} - T_o)$ = Accessible Resource Base (i.e. heat in place) at T < 160 °C
$H^h = Cv \cdot V^h \cdot (T_m^h - T_o)$ = Accessible Resource Base (i.e. heat in place) at T > 160 °C
* GWy_t = gigawatt-year (thermal) = 10^9 watt-year (thermal) = 7.56 . 10^{15} cal

some cases an appreciable error on the depth d^l of the 160°C isothermal surface, and thus on the calculation of the volumes V^l and V^h Consequently, the approximation of the gradient affects the calculation of the ARBs to a greater extent percentagewise for the volumes at T < 160°C.

— In conclusion, taking into account the approximation limits of the various factors, it can be said that the approximation of the values calculated for the total heat in place to 3 km depth of the various type A provinces (see results in Table 1) is of some ±20% at most. On the contrary, where the heat in place of the expected production areas of the preferential sectors is concerned, it can be concluded that the approximation of the calculated values (see results in Table 2) is of the order of a few per cent for the resources at T > 160°C and a maximum or ±25% for the resources at T < 160°C.

An approximation of this magnitude for the high-temperature ARBs should not arouse surprise, but should rather be considered acceptable for a preliminary estimate of the geothermal potential in relatively widespread areas for which detailed data do not always exist. A better approximation of the results of the estimate for the high-temperature ARBs could certainly be obtained on a number of preferential areas where geolithological, porosity and temperature gradient data are available on a sufficiently detailed scale.

Potential Reserves and Producible Electricity

As seen above, for the calculation of the potential reserves of the preferential sectors considered, starting out from the values of H^l and H^h, the relative recovery factors R^l and R^h were applied.

Unfortunately, the evaluation of the geothermal energy recovery factor is a very complex problem which is still open to much debate, and which probably will remain so for a long time, until the case history of calculations based on actual exploitation data is sufficiently large.

For this reason, while we are unable to say by how much, we have preferred to stick to conservative hypotheses and to establish values of R^l and R^h that are probably underestimated.

Consequently, all figures obtained for the extractable energy, both at high and intermediate-to-low temperature (see results of $\overline{H}^l$ and $\overline{H}^h$ in Table 3), must be viewed as minimum figures.

As far as the electric energy that can be produced from the high-temperature potential reserves is concerned, the values of the conversion coefficient (e_1 for the single flash and e_2 for the dual flash) must be considered as practically exact. Hence, the approximation of the values of E_1 and E_2 (see results in Table 3) remains that of $\overline{H}^h$ which, as stated previously, is estimated on the conservative side.

The same applies to the estimated values of C_1 and C_2 (see results in Table 3).

CONSIDERATIONS ON THE RESULTS OF THE ESTIMATES

Accessible Resources Bases (ARBs) of the Type A Provinces

As can be seen in Table 1, the total surface area of these provinces is around 1,460,000 km², of which 50,000 refer to Central America and 1,410,000 to South America. In relation to the respective overall surface areas, it can thus be said that the type A geothermal provinces represent nearly 10% of the territory of Central America and slyghtly less than 8% of that of South America.

Taken together, the ARBs to 3 km depth of the type A geothermal provinces of these two great regions of the world amount to 311 x 10^{21} cal (~ 41 million GWy_t), of which 13 x 10^{21} cal (~ 4.2%) correspond to Central America, and the rest to South America.

In relative terms, however, the situation is a little more favorable for Central America than for South America. Indeed, with an overall mean concentration of 28.1 GWy_t/km^2, the type A provinces of Central America attain a value of 34.6, while the type A provinces of South America display concentration values ranging between a minimum of 22.9 in the Peruvian northern-central Andes, and a maximum of 32.2 GWy_t/km^2 in the central Andes and highlands.

The order of classification that can be deduced from the last column of Table 1 on the basis of ARB values per area unit should, however, be read with a certain degree of caution given the different incidence that the mean temperature gradient values assigned may have had in some cases in relation to the surface areas of the various provinces. For South America, in fact, we cannot exclude that the analysis of the geological situations carried out on large scale maps may have led us to attribute to a type A province portions of territory that an analysis in greater detail of the possible average values of the temperature gradient would have made us assign to the category of the type B provinces.

Aside from this differing concentration of the ARBs, it will be noticed that, although the estimate is limited to a depth of 3 km, the heat in place of the type A provinces alone of Central and South America is a huge amount, corresponding to the energy equivalent of approximately 31,000 billion PET. The significance of this figure, however, must be considered only as an entirely theoretical reference; indeed, as we shall point out in more detail below, only a small part of territory of the type A provinces, and a tiny fraction of their heat in place, may be suitable for geothermal development and heat extraction for practical utilization.

Accessible Resource Bases of the Type A Preferential Sectors

As can be seen in Table 2, the expected production zones included in the 15 preferential sectors singled out in Central and South America cover in the aggregate a

Table 3 – Data used and results of calculations of the "potential reserves" to 3 km depth, electric energy producible and capacity installable in the type a geothermal sectors: of central and south america

NUMBER AND DENOMINATION OF SECTOR	H^{ℓ}	H^{h}	ASA	R^{ℓ}	R^{h}	$\bar{H}^{\ell}$			$\bar{H}^{h}$			T^{h}_{m}	e_1	e_2	E_1		E_2		C_1	C_2
	cal . 10^{18}	cal . 10^{18}	km^2	%	%	TOTAL cal . 10^{15}	TOTAL GWy_t*	PER UNIT AREA MWy_t/km^2	TOTAL cal . 10^{15}	TOTAL GWy_t*	PER UNIT AREA MWy_t/km^2	°C	%	%	TOTAL GWy_e**	PER UNIT AREA MWy_e/km^2	TOTAL GWy_e**	PER UNIT AREA MWy_e/km^2	MW_e	MW_e
CENTRAL AMERICA:																				
A/1-1: Guatemala-Salvador Volcanic Cordillera	78.8	738.9	2.200	3	1.5	236.4	31.3	14.2	1.108.3	146.6	66.6	315	11.5	13.6	16.86	7.7	19.94	9.1	674	798
A/1-2: Central America Volcanic Cordillera	89.5	839.6	2.500	3	1.5	268.5	35.5	14.2	1.259.4	166.6	66.6	315	11.5	13.6	19.16	7.7	22.66	9.1	766	906
A/1-3: Hondurian Sector	34.1	122.5	600	1.6	0.8	54.6	7.2	12.	98.	13.	21.7	240	8.5	10.6	1.11	1.8	1.38	2.3	44	55
A/1-4: Isthmian Sector	36.	222.9	800	2.4	1.2	86.4	11.4	14.3	267.5	35.4	44.2	272	10.	12.1	3.54	4.4	4.28	5.4	142	171
TOTAL CENTRAL AMERICA	238.4	1.923.9	6.100	–	–	645.9	85.4	14.	2.733.2	361.6	59.3	–	–	–	40.67	6.7	48.26	7.9	1.626	1.930
SOUTH AMERICA:																				
A/2-1: El Pilar-Casanay	34.2	211.7	800	2.4	1.2	82.1	10.9	13.6	254.	33.6	42.	272	10.	12.1	3.36	4.2	4.07	5.1	134	163
A/3-1: Merida and Western Colombia Cordilleras	32.	146.4	600	1.8	0.9	57.6	7.6	12.7	131.8	17.4	29.	255	9.3	11.5	1.62	2.7	2.	3.3	65	80
A/3-2: Colombian Central Andes	65.9	416.3	1.500	2.6	1.3	171.3	22.7	15.1	541.2	71.6	47.7	282	10.5	12.4	7.52	5.	8.88	5.9	301	355
A/3-3: South Colombian and Ecuadoran Andes	167.3	1.222.5	3.800	2.8	1.4	468.4	62.	16.3	1.711.5	226.4	59.6	298	11.	13.	24.90	6.6	29.43	7.7	996	1.177
A/4-1: Axial Belt of Central-Northern Peruvian Andes	43.9	182.3	800	1.8	0.9	79.	10.4	13.1	164.1	21.7	27.1	253	9.2	11.4	2.	2.5	2.47	3.1	80	99
A/5-1: Southern Peru Volcanic Cordilleras	69.2	505.9	1.600	2.8	1.4	193.8	25.6	16.	708.3	93.7	58.6	298	11.	13.	10.31	6.4	12.18	7.6	412	487
A/5-2: Peruvian-Bolivian Puna	112.5	535.5	2.000	2.	1.	255.	29.8	14.9	535.5	70.8	35.4	265	9.7	11.8	6.87	3.4	8.35	4.2	275	334
A/5-3: South Bolivia-North Chile Volc. Cordill.	87.	696.	2.000	3.	1.5	261.	34.5.	17.3	1.044.	138.1	69.	310	11.4	13.5	15.74	7.9	18.64	9.3	630	746
A/5-4: Chilean-Argentinian Puna	69.2	505.9	1.600	2.8	1.4	193.8	25.6	16.	708.3	93.7	58.6	298	11.	13.	10.31	6.4	12.18	7.6	412	487

Table 3 – continuation. . .

NUMBER AND DENOMINATION OF SECTOR	H^{ℓ}	H^h	ASA	R^{ℓ}	R^h	$\bar{H}^{\ell}$			$\bar{H}^h$			T^h_m	e_1	e_2	E_1		E_2		C_1	C_2
	cal . 10^{18}	cal . 10^{18}	Km^2	%	%	TOTAL		PER UNIT AREA	TOTAL		PER UNIT AREA	°C	%	%	TOTAL	PER UNIT AREA	TOTAL	PER UNIT AREA	MW$_e$	MW$_e$
						cal . 10^{15}	GWy$_t$*	$\frac{MWy_t}{Km^2}$	cal . 10^{15}	GWy$_t$*	$\frac{MWy_t}{Km^2}$				GWy$_e$**	$\frac{MWy_e}{Km^2}$	GWy$_e$**	$\frac{MWy_e}{Km^2}$		
A/6-1: Cordillera de Oliva-Aconcagua-Neuquen	58.4	499.1	1.500	3.	1.5	175.2	23.2	15.4	748.6	99.	66.	313	11.5	13.6	11.38	7.6	13.46	9.	455	538
A/6-2: Patagonian Andes	45.7	313.5	1.000	2.8	1.4	128.	16.9	16.9	438.9	58.1	58.1	295	10.8	12.9	6.27	6.3	7.49	7.5	251	300
TOTAL SOUTH AMERICA	785.3	5.235.1	17.200	–	–	2.035.2	269.2	15.7	6.986.1	924.1	53.7	–	–	–	100.28	5.8	119.15	6.9	4.011	4.766
GRAND TOTAL	1.023.7	7.159.	23.300	–	–	2.681.1	354.6	15.2	9.719.3	1.285.7	55.2	–	–	–	140.95	6.	167.41	7.2	5.637	6.696
						268.10^6 PET			972.10^6 PET											

Symbols of Table 3:

H^{ℓ} = Accessible Resource Base at T < 160 °C (values reported from Tab. 2)
H^h = Accessible Resource Base at T > 160 °C (values reported from Tab. 2)
Asa = Surface area of type A sectors
R^{ℓ} = Recovery factor of thermal energy for volume V^{ℓ} at T < 160 °C
R^h = Recovery factor of thermal energy for volume V^h at T > 160 °C
$\bar{H}^{\ell}$ = "Potential Reserves" (thermal energy recoverable for volume V^{ℓ}) at T < 160 °C
$\bar{H}^h$ = "Potential Reserves" (thermal energy recoverable for volume V^h) at T > 160 °C
T^h_m = Average temperature of volume V^h at T > 160 °C

$e_1 = f(T^h_m)$ = Conversion factor of thermal energy into electric energy for a "single flash" cycle
$e_2 = f(T^h_m)$ = Conversion factor of thermal energy into electric energy for a "dual flash" cycle
$E_1 = e_1 \bar{H}^h$ = Electric energy producible from "Potencial Reserves", by using the "single flash" cycle
$E_2 = e_2 \bar{H}^h$ = Electric energy producible from "Potential Reserves", by using the "dual flash" cycle
C_1 = Electric capacity corresponding to E_1 for a 25 years production period
C_2 = Electric capacity corresponding to E_2 for a 25 years production period
*GWy$_t$ = gigawatt-year (thermal) = 10^9 watts-year (thermal) = 7.56 . 10^{15} cal
**GWy$_e$ = gigawatt-year (electric) = 10^9 watt-year (electric) = 8.76 . 10^9 kWh (electric)

surface area of about 23,300 km^2. Of these, 6,100 km^2 correspond to the 4 preferential sectors of Central America, and 17,200 km^2 to the 11 analogous sectors of South America. In relation to the total surface areas of these two great regions, it can therefore be stated that the zones of probable geothermal production correspond to little more than 1% of the entire territory of Central America, and to a little less than 1 ‰ of that of South America. It follows that Central America is, on the whole, somewhat better off, from the geothermal standpoint, than South America.

Nevertheless, to make a more homogeneous comparison from this point of view, only portions of the respective territory classified as geothermal provinces of type A should be considered. Following this criterion (see comparative Tables 1 and 2) ratios of surface area between preferential sectors and type A provinces of about 12% for Central America (6,100 out of 50,000 km^2) and 1.2% (17,200 of 1,410,000 km^2) for South America are obtained. In this way, too, it can be evidenced that Central America has, on the whole, a "geothermal vocation" which is much better characterized than that of South America.

In particular, this refers to the high temperature resources (H^h). As is shown in the last column of Table 2, the average heat concentration is almost 42 GWy_t/km^2 in Central America, and slightly over 40 GWy_t/km^2 in South America.

The opposite is true for the moderate-to-low temperature resources (H^l), corresponding to an overall average concentration of a little more than GWy_t/km^2 in Central America as against the slightly more than 6 GWy_t/km^2 in South America.

This different concentration of the two types of resource (H^l and H^h) does not mean that all the preferential sectors of Central America have specific values of H^l that are always lower, and of H^h that are always greater, than the analogous ones of the South America sectors; indeed, where H^h are concerned, in South America, too, we can recognize the existence of two sectors (A/5-1 and A/6-1) which are comparable to the two best sectors (A/1-1 and A/1-2) of Central America. On the contrary, it is precisely in Central America that the sector (A/1-3) with the lowest concentration of H^h is located.

Still with reference to the high temperature resources, the order of classification that can be deduced from the last column of Table 2 must be considered reasonably significant, since it mainly reflects the different value of the temperature gradient attributable to the areas of probable production located within each preferential sector.

With regard to the total value of the heat in place, it can be noted at the bottom of Table 2 that, although estimation is limited only to the preferential sectors of the type A provinces and to a depth of 3 km, huge values are nonetheless obtained: over 1000 x 10^{18} cal (~ 100 billion PET) for the resources at $T < 160°C$, and over 7,000 x 10^{18} cal (~ 700 billion PET) for those at $T > 160°C$. But, as already emphasized in the preceding section for the heat in place in the type A provinces, also the above values must be considered as purely theoretical, since they constitute the "resource base" but certainly not the "potential reserves."

Potential Reserves and Electric Energy of the Type A Preferential Sectors

From a comparison between Tables 2 and 3 it can be inferred that the potential reserves of the sectors considered, whether of moderate-to-low ($\bar{H}^l$) or high ($\bar{H}^h$) temperature, constitute a very small permillage of the resources to 3 km depth.

Taken together, the reserves of type $\bar{H}^l$ amount to nearly 2,700 x 10^{15} cal (approx. 355 GWy_t), of which little more than three-fourths refer to South America and the rest to Central America.

As was done for the heat in place of the type A provinces and of the preferential sectors located in them, it should be stressed for the extractable heat at $T < 160°C$ as well that, even though it represents only a few thousandths of the resources, it still amounts to quite a high value, corresponding to the energy equivalent of almost 268 million tons of oil.

Moreover, it must be said that the concentration of the moderate-to-low potential reserves evidences (see Table 3) values ranging between a minimum of 12 MW_t/km^2 in sector A/1-3 and a maximum of almost 17 MW_t/km^2 in sector A/6-2, with an overall average of slightly more than 15 MW_t/km^2. Taking this last value as a reference, it can be said that the concentration of heat at $T < 160°C$ is higher on average in South America (nearly 16 $MW_t km^2$) than in Central America (approx. 14 MW_t/km^2).

The type $\bar{H}^h$ reserves are considerably greater than those of type $\bar{H}^l$ As a whole, they amount to a little over 9,700 x 10^{15} cal (almost 1,300 GWy_t), for an energy equivalent of about 970 million tons of oil.

The aforesaid total is subdivided as follows: Central America, more than 2,700 x 10^{15} cal (~ 72%).

The concentration of these reserves differs greatly from sector to sector, with a minimum of almost 22 MWy_t/km^2 in sector A/1-3 and a maximum of 69 MWy_t/km^2 in sector A/5-3. The overall average is somewhat more than 55 MWy_t/km^2, but in South America the average is a little under 54 MWy_t/km^2 while in Central America it exceeds, even if just slightly, 59 MWy_t/km^2. It is thus confirmed that, as far as high temperature geothermal energy is concerned, the basis situation in Central America is better, on average, than that of South America.

This conclusion is further supported by the average values of concentration of producible electric energy. Indeed, if reference is made to a fluid utilization by means of the "dual flash" cycle, compared with an overall average of 7.2 MWy_e/km^2, Central America as a whole nearly attains the specific value of 8 MWy_e/km^2, while in South America the value is a little below 7 MWy_e/km^2.

Sector by sector, however, the situation is quite varied. As it happens, the minimum specific value of the producible electric energy (2.3 MWy_e/km^2) is found in Central America (sector A/1-3), where as the maximum values (9 or somewhat more MWy_e/km^2) are found in two sectors of Central America (A/1-1 and A/1-2) and in two sectors (A/53 and A/6-1) of South America.

The same conclusion is reached, except for the lower specific values, if reference is made to the concentration of electric energy producible by means of the "single flash" type cycle.

As for the total of electric energy producible, the values obtained for Central America are somewhat less than 41 and somewhat more than 48 GWy_e for the two utilization cycles "single flash" and "dual flash", respectively. For South America, on the other hand, the corresponding total values are 100 and 119 GWy_e respectively.

The grand total of the two regions together is thus about 141 and 167 GWy_e, depending on whether the "single flash" or "dual flash" conversion cycle is considered. It follows that, of the estimated overall total of electric energy producible in the whole region in question, around 29% corresponds to Central America and 71% to South America.

The total geothermoelectric generating capacity, calculated for a utilization period of 25 years with a 100% plant factor, proves to be approx. 5,600 MW_e for the "single flash" cycle, and some 6,700 MW_e for the "dual flash" cycle.

Of these two different totals, approx. 1,600 and 1,900 MW_e respectively for the two types of cycle considered refer to Central America, while about 4,000 and 4,800 MW_e refer to South America.

The relative percentages (∼ 29% for Central America and 71% for South America) obviously reflect the same values of the electric energy producible in the two regions.

SUMMARY OF THE PRESENT SITUATION OF GEOTHERMAL DEVELOPMENT IN CENTRAL AND SOUTH AMERICA

To give an idea of the current situation with respect to the development perspectives of geothermal energy in Central and South America, as outlined in the preceding sections, a summary is given below of the results obtained and/or of those foresseable in the countries in which activities of research, exploration and exploitation of geothermal resources have been carried out or are in progress.

The data reported for the various countries, listed below in alphabetical order, have been updated until at least 1983 and have been drawn from the literature published as of 1985 or from unpublished documents and personal information in the author's possession. For this reason, aside from the details, it cannot be ruled out that, for a few countries, the research or exploration in some zones may be in a somewhat more advanced stage than is now known to us.

Argentina

The preliminaryt investigations have concerned almost the whole Andes belt and a part of the sub-Andean sectors of the country. Seven large regions of potential interest have been recognized: Puna, the Northern Cordillera, the Central Cordillera, the Southern Cordillera, the Norther sub-Andean Region, the Sierras Pampeanas, and the Southern Mendoza Region.

The large-scale reconnaissance studies of the foregoing regions made it possible to single out some 15 prospect zones:
Jujuy, Santa-Catamarca, Tinogasta, Iglesia, Tupungato, Sosneado, Chosmalal, Neuquém, Chubut, Santa Barbara, Metán, Belén, Famatina, Rio Hondo and Payun Matru.

Detailed reconnaissance studies conducted in some of these zones have led to the identification of the following favorable areas: Tuzgle (in the Jujuy zone), Copahue and Domuyo (in the Chosmalal zone), El Ramal in the Santa Barbara zone.

The pre-feasibility studies have so far mainly regarded the areas of Copahue and Domuyo, and, to a lesser degree, that of Tuzgle.

A feasibility study has recently been started in the Copahue area and 2 wells have already been drilled — both of them productive — to depths of approximately 1400 and 1200 m. The temperature in the reservoir is about 240°C. Envisaged in this area is first of all the installation of a geothermal power unit of a few MW_e, and immediately thereafter the development of the field with the aim of installing at least 50 MW_e. The estimated potential, in terms of electric energy, of the Copahue field is reported to be some 5 GWy_e.

Bolivia

Following preliminary investigations carried out mainly in the Western Cordillera, and in part also in the Cordillera Real, more or less detailed reconnaissance studies concerned the following zones: Laguna Colorada, Laguna Verde, Salar de la Laguna, Salar de Empexa, Volcán Sajama, Volcán Ollague, Laguna Cachi and Quetena, for a total surface area of some 10,000 km².

So far pre-feasibility studies have been carried out only in the areas of Empexa and Laaguna Colorada/Sol de Mañana, both located in the southwestern sector of Bolivia.

In the area of Laguna Colorada/Sol de Mañana and environs — where, moreover, a shallow well producing steam was drilled — a feasibility study has recently begun that includes, among other things, the drilling of at least three deep wells. The estimated temperature in the reservoir, below 500 m, is over 230°C. The main goal of the study is to determine the technical feasibility and the economic viability of installing a geothermal power plant of at least 30 MW_e in the zone; a complementary objective is that of studying possible direct uses of the geothermal heat for the exploitation and processing of some valuable salts deposited in nearby Salar de Unyuni.

Chile

The inventory of the thermal manifestations and the preliminary investigations concerned a surface area of more than 100,000 km², in the provinces of Antofagasta and Tarapaca, both located in the northern part of country.

Some 20 zones of potential interest have been identified: Jurase, Untupuyo, Churiguaya, Surire, Polloquere, Chucmillani, Berenguela, Quitariri, Puchuldiza, Chusmiza, Enquelca, Pampa Lirima, Colpagua, Manina, Pica, Acostán, El Tatio, Alitar, Aguas Calientes, Tilopozo and Tusajto.

In some of the more promising of these zones — that is, El Tatio, Puchuldiza, Surire and Pampa Lirima — detailed reconnaissance and pre-feasibility studies have also been carried out.

Deep exploration and the other activities connected to the feasibility studies seem to have been conducted only in the central part of the areas of El Tatio and Puchuldiza.

At El Tatio, at least 13 wells have been drilled so far, 6 of them of the "slim hole" type (ϕ 4") and the others with ϕ = 8", to depths ranging between a minimum of 600 and a maximum of 1,800 m. The maximum temperature measured in the reservoir (around 1,500 m) is 260°C. The flow rate of the fluid found so far would reportedly allow supply of a 15MW_e power unit; but the potential of the field is probably much greater. Not included in this description are two shallow wells drilled in the 1920s. One of these wells, called "Hurricane", proved to be productive and still is. It produces superheated steam, but at a modest pressure.

At Puchuldiza, 6 wells seem to have been drilled to date (Ø = 8"?), to depths ranging between 450 and 1,150 m. The maximum temperature recorded in the reservoir (around 1,000 m) is 200°C. The estimated geothermoelectric potential of this field, which is thought to cover a surface area of more than 100 km², is believed to be between 120 and 180 MW_e.

Colombia

The reonnaissance studies have been concentrated in the two zones held to be of greatest potential interest, that is, in the middle sector of the Colombian Central Cordillera (zone of the Ruiz Massif), and in the Southern Volcanic Cordillera (Cauca and Narinõ). The research in the latter zone has also evidenced the interest of the sector bordering on Ecuador (area of Tufiño-Chiles), where joint continuation of the investigations is planned in collaboration between Colombia and Ecuador.

Other zones identified by the reconnaissance studies are those of Azufral de Tequeres, Cuñasol, Doña Juana, Galeras, Pucaré, Sotarà and Huila, located in the Southern Cordillera, and that of Paipa, located in the Eastern Cordillera of Colombia. Together these zones cover a surface area of some 10,000 km².

Pre-feasibility studies have been conducted in some preferential areas of the central sector of the country (Ruiz Massif) and have made it possible to concentrate attention for future activities in the areas of Nereidas, Laguna del Otún and Volcán Machín.

Pre-feasibility studies are also in progress in some areas of the southern sector (Chiles-Cerro Negro).

The estimated temperatures of the potential reservoirs in all these areas are generally above 200°C.

Costa Rica

After a general inventory of the areas with major thermal manifestations, attention in the last few years has been concentrated on a part of the Cordillera de Guanacaste, where a study on a zone covering several thousand square kilometers was followed by a pre-feasibility study in the area of the Miravalles and Rincón de la Vieja volcanoes.

The latter study permitted identification of a geothermal field on the southern flank of the Miravalles volcano. For this field the feasibility study relative to a first 55 MW_e generating unit has been completed. The 7 wells drilled thus far (depths ranging between 1,150 and 2,000 m) have confirmed the existence, between 800 and 1,300 m, of a water-dominated reservoir with a temperature of the order of 230-240°C.

The estimated potential of the field is at least 3 GWy_e, and it is already planned to install 110 MW_e.

Aside from the exploration and development activities in the area of Miravalles, in the coming months it is planned to begin a systematic reconnaissance study of the whole coutry, which will be followed by a pre-feasibility study of some preferential areas.

Ecuador

As already mentioned for Colombia, the zone of Chiles-Tufiño-Cerro Negro, located astride the Colombia-Ecuador border, has been studied in the framework of a preliminary geothermal research program carried out in collaboration between the two countries over a zone of some 2,000 km².

The reconnaissance study also regarded other zones of the Ecuadoran Andes sector, which from north to south are: Imbabura-Cayambe, Ilalo-Chalupas, Volcán Chimborazo and Cuenca Azogues, for a total surface area of approximately 9,000 km². The estimated temperatures in the preferential areas of these zones vary between about 150 and 250°C.

The pre-feasibility studies, currently in the initial stage, are for the moment concentrated only in the northern sector of the country (Tufiño), near the Colombian border, and in the zone of Chalupas, not far from Quito.

El Salvador

The reconnaissance studies regarded practically the whole country. The preferential areas identified, and on which prefeasibility studies have already been carried out, are: Ahuachapán-Chipilapa, Berlín, Chinameca and San Vicente, which together cover a surface area of over 2,000 km². The estimated temperature of the reservoir in the most interesting part of these areas ranges between around 200 and 250°C.

Deep exploration and the other activities linked with the feasibility studies have been carried out, or are under way, in all the preferential areas cited.

The area of Ahuachapán, in particular, has been in the development stage since the first half of the 1970s. So far about 30 wells have been drilled in this field (depths ranging between 600 and 1,800 m), some of which are utilized for reinjection of waste water. The temperature of the reservoir, generally located between about 600 and 900 m depth, is some 230-240°C. The power plant currently in operation at Ahuachapán, which is the first geothermal power plant in all of Central and South America, has a total capacity of 95 MW_e distributed over three units: two of the "single flash" type, 30 MW_e each, and a 35 MW_e one of the "dual flash" type.

In the nearby area of Chipilapa only one well has been drilled so far (depth about 900 m); but for the coming years the development of this area and the installation of a 30 MW_e power plant is planned.

At Berlín, 6 wells have been drilled so far, to depths ranging between some 1,400 and 2,080 m; the maximum measured temperature is 300°C; some wells produce steam. It is planned to install a 55 MW_e unit of the "dual flash" type in this area.

Deep exploration has begun also in the areas of Chinameca (2 wells) and San Vicente (1 well).

Geothermal exploration in the areas of Berlín, Chinameca and San Vicente is currently suspend for nontechnical reasons. For the time being, it seems that exploitation, development and exploration activities continue in the field of Ahuachapán and in the nearby area of Chipilapa; moreover, a pre-feasibility study is envisaged in the area of Coatepeque.

Guatemala

A preliminary reconnaissance study, which regarded practically the whole volcanic cordillera of the country, made it possible to identify over 20 zones of potential interest: Tajamulca-Tacanà, San Marcos, Zuníl, La Momoria, Totonicapán, Mostenango, Quichè, Sacapulas-Zacualpa, Ahitlean, Chimaltenango, Amatitlán, Ixpaco, Sanarate, Ayarza, Moyuta, Monjas, Ipala, Zacapa, Camatau, Grandos, Esquipulas, Asunciòn, Mita, Polochïc.

However, detailed studies have so far only been carried out in some of the above zones, namely: Amatitlan, Ixpaco, Moyuta, San Marcos and Zuníl.

The pre-feasibility studies concerned the areas of Amatitlán, Moyuta and Zunil, for a total surface area of over 200 km². In these three areas, the estimated temperature of the reservoir ranges between 180 and 280°C.

At Moyuta, two wells of reduced diameter have also been drilled to depths of between some 800 and 1,000 m; but they did not permit definition of the real interest of the zone. Indeed, the maximum temperature measured (114°C) is only slightly higher than that of the fumaroles existing in the environs.

The situation in the area of Zuníl is quite different. Here 5 wells out of 6 (depths between approximately 810 and 1,310 m) turned out to be productive. The maximum temperature encountered in the reservoir, around 1,300 m, is 287°C. It is planned to install a first geothermoelectric unit of 15 MW_e in this area in the near future.

Honduras

The reconnaissance studies carried out in various sectors of the country have led to the identification of three groups of zones of potential interest. The first group, with an estimated reservoir temperature of between 150 and 200°C, includes: San Ignacio, Platanares, Azacualpa, El Olingo and Sambo Creek; the second group, with reservoir temperatures of around 150°C, includes: Pavana, Trinidad, El Olivar, San Rafael, Limones and Los Almendros; the third group, with reservoir temperatures ranging between 100 and 150°C, includes Humaya, Aguacatro, Quebrada Grande, Agua Caliente and La Plazuela.

At present, a systematic pre-feasibility study is in progress which takes in the whole central sector of the country, for a total surface area of about 10,000 km².

Nicaragua

The reconnaissance studies concerned almost all the most promising western sector of the country, within and astride the so-called "Central Depression." They led to the selection of the following zones of preferential interest: Volcán Coseguina, San Cristobal-Casita, San Jacinto-El Hoyo-Momotombo, Managua-Chiltepe, Masaya-Tipitapa, Apoyo-Mombacho, Isla Zapatera, Isla Ometepe and Las Lajas.

Among these, considered of priority interest, and thus investigated by pre-feasibility studies, were the zones of Volcán Momotombo Sud, El Hoyo-San Jacinto and Granada-Masaya, which together cover an area of more than 3,000 km².

In the area of Momotombo Sud, deep exploration was began more than 10 years ago and was followed by the field development and exploitation. So far, at least 35 wells have been drilled, to depths ranging between a minimum of 300 and a maximum of 2,250 m. In this field two main productive layers seem to exists, one located at about 1,000 m and another, deeper one. The temperature of the first productive layer is around 230°C; but at about 2,000-2,200 m values of the order of 325°C have been recorded.

In this field, a 35 MW_e unit of the "single flash" type is already in commercial operation; however, since the potential of the field, in terms of producible electric energy, is at least 2.5 GWy_e, it is planned to double the present installed capacity in the near future.

Panama

The general reconnaissance study of the country allowed the identification of the following zones of potential interest: El Valle, Chitra-Calobre and Baru-Colorado (Cerro Pando).

In these three zones pre-feasibility studies are now in progress. Chemical geothermometers on some thermal springs provided rather modest temperatures (100-150°C); however, additional investigations are under way to verify the significance of these values (which are probably affected by mixing with cold water), and to obtain other data on the depth of the reservoir and the hydrogeological situation, before deciding where to pass to the subsequent feasibility study.

Peru

On the basis of preliminary geological investigations, including reconnaissance of the thermal manifestations, 6 regions of potential interest were identified which together cover a surface area of approximately 200,000 km². From NW to SE, these regions are: Cajamarca-La Libertad, Callaján de Huaylas, Churín, the Central Region, the Southern Volcanic Cordillera, and Puno-Cuzco.

So far, more or less detailed reconnaissance studies have regarded the Southern Volcanic Cordillera and the Northern Cordillera. In the latter region, however, there are no traces of volcanic activity. On the basis of these studies, some areas of potential interest, located in the Southern Volcanic Cordillera (Tutupaca, Calacoa, Salinas, etc.) and the North-western Andean sector (Cajamarca, etc.) were identified.

Venezuela

On the basis of general geological studies and the inventory of the manifestations, the zones of potential interest of the country have been singled out. They are grouped into the following 5 regions: Eastern Province (Cordillera de Merida), Falcón Sub-region, Central Province, Northwestern Province (including the Sub-region of Nueva Esparta), and the Bolivar Sub-region.

More or less detailed reconnaissance studies have been carried out only in the zones of Barcelona Cumana (located in the north of the country in the Central Province) and El Pilar-Casanay (located in the North-western Province), for a total of nearly 5,000 km². In the areas of these zones with the best prospects, the reservoir temperature estimated on the basis of chemical geothermometers seems to be above 200°C.

Aside from the more in-depth geochemical and isotopic studies now in progress on some manifestations located in the two zones mentioned above, it does not appear that systematic pre-feasibility studies have been carried out, or are planned, in this country.

Others Countries

As far as the other countries of Central and South America are concerned, namely Belize, Brazil, Guiana, French Guiana, Paraguay, Surinam and Uruguay, general investigations or reconnaissance and pre-feasibility studies specifically directed at applied geothermal research do not seem to have been (or are being) carried out.

Only in the case of Brazil do we have knowledge of a general study by Hamza & Eston (1981), in which the large-scale geothermal situation of the various sectors of the country are discussed. This study evidences why the prospects of the country for the discovery of fluids at T > 150°C within depths now economically accessible are rather scarce. It concludes that the only possibilities of practical interest remain in the field of the direct applications of geothermal heat, and perhaps also in the framework of a combined exploitation of geopressurized systems. Such systems, in fact, are likely to exist along the continental platform and perhaps also in the sector of the country geologically corresponding to the so-called "Brazilian shield".

Apart from the differences of a geological nature, this conclusion can probably be made also for the other countries of the South American continent mentioned above (Guiana, French Guiana, Paraguay, Surinam and Uruguay), as well as Belize in Central America. Indeed, all these countries fall within crustal sectors where the heat flow stays at normal values or is even lower than the average value for the earth.

FINAL CONSIDERATIONS AND CONCLUSIONS

Even though, as already stressed above, the estimates we have made of the potential geothermal reserves of Central and South America are to be considered rather conservative, they are nonetheless sufficient to define a general but quantitative reference framework usefull for delineating the minimum levels of development that geothermal energy could have in Central and South America.

For this purpose it is necessary to distinguish two cases: that of moderate-to-low temperature reserves, which are suitable only for direct applications, and that of the high temperature reserves, which can be utilized for the production of electric power.

In the first case, the 355 GWy_t estimated for the preferential sectors only of the type A provinces, although "geologically available," can hardly constitute a target of practical utilization for the whole of the region considered. This is basically because the market demand for moderate-to-low temperature geothermal heat in the region in question (as in the rest of the world, too) is rather low for a series of reasons (economic, climatic, technical, etc.), examination of which lies outside the objetctives of this paper.

However, to give an idea from this point of view, it is sufficient to remember that in 1985 the world total of direct applications (including uses for balneology) was of the order of just 12,000 MW_t (Cataldi & Sommarugan, 1986), a value corresponding to little more than 3% of the above mentioned 355 GWy_t "geological available" in the preferential sectors alone of Central and South America.

Obviously, this percentage would be considerably lower if our estimate would have also included the moderate-to-low temperature reserves of the type B and C provinces, and if one were to compare the present world total of direct uses with the total heat at $T < 160°C$ available within 3 km depth in all of Central and South America.

The fact that we have not estimated the potential reserves at $T < 160°C$ in the type B and C provinces does not mean, however, that these reserves do not exist, much less that in some areas of the type B and C provinces direct utilization is precluded. We only wish to stress that, even limiting consideration (and in conservative terms) to the preferential sectors alone of type A provinces, the moderate-to-low temperature heat proves to be so great that it is difficult to imagine, even in the long run, its integral development for practical purposes.

In other words, as compared to a great availability of the source, today there lacks an adequately strong demand for moderate-to-low temperature geothermal heat.

The situation with respect to the development prospects of high-temperature potential reserves is very different, and much more attractive.

It has been seen that these reserves, in the two regions considered together, amount to approximately 1,300 GWy_t and that they enable generation of 141 or 167 GWy_e respectively, depending on whether the "single flash" or "dual flash" conversion cycle is used (for a period of 25 years and with a full plant capacity factor). The installable geothermoelectric capacity in the two cases is of the order of 5,600 MW_e for the "single flash" cycle and 6,700 MW_e for the "dual flash" cycle.

A capacity of this order of magnitude must be considered amply compatible with the increasing electric production requirements in the countries of marked "geothermal vocation" of Central and South America[1]. Indeed, taking into account that the total electric capacity in these countries in December 1983 was almost 27,000 MW_e (of which about 3,000 for the six countries of Central America and somewhat less than 24,000 for the seven countries of South America), with an annual average rate of increase of 4.5-5%, it is reasonable to estimate that the abovesaid total capacity can be doubled before the year 2000 and tripled within about 25 years from now. In general terms, therefore, one should conclude that in Central and South America there are no hindrances for geothermal development deriving from an insufficient future demand for electric energy.

On the other hand, it is unreasonable to think that the potential geothermoelectric capacity of 5600-6700 MW_e estimated by us can all be installed within about 25 years from today. It is to be presumed, instead, that for a full development of this capacity, at least 35-40 years may be necessary, unless a marked acceleration of geothermal development occurs.

What then, is the contribution that can be expected from geothermal energy, in terms of electric production, in the group of countries that partly fall within the type A provinces, and which we have said to have a "geothermal vocation"?

In 1983 the situation was as follows: in Central America 130 MW geothermoelectric was installed, of a total electric capacity of about 3,000 MW_e ($\sim$ 4.3%); in terms of production, however, geothermoelectric energy was approximately 7% of the total electric generation. In South America, on the other hand, in 1983 no geothermal power plant had yet been installed; the overall ratio of geothermal vs. total electric energy that resulted for the two regions together in that year was thus about 0.5% both in terms of installed capacity and electric generation.

A forecast for the future would require a detailed analysis of the increases of electric capacity and of production foreseeable for each of the countries having a "geothermal vocation". Buth since this lies beyond the scope of this paper, let us limit ourselves to saying that our forecast is that by the year 2,000 the geothermal contribution could be about 6-7% in Central America and no more than 1% in South America. In the first decade of the next century, however, the situation is likely to improve, reaching almost 10% in Central America and 2% in South America.

In order that these forecasts prove correct, however, it is indispensable to proceed swiftly on the programs already begun. On the other hand, to obtain better projections, new initiatives are necessary aimed at implementing future geothermal development programs in accordance with a clear distinction between the research activities for the identification of prospect areas and the deep exploration/exploitation activities aimed at developing a geothermal field.

The first group of activities (which can be termed under the heading "research project") generally has a modest cost and is basically similar in character for all countries. It includes regional or semi-detailed investigations (reconnaissance study) and detailed prospectings on particular areas (prefeasibility study), aimed at the objectives proper to geothermics: geological, volcanological and tectonic investigations, identification and hydrogeological study of the

[1] Bearing in mind what was said in the preceding sections, and considering the results of the estimates of the high-temperature potential reserves, the following countries can be considered to have a "geothermal vocation": Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama in Central America; Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela in South America.

manifestations, geochemical and isotopic analyses, determinations of the temperature gradient and of the heat flow, geophysical prospectings on various scales, etc.

All these activities should be carried out in a coordinated manner in each single country and where possible, for the border zones, in the framework of interregional initiatives. However, although being a "research project", they should always be considered to have the character of an industrial pre-investment, and as such should lead no only to the identification and geological characterization of the most promising areas, but also to the assessment of their potential reserves before the subsequent and more costly phase of deep exploration is started. Indeed, since the cost of a "research project" (reconnaissance study plus prefeasibility study) is always very modest in relation to the drilling cost of a geothermal field, it appears necessary in every case to try to obtain an estimated value of the geothermoelectric potential of the prospect areas in order to provide the decision-makers with one of the factors needed to estimate the cost/benefit ratio of the geothermal development in a given area.

The second group of activities (which could be termed "exploration and development project") is specific to each of the prospect areas identified and characterized by a "research project". In general, however, it can be said that an "exploration and development project" regards the organic, interconnected implementation of all those activities that, although subdivided into homogeneous blocks and stages (feasibility study, experimentation, exploitation, etc.), entail considerable costs, and in any case have the character of a sizeable industrial investment.

From the latter viewpoint, we are fully aware of the difficulties inherent in finding the necessary investment capital, as well as of other general or specific problems that hinder the takeoff of geothermal development in numerous countries of Central and South America. But this is a question that lies outside the scope of this paper.

We should like to conclude by emphasizing once again that, although estimated in conservative terms, the potential high-temperature reserves of Central and South America are such as to merit careful consideration both from the standpoint of more in-depth geoscientific investigations and from that of the setting up, in the various countries having a "geothermal vocation", of programs to develop and exploit this nonconventional but important source of energy.

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