Report 2, 1990

LECTURES ON THE CHARACTERIZATION AND THE EXPLOITATION OF GEOTHERMAL RESERVOIRS IN FRANCE

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PREFACE

Since the foundation of the UNU Geothermal Training Programme in Iceland in 1979, it has been customary to invite annually one geothermal expert to come to Iceland as a UNU Visiting Lecturer. The UNU Visiting Lecturers have been in residence in Reykjavik from one to eight weeks. They have given a series of lectures on their speciality and held discussion sessions with the UNU Fellows attending the Training Programme. The lectures of the UNU Visiting Lecturers have also been open to the geothermal community in Iceland, and have always been well attended. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists with an international reputation have found time to visit us. The following is a list of the UNU Visiting Lecturers from 1979 to 1990:

1979	Donald E. White	United States
1980	Christopher Armstead	United Kingdom
1981	Derek H. Freeston	New Zealand
1982	Stanley H. Ward	United States
1983	Patrick Browne	New Zealand
1984	Enrico Barbier	Italy
1985	Bernardo S. Tolentino	Philippines
1986	C. Russel James	New Zealand
1987	Robert Harrison	United Kingdom
1988	Robert O. Fournier	United States
1989	Peter Ottlik	Hungary
1990	André Menjoz	France

The UNU Visiting Lecturer of 1990, Mr. André Menjoz, has worked on reservoir engineering studies of the geothermal resources of France since 1978. He is presently the assistant director of the Joint Institute for Geothermal Research of BRGM (Bureau de Recherches Geologiques et Minieres) and AFME (French Agency for Energy Management), and head of the reservoir and modelling service of the institute. The world potential for harnessing geothermal waters in the sedimentary basins is vast. France is one of the leading users of geothermal water from sedimentary basins in the world. It is, therefore, of great value for the participants of the UNU Geothermal Training Programme to learn from the experience of the French experts. We are grateful to Mr. André Menjoz for giving us insight into various aspects of the exploration and exploitation of the geothermal resources of France in his five lectures in Reykjavik in September 1990, and for preparing the lecture notes that are presented here.

Ingvar Birgir Fridleifsson,
Director,
United Nations University
Geothermal Training Programme.

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THE GEOTHERMAL RESOURCES IN FRANCE AND THE USE OF GEOTHERMAL HEAT

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INTRODUCTION

France has been working in the field of geothermal energy for more than 15 years. High enthalpy resources do not exist in metropolitan France, but only in its overseas departments and territories. The geothermal station at Bouillante in Guadeloupe (French West Indies) was connected to the electricity distribution network in 1985. This is at present the only high enthalpy plant in operation on French territories, although French companies are involved in high enthalpy operations in other countries.

On the other hand low enthalpy geothermal energy is widely used in France for heating housing. It developped within a few years after the 1970s energy crisis, and its originality lies in several factors:

- the resources are well known, thanks to appropriate legislation and systematic inventory work,
- the energy extraction method is well-suited to the resource, in particular the use of doublets, techniques and materials specific to the industry,
- the public authorities favour a policy of development, with technical assessment and insurance of drilling risks,
- means and structures are being set up to optimise projets, enable continuous improvement of exploitation conditions and increase knowledge of exploited or potential reservoirs.

At present there are approximately sixty geothermal operations in France which have provided low enthalpy geothermal energy for several years (over 20 years for some), used directly for heating.

The experience acquired in the fields of organisation, management, technical development, optimisation and use of geothermal energy has enabled the whole process to be mastered, even in the rather unfavourable context of the relatively low cost of conventional energies. This experience is a factor of success for new operations being developed in the framework of energy policies and protection of the present and future environment.

The low enthalpy geothermal resources in metropolitan France are located in the sedimentary basins. Thanks to suitable legislation (publication of geological information obtained during work, in particular in the oil industry), the hot-water aquifers are as well-known as anywhere in the world.

LOW ENTHALPY GEOTHERMAL RESOURCES IN FRANCE

France is relatively well-provided with deep hot water beds at temperatures of over 50°C (fig. 1). The two main areas of geothermal development are the two great sedimentary basins in France, (1) the Paris basin and (2) the Aquitaine basin. There is also potential in (3) Alsace, (4) Limagne, (5) Languedoc and probably in Bresse and (6) the Rhône valley (see map of geothermal resources in France).

Of the sixty or so operational projects, about fifty are in the Paris basin. Most of these take water from the Dogger, but some from the Neocomian or Albian. These installations are used to heat housing and produce hot water; the operations on the Albian provide winter heating and summer air-conditioning for offices and one project on the Neocomian is used for interseasonal heat storage.

Work on the inventory of national resources was led by BRGM in collaboration with Elf Aquitaine, between 1975 and 1983. This work resulted in detailed mapping of the following parameters: depth, temperature, salinity, transmissivity, lithology and thickness.

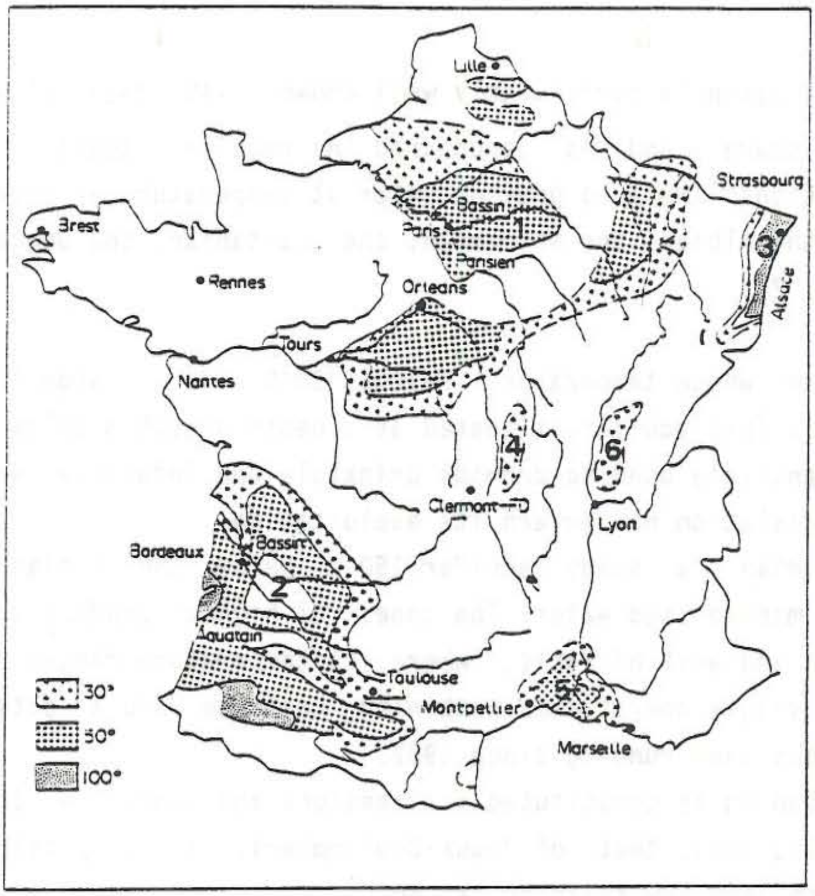

Fig. 1 - Map of geothermal resources in France. Sedimentary basins where the deepest economically exploitable aquifers have temperatures higher than 30, 50 and 100°C.

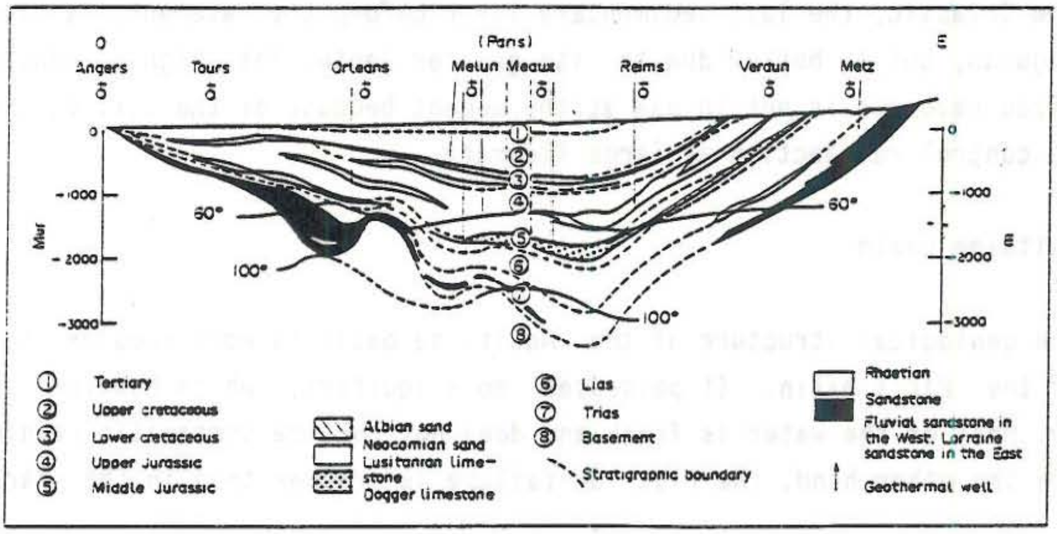

Fig. 2 - Schematic section of deep aquifers in the Paris basin.

The Paris basin

The Paris basin is particularly well known - 1400 deep oil wells have been drilled there - and is structured in regular layers. Five large aquifer formations likely to provide water at temperature of over 30°C are known there: the Albian, the Neocomian, the Lusitanian, the Dogger and the Triassic (fig. 2):

- **The Albian** whose temperature reaches 30°C, is a large fresh water reservoir. This aquifer, situated at a depth of 600 m below Paris, has been intensively used to provide drinkable and industrial water. Very stric legislation now govern its exploitation.
- **The Neocomian**, a sandy aquifer 150 m below the Albian, contains slightly mineralised water. The zones of highest productivity are to the south and west of Paris, where its temperature ranges from 30 to 40°C. A single operation, combining heat use and a potable water supply, has been running since 1982.
- **The Lusitanian** is constituted of limestone and sandstone. In the most favourables area, that of Meaux-Coulommiers, it is possible to tap water with very low salinity, at 60°C.
- **The Dogger** stretches over 15 000 km^2 and covers a large part of the Paris region. The many projects exploiting this aquifer have provided ever-increasing knowledge of the characteristics of this geological formation.
- **The Triassic**, the last sedimentary layer before the basement, is less regular, but is hotter due to its greater depth. This highly mineralized resource is not in use at the moment because of the difficulties to control reinjection at large flowrate.

The Aquitaine basin

The geological structure of the Aquitaine basin is more complex than that of the Paris basin. It possesses more aquifers, which however are smaller. Most of the water is fresh and does not require systematic reinjection. On the other hand, the risk of failure is greater than in the Paris basin.

STATE OF GEOTHERMAL OPERATIONS

Sixty nine geothermal heating operations have been created in France to date. Among these operations:

- 15 are situated in Aquitaine and use a single well system without reinjection. The water can be used for industrial purposes or as drinking water after use of the heat. This double use of the water (both for heat and water) is possible thanks to the very high quality of the water collected in this region. The Begles operation functions as a doublet for interseasonal heat storage.
- 54 operations were realised in the Paris basin, of which:
  - * 3 use a single well, exploiting the Neocomian-Albian aquifers. They are used for heating and air-conditioning. The low temperature of the resource used by these operations (35°C) necessitates boosting by heat pump. The high quality of the water means that it can be re-sold after the heat has been used.
  - * 49 operations take water from the deep Dogger aquifer. Three of them have two doublets, giving a total of 102 wells for the 49 operations (plus a replacement well drilled at the beginning of 1989 for the oldest operation at Melun l'Almont).
  - * 1 doublet on the Triassic, and one single-well operation.

Eight operations have at present been stopped for technical and economical reasons.

CONTEXT OF GEOTHERMAL DEVELOPMENT IN FRANCE

General context

The first oil crisis in 1973 brought to light the limits of oil resources and the vulnerability of supplies. In this new context, the French government quickly took a number of measures in order to lessen dependence in the energy domain. In 1975 a delegate for alternative energies was appointed, whose task is to promote the use of energy sources not yet exploited on the industrial scale, in particular geothermal energy. A number of organisations have a role to play, at their individual levels, in the development of the geothermal industry:

- The AEE (Agence pour les Economies d'Energie - Energy Economy Agency), and above all the AFME (Agence Française pour la Maîtrise de l'Energie - French Energy Agency).
- The Comité Technique de Géothermie (Technical Committe for Geothermal Energy) set up by the Ministry of Industry.
- Specific organisations; the IMRG (Institut Mixte de Recherches Géothermiques - Joint Intitute for Geothermal Research), the SIE (Service d'Information pour l'Energie - Energy Information Service) for information, and the SAF (Société auxiliare de Financement - Auxiliary Financing Company) for geological risk insurance cover.

Finally, in addition to the general laws applying to the subsurface and to water, specific laws have been passed, notably in 1978 with the decree bearing on research and exploitation permits for geothermal energy.

Legislative framework

In France, the subsurface belongs to the State, which can grant concessions for the exploitation of ressources within the framework of the Mining Code. Two main decrees concern the geothermal industry, of which the following points should be noted:

- a research permit is obligatory before drilling begins, and an exploitation permit is required before the resource is used.
- the authorisation process includes a public inquiry and the presentation of an environmental impact study for each project.

The research and exploitation permits are granted by the Prefet (Departmental Authority) after investigation by the DRIRs (Regional Directorates for Industry and Research). The DRIRs are in charge of the problems concerning management and control of resources. For geothermal stations in the Dogger of the Paris basin, regular controls are required, for protection of the groundwater. Geothermal energy is also concerned, at least in part, by the legislation on heat networks. A law passed in 1977 enables housing owners to cancel their existing heating contracts and be connected to heat networks using local energies. The law of July 15th, 1980 states that it is the responsability of local collectivities to take the initiative to create heat networks.

Legal structure of exploitation companies

Wether in the Dogger or other aquifers, the promotion of a geothermal operation and the exploitation of supposed resources imply the setting up of appropriate legal and financial structures. The choice of the form they take depends on the same criteria as those of the town council or user syndicates faced with the geothermal opportunity: decisions between risks and profitability, immediate or long-term profits, total or shared appropriation of the resources. It must be borne in mind that risks are increased by the absence, within the council or syndicate initiating the operation, of the technical, legal and financial skills necessary for the implementation and success of the project. Various structures are possible:

- Public or parapublic ownership by a combined syndicate with the status of a local collectivity, comprising local users with public status (council housing office, commune, hospital,..) or by the user organisations themselves, if they are large enough.
- Combined ownership, a formula where the investor can be public for the subsurface and private for the surface, in different legal form, such as a mixed economy company or a GIE (Economic Interest Group).
- Another solution which seems suitable for the geothermal industry is that of public service concession, which has already proved its worth in the construction and use of roads and underground car parks.

Incitements: geological risk insurance

Geological risk insurance covers both short-term risk and long-term risk. Established in 1975 by the Ministry of Industry, the first well insurance proposed to the prime contractor gave 80% and then 90% cover of the risk of not finding the expected flowrate and temperature. The Ile de France Region had even decided to increase the cover to 100% when prime contractors were publics bodies.

To cover the long-term geological and mining risk, considered to be a brake on the development of the geothermal industry, a long-term guarantee fund was set up in 1980. This fund possessed an initial foundation of 5 million francs given by the Ministry of Industry, and has since then been supplied by the subscriptions paid by Prime Contractors. In order to increase the fund's efficiency, it has proved necessary to add the guarantee of group of insurers. The fund is called in the case of a declared loss whose origin is of geological nature. The guarantee is valid for 15 years. Since 1990 an additional contribution of 10 MF by AFME enables this fund to cover preventive-type investments (e.g., corrosion inhibiting treatment).

Incitements: financial aid

The types of financial assistance granted to geothermal operations have changed as new structures and national policy on the development of geothermal energy have emerged. They apply to the various studies (regional inventories, feasibility studies, specific tests,..) and investments relating to the realisation of operations. Assistance for studies has generally taken the form of subsidies with a ceiling of 50%, whereas assistance for operations has been in the form of subsidies and loans at favourable rates of interest. In 1983, when the special fund for large-scale work was set up, an operation could be subsidised for 20% of the cost of the first well, and in addition for 15% of the total investment for the second well and the heat network. The additional finance could be obtained by loans reserved for local collectivities at rates which were sometimes lower than the rate of inflation at the time. The Ile de France Region also in some cases granted loans on particularly advantageous terms (base of 10% of the investment, repayments deferred for 2 years, interest rate less than 5%).

EXPLOITATION AND USE OF THE RESOURCE

The geothermal loop

Depending on the fluid salinity, the resource is exploited using either a single well (as for the aquifers of the aquitaine basin, the Albian and the Neocomian in the Paris Basin) or a doublet (Dogger aquifer). The doublet technique, which has thus been adopted on the great majority of installations, consists of circulation of the geothermal water in a closed circuit, called a geothermal loop. The fluid is extracted by the production well, loses its heat to the distribution network as it goes through the heat exchanger, and is finally reinjected into the original aquifer via the injection well (fig. 3).

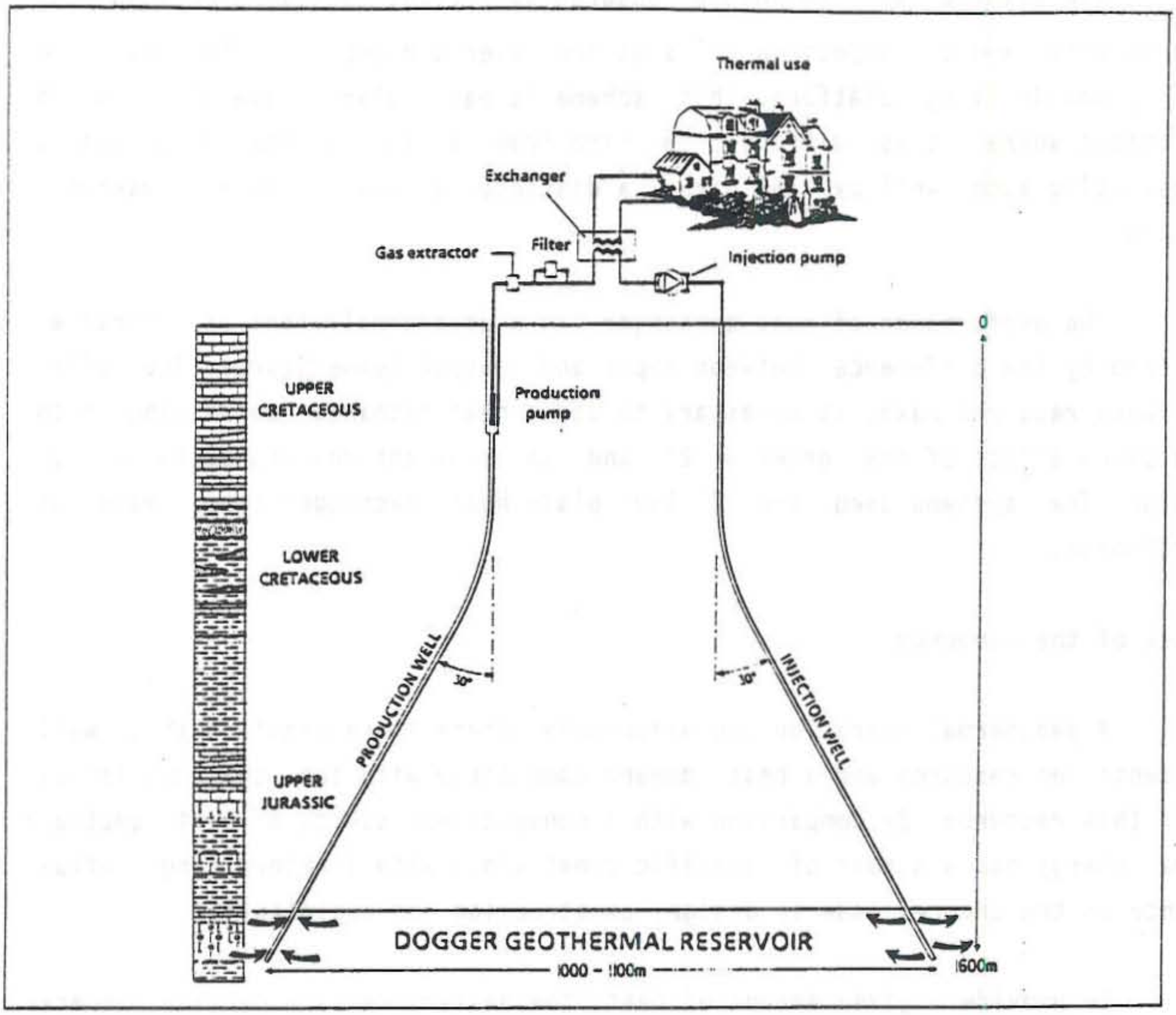

Fig. 3 - Schematic diagram of a geothermal loop for the Dogger reservoir.

An artesian flowrate is obtained on most sites, but as it is often insufficient, a production pump is generally installed. The different types of pump used all have an immersed hydraulic part, lowered to a depth of between 100 m and 400 m, in a pumping chamber. The hydraulic part must be positioned deep enough in the well, taking care of dewatering and bubble pressure. Submersible pumps, based on techniques from the petroleum industry, are at present the most commonly used. Not only their hydraulic part, but also the electric motor, are immersed in the geothermal fluid. Turbopumps have a hydraulic part driven by a turbine, which itself is activated by the circulation of geothermal water pressurised at the surface using a boost-pump. This type of equipment has lower efficiency than the previous one, but should offer the advantage of lower maintenance costs.

The slanted well technique ensures sufficient distance between the production and the injection wells at the reservoir depth, while requiring only one drilling platform. This scheme is particularly useful in urban context where it is difficult to find free areas. In the Paris basin, deviating each well by 30° gives a distance of over 1 km at reservoir level.

The performance of heat exchanger in a geothermal plant is characterized by the difference between input and output temperatures. The efficiency required makes it necessary to use a heat exchanger possessing both a pinch effect of the order of 2°C and an excellent resistance to corrosion. The systems used are of the plate heat exchanger type, made of titanium.

Use of the resource

A geothermal operation can arise only where there exists both a well identified resource and a heat demand compatible with the characteristics of this resource. By comparison with a conventional source of heat, geothermal energy has a number of specific constraints with a determining influence on the choices made in design, construction and exploitation.

To provide a given amount of heat, the heaters require certain temperatures, depending on their type. Graph A on figure 4 gives the temperatures of the heat transfer fluid on entry to and exit from the heater as a function of outdoor temperature, for conventional radiators and for floor heating panels. They are four straight lines diverging from a common origin at 17°C on the x-axis, this being the outdoor temperature above which heating is considered unnecessary. The usable temperature of the water in the distribution network is equal to that of the resource at wellhead, minus the losses and the pinch effect at the heat exchanger. The x-coordinate of intersection of the horizontal line representing this temperature, 65°C in this example, with the lines typical of exit temperatures, give the outdoor temperature below which geothermal heating is inefficient.

The heating power needed by a typical operation using geothermal energy, as a function of outdoor temperature, is represented by a straight line on graph B. This line connects the points representing respectively zero needs (outdoor temperature: +17°C) and maximum heat demand (-7°C).

The power output is a linear function of the flowrate and of the temperature difference on the heat exchanger; this difference depends on the type of heater used. It is therefore possible, for radiators and floor panels, to represent the variation of power output as a function of the outdoor temperature by two straight lines. Each of these lines passes through two significant points:

- the first one is given by the transition temperature, which is by definition equal to the outdoor temperature below which geothermal energy can no longer provide power required. In the example shown, this transition temperature is 9°C for heating floor panels and 10°C for radiators.
- the second point is zero power output. The x-coordinate of this point is given by the intersection point defined in graph A for each of the two heaters. It should be noted that these lines show clearly that the power supplied by geothermal energy becomes less as the outdoor temperature decreases, if this is lower than the transition temperature.

Below the transition temperature, the power output supplied by geothermal energy is the straight line passing through these two points. Above this temperature, the power can be read off on the straight line re presenting the heat demand.

The monotonic curve C shows the cumulated frequencies of the average daily temperatures. For example, in the case shown, the outdoor temperature is statistically below 12°C during 4700 hours. To each outdoor temperature corresponds a heat demand, given directly by graph B. With this new scale as the x-axis, the area delimited by the monotonic curve represents the total energy consumed during the heating season. In the example shown, it appears that geothermal energy covers 35% of the demand, if the operation served is heated only by radiators, and 60% if it has heating floor panels.

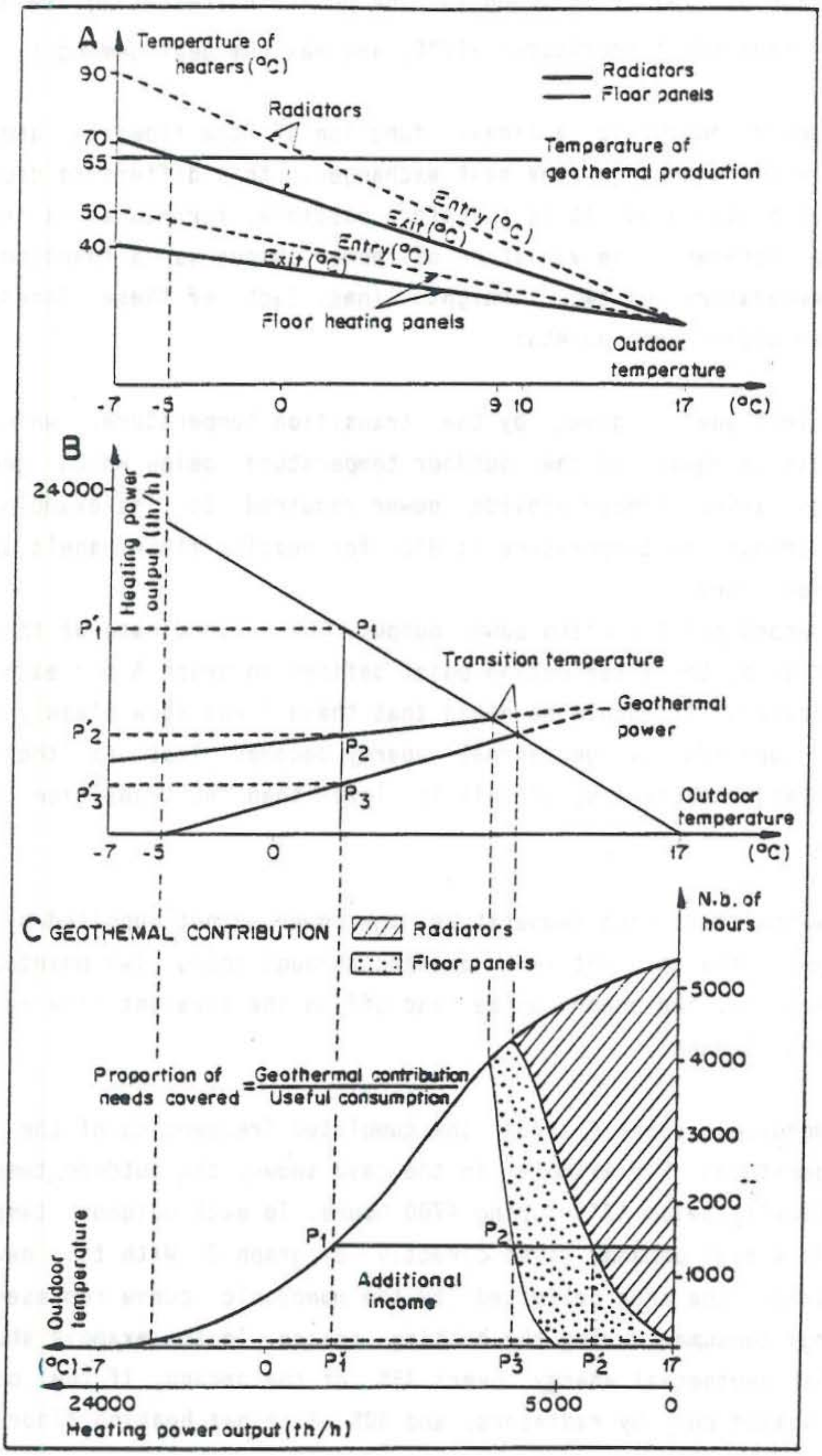

Fig. 4 - Determination of the ratio of needs covered by geothermal energy.

Optimization of the exploitation

The search for maximum production in a geothermal project often requires the flowrate to be increase by use of a pump. This purpose can also be served by increasing both the temperature difference at the exchanger and the duration of use in the year.

As shown on graph A, the return temperature of the network depends on the type of heater installed in the buidings. The units served by geothermal operations usually include a large proportion of old buildings, with every type of heater. The project designers must then plan, for series connection of consumption points, to begin with the buildings equipped with radiators and end with the buildings heated by heaters with low output temperature. This is known as the cascade system. The installation of heat pumps can also contribute to lowering the return temperature. Several structures are possible, depending on whether or not the heat pumps are centralised.

DEVELOPMENT OF NEW TECHNIQUES AND NEW FIELDS

In order to examine the geothermal potential of deep rocks, widely spread in the world, an important experimental programme was initiated in 1987. The development is concentrated on long-term research for future exploitation of hot dry rocks, following the works done on the sites of Los Alamos (USA) and Cornwall (UK). At present, the Franco-German stimulation and artificial fracturating programme, comprising injection and water recovery tests in under way on the Soultz-sous-Forets site (Alsace). This work forms part of the EEC "new targets" programme.

In the same area another research programme has been initiated to quantify the feasibility of geothermal exploitation in sedimentary layers (Triassic) above the previous target (granite). Well-known from a lot of oil wells, this area is characterized by an abnormal local gradient of 100°C/km, typical of a graben structure with a thick sedimentary cover. Having identified the thermal potential, the aim of present research is to prove and to quantify the hydraulic productivity of this highly fractured system.

CONCLUSIONS

France is very poor in traditional energy sources. The country has no major oil or natural gas field and coal reserves are either going to be depleted or are not economical. So it is logical that the price of energy in France is considerably higher than in the U.S. The presence of large sedimentary basins, in addition to the occurence of the two past oil crisis were a powerful opportunity to develop low enthalpy geothermal exploitation using the doublet technique. Current use of geothermal heating results in saving more than 150 000 tons of oil per season. With around fifty plants in operation, France is one of the largest user of geothermal energy for direct heating applications after Iceland.

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Table 1 - List of the geothermal operations in the Paris basin.

OPERATIONS	*D or S*	*START. DATE*	*AQUIFER*	*T (°C)*	*SITUATION JULY 1990*
ACHERES	*D*	*12/83*	*DOGGER*	*55*	*STOPPED 89*
ALFORTVILLE	*D*	*11/86*	*DOGGER*	*75*	
AULNAY R.D.V.	*D*	*1982*	*DOGGER*	*72*	
AULNAY G.S.	*D*	*01/85*	*DOGGER*	*71*	
BEAUVAIS	*D*	*10/82*	*DOGGER*	*47*	*STOPPED 88*
BLANC MESNIL	*D*	*11/85*	*DOGGER*	*68*	
BONDY	*D*	*11/84*	*DOGGER*	*64*	*STOPPED 89*
BONNEUIL/MARNE	*D*	*10/86*	*DOGGER*	*80*	
BRUYERES LE CHATEL	*S*	*05/83*	*NEOCOMIAN*	*34*	
CACHAN	*2D*	*10/85*	*DOGGER*	*70*	
CERGY-PONTOISE	*D*	*07/82*	*DOGGER*	*56*	
CHAMPIGNY	*D*	*10/85*	*DOGGER*	*78*	
CHATEAUROUX	*S*	*10/85*	*TRIASSIC*	*32*	
CHATENAY MALABRY	*D*	*10/84*	*DOGGER*	*68*	
CHELLES	*D*	*10/86*	*DOGGER*	*66*	
CHEVILLY LARUE	*D*	*10/85*	*DOGGER*	*75*	
L'HAY LES ROSES	*D*	*10/85*	*DOGGER*	*75*	
CLICHY	*D*	*11/82*	*DOGGER*	*70*	-
COULOMMIERS	*D*	*10/81*	*DOGGER*	*85*	
LA COURNEUVE NORD	*D*	*02/83*	*DOGGER*	*58*	
LA COURNEUVE SUD	*D*	*05/82*	*DOGGER*	*59*	
CREIL 1	*2D*	*1976*	*DOGGER*	*59*	*STOPPED 86*
CREIL PLATEAU	*D*	*10/83*	*DOGGER*	*59*	
CRETEIL	*D*	*10/85*	*DOGGER*	*79*	
EPERNAY	*D*	*02/83*	*DOGGER*	*60*	*STOPPED 87*

EPINAY-SOUS SENART	D	10/84	DOGGER	75	
EVRY	D	07/83	DOGGER	72	
FONTAINEBLEAU	D	12/83	DOGGER	74	
FRESNES	D	12/86	DOGGER	72	
GARGES LES GONESSE	D	10/84	DOGGER	68	STOPPED 85
IVRY SUR SEINE	D	12/83	DOGGER	64	
LA CELLE St CLOUD	D	04/83	DOGGER	61	
LE MEE SUR SEINE	D	1978	DOGGER	73	
MAISONS ALFORT I	D	08/85	DOGGER	72	
MAISONS ALFORT II	D	12/86	DOGGER	72	
MEAUX BEAUVAL I	D	10/83	DOGGER	79	
MEAUX BEAUVAL II	D	04/84	DOGGER	79	
MEAUX COLLINET	D	10/82	DOGGER	79	
MEAUX HOPITAL	D	10/83	DOGGER	77	
MELLERAY	D	08/82	TRIASSIC	74	STOPPED 88
MELUN L'ALMONT	D	1971	DOGGER	71	
MONTGERON	D	1982	DOGGER	73	
ORLY I	D	01/84	DOGGER	76	
ORLY II	D	10/86	DOGGER	77	
PARIS MAISON RADIO	S	1962	ALBIAN	27	
PARIS AGF	D	04/90	ALBIAN	27	
RIS ORANGIS	D	10/83	DOGGER	72	
SEVRAN	D	10/83	DOGGER	69	STOPPED 89
SUCY EN BRIE	D	11/84	DOGGER	78	
THIAIS	D	10/86	DOGGER	76	
TREMBLAY LES GONESSE	D	10/84	DOGGER	74	
VAUX LE PENIL	D	12/83	DOGGER	72	
VIGNEUX	D	10/85	DOGGER	72	

VILLENEUVE LA GARENNE	D	1976	DOGGER	55	
VILLENEUVE St GEORGES	D	10/85	DOGGER	77	
VILLIERS LE BEL	D	10/85	DOGGER	67	

Table 2 - List of operations in the Aquitaine basin.

OPERATION	START.	T (°C)	OBSERVATIONS
BLAGNAC	1981	58	
BEGLES	1984	20	HEAT STORAGE DOUBLET
BORDEAUX BASE 106	1986	55	
BORDEAUX BENAUGE	1982	44	
BORDEAUX GRAND PARC	1986	46	
BORDEAUX MERIADECK	1982	53	
BORDEAUX STADIUM	1980	34	
CASTELJALOUX	1990	42	HEATING AND HYDROTHERAPY
JONZAC	1981	61	
LAMAZERE	1983	57	HORTICULTURAL HOTHOUSES
LIBOURNE	1982	23	DRINKABLE WATER WELL
MONT DE MARSAN 1	1977	61	
MONT DE MARSAN 2	1984	54	
PESSAC	1983	48	
St PAUL LES DAX	1979	47	

STRUCTURE AND CHARACTERISTICS OF THE PRODUCTION OF THE DOGGER RESERVOIR IN THE PARIS BASIN

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INTRODUCTION

The geothermal industry in France has grown very quickly, most of the plants having been installed between 1976 and 1986 (fig. 1). During this short period 110 wells were drilled, tested and sampled, allowing the initiation of a detailed study for a better knowledge of the Dogger resources. For several years the research programme has benefitted from joint financing from the BRGM and the AFME, and since 1986, from the EEC (DGXII). Compiling and assessing all the available data on geothermal wells, a general method, which can be applied in other geothermal fields, has progressively been identified, with the help of a multi-field approach involving sedimentology, geochemistry, hydrodynamic and thermal modelling.

Based on previous investigations from the petroleum exploration, in addition to the large amount of geothermal data collected, the method used starts with a detailed local analysis per well (vertical structure of the reservoir). This first analytical step is required for a progressive approach in the different techniques: knowledge of paramaters distribution, understanding of reservoir state, analysis of reservoir behaviour under exploitation with doublets.

From these local and accurate informations, the various analysis of the reservoir parameters converge towards the identification of an heterogeneous structure, with a great number of thin productive layers. Compared to the total thickness of the limestone facies (150-250 m), the low value identified for the cumulated net pay (around 20 m) is of great importance to forecast the breakthrough time of the cold waters induced by the injection process in a doublet scheme. The detailed characterization of the productive layers is the result of a systematic use of the flowmeter log; a major diagraphy, particularly suitable for low enthalpy range and the description of production vertical profile.

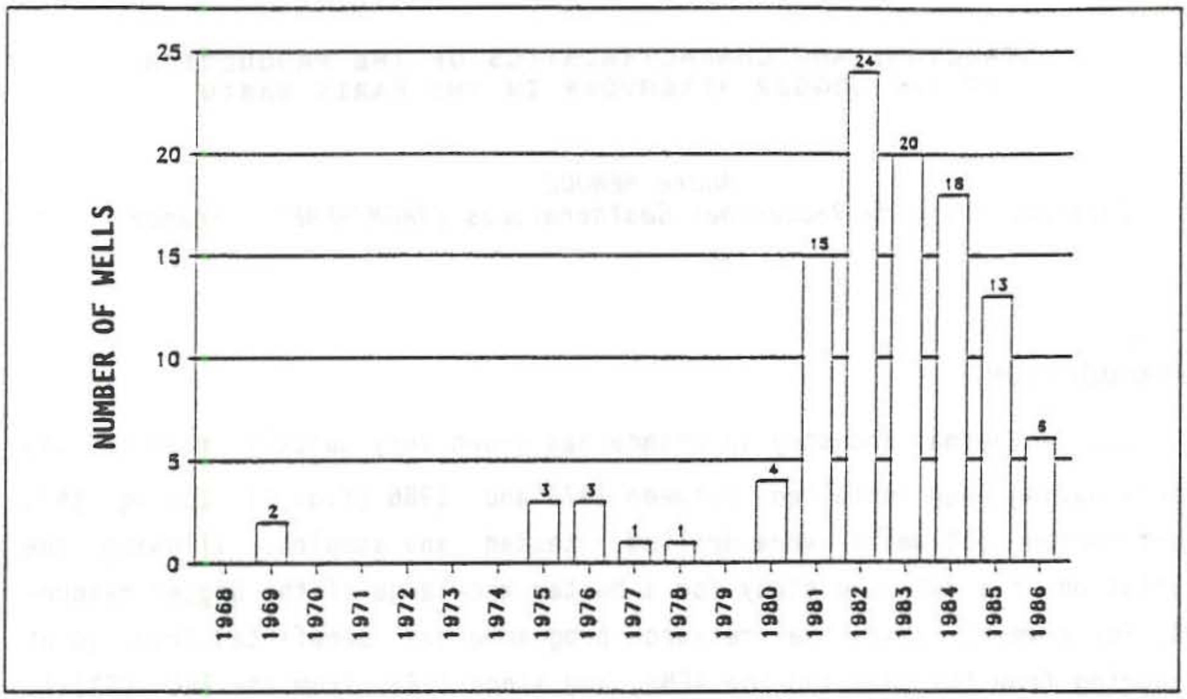

Fig. 1 - Chronogram of realisation for the 110 geothermal wells in the Paris basin.

SPECIFIC OBJECTIVES OF GEOTHERMAL TESTS

In a first period, geothermal testings have been adapted from the petroleum methodology, taking into account the technical equipments required for downhole measurements at depths around 1800 m. Then, progressively, the experimental conditions became more and more specific to satisfy geothermal requirements:

- The main objective of low enthalpy geothermal exploitation is the production of hot water with continuous and large flowrates, up to 200-300 m^3/h on average. The durability of the flowrate with an acceptable drawdown can not be assessed without a good knowledge of: (i) the long range transmissivity and (ii) the hydraulic continuity of the reservoir. The durations of the tests are thus longer than those of oil DST (Drill Stem Test).
- The total flowrate produced must be reinjected (a consequence of the close loop system) and as the viscosity of the cold fluid is higher by at least 50%, compared to the native one, the corresponding over-pressure has to be forecasted accurately. A particular care is thus required to quantify the short range parameters around the injection well. This introduces the important concept of effective wellbore

radius, included in the overall skin factor obtained from production tests.

- The second objective conditionning the success or the failure of a geothermal project is the evaluation of the average production temperature, which in turn defines the required flowrate for a given thermal power. This requirement is a second reason to increase flow-test duration, in order to improve the representativity of reservoir temperature measurements. Geochemical analysis of the fluid benefit from these experimental conditions (uncontaminated water samples).
- Finally, looking at the breakthrough time concept, attached to the doublet scheme, an accurate estimate of the cumulated net pay is required, both in the vicinity of each well and also between the wells. The net pay parameter is a constraint for the choice of the distance between the wells at reservoir level.

GEOTHERMAL MEASUREMENTS ON WELLS

As mentioned above the typical features of geothermal tests on low enthalpy wellbores are mainly the search for measurements reliability and sufficient duration. All the loggings are done by petroleum servicing companies.

The diagraphies done are the standard ones. The detailed analysis of the records shows that the true productive thickness is on average 30% of the diagraphic estimations, with maximum values from 10 to 60%. The diagraphic informations recorded include geometrical parameters (vertical and deviated depths, azimuth, geological markers,..) and total porosity. Petroleum DST are not used and the production tests are performed on the total openhole section, that means on a length of 100 to 150 m from the casing shoe down to bottomhole. Each well is tested for production at constant and high flowrate, defined in the range of future exploitation ones. The testing schedule is composed of a first period of drawdown (12 hours), generally by air-lift, followed by a 12 hours build-up period. This last record gives the transmissivity, the extrapolated static pressure and the skin factor of the well. In addition, an injection-fall off test is performed on the second well (injection) to compare injectivity and productivity parameters. Finally, the global behaviour of the doublet is evaluated with interference or loop test to control the hydraulic continuity of the reservoir between the two wells. For all the hydraulic tests, pressure and temperature are continuously recorded downhole around the depth of casing shoe. Geochemistry is analysed from a few downhole sampling and from measurements at wellhead during production.

During production, and a few hours before shut-in, a flowmeter log is run to define the location and the production of the different productive layers.

LOCATION OF GEOTHERMAL WELLS

The location of the 110 geothermal wells studied is shown on figure 2. It can be mentioned that the location of the wells is not the consequence of a previous exploration programme. The geographical density of wells is rather irregular and concentrated in specific areas where the distance between doublets must be optimized. The targets have been choosed after the identification of heating needs at surface (new towns for instance) and taking into account the resource characteristics known at this time. The coordinates used to plot the position of wells on figure 2 are those of the impact of each one in the reservoir. The average distance between the two wells of a doublet is around 1 km.

ANALYSIS OF WELL DATA

All the data used have been collected from the drilling and testing reports, and then compiled using the same methods in order to build a database for the wells. The primary informations can be classified in five groups:

- the geometrical parameters recorded are used to correct the deviated depths at which data are obtained (81% of the wells are slanted ones),
- the geological parameters include the facies markers (vertical and deviated depths),
- the thermal parameters are obtained from dynamic or static temperature profiles,
- the chemical parameters used to define the fluid total salinity and a specific database integrating the detailed fluid composition (chemical and isotopic),

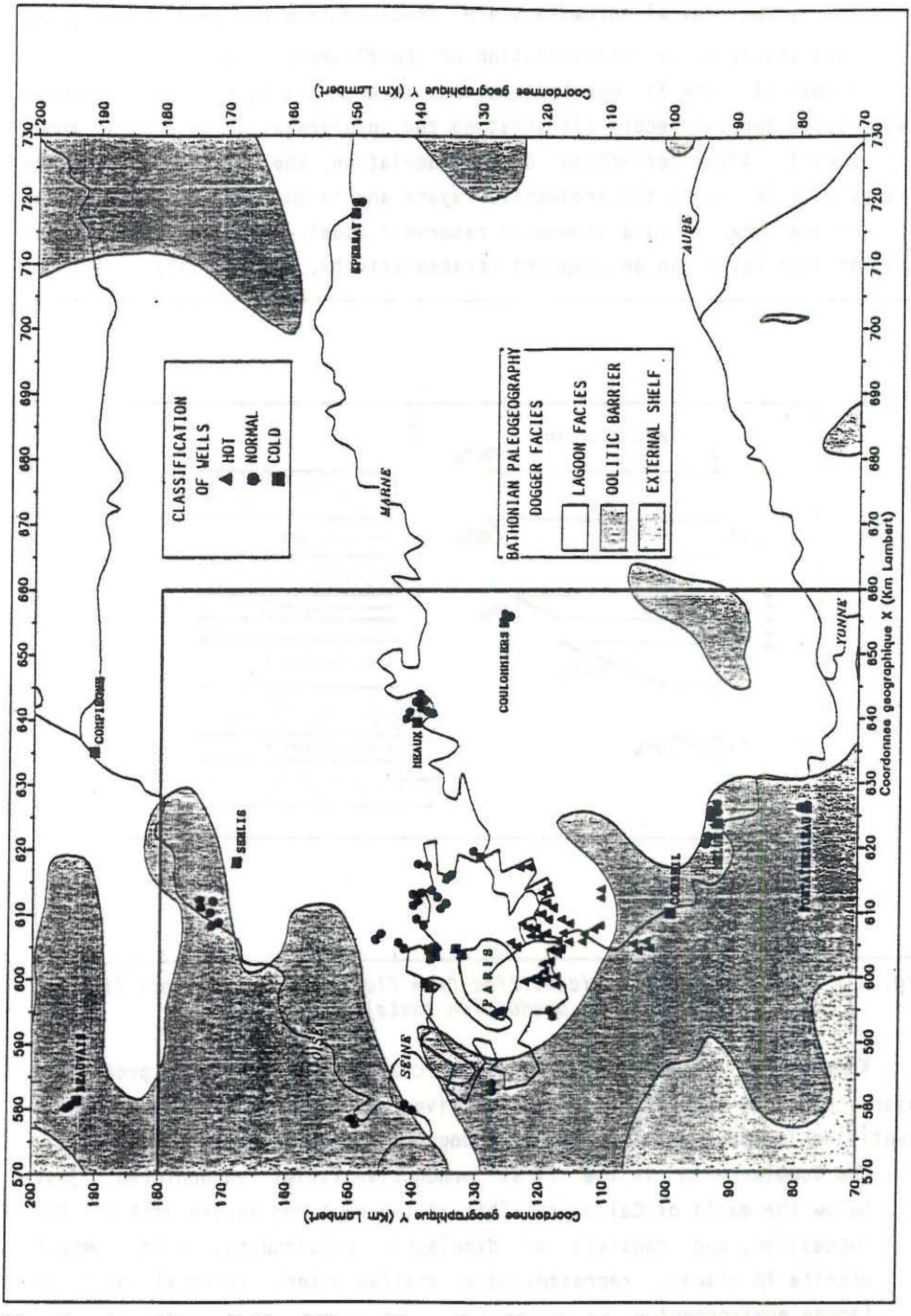

Fig. 2 - Location of the 110 geothermal wells in the Dogger reservoir.

- **the hydrodynamical parameters** are compiled from the production tests data and from the interpretation of the flowmeter-log.

A special care is devoted to the interpretation of the flowmeter loggings; a typical record illustrating the interpretation method is shown on figure 3. After correction of the deviation, the first step of the analysis is to locate the productive layers and to quantify the production of each one. Then using a schematic reservoir model, the main characteristics of each layer can be computed (transmissivity, permeability, ..).

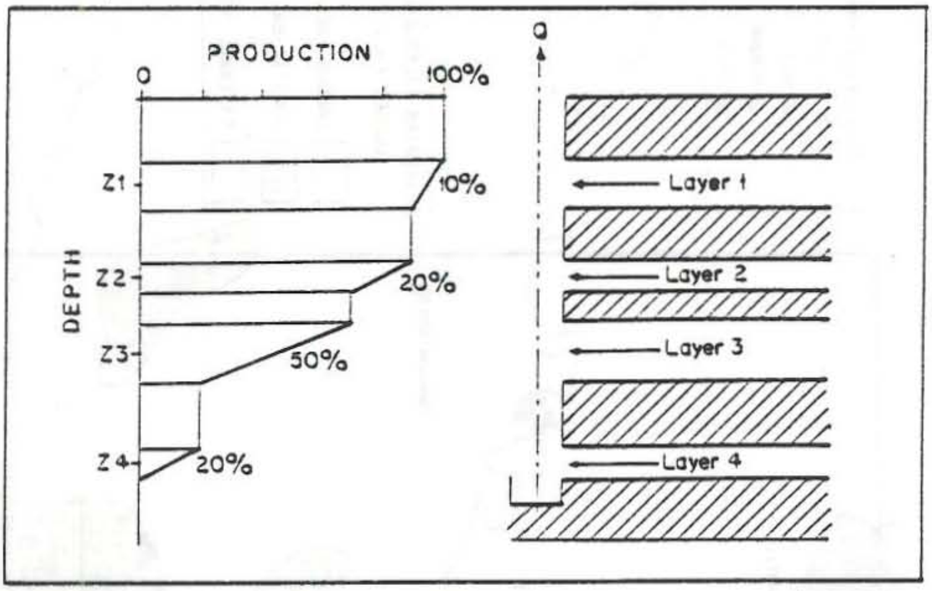

Fig. 3 - Production profile identified from flowmeter measurements (the log is run upward during production tests).

Knowing the geometrical and physical characteristics of the productive layers, each one can be assigned to a given facies among the three units identified in the typical sequence of Dogger in the Paris basin (fig. 4):

- **The Comblanchian** is the first productive facies encountered, just below the marls of Callovian. This is the most regressive unit of the succession, and consists of bioclastic calcirudite, with compact micrite in places, representing a shallow water, internal shelf or lagoon environment.

- **The Oolitic unit** consists of predominantly oolitic calcarenites. It can be subdivided on the basis of the influences of internal or external marine domains on the petrophysical characteristics of rock.
- **The Alternances or Cyclical unit,** oolitic-marly, characterised by a wide variation in sedimentary type in a succession of thin repetitive truncated sequences consisting of three terms. The sequential subdivision, based on the logical succession of paleoenvironments, indicates seven distinct episodes corresponding to pulsations leading to the development of sequences at the tops of which the deposition conditions were those of a shallow high-energy barrier.

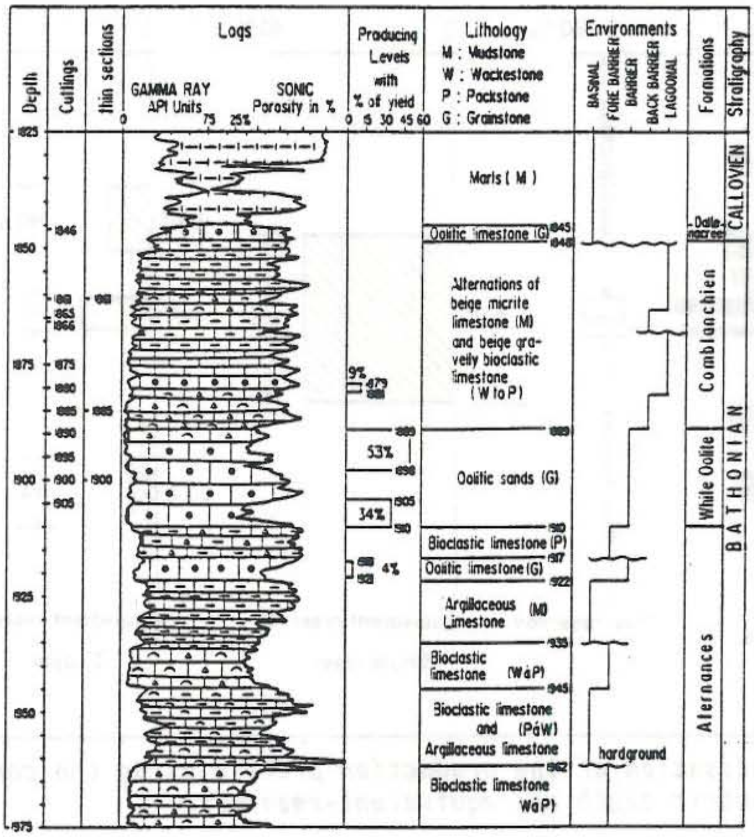

Fig. 4 - Typical sequence of Dogger in the Paris basin

The identification and the classification of productive layers according to the three above facies is typical of the geothermal approach and slightly different from the petroleum one. As the productive layers are numerous, with no individual correlation, the observed true structure is too complex to allow reservoir numerical modelling. In order to build a synthetic model some simplifications are required, leading to the practical concept of equivalent-reservoir. For the analysis of regional distributions and hydrodynamical modelling, two schemes have been used (fig. 5):

- **The single layer-equivalent** is characterised by an average productive depth around which the thickness of the individual layers is cumulated. This scheme is the main geometrical support for regional studies. **The three layers-equivalent** defined by three average depths attached to the corresponding facies. The thickness of the layers is cumulated and assigned to the respective depths.

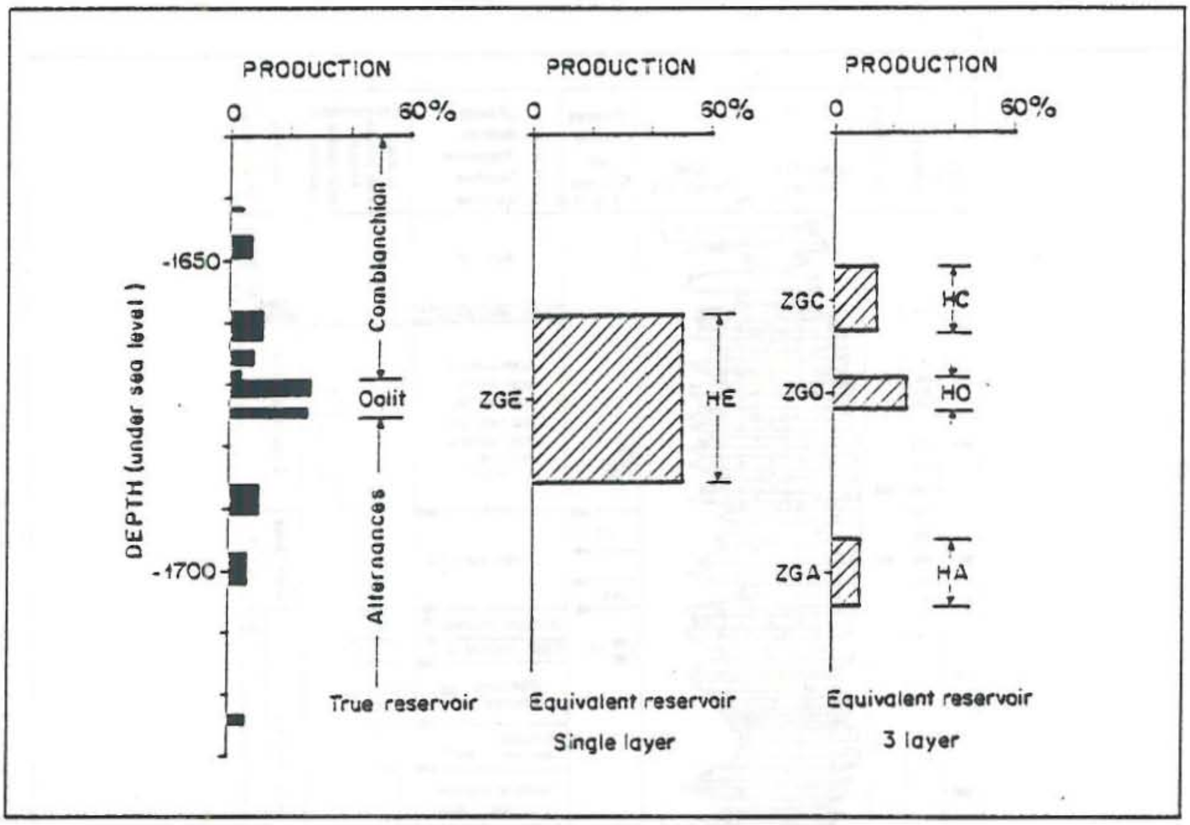

Fig. 5 - Schematisation of the production profile using the concepts of barycentric depth and equivalent-reservoir.

The typical vertical locations of the equivalent-reservoirs ZG, considered above, are obtained from a statistical average of the depths Zi of each layer, weighted by the individual production Qi according to the relation:

$$ZG = \frac{\Sigma\, Zi \,.\, Qi}{\Sigma\, Qi} \qquad \text{(barycentric depth)}$$

STRUCTURE OF A RECORD FOR THE TABLE "SURFACE"
(one record per well)

- Label of geothermal operation
- Underground company
- Label of the well (primary index)
- Type of well
- National classification index
- X-coordinate of wellhead
- Y-coordinate of wellhead
- Altitude of ground level
- Label of department
- Department code
- End of drilling date
- Exploitation starting date

STRUCTURE OF A RECORD FOR THE TABLE "FACIES-GEOMETRY" (one record per well)

- Label of the well (primary index)
- X-coordinate of upper marker (casing shoe)
- Y-coordinate of upper marker
- Z-coordinate of upper marker (altitude)
- X-coordinate of lower marker (bottom of the well)
- Y-coordinate of lower marker
- Z-coordinate of lower marker (altitude)
- Reference deviated depth
- Reference vertical depth
- Deviation angle
- Altitude of top of Dogger
- Altitude of top of Oolit
- Altitude of top of Alternances

STRUCTURE OF A RECORD FOR THE TABLE "TESTING"
(one record per well)

- Label of the well (primary index)
- Testing date
- Artesian flowrate
- Upper depth of the tested interval
- Lower depth of the tested interval
- Deviated depth of the P-T probe
- Vertical depth of the probe
- Static pressure at probe depth
- Production temperature measured
- Total salinity measured
- Intrinsic transmissivity
- Shut in pressure at wellhead
- Skin factor of the well

STRUCTURE OF THE TABLE "COMPILED RESULTS"
(one record per well and per facies)

- Label of the well (primary index)
- Barycentric X-coordinate of production
- Barycentric Y-coordinate of production
- Barycentric Z-coordinate of production
- Vertical barycentric depth of prod.
- Intrinsic transmissivity
- Cumulated productive depth
- Intrinsic permeability
- Total porosity
- Relative flowrate
- Total salinity
- Reservoir pressure
- Reservoir temperature
- Potentiometric level

(The last four parameters are not identified for each facies, the average values used are those of the single layer equivalent).

STRUCTURE OF A RECORD FOR THE TABLE "LEVELS
(one record per layer for a given well)

- Layer number (secondary index)
- Deviated depth of the upper limit
- Deviated depth of the lower limit
- Relative production
- Total porosity
- Facies of the layer
- Deviated thickness
- Vertical depth of the upper limit
- Vertical depth of the lower limit
- Vertical thickness
- Altitude of the upper limit
- Altitude of the lower limit
- Intrinsic transmissivity of the layer
- Intrinsic permeability
- Barycentric X-coordinate
- Barycentric Y-coordinate
- Barycentric Z-coordinate

Fig. 6 - Structure and contents of the geothermal wells database.

THE WELL DATABASE

For future uses, all the raw and interpretated data are stored systematically in structured files to give a database of the relational type. In practice, this structure is equivalent to a set of tables (concept of row and column), linked by a common index. Two kinds of tables are identified:

- the global tables, with a number of rows aqual to the number of wells (primary index). A given row (or record) is subdivided into a fixed numer of fields in which the parameters are stored (columns). The parameters are those identified for the single layer-equivalent model.
- the specific tables for each well with a variable number of rows equal to the number of productive layers (secondary index). Such a tables contains the individual parameters of the layers.

The structure and the content of the main tables are detailed on figure 6. This database is a powerful tool to extract statistical informations on the geothermal sample and geographical correlations. It is finally the required basis for further analysis of the regional distribution of reservoir parameters.

THE VERTICAL STRUCTURE OF DOGGER PRODUCTION

A first application of the database is to examine and to compare the production profiles of the various wells. With the accurate datas available the structure identified is very typical as it was unknown before the geothermal development in the Paris basin. Figure 7 is an example from the well Aulnay-sous-Bois, located northest of Paris. This well has been completely cored and serves as a reference for the detailed analysis of all the geothermal wells. The main conclusion is the identification of an important and systematic vertical heterogeneity:

- the production of the Dogger is stratified with numerous productive layers (10 to 20 as an average),
- these layers are very thin, with metric or sub-metric scale, and are spread over a vertical interval of around 50 m,

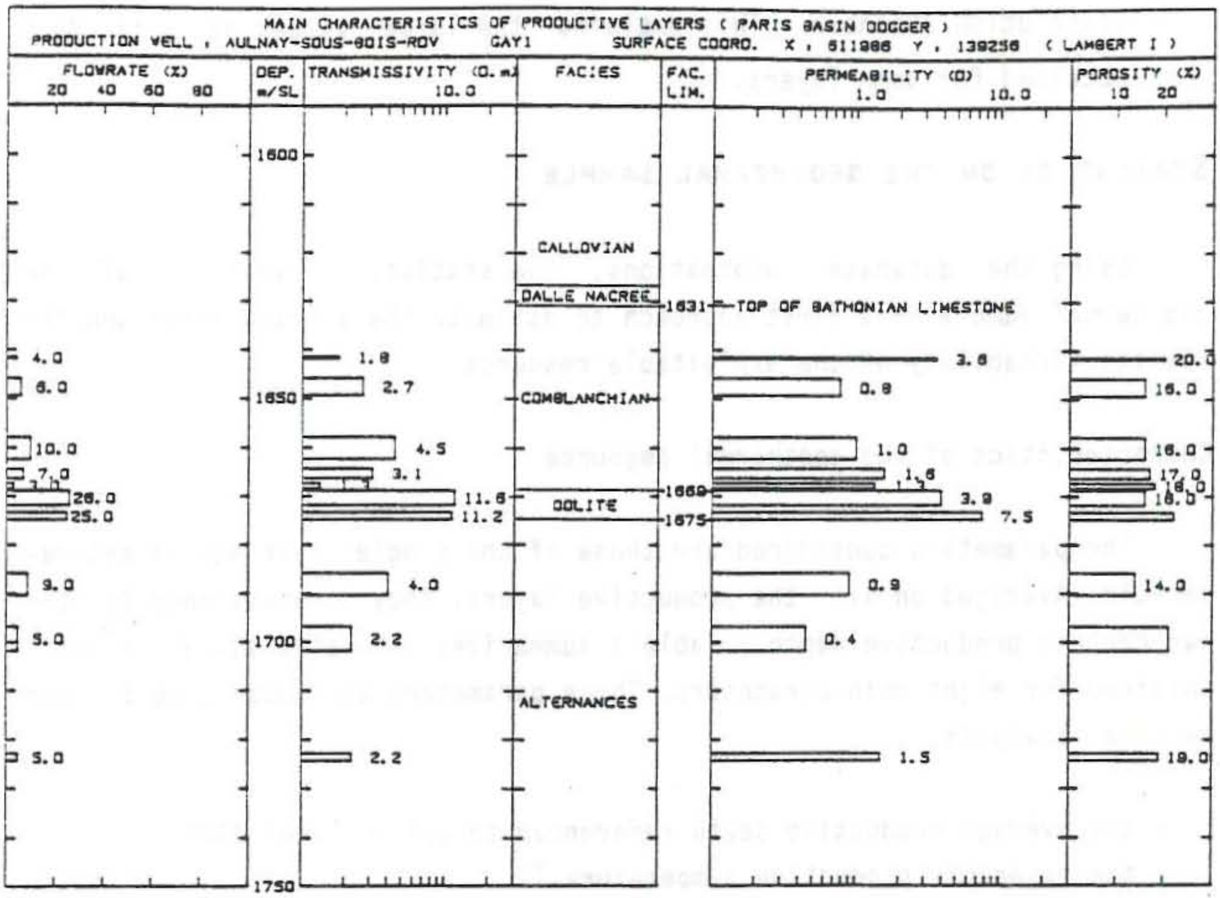

Fig. 7 - Typical vertical structure of the production in the Dogger reservoir (location and parameters of the productive layers).

- the cumulated productive thickness, of the order of 15 to 20 m, is limited compared to the total thickness of the limestone facies (10 to 15%),
- taking into account the great number of layers, the lateral continuity of a given one can not be systematically proved even between the two wells of a doublet, that means over a range of 1 km. It is the main reason why, the continuity has been searched and demonstrated for, (i) all the layers and (ii) according to the three main facies (Comblanchian, Oolit, Alternances),
- finally, it can be mentioned that the permeability interpretated from production tests is rather high. The average value of 2 Darcy is 10 times larger than the value obtained in laboratory on core samples. In fact, the in situ measurements integrates the matrix component, but also the important and variable contribution of fractures and

dissolution channels. This explains the large values of 5 to 20 D obtained for some layers.

STATISTICS ON THE GEOTHERMAL SAMPLE

Using the database informations, the statistical analysis of the geothermal sample is a first approach to estimate the average value and the spatial variability of the exploitable resource.

Characteristics of the geothermal resource

The parameters considered are those of the single layer equivalent-reservoir. Averaged on all the productive layers, they are assigned to the barycentric productive depth. Table 1 summarizes the statistical results obtained for eight main parameters. These parameters are those used for the regional analysis:

- the average productive depth referenced to ground level ZGMS,
- the reservoir production temperature TP,
- the total salinity of the fluid TDS,
- the fluid density RO,
- the intrinsic transmissivity KH,
- the intrinsic permeability K,
- the vertical cumulated productive thickness H,
- the total porosity PORO.

The analysis of the values of table 1 allows the quantification of the geothermal resource:

- the thermal potential of 70°C allows the fluid exploitation for heating with a temperature drop of 30°C before reinjection, but looking at the high mineralisation (20 g/l), injection is necessary.
- on average, taking into account the combined and inversed effects of temperature and salinity, the fluid density is close to 1, the value of fresh water. In fact, this average information is not true at local scale and particularly in specific areas.
- for production, one can note the large values of transmissity and permeability, allowing the exploitation at high flowrates with an acceptable drawdown.

On the other hand, the statistical parameters (standard deviation, maximum and minimum) give a first information on the large spatial variability, especially for the matrix parameters.

Variables	ZGMS	TP	TDS	RO	KH	K	H	PORO
Unit	m	°C	g/l	kg/m^3	D.m	D	m	%
Nb. of points	110	110	91	76	110	104	104	94
Average	1670.0	69.5	20.7	999.9	38.1	2.2	18.3	15.6
Standard dev.	129.2	7.8	6.7	5.9	23.5	1.4	8.0	2.4
Minimum	1180.7	46.9	6.4	987.2	2.7	0.2	5.6	10.0
Maximum	2095.8	85.4	35.0	1010.5	113.8	6.9	47.0	23.4

Table 1 - Statistical results on the geothermal sample.

The correlation matrix on table 2 is a tentative to identify some coupling relations between variables. The coefficients are systematically low, with the exception of temperature versus depth, quite normal in a sedimentary basin.

Variables	ZGMS	TP	TDS	KH	K	H	PORO
ZGMS	1						
TP	0.69	1					
TDS	0.33	0.07	1				
KH	0.36	0.39	0.58	1			
K	0.29	0.39	0.38	0.74	1		
H	-0.06	-0.08	0.31	0.36	-0.26	1	
PORO	-0.15	-0.12	0.37	0.33	0.16	0.32	1

Table 2 - Correlation matrix of the main geothermal parameters.

The various histograms of figure 8 give a global view of the exploited resource characteristics.

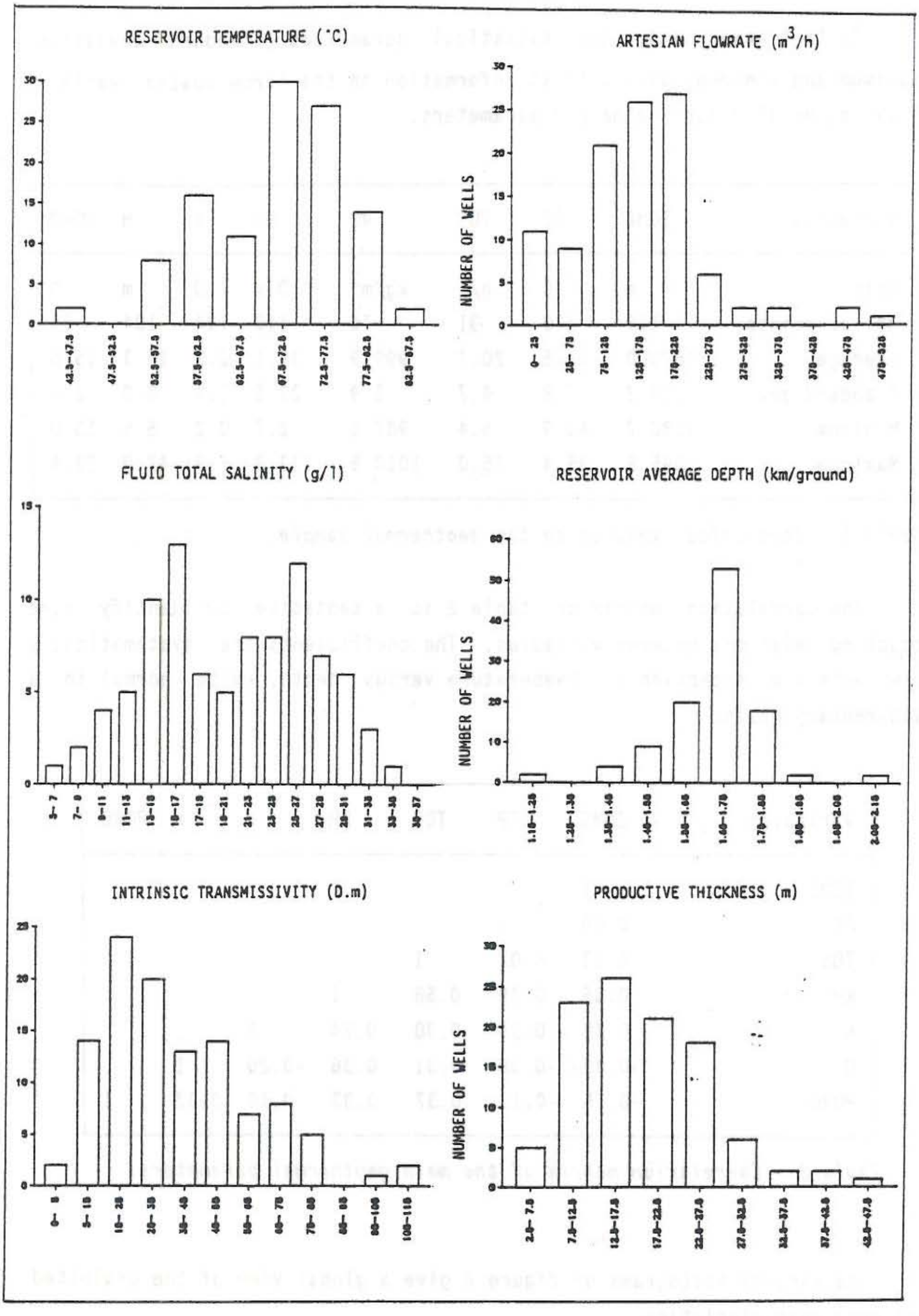

Fig. 8 - Histograms of the main characteristics of the geothermal resource in the Paris basin (vertical average for all the layers).

Contribution of the three facies

The introduction of the faciologic classification brings an additional information to correlate the amplitude and the variability of the parameters with sedimentology, depositional conditions and the later evolution of the porous matrix during the diagenetic processes. The oolitic facies is always present all over the area studied, with a major contribution to the total flowrate (at least 50%). The three facies exist and are productive in all the central part of the basin, where the Comblanchian (lagoon facies) is thicker. In the south of Paris, the contribution of Comblanchian and Alternances are more hazardous. Comparing the histogram of transmissivity and the paleogeographic model (fig. 9) confirm the main importance of the facies of oolitic barrier; the permeability of which has been increased by circulations of meteoric waters after deposition.

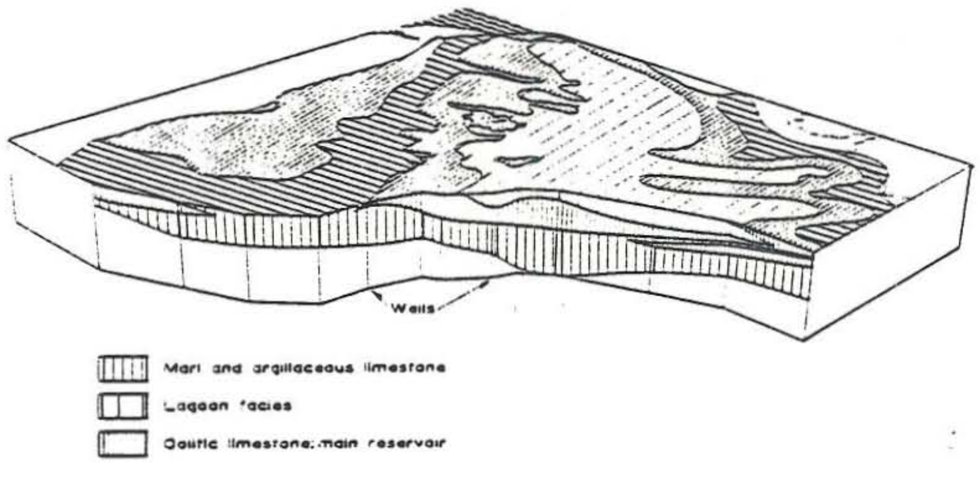

Fig. 9 - Block diagram of paleogeography of the Dogger reservoir at the end of the Bathonian.

CONCLUSIONS

The 110 geothermal wells drilled and tested, in the central area of the Paris basin, represent an important source of informations for the detailed knowledge of the Dogger reservoir. With the help of flowmeter logging, the major diagraphy for low enthalpy reservoirs, an accurate decription of the production profile has been obtained. The main lessons are, (i) the vertical heterogeneity and (ii) the stratification of the production in numerous and thin layers.

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REGIONAL DISTRIBUTION OF THE DOGGER PARAMETERS AND RESERVOIR KNOWLEDGE - PARIS BASIN

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INTRODUCTION

The main concept of reservoir characterization becomes progressively a sientific and specific discipline to address the requirements of deep resources evaluation and basins knowledge. Because analytical aspects are numerous and complicated, the aim of the approach is to define the numerical model of the reservoir parameters with the help of database structure; the input needed to predict flow and heat transfers. The result is a set of coupled distributions in space and time where each parameter brings additional informations from its various interactions and memory.

The synthesis performed on the Dogger case study is the conclusion of several years of research focused on the central area of the Paris basin and the analysis of a hundred geothermal wells. It demonstrates the feasibility of a multi-field approach in three ways: geology-sedimentology, fluids geochemistry and geostatistics-reservoir modelling.

The first topic is attached to sedimentologic characterization and diagenetic evolution of the reservoir. This includes the identification of the numerous productive layers and the evaluation of the individual parameters from diagraphies and petrophysical measurements on cores.

For the second topic, the geochemical synthesis includes a development of the analytical methodology and various conclusions relating to fluid chemical heterogeneities, isotopic composition and the limits of quantitative techniques for fluids dating. The characterization of rare and inert gaseaous species allows the study of thermodynamical processes linked to fluid composition and the use of geochemical geothermometers.

The last approach related to reservoir modelling is based on the compilation of geometrical, thermal and hydraulic data obtained from well testings. The well database built on this set of data gives the vertical structure of productive layers and the regional distribution of the main parameters using the geostatistical method. From this latter all the available data are bring together to construct a synthetic model of the reservoir. The main conclusion is the identification of spatial heterogeneities and specific anomalies induced by the correlation between the coupled parameters. This new concept of interdependance or coherence of the spatial distributions is an important information for the calibration of the synthetic reservoir model.

OBJECTIVES AND METHODOLOGY OF THE REGIONAL INVESTIGATIONS

The estimation of the parameters distribution is quite a common practice in reservoir engineering as soon as the number of point informations is sufficiently large. For this purpose and in addition to the latter constraint, the second main condition, to be examined carefully, is the spatial density of the available measuring points. The sampling distribution from which data are obtained is never uniform in practice, and thus the method to be used must include the concept of distance between the location for estimation and the known points. This kind of problem can be easily solved using the geostatistical approach.

Trying to justify the regional approach of parameters distribution one can identify two main objectives:

- **the overall knowledge of the geothermal resource** in order, (i) to understand the average characteristics, (ii) to explain the various abnormal areas, and (iii) to locate the optimized locations for future exploitations. After identifying the structure and vertical heterogeneities of the reservoir in a limited number of places (wells) in a first step, the aim of the second one is to estimate the physical and hydraulic lateral continuity of the productive layers. Such an investigation at large scale with the identification of regional trends is also a way to improve the numerical estimations, comparing these results with the paleogeography and the history of the whole basin.

- **the detailed knowledge of reservoir characteristics** at the doublet scale to improve the exploitation forecasts of the existing wells. Verification of the hydraulic continuity of the reservoir and the possible local limits is especially important in the case of development of the resource by well doublets with reinjection. Firstly, it's because of reinjection and the local continuity of the reservoir that their productivity can be maintained; thanks to hydraulic interference between the two doublet wells the exploitation pressure can be maintained fairly constant over a period of time . However, in the case of scarce and thin productive layers there is a risk of quick recyclage of reinjected cold water towards the production well. Exact knowledge of the geometrical characteristics enables the distance between the wells and the production flow rate to be planned in correspondance with the desired lifetime of the system.

Geostatistics is a method of estimating based on the theory of regionalized variables (Chiles, 1977). Its implementation comprises two main stages:

- Determination of a variogram which defines the structure of the experimental values: continuity, uncertainty factor, notion of overall regional drift, notion of range, i.e. the distance from the interior of which a correlation exists between the values of the variable under consideration.
- Estimation of the value of the variable at every one of the intersections of a regular grid by exploiting the aforementioned variogram model.

This method, well adapted to the problem under consideration enables an efficient and reliable relation to be established between, the analysis of spot data on the wells, and the simulation of reservoir behaviour by heterogeneous models requiring a large quantity of data. The method offers three main advantages:

- automatic mapping of the estimated parameters,
- mapping the precision of the estimations (standard deviation),
- automatic generation of data files at the geometric grid intersections identical to that required by the simulation models.

The general frame of the whole approach is illustrated on figure 1.

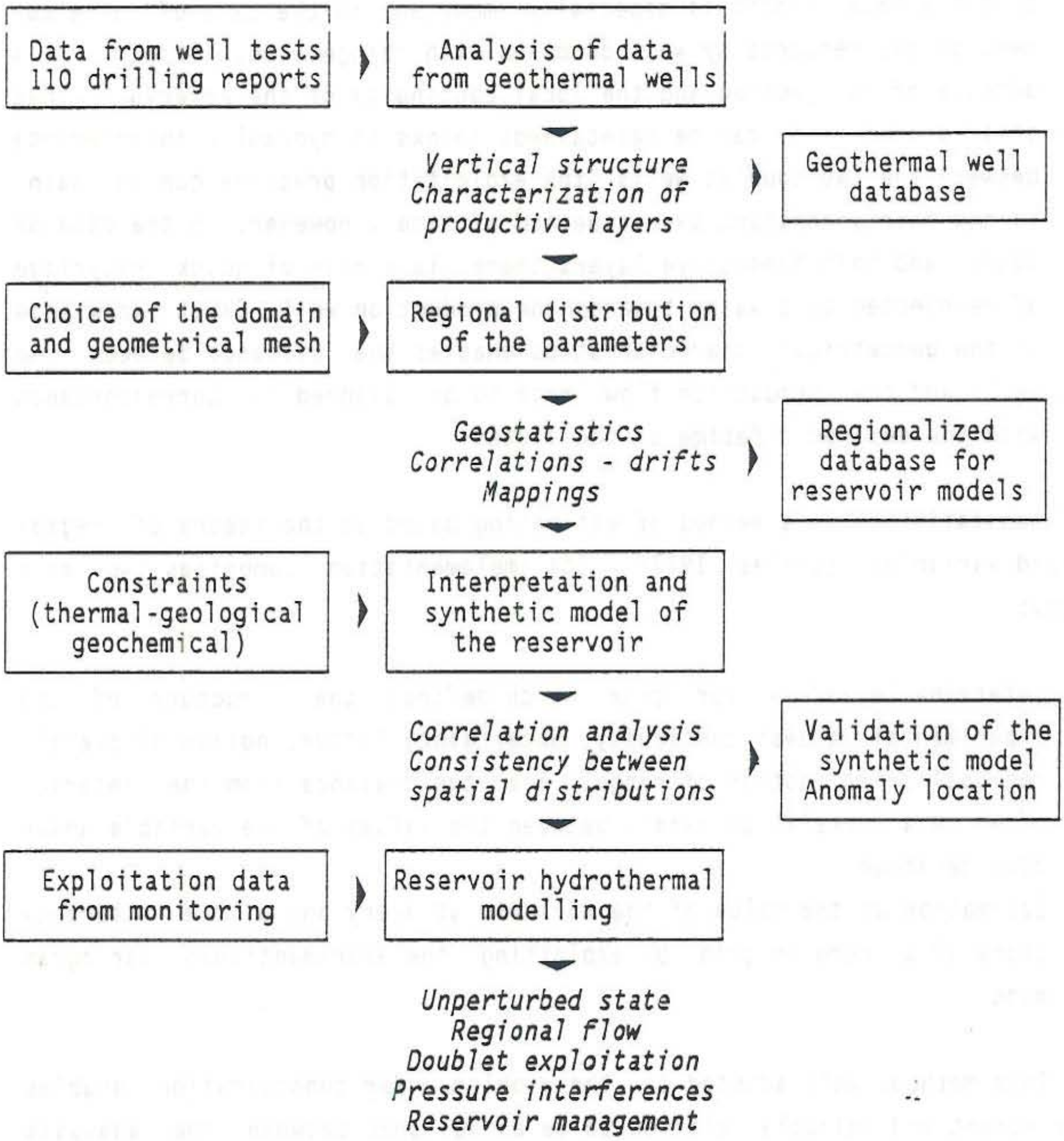

Fig. 1 - General frame of the approach for the reservoir characterization.

Parameters studied

The nine main parameters selected are those required by the modelling and the estimation of the geothermal energy resource, this includes both the porous matrix and the fluid characteristics:

- the average barycentric depth of the productive layers ZGMS, referenced to ground level,
- the reservoir production temperature TP,
- the fluid total salinity TDS,
- the density of the fluid RO,
- the intrinsic transmissivity Kh,
- the relative transmissivity Kh/μ,
- the relative permeability K/μ,
- the cumulated productive thickness h,
- the reservoir static pressure HPP.

Study domain

The domain choosed for the detailed regional study is a rectangular area, 90 km along the west-east axis and 100 km along the north-south axis. The area is sampled by 106 geothermal wells (see figure 2 for the location of the wells). The four last wells, available but not displayed, have been included in the geostatistical analysis to obtain some kind of long range correlation at basin scale.

REGIONAL DISTRIBUTIONS : SELECTED EXAMPLES

Three distributions are selected here among the nine studied. Each map is composed of the contour lines for the variable choosed, the location of the wells used, the main cities and rivers. The limit of the marly belt, an impervious boundary at the south-west, is only a graphical superposition. This information (in fact a geological constraint) is not included in the analysis.

Figure 2 gives a view of the average productive depth, in meters relative to ground level. This typical parameter of the reservoir is obtained by averaging the depth of the individual productive layers of each well, weighted by the relative production of each one (flow-meter information) . A regional drift, northwest-southest is identified; it is consistent with the direction of subsidence of the basin, and a ratio of 5 m/km, typical of shelf basins. 50% of the exploited wells are located in the range 1600-1700 m. From the varigram analysis, the parameter is found continuous, with a correlation range of 20 km. This map, associated with the equivalent for productive thickness, give the geometrical support for the synthetic model and the distribution of the other parameters.

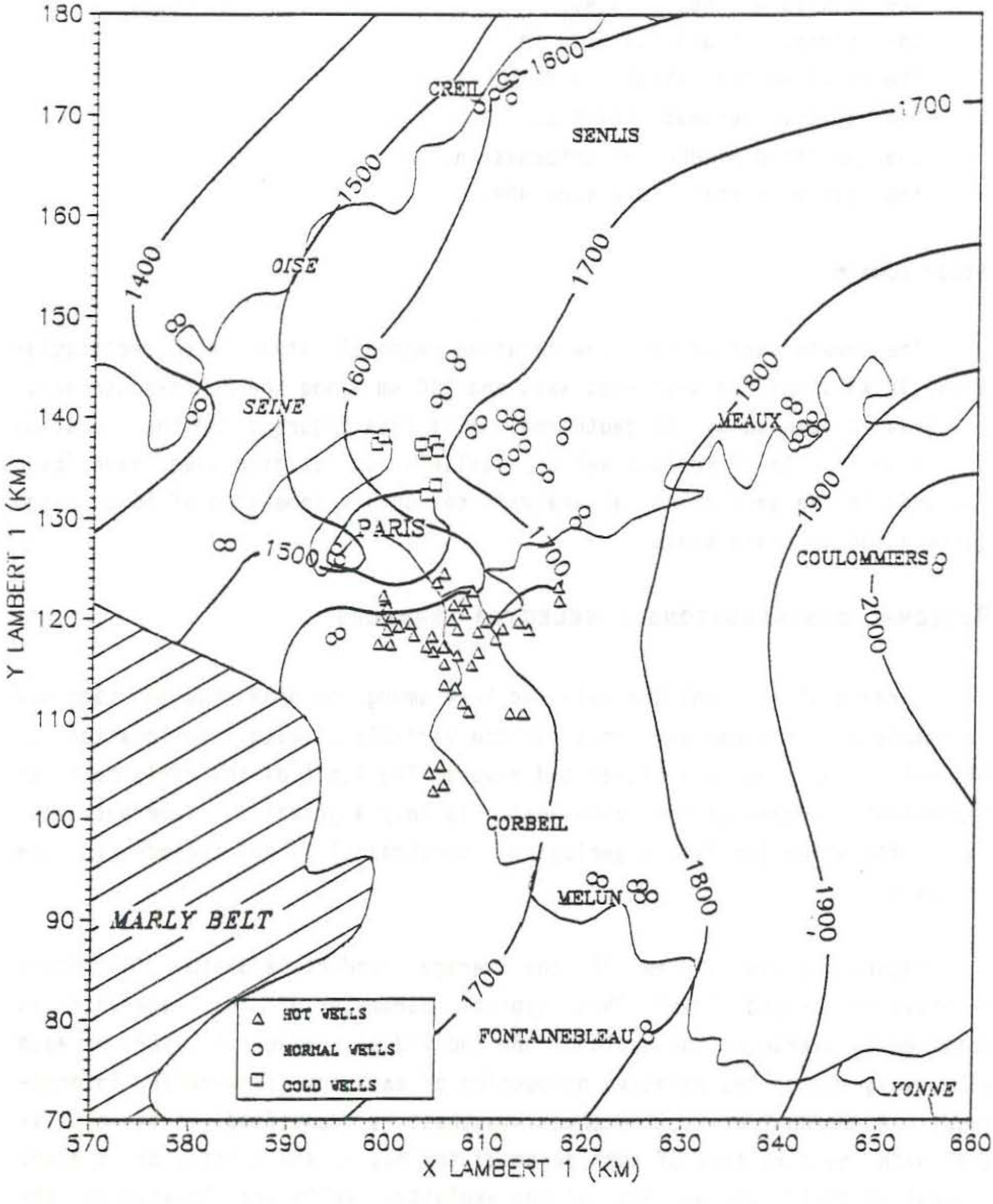

Fig. 2 - Spatial distribution of the average productive depth in the Dogger reservoir (Results of the geostatistical analysis).

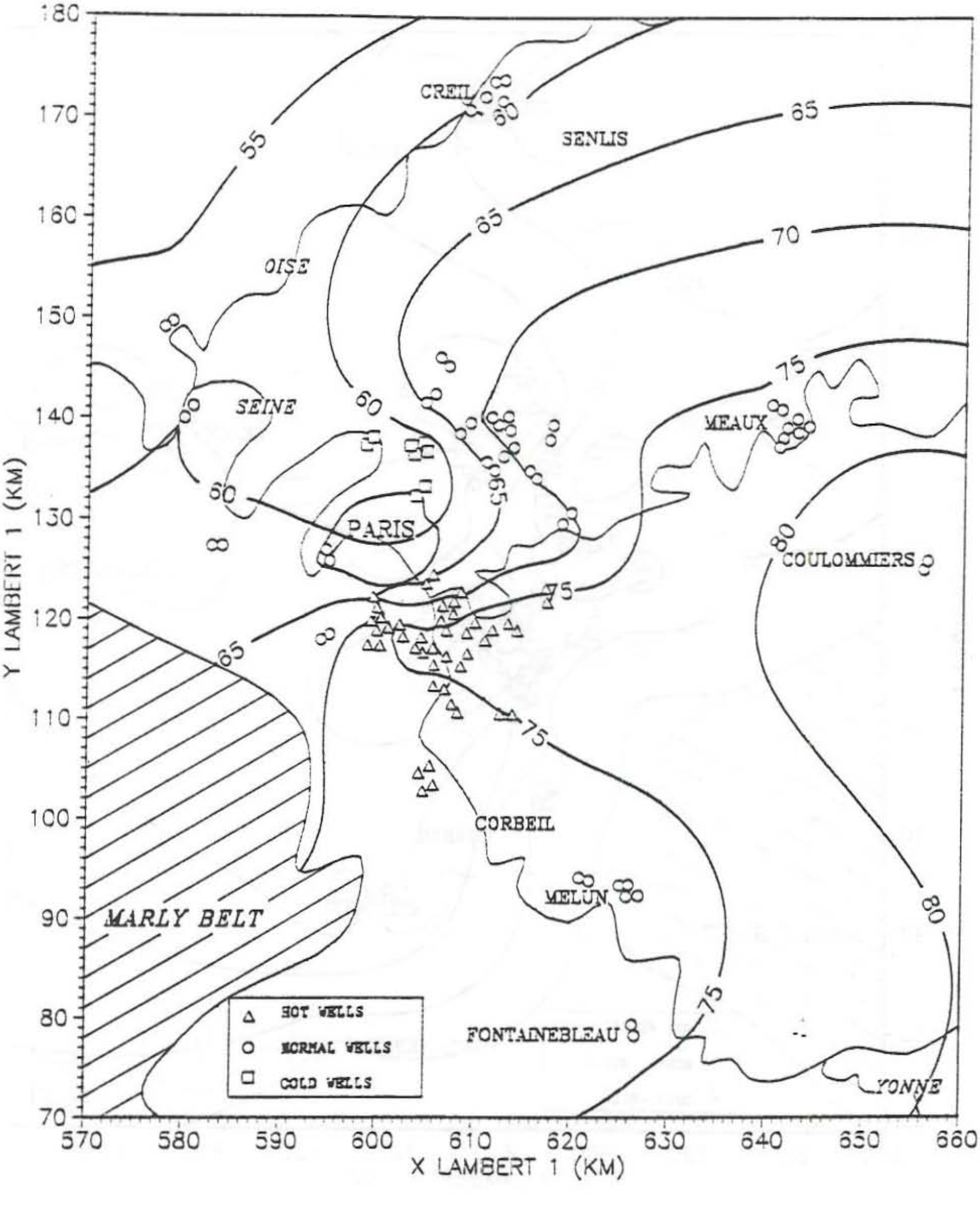

Fig. 3 - Spatial distribution of production temperature in the Dogger reservoir (Results from the geostatistical analysis).

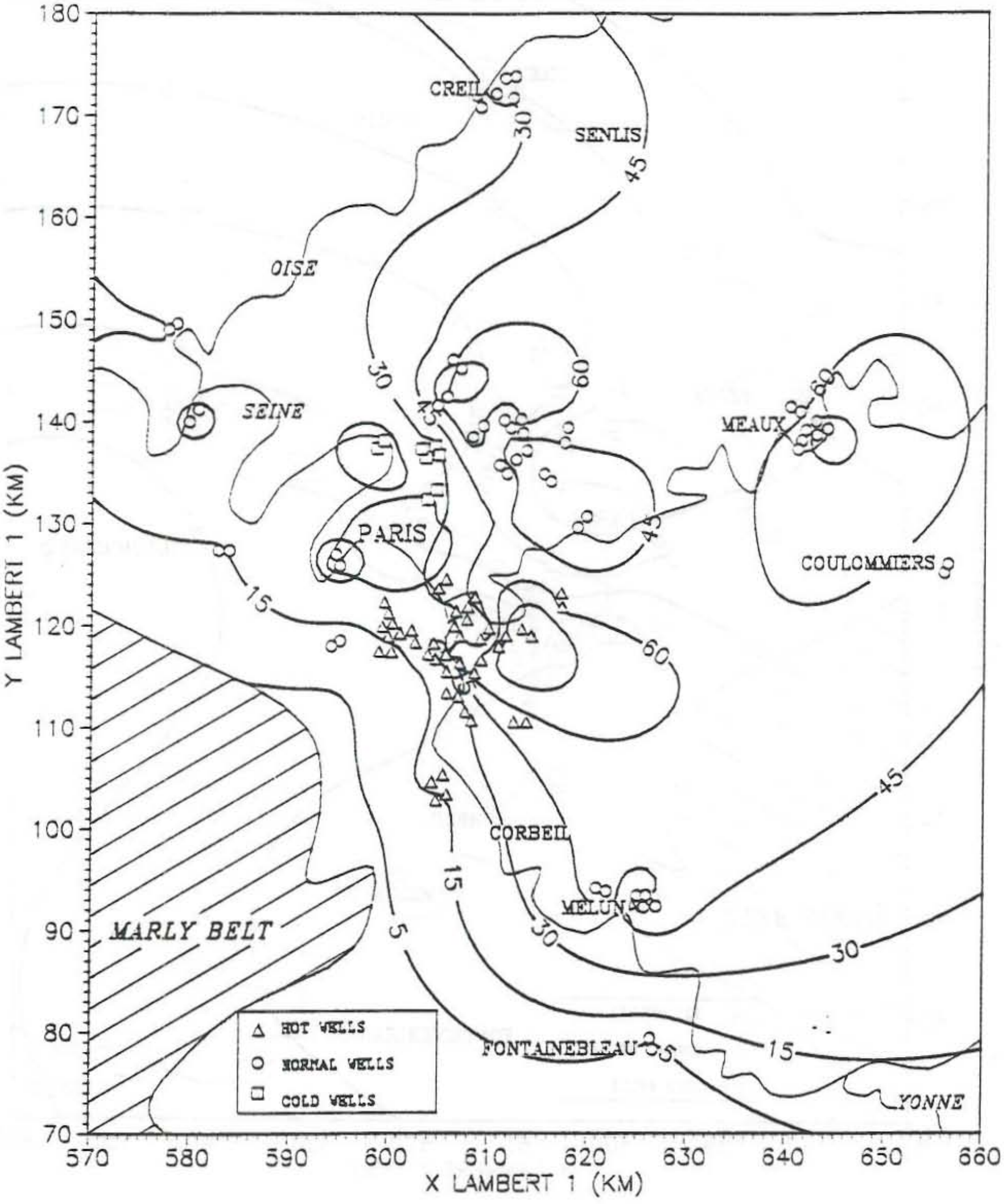

Fig. 4 - Spatial distribution of the intrinsic transmissivity of the Dogger reservoir (Results from the geostatistical analysis).

Reservoir native temperature is shown on figure 3, with the same regional drift orientation, as a consequence of the average correlation with depth. This spatial distribution of temperature is continuous, the standard deviation of the geostatistical estimation is less than 5°C at a distance of 10 km from a given well. For the same productive depth (1700 m) and on the basis of a continental geothermal gradient of 33°C/km, two abnormal areas are identified: (i) a hot anomaly (+10°C) at the south of Paris, and (ii) a cold one (-8°C) just at the north.

The spatial distribution of the intrinsic transmissivity, integrating both the permeability and the net pay is displayed on figure 4. No regional drift is identified in this case, and the structure of the parameter is mainly heterogeneous. At small scale and for a few doublets, the measured values were characterized by a variation of 100% over a distance of 1 km. However at regional scale the distribution is consistent with the structure of the paleaogeographic model. For instance, the estimated transmissivity decreases continuously down to zero towards the southwest direction. The existence of an impervious boundary (the marly belt) is thus obtained, independently of any imposed geological constraint. That means that this information is an intrinsic property of the data structure. On the other side, the maximum transmissivity is obtained in the deepest area, where the thickness of the productive layers is maximum, and all the facies present. The complete understanding of the distribution can't be achieved through the analysis of present-day informations. This requires the knowledge of past phenomenas and especially the diagenetic evolution of the matrix.

REGIONALIZED DATABASE AND SYNTHESIS

The first characteristic of the Dogger production is the vertical heterogeneity. As no correlation was identified between the individual productive layers, the first tentative was made by grouping all the layers in three classes according to the main facies (Comblanchian, Oolit, Cyclical unit). Examined at regional scale and for the purpose of mapping, the characterization of each facies failed, as a consequence of too important random components. The detailed analysis of geographic sub-zones is the only case in which a regionalized data structure was identified for the main reservoir parameters. Finally, a single aquifer-equivalent was assumed. The individual productive thickness is thus cumulated and assigned to the barycentric productive depth to obtain the geometry of the synthetic model.

The second characteristic of the reservoir parameters is the important lateral variability illustrated on figure 5. This diagram is an extract of the regionalized database where the distributions of five parameters have been superposed to examine correlations.

The reservoir topography at the bottom shows the amplitude of the dip angle. The typical relief in the center (anticlinal of Meudon) separates the two abnormal hot and cold zones mentioned above. The two thermal anomalies are in spatial coincidence with the equivalent anomalies for salinity. According to the topography distribution, these perturbations may be induced by two kinds of local phenomenas: regional flow and/or abnormal geothermal flux. The maximum values of transmissivity are found in the deepest area, and also in coincidence with two hot and salty areas. Finally, the upper map charcaterizes the hydraulic potential and the regional flow path.

The analysis of the synthesis diagram brings to light the existence of a coupling between the main parameters:

- hydraulic head and pressure are conditioned by the relative transmissivity,
- relative transmissivity depends on fluid viscosity and therefore on temperature and salinity distributions,
- temperature and salinity distributions are induced by regional flow,
- and in turn, flow is determined by hydraulic head or pressure.

This leads to the following major consequences for basin range modelling:

- the usual gravity driven flow under the assumption of constant density (hydrogeological approach) may be locally perturbed by an additional component, the density driven flow,
- in such a sedimentary basin, the spatial distribution of a given parameter is not independent, but related to the structure of the other coupled variables. This leads to the concept of consistency

between distributions; an additional fitting criteria to improve reservoir characterization.

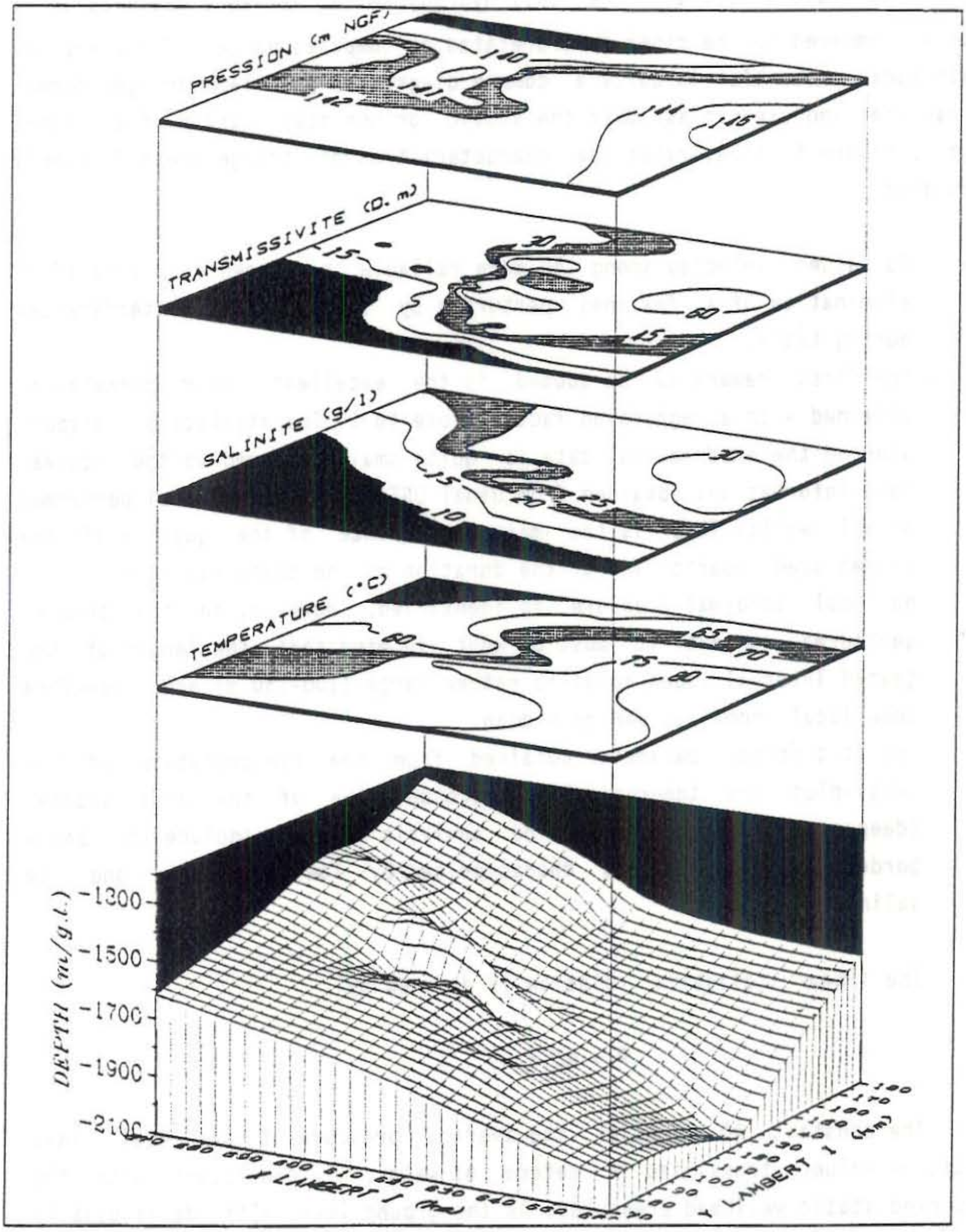

Fig. 5 - Visualization of the Dogger reservoir database. Superposition of 2D mappings for reservoir parameters and of a 3D view of the average productive depth (geothermal area of 10 000 km^2 around Paris).

PRESSURE-ALTITUDE CORRELATION

The fluid pressure is the only hydrodynamical variable measured on a well, compared to the other interpretated or computed values. The pressure-altitude cross-plot is quite a common diagram in petroleum or geothermal practice, and used to estimate the static or non static state of a reservoir. Figure 6 illustrates the characteristics of the geothermal sample studied:

- 88 values, selected among the more reliable, have been displayed after elimination of a few ones perturbed by the hydraulic interferences during tests,
- the first remark to be quoted is the excellent linear correlation obtained with a regression factor close to 1. The statistical dispersion od the experimental data is quite small compared to the equivalent informations obtained from usual DST (Drill Stem Tests) performed on oil wells. This is the main consequence of the quality of the probes used (quartz) and of the duration of the tests (12-24 h).
- no local abnormal pressure is identified. However, in the present geothermal context, it must be kept in mind that the length of the tested interval (open hole) is rather large (100-150 m) and therefore some local anomalies can be hidden.
- the statistical parameter obtained from the interpretation of the cross-plot are theoretically representative of the area studied (deepest zone of the basin). The analysis does not include the basin borders and the outcrops characterized by low temperature and low salinity fluids.

The linear statistical relation is defined by:

$$P = A0 + A1 \cdot Z$$

The constant A0 expresses the average pressure at sea level. This positive value, translated in meters of water, is consistent with the observed static wellhead pressures. As the ground level altitude is usually less than this latter value, 94% of the geothermal of the area are artesian. Converted to the convenient unit, the factor A1 is the density of the fluid, averaged along a streamline issued from the measuring point and reaching the outcrops. This vertical pressure gradient, a little higher (1.1%) than the fresh water hydrostatic gradient is controlled by the distribution of the fluid density at basin scale. To quote a few guidelines, the analysis shows that:

- the present reservoir state is quasi-hydrostatic,
- an hydraulic connection (or continuity) is proved between the center of the basin and the outcrops in the eastern border,
- an invasion of meteoric waters is still in progress from these latter,
- on average and at basin scale, the horizontal component of the regional velocity is small.

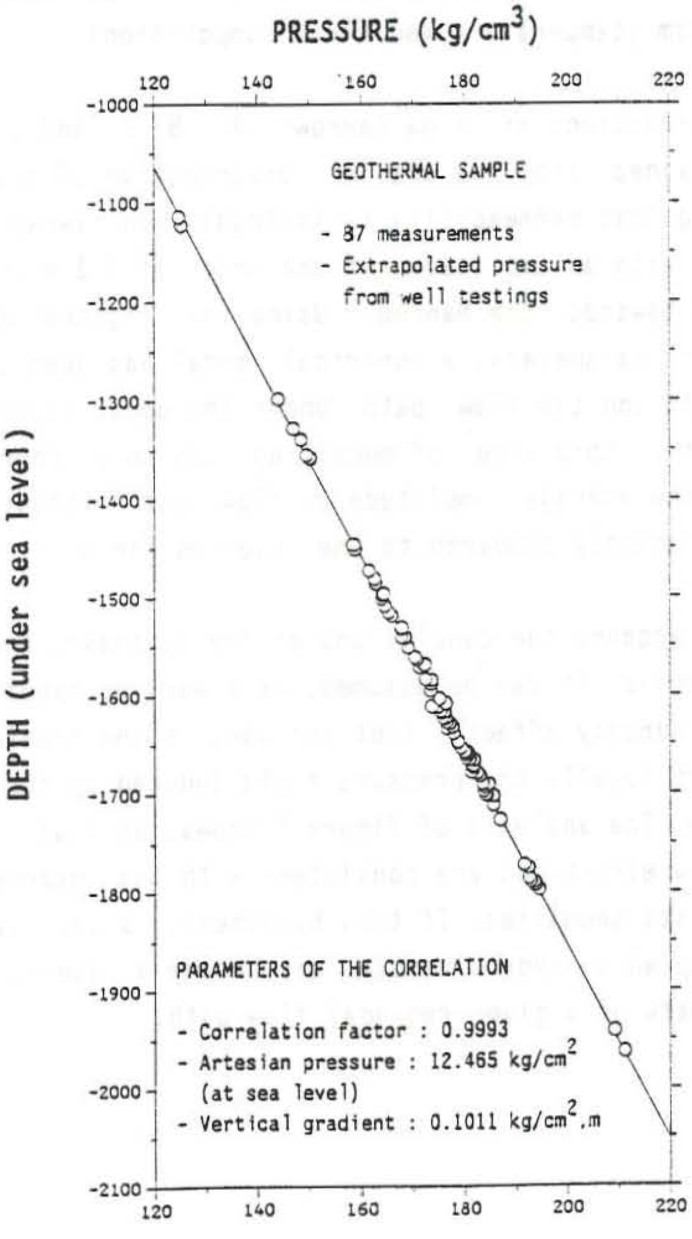

Fig. 6 - Correlation of fluid pressure with altitude in the Dogger reservoir (experimental data from well testing).

REGIONAL FLOW IN THE GEOTHERMAL AREA

A few studies have been devoted to qualitative or quantitative estimates of regional flow at basin scale in the Dogger, mainly for oil exploration purpose. On this basis, the quality of geothermal data have allowed additional analysis to be performed in two main ways:

- detailed mappings focussed on the geothermal area from experimental data,
- fitting and control, taking benefit of the parameters coupled to hydrodynamism (temperature and fluid composition).

The main directions of flow (arrows A, B, C and D) displayed on figure 7 are obtained from the spatial distribution of measued pressures (fig. 5) assuming that permeability is isotropic. On average, the regional velocity is low, with an amplitude of the order of 0.3 m/yr. (Darcy velocity) orientated towards the Manche. Using the regionalized database to quantify reservoir parameters, a numerical model has been used to compute the pressure field and the flow path. Under the usual assumption of constant fluid density, this kind of modelling can only reproduce the main orientation and the average amplitude of flow, but without any local and typical pressure anomaly compared to the observed field.

Taking into account the conclusions of the synthesis and the existence of coupled phenomenas, it can be assumed, as a working hypothesis, that the influence of the density effects (not included in the previous modelling) is able to perturb locally the pressure field induced by the gravity driven component od flow. The analysis of figure 7 shows, at least qualitatively, that the main flow directions are consistent with the observed temperature distribution and its anomalies. If this hypothesis is validated, the use of the variables coupled to hydrodynamism can become a powerful technique to control the estimate of a given regional flow path.

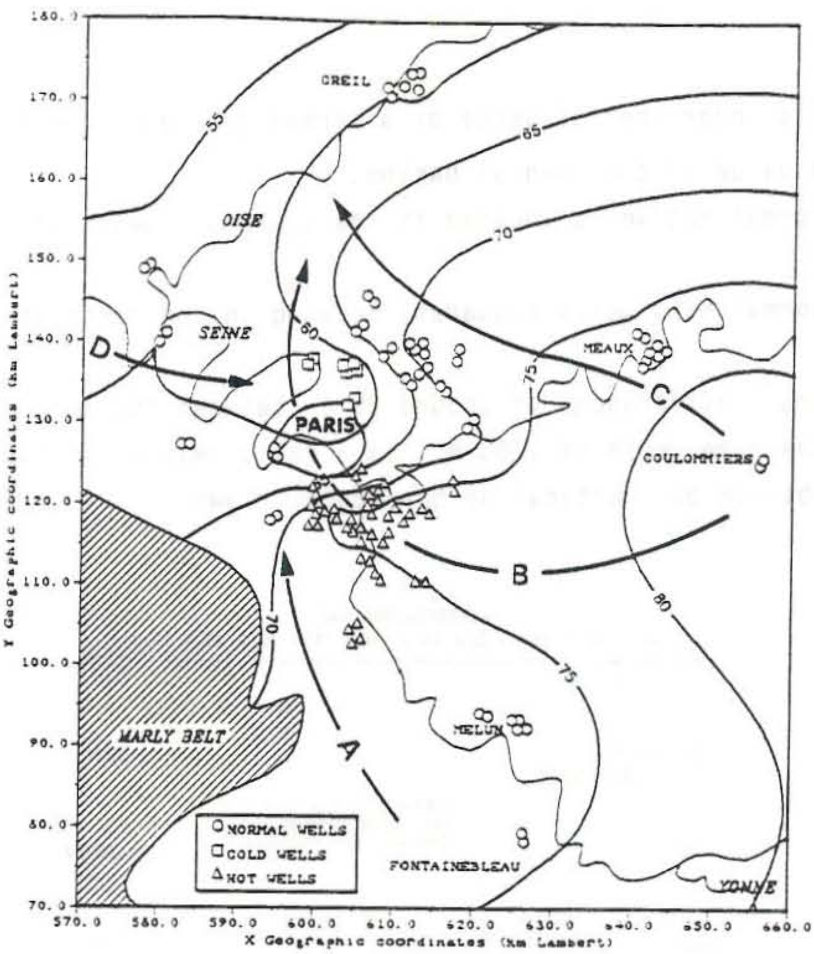

Fig. 7 - Main directions of regional flow in the geothermal area superposed with a map of reservoir temperature.

TEMPERATURE-DEPTH CORRELATION

The analysis of temperature-depth cross-plot is a common practice in geothermal exploration; it allows to suspect the influence of local flow in addition to the permanent effect of the geothermal flux. The 110 temperature values reported on figure 8 show that a lot of data deviates from the average linear law identified at the scale of the Paris basin (33°C/km). Knowing the range of thermal conductivity variation, these positive or negative deviations correspond to thermal gradients that are incompatible with observed geothermal fluxes under the hypothesis of a pure thermal conduction phenomena.

After identifying abnormal thermal gradients on the cross-plot, the most interesting result is the availability to locate geographycally the corresponding wells in very precise zones. For this purpose, the same symbols are used on figures 7 and 8. On a thermal point of view this approach leads to the identification of three classes of wells:

- the wells under the influence of a normal gradient (cercles) with the average value of continental basins,
- the abnormal hot wells located in the south-southeast of Paris (triangles) ,
- the abnormal cold wells (squares) located in the north of Paris.

The overall difference of around 20°C between the cold and the hot zones, for the same depth of 1700 m, is a valid reason for suspecting the local perturbation by vertical or horizontal flows.

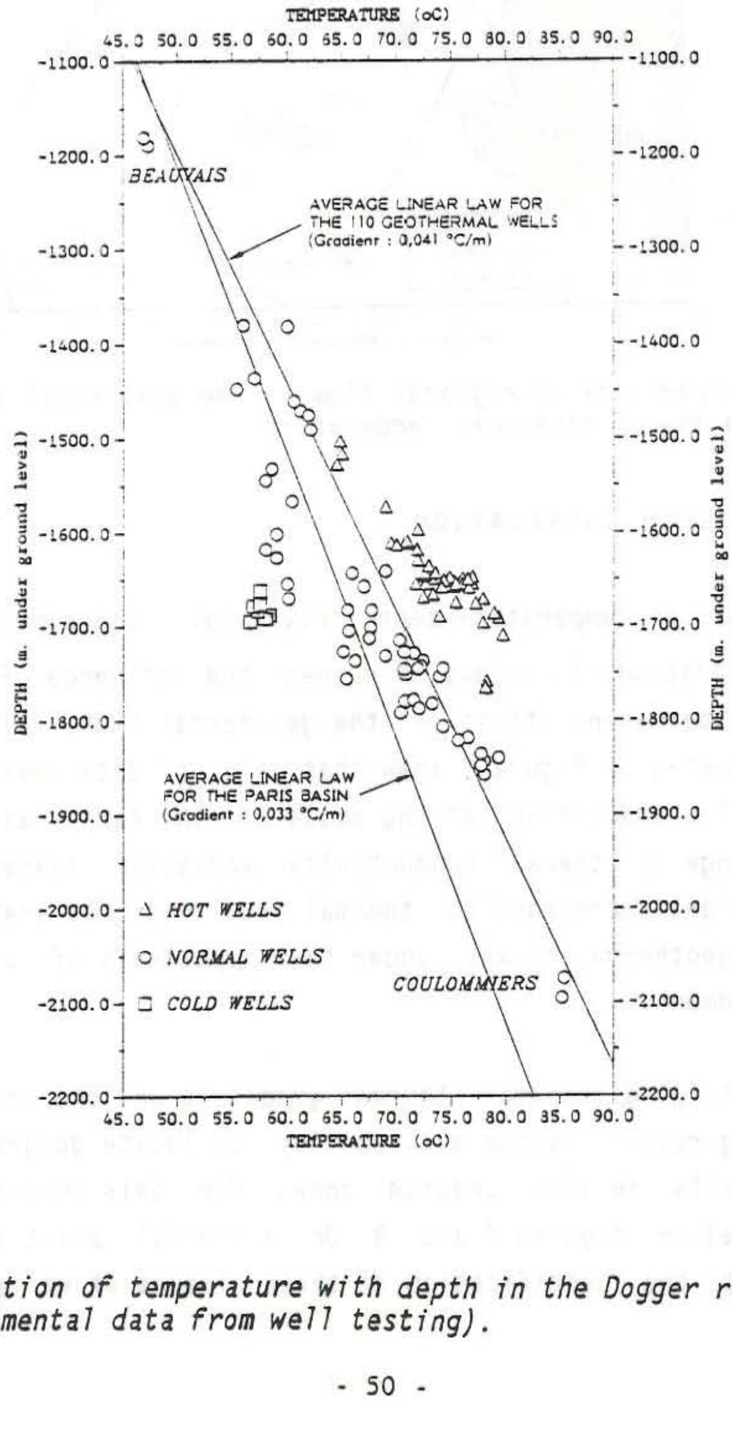

Fig. 8 - Correlation of temperature with depth in the Dogger reservoir (experimental data from well testing).

For a practical validation with modelling, a more sophisticated formulation is required when compared to the constant density approach. The hypothesis of flow in the thermal conductive problem introduces a competition between the conductive and the convective heat transfers; the former being mainly vertical while the latter has horizontal and vertical components. In such a case, the characterization of the reservoir topography becomes essential and determining.

CONCLUSIONS

The knowledge of the spatial distribution of a given reservoir parameter is highly dependent on the number and the density of known measuring points (the wells). For the Dogger case in the Paris basin and with the help of the wells database previously built from the data of 110 geothermal boreholes, a complete set of distributions for the the main parameters have been obtained. Using the geostatistical analysis two groups of parameters have been identified: (i) the geochemical and fluid parameters which are continuous and affected by a reliable regional drift, and (ii) the matrix parameters, more heterogeneous, without any regional drift and characterized by variable random components.

Hydrodynamism is characterized by a quasi-hydrostatic state, under the influence of a low invasion by meteoric waters from the outcrops. The analysis of thermal correlation with depth reveals important anomalies, accurately located in specific zones, and probably induced by a non homogeneous flow path, both gravity and density driven. The distribution of the total mineralisation of the fluid is very similar to those of temperature, and this consolidates the hypothesis of local or preferential flows. At present, the origin and the age of the fluids involved in the various mixing processes, and able to bring further geochemical constraints to the synthetic reservoir model, are still imprecise. An important lesson of this multi-field approach, applied to the Dogger case study, is the identification of a coupling between the major variables, which can be used as a calibration criteria.

In the way of the resource and reservoir management, the present synthesis provides a more reliable description of the reference state and consequently the support needed to quantify with numerical modelling the incidence of geothermal exploitation with doublets.

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LOW ENTHALPY GEOTHERMAL EXPLOITATION: THE DOUBLET SCHEME

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INTRODUCTION

On its principle, the doublet scheme combining a production and an injection well is not a new concept. Very early the use of water injection had long been practised in oil secondary recovery and in artificial recharge of aquifers. In these two cases the objectives of reinjection are: (i) to improve oil recovery, (ii) to control pressure depletion or (iii) to maintain a given exploitable flow rate. Generally reservoir management is focused on a group of wells with no systematic balance between injection and total production flow rates. The theory of reservoir hydrodynamism has been intensively studied by Da Costa et Bennett (1960), Muskat (1946), Bear (1979).

In France, the application to low enthalpy geothermal exploitation started at the beginning of the seventies, with the first doublet of Melun l'Almont in the south of Paris. Using the technical and classical knowledge of oil and water exploitation, the geothermal approach becames progressively more specific. A few major characteristics can be listed to identify the typical features of the geothermal exploitation in the Paris basin:

- at the early design stage, the management of the resource is not examined on a field basis. Each doublet has a distinct administrative owner, its own economical efficiency and thus the wells are always considered by pairs. Compared to the classical five spots pattern of the oil field industry, the elemental patch is here the producer-injector well-pair. It can be considered alone or in a given exploitation environment.

- as the heat resource is located both in the rock and in the moving fluid, the thermal behaviour of the reservoir and the production are strongly influenced by heat transfers coupled to hydrodynamism.

- at any time the total flow produced is reinjected (closed loop system). The only contact between geothermal fluid and distributed waters is through the thermal exchanger without any mixing process.

- the exploitation flowrates and the transmissivity values are higher than in the case of oil wells.

- the temperature and the salinity of the fluid are higher than in the case of drinkable water exploitation.

These above differences or constraints introduce the important concept of thermal breakthrough defining the life time of the system as a consequence of the general design and of the geometrical location of the wells at reservoir depth.

The approach of the hydrothermal doublet was investigated by Houpeurt (1965) and further by Gringarten et Sauty (1975),Sauty et al (1980), Goblet (1980) for the methodology and modelling.

For the Paris basin geothermal exploitation the waste waters can not be evacuated through the surface network in a urban context. The total flow is reinjected in the same Dogger aquifer for four main reasons after optimization of the distance between the wells:

- the high average total salinity of 20 g/l do not allow the use of a dilution process,

- the above phenomena is amplified by the important value of the exploitation flow rate produced from 150 up to 350 m^3/h,

- reinjection prevents too large pressure drops and stabilizes average reservoir pressure,

- therefore, reinjection of the total flow maintains the global hydraulic balance and the durability of the fluid production.

HYDRODYNAMISM OF A SINGLE DOUBLET

To examine the typical hydrodynamism of a single doublet one can consider the simplest theoretical case defined by the following assumptions:

- aquifer of constant thickness h and of infinite lateral extend,
- homogeneous and isotropic porous medium with constant permeability and porosity,
- impervious bedrock and caprock,
- two wells, with a distance D between them, working at constant flow rate Q (+Q for the injector and -Q for the producer).

Assuming the validity of the Darcy law, the pressure or the hydraulic head variation induced by the exploitation of a single well is given by the classical exponential-integral solution of the line source well:

$$dP = P(r,t) - Pi = -\frac{Q.\mu}{4\pi.k.h} . E_1\left(-\frac{\phi.\mu.Ct.r^2}{4.k.t}\right) \qquad (1)$$

thus, for $\frac{4.k.t}{\phi.\mu.Ct.r^2} > 100$, the log-approximation is reached:

$$dP = \frac{Q.\mu}{4\pi.k.h} \text{ Ln } \left(\frac{e.\phi.\mu.Ct.r^2}{4.k.t}\right) = -\frac{Q.\mu}{4\pi.k.h}\left(\text{ Ln } \frac{k.t}{\phi.\mu.Ct.r^2} + 0.809\right) \qquad (2)$$

			I.S. units	CGS-Darcy
with	Q	: flow rate	m^3/s	cm^3/s
	μ	: fluid viscosity	Pa.s	cp
	k	: intrinsic permeability	m^2	D
	h	: productive thickness	m	cm
	ϕ	: porosity		
	Ct	: medium total compressibility	Pa^{-1}	atm^{-1}
	e	: Euler constant		

The classical equation (2) shows that the drawdown in a single well is an increasing function of time, and proportional to the flow rate.

Considering two wells of opposite strength located at (+a,0) and (-a,0), the solution of the flow problem is obtained making used of the superposition principle. This powerful technique makes possible the generation of pressure behaviour for any number of wells and for various production-rates schedules from the basic constant-rate solution (2).

In the area of validity of the log-approximation and assuming that the fluid viscosity remains constant, the spatial distribution of the hydraulic potential is given by:

$$P = Pi + \frac{Q.\mu}{4\pi.k.h} \text{Ln} \frac{(x+a)^2 + y^2}{(x-a)^2 + y^2} \qquad (3)$$

Therefore, the lines of constant drawdown (or build up) dPo in the reservoir are circles with:

- the centre located at $x = \frac{E^2 + 1}{E^2 - 1}$ and $y = 0$
- a radius $R = \frac{2.E}{E^2 - 1}$
- and $E = \exp (2.\pi.k.h.dPo / Q.\mu)$

These simple relations are commonly used to define analytically the size of the hydraulic protective perimeter for a prescribed pressure variation in the reservoir (fig. 1).

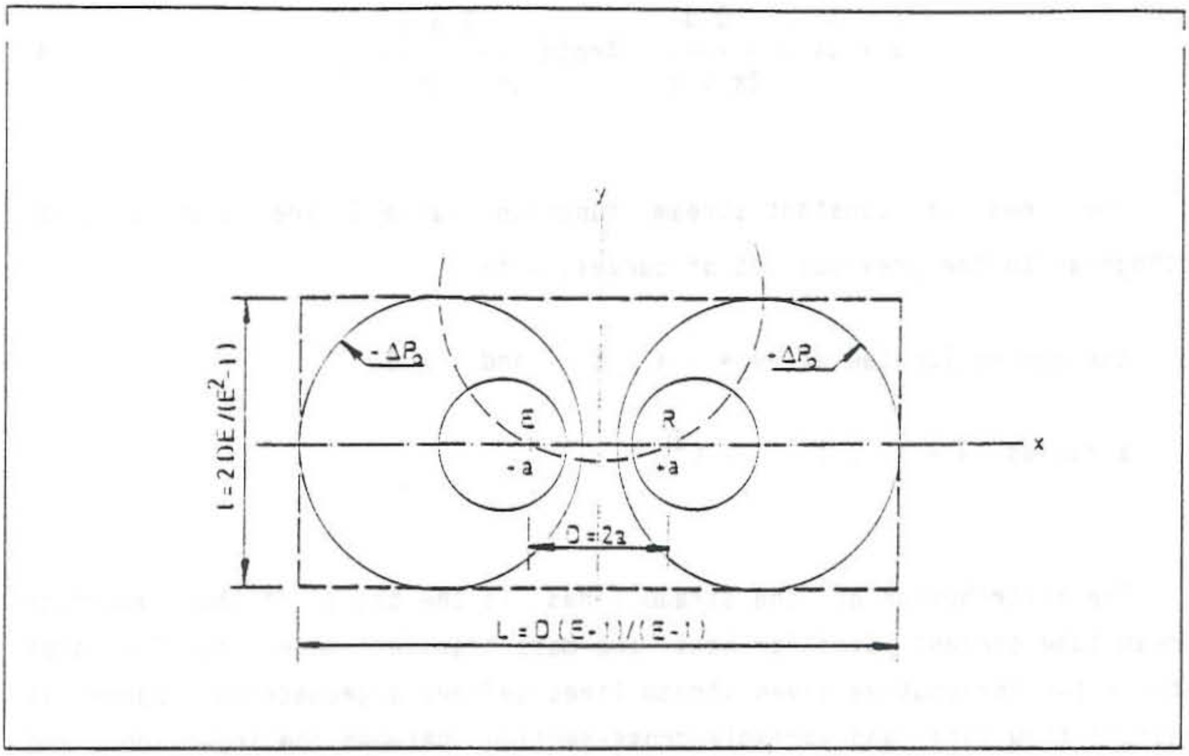

Fig. 1 - Geometrical characteristics of pressure distribution and stream lines around a doublet.

As a consequence of the superposition principle two typical features of the doublet scheme, when compared to the single well system, can be derived from equation (3):

- at a given location in the reservoir and assuming that the log-approximation is valid, the pressure drop induced by the exploitation is constant in time as long as the flow rate remains unchanged,
- for any point in the reservoir, the amplitude of the drawdown (or the build up) induced by a doublet is lower than the single well-equivalent. This is due to the composition of the opposite hydraulic influences of the two wells. For the same production flow rate the hydraulic protective perimeter is thus much smaller in the case of a doublet than in the case of a single well system.

The flow path around the two wells of a doublet can be examined looking at the distribution of the stream function ψ :

$$\psi = \psi i + \frac{Q.\mu}{2\pi.k.h} \; . \; \mathrm{Arctg} \; \frac{2.a.y}{a^2 - x^2 - y^2} \tag{4}$$

The lines of constant stream function value C are also circles, orthogonal to the previous set of curves, with:

- the centre located at $y = - a / C$ and $x = 0$
- a radius $R = a. \sqrt{1 - 1 / C^2}$

The distribution of the stream lines is the basis of the important stream tube concept used for heat and mass transfer modelling. The area between two consecutive given stream lines defines a geometrical channel at constant flow rate and variable cross-section between the injection and the production well. Each stream tube is therefore characterized by a flow rate and a typical time of transfer along it (breakthrough time). In more complex cases, the geometry of a stream line can be obtained numerically in a step by step process integrating the successive positions in space of a particule issued from the injection well through the velocity field.

THERMAL BEHAVIOUR OF A SINGLE DOUBLET

The approach of the reservoir thermal behaviour around the wells is imposed by two intrinsic features of the doublet scheme:

- the injection-production process creates an artificial velocity field and an hydraulic link between the wells which is maximum along the shortest stream line. After a typical period (hydraulic breakthrough time), an increasing proportion of the injected flow rate reaches the production well. The production flow composition is thus a variable mixture with time of the reservoir original fluid and of the injected water. This typical time is a function of reservoir characteristics, geometry and the average production flow rate.

- as the fluid is cooled by the heat exchanger before reinjection, a cold body develops and grows around the injection well. The early isotropic cylindrical shape is progressively distorded by the velocity field, up to the initiation of a connexion towards the production wells (fig. 2). Then, when the cold waters reach the production well at thermal breakthrough time, the mixture process induces a progressive decrease of the whole production temperature. This phenomena which leads to the system life time definition is attached to the concepts of thermal velocity and thermal fronts.

THERMAL VELOCITY AND FRONTS.

As a consequence of injection, the displacement of a thermal front by convection inside the porous medium creates a temperature gradient between the moving fluid and the solid matrix. This transient conduction process will reach a new equilibrium state characterized by a negligeable thermal gradient between the two phases. It has been demonstrated (Houpeurt, 1965) that this equilibrium is instantaneous at practical time scale and for the usual porous media. The equilibrium temperature (average aquifer temperature) is the result of the local mixture of the hot rock with the cold water particules moving in the pores. Neglecting thermal diffusion processes the theoretical interface between the original hot aquifer and the cooled area is named thermal front. The velocity of the thermal front (thermal velocity Vth) is greater than the average Darcy velocity Vd in the ratio of fluid and aquifer heat capacity, and lower than the true velocity of water particules Vr.

For the usual following parameters:

- heat capacity of fluid Cf = 4.18 MJ/m^3,K
- heat capacity of rock Cr = 2.09 MJ/m^3,K
- total porosity $\phi = 0.15$
- effective porosity $\omega = 0.10$

one can obtain the overall aquifer heat capacity Ca, applying some kind of mixing formula:

$$C_a = \phi \,.\, C_f + (1 - \phi) \,.\, C_r = 2.40 \text{ MJ/m}^3\text{,K}$$

and thus, the relation between the three velocities mentioned above:

$$Vd \;<\; Vth = 1.7 * Vd \;<\; Vr = 10 * Vd$$

with,

$$Vth = \frac{Cf}{Ca} \,.\, Vd \tag{5}$$

$$Vd = \omega \,.\, Vr \tag{6}$$

The application of the thermal velocity concept to pure convection without any diffusion phenomena in the reservoir leads to the typical pattern of the doublet shown on figure 2. The successive positions of the thermal front (defined above) represented in full line are isochronal lines; the stream lines (dotted lines) are characterized by their own thermal breakthrough time.

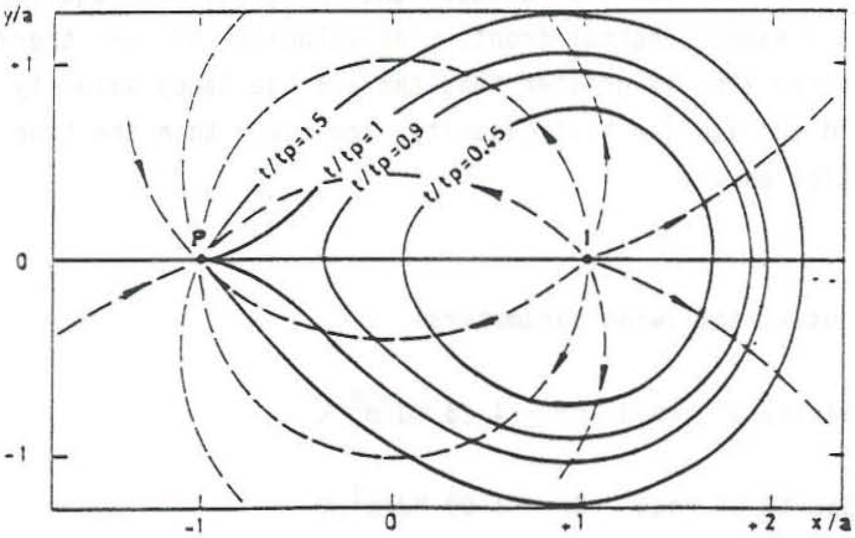

Fig. 2 - Typical hydraulic and thermal pattern of a doublet.

Figure 3 is an example of the typical evolution of the temperature versus time at the production well of a doublet. It shows the influence of heat transfer through walls and heat conduction in the aquifer on the recycling curve for pure convection. The temperature drop is gradual and production can continue beyond the lifetime, provided that pumping temperature remains compatible with surface plant characteristics and economic profitability criteria.

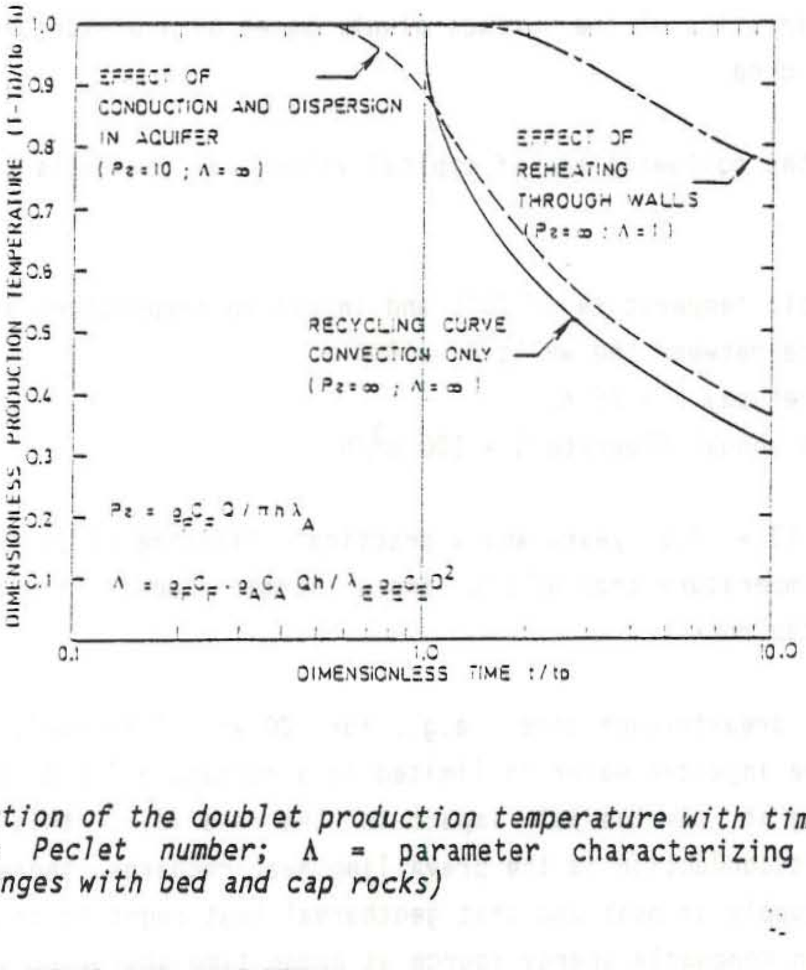

Fig. 3 - Evolution of the doublet production temperature with time. (Pe = Peclet number; Λ = parameter characterizing the heat *exchanges with bed and cap rocks)*

BREAKTHROUGH TIME AND LIFETIME

Assuming that the major thermal phenomena in the reservoir is convection, and neglecting the influences of diffusion and regional flow, the thermal velocity can be integrad analytically along the shortest streamline to give the typical breakthrough time tB:

$$tB = \frac{\pi}{3} \cdot \frac{Ca}{Cf} \cdot \frac{D^2 \cdot h}{Q} \qquad (7)$$

This relation shows the influence of the three main parameters D, h and Q. D and Q are choosed as a result of the design process through modelling. The parameter h is characteristic of reservoir production and must be measured accurately. The thermal breakthrough time is equivalent to the time of arrival of the first cold water particules to the production well. At this time, as the corresponding recycled flow rate is very small, the equivalent temperature drop is negligible. As time increases the production temperature drop becomes more significant and this allows the definition of the lifetime. It is a practical concept taking into account the characteristics of the surface plant, based on a prescribed admissible temperature drop.

Using the following set of typical values for the Paris basin exploitation:

- reservoir temperature of 70°C and injection temperature of 35°C,
- distance between the wells D = 1000 m,
- total net pay h = 25 m,
- average annual flowrate Q = 100 m^3/h,

one obtains tB = 17.2 years and a practical lifetime of 39.4 years for a precribed temperature drop of 2°C and a thermal conductivity of 2.5 W/m,K in bed and cap rocks.

At the breakthrough time (e.g., for 20 yr. lifetime), the thermal impact of the injected water is limited to a rectangle 1.5 D long and 1.1 D wide. Looking at the thermal impact in the reservoir, this means that, wherever heat conduction is the prevailing heat recharge, there is practically no resupply of heat and that geothermal heat ought to be regarded as a fossil, non renewable energy source at human time scale.

A useful practical application can be deduced, looking at the ratio between the thermal velocity and the true velocity of fluid. As the value of this ratio is around 6, the use of a chemical tracer injected with the cold waters, leads to a chemical breakthrough occuring 6 times faster than the thermal breakthrough. Chemical tracing is thus a powerful opportunity to validate the overall doublet design early before the first temperature drop at the production well.

DIMENSIONLESS PARAMETERS

With the assumptions used here and the analytical solution, type-curves can be built to help the doublet design, using four dimensionless parameters:

- the dimensionless time **tD** = t / tB, equal to 1 at breakthrough time,
- the dimensionless temperature **TD** = $(T - T_i) / (T_o - T_i)$ where To and Ti are respectively the constant reservoir and injection temperatures; TD equal zero before recycling and 1 at infinite time,
- the Peclet number **Pe** = $(Cf / \lambda a) . (Q / \pi h)$ characterizes the effect of thermal diffusion and dispersion compared to convection, inside the aquifer,
- the exchange parameter $\Lambda = (Cf / \lambda e) . (Ca / Ce) . (Q . h / D^2)$ characterizes the effect of the thermal exchange with bedrock and caprock.

with

λa : overall aquifer thermal conductivity,
λe : thermal conductivity of bed and cap rocks,
Ce : heat capacity of bed and cap rocks.

GROUP OF DOUBLETS

The increase of the heat demand from surface users implies the multiplication of individual doublets. This needs to solve the specific problem of hydraulic and thermal interferences between them in order to design and manage the wells through a double optimization process:

- to protect the individual production characteristics of each doublet,

- to get the highest efficiency of the heat whithdrawal scheme which depends on its ability to produce the maximum heat from the minimum reservoir volume.

The design of the multiwell system, similar to the water flooding five spot scheme, is usually done through reservoir numerical modelling. As for oil production, it can be demonstrated that optimum sweeping and recovery factors are obtained when the wells are located at the nodes of a regular mesh. Geothermal doublets can be sited in such a way that the effects are not negative for the lifetimes of the different units, and may even be favourable, provided that structures are at a distance equal to, or greater than, the spacing of the individual doublet wells, and the injection wells are in quincuncial pattern.

Figures 4 and 5 shows an axample of the hydraulic and thermal impact on the reservoir state, induced by the exploitation of three doublets operating at a constant flowrate. This example introduces the importance of pumping and protective perimeters.

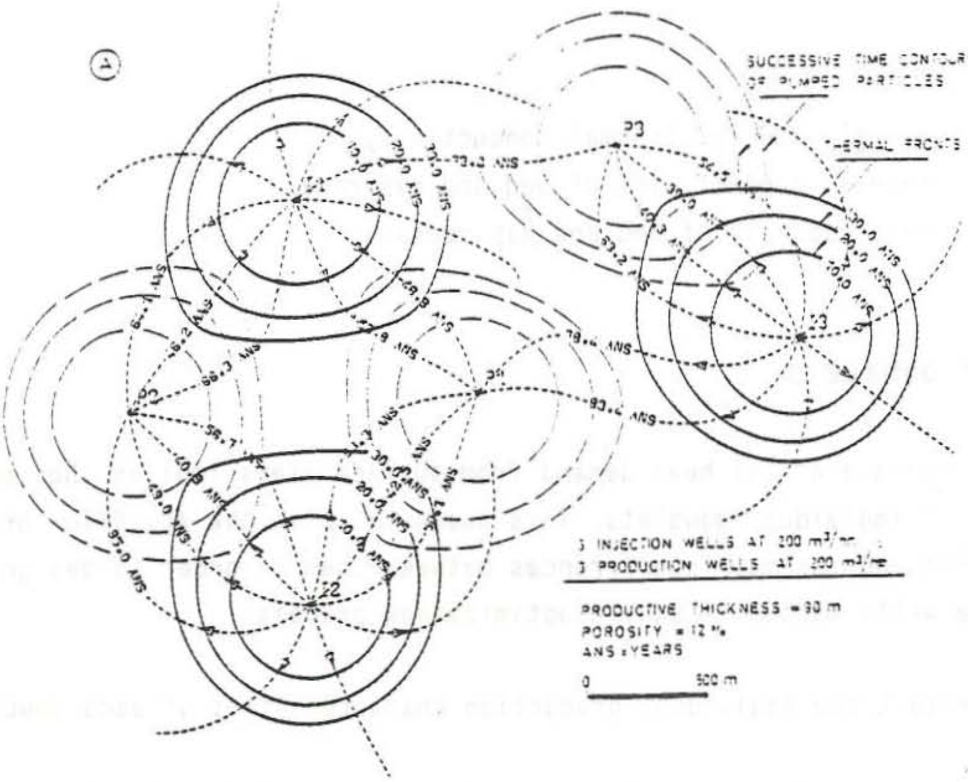

Fig. 4 - Thermal impact of a system consisting of three doublets: distribution of thermal fronts for reinjection and "thermal boundaries" defining the exploitation volume.

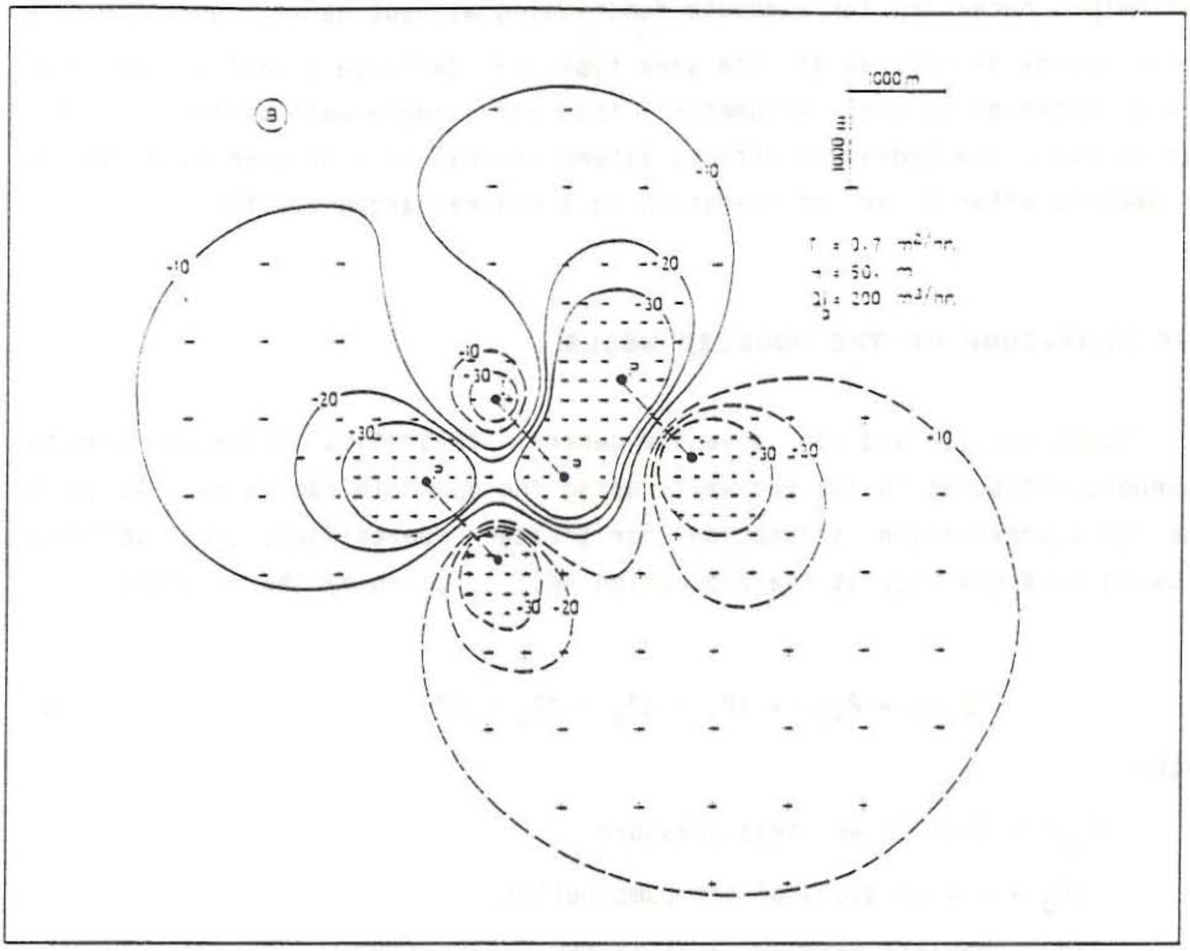

Fig. 5 - Hydraulic impact of a system consisting of three doublets: modification of pressure field, in meters of water, in relation to initial static pressure.

Deep groundwater which is exploited for geothermal energy purposes is considered a mineral resource by the French law. In the case of low-temperature resources, a prospecting licence for a limited period is issued and is followed by an exploitation permit giving the holder exclusive rights for a definite volume. The protective perimeter fixes the boundaries within which undergroung works, which could be harmful to the operation, are regulated. The protective perimeter is defined so as to circumscribe hydraulic and thermal impacts of reservoir exploitation. The production perimeter is defined on the basis of examination of project conditions and the protective perimeter, which is a legal and administrative concept, is then superimposed.

It can be observed through comparison of relative amplitudes for hydraulic and thermal impacts for each system that the protective perimeters necessary for adequate functioning without harmful effects from later nearby structures of the same type are definitely smaller for doublets (order of several kilometers) than for single-well systems. In the latter case, the hydraulic effects extend several tens or even hundreds of kilometers after 20 yr. of operation in a non-recharged aquifer.

THE BEHAVIOUR OF THE DOUBLET WELLS

Equations (2) and (3) give the general theoretical frame to examine downhole pressures in the two wells using the openhole radius rw. Assuming the log-approximation assumption for greater convenience, the wellhead flowing pressure P_{WHF} at the production well is given by the relation (8):

$$P_{WHF} = P_{WHS} + dP_p - dP_d - dP_s - dP_f \qquad (8)$$

where:

P_{WHS} = Shut-in wellhead pressure

dP_p = Overpressure of the pump outlet

dP_d = Dynamic pressure drop in the reservoir

$$= \frac{Q.\mu o}{2\pi.k.h} . \mathrm{Ln}\left(\frac{D}{rw}\right)$$

dP_s = Skin effect pressure variation at sandface

$$= \frac{Q.\mu o}{2\pi.k.h} . S_H$$

dP_f = Friction losses in production casings and tubings.

$$= a . (\mu o)^{0.21} . (Q)^{1.79} . (Di)^{-4.79} . L$$

with, μo = viscosity of native fluid

S_H = hydraulic skin factor

Di = internal casing diameter

L = length of production casing section

a = constant value determined by the choice of the practical units used.

The production wellhead pressure is constant with time, as long as the flowrate remains unchanged. The production pump is generally located around a depth of 200-250 m. The distance between the pump water inlet and the dynamic water level is determined in order to have the minimum pressure point higher than the bubble pressure of the fluid.

For the injection well, a correction must be added to take into account the higher value of injection water viscosity μi and the moving front of mobility in the reservoir. If the injection viscosity is used in place of the native one, this last phenomena is quantified by a new skin factor (thermal skin S_T). The wellhead flowing pressure P_{WHF} at the injection well is obtained with a relation similar to equation (8):

$$P_{WHF} = P_{WHS} + dP_d + dP_s + dP_f \qquad (9)$$

where,

dP_d = Dynamic overpressure in the reservoir

$$= \frac{Q.\mu i}{2\pi.k.h} . Ln\left(\frac{D}{rw}\right)$$

dP_s = Overall skin effect pressure variation at sandface

$$= \frac{Q.\mu i}{2\pi.k.h} . (S_H + S_T)$$

with the thermal skin factor defined by the following approximation:

$$S_T \simeq Ln\left(\frac{\mu i}{\mu o}\right) + \left(1 - \frac{\mu o}{\mu i}\right).\left(Ln \frac{\phi.\mu o.Ct}{k} . \frac{Cf}{Ca} . \frac{Q}{h} - 1.95\right) \qquad (10)$$

Thus, as the injection viscosity is higher than the native one, the injection pressure required for the surface pump design is varying with time. In practice, this evolution is a low trend of the order of a few bars over the doublet lifetime period. The above thermal concept and value is theoretically true as long as the superposition principle is valid; that means for the first half-lifetime period, when the shape of the cold injected volume is closed to a cylindar.

Finally, knowing the differential pressure for the two pumps, the electrical power consumption can be easily determined and introduced in the economical approach.

MODELLING APPROACHES TO FORECAST RESERVOIR BEHAVIOUR

The hydraulic and thermal behaviour of the reservoir under exploitation is obtained through the resolution of a set of non-linear coupled equations, including:

- mass balance and Darcy law to solve the flow problem,
- energy balance in the aquifer with the heat exchange through walls to obtain the evolution of temperature,
- boundary and initial conditions.

The objectives of the approach and the reservoir knowledge are the two major criteria to choose the model. The main objectives are schematically:

- the optimization of the wells location and the doublet design to build a project taking into account the existing production environment,
- the detailed forecast or the exploitation monitoring of a given doublet.

For the first class of objectives, a usual simplification is introduced by considering a steady state horizontal flow and a purely convective scheme for heat transfer as a result of the high Peclet number. The viscosity changes resulting from temperature contrasts and their effects on stream tube geometry are neglected. Only vertical heat conduction occurs in the confining rocks. The initial reservoir temperature is assumed constant. At the early development stage of a geothermal field the reservoir parameters are assumed constant and an analytical model can be used. The approach is fast and convenient to examine a great number of options when the degree of freedom is large. Then, when the number of wells increases, more data are available and the spatial distribution of the reservoir parameters can be quantified. In this case, the reservoir is assumed heterogeneous and a numerical model is required to compute the velocity field. This kind of model, using the finite differences technique for instance, can cover large areas for the evaluation of pressure interferences.

The way to compute the unknown variables is similar to the modelling approach of secondary recovery in oil fields, using the stream tube concept with the following steps:

- computation of the velocity field induced by the injection and the production wells,
- for all the injection wells, definition of the geometry of a given number of stream tubes issued from them, characterized by their flowrate and their breakthrough time,
- determination of the recycling function for each production well, as a consequence of the number of stream tubes reaching them when time increases,
- taking each stream tube in turn, computation of the energy balance and heat transfers to get the successive geometrical positions of the thermal front,
- and finally, for each production well, determination of the production temperature evolution with time, using the characteristics of the recycled stream tubes outlet.

For the second class of objectives attached to exploitation problems, a more accurate description of the geometry around the wells is required. This task is achieved with local modelling at the doublet scale, using for geometry a sub-set of the previous model to quantify the new boundary conditions. This last kind of model using finite differences or finite elements techniques are able to simulate transient pressures, diffusion phenomena or front propagation with viscosity contrasts. In this case, the stream tube concept is not used. The values of temperature and pressure in the reservoir are computed at any point, as continuous distributions in space and time.

CONCLUSIONS

Geothermal reservoir exploitation by single-well pumping techniques leads to progressive depressurization which can considerably reduce hydraulic efficiency of nearby existing or planned installations of this type.

Doublet wells mostly avoid these problems but generally they are more complex and expensive. All water is reinjected after removal of its thermal energy so that the pressure field disturbance is limited to the immediate neighbourhood of the structures. There is a danger of thermal recycling when the cold front of reinjection reaches the production well and there must be a minimum distance between wells for a given installation life. However, water injection has a slight impact in this case and siting of other nearby doublets can be optimized for efficient geothermal resources exploitation.

The protective zone, necessary for correct functioning of the structures so that there are no harmful effects from later installations, is definitely smaller in the case of doublets.

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CURRENT STATE OF GEOTHERMAL EXPLOITATION IN THE PARIS BASIN

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INTRODUCTION

At present, the geothermal exploitation in France is characterized by sixty plants using geothermal energy for direct use in district heating systems. As shown on figure 2, drilling and connection to networks occured mainly during the years 1980-1985. The development of low enthalpy geothermal energy which was directly related to the two oil crisis, has been concentrated in two main areas: the Paris and the Aquitaine basins (fig.1). The lapses occuring during oil crisis and the peak of commissioning of new projects are due to the period of study and installation, necessary to achieve production. Full-scale production was thus not achieve until 1976 after the 1973 crisis, and until 1983 after the 1979 crisis. Since 1969, 55 doublet projects have been set up in the Paris basin, and 12 single-wells in Aquitaine.

From 1985 to 1990, the research and technical efforts have been focused on detailed reservoir knowledge, corrosion-scaling process induced by the fluid composition, methods and techniques for maintenance, rehabilitation of some wells and equipments after work-over operations.

For a brief review, it can be mentioned that, since 1985:

- 7 more doublets have been installed on the Dogger reservoir, in the Paris basin,
- 2 more projects have been set up in Aquitaine,
- 1 new injection well has been drilled for an existing project (on the oldest doublet of Melun l'Almont at the south of Paris),
- 1 project on the triasic facies has been shut down (Melleray),

- and 7 projects on the Dogger reservoir have been shut down, mainly for economical and financial reasons.

Concentrated in two main areas, the Paris and Aquitaine basins, the French geothermal potential is large. The improved knowledge obtained during the last five years spared to the valorization of existing plants will allow a new start of geothermal exploitation. Nevertheless this latter is highly dependent on the international energy context.

Since the early seventies, the geothermal development of the french sedimentary basins represents a useful case study. It has been favoured by three main technical and economical factors: (i) the existence of a productive hot reservoir at reasonable depth, (ii) an important heat market at surface, suitable for this energy production at low temperature level and (iii) an enciting policy from the state in favour of the development of new energies concepts.

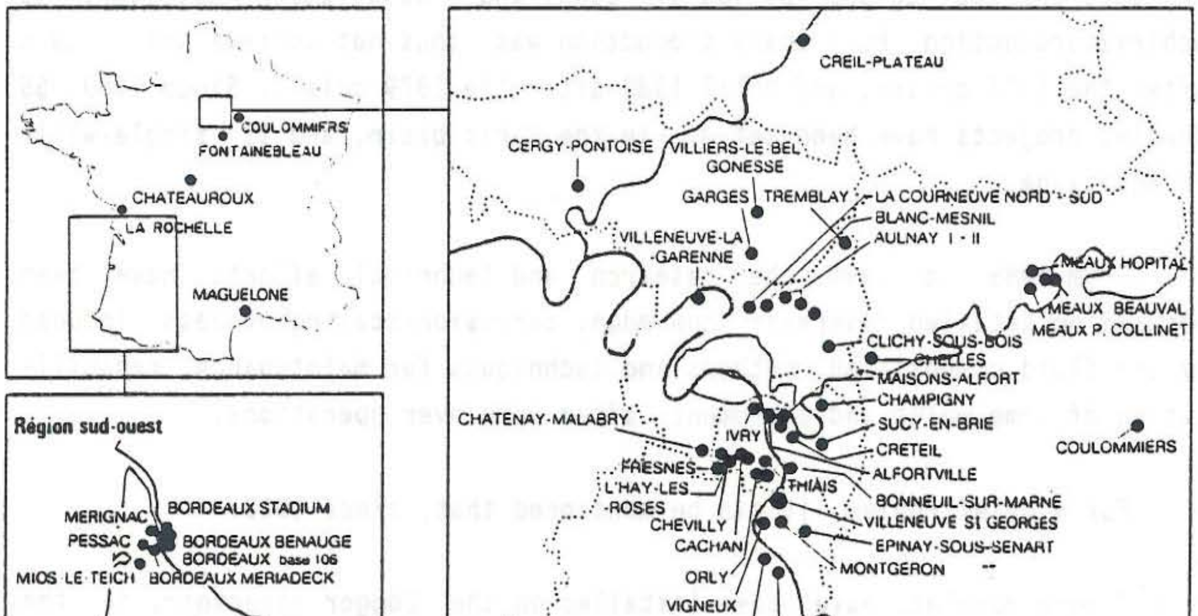

Fig. 1 - Geothermal exploitation in France: location of single-well and doublet systems.

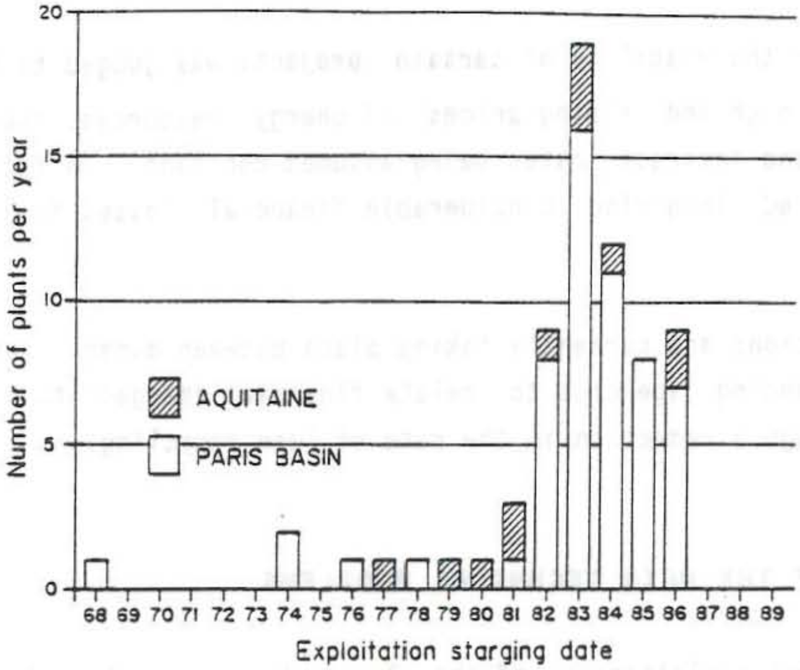

Fig. 2 - Geothermal activity in France: number of projects per year with date of commissioning.

REVIEW OF THE ECONOMIC AND FINANCIAL CONTEXT

The period 1985-1990 was marked by a fall in the price of the conventional heating fuels: oil, gas and coal. To quote an example from Ministry of Industry statistics, imported crude oil prices fell on average from FF 1842 per tonne in 1985 to FF 641 per tonne in 1988 (prices in current francs). This fall has been directly responsible for the significant reduction in receipts of new geothermal energy projects.

The majority of projects have been set up by public bodies to heat existing residential and commercial buildings. To encourage use of the geothermal network, subscriber contracts generally contain safety clauses stipulating that the cost of geothermal energy shall not exceed the cost the conventional energy it replaces.

To this loss in revenue due to the fall in fossil fuels prices have been added increased operating costs of loan repayment due to technical problems. The safety clause puts the financial management of geothermal energy at a serious disadvantage, since it makes projects dependent on changes in the international context that are very difficult to predict.

Moreover the viability of certain projects was judged to be independent of the high and rising prices of energy resources, the continuing price rises and interest rates being assumed constant. In fact quite the reverse occured, incurring considerable financial losses for a few projects.

Negociations are currently taking place between owners, public authorities and funding agencies to relate financial charges to the economic context through a reduction in the rate of loan recycling.

ANALYSIS OF THE MAIN TECHNICAL PROBLEMS

Geothermal exploitation of the Dogger has schematically been faced with two main problems: a shortage of reliable pumping systems, corrosion and scaling.

The pumping problems, which caused considerable exploitation losses, have now been practically resolved thanks to better sized and improved electrical connections in the immersed pumps.

However, that of corrosion and scaling is not quite yet resolved. The action of sulphides in the chloride environment results in corrosion of the metal sections of the geothermal loop, with widespread corrosion of the soft steel (K55) casing and corrosive spotting of the sections of stainless steel (316L) piping, and the deposition of iron sulphide scale. The scale and suspended particles generated cause pump breakdowns, filter and exchanger clogging, and an overall reduction in hydraulic production, with head losses and clogging of the injection well.

A substantial workover program realized in 1986 was a powerful opportunity to examine in detail the in situ state of a few injection and production wells after several years of continuous exploitation. This program was initiated after the identification of important anomalies characterized by: (i) an increase in stabilized production drawdown, (ii) an increase of required injection pressure at wellhead, and (iii) an overall progressive drop of the flowrate. Detailed studies for diagnosis and downhole investigations were imposed by the huge economical consequences: the over-use of electricity for pumps and the reduction of the thermal power distributed to users. The diagnosis from surface measurements was not simple; it requires the identification of the perturbed areas along the underground system and the quantification of the unexpected phenomenas. Then, with the help of pressure logging, the overall decrease of production was recognized as the consequence of the total volume of soft deposits (iron sulphides). This deposition process affects three zones of the observed wells:

- the most important effect of soft deposits was identified along casings with a thickness reaching one inch in some cases. The hydraulic consequence on pressure losses is tremendous as this latter is proportional to the internal diameter at power 5.
- for injection wells, deposition can then occur at sandface, in front of the productive layers. This phenomena, similar to mud cake effects, acts as the additional skin factor on a damaged well and induces a local over-pressure.
- finally, at bottomhole, the sedimentation can progressively fill the safety length below the last productive layer. In such a case, the lower productive layers can be hidden, reducing the total net pay and the whole flowrate.

These investigations has led to new considerations for the geometrical design of the last wells drilled in the Paris basin.

The increased understanding of and the need to control these problems lead to a new design for the geothermal loop. It is worth noting that while these problems of overall reliability occur randomly over the field as a whole, the problems of corrosion and scaling are related to certain chemical characteristics of the reservoir that show geographical variations (see fig. 6), which would explain why the doublets in the northeast of the Paris basin have been particularly affected.

DEVELOPMENTS IN GEOTHERMAL TECHNOLOGY ON THE DOGGER CASE

The question of a unique model

The concept of the standard doublet is nowadays refined and adapted to aquifer present conditions. In areas with high sulphide contents, the use of anti-corrosion treatments is now recognised as essential. To protect the geothermal loop as a whole, the treatment additives must be injected at the bottom of the production well, at the level of the casing shoe.

Technological problems still remain concerning:

- reliable, inexpensive procedures for downhole injection,
- the choice of appropriate inhibiting agents,
- the adjustment of the additive treatment to the geothermal production.

Moreover owing to the high cost of electricity and the strong artesianism in certain areas, it could prove viable to use immersed pumps for artesian production.

For a long time, the geometrical design of wells (internal diamaters) has been adapted as a compromise between the diameters of oil and water wells. The former geothermal wells were characterized by 7" casings and a diameter of 6" for the openhole in the reservoir. The new design for the last wells drilled is defined by 9"5/8 casings and 8"1/2 for the openhole section. The increase in internal diameter for the wells implies several advantages:

- a significant reduction of pressure losses along the cased section,
- when deposits are present, a larger thickness is admissible without any drastic incidence on nominal unperturbed pressures,
- the opportunity to pull down later a new casing when the corrosion damages are becoming too large in relation to safety conditions.

The appearance of new diagnosis and rehabilitation techniques :

It has been necessary to develop new techniques for the diagnosis and rehabilitation of geothermal projects on the Dogger. New concepts in doublet design are now being considered.

Well-logging tools currently employed in the petroleum industry to analyse casing corrosion (mechanical caliper, electromagnetic and ultrasonic tools) have been adapted for use in the field of geothermal energy.

In the case of soft deposits for sulphide-rich areas, the diagnosis methodology has been precised by the choice of the appropriate existing tools. When the thickness of soft deposits is important along casings, the informations obtained from the standard flowmeter log are not reliable. The velocity of the spinner is perturbed by the suspended particles at high concentration. It seems better to use pressure logs at a given flowrate, computing the local pressure drop to identify the effective hydraulic radius, and consequently an estimate of the thickness of deposits. In complement to other investigations, this method is useful for the decision of a cleaning and workover process.

To assess the development of the geothermal field and to have available a historical record of the major parameters of doublet projects, l'Agence Française pour la Maîtrise de l'Energie (A.F.M.E.) has set up a remote monitoring system. This unique system, which has now been in operation for three years, makes it possible, amongst other things, to know at any given time the operational parameters of a doublet, using a telephonic monitor (Minitel). The centralisation, storage and exploitation of the data collected make it possible to improve the global models of exploitation of the field and to assess the extent of interference between adjacent doublets (see fig. 3).

It is intended to improve the system through the collection of new data on the loops (dynamic pressure on extraction in the pump chamber, fluid corrosivity, chemical measurements) and to add more software for:

- checking the pertinence of the collected data,
- automatic diagnosis by expert-system, at the doublet or doublet-field level, of hydraulic and/or thermal inteferences,
- information, by statistical series, on the geothermal energy balance.

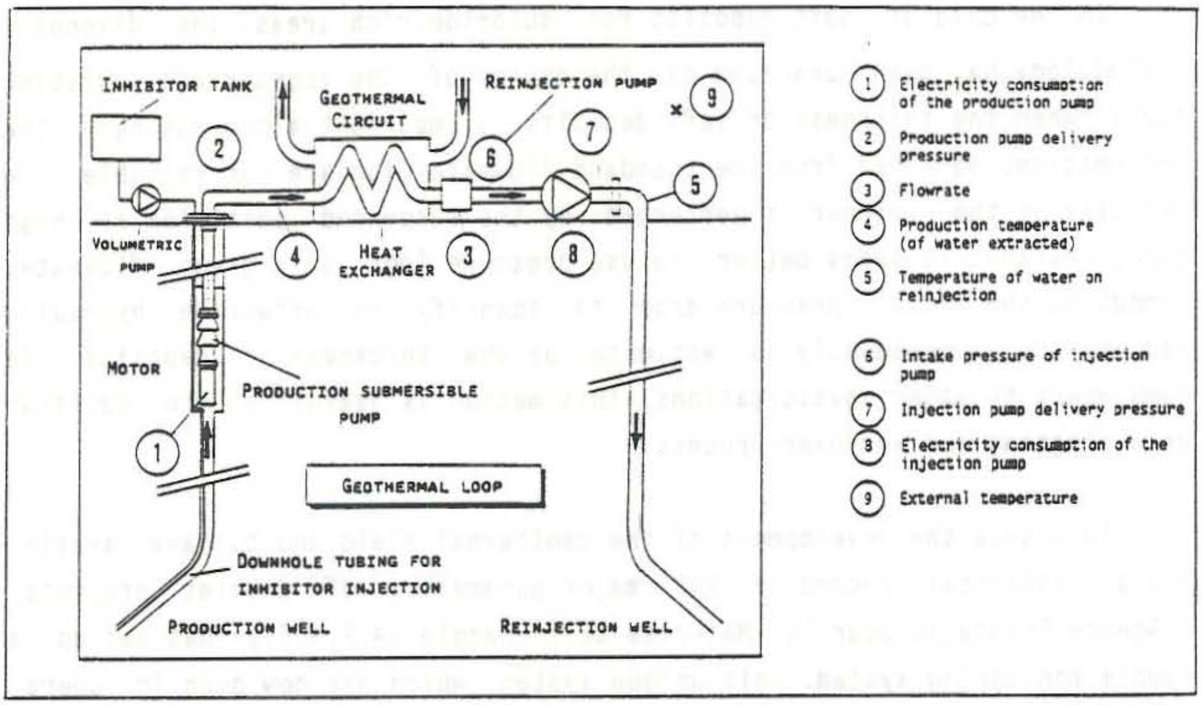

Fig. 3 - Diagram showing the principle of a geothermal loop, with measuring points for remote data acquisition.

A new procedure of well descaling by injection of water under high pressure (jetting) has also been tested. Descaling is currently being oriented towards the adaptation of processes to the degree of scaling - jetting for slightly fouled wells, and mechanical cleaning followed by jetting where the fouling is considerable. Chemical descaling processes are also being investigated.

For highly damaged wells, when puncturing is very likely, two techniques have been employed - partial repair by a "casing patch", or complete recasing using composite fiberglass/epoxy resin casing.

It seems that it will be possible in the future to consider new designs of geothermal doublets that will remove the problems of corrosion or to apply simple treatments. It is possible for example to envisage:

- composite casing material,
- steel casing with composite internal casing,
- mixed doublets, with the extraction well in composite and the reinjection well in steel with a surface anti-corrosion treatment.

PRESENT STATE OF SCIENTIFIC KNOWLEDGE ON THE RESOURCE

Physical characterisation and modelling of the reservoir

Detailed information on the parameters of the Dogger reservoir has greatly benefited from the 110 geothermal boreholes drilled in the central part of the Paris basin during the last fifteen years. The abundant borehole data provide the widely spread information necessary for knowledge of the geothermal resource and for modelling the reservoir being exploited by the doublet technique.

Analysis of these data and in particular the systematic reading of production profiles have shown a significant vertical inhomogeneity in the reservoir relative to production, ie, the productive structure is stratified. The net total productive thickness of the order of 20 m on average, can be subdivided into ten to fifteen levels with particularly high permeability (2-20 Darcy). Accurate identification of the true productive thickness is essential for determination of the distance between the deviated wells in the reservoir (about 1 km) and the time of thermal breakthrough of the doublets with the reinjection of the exploited cooled waters, ie, the concept of lifetime.

At the regional level, the geostatistical treatment of scattered data in a regionalised database has also identified lateral inhomogeneities for each of the main hydraulic, thermal and chemical parameters. Except for pressure, the fluid state variables do not appear to be correlated with depth as might be expected in such a sedimentary basin. Thanks essentially to the tests, excellent correlation has been obtained between pressure and the depth of the fluid production. This indicates a continuous, quasi-hydrostatic reservoir that is being invaded by meteoric waters. From the thermal point of view, the study of correlations with depth has revealed important anomalies that it has been possible accurately to locate in certain zones, such as the north and the south of Paris (fig. 4), and that are probably related to flows arriving either from the Dogger or underlying aquifers. The spatial distribution of total fluid mineralisation shows anomalies that are very similar to those of temperature. This similarity at least qualitatively supports the hypothesis of local or preferential flows, which remains as yet imprecise - the origin and age of the brines identified in the process of mixing with the meteoric waters are still unknown. In this context, the coherence of the spatial distributions of the various parameters is the main condition for the validation of the synthetic model of the reservoir.

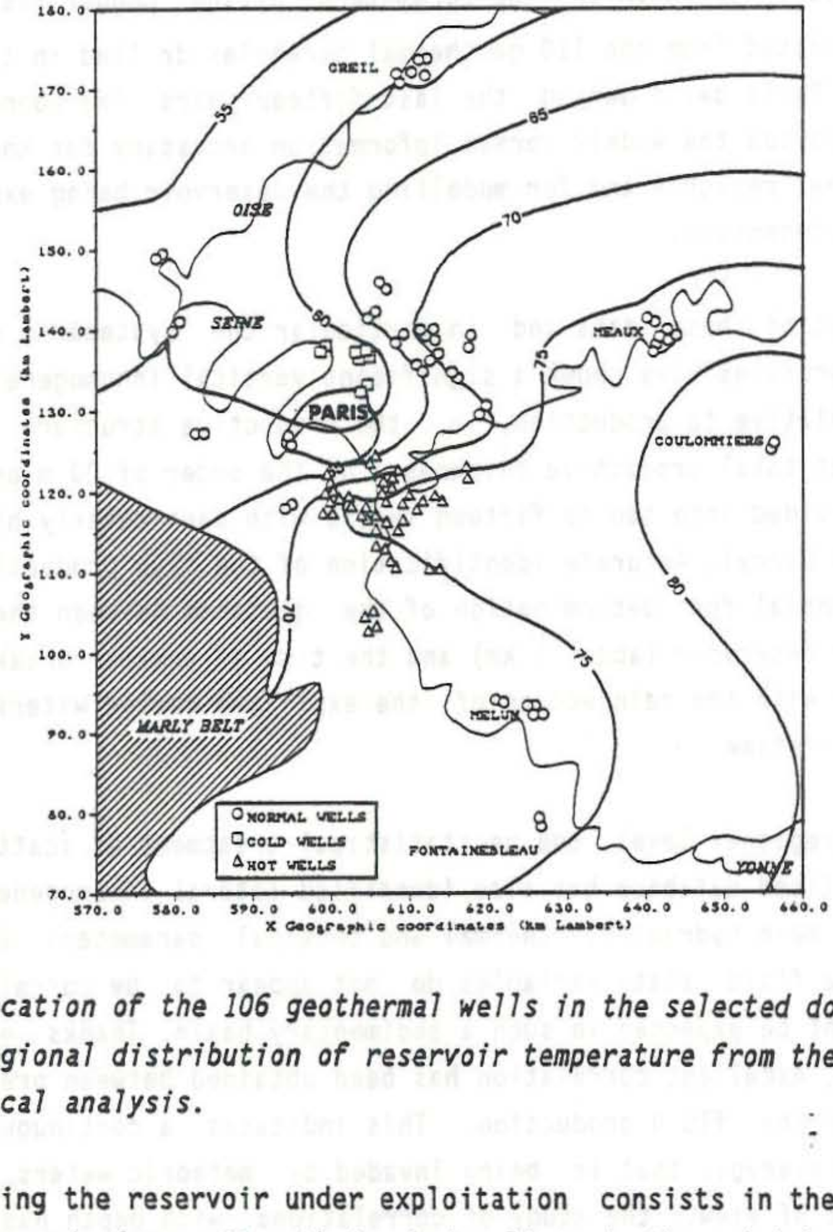

Fig. 4 - Location of the 106 geothermal wells in the selected domain and regional distribution of reservoir temperature from the geostatistical analysis.

Modelling the reservoir under exploitation consists in the design of the doublets and forecasting their hydraulic and thermal behaviour. The standard approach is based on simulation by homogeneous models, the reservoir being characterized by constant average parameters. Current knowledge of the true distributions of parameters has enabled the use of more accurate heterogeneous models that can be verified by measurements acquired periodically by a system of automatic monitoring of the operational parameters of the various doublets (system developed by AFME).

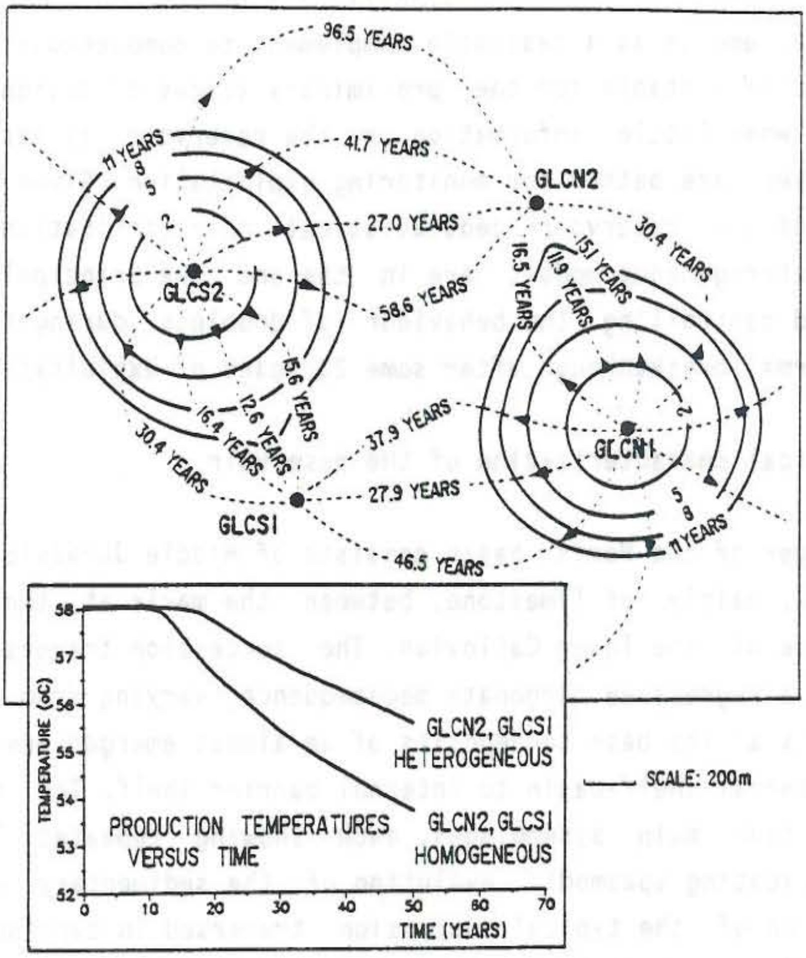

Fig. 5 - Distribution of streamlines and thermal fronts around two doublets (150 m^3/h each). Evolution of the fluid temperature at the production wells vs time, comparing homogeneous and heterogeneous approaches.

Figure 5 gives an example of heterogeneous modelling of a reservoir focussed on two neighbouring doublets and showing the results of the simulation in the form of streamlines between the two wells, the variation of thermal fronts with the injection of coolded water, time of thermal breakthrough for each streamline and the variations in the temperature at the production well with time. Comparison of the results of the two types of simulation for the same site has shown that the forecasts based on the homogeneous approach were generally 10-15% on the pessimistic side, in particular for the variables linked to transfer/migration time and thermal exchanges.

To summarise, heterogeneous models, which are both more complex and more accurate, emerge as a desirable complement to homogeneous models. The latter are quite suitable for the preliminary stages of design and sizing of doublets when little information on the reservoir is available. The former, however, are better for monitoring exploitation. Given an accurate description of the reservoir (geostatistical characterisation, for example), the heterogeneous models are in the end the principal tools for assessing and controlling the behaviour of doublets during the critical phase of thermal breakthrough after some 20 years of exploitation.

Sedimentological characterization of the reservoir

The Dogger of the Paris basin consists of Middle Jurassic (170 Myrs. old) deposits, mainly of limestone, between the marls at the top of the Lias and those of the lower Callovian. The succession traversed by these boreholes is a regressive carbonate megasequence, varying from fairly deep water deposits at its base to deposits of an almost emerged environment at its top - external shelf-basin to internal barrier shelf. The megasequence consists of four main assemblages, each showing repeated lower order sequences indicating spasmodic evolution of the sedimentary environment. The description of the typical succession traversed in continuous coring (Aulnay-sous-Bois borehole) is given below in chronostratigraphic order from base to top:

1840-1834 m	Marl
1834-1733 m	Oolitic-marly, a succession of thin repetitive truncated sequences,
1733-1724 m	Oolitic unit, this unit consists of predominantly oolitic calcarenites. It can be subdivided on the basis of the influences of internal or external marine domains on the petrophysical characteristics of the rock,
1724-1688 m	Comblanchian unit, this is the most regressive unit of the succession, representing a shallow water, internal shelf or lagoon facies.

The limestones have very variable hydrological properties, both vertically, as shown by the existence of a number of different productive levels, and laterally, as shown by the fact that the productive levels cannot be individually correlated. Without grouping them into the three units mentioned above - Comblanchian, Oolitic and Cyclical - the lateral continuity of the productive levels could not therefore be assumed.

The investigations also showed a direct relation between the existence of porosity and the sedimentary environment, in particular the environments in which sandy sediments (oolitic limestones) with matrix porosity were deposited. These reservoirs have evolved differently during diagenesis. Thus the void network in the cyclical unit was reduced by the deposition of cement and by compaction, whereas the sandy facies in the OOlitic and Comblanchian units have partly preserved their original porosity, and have even had it increased in places by fracturing and dissolution. A certain number of observations can be made on the results of petrophysical measurements on representative samples of the facies encountered:

- Reservoirs the porosities of which according to logs have the same values may have very different productivities,
- High permeabilities are observed in samples with high macroporosity (pore entry radius μ). These values were obtained in the barrier facies and in particular in the Oolitic unit,
- Absolute values of permeability measured on cores, independent of facies and porosity, bear no relation to the productivity of the rock. They are underevaluated, in certain cases, by a factor 10 relative to the value of permeability derived from production tests. Nevertheless, in relative terms, the highest values of permeability measured on cores show a good correspondence with the best productive levels identified by flow-meter.

The productive levels show a very wide range of permeability from 0.2 to 21 Darcy. To the patrix permeability of these levels, observed on the microscopic scale, may be added secondary permeabilities due to fracturing and dissolution observed macroscopically on the cores.

Geochemical aspects

Geochemical investigations of the Dogger reservoir reveal a particularly complex and commonly agressive resource that necessitates precise rules for exploitation.

The overall chemical composition of the fluid at a given point depends on local interactions, both old and recent, and on general phenomena that affect the basin as a whole. Among the complex interacting factors are movements of the water body, both vertically and laterally, inhomogeneities of temperature and the result of former bacterial activity.

One on the effects of this heterogeneity is vertical chemical stratification of the reservoir, which makes interpretation of analysis more comlex as they are in general made on fluids sampled at the surface. The spatial distribution of sulphides is controlled by former bacterial activity (fig. 6). Schematically, two situations can be distinguished.

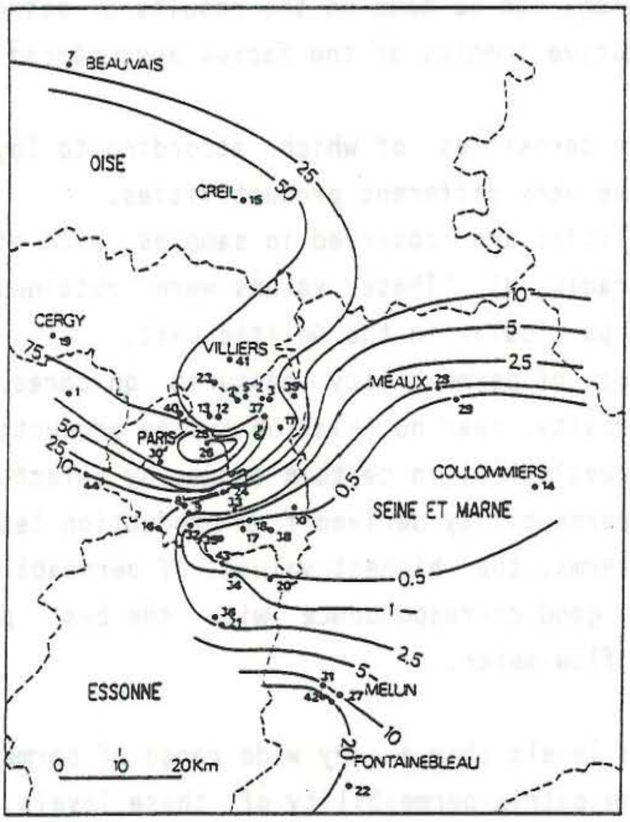

Fig. 6 - Dissolved sulphide contents in Dogger reservoir (measurement points and contours in mg/l).

In the sulphide-rich zones, such as to the northeast of Paris, where former bacterial activity was intense, the sulphide level is such that it naturally limits the possibility of present day bacterial development. In the southern parts of the Paris area, were sulphides levels are low, the development of sulphate-reducing bacteria is possible. An increase in sulphide values is currently occuring on certain sites in this area (eg, Orly) due to bacterial activity.

The period 1985-1989 can be divided into three phases corresponding to the diagnosis of the problems of corrosion and scaling, the validation of certain treatments and the initiation of renewed research for more reliable and less costly procedures.

Following the development of exploitation problems, a substantial workover program was initiated in 1986 on some doublets on the Dogger. Analyses of scale showed that iron sulphides were recognised as the cause of the coupled phenomena of scaling and corrosion observed in the wells.

During the period 1987-1990, different types of inhibitor were tested, leading to the conclusion that organic corrosion inhibitors (filming amines) were affective after prior conventional cleaning of the well.

Research is now in progress to:

- increase the information available on fluid characteristics at the level of the reservoir, using appropriate methods of sampling,
- identify new (mineral) inhibitors easier to use,
- assess the feasibility of procedures based on the catalytic oxidation of the sulphides.

CONCLUSIONS

The evolution of the geothermal energy exploitation in France and in the last five years was marked by the cessation in launching of new projects and the recent or expected shutdown of several projects in the Paris area. This crisis, brought on by the collapse in the price of fossil fuels (which served as reference for the calculation of the selling price of geothermal energy) has been aggravated by the reversal of the inflation/ interest rate differential and, in some instances, by technical problems related to corrosion and scaling, the cost of overcoming which increase the total cost of exploitation.

Research has been given a strong impetus by the search of solutions to the problems related to corrosion and scaling in the wells, while continuing, in particular in the Dogger of the Paris basin, to increase the general knowledge of the geothermal field so as in the end to achieve improved overall management.

The prospects for geothermal energy, the potential for which in France is considerable, seems to follow three main lines:

- The exploitation, using more sophisticated techniques (composite materials, chemical treatments, etc.), of resources of low (Dogger, triassic) or very low (Albian, Neocomian) enthalpy for heating (with or without associated thermodynamic systems) or for industrial or agricultural applications.
- Development of medium to high enthalpy resources in the overseas territories and in the Rhine graben.
- Investigation of the possibilities of hot dry rocks, with the prospect of a European scientific pilot project at Soultz-sous-Forêts in Alsace.

The general dynamics of exploitation of geothermal energy in France nevertheless remains linked to the global energy context in a period of relative neutrality of the public authorities.

It should be noted that the drilling of a new injection well at Melun (the oldest doublet on the Dogger) after almost twenty years of exploitation tends to demonstrate the viability of geothermal energy, provided that the reference period considered is sufficiently long.

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