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# ASSESSMENT OF SELECTED NEW GEOTHERMAL SITES IN EUROPE

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## ABSTRACT

European geothermal activity has been well established in Italy (a member of the European Community) - high enthalpy sources, 450 MWe on line or under construction ; and Iceland (not a member of the European Community) - large scale, low enthalpy, direct utilisation. In the recent past, several new sites have been under intense investigation and development.

These include the Paris and Aquitaine Basins in France, the Milos and Nisyros Islands and Macedonia in Greece, the Latera reservoir in Central Italy, the Central sedimentary area of Spain and the hot dry rock prospects in Cornwall, United Kingdom.

The ultimate purpose of the European Community and the research and developement efforts of the member states is to recover 50 million tons of oil equivalent (T.O.E.) through various forms of geothermal energy, amounting to 5% of the total energy consumption and savings of $10 million in import reductions at current oil prices.

Europe is a continent containing most types of geothermal systems, such as geopressured, hot dry rocks and high and low enthalpy resources. This paper presents the general European geology, emphasizing those episodes that were essential in the creation of geothermal resources. Each individual new site is then examined including its geology, a description of the resource type and the outcome of the investigations to-date. Finally, the economics of development are reviewed taking into account the logistics. local markets and general economic feasibility of power generation and/or direct utilisation.

Conclusions are drawn on the desirability and economic attractiveness of new geothermal developments.

## INTRODUCTION

The geologic structure of Europe and consequently its geothermal potential are dictated by the geodynamics of the Eurasian plate. Figure 1 from Sommaruga (1981) and Ungemach (1982) depicts the distribution of European geothermal provinces as they could be interpreted using this rationale.

In general, Western Europe is an area of old and rigid continental crust. It displays crystalline massifs such as the Armorican. Cornwall, Finnoscandinavian, Castillian Meseta, Corsican - Sardinian, Rhodopian and Bohemian massifs. There are a number of sedimentary fills in intracratonic and foredeep basin:; such the Paris and Aquitaine basins in France, Wessex, East Yorkshire and Northern Ireland in the United Kingdom, the Danish, North German, Holland, Thrace - Macedonia in Greece, the Alpine and Pyrrenean basins and the Po Valley in

Continental rifting has formed large graben systems in France and Germany such as the Rhine graben, the Limagne and the Rhone rift valley in France, the Campidano graben in Sardenia and the Eastern Spanish coastal grabens.

A younger crust stretches over the Mediteranean area resulting from the collision of the Eurasian and African plates. This is manifested in the seismicity zones and recent volcanism of the Central and Southwestern Italy and Eastern and Southeastern Greece. The most striking features with obvious geothermal implications are the Eolian and Aegean active volcanic island arcs which include Milos, Nisyros and Santorini in Greece and Vulcano and Lipari in Italy.

The description above has an obvious consequence in the lopsided distribution of geothermal energy resources in Europe. While most of Northern and Central Europe is characterized by low to normal heat flows and low grade geothermal deposits, South and Southeastern Europe and especialy the closing Mediteranean area exhibit high heat flow and extensive, high enthalpy geothermal systems. Historically, the major European geothermal energy developement has been in Tuscany in Central Italy where power production started in 1904. Since then, several reservoirs have been discovered and brought on line with approximately 460 MWe in production or under construction.

The main use of geothermal energy in Iceland is low-temperature direct utilisation which was initiated in Reykjavik in 1930. About 70% of space heating in that country derives from geothermal energy. More than three dozen district heating systems exist of which about two thirds are public ant the rest are privately owned and operated.

More recently, in the 1970's. a massive effort for direct utilisation of low grade heat brines has been undertaken in the Paris urban and suburban areas tapping the Dogger carbonate reservoir which extends for approximately 10,000 sq.km. As of late 1984, more than 100,000 homes are geothermaly heated using a retroffiting scheme.

In the late 1960's, exploration of Greek geothermal resources revealed several promising sites. Subsequent drilling, first on Milos and then on Nisyros identified high enthalpy and extremely high temperature resources, capable of sustaining large output geothermal power generation. Other geothermal prospects are presently under investigation in the island of Lesbos and in Macedonia.

In Spain, geothermal exploration has identified hot water deposits in the Madrid area, capable of supplying space heating. In the quaternary graoen of El Valle. South of Barcelona, a medium enthalpy resource. (ca. 120°C at 1500m) has been discovered.

Finally, in the United Kingdom experiments for geothermal utilization have been conducted in the extensive hot dry rock formations in Cornwall.

producer wells completed at a distance of *300* m with the producing well at a bottom-hole temperature of 80°C.

## UNITED KINGDOM

Geothermal resources at temperatures, depths and reservoir performance ranging from 40 to 80°C, 1500 to 3000 m depth and 5 to 20 darcy-meters are attributed to the sedimentary units of mesozoic and paleozoic age shown in Figure 2.

Two wildcat wells drilled in the early 1980's in the Wessex and North Ireland basins have evidenced geothermal deposits of commercial interest in Triassic sandstones at Southampton (BHT : 74°C, TD : 1500m, kh : 5dm) and Larne (BHT : 40°C, TD : 1400m, kh 12dm). A third exploration hole is to be drilled in late 1984 near Grimsby in the East Yorkshire basin and is intended to exploit a peraotriassic sandstone aquifer.
An assessment of the UK geothermal potential carried out by Gale and Rollin (1984) led to a resource and reserve estimate. The amount of heat stored at depths less than 7km and temperatures above 10°C was estimated at 85 $10^6$ TWh (thermal). However identified resources and recoverable reserves of low grade geothermal heat can only be considered in those sedimentary basins mentioned above.

Regardless of utilisation opportunities and narket conditions the heat recoverable from mesozoic and paleozoic aquifers has been estimated at 4 to 20 $10^3$ TWh depending upon the resource recovery scheme involving either a single production hole or a combined production-reinjection well couplet, as practised in the Paris Basin. The first estimate corresponds to a single well and a 30°C rejection temperature. Should the resource be tapped via a couplet and the reinjection temperature be depleted to 10°C by means of heat pumps this figure could be multiplied by a factor of five.

It can be seen in Table 1 that, according to the present exploration status, more than 40% of the identified resources in the U.K. are in the Sherwood sandstones (lower Triassic, upper Permian) in the East Yorkshire and Lincolnshire basins. When contemplating the actual heating market opportunities the situation is not favorable with at least five to ten candidate geothermal districts. At depths greater than 3km higher temperatures can be sought but there is litttle probability that permeable water bearing rocks would be found because of either tight basement rocks or compacted sediments.

This analysis explains why the HDR concept of heat mining has aroused considerable interest in Britain. Hot dry rock experiments are conducted at the Rosemanowes quarry site in Cornwall at a depth of 2200m. The idea is to stimulate large volumes of jointed granite by reactivating natural fractures via explosive stimulation and hydraulic pressurization. Unfocused explosives fired below the plastic limit are assumed to develop a near wellbore systen of radially oriented self-propped fractures. The fractures provide access to the natural joints by repetitive massive hydraulic pressurization and venting cycles.

The following conclusions have been drawn from early loop-circulation tests :

1- The hot dry rock loop acts as a large volumetric diffusive system between two poorly connected, but with high productivity and injectivity wells. There is no evidence of a highly conductive fracture system joining the wells.

2 - Over 300.000 $m^3$ have been injected in the reservoir and less than 100.000 $m^3$ have been recovered thus far.

3 - The system can be circulated at 30 lit/sec (240,000 PPH) below 10 MPa (145 psi) wellhead pressure but at the expense of severe fluid losses in the fractured medium away from the recovery well.

4 - Because of stress and rock strength anisotropy which is a distinct feature of basement rocks, shearing takes precedence over tension in fracture propagation. As a result, fractures grew downwards instead of the expected upward trend. However, shearing triggered an intense microseismic activity allowing reservoir evaluation from the clustering of the microseismic events.

Although pressure records tend to indicate natural fracture reopening, reservoir growth has proceeded perpendicular to the minimum horizontal stress and not along a known joint direction. Thus it is assumed that connections consist of a set of reactivated joints contained by in-situ stresses.

There is evidence from seismo-acoustic emission and seismic event mapping, hydraulic, thermal and tracer testing, of a large stimulated volume of about 1 $km^3$, exhibiting a rock-to-fluid contact area of at least 1 $km^2$. However, the heat transfer area is considerably less as described by Ungemach (1983) and Batchelor (1983). There is no indication of channelling or well short-circuiting in the Cornwall experiments.

The next stage of the project will consist of drilling a third well at a target depth of 3,000 m to intersect the seismically active structure below the two wells and therefore attempt to exploit the developed fractured zone with reduced fluid losses.

In the United Kingdom, considering the low cost of natural gas and coal and the high cost of fuel oil, geothermal energy can compete only in areas where the load factor is above 70% and where no reinjection wells are required. Natural gas-generated energy (assuming 70% boiler efficiency) is estimated at 2.2 ¢ (U.S.)/KWh while in the case of fuel oil and coal the cost are 3.3 ¢ (U.S.)/KWh and 1.2. ¢ (U.S)/KWh respectively (Harrison, 1984).

Assuming that the figures presently established in Northen France could be applicable to U.K. the unit costs of direct geothermal utilization would be between 1.9 ¢/KWh and 2.6. ¢/KWh depending on fluid temperature and local conditions. These costs are more attractive when compared to those of fuel oil but are less attrative when compared to coal and perhaps, in certain instances, to natural gas.

## GREECE

The geothermal activity in GREECE has been primarely focused on islands of the active Aegean volcanic arc (Figure 3).

Five deep wells have been drilled on Milos, identifying a high-temperature, high-enthalpy geothermal reservoir. Two of the wells (MA-1 and 4MZ-1) were drilled in 1975-76. The three other wells (M-1, M-2 and M-3), drilled in 1980-82, all proved productive.

Total flow rate from the five wells is in excess of 350 tons/hr (at 12 kg/cm$^2$) with a steam flow rate in excess of 150 tons/hr (at 10 kg/cm$^2$). This would result in an electric output of a condensing power plant of approximately 17 MWe. The Greek governement has already awarded a contract for a 2.5 MWe pilot plant while an extensive feasibility study and a drilling program for 5 additional wells is presently in the formative stage.

Economides et al. (1983) have estimated that the Milos reservoir contains at least 8.2 x 10$^{11}$ kg, capable of driving a 60 MWe plant for over 85 years.

In 1982-1983 two exploratory wells were drilled in the Nisyros Caldera at the Eastern edge of the Aegean Volcanic Arc. Both wells indicated an extremely high temperature resource. The first well, Nisyros-1 (TD = 1.800 m, BHT = 350°C), although partially damaged during testing, produced a total flow rate of 12 tons/hr (at 10 kg/cm$^2$) with a vapor quality of 85%. The second hole Nisyros-2 (TD = 1.550 m, BHT = 315°C) was sucessfully completed and yielded 63.3 tons/hr (10 kg/cm$^2$) of two phase fluid with a vapor quality of 48% (noncondensable gas content 3% wt). A small geothermal power plant rated at 3 MWe is scheduled for 1988.

Including the larger islands of Crete and Rhodes the electric energy generation (as of 1982) in the Aegean area utilised 78.0% fuel oil, 21% diesel and 0.6% gas. Submarine cables are presently linking certain islands. The total energy consumption, in 1982 was 1038 GWh amounting to $ 2.34 million of which almost 60% were attributed to fuel costs. The average generating costs were 5.5 ¢ (US)/KWh with a high of 36.3 ¢ (U.S)/KWh at Meghisti to a low of 3.7 ¢ (U.S.)/KWh at Lesbos. (Source : Special Programme on Energy for Regional Development of the Greek Islands 1984 - 1988, Report submitted to E.E.C., 1984).

In the same report the Public Power Corporation of Greece has estimated the initial costs for the development installation and distribution of a 60 MWe plant on Milos at $26 million while the costs for a 3 MWe plant on Nisyros were estimated at 56.2 million. These figures (if in fact realized) would result in an extremely attractive geothermal power production, significally better than the present hydrocarbon-based power generation.

Several other prospects, subject though to higher exploration risks, are presently being investigated in the Aegean Sea in the Islands of Santorini and Lesbos and on the mainland at Platystomon and Loutraki-Sousaki near Athens and in Northen Greece in Macedonia and Thrace. A promising resource has been discovered recently in Macedonia at Nigrita and Xanthi. It consists of shallow depth (200 to 500 m) low temperature (46 - 60°C) $CO_2$ rich aquifers trapped along the border faults of young and distensive graben structures. This low cost heat is capable for direct use and in particular for agricultural applications. A project for green house heating has been commissioned in Xanthi.

**SPAIN**

Albert - Beltran and Banda (1984) have subdivided the geothermal resources of mainland Spain into two main provinces (Figure 4) :

(a) Central Spain, which is an area of old and relatively stable continental crust with normal temperature gradients. Geothermal objectives are concentrated on the four major sedimentary units - Ebro, Duero, Tagus and Cuadalquivir basins which cover an area of approximately 100,000 sq km$^2$. Temperatures of 60 to 100°C may be encountered at depthes above 1,500 m in either tertiary or mesozoic formations.

(b) Eastern and Southeastern Spain which include coastal aquifers, hydrothermal springs and structures along the Mediterranean sea line and in parts of the Celtiberian chain and Betic Cordiliera.

Geothermal exploration started in Spain in the late 1970's and concentrated on four main targets : in mainland Spain at Murcia, Burgos and Madrid and in the Canary Island of Lanzarote. An exploratory hole is being drilled at El Valle, South of Barcelona in a distensive quaternary graben structure.

There are strong indications that a medium enthalpy resource at ca. 130°C might exist at depths of 1,500 m to 2,000 m.

Commercial development includes a mature project at San Sebastian de los Reyes in the Madrid suburbs with a target to heat 4000 dwellings using a geothermal couplet. A first well drilled at 1,800 m (TD = 1800 m, BHT = 80°C, production = 200 m$^3$/h) has identified a productive sandstone aquifer. The decision to drill the reinjection well was postponed until suitable design features for safe injection at high flow rates are defined.

FRANCE

The main geothermal provinces under French jurisdiction are, in the Paris Basin, the Aquitaine Basin (Ungemach, 1984) and the high enthalpy resources of Bouillante (Guadeloupe) in the West Indies. (Jaud and Lamethe, 1984).

In the Paris Basin (Figure 5) an established, presently exploited formation, is the Dogger carbonate reservoir which extends to as much as 10,000 sq.km encompassing much of the Paris metropolitan area. The depth of the producing horizon ranges from 1,200 m to 1,800 m with bottom-hole temperatures ranging from 45°C to 85°C. The permeability thickness product varies from 10 to 80 dm with an average value of 20 dm. Wells currently sustain flows in the range of 200 - 250 m$^3$/hr (440,000 PPH - 550,000 PPH).

The common exploitation scheme consists of an injector/producer couplet with a closed loop process-to-process heat exchanger. Heat pumps are occasionaly added to either boost the wellhead temperature or deplete the reinjection temperature of the effluent.

Installed capacity in each system varies from 5 to 10 MW thermal with an average value of about 7 MW thermal. By November 1984, 41 such systems are due to opperate in the area, supplying heat to approxinately 120,000 dwellings with a yearly savings of 150,300 T.O.E. ($30 million in import savings).

The average geothermal unit cost stands at approximately 10% less than the reference hydrocarbon (gas and fuel oil) and coal cost (approximately 5 ¢/KWh).

The Aquitaine Basin in Southwest France (Figure 6) has been the site of several commercial geothermal development schemes such as in Bordeaux, Toulouse and Mont de Marsan. In the Bordeaux area the reservoir is at 1,000 m depth and consists of temperatures of 40°C to 50°C. At Mont de Marsan the reservoir, at 1,800 m - 2,000 m, is a fractured Jurassic dolomite with temperatures in the 60°C range. In the Toulouse area and further to the South, the reservoirs consist of Eocene sands at 1,500 m depth and temperatures of approximately 60°C.

In contrast with the Paris basin, the geothermal fluids of the Aquitaine basin consist of fresh water, thus not requiring reinjection for environmental reasons. However, in the Bordeaux area, excessive depletion of the reservoir may require reinjection for pressure maintenance.

In Aquitaine, addition of heat pumps, especially in the Bordeaux area, is a prerequesite because of the lower formation temperature. In Mont de Marsan a higher wellhead temperature and a cascading utilization scheme can avoid the necessity for heat pumps. The costs of production are roughly the same as those in the Paris Basin. The savings from the lack of reinjection are offset by the milder climate and the more scattered heat consumers.

It is foreseen that by the late 1980's about 500,000 TOE's could be saved via geothermal heating realizing yearly savings of over $ 100 millions (in 1984 currency). Approximately 30% of the fluids will be supplied by shallow and tepid aquifers.

Of particular interest is the recently put on line, 4.2 MWe dual flash condensing power plant at Bouillante, in Guadeloupe, West Indies and described by Jaud and Lamethe (1984). A volcanic reservoir composed of sands and tuffs, fracture controlled, has been discovered at 600 - 2,500 m depth.

Four wells have been drilled, two of wich are productive. The bottom-hole temperature is 240°C and the total fluid production is 200 tons/hr with 40 tons/hr of steam at 6 bars wellhead pressure. The power output accounts for 6% of the needs of the island.

The total cost of the development of the field exceeded $25 millions. However the generating cost via the geothermal plant is 7.4 c/kWh while the existing 20 MW diesel plant results in costs of 8.5 ¢/KWh. For a 25 MWe geothermal plant the cost is estimated to drop to 5.5 ¢/KWh.

## CONCLUSIONS

An assesment of selected European geothermal sites has been presented.
These included a diverse array of resources ranging from the high enthalpy Greek reservoirs to the very low enthalpy French and British aquifers.

Considering that Western Europe is largely an oil-importing community, geothermal utilisation and exploitation is well in its way to be a proven and viable alternative energy route. Conventional geothermal resources could ultimately provide 5 million TOE's while the less proven hot dry rock technology could multiply this figure by an order of magnitude.

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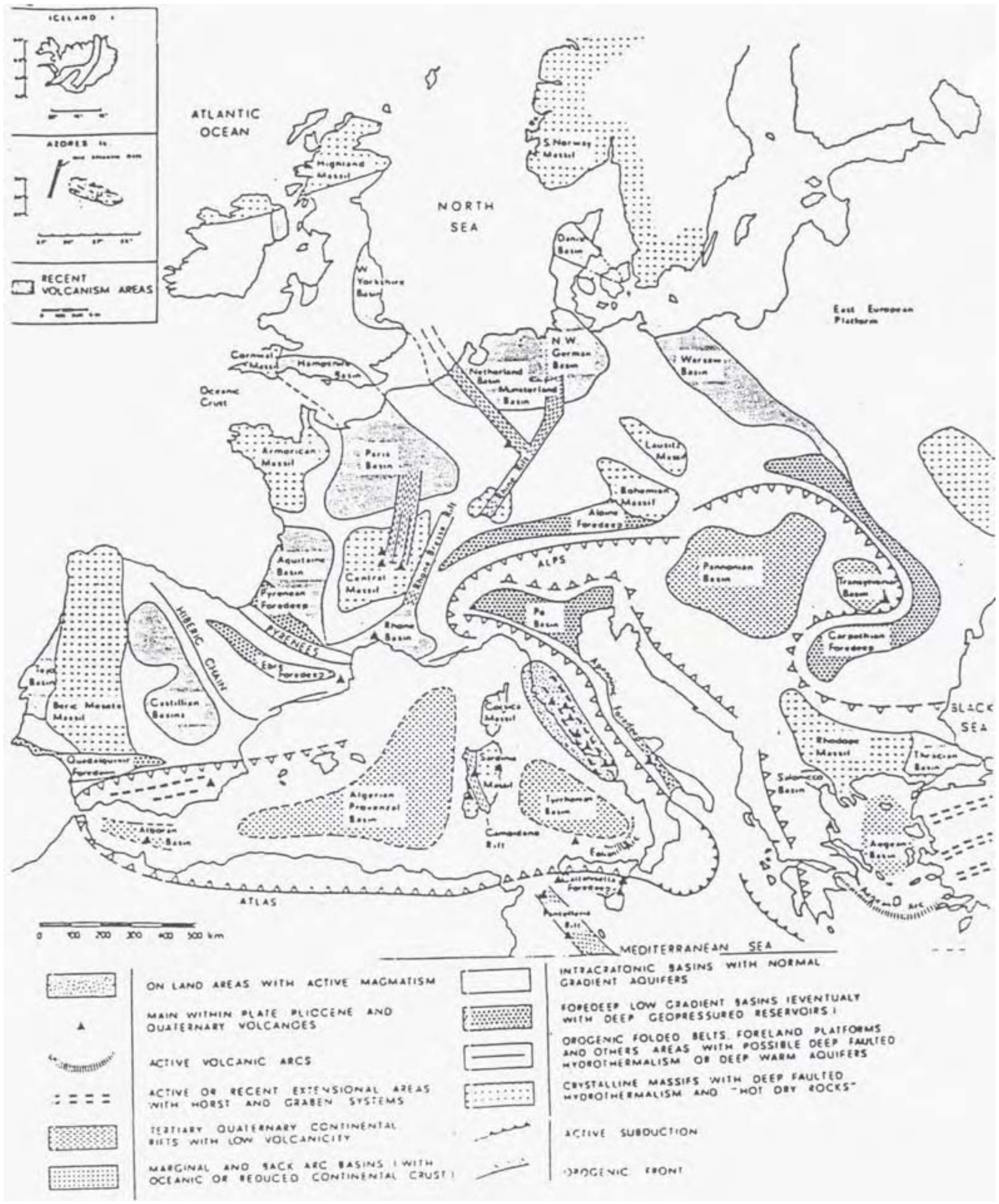


Figure 1. Geothermal Provinces of Europe (From Sommaruga, 1981)

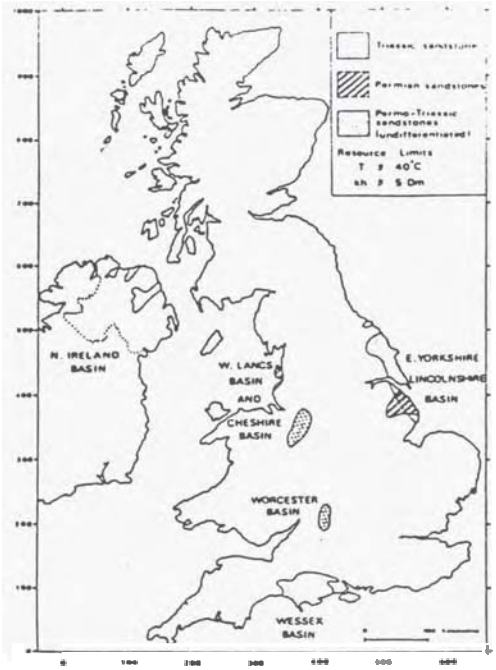


Figure 2. U.K. Sedimentary Basins ( From Gale and Rollin, 1984)


Figure 3. The Aegean Volcanic Arc (From Economides et al., 1983, after McKenzie)

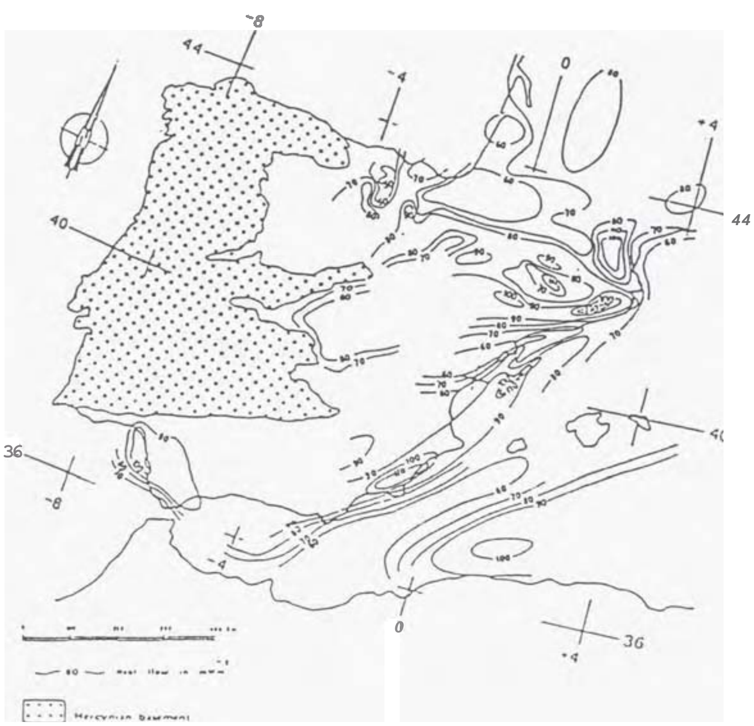

Figure 4. Heat Flows in the Iberian Peninsula (From Albert-Beltran and Banda, 1984)

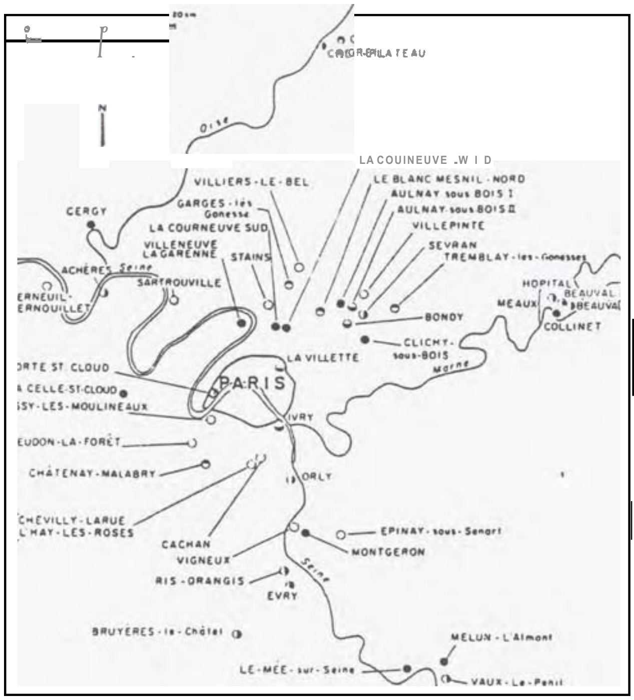


Figure 5. Geothermal Development Sites in the Paris Area ( From BRGX and AFME)