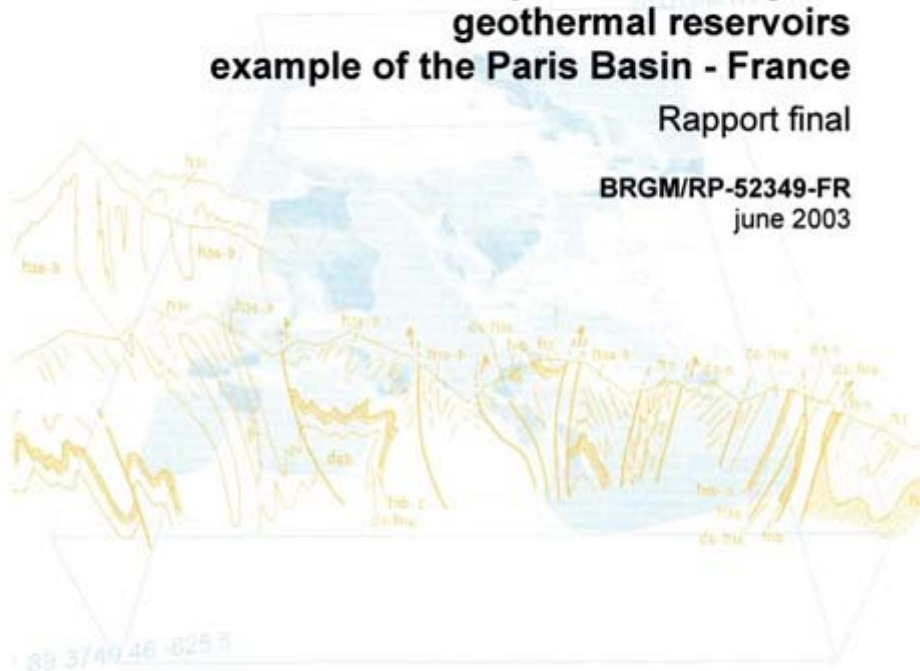




Feasibility of CO₂ storage in geothermal reservoirs example of the Paris Basin - France

Rapport final

BRGM/RP-52349-FR
june 2003



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BRGM-CFG-ANTEA contribution to
the GESTCO project

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Abstract

The principal objective of GESCO is to make a major contribution to the reduction in CO₂ emissions to the atmosphere and so ensuring Europe a continued stable supply of affordable and environmentally acceptable energy. A solution will thus be sought to the problem: **Is geological storage of CO₂ a viable method capable of wide-scale application?** The GESTCO project intends to provide the first documentation that, for emission sources within selected key areas, sufficient geological storage capacity is available.

Within this framework, the BRGM/ANTEA/CFG consortium took care to provide:

- an inventory of the CO₂ emitters in France - location and quantification of the principal emissions,
- an inventory of the principal deep aquifers present in the Paris basin - principal characteristics of the aquifers,
- an evaluation of the storage capacities of CO₂ in one of the four principal case-study: low enthalpy geothermal reservoir,
- technical solutions for CO₂ injection in geothermal aquifers,
- evaluation of the cost of CO₂ storage in such an aquifer.

The principal results achieved within the framework of this study are:

- 1 - The CO₂ emissions are concentrated, in France in three principal areas: Lorraine (power stations and steel-plants), IN Provence (oil refineries, power station and steel-plants), the estuary of the Seine river (refinery and power station) and the Nord - Pas-de-Calais Area (refinery and steel-plants). These principal transmitters all are located either at the site of the old coalfields and iron or steel-plants, or along the estuary of the large rivers (oil terminals and petrochemistry). They are distributed geographically primarily around the Paris basin, one of the principal French sedimentary basins.
In the centre of the Paris basin, in the "Ile-de-France" area, the industrial activity is disseminated but produced more than 8 Mt/y of CO₂.
- 2 - The Paris basin is a sedimentary basin made up of an alternation of permeable and impermeable layers. In the permeable layers, aquifers develop. They are made of fresh water near the surface and salted water more deeply. These aquifers being laid out in "piles of plate", are generally exploited for the water supply near the outcrops and forsaken when the salinity increases with depth. These are the deep and salted aquifers, which are the subject of the studies, carried out within the framework of this work.

Seven aquifers are identified in the Paris basin: (i) sands of the Gault, (ii) Wealdian sands, (iii) Lusitanian limestones, (iv) Dogger limestones, (v) Rhaetian sandstones, (vi) Keuper sandstones and (vii) Bundsandstein sandstones. Only the Bundsandstein, Keuper and Dogger aquifers show the sought characteristics, i.e. an aquifer covered by

more than 500 m and less than 3000 m, continuous and thick, showing good characteristics of permeability.

The Keuper and Bundsandstein sandstones show all the required characteristics and would make it possible to store about 650 Mt of CO₂, volume that is more than 15 times the CO₂ emission resulting from the energy production sector in France (approximately 44 Mt per year).

Dogger limestones also show the required characteristics although reservoir qualities are intrinsically worse but they can be often strongly increased by an important fracturing. This aquifer has a storage capacity more reduced, approximately 8 Mt of CO₂, which represents approximately one year of the total production of CO₂ in all the Ile-de-France area. This aquifer presents moreover the advantage of being to exploit for these geothermal qualities and thus of having the whole of the infrastructures necessary to the CO₂ injection: injection wells, pumping stations.

- 3 - For the Dogger aquifer, the assumption of CO₂ trapping by mineralogical precipitation does not seem realistic. Indeed, a geochemical modelling makes it possible to show that, in the case of an injection of saturated fluid with CO₂ (0.92 mol/kgw), with a pressure of 160 bars, the solution pH would reach values of 3.6, typical of very aggressive water. This pH would involve the dissolution of carbonates near the injection well. This phenomenon could involve a risk of lost of the well. The carbonate precipitation is effective but is relatively limited. Thus, for 18,000 t of CO₂ injected during 20 years in the portion of reservoir modelled, 400 t would be trapped at the end of 20 years of injection whereas more than 17,000 t would be released at the production well. The remains are dissolved in the aquifer.

However, the extreme conditions of modelling do not allow a definitively negative conclusion as for the capacities of CO₂ trapping by the aquifer. The model was calculated only for 1% of the volume concerned with the geothermal loop and for the most direct way between the injection and production wells.

- 4 - The technical feasibility of the CO₂ injection in the production wells was also studied.

It confirms the preceding result, i.e. which it is not reasonable to imagine to use the existing injection wells for the CO₂ injection. Indeed, the injection casings are subjected to a strong corrosion resulting from the natural aggressiveness of the geothermal fluids. One can consider that the mean level of corrosion of the casing of the injection wells is about 30 to 40%. The CO₂ injection could involve a real risk of casing perforation and also of pollution of the overlying aquifers. As for the CO₂ injection in supercritical form, the pressures necessary (about 100 bars) would be likely to destroy the injection casing wall.

However, the currently available materials make it possible to consider the design of specific devices dedicated to the CO₂ injection. For example, stainless steel with a minimum chromium concentration of 13%, could be choice for wet CO₂ injection tubing and carbon steel tubing for dissolved CO₂ injection.

Thus, it would be possible to inject dissolved CO₂ but with the already described consequences:

- porosity increase around the injection well,
- risk of casing perforation,
- storage capacity limited,
- that is to say that the CO₂ injection in supercritical form, seems to be the more efficient solution.

Indeed, this solution would allow, for an injection pressure of 100 bars at the wellhead, to inject 180,000 t of CO₂ per year and per injection well. This capacity is very largely higher than the production of the power stations associated with the geothermal exploitations (emission of about 5 to 15,000 t/y) which would also allow the reduction of the GHG emissions produced by the industrial activity in the environment of the geothermal installations.

An economic analysis taking into account the investments necessary for the realisation of a doublet system equipped for the heat production and the CO₂ injection (i) in a dissolved form for the first assumption and (ii) in a supercritical form for the second assumption, shows that geothermal energy remains has competitive heating system even when combined with the simultaneous injection of CO₂ in supercritical or dissolved form and that the price of energy production remains, in all the cases, lower than the selling price of energy produced by the fuel or gas power stations.

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1. Introduction

This investigation was conducted within the framework of the GESTCO (**GE**ological **ST**orage of **CO**₂) project. It was financed by the European Community under the 5th Framework Research and Development Programme.

The aim of the project is to provide the data required to comply with the commitments of the European States for reducing greenhouse gas (GHG) emissions, in particular through storage in a geological medium.

The Kyoto protocol

(consult <http://www.enpc.fr/de/trav-elev/cc/pnlcc/pnlcc.htm>)

The 1997 Kyoto Protocol attributed quantified goals to developed nations for reducing their greenhouse gas emissions by 2008-2012 (with respect to the reference year of 1990). This was the first concrete commitment to implement the Rio Convention.

GHG emissions between 2008 and 2012 must be reduced by 5.2% compared to their global 1990 levels. This is a worldwide objective in which all signatory countries will participate, depending on their current emissions. At a European level, the EU as a whole, as committed to reduce emissions by 8%.

National policies must be implemented in order to reach this objective, but countries have a degree of manoeuvring room. A system of trading emission credits is being implemented, whereby countries emitting excessive GHG can purchase emission credits from countries whose emissions are lower than those allowed by Kyoto.

The Kyoto protocol in France

(consult <http://www.enpc.fr/de/trav-elev/cc/pnlcc/pnlcc.htm>)

After distribution of the commitment agreed to by the European Union among its member states, France was assigned the objective of stabilising emissions. In contrast to appearances, this is a lofty goal, since it is estimated that French emissions, which in 2000 reached levels comparable to those of 1990, will spontaneously exceed this level by 10 to 15% in 2010 in the absence of new measures. The CO₂ productions per European Community country, as well as the objectives set for the period 2008-2012, are listed in Table 1.

The commitment for stabilisation was made at government level. Although greenhouse gas emissions depend considerably on national government decision, they are also highly dependent on a number of other decision-making levels, such as local political authorities, businesses, and consumers).

in Mt of C	1990	1998	1999	% difference 1998-1999	% difference 1990-1999	Kyoto objective 2008-2012
Luxembourg	3	2	2	4.40	-28.30	-28.00
France	99	101	99	-2.80	-0.70	0.00
Sweden	13	14	13	-2.80	-0.60	4.00
Austria	16	17	17	-0.70	6.10	-13.00
Italy	108	115	115	0.10	6.00	-6.50
Spain	58	69	74	7.10	28.60	15.00
Belgium	29	33	32	-3.10	11.80	-7.50
Holland	43	47	45	-2.50	6.40	-6.00
U.K.	156	147	146	-0.90	-6.50	-12.50
Germany	264	234	224	-4.20	-15.00	-21.00
Portugal	11	15	17	11.90	53.10	27.00
Finland	15	16	16	-3.10	8.40	0.00
Ireland	9	10	11	3.90	24.10	13.00
Denmark	14	16	15	-7.60	-7.20	-21.00
Greece	19	22	22	0.80	18.20	25.00
EU 15	855	858	847	-1.30	-0.90	-8.00

Table 1 - CO₂ emissions in the EU (source: Observatoire de l'énergie – Bilans de l'énergie [Energy Watch – Energy Balances]).

The GESTCO project (GEological STorage of CO₂)

The goal of the GESTCO project is to provide essential data in order to identify sites whose size is sufficient to enable the storage of CO₂, one of the most abundant greenhouse gases produced over a period of 30 years (Christensen, 2002). The contribution of CO₂ to the global warming potential in 2000 was 69% (source: CITEPA, February 2002).

In France, the proportion of emissions from manufacturing industries and the energy sector accounts for 37% of all CO₂ emissions (Table 2).

Sector	Production in Mt of C
Transport	40
Residential and services	27.2
Industry and agriculture	23.5
Power plants	10.2
Other (energy branch)	4.8
Total	105.7

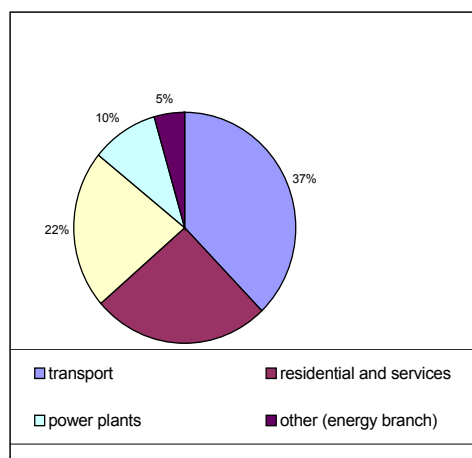


Table 2 - CO₂ emissions per sector of activity in France in 2000 (source: Observatoire de l'énergie – Bilans de l'énergie [Energy Watch – Energy Balances]).

Among the solutions for controlling CO₂ emissions into the atmosphere, those involving actions on industrial flue gas enable large and well-localised quantities to be dealt with (in contrast to residential emissions that are more diffuse and for which interventions are on another level). Techniques for the separation and recovery of this gas can be implemented at a reasonable cost, making it possible to store it. An important factor in the decision-making process is the preparation of an inventory of the main CO₂ emitters, since this will optimise the potential locations of storage sites.

Thus, this study will identify and analyse, since the principal CO₂ emitters until the storage of this greenhouse gas, the different parameters to be taken into account, that is to say:

- location of the principal CO₂ emitters in France (WP1);
- identification of principal deep geological reservoirs able to store this gas in the Paris basin, area of France around which concentrates the principal CO₂ emitters (WP2);
- proposals of technical solutions allowing the storage of CO₂ in the deep geothermal reservoir located in the centre of the Paris basin (WP5);
 - evaluation of the capacity of the Dogger geothermal reservoir to store CO₂ by chemical dissolution,
 - evaluation of the technical feasibility of injection of CO₂ in the geothermal wells in production and of possible proposals for technical solutions;
- financial evaluation of the cost of the CO₂ storage in the geothermal reservoir of the Paris basin (WP6);
- contribution to the development of the databases necessary to the exploitation of the Decision System Support, tool dedicated to the financial evaluation of CO₂ storage scenarios.

2. Inventory of CO₂ sources in France

The search for potential underground CO₂ storage sites must parallel that of surface emission sites. Behind this preoccupation lies the question of the possibility of CO₂ transport in pipelines. In this case, the CO₂ would most probably be conveyed in the liquid form. In the USA, there is already an extensive CO₂ pipeline infrastructure carrying CO₂ to oilfields as part as CO₂ enhanced oil recovery operations.

However, to minimise costs and risks, surface transport of CO₂ should be reduced to the strict minimum, explaining why special attention should be paid to closely examining the correspondence between the locations of surface emission sites and possible underground trapping sites.

2.1. DOCUMENTARY SOURCES AND THEIR CONSISTENCY

The aim of this study is thus to produce a synoptic document at the scale of France, showing the location of CO₂ emission sources and the quantities discharged into the atmosphere.

The search for CO₂ emission sites was carried out using documents of varied origins rather than by direct consultation with businesses. The reason is that this approach had already been used by different French and foreign organisations.

The main documentary sources identified are given below, as well as their consistency. The latter point is important, since available data unfortunately do not always refer to the same years. This is a problem for energy consumption processes that are intimately linked to climatic variations.

2.2. ORIGIN OF DOCUMENTS USED

The data were obtained primarily from three sources:

- an inventory of CO₂ emission sites conducted by the Centre Interprofessionnel Technique d'Etudes sur la Pollution Atmosphérique (Interprofessional Technical Centre of Studies on Atmospheric Pollution) (CITEPA);
- a similar inventory prepared by the Dutch company ECOFYS and sent to the BRGM in the context of the GESTCO project. The study is ongoing at the scale of Europe, thus not limited to France;
- energy data published by the French Ministry of Industry (source: l'Observatoire de l'énergie - Energy Watch).

ECOFYS and the CITEPA used a similar approach to estimate annual CO₂ emissions:

- evaluation of the annual quantity Q of energy or materials produced on each site,

- evaluation of the quantity of CO₂ (C) emitted per unit of energy produced or per tonne of manufactured product (ammonia, cement, steel, etc.), called the "emission factor" (F),
- estimation of the annual operating duration D of the installation: this parameter is useful only for power plants, since it is evident that other industries work more-or-less all year round, if for no other reason than profitability.

The figures in the inventories are thus the product $Q \times F \times D$.

REGION	Energy production (GWh)						Fossil fuel energy production		
	1990		1992		1995		1990	1992	1995
	Total	Nuclear	Total	Nuclear	Total	Nuclear			
Alsace	9 072	8 573	7 517	7 040	11 396	10 950	499	477	446
Aquitaine	23 509	22 229	23 490	22 366	25 621	24 866	1 280	1 124	755
Auvergne	26	0	27	0	17	0	26	27	17
Brittany	33	0	14	0	71	0	33	14	71
Burgundy	769	0	428	0	799	0	769	428	799
Centre	69 309	69 243	75 502	75 442	72 769	72 695	66	60	74
Champagne-Ardenne	15 721	14 110	16 229	16 089	15 063	14 897	1 611	140	166
Corsica	668	0	633	0	766	0	668	633	766
Franche-Comté	283	0	296	0	369	0	283	296	369
Ile-de-France	4 905	0	8 257	0	3 388	0	4 905	8 257	3 388
Languedoc-R.	1 164	0	673	0	622	0	1 164	673	622
Limousin	46	0	66	0	177	0	46	66	177
Lorraine	28 278	17 448	43 994	32 509	43 216	32 480	10 830	11 485	10 736
Midi-Pyrénées	2 700	1785	7 997	7 025	15 690	14 888	915	972	802
Nord - Pas-de-Calais	40 133	34 953	39 416	34 516	40 781	37 151	5 180	4 900	3 630
Lower Normandy	14 976	14 888	16 504	16 430	16 624	16 576	88	74	48
Upper Normandy	37 730	32 032	46 852	40 957	54 543	49 769	5 698	5 895	4 774
Pays-de-la-Loire	6 636	0	6 884	0	3 812	0	6 636	6 884	3 812
Picardy	274	0	303	0	315	0	274	303	315
Poitou-Charentes	30	0	26	0	52	0	30	26	52
Provence – Alpes - Côte d'Azur	4803	0	3 997	0	4 282	0	4 803	3 997	4 282
Rhône-Alpes	81970	79645	70 822	69 436	85 418	84 065	2 325	1 386	1 353

Table 3 - Variations of energy supplied by fossil fuel power stations in 1990, 1992 and 1995 (source: Ministry of Industry "Energy in the Regions").

Fossil fuel energy was calculated as the difference between total heat energy produced and that from nuclear power stations. It appears (Table 3) considerable variations between regions as Lorraine, Upper Normandy, Provence, Nord - Pas-de-Calais, Ile-de-France and, Auvergne, Lower Normandy and Poitou-Charente.

2.3. CONSISTENCY OF DOCUMENTARY SOURCES

Not all the CITEPA inventories were available at the time this document was drafted. The only data in our possession concerned the Ile-de-France and Nord - Pas-de-Calais

regions, i.e. those prominent in the GESTCO project programme. Comparison by industrial sectors provides the following results.

2.3.1. Power plants

It was mentioned above that three parameters participate in the evaluation of quantities of CO₂ emitted: power of the installations, the emission factor (quantity of CO₂ required to provide a given quantity of energy), and the annual operating duration of the installation.

2.3.2. Operating durations of power plants

Conventional power stations do not operate continuously, i.e. all year long, but only in the winter. Energy installations that operate continuously are hydroelectric dams and nuclear power plants. Energy production is consequently modulated to the harshness of the winter, explaining the relatively large differences noted from one year to another (Table 3). These differences primarily concern the Ile-de-France, Nord - Pas-de-Calais and Pays-de-la-Loire regions.

The operating durations adopted a priori for the GESTCO project by ECOFYS are as follows:

Type of fuel	Duration (hours/year)
Coal	2966
Oil	1007
Gas	5342

But these estimates are evaluated from standard durations of operation for power stations used with full output. However the case of France is particular for power plants burning oil, gas or coal because they are used to control the peaks of consumption that cannot be assumed by the nuclear power stations. The utilisation period of the French power stations using fossil resources is thus less important than in Europe, which explains the differences in estimates of the CO₂ discharges between ECOFYS and the Ministry for French Industry.

The data in Table 4 show the power of conventional plants, region by region, estimated by the difference between total power and that produced by nuclear power stations, as well as the electrical energy produced. The quotient gives a rough idea of the mean annual operating duration.

Nevertheless, this table does not distinguish between coal- and oil-fired power plants. The former are probably predominant, and so it becomes clear that – all else being equal – the values calculated by ECOFYS are an overestimation of CO₂ emissions.

Note: gas-fired power plants are probably considered as cogeneration units and not turbines

A comparison of emissions estimated by ECOFYS and those estimated by CITEPA in fact reveal rather considerable differences (Table 5).

Region	Installed power of power stations		Fossil-fuel electricity		Mean operating duration
	Total	Nuclear	Total installed power	Energy produced	
Units	MW	MW	MW	GWh	Hours
Alsace	1 954	1 940	14	446	n.s.
Aquitaine	5 130	4 032	1 098	755	688
Auvergne	0	0	0	17	n.s.
Brittany	424	0	424	71	167
Burgundy	253	0	253	799	3 158
Centre	13 550	13 550	0	74	n. s.
Champagne-Ardenne	2 977	2 970	7	166	n. s.
Corsica	297	0	297	766	2 579
Franche-Comté	18	0	18	369	n. s.
Ile-de-France	5 560	0	5 560	3 388	609
Languedoc-Roussillon	1 685	0	1 685	622	369
Limousin	8	0	8	177	n. s.
Lorraine	9 271	5 940	3 331	10 736	3 223
Midi-Pyrénées	3 387	2 970	417	802	1 923
Nord - Pas-de-Calais	7 441	6 048	1 393	3 630	2 606
Lower Normandy	2 993	2 970	23	48	n. s.
Upper Normandy	11 022	8 910	2 112	4 774	2 260
Pays-de-la-Loire	3 208	0	3 208	3 812	1 188
Picardy	40	0	40	315	n. s.
Poitou-Charentes	29	0	29	52	n. s.
Provence-Alpes-Côtes d'Azur	1 998	0	1 998	4 282	2 143
Rhône-Alpes	17 287	14 922	2 365	1 353	572

Table 4 - Summary estimation of the annual operating duration of fossil-fuel power stations in 1995 (source: Ministry of Industry "Energy in the Regions"); n. s.: non-significant.

Industries	Sites (and Department)	Fuel	Estimation of CO ₂ emissions (Mt/year)	
			GESTCO (ECOFYS)	CITEPA
Power plants	Vitry (94)	Coal	3.131	0.807
	Vaires s/Marne (77)	Coal	1.445	0.593
	Champagne s/Oise (95)	Coal	1.475	0.494
	Montereau (77)	Coal	2.210	0.379
	Porcheville (78)	Oil	1.338	0.152
Cement factories	Dannes (62)	---	0.428	0.347
	Lumbres (62)	---	0.699	0.469
	Gargenville (78)	---	0.373	0.311
Ammonia plants	Rouen Grand Quevilly	---	0.550	---
	Waziers	---	0.275	0.257
	Nangis (Grandpuits)	---	0.562	0.487
	Pardies	---	0.132	---
	Gonfreville	---	0.160	---
	Ottmarsheim	---	0.341	---

Table 5 - Comparison of ECOFYS and CITEPA estimations of CO₂ emissions for different industries.

It was seen in Table 4 that French Ministry of Industry data indicate that the mean annual operating duration of Ile-de-France power plants should have been about 600 hours in 1995. This is only about 20% of the operating duration attributed by ECOFYS for coal power stations (2966 hours/year). Even if we refer to 1992, the calculation gives 8257/5.560, i.e. 1485 hours, which is still far below the ECOFYS hypothesis.

Conversely, when the calculated values in Table 4 did not differ substantially from the value of 2966 hours/year (Lorraine, Nord Pas-de-Calais, Upper Normandy, Provence-Alpes-Côte d'Azur and Corsica) it was considered that the ECOFYS estimations were reliable, and it is these figures that were used for the rest of the work.

Emission factors

The CITEPA inventory does not mention these factors. ECOFYS adopted values of 1015 tonnes of CO₂ per MWh for coal-fired plants, 568 for oil-fired plants and 340 for gas-fired plants. It is difficult to say if these values differ from those of CITEPA.

2.3.3. Cement plants

In contrast to power stations, cement plants normally have a relatively continuous activity throughout the year, independent of climatic conditions, and probably fairly constant from one year to another. ECOFYS adopted an emission factor of 0.76 kg of CO₂ per kg of cement produced. A comparison of the corresponding estimations with those of CITEPA is given in Table 5 above.

There are some discrepancies, but they are of the same order of magnitude. In the scope of the present work, attention is focused on the principal sources of emission higher than 1 Mt/year, which is why only one cement plant (Montalieu) was included in our inventory, with the value estimated by ECOFYS.

2.3.4. Factories manufacturing nitrogen products (ammonia)

Comparing the figures of ECOFYS and CITEPA shows a relatively good agreement (Table 5). There appear to be two sources of emission at the Waziers site (Nord - Pas-de-Calais) and the Grandpuits site (Seine-and-Marne), which is called "Nangis" in the CITEPA study. According to ECOFYS, their sum leads to an estimation 7 to 15% higher than that of the CITEPA, which is not a problem at the scale at which we are working.

This may be a simple divergence in the emission factor chosen, since that of CITEPA is unknown and that of ECOFYS is 1.2 kg of CO₂ per kg of NH₃ produced. Tables 5 and 6 show that these industries are relatively modest as CO₂ sources in comparison to power plants, steel mills and refineries. This is why they are not considered in the rest of the study, except for the Ile-de-France inventory.

2.3.5. Conclusion

It is difficult to compare documentation sources on CO₂ emissions.

In the ECOFYS and CITEPA studies, the procedure and calculations were similar, i.e. accounting for the industrial production of each site, “emission factors” and the annual operating duration of the installations. But:

- the reference years are not the same: 1994 for CITEPA, not stated by ECOFYS, and 1990, 1992 or 1995 for the French Ministry of Industry, to which we refer when necessary;
- emission factors are not specified in the CITEPA studies, which prevents any comparison with the work of ECOFYS;
- annual operating durations were overestimated in the case of power plants in the ECOFYS study because of the particular utilisation of conventional power plants in France.

Even so, orders of magnitude are apparently the same and thus enable the principal sites of CO₂ emission in France to be outlined.

2.4. ORIGINS OF PRINCIPAL CO₂ EMISSIONS

Spot emissions of CO₂ in France higher than 1 Mt/year are listed in Table 6 (source: ECOFYS).

Type of industry	Site	CO ₂ /year (k tonnes)
Steel	Dunkirk	7011
	Florange	3166
	Fos-sur-Mer	5315
Electricity	Gardanne	3718
	Carling	4482
	Le Havre	4260
	Blenod	3010
	Cordemais	5253
	La Maxe	1505
Refineries	Lavera	2023
	Feyzin	1234
	Donges	2064
	Fos sur Mer	1127
	Port Jerome	1503
	Petit Couronne	1358
	Dunkirk	1288
	La Mede	1398
	Gonfreville l'Orcher	3118
Cement	Montalieu	1531
Gas production	Lacq	1061

Table 6 - List of the principal sources of CO₂ emission in France, from ECOFYS data.

The most intense sources would appear to be caused, in **decreasing intensity**, by:

- steel making (Dunkirk, Fos-sur-Mer, Nord, Lorraine);
- power plants (Carling, Le Havre, Cordemais, etc.);
- hydrocarbon refineries (Gonfreville-L'Orcher, Donges, Lavera, La Mede, and at least 6 other important sites);

- cement factories;
- urban heating systems and municipal waste incineration plants, e.g. in the greater Paris region (see Table 7).

Concerning certain energy transformation units (in particular power plants), there are substantial variations from one year to another and evidently from one season to another within the same year. These variations arise from climatic conditions and the resulting heating requirements. Emissions are clearly lower or absent in summer and, all else being equal, are higher during harsh winters.

2.5. LOCATION OF THE PRINCIPAL EMISSION SOURCES

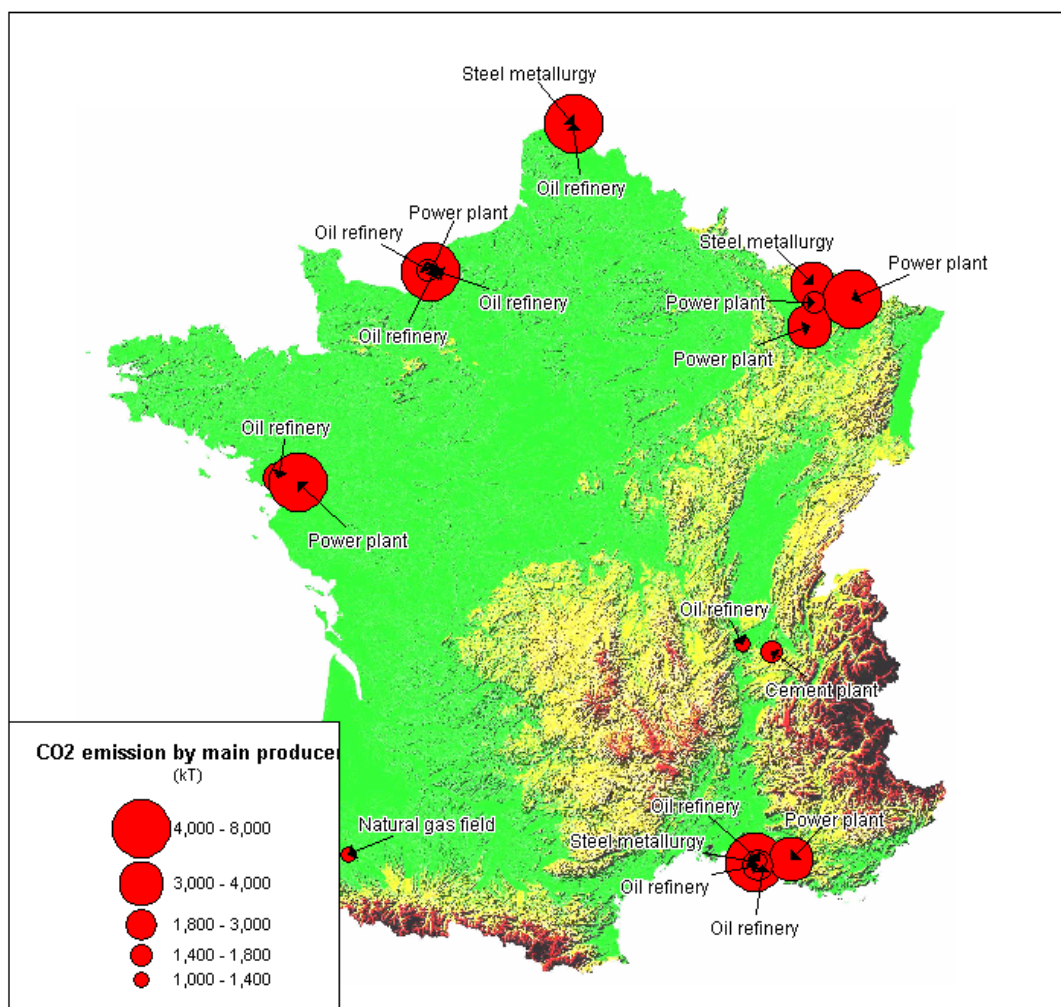


Fig. 1 - Location of the principal sources of CO₂ emission in France.

Examining the location of sources theoretically emitting more than 1 Mt/year (Table 7) reveals a concentration in five main areas (Fig. 1), accounting for more than 7 Mt of CO₂/year:

- Nord-Lorraine,

- Basse-Seine (Le Havre-Rouen),
- Golfe de Fos,
- Dunkirk region,
- Loire estuary (Nantes, St Nazaire).

Except for Lorraine and Dunkirk, these areas are the **estuaries of the principal French rivers**: the Seine (Le Havre, Rouen), the Loire (Nantes, Saint-Nazaire) and the Rhône (Golfe de Fos). In other terms, many of the CO₂ emission sites have “wet feet” (fig. 1), explained by:

- the thermodynamic need for a cold water source for power plants,
- the ease of fuel supply for refineries, coke plants or other steel-related installations.

Even though the cement manufacturing process basically involves a decarbonation of limestone with the departure of CO₂, it is noted that cement plants are not a major source of emission. This result was not predictable before the studies.

Area	Site	Type of industry	CO ₂ /year (k tonnes)
Nord – Lorraine	Carling	Power plant	12 200
	Blenod	Power plant	4 500
	Florange	Steel plant	3 000
	La Maxe	Steel plant	3 200
Basse Seine	Le Havre	Power plant	1 500
	Gonfreville l'Orcher	Refinery	10 300
	Port Jerome	Refinery	4 300
	Petit Couronne	Refinery	3 100
Dunkirk	Dunkirk	Refinery	1 500
	Dunkirk	Steel plant	1 400
Loire estuary	Cordemais	Refinery	8 300
	Donges	Power plant	7 000
Lyons region	Montalieu	Refinery	1 300
	Feyzin	Cement factory	7 400
Golfe de Fos	Fos-sur-Mer	Refinery	5 300
	Lavera	Steel plant	9 800
	Fos sur Mer	Refinery	5 300
	La Mede	Refinery	2 000
Bearn	Lacq	Refinery	1 100
		Gas production	1 400

Table 7 - Principal areas of CO₂ emission, GESTCO/ECOFYS data (rounded off to hundreds of tonnes).

The five areas alone theoretically emit as much CO₂ as entire French regions. For example, and according to the CITEPA estimations, sites discharging more than 0.1 Mt/year of CO₂ for the entire Ile-de-France Region only represent a cumulative emission of less than 12.5 Mt/year, at least for 1995, the date of the inventory (Table 8).

These values can in fact vary considerably by several million metric tons/year for power plants because of climatic conditions that cause seasonal load variations (see Table 3 above).

The constant nature of the ratio of CO₂ emission between French regions is illustrated by a recent review published by the CITEPA in 2002 (see fig. 2 and Table 8).

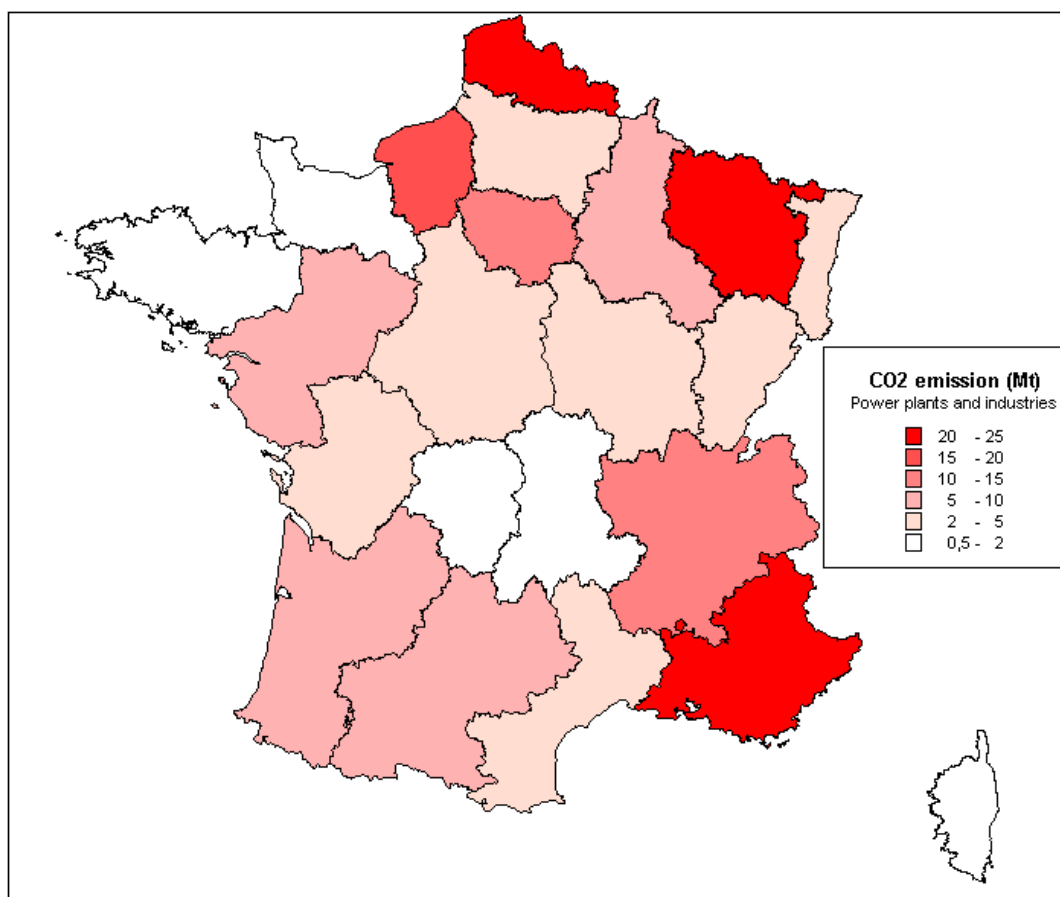


Fig. 2 - Distribution of CO₂ emissions in French regions (source: CITEPA/CORALIE, 1995 data).

This analysis of the distribution of CO₂ emissions in France clearly shows that the principal greenhouse gas (GHG) emitting regions are located in the Paris Basin, in particular Nord Pas-de-Calais, Lorraine, Basse Seine and Ile-de-France. This geographic entity produces 61.2% of emissions, i.e. 98 Mt among the 160 produced in France by the industrial and energy sectors (source: CITEPA).

The socio-economic profiles of these regions are quite different. In Nord - Pas-de-Calais and Lorraine, there is a high concentration of smokestack industries (metallurgy) and associated activities (energy production). Ile-de-France is home to a high concentration of processing activities or service sectors (primarily energy production) and the Lower Seine constitutes the lungs of the Paris Basin (refineries).

In the following discussion, two of these regions were analysed in more detail.

Region	Population*	Area*	CO ₂ (Mt)**
CORSICA	250,371	8,815.64	0.6
AUVERGNE	1,321,214	26,220.08	1.5
BRITTANY	2,795,638	27,379.14	1.8
LIMOUSIN	722,850	16,986.31	1.8
FRANCHE-COMTE	1,097,276	16,253.25	2.0
LANGUEDOC-ROUSSILLON	2,114,985	27,705.67	2.7
POITOU-CHARENTES	1,595,109	25,907.99	3.6
ALSACE	1,624,372	8,296.37	4.5
MIDI-PYRENEES	2,430,663	45,450.69	5.6
AQUITAINE	2,795,830	41,836.93	7.2
RHONE-ALPES	5,350,701	44,691.23	10.8
PROVENCE-ALPES-COTE D'AZUR	4,257,907	31,682.24	20.1
LOWER NORMANDIE	1,389,971	17,726.35	1.8
CENTRE	2,371,036	39,470.56	2.7
BURGUNDY	1,609,653	31,695.71	3.4
PICARDY	1,810,687	19,445.79	4.8
CHAMPAGNE-ARDENNES	1,347,348	25,544.96	5.0
PAYS-DE-LA-LOIRE	3,059,112	3,2277.9	7.9
ILE-DE-FRANCE	10,660,554	11,992.08	12.5
UPPER NORMANDIE	1,737,130	12,304.07	18.4
NORD - PAS-DE-CALAIS	3,959,808	12,437.61	20.2
LORRAINE	2,305,232	23,592.66	21.3
Total production			160.2
Paris Basin			98.0

Table 8 - Distribution of CO₂ production per French region (sources: **CITEPA/CORALIE, 1995 data and *MapInfo).

2.6. CO₂ EMISSIONS IN THE ILE-DE-FRANCE REGION

From the standpoint of CO₂ emission, the central part of the Paris Basin (Ile-de-France) is characterised (Table 9):

- by an annual quantity that is undoubtedly more modest than that of the five areas mentioned above, not quite 8 Mt (industrial section, 1994). This ranking should be put in perspective, however, since Table 3 showed a theoretical variation reaching 5 Mt for power plants, depending on the year, e.g. between 1992 and 1995,
- more objectively, by a higher number of emission sites, i.e. more than 20,
- also by emissions involving a broader area: between the Seine-et-Marne sites (Grandpuits, Montereau) and those of the Yvelines near Mantes (Gargenville, Porcheville), the distance is about 100 km.

Overall, this region can be characterised by emission sites that are of modest size and are relatively diffuse geographically (Fig. 3). In this respect it is clearly distinguished from the five principal emission sectors in the entire country. The consequences of this difference in terms of the search for geological traps for CO₂ storage are not yet clearly perceivable, but it is obvious that they will not be ignored.

Site	X ext. Lambert II m	Y ext. Lambert II m	E longitude °	N latitude °	CO ₂ kt/year	NO _x t/year	SO ₂ t/year	CO t/year	NH ₃ t/year	Origin
Vitry-sur-Seine	606,000	2,421,200	2.41939	48.79012	807	2,608	4,633	120		Power plant
Grandpuits	645,000	2,399,000	2.94752	48.58903	640	2,300	4,868	212		Refinery
Vaires-sur-Marne	623,000	2,430,250	2.65112	48.87107	593	1,141	4,436	88		Power plant
Grandpuits	645,000	2,399,000	2.94752	48.58903	487	1,173	232	<50	1305	Chemical factory
Ivry-sur-Seine	603,700	2,424,800	2.38814	48.82249	470	1,168	1,458	443		Waste incineration
Orly	602,000	2,414,000	2.36495	48.72543	353	1,124	339	5,239		Airport
Saint-Ouen	600,000	2,434,000	2.33778	48.90518	344	1,018	1,700	294		
Saint-Ouen	600,000	2,434,000	2.33778	48.90518	313	405	811	51		Waste incineration
Plessis-Gassot	607,000	2,448,000	2.43344	49.03095	263	<150	<150	<50		
Saint-Ouen	600,000	2,434,000	2.33778	48.90518	246	1,018	484	<50		
Roissy-en-France	614,000	2,446,000	2.52903	49.01286	507	1,892	254	8,177		Airport
Champagné-sur-Oise	594,000	2,459,300	2.25563	49.13250	494	1,748	3,360	74		Power plant
Cormeilles-en-Parisis	590,800	2,440,600	2.21222	48.96443	383	1,521	1,530	208		Mineral Industry
Montereau	644,500	2,376,500	2.93841	48.38680	379	1,123	1,714	6,005		Power plant
Maisons-Lafitte	586,000	2,439,000	2.14676	48.94996	339	<150	<150	224		
Claye-Souilly	625,200	2,438,000	2.68155	48.94063	338	<150	<150	<50		
Gargenville	562,500	2,442,200	1.82585	48.97778	311	195	<150	169		
Issy-les-Moulineaux	596,000	2,424,500	2.28334	48.81979	209	682	<150	197		Waste incineration
Porcheville	558,000	2,441,000	1.76454	48.96671	152	235	1,913	4,000		Power plant
Limay	556,000	2,444,000	1.73693	48.99354	144	<150	<150	699		
Flins-sur-Seine	564,500	2,441,800	1.85318	48.97429	139	<150	1,175	<50		
Saint-Ouen-l'Aumône	583,000	2,449,200	2.10542	49.04155	123	<150	970	<50		District Heating
Bray-sur-Seine	666,000	2,380,000	3.22912	48.41643	105	<150	<150	<50		
Paris Vaugirard	597,500	2,425,500	2.30375	48.82879	126	n.d.	n.d.	n.d.	n.d.	
Paris Grenelle	596,500	2,427,500	2.29012	48.84676	128	n.d.	n.d.	n.d.	n.d.	
Paris La Villette	603,000	2,432,500	2.37867	48.89169	133	n.d.	n.d.	n.d.	n.d.	
Paris Bercy	604,000	2,425,500	2.39223	48.82878	126	n.d.	n.d.	n.d.	n.d.	
Total Ile de France					8,650					

Table 9 – Gas emissions in the Ile-de-France region (source: CITEPA, 1994).

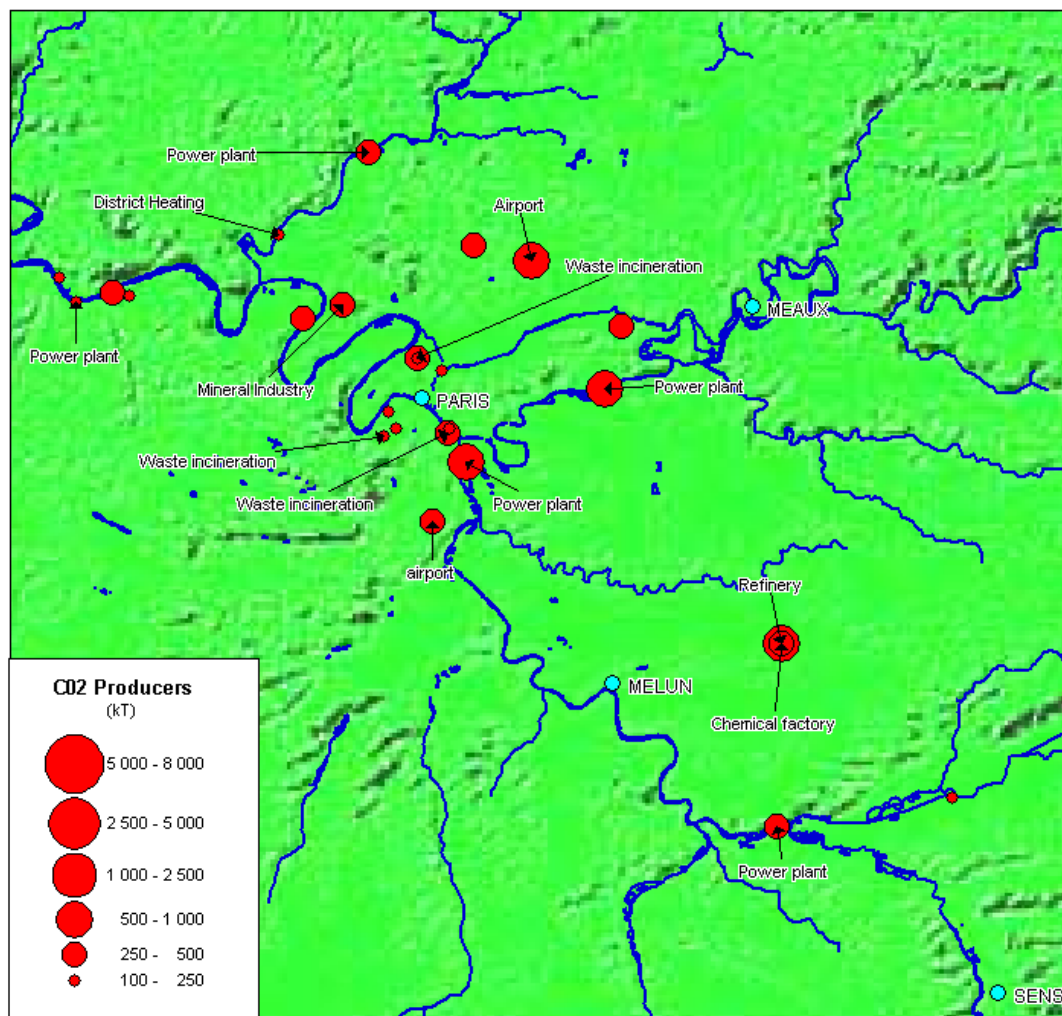


Fig. 3 - The principal CO₂ emitters in the Ile-de-France region.

All else being equal, the probability of finding a trap close to emission sources is higher in the Ile-de-France region than in the five major sectors identified (larger area, more sites). Since emissions are less intense, however, the incidence at the national level in terms of decreasing CO₂ emissions will be lower.

2.7. CO₂ EMISSIONS IN THE NORD PAS-DE-CALAIS REGION

In contrast to the above case, emissions in Nord - Pas-de-Calais are concentrated primarily in the greater Dunkirk area, which alone accounts for 71% of emissions in the region (Table 10). Most of the emissions are the result of concentrated metallurgical activity and associated sectors (coke plants, power plants).

The rest of the CO₂ sources is extremely dispersed and not extensive (Fig. 4). In this respect, the treatment of GHG should be facilitated by this concentration, provided there are geological reservoirs close to these sites.

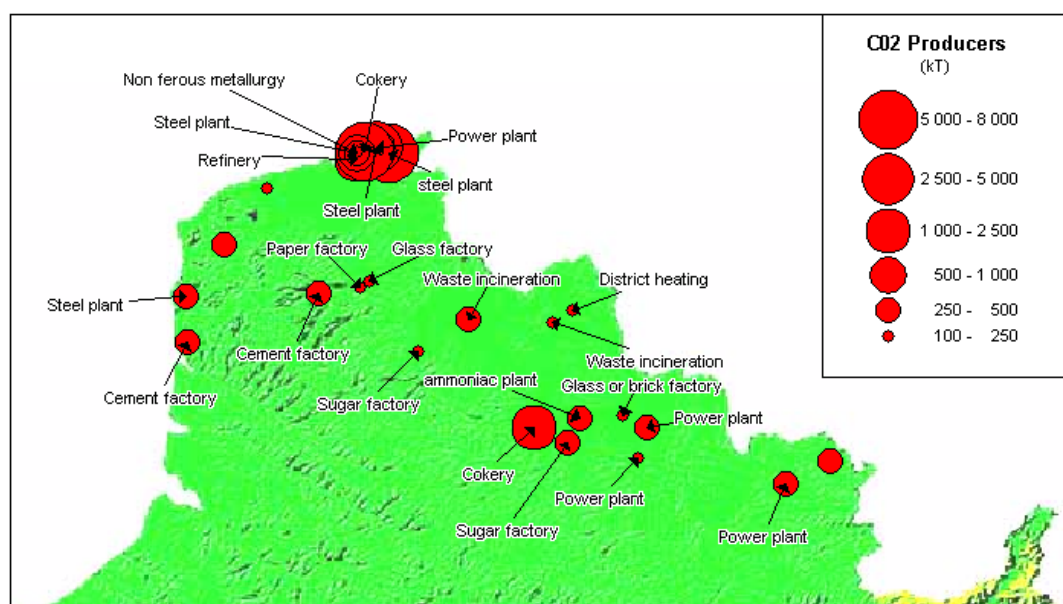


Fig. 4 - The principal CO₂ emitters in the Nord - Pas-de-Calais region.

2.8. IMPLICATIONS FOR THE SEARCH FOR CO₂ STORAGE SITES

The concentration of CO₂ emissions in several well-delimited geographic sectors affects the search for storage sites. The transport of CO₂ is technically possible, but the operation is as costly as it is risky. The gas pipeline system in France is sufficiently dense to imagine adaptation to the problem of CO₂ transport, enabling the gas to be conveyed from its site of emission to the site of storage (Fig. 5). The following two figures (Figs 5 and 6) illustrate the concomitance between the location of the principal CO₂ emitters, the presence of compression stations or gas terminals, and the proximity of existing gas storage sites (methane).

However, the risk of this transport for the public must be examined, since the rupture of a CO₂ pipeline is a major industrial accident, with the emission of more than 1 Mm³ of suffocating gas in 24 hours (Joule II report). As a result, the search for storage sites should be concentrated in the **immediate proximity**, no more than several tens of kilometres, from the storage sites. This is why it is essential to search for favourable geologic sites for the underground storage of this gas at the same time as minimising transport distance.

The most favourable geological sites should be composed of:

- permeable rock, the only type that has the capacity to store the fluid;
- an impermeable cover to ensure storage security by preventing gas return to the biosphere;
- a suitable structure (trap) to limit (or favour) lateral transfers.

Sites	X ext. Lambert II m	Y ext. Lambert II m	Longitude/E °	Latitude/N °	CO ₂ kt/year	NO _x t/year	SO ₂ t/year	CO t/year	NH ₃ t/year	Source
Dunkirk	603 500	2 670 200			7 011					Steel plant
Dunkirk	599 686	2 673 047	2,3333	51,0510	2 940	7 095	7 052	4 407	<100	Power plant
Dunkirk	594 574	2 669 786	2,2607	51,0218	1 496	842	3 517	401 963	<100	Refinery
Dunkirk	594 574	2 669 786	2,2607	51,0218	623	344	1 239	250	<100	Steel plant
Dunkirk	594 574	2 669 786	2,2607	51,0218	140	342	768	76	<100	
Grande Synthe	596 329	2 671 947	2,2856	51,0412	5 910	2 015	4 861	2 041	<100	Cokery
Loon Plage	594 283	2 671 400	2,2565	51,0362	750	1 541	7 870	23 141	<100	Steel plant
Loon-Plage	594 283	2 671 400	2,2565	51,0362	280	670	2 401	271	<100	Non ferrous metallurgy
Loon-Plage	594 283	2 671 400	2,2565	51,0362	189	<150	958	72	<100	
Total Dunkerque					19 339					soit 71%
Aniche	665 580	2 600 842	3,2584	50,4000	145	1 154	2 129	<50	<100	Glass or brick factory
Arques	597 567	2 636 963	2,3034	50,7275	173	771	685	<50	<100	Glass factory
Blendecques	595 297	2 635 458	2,2714	50,7140	123	<150	<150	81	<100	Paper factory
Bouchain	669 713	2 589 445	3,3144	50,2973	115	433	491	<50	<100	Power plant
Boulogne	548 479	2 632 731	1,6104	50,6874	349	265	884	4 785	<100	Steel plant
Boussois	721 624	2 588 875	4,0413	50,2842	322	1 760	4 006	<50	<100	
Calais	570 352	2 661 843	1,9170	50,9499	104	156	598	<50	<100	
Corbehem	631 243	2 033 613	3,0400	50,3370	451	1 234	2 475	76	<100	Sugar factory
Coudekerque	602 900	2 671 400			1 288					Oil refinery
Dannes	548 954	2 620 754	1,6186	50,5800	347	1 461	201	188	<100	Cement factory
Drocourt	642 012	2 597 829	2,9273	50,3750	1 850	567	427	566	<100	Cokery
Haubourdin	646 960	2 625 911	3,0000	50,6266	108	<150	243	<50	<100	Waste incineration
Hornaing	662 204	2 037 650	3,4791	50,3750	477	1 169	3 964	70	<100	Power plant
Lestrem	624 319	2 626 771	2,6808	50,6356	282	360	750	93	<100	Waste incineration
Lillers	610 966	2 618 264	2,4922	50,5597	135	374	776	<50	<100	Sugar factory
Lumbres	584 244	2 633 840	2,1153	50,6993	469	567	933	289	<100	Cement factory
Madeleine	652 190	2 629 021	3,0742	50,6541	205	212	166	739	<100	District heating
Pont-sur-Sambre	709 414	2 582 629	3,8686	50,2305	478	1 571	2 646	71	<100	Power plant
Rety	558 826	2 646 923	1,7550	50,8154	351	<150	<150	<50	<100	
Waziers	654 373	2 600 062	3,1010	50,3941	257	330	<150	<50	132	
Total Nord Pas-de-Calais					27 368					

Table 10 - Gas emissions from Nord - Pas-de-Calais (source: CITEPA, 1994).

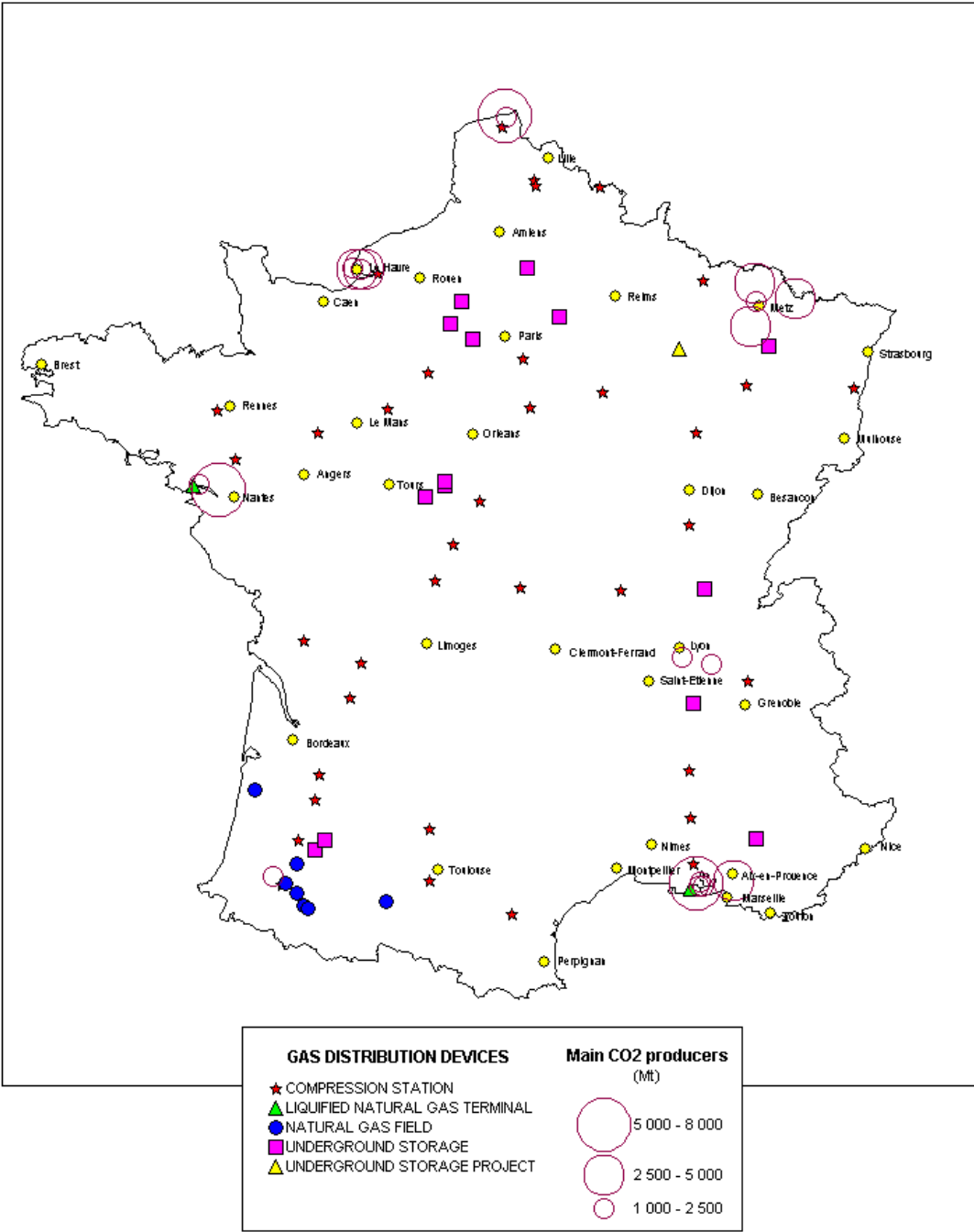


Fig. 5 - Location of the principal current gas and underground storage infrastructures.

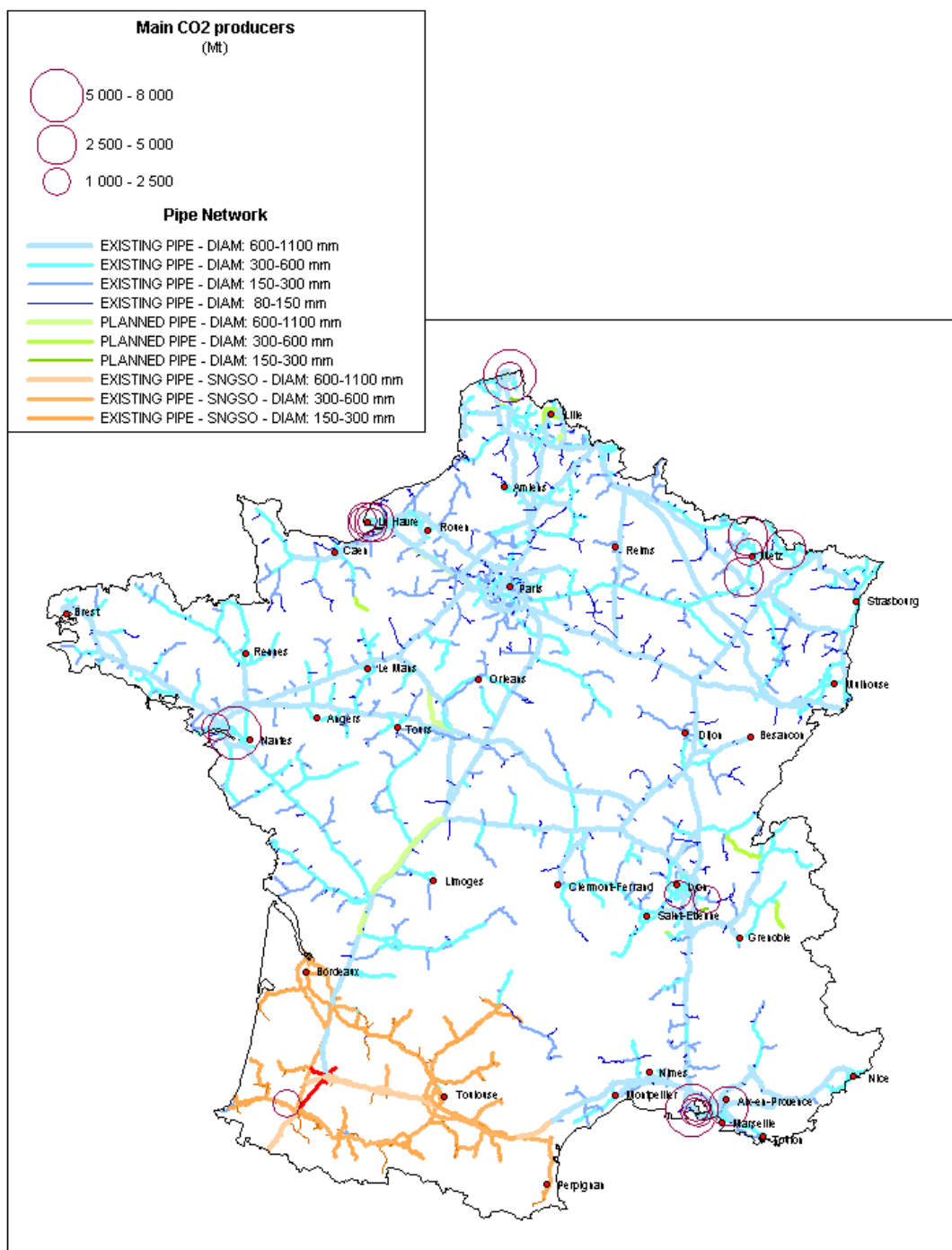


Fig. 6 - French gas pipeline network (source: Gaz de France).

In addition, the reservoir rocks should be more than 1000 m deep to enable the future storage of CO₂ in its supercritical form.

The depth map of the basement roof reveals practically ubiquitous sedimentary formations more than 1000 m thick under the principal CO₂ emitters (Fig. 7). Exceptions are the regions of Nord Pas-de-Calais and Nantes regions, for which transport of CO₂ seems unavoidable.

Reservoir formations exist in the Paris Basin, the French region concentrating most of the GHG emissions. They are permeable rocks containing either fresh- or salt-water aquifers or hydrocarbons. The desire to use a geological reservoir already in service, however, will clearly cause utilisation conflicts that could jeopardise a storage project. This is why our inventory concentrates on the reconnaissance of reservoirs containing either salty aquifers, or other fluids for which the injection of CO₂ would improve recovery (hydrocarbons), or fluids in which injection would have no effect on their use (geothermal sources).

The objective of France's participation in the GESTCO project is, following an initial inventory of permeable formations devoid of usable fresh water, to analyse the technical consequences of injecting CO₂ into an aquifer used for energy production (low enthalpy geothermal source).

Moreover, this search for reservoirs will be carried out only in the Paris Basin for the reasons explained above.

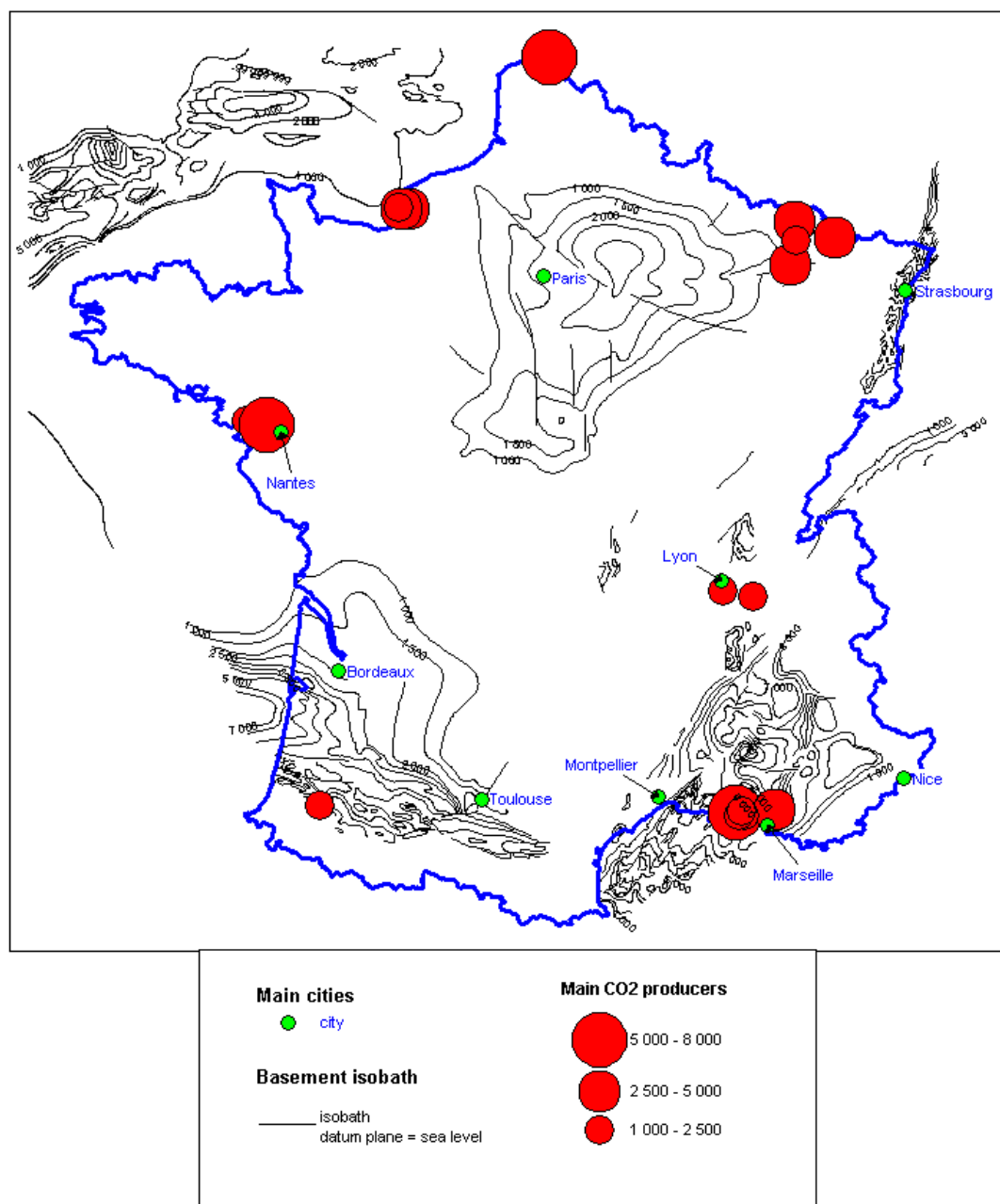


Fig. 7 - Depth of the basement under sedimentary deposits.

3. Geology of the Paris Basin reservoirs

In order to map the aquifers favourable to the CO₂ injection, a geological synthesis is specifically committed within the framework of this work. It is based on the interpretation of more than 2000 wells drilled in the basin of Paris at the time of the oil exploration surveys. This study has also got benefit from the support of the BRGM project "Geological Reference for France", financed by the Ministry for the French Industry, which aims to harmonise the description of the whole of the wells carried out in France.

3.1. DEFINITION OF RESERVOIR BEDS

This study considers a reservoir bed as any sedimentary formation having the following three qualities.

- it is composed of reservoir rock with known porosity properties. The term "reservoir" that was originally applied mainly to the petroleum sector, is used here in a broad sense to refer to the presence of an interconnected porous network in the rock that can contain or accept a fluid (oil, water, gas);
- it is sealed by a system such that any stored fluid will remain trapped in the formation and cannot emerge naturally via the top or laterally. The principal favourable systems are structural traps (drag fold or salt dome, anticlinal closure, etc.) and stratigraphic traps (pinch-outs, etc.);
- its volume is sufficient and continuous in both thickness and lateral spread.

This study presents a review of possible targets, with the exclusion of:

- formations covered by less than 500 metres or more than 3000 metres of rock;
- formations that are too thin or too discontinuous, often poorly understood;
- beds whose reservoir characteristics result from considerable fracturing, even though they are sometimes the targets of petroleum exploration.

3.2. DIFFERENT TYPES OF RESERVOIR BEDS

A number of reservoir beds have been identified in the Paris Basin from reconnaissance for various petroleum, mineral, geothermal, hydrogeological, gas-storage projects, etc. Known for their petroleum, geothermal or aquifer potential, these beds are also those that are potentially usable for CO₂ storage. Their lithologies may be varied, but generally fall within two main categories:

- **Clastic formations:** composed of sandstone, or in places sand, the main periods of accumulation were the post-orogenic phases. As a result of highly active erosion, the dismantling of reliefs results in the production of large quantities of sandy material that can form very thick strata in a continental fluvial or deltaic regions. The high energy of the depositing agents (rivers and ocean currents) leads to the segregation of relatively coarse material (sand and sometimes conglomerate) favouring the existence of a relatively large porous system.

- Carbonate formations: the production of carbonate particles is often related to biological activity, e.g. carbonate skeletons of organisms, biopisolithic type calcritisation), but also can result from chemical precipitation (ooliths). These conditions are generally found in warm shallow seas, in barrier environments exposed to ocean currents. As with clastic formations, the high energy of the transport and depositional agents segregates material that is coarser than elsewhere and that can harbour a large porous system.

The retention of the original porous space until present time depends on a large number of factors. Generally, substantial transformations could have occurred, some of which (late precipitation of cement in pores, compaction) reduce porosity (poronecrosis). Others, on the contrary (dissolution, dolomitisation, fracturing) increase the porous volume (porogenesis).

3.3. THE PARIS BASIN

3.3.1. Description

The Paris Basin occupies a large half of northern France (Fig. 8). It is bounded to the north by the Ardennes and to the east by the Vosges. To the south and southwest, it extends to the Massif Central and the Armorican Massif, respectively.

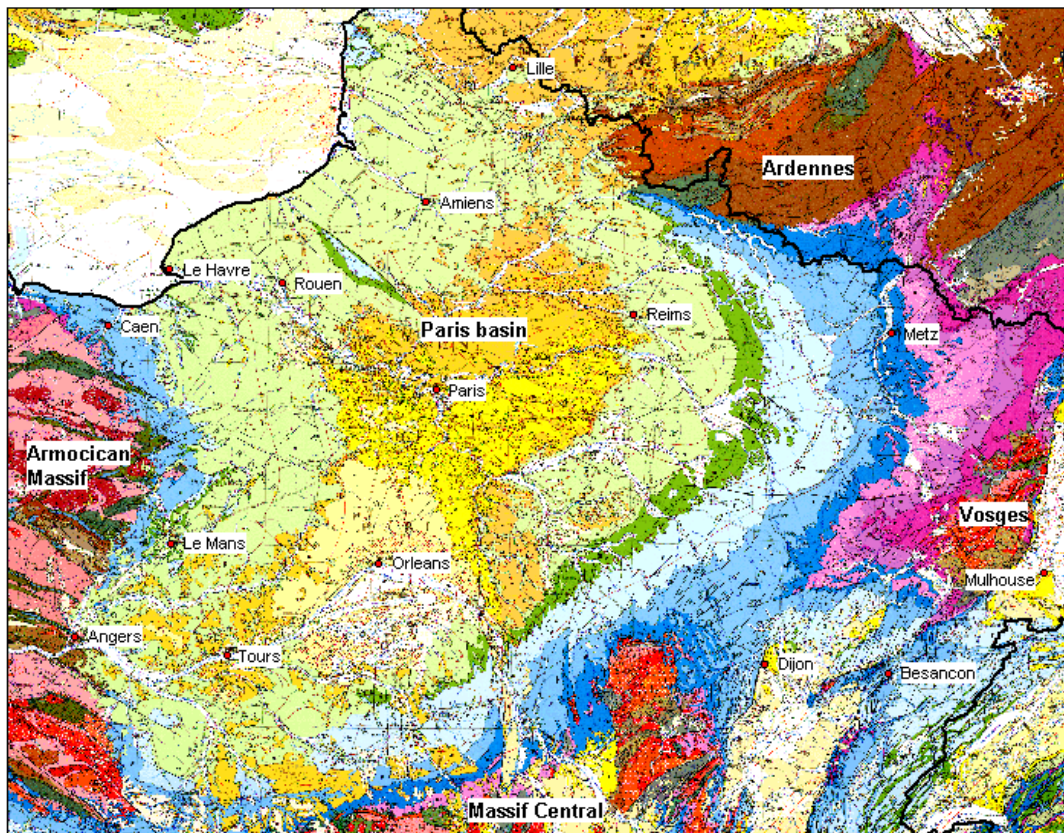


Fig. 8 - Geological map of the Paris Basin (extracted from the 6th Edition of the 1:1,000,000-scale Geological Map of France, 1996).

Geologically it is an intracratonic basin, i.e. a vast depressed area installed in the heart of a former basement (or craton). Its history is one of polyphasic filling of this vast depression, whose curvature is irregularly accentuated under the increasing weight of sediments, and also because of tectonic movements.

During the Palaeozoic, isolated sub-basins received deposits that were occasionally thick, especially in the Devonian, Carboniferous and Permian. Our knowledge of these deposits is far from extensive, based on a limited number of drilling results and seismic profiles or geophysical coverage. They are not within the scope of this study.

The Paris Basin is composed primarily of Mesozoic rock and its filling probably started in the Triassic. Its overall structure is a regular stacking of beds, but when looked at in detail, the terrains have a complex arrangement marked by a large number of lateral facies changes. There is considerable geological information available on the post-Permian formations and the geometry of these beds is now well known.

The main inventoried reservoir beds, shown on the synoptic log (Fig. 9) and the synoptic section (Fig. 10), are:

- Lower and Upper Triassic sandstone-conglomerate layers of the Bundsandstein and the Keuper and Rhaetian, respectively;
- Lower Jurassic sandstone and sandy and oolitic limestone;
- Dogger oolitic limestone;
- Middle and Upper Oxfordian sandstone and oolitic limestone;
- Lower Cretaceous with Wealden facies sand and sandstone;
- Albian sand and sandstone.

The two selected target beds are those of the Triassic and the Dogger.

3.3.2. Description of the main reservoir beds in the Paris Basin

a) Triassic reservoir beds

The Triassic reservoir beds correspond to two vast sandstone formations extending throughout the region:

- Lower Triassic sandstone (Bundsandstein) in Lorraine;
- Upper Triassic sandstone (Keuper) forming a western sub-basin, west of a line connecting Reims - Sens - Nevers.

These reservoir beds are among the largest aquifer reservoirs of the Paris Basin and were selected for a detailed description. They are dealt with in a specific section.

b) Rhaetian reservoir bed

The Rhaetian paleogeography is contrasted, and clastic facies are limited primarily to the edges. The largest formations are located in the NE quadrant of the basin, related to clastic inputs from what is now Luxembourg (Fig. 11).

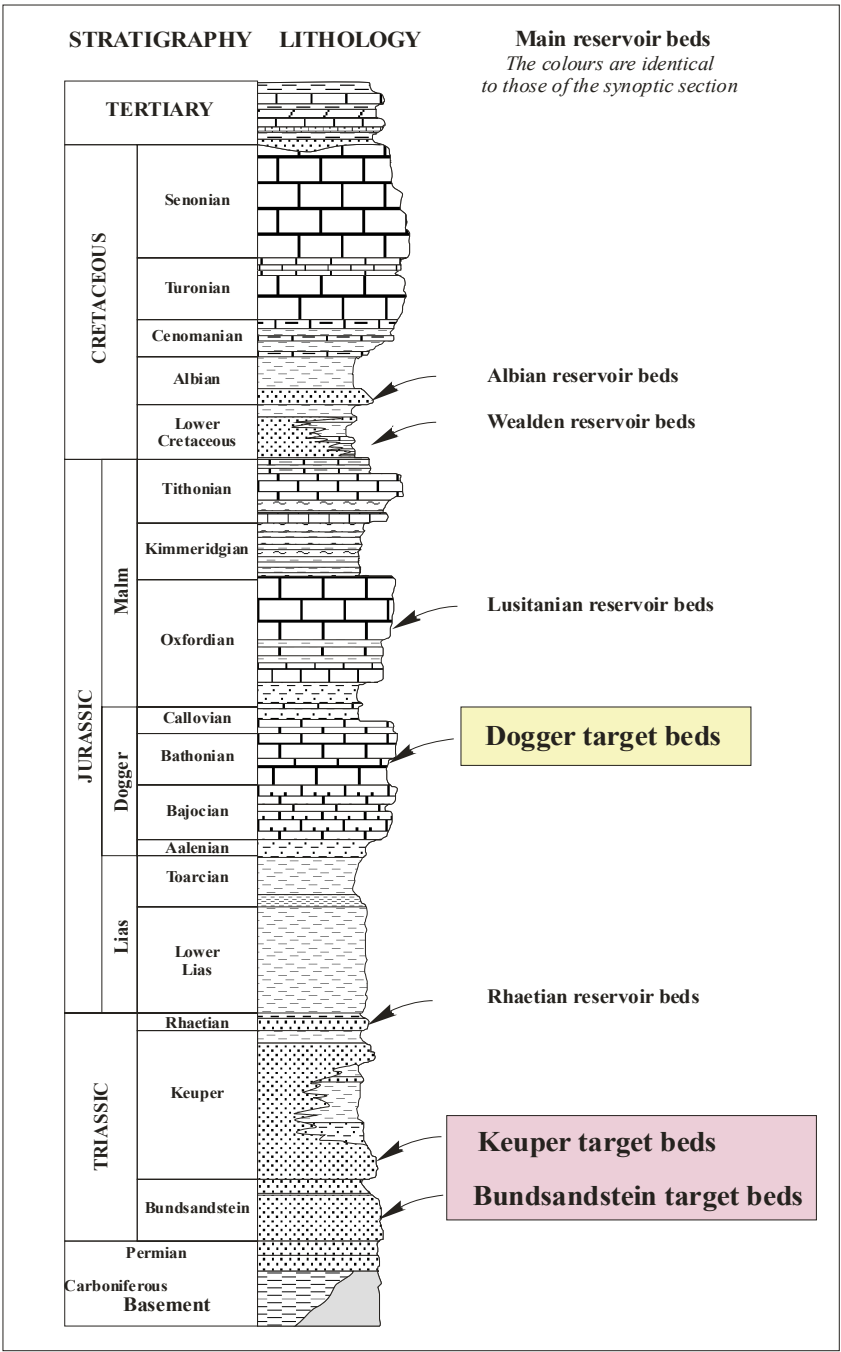


Fig. 9 - Synoptic log of sedimentary formations in the Paris Basin – France.

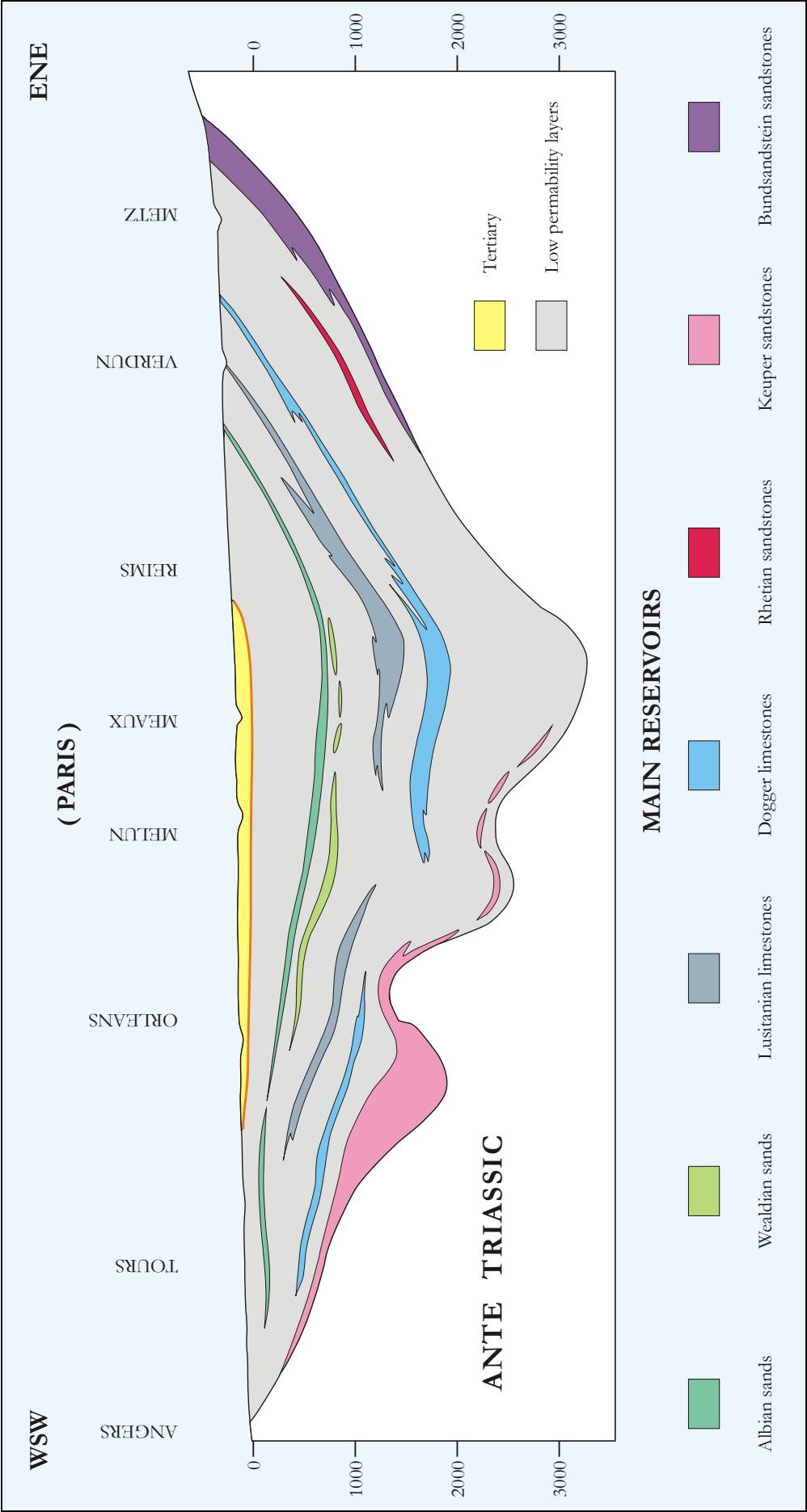


Fig. 10 - Main reservoirs identified in the Paris Basin.

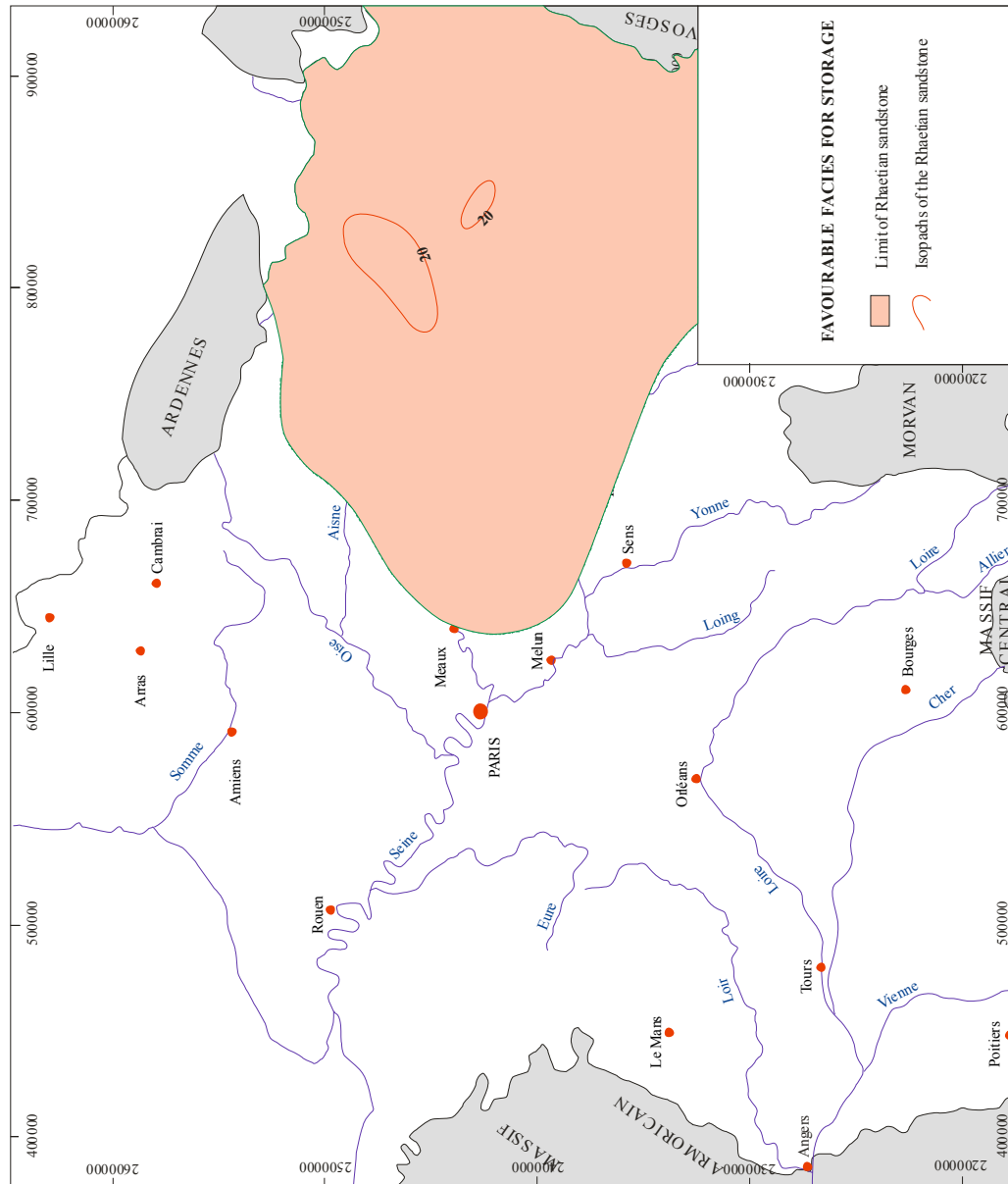


Fig. 11 - Extension and thickness of the Rhaetian sandstone in the Paris Basin. Adapted from Maget, 1983.
Low temperature geothermal potential in France (BRGM Report 83 SGN 375 SPG, plate 29).

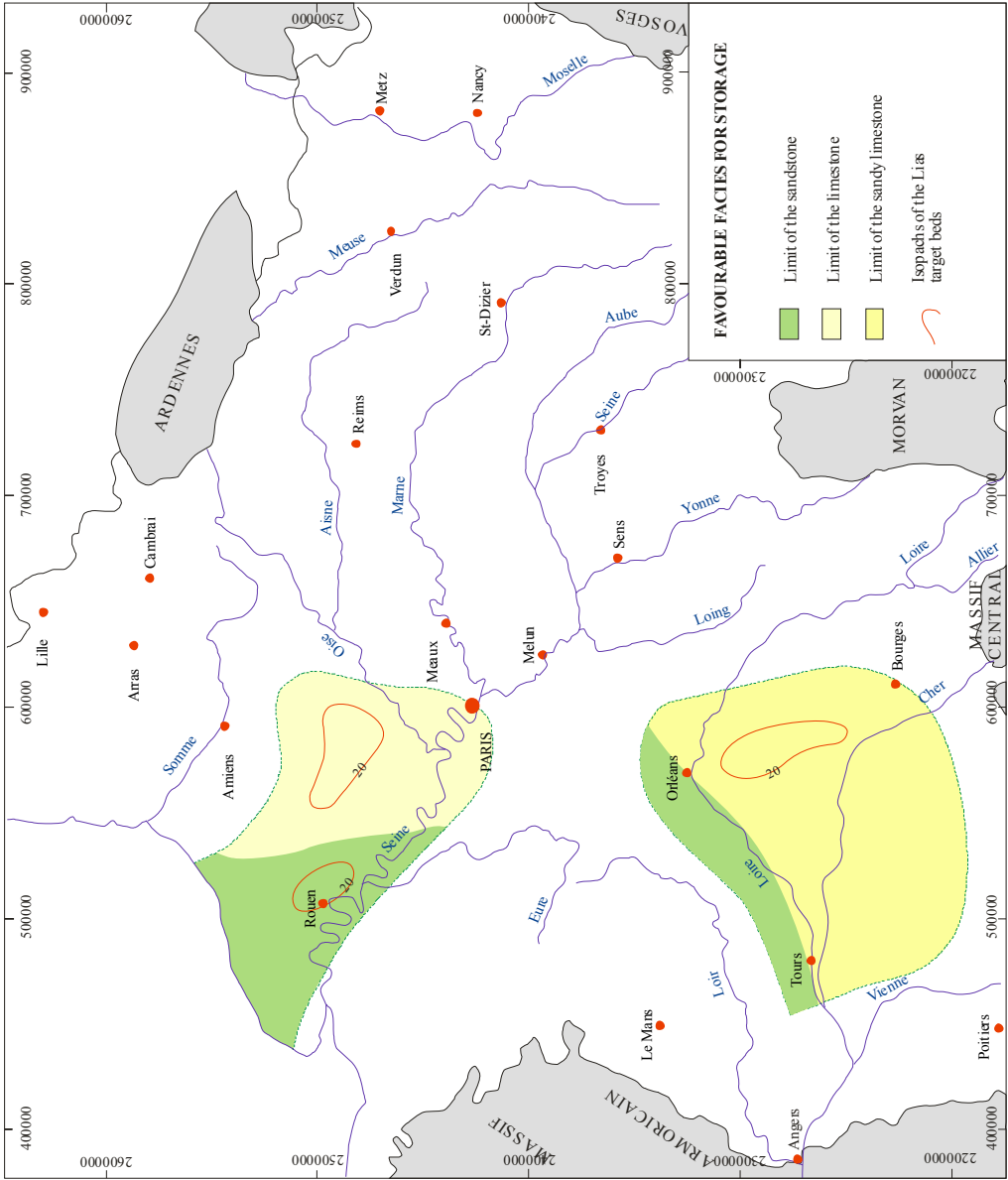


Fig. 12 - Lithofacies, extension and thickness of the Lower Jurassic reservoir beds in the Paris Basin adapted from Maget, 1983. Low temperature geothermal potential in France (BRGM Report 83 SGN 375 SPG, plate 28).

Lorraine is characterised by the development of sandstone formations with a coastal-marine and, in places, a river-delta nature. The Rhaetian sandstones of Lorraine are white, yellowish or reddish, medium- to fine-grained, cross-bedded sandstones. They may be partially cemented by carbonates or silica. Argillites are intercalated, in particular in the upper part, signalling the formation of Levallois clays (Upper Rhaetian). The sandstone becomes progressively richer in clay from northeast to southwest; clays become clearly predominant southwest of Reims.

The average thickness of the Rhaetian sandstone is 20 to 25 metres, decreasing towards the southwest (12 to 15 metres) and under several local undulations. The sandstone contains more clay in this direction, rapidly losing its reservoir quality.

c) Lower Jurassic reservoir beds: Hettangian, Lower and Upper Sinemurian (Pliensbachian)

The Lower Jurassic is characterised by a multiphase transgression that largely exceeded that of the Muschelkalk. In this context, the coarse-grained facies that are potentially favourable for fluid storage are distributed primarily at the boundaries of the transgression. They exhibit a pronounced lateral variability, commonly related to the local supply of erosion products.

Some, more carbonate-rich facies may reflect former high-energy marine environments that accompanied the progression of the sea onto the emerged domain. The main potential reservoir beds (Fig. 12) are described at the different boundaries of the basin:

- the Ardennes boundary of the basin, from Hirson to Luxembourg, is marked by clastic sediments for a large part of the Lower Jurassic, reflecting local inputs of erosion products from the Ardennes;
- the Armorican boundary is characterised by a more-or-less continuous belt of high-energy coastal facies found in the transgression, in particular during the Lotharingian. From the Creuse River valley up to the south of the Seine, the predominant facies is calcareous sandstone. To the north in the lower Seine valley and the "Pays de Caux", the boundary facies are much more sandy;
- the northern Massif Central played a boundary role only at the onset of the transgression during the Hettangian. This role ceased in the Sinemurian as a result of the total submersion of this area. Deposits with reservoir potential are limited to Hettangian coastal (oolitic limestone) or lagoonal (dolomite) facies that may be mixed with locally supplied clastics. Between the Loire and Creuse valleys, the Hettangian can reach a thickness of 40 metres.

d) Dogger reservoir beds

As of the early 1950s, the Dogger has been a major target for petroleum exploration. Several hundred wells have enabled a detailed study of the nature and geometry of the facies. A number of reviews have been published on all or parts of the available information.

The Dogger sedimentation is characterised by the installation of vast systems of carbonate shelves, delimiting an external open-sea domain from an internal restricted-marine domain.

The reservoir potential of the strata is generally related to the energy of the depositional environment. It is most favourable in the high-energy facies of the barrier and peripheral platforms. Sediment particle size is coarser than elsewhere (medium- to coarse-grained carbonate sand) because of the agitation of waters. The original porosity is commonly high. As a result of subsequent evolution (compaction, cementation, recrystallisation, dissolution, etc.), a varied proportion of this porosity may be retained up to the present day.

The Dogger is part of the targets selected for a detailed description, and is dealt with in a special chapter.

e) Middle and Upper Oxfordian reservoir beds (Lusitanian)

Following a period of dominantly marly sedimentation from the Late Callovian to the Early Oxfordian, a system of extensive carbonate platforms again developed as of the Middle Oxfordian. High-energy facies favourable for gas storage correspond primarily to two types of deposit:

- **carbonate barrier deposits:** oolitic and gravelly limestone (Fig. 13), in places reefal. They accompanied the filling of the basin at the end of the regressive "Callovo-Oxfordian" then "Sequanian" sequences (sequences S1 and S2 of the petroleum industry, respectively);
- **sandy clastic deposits** occupying the northwestern part of the basin (Fig. 14), between the Armorican Massif and the Ardennes. They mark the resumption of subsidence and of erosion at the basin boundaries, at the base of the "Sequanian" sequence.

f) Wealden reservoir beds

Following the generalised emergence of the Paris Basin at the end of the Jurassic, a vast triangular area of deposition, spreading from northwest to southeast, was gradually filled with margin-erosion products during Valanginian, Hauterivian and the beginning of Barremian. To the southeast, Wealden facies clastics abut against the northwestern wall of the Burgundy high.

The southeastern end is marked in several places by intercalations of shallow-marine facies: coastal sand and neritic limestone, locally reefal. They are the result of a succession of increasingly penetrating transgressions from the Tethys in the southeast. Again emerging during the Valanginian, the Burgundy high was submerged during the Hauterivian and again during the Early Barremian.

The Aptian transgression was greater than the preceding ones. It terminated the Wealden continental sedimentation by invading the entire basin and joining the northern sea.

The Wealden clastic series (Fig. 15) is relatively undifferentiated to the northwest of Paris. To the southeast, however, petroleum geologists have distinguished several formations that are reservoir layers.

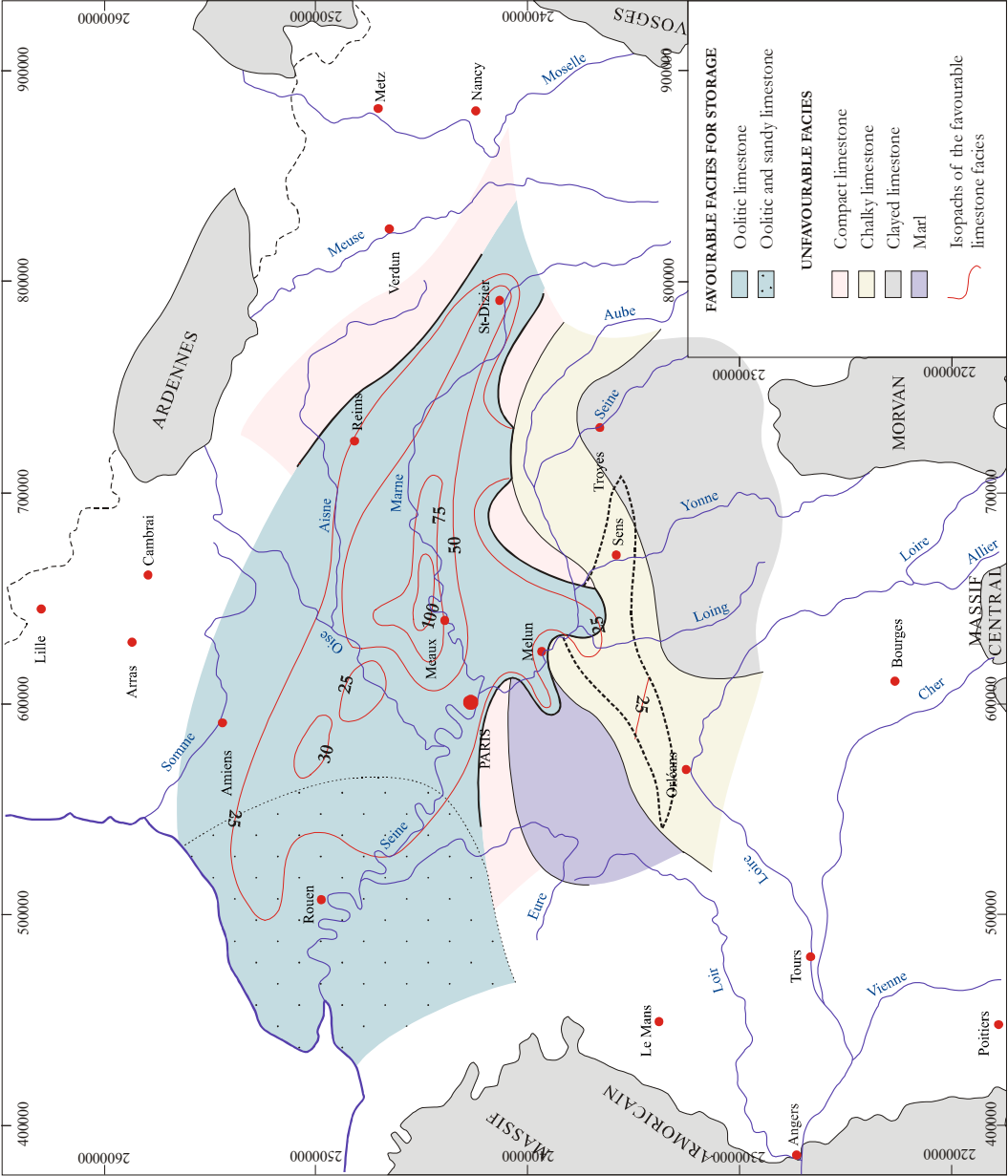


Fig. 13 - Lithofacies, extension and thickness of reservoir beds of the "Callovo-Oxfordian" sequence in the Paris Basin.
(Adapted from Maget, 1983 Low temperature geothermal potential in France (BRGM Report 83 SGN 375 SPG, plate 13).

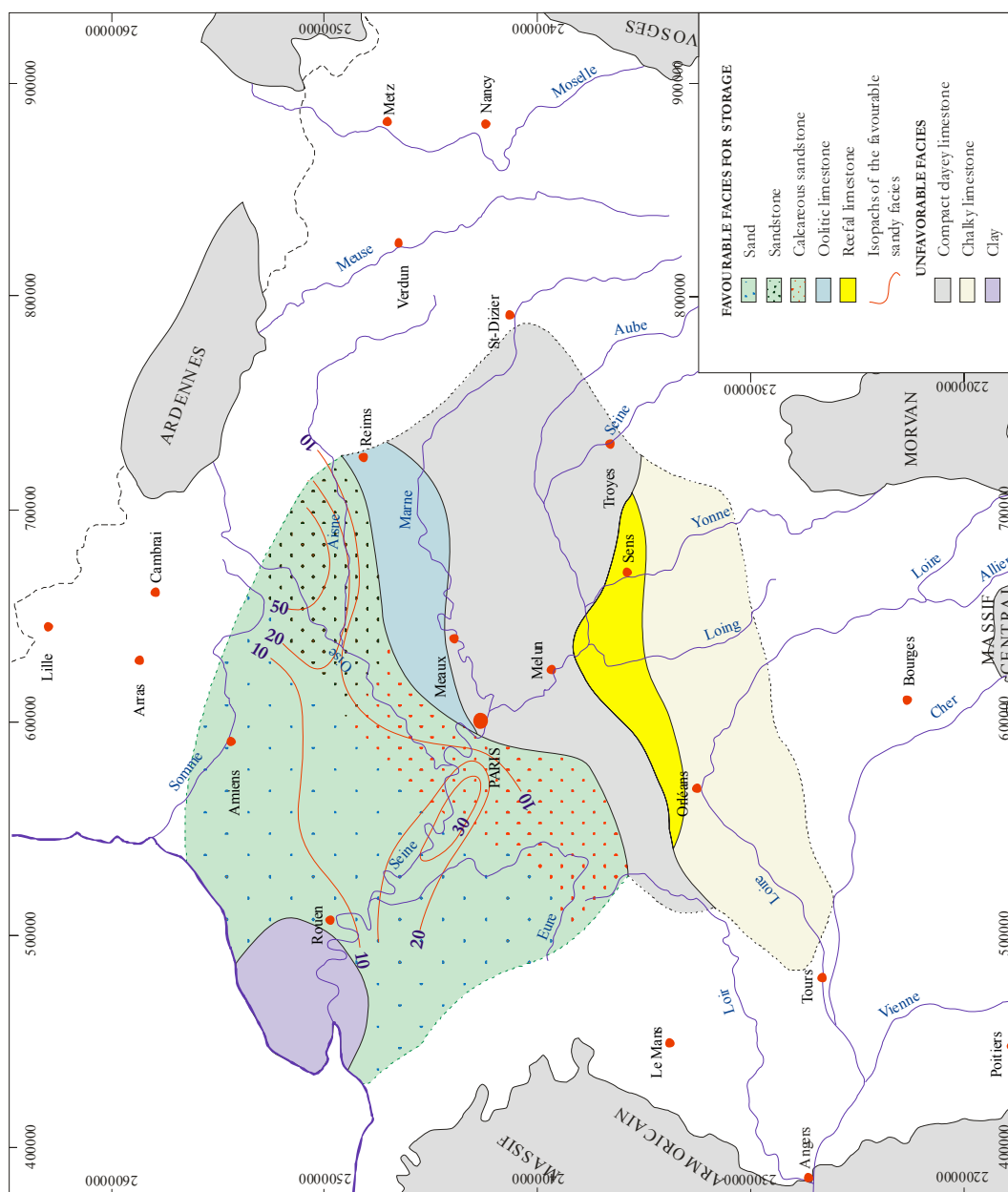


Fig. 14 - Lithofacies, extension and thickness of reservoir beds of the "Séquanian" sequence in the Paris Basin.
Adapted from Maget, 1983 (Low temperature geothermal potential in France. BRGM Report 83 SGN 375 SPG, plate 13).

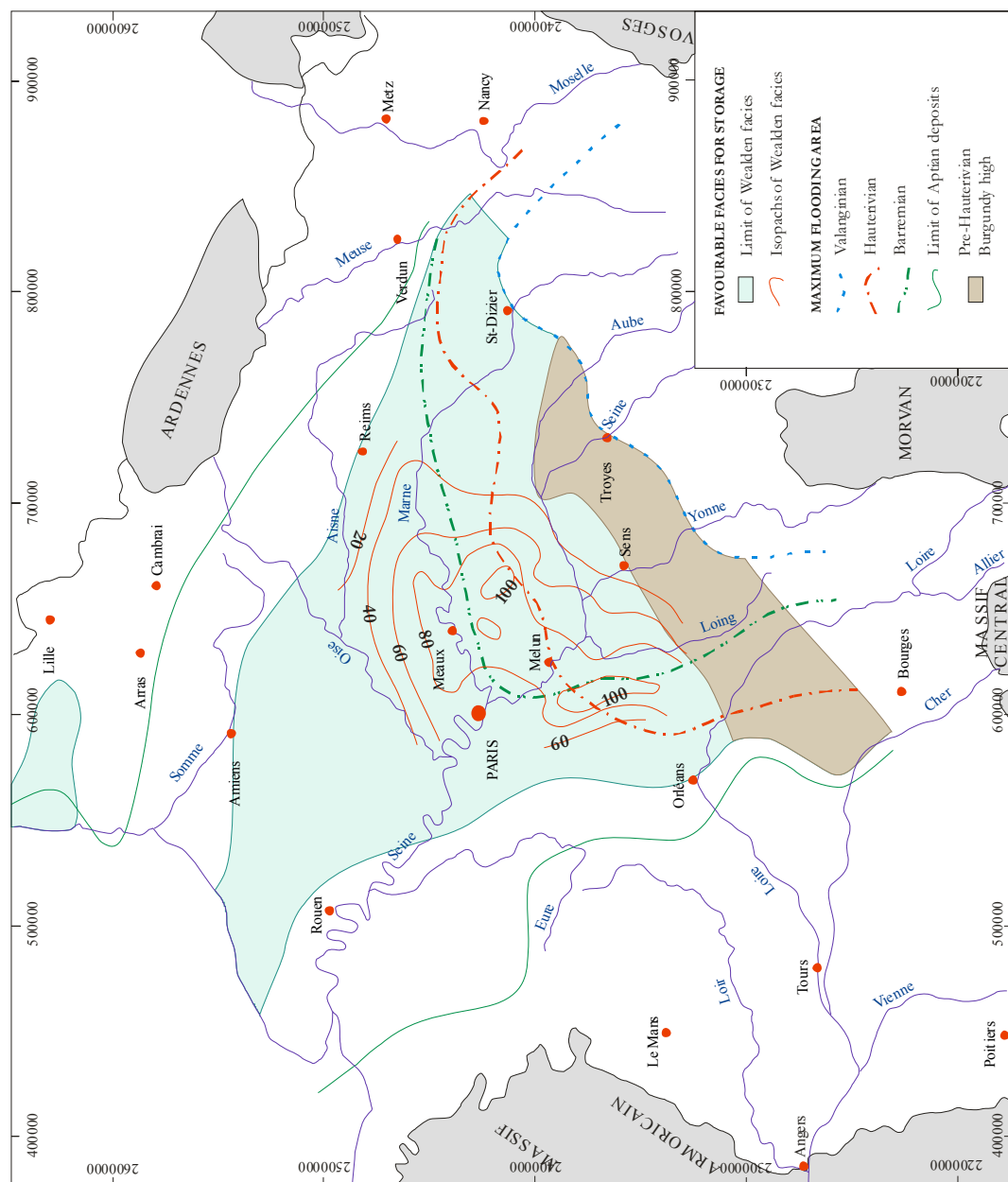


Fig. 15 - Extension, facies and thickness of reservoir beds with Wealden facies in the Paris Basin
(Adapted from Manivit, Medioni and Megnien - 1980, vol. 101, fig. 16.6, p. 447).

The useful thickness (i.e. not taking into account intercalations of facies with little or no permeability) between Meaux and northwest of Orleans is lower at between 50 and 70 metres.

g) Albian reservoir beds

The Albian sand is a deep aquifer whose use is strictly controlled in the Paris Basin. Reserved for drinking water, it is a strategic reserve and is mentioned here only for the record.

h) Conclusion

From the data provided here, it appears clearly that all the conditions specified in the conclusion of the previous chapter (see chap. 2) are joined together only for the Triassic and dogger aquifers. These two geological formations are the object of a more detailed study in the following chapters

3.3.3. The Triassic reservoirs

The “reservoir” potential of the Triassic is related to the paleogeographic evolution and can be broken down into two large clastic units. The Lower Triassic sandstone (Bundsandstein) in the east (limited to Lorraine in France), and the Upper Triassic sandstone (Keuper) in the west (west of a line connecting Reims - Sens - Nevers). These units are discussed separately.

a) Bundsandstein

- **Origin of the deposits**

The resumption of sedimentation during the Early Triassic marked a considerable paleogeographic change. Following the filling of small basins with piedmont dejection-cone deposits during the Permian, the Triassic was a period of extensive west-to-east continental transit over the Paris Basin. The region of accumulation was far to the east (Fig. 16) at the boundary of the Germanic sea in present day Germany.

During the Early Bundsandstein, a large part of sedimentation was provided by the reworking of the nearby Permian deposits. Subsequently, in the Middle Bundsandstein, the sediments were derived from regions much farther away within the Paris Basin, in the context of an arid, then semi-arid climate. A broad channel between the Morvan and Champagne ensured their transit towards the east of France. Westward progression of the Germanic sea during the Late Bundsandstein was marked by a more deltaic type of deposition, with clear-cut marine influences.

- **Lithostratigraphy**

The Early Triassic deposits of Lorraine comprise a thick, dominantly reddish, continental accumulation of medium- to coarse-grained sandstone, with common conglomerate layers, deposited in a very extensive river-channel system. The deposits in France are limited to Lorraine, which at the time was the western boundary of the Germanic Basin. They form a succession of beds, each overlapping the preceding one to a varied extent towards the west, reflecting the transgressive expansion of the

Germanic domain in this direction. The deposits are highly polarised, becoming finer grained from southwest to northeast, farther from the input zones and closer to the Germanic sea.

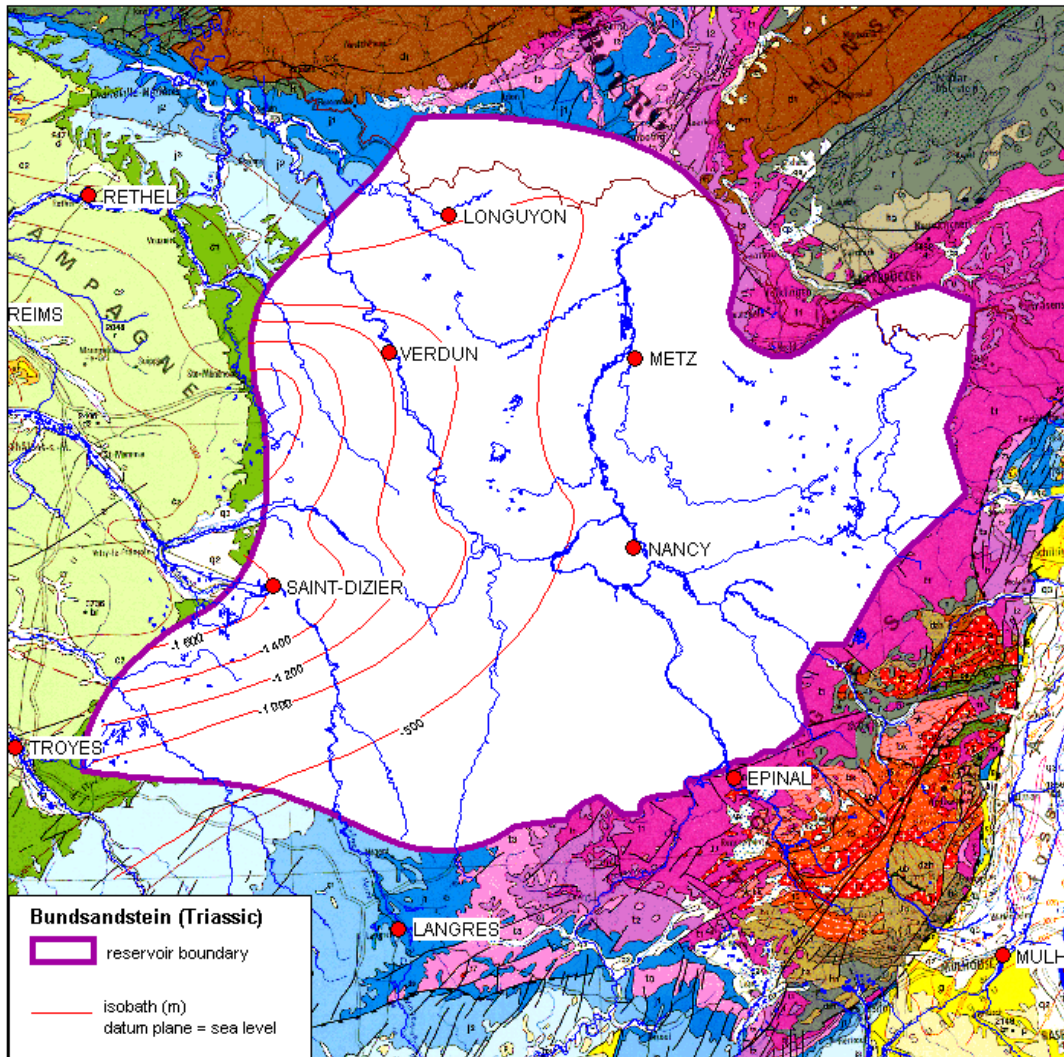


Fig. 16 - Geometry of the Bundsandstein reservoir (Triassic).

The lithostratigraphic succession is as follows:

- the *Lower Bundsandstein* is represented only in eastern Lorraine by the Annweiler Sandstone (*Grès d'Annweiler*), which comprises fine-grained, commonly arkosic, sandstone beds with a generally horizontal stratification and thin clay interbeds. It is reddish, in places with yellow spots from spathic dolomite cementing. Several beds are quartzitic as a result of silica cementing. It is laterally equivalent to the *Couches de Senones* in the sandy middle Vosges;
- the *Middle Bundsandstein* corresponds primarily to the **Vosges Sandstone**, an accumulation of sandstone that is commonly conglomeratic and whose maximum thickness is 400 metres. It contains two alternating facies:

- a "channel" facies of light-pink coarse-grained sandstone, generally well cemented by epitaxial silica, with cross bedding shown up by pebble beds or benches of conglomerates,
- a "puddle" facies composed of dark-red fine-grained sandstone with a clayey component either as a matrix or forming actual beds. It is relatively brittle with a horizontal or gently dipping stratification.

The Vosges Sandstone is bounded by two conglomeratic units:

- the *Lower Conglomerate* at the base, often considered as the discontinuous base of the Vosges Sandstone. It is composed of true conglomerate and conglomeratic sandstone, generally poorly consolidated due to an absence of epitaxial silica cement. The clasts (quartz, quartzite, lydite, rhyolite, granite, etc.) rarely exceed 3 cm in size. The colour is dark red to violet-grey;
- the *Main Conglomerate* at the top: 15 to 20 metres thick on average, it is capped discontinuously by thin sandstone-clay deposits from the "violet boundary zone" (maximum 2 metres). It forms a stack of lenticular cross-bedded, commonly graded, conglomerate beds, each about 1 metre thick. The clasts (quartzite, lydite and crystalline and other rocks) can be as much as 30 metres in size.

The Upper Bundsandstein includes two lithostratigraphic parts:

- the Intermediate Beds at the base, divided in two:
 - Lower Intermediate Beds composed of coarse-grained poorly sorted sandstone with a high feldspar content, forming thick, wine-coloured cross-bedded strata. They show small dispersed pebbles with quartz and common small dissolution cavities lined with psilomelane,
 - Upper Intermediate Beds composed of finer grained sandstone with no pebbles and only rare dissolution cavities, but with common clay lenses;
- The **Voltzia sandstone** at the top: a complex mixed series of sandstone, clayey sandstone, argillite and, in places, carbonate benches (sandstone dolomite, limestone, etc.). It comprises two successive formations:
 - Gritty sandstone at the base, formed from different intermixed facies; fine-grained well-sorted sandstone ("fresh sandstone"), medium-grained poorly-sorted sandstone with plant debris ("plant sandstone"), clay beds and intraformational breccias with reworked dolomite clasts,
 - Clayey sandstone: an alternation of thin, horizontally-laminated bioturbated sandstone, bioturbated clayey sandstone and dolomitic sandstone or sandy dolomite containing marine fauna.

- **Extension and depth of deposits**

The first deposits, from the Lower Bundsandstein, are found in eastern Lorraine. Those from the Middle and Upper Bundsandstein, however, extend farther to the west and southeast, but do not go beyond the western limit of Lorraine. Other than in this eastern domain, sedimentation began only in the Middle Triassic (Muschelkalk).

In summary, the thickness of Bundsandstein exceeds 400 metres in Lorraine (Fig. 17).

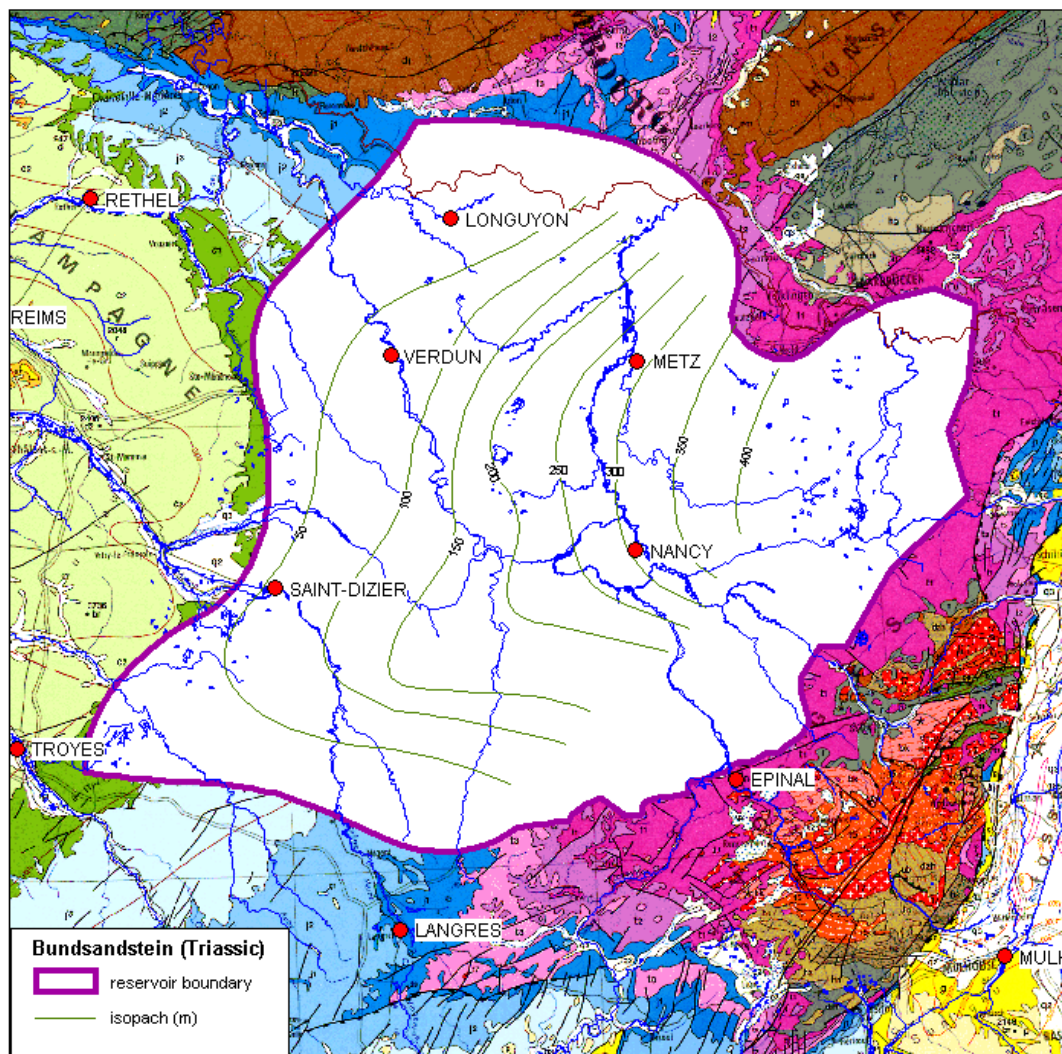


Fig. 17 - Thickness of the Bundsandstein reservoir (Triassic).

A third section, oriented SW-NE, shows the Bundsandstein geometry from the Morvan to northeastern Lorraine. Encroachment over the pre-Triassic basement was much more gradual here than at the Ardennes boundary. The Muschelkalk and Keuper are primarily clayey facies, although the Rhaetian sandstones are highly continuous.

- **Depth of the deposits**

Starting from the edge of the exposures, the depth to the top of the Bundsandstein sandstone increases westward (Fig. 16), reaching about 1800 metres east of the Marne valley (Châlons-sur-Marne and Vitry-le-François).

b) Keuper sandstone

These two reservoirs have been discovered very recently (1979) and are the result of the exploration works of ESSO Rep company.

- **Origin of the deposits**

With the progression of the Germanic sea towards the centre of the Paris Basin, coarse-grained fluvial clastic deposits of the Lorraine Bundsandstein were rapidly covered by marine carbonates. Clastic sedimentation nevertheless continued at the edge of the spreading marine domain, and a thin, practically continuous, "Clastic sole" thus extends from Lorraine to the Champagne border and south-southwestward in a broad channel between the Morvan and Champagne.

The resumption of tectonic activity at the end of the Muschelkalk resulted in the formation of a secondary more western basin, west of Champagne and the Morvan. Its existence was revealed by oil drilling. The evolution of this domain was independent of that of the eastern domain and subsidence reflects the activity of deep basement faults.

Several peripheral deposits reached the southern edge of the Paris Basin.

- **Lithostratigraphy**

Erosion of the Hercynian boundaries produced a large quantity of clastic sediment that filled the basin undergoing formation. Two major fluvial units were created in the course of the two successive episodes of erosion (Fig. 18):

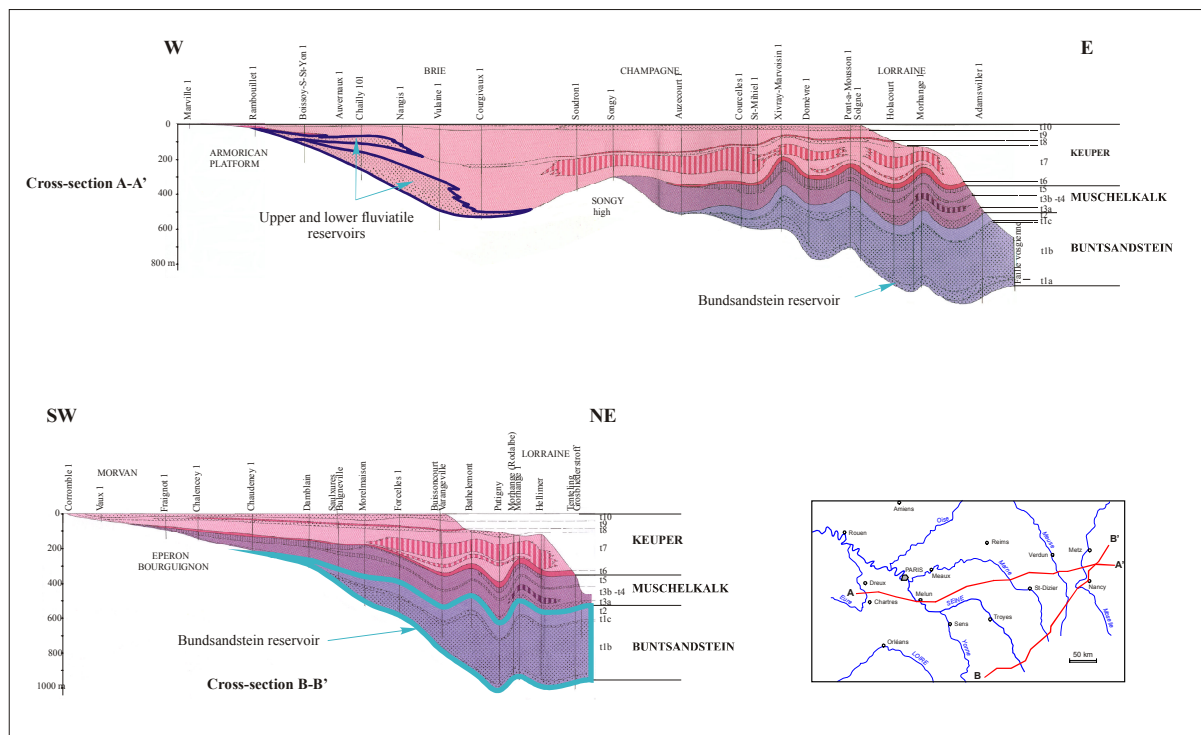


Fig. 18 - Triassic reservoirs: synoptic cross sections.

The **Lower fluvialite reservoir** between the Muschelkalk (or the beginning of the Early Keuper) and the Middle Keuper (Donnemarie sandstones). It consists of piedmont deposits, conglomeratic at the base, grading up to finer grained, relatively rhythmic,

sandstone at the top. In the central part of the basin (Fig. 19), particle size decreases from west to east, while in the southern part, this occurs in a south to north direction.

The **Upper fluviatile reservoir** accumulated during the Late Keuper (Chaunoy sandstones) in two sub-basins – one to the south of the Loire River and the other in the Brie region (Fig. 20). It is composed of a relatively rhythmic alternation of sandstone, with occasional conglomerate, and argillite. At Brie we find mainly sandstone and conglomerate that form an upward-fining unit. The sediments in the Sologne comprise alternations of conglomerate, sandstone and argillite.

The distribution of conglomeratic beds defines the axes of two paleo-valleys; that of the Lower Seine downstream from Paris, and that of the Lower Loire upstream from Tours.

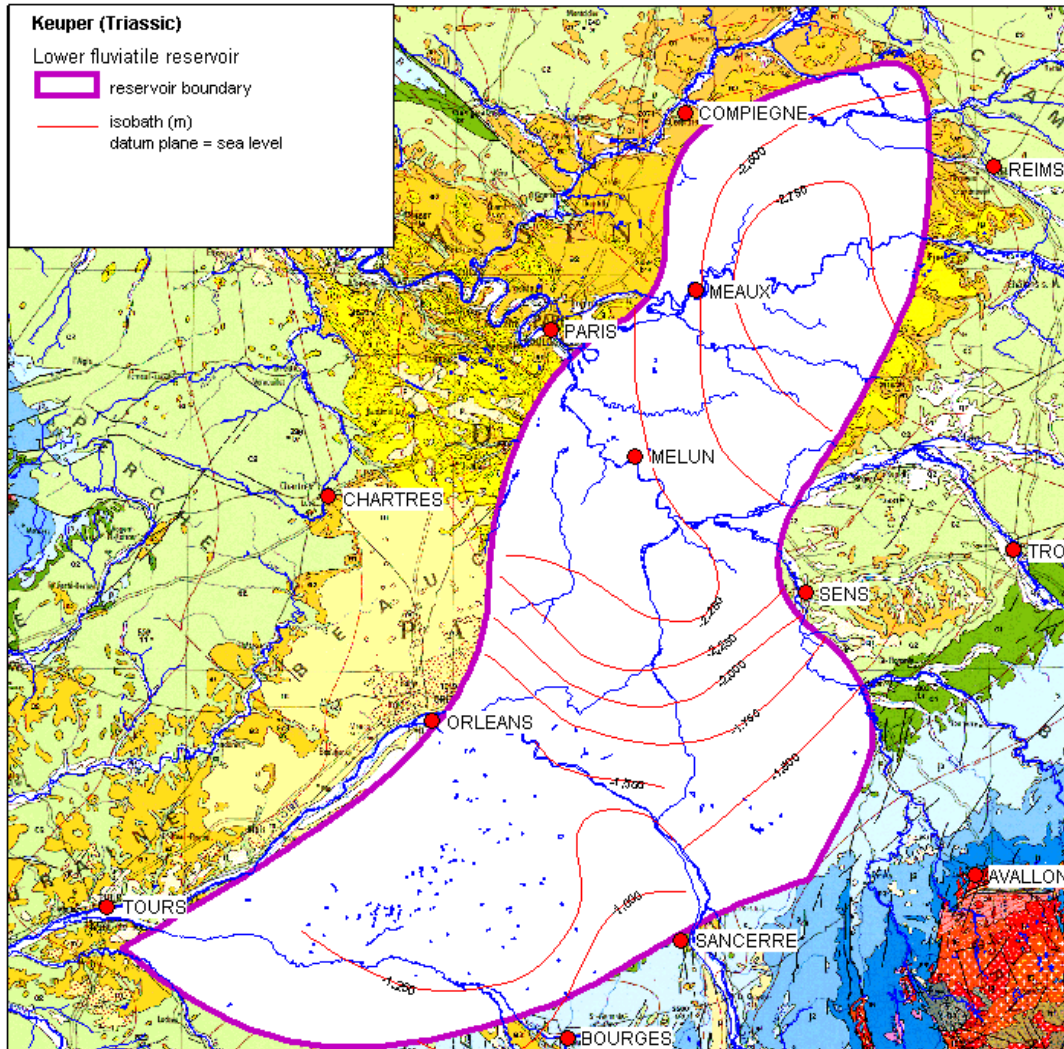


Fig. 19 - Geometry of the Lower fluviatile reservoir (Keuper).

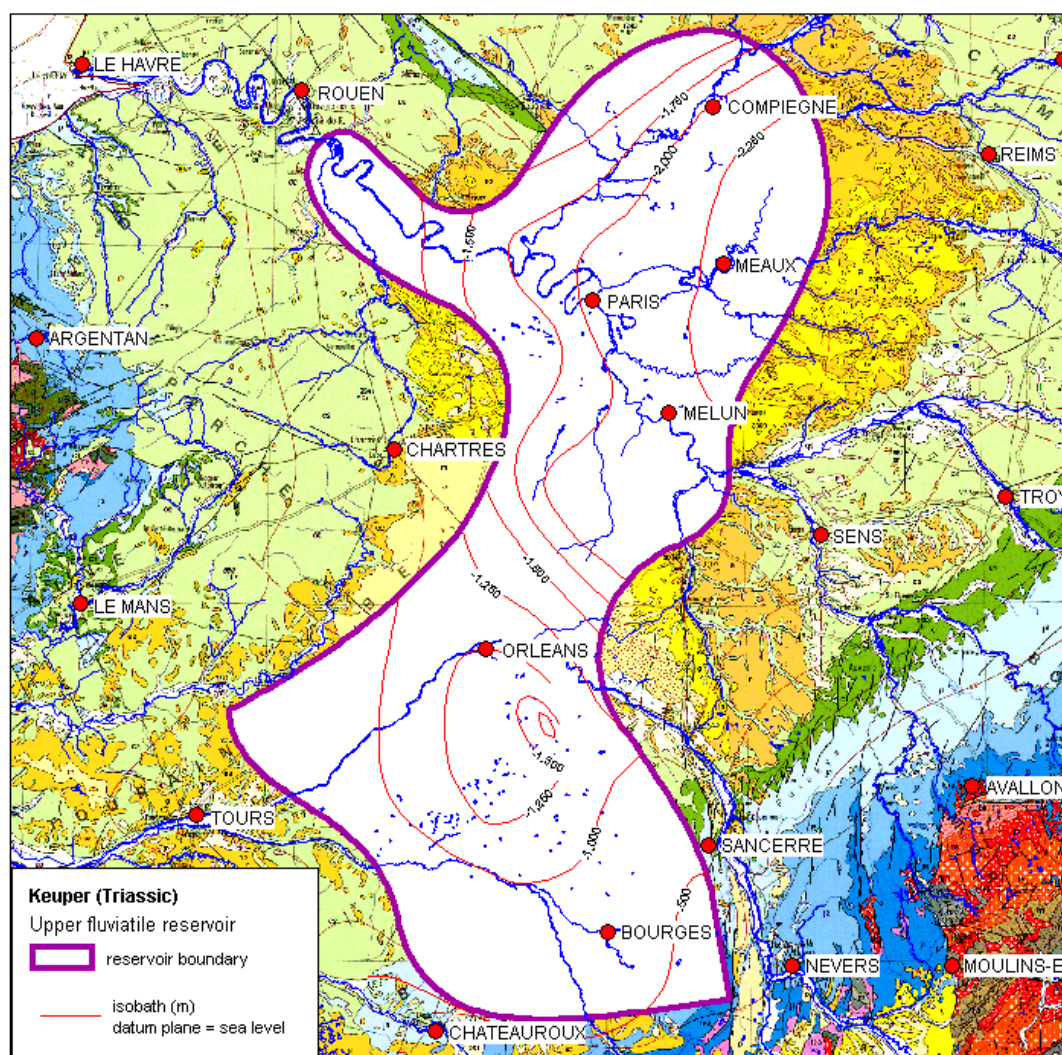


Fig. 20 - Geometry of the Upper fluviatile reservoir (Keuper).

A brief marine incursion in the eastern part of the western domain resulted in the intercalation of anhydritic clays between the two fluviatile reservoirs.

- **Extension and depth of the deposits**

The geometry of the two fluviatile reservoirs is shown in a synoptic W-E section of the Paris Basin:

- the *Lower fluviatile reservoir* developed from the Ardennes boundary up to Poitou and the western edge of the Morvan, circumventing the Songy dome to the west (Fig. 21). The western boundary passes through Soissons, the east of Paris, Orleans and Tours, and the northeast of Poitiers. The sandy reservoir was formed by progradation from this western boundary towards the centre. The eastern boundary of the domain is marked by the passage of clayey facies under a marine influence, along a line connecting Reims - Troyes – Nevers;

- the *Upper fluviatile reservoir* is larger, but offset to the west (Fig. 21). Related to the transgression, the deposits overlap towards the west in the region of Tours, Orleans and above all in the Seine valley, where they reach Rouen.

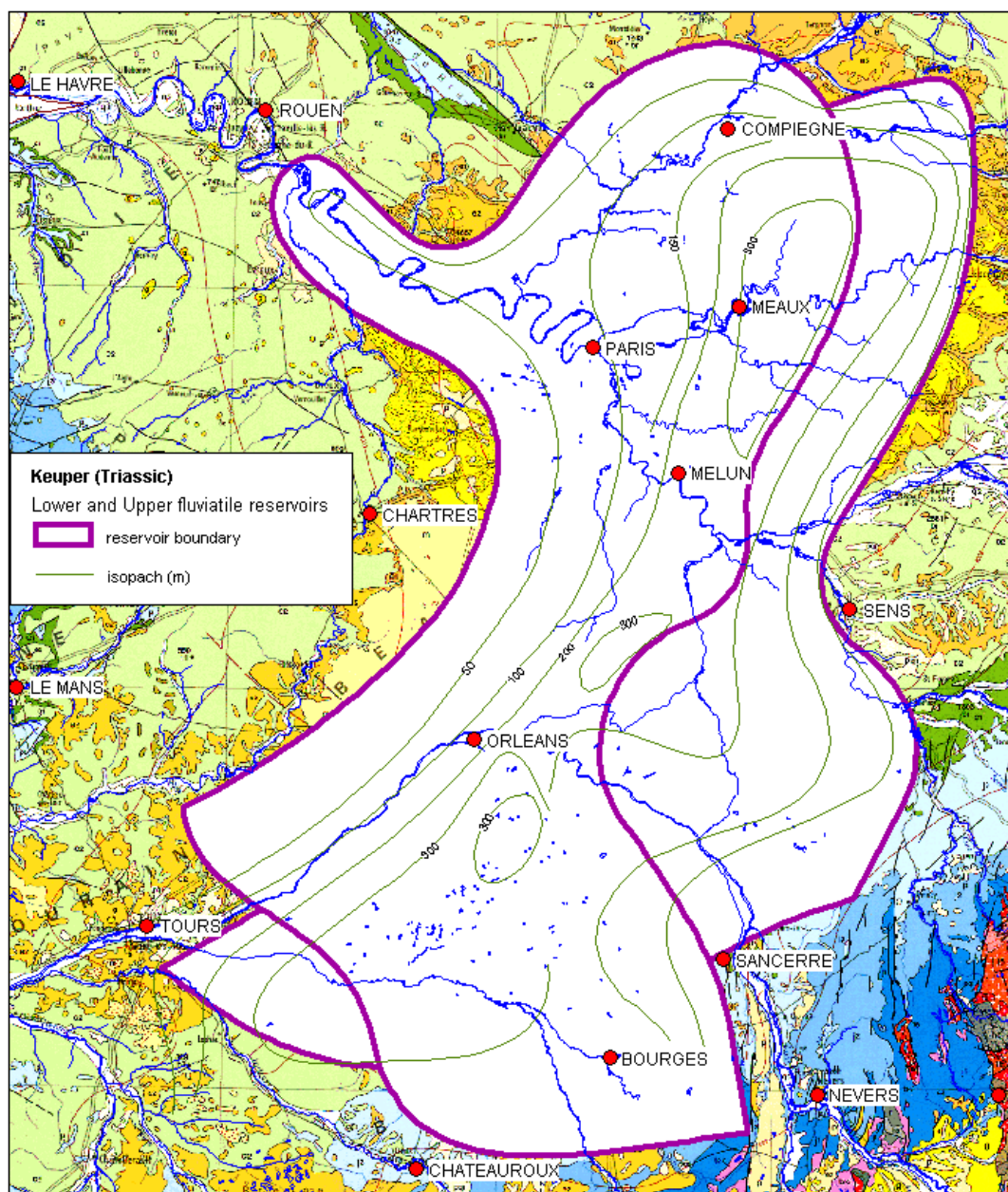


Fig. 21- Cumulative thickness of the two fluviatile reservoirs (Keuper).

At the boundary of the Armorican Massif, under Sologne, Touraine and northern Berry, the two fluviatile reservoirs are superimposed within a practically continuous sandstone succession.

The thickness of the deposits was largely controlled by the activity of deep basement faults, and in particular the Sennely Fault. Two subsiding basins formed principally

during the deposition of the Upper fluviatile reservoir, corresponding to two thicker zones (Fig. 21):

- the Brie Basin where the cumulated thickness of the two reservoirs exceeds 300 metres. Two sub-basins exist; one on both sides of the Marne River to the west of Meaux, and the other between Orleans and Sens;
- the Sologne Basin is triangular between Orleans, Vierzon and the lower Indre valley (Loches). It is more than 400 metres thick in the centre of Sologne, in the Contres and La Ferté-Saint-Aubin area.

• Depth of the deposits

The top of the Upper fluviatile reservoir is located at a maximum depth of 1800 metres (Figs. 19-20) under Sologne, on the western side of the Sennely Fault.

The top of this layer is even deeper under Brie, especially east of Melun where it is more than 2500 metres deep south of the Bray-Vittel Fault and 2800 metres deep north of this fault, to the west of Meaux.

3.3.4. The Dogger reservoirs

Since in the early 1950s, the Dogger reservoir has been a preferred target of oil exploration. Several hundred wells have enabled a detailed study of the nature and geometry of the constituent facies. All or part of available information has been the subject of a number of reviews.

• Origin of the deposits

In contrast to the relative uniformity of the end-Lias deposits, the Dogger was formed by the creation of a system carbonate shelves, including an external open-sea domain and an internal restricted-marine domain. They are separated by a high-energy marine domain corresponding to a barrier system, and by peripheral reef flats. The lateral succession of environments within each shelf is as follows:

- *external open-sea domain*: a low-energy marine environment: marl, mudstone or mudstone with micropellets;
- *fore-barrier reef flat*: moderate to high energy: grainstone and gravelly and bioclastic packstone;
- *barrier*: very high energy: bioclastic or oolitic grainstone;
- *back-barrier reef flat*: moderate to high energy: oolitic grainstone, wackestone with intraclasts, pellets, oncoliths and bioclasts;
- *lagoon*: low energy: subtidal bioclastic wackestone-mudstone, wackestone; intertidal packstone with pellets, biopisoliths and bioclasts; supratidal wackestone-mudstone with algae, fenestrated and desiccation structures.

This system, with a varied extension and morphology, developed four times according to four diachronous megasequences of the Dogger limestone:

- **megasequence S1**: Aalenian to Middle Bajocian (in part);
- **megasequence S2**: Middle Bajocian (in part) to Late Bajocian;

- **megasequence S3:** Early Bathonian to Late Bathonian (in part);
- **megasequence S4:** Late Bathonian (in part) to Middle Callovian.

The Dogger deposits reflect a structural control during sedimentation. As much as 400-450 metres of sediment accumulated in a central, slightly subsident, area. Two major structural features governed the shelf formation:

- the Seine-Sennely Fault, a major basement fault striking NNW-SSE. A trough of marly sedimentation was active along this border throughout the Dogger, separating the Armorican and Central shelves, especially at the time of their greatest development at the end of Megasequence S3;
- the major Bray-Vittel Fault that partially controlled the subsidence and morphology of the shelves (megasequences S3 and S4). During Megasequence S3, its eastern edge in Lorraine was marked by another marly trough separating the Central and Ardennes shelves for a certain time.

Facies distribution up to the Middle Bajocian (in part – end of Megasequence S1) was still oriented by a primarily NE-SW structural trend inherited from the Lias, notably with a still active Burgundy block. The barrier facies during this period remained were restricted to the edges of the basin.

A radical structural change began in the Late Bajocian, with an attenuation of the NE-SW direction delimiting the Burgundy block and deposition along a NW-SE direction in relation to the activity of major basement Bray-Vittel and Seine-Sennely faults (see above). This second period corresponded to the development of broad shelves that were no longer necessarily at the basin edges.

• **Lithostratigraphy and extension of the deposits**

The reservoir potential of the beds is related to the energy of the depositional environment. It is more favourable in the high-energy facies of the barrier and surrounding reef flats. The particle size of these sandy facies is generally medium to coarse, with a high original porosity that has been conserved until the present time.

Different reservoir beds have been identified by petroleum geologists in the four diachronous megasequences. Schematic cross-sections show the arrangement of the different facies along a SW-NE direction in the basin (Fig. 22). The reservoir beds of the different megasequences are discussed successively, starting with the deepest:

- **megasequence S1:**
The oolitic facies of the high-energy barrier are limited to the Ardennes boundary, where they were contemporaneous with the transgression (skeletal limestone);
- **megasequence S2:**
The barrier facies spread to the entire basin boundary at the end of the Bajocian. The extension of Upper Bajocian reservoir beds is shown on Figure 22;

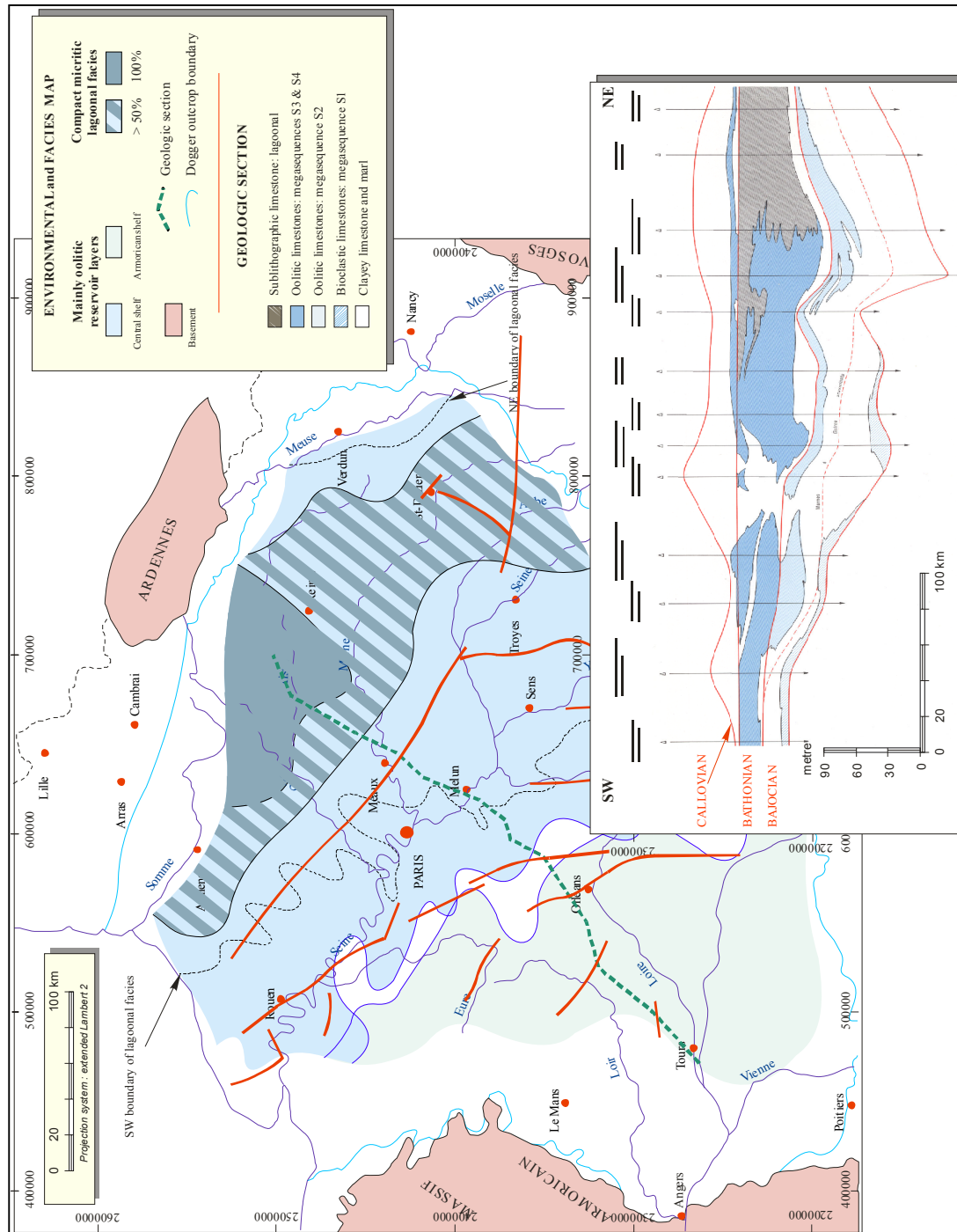


Fig. 22 - Facies distribution of the Dogger reservoir (map and cross-section).

- **megasequence S3:**

This period marked the greatest amplitude of the barrier-lagoon system. Barrier facies were much more extensively developed than those of the preceding megasequences. Towards the end of the megasequence, the Paris Basin was occupied by two shelves: the principal shelf in the centre and the Armorican shelf to the west. Stripping the facies at the top of Megasequence S3 reveals the magnitude of the high-energy facies and the relationships between the shelves (Fig. 22). The two shelves are separated by a narrow marly trough whose path follows that of the Seine-Sennely Fault;

- **megasequence S4:**

The Central shelf is reduced to a gravelly-oolitic formation of limited extent: the "Dalle Nacrée" (flaggy limestone). The Armorican shelf passes laterally to open-marine clayey-silty facies and is thus not favourable for gas storage.

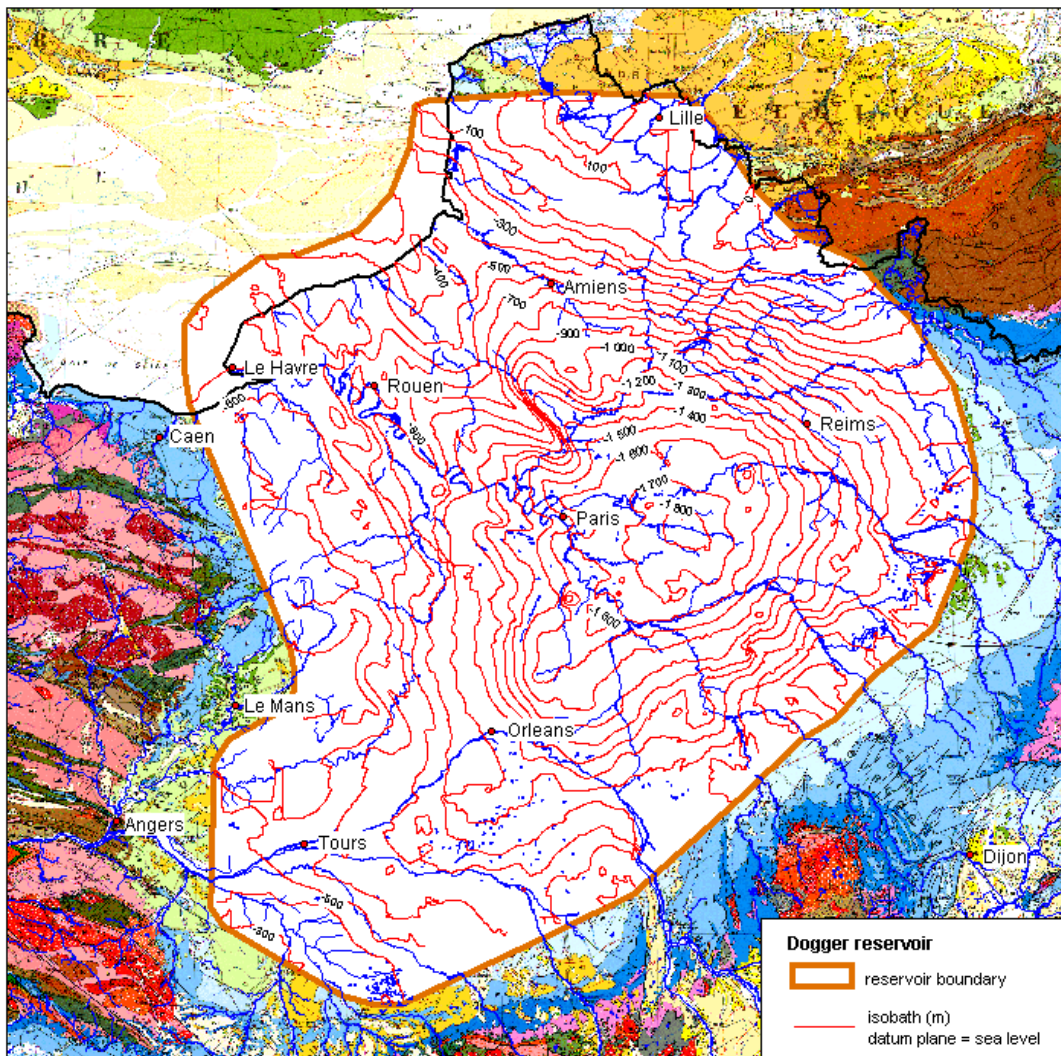


Fig. 23 - Geometry of the Dogger reservoir.

- **Depth of the deposits**

At the basin boundaries:

- **megasequence S1:**

The deposits at the Ardennes boundary (skeletal limestone) are about 40 metres thick. Thicknesses are variable in Lorraine (coral limestone) with 30 metres south of Chambley, 50-60 metres north of Chambley and 20-30 metres towards Longuyon-Gorcy. Bioclastic deposits in Burgundy are 40-60 metres thick.

- **megasequence S2:**

Deposits are thin at the Armorican boundary south of the Perche spur: 10-15 metres towards Mamers (Villaine-la-Carelle oolite), and 4-5 metres more to the west (Damigny oolitic limestone).

At the Burgundy boundary, crinoidal limestone thickens northeastward: 5-10 metres in the Berry and Nièvre area, 15 metres in the Avallon area, and 30-40 metres in the Châtillon area.

In Lorraine oolitic beds represent 30-35 metres of deposition with different local facies (Millet-seed oolite, *Clypeus ploti* oolite, Jaumont oolite, etc.).

- **megasequence S3:**

In Burgundy, the principal porous facies of the sequence is white oolite. Its thickness varies considerably, with 20-30 metres towards Chaumont, 40-50 metres in the Châtillon area and 60-80 metres in the southern part of the Yonne Department.

In Lorraine, the thickness of the "Dalle d'Etain" (Etain flagstone) increases northward, i.e. 20 metres around the municipality of Etain and 40 metres in the vicinity of Longuyon and Verdun.

At the Ardennes boundary and in the Boulonnais region, oolite thicknesses are much lower, increasing westward from 6 to 15 metres.

At the Armorican shelf boundary, the deposits are highly varied: 8-12 metres around the Perche spur (Blainville limestone), 25 metres for the Chauvigny oolite in the Poitou region, and 30-35 metres in the Indre Department (Saint-Gaultier reef formation).

- **megasequence S4:**

The "Dalle Nacrée" (flaggy limestone) facies are not all favourable. The limestone is very thick in Burgundy, reaching 30-40 metres, and much thinner in Lorraine at 15 metres.

Available thickness data are the sum of all reservoir beds of the four megasequences. Figure 24, taken from the review of the geothermal potential of the Paris Basin (Housse and Maget, 1976, revised in 1983), shows the distribution of these thicknesses. Synoptic cross-sections (Fig. 22) clearly show that it is the Megasequence S3 beds that contribute predominantly to the overall thickness

There are two sectors (Fig. 24) where the cumulated thickness exceeds 100 metres:

- the *central sector* contains two overthickened areas (more than 150 metres);
- the *western sector*, i.e. the Armorican shelf deposits, contains a highly localised overthickened area (more than 175 metres).

- **Depth of the deposits**

The depth to the top of the Dogger limestone is maximal in the Brie region east of Paris, where it exceeds 1500 metres and in particular in the Coulommiers area where it reaches 1800 metres, with a slight offset due to the Bray-Vittel Fault.

Another deep area occurs in Sologne, south of Paris, where it is limited to the east by the Sennely Fault. Maximum depth is around 1100 metres (Fig. 23).

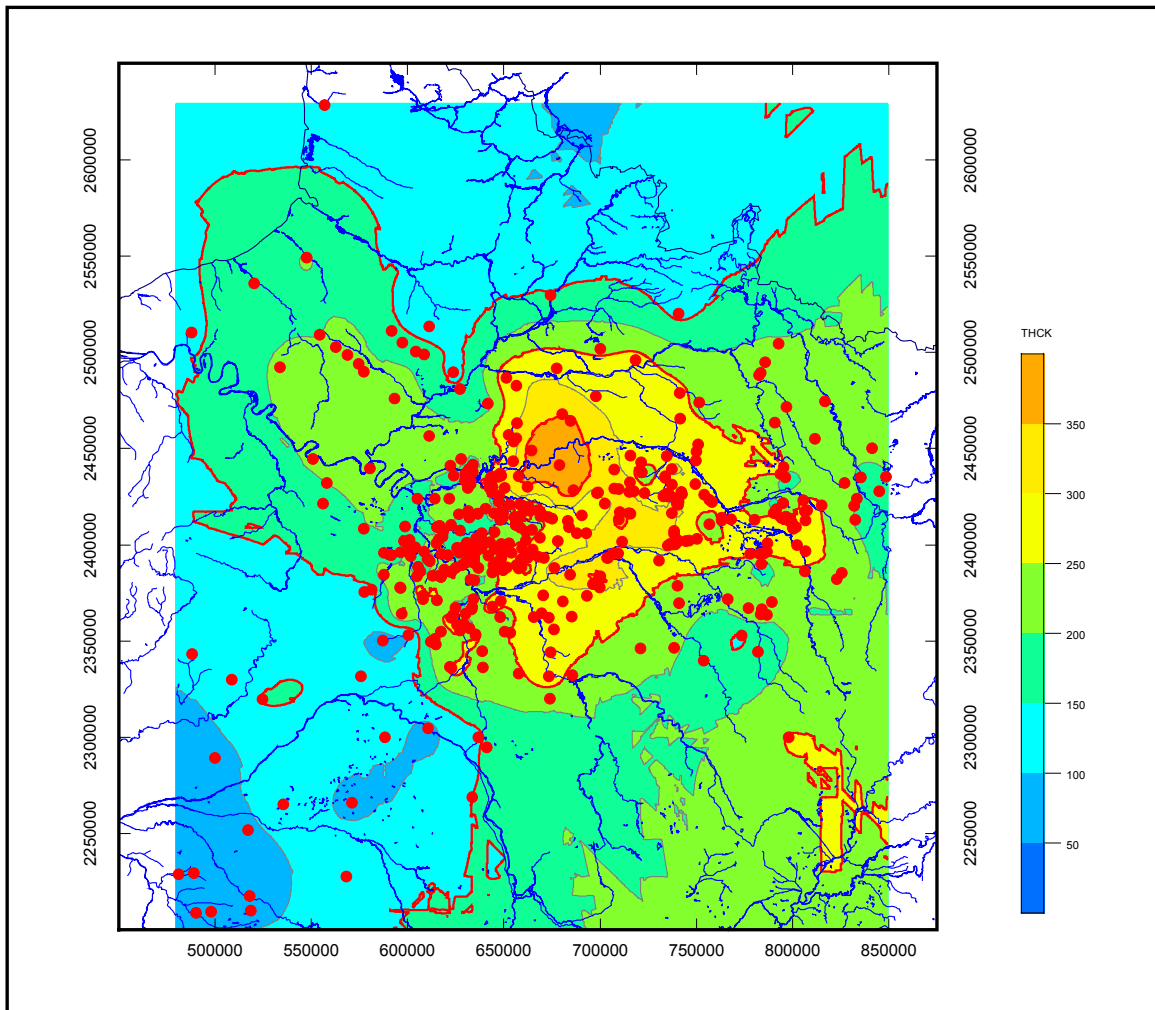


Fig. 24 - Thickness of the Dogger reservoir.

3.3.5. Conclusion

Geothermal exploration studies have shown in particular (Maget, 1983) that the Megasequence 3 oolite layers are the principal reservoir in the Dogger succession. Their porosity has commonly been increased by diagenetic dissolution and their volume is very large.

The Megasequence S2 oolitic beds are generally finer grained and tests conducted in geothermal wells have shown a very low permeability.

The Megasequence S1 beds are very commonly cemented and are commonly thin.

The "Dalle Nacrée" (Megasequence S4) is sufficiently thick only to the south of the Paris region and in Burgundy (30-40 metres). Elsewhere it is cemented and relatively thin.

3.4. STORAGE CAPACITY OF THE PARIS BASIN

The central part of the Paris Basin was chosen as a potential area for an underground storage of in the Middle Jurassic and Triassic formations, which are targets for oil and geothermal exploitation. It consists of a thick sedimentary pile underlying some of the major sources of CO₂ in France.

3.4.1. Triassic aquifers

Two main aquifers are concerned in the central and southern part of the Paris Basin: the Keuper fluviatile sandstones (Chaunoy and Donnemarie formations). These reservoirs are entirely sealed by anhydritic clays and are still exploited for their oil resource or for natural-gas storage at Chemery, in the far south of the basin. They display high salinities ranging between 30 and 180 g/l, which excludes any potential as water resource. An attempt to use the Triassic sandstone as a geothermal resource was made at Melleray, in the south of the Paris Basin, but was abandoned due to the expected plugging effect of particles at the injection well. The reservoir depth, temperature and pressure range respectively between 1500 and 3000 m, 70 and 120 °C, and 200 and 300 bar. Crude estimate of the aquifer surface area, average thickness and porosity are given below, together with evaluations of Q_{aqui} and Q_{traps} , representing the storage capacity of the entire aquifer and of the aquifer confined in traps, respectively.

Formation	Area <i>Km²</i>	Average net thickness <i>Km</i>	ϕ mean porosity	V_p total pore volume <i>Km³</i>	Q_{aqui} storage capacity (entire aquifer) <i>Mt CO₂</i>	Q_{traps} storage capacity in traps <i>Mt CO₂</i>
Buntsandstein	21,000	0.200	0.1	420	17,640	529
Keuper	27,500	0.025	0.15	103	4,331	130
Triassic	48,500	0.225		523	21,971	659

where: $Q_{aqui} = V_p \times h_{st} \times \rho_{CO_2}$ [Eq. 1]

and $Q_{traps} = Q_{aqui} \times Trapped\%$ [Eq. 2]

with V_p being the Area * Average net thickness* ϕ , h_{st} being the storage efficiency or fraction of pore volume that can be filled with CO₂ (assumed to be 6% for an open aquifer or an open trap), ρ_{CO_2} being the volumetric weight of CO₂ at P,T conditions (considered to be 0.7 t/m³), and $Trapped\%$ assumed to be 3%.

Digital depth and isopach maps of the Triassic sandstones are given in Figures 16, 17, 19 and 20. The data, obtained from the lithostratigraphic and well logs of several tens of boreholes, provide a good evaluation of the reservoir geometry. The volumetric evaluation of the reservoir coupled with statistical processing of the reservoir properties deduced from the borehole data, furnishes a realistic evaluation of the storage capacity of the formation. Nevertheless, the calculation errors will have to be determined by assuming estimated individual errors for each parameter if a more precise estimation is required in the future.

3.4.2. Dogger aquifers

Over the past 20 years, France has specialised in the development of low-enthalpy (temperatures over 50°C) geothermal resources for heating purposes. Two major sedimentary basins are involved: the Paris Basin around Paris and the Aquitaine Basin in the southwest. Because CO₂ emission sources are mainly concentrated in the Paris Basin, we focused on this area. Fifty-five geothermal doublets (composed of an injection well and a production well) have thus far been drilled in the vicinity of Paris. Even though some of the doublets are no longer in operation, this still represents the most important utilisation of low-enthalpy geothermal energy in the world. The aquifer contains brackish to saline waters with salinities ranging between 10 and 35 g/l, thus excluding its use as a water supply. Some very limited hydrocarbon structures also exist in this aquifer, primarily located to the east and south of the main geothermal area.

The Middle Jurassic aquifer of the Paris Basin is predominantly limestone, 200-300 m thick (2/3 Bathonian and 1/3 Bajocian/Aalenian) and must therefore be more sensitive than a sandy reservoir to the injection of acidic gases such as CO₂. Coupled chemistry-transport models will be used both to constrain the potential CO₂ storage capacity and to evaluate the effects of dissolved CO₂ in the carbonate reservoir. Only dissolved CO₂ will be considered in these models, since available codes at the BRGM at the present time cannot compute chemical reactions and transport in a diphasic phase (see Chapter 8).

The Middle Jurassic aquifer is sandwiched between Callovo-Oxfordian argillites above and Liassic shales below. The former is about 100 m thick and is considered as an excellent clayey barrier with very low permeabilities (between 10⁻¹² and 10⁻¹³ m/s) —it is one of the targets for the French underground research laboratory investigating the possibility of storing radioactive wastes in the easternmost part of the Paris Basin. The Liassic shales are even thicker (about 200 m) and are also considered as an excellent barrier. An impermeable NW-SE-trending marly belt west of Paris also limits the geothermal area. In the geothermal area currently in operation, reservoir depth, temperature and pressure range between 1700 and 2000, 60 and 80 °C and 14 and 15 MPa, respectively. Average porosity is 10% and transmissivity is high, generally greater than 30 D.m. (based on the report financed jointly by BRGM, ADEME and the EEC, Contract EN 3G-0046F).

As with the Triassic saline aquifer, a crude estimate of Q_{aqui} and Q_{traps} was carried out on the basis of digital depth and isopach maps of the Middle Jurassic reservoir. Data obtained from the geothermal wells define the CO₂ storage capacity in the entire geothermal reservoir, as illustrated by Figure 25.

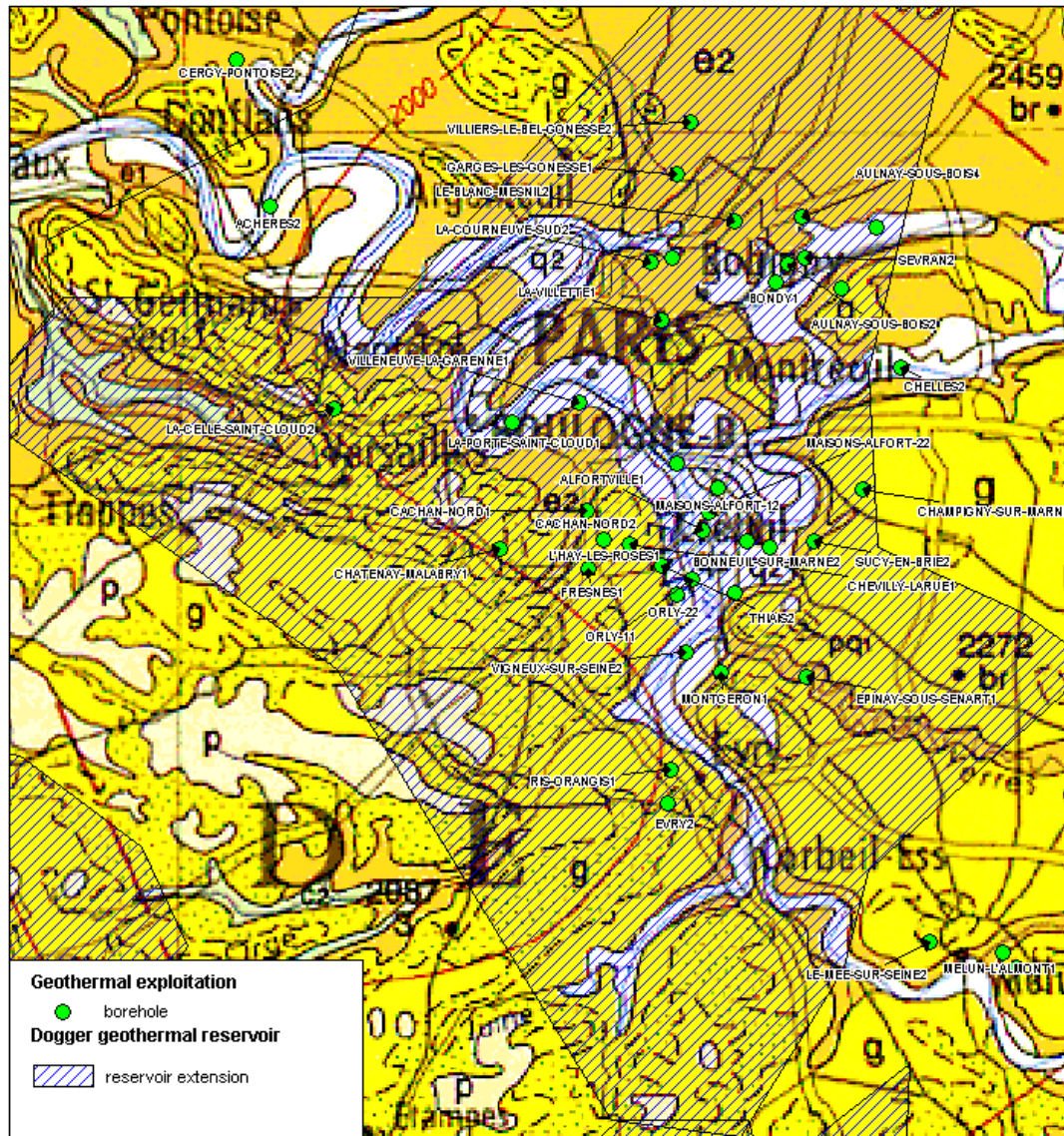


Fig. 25 - Extension of the Middle Jurassic geothermal reservoir, Paris block.

Formation	Area <i>Km²</i>	Average net thickness <i>Km</i>	ϕ mean porosity	V_p total pore volume <i>Km³</i>	Q_{aqui} storage capacity (entire aquifer) <i>Mt CO₂</i>	Q_{traps} storage capacity in traps <i>Mt CO₂</i>
Dogger	15,000	0.100	0.1	150	4,320	8.64
Paris geothermal reservoir	2,484	0.020	0.15	7	215	0.43

A value of 0.48 t/m³ is considered for ρ_{CO_2} , assuming a mean temperature and pressure of 70 °C and 14.5 MPa, respectively.

The estimate considers a *Trapped%* value of 0.2%; a value which assumes that the largest traps were filled with hydrocarbons and that most of the hydrocarbon structures have now been found. This value was estimated as two times the sum of the CO₂ storage capacity in hydrocarbon traps deduced from the oil volume. Only half the hydrocarbon structures (among the most important ever found) were studied because of confidentiality reasons. The calculation nevertheless demonstrates that the CO₂ storage capacity in traps is negligible with respect to that of the entire aquifer.

3.5. HYDROCARBON STRUCTURES

A crude estimate of CO₂ storage capacities was carried out for oilfield structures involving the top of the Middle Jurassic and Upper Triassic formations. All data were obtained from a public report entitled *Monographies des principaux champs pétroliers de France (1993)*. This report is not exhaustive since it provides data for only 1/3 of the oil fields in the centre of the Paris Basin. These oil fields may nevertheless be considered as representative in view of the fact that they contain some of the largest structures and different trap types encountered so far (anticline, fault and mixed traps).

The maximum CO₂ storage capacity for individual structures ($Q_{\max \text{ structure}}$) was calculated from the trap geometry, assuming maximum net thickness of the structure:

$$Q_{\max} = \text{area} \times \text{MaxNetThickness} \times \phi \times \rho_{\text{CO}_2} \quad [\text{Eq. 3}]$$

where $\rho_{\text{CO}_2} = 0.7 \text{ t/m}^3$ for the Middle Jurassic structures, and ϕ is the porosity.

This calculation overestimates the CO₂ storage capacity of the trap, since it does not take integrated net thickness into account. A more realistic estimate can be obtained from cumulative oil volume produced, for which the calculation gives the lower limit of CO₂ storage capacity ($Q_{\min}$).

$$Q_{\min} = V_{\text{Uoil}} \times \rho_{\text{CO}_2} \quad [\text{Eq. 4}]$$

where $V_{\text{Uoil}} = V_{\text{oil(st)}} \cdot B_o / 1000$, with $V_{\text{oil(st)}}$ (in millions of standard m³) being the volume of oil at standard conditions, and B_o being the oil formation volume factor. This equation assumes that a free gas phase does not exist in these fields, gases being distributed primarily between the oil and water phases.

Table 11 shows that the Triassic Chaunoy oil field provides the most interesting storage potential. These results are in conformity with qualities of the studied reservoirs. The Dogger reservoirs are made of oolitic limestones of which the permeability is very low. The quality of this reservoir results primarily from the development of a secondary porosity issued from dissolutions along fractures or sedimentary discontinuities. The Triassic sandy reservoirs are more favourable because of their sandy constitution that is little consolidated.

	Reservoir structure main in bold	X	Y	Depth to reservoir top	Initial reservoir temperature	Initial deep temperature	Maximum thickness	Maximum net thickness	Productive area	Mean porosity	CO ₂ reservoir density	Maximum CO ₂ storage capacity	Cumulative oil production (up to 1991)	Status (1991)	Oil density at standard conditions	Oil formation volume factor	Oil volume	Subsurface oil volume	CO ₂ storage capacity deduced from the oil volume
		grades	grades	mBSL	°C	bars	m	m	m ²		t/m ³	t	t		t/m ³			m ³	t
Chailly, Brie, Chartrettes	Middle Jurassic	0.3270 E	58.8641 N	1582	72	171	15	5	23000 000	0.15	0.7	12 100 000	1880 000	closed for economic reason	0.848	1.02	1980 000	2020 000	1410 000
Coulommès	Middle Jurassic	0.6828 E	54.3231 N	1677	75		35	35	15000 000	0.15	0.7	55 100 000	1840 000	in production	0.86	1.082	2140 000	2310 000	1620 000
Marolles-en-Hurepoix	Middle Jurassic	0.0764 E	53.9538 N	1378	65	149.3	5	3.5	500 000	0.09	0.7	110 000	92 000	closed in 1986	0.884	1.007	108 000	107 000	75 100
Valence-en-Brie	Middle Jurassic	0.6159 E	53.8209 N	1629	73	173.6	25	3.8	1500 000	0.08	0.7	319 000	103 000	in production	0.885	1.039	120 000	125 000	87 600
Villemer	Middle Jurassic	0.4971 E	53.6641 N	1435	72	156.9	20	13	12000 000	0.14	0.7	15 300 000	654 000	concession	0.868	1.052	753 000	793 000	555 000
TOTAL DOGGER																		5355 000	3747 700
Chailly, Brie, Chartrettes	Upper Triassic	0.3270 E	58.8641 N	2136	94	214	60	4	5000 000	0.15	0.7	2 100 000	13 000	in production					
Chaunoy	Upper Triassic	0.5179 E	53.9551 N	2147	100	235	58	25	53000 000	0.13	0.7	12 1000 000	4370 000	in production	0.8399	1.085	5200 000	5640 000	3950 000
Donnemarie	Upper Triassic	0.8669 E	53.8730 N	2538	115	265	37	15	10000 000	0.11	0.7	11 600 000	336 000	in production	0.8429	1.16	399 000	462 000	324 000
Saint-Germain	Upper Triassic	0.4212 E	53.9741 N	2145	99	237	67	28	8400 000	0.145	0.7	23 900 000	341 000	in production	0.85	1.131	401 000	453 000	317 000
Villemer	Upper Triassic			2045	88	225		2.5	2500 000	0.147	0.7	643 000		concession					
TOTAL TRIAS																		6555 000	4591 000

Table 11 - Crude estimations of the CO₂ storage capacity of individual oil structures in the Middle Jurassic and Upper Triassic formations in the central part of the Paris Basin.

4. CO₂ storage in geothermal reservoirs

The study of the technical feasibility of the CO₂ storage in a deep aquifer required to demonstrate that deep aquifers, equipped with the whole of the infrastructure necessary for the CO₂ injection, are available near the sources of CO₂.

The only favourable situation joining together source of CO₂, deep aquifer filled with a water unfit for human consumption and equipment of pumping related to the exploitations, meets only in the area of Ile-de-France. They are the low enthalpy geothermal exploitations exploiting the aquifer of the Dogger.

The present chapter tries to analyse the reality of a possible sequestration of CO₂ in this aquifer by mineralogical trapping, solution which would allow the CO₂ injection in dissolves form, in the well of injection of the geothermal doublet. Then one proposes technical solutions allowing the injection of CO₂ either in a dissolved or in a supercritical form and one analyses the consequences on the equipment of drilling and safety of the wells.

Lastly, one carries out a financial evaluation of the cost of the various solutions suggested, on the basis of result obtained, for the storage of CO₂ in the geothermal reservoir of the basin of Paris.

4.1. INJECTION OF CO₂ IN A GEOTHERMAL DOUBLET OF THE PARIS BASIN (DOGGER AQUIFER): 1D REACTIVE TRANSPORT MODELLING

4.1.1. Introduction

Previous studies have shown that the Paris Basin contains sedimentary formations that, in terms of geological and petrophysical qualities (permeability, transmissivity), are favourable for the storage of CO₂ (reservoir formations). The purpose of the modelling work was to investigate, from a geochemical standpoint, the feasibility of CO₂ injection via a geothermal doublet system located in the Dogger carbonate aquifer of the Paris Basin. The main points to be addressed were:

- 1) What would be the chemical impact of CO₂ injection on the reservoir?
- 2) Can we expect significant CO₂ storage due to mineral trapping in this context?

The simulations were conducted using the BRGM coupled hydrodynamics-transport-geochemistry code MARTHE+SCS. Values of the model parameters (physical properties of the reservoir, temperature, pressure, injection flow rate, water and rock chemistry) were derived from available field data. Technical aspects of the actual injection process are dealt with in the following chapter of this report.

4.1.2. Description of the simulation tool

In order to simultaneously simulate CO₂ migration and chemical interactions, it is necessary to use a coupled code taking into account hydrodynamics, mass transport and geochemistry. The modelling tool used was MARTHE+SCS: MARTHE is a 3D Hydro-Transport Modelling Software developed by the BRGM (Thiery, 1990); SCS stands for Specific Chemical Simulator, the concept of which has been adopted by BRGM for geochemical modelling strategy when dealing with problems involving coupled processes (Kervévan and Baranger, 1998; Kervévan *et al.*, 1998). The basic concept of this approach is that a new SCS is developed for each new specific study. This can be done only by using suitable tools to greatly facilitate the code writing process. The choice made by BRGM in this respect was the ALLAN and NEPTUNIX 4 software packages, distributed by Dassault Data Services and CS-SI, respectively. The combined use of these two software packages enables simulators to be generated automatically, provided the processes involved in the system being modelled can be described by a set of algebraic and/or ordinary differential equations.

Because an SCS takes into account only those specific processes relevant to the problem being studied, computing efficiency is greatly improved. The code generated for any SCS is much smaller than that of more general software such as EQ3/6 (Wolery, 1995). In addition, the rapidity and the ease with which SCS can be generated with ALLAN and NEPTUNIX 4 enables the uncomplicated addition or suppression of processes to produce a customised simulator.

Consequently, an SCS dedicated to the “Gestco” geochemical problem was developed in this study in order to be further coupled with MARTHE for the numerical simulation of CO₂ injection in a geothermal doublet system. The next section details the geochemical processes used in our model.

4.1.3. Description of the “Gestco” SCS

Based on results obtained with preliminary EQ3/6 simulations, we defined a set of aqueous, gaseous, and mineral species that had to be considered so that the model represented the actual geochemistry of the Dogger carbonate aquifer. Ultimately, the geochemical simulator took 3 minerals into account (*calcite*, *quartz*, *dis-dolomite*), 32 aqueous reactions involving 42 relevant dissolved species and 11 chemical elements (O, H, Na, K, Ca, Mg, Al, Si, S, C, Cl), and CO₂ as a gas. All reactions are listed in Tables 12 and 13. It should be noted that equilibrium constants vary with temperature (*T* in °C) according to the following polynomial law:

$$\log(K_{eq}) = a + b \cdot T + c \cdot T^2 + d \cdot T^3$$

where *a*, *b*, *c*, and *d* are tabulated parameters specific to each reaction.

Reactions
$\text{H}_2\text{O} = \text{OH}^- + \text{H}^+$
$\text{NaOH(aq)} + \text{H}^+ = \text{Na}^+ + \text{H}_2\text{O}$
$\text{NaHSiO}_3(\text{aq}) + \text{H}^+ = \text{Na}^+ + \text{SiO}_2(\text{aq}) + \text{H}_2\text{O}$
$\text{NaCl} = \text{Na}^+ + \text{Cl}^-$
$\text{NaAlO}_2(\text{aq}) = \text{Na}^+ + \text{AlO}_2^-$
$\text{HSO}_4^- = \text{SO}_4^{--} + \text{H}^+$
$\text{CaCl}^+ = \text{Ca}^{++} + \text{Cl}^-$
$\text{CaCl}_2(\text{aq}) = \text{Ca}^{++} + 2 \text{Cl}^-$
$\text{CaCO}_3(\text{aq}) + \text{H}^+ = \text{Ca}^{++} + \text{HCO}_3^-$
$\text{CaHCO}_3^+ = \text{Ca}^{++} + \text{HCO}_3^-$
$\text{CaSO}_4(\text{aq}) = \text{Ca}^{++} + \text{SO}_4^{--}$
$\text{KCl(aq)} = \text{K}^+ + \text{Cl}^-$
$\text{KSO}_4^- = \text{K}^+ + \text{SO}_4^{--}$
$\text{KHSO}_4(\text{aq}) = \text{K}^+ + \text{SO}_4^{--} + \text{H}^+$
$\text{MgCl}^+ = \text{Mg}^{++} + \text{Cl}^-$
$\text{MgCO}_3(\text{aq}) + \text{H}^+ = \text{Mg}^{++} + \text{HCO}_3^-$
$\text{MgHCO}_3^+ = \text{Mg}^{++} + \text{HCO}_3^-$
$\text{CO}_2(\text{aq}) + \text{H}_2\text{O} = \text{HCO}_3^- + \text{H}^+$
$\text{CO}_3^{--} + \text{H}^+ = \text{HCO}_3^-$
$\text{HSiO}_3^- + \text{H}^+ = \text{SiO}_2(\text{aq}) + \text{H}_2\text{O}$
$\text{Al(OH)}^{++} + \text{H}_2\text{O} = \text{AlO}_2^- + 3 \text{H}^+$
$\text{Al(OH)}_2^+ = \text{AlO}_2^- + 2 \text{H}^+$
$\text{Al}^{+++} + 2 \text{H}_2\text{O} = \text{AlO}_2^- + 4 \text{H}^+$
$\text{HAlO}_2(\text{aq}) = \text{AlO}_2^- + \text{H}^+$
$\text{NaHCO}_3(\text{aq}) = \text{Na}^+ + \text{HCO}_3^-$
$\text{NaCO}_3^- + \text{H}^+ = \text{Na}^+ + \text{HCO}_3^-$
$\text{NaSO}_4^- = \text{Na}^+ + \text{SO}_4^{--}$
$\text{MgSO}_4 = \text{Mg}^{++} + \text{SO}_4^{--}$
$\text{HCl(aq)} = \text{H}^+ + \text{Cl}^-$
$\text{CaOH}^+ = \text{Ca}^{++} + \text{OH}^-$
$\text{KOH(aq)} + \text{H}^+ = \text{K}^+ + \text{H}_2\text{O}$
$\text{H}_2\text{SiO}_4^- + 2 \text{H}^+ = \text{SiO}_2(\text{aq}) + 2 \text{H}_2\text{O}$

Table 12 - List of aqueous reactions taken into account in the “Gestco” SCS.

	Reactions
Carbon dioxide	$\text{CO}_2(\text{g}) + \text{H}_2\text{O} = \text{HCO}_3^- + \text{H}^+$
Calcite	$\text{CaCO}_3(\text{c}) + \text{H}^+ = \text{Ca}^{++} + \text{HCO}_3^-$
Quartz	$\text{SiO}_2(\text{c}) = \text{SiO}_2(\text{aq})$
Dis-Dolomite	$0.5 \text{CaMg}(\text{CO}_3)_2(\text{c}) + \text{H}^+ = 0,5 \text{Ca}^{++} + 0,5 \text{Mg}^{++} + \text{HCO}_3^-$

Table 13 - List of gaseous and mineral reactions taken into account in the “Gestco” SCS.

The activities of charged species were calculated using the B-dot equation (Helgeson, 1969), which is an extended Debye-Hückel model:

$$\log \gamma_i = -\frac{A_\gamma z_i^2 \sqrt{I}}{1 + \dot{a} B_\gamma \sqrt{I}} + \dot{B} I$$

where A_γ and B_γ are the Debye-Hückel coefficients and $\dot{B}$ the B-dot coefficient (all varying with temperature according to a polynomial function), z is the charge and $\dot{a}$ the hard core diameter of the species, and I is the ionic strength. The activity coefficients of neutral polar species were set to unity. The activity coefficient of CO₂ (aq) was computed with the Drummond expression (1981):

$$\ln \gamma_i = (-1.0312 + 0.0012806.T + \frac{255.9}{T}).I - (0.4445 - 0.001606.T).(\frac{I}{1+I})$$

Water activity is given by:

$$\log a_w = \frac{1}{55.51} (-\sum m + \frac{2}{3} A_\gamma I^{1.5} \sigma(\dot{a} B_\gamma \sqrt{I}) - \dot{B} I^2)$$

where $\sum m$ is the sum of molalities and $\sigma(x) = \frac{3}{x^3} (1 + x - \frac{1}{1+x} - 2 \ln(1+x))$.

All thermodynamic data (K_{eq} ; a , b , c , d coefficients; A_γ , B_γ ...) were extracted from the data0.sup.R2 database of the EQ3/6 v7.2b software package (Wolery, 1995).

Dissolution-precipitation reactions of minerals are described according to the following kinetic law, derived from the Transition State Theory:

$$v_r = S.k_{forw}.(a_{H+})^p.(1-Q/K_{eq}) \quad \text{with} \quad S = s.(6 V_m / d).n$$

where v_r is the net reaction rate (mol.s⁻¹/ kg_{H2O}), S the reactive surface (cm²/ kg_{H2O}), k_{forw} the kinetic constant of the dissolution reaction (mol/cm²/s), a_{H+} the proton activity, Q the ionic activity product, K_{eq} the total reaction equilibrium constant, s the reactive fraction of the mineral specific surface, V_m the mineral molar volume (cm³/mol), d the mineral average diameter (cm) and n the number of moles of mineral in the system. The value of s is generally unknown and in the simulator this coefficient is often used as an adjustment parameter; the values used in this study are listed in Table 14.

The kinetic constants (k_{forw}) were estimated by linear interpolation from values at 25 and 60 °C:

$$\log k_{forwT} = \log k_{forw25^\circ C} + (\log k_{forw25^\circ C} - \log k_{forw60^\circ C}) * (T-25)/(25-60)$$

with T in Celsius degrees.

Mineral Phase	Kforw 25°C (mol/cm ² /s)	Kforw 60°C (mol/cm ² /s)	Surface (cm ² /kgH ₂ O)	Factor s	Surface (cm ² /kgH ₂ O)
Calcite	4.47e-10	1.29e-09	2.83e+02	2.75e+00	7.79e+02
Quartz	2.14e-18	1.10e-16	8.85e+03	2.73e+02	2.42e+06
Dis-Dolomite	5.02e-12	1.51e-11	1.18e+02	1.00e+00	1.18e+02

Table 14 - Mineral properties: kinetics at 25 and 60 °C, surface and factor s.

4.1.4. Simulation conditions and results

Due to the numerical complexity of the 3D problem, and because of calculation time limitations, we restricted our investigations to a 1D-domain along a characteristic stream tube between the injection and the production wells. The stream tube concept is a classical approach in petroleum and geothermal reservoir engineering: it leads to the definition of a representative 1D hydrodynamic model provided the current flow path was previously estimated.

In order to simulate the shortest transfer time for injected CO₂, we selected a stream tube based on the straight line distance between the injection and production wells. We were thus voluntarily in the least favourable conditions for mineral trapping, since both water flow velocities and concentrations of dissolved CO₂ are highest in this case. Assuming that hydrodynamic parameters are homogeneous throughout the system and that the doublet is equilibrated (i.e. recharge and pumping flow rates are identical in absolute value), and provided regional flow is negligible in the Dogger aquifer, the streamline pattern (Fig. 26) can be determined by using an analytical expression (Bear, 1979).

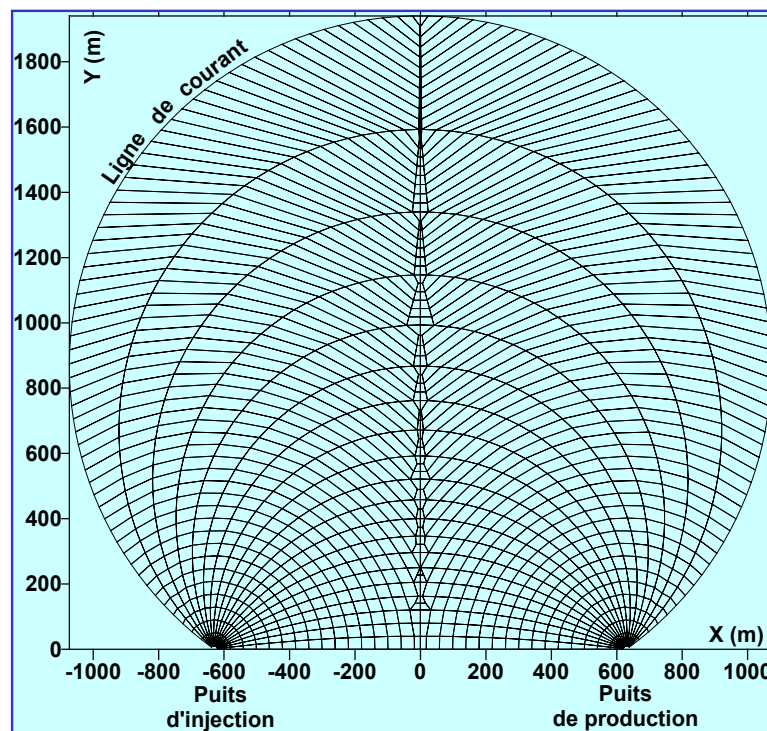


Fig. 26 - Example of a typical streamline pattern for an equilibrated doublet.

Using this approach, we considered only a fraction of the entire streamline field (Fig. 26 represents half of this field). In our system, the area of the stream tube taken into account accounts for 1% of the total area. It is thus necessary to be aware of the difficulty in extrapolating to a complete doublet system the results (mass balances, time of transfer, etc.) obtained from a single stream tube model.

In order to define a “typical” Paris Basin doublet system, we selected the characteristic parameters among data from previous BRGM studies on the Dogger reservoir.

- **Geometry:**
 - Reservoir depth (Dogger) = 1730 m,
 - Average reservoir thickness = 26 m,
 - Distance between wells = 1400 m;
- **Hydrodynamics:**
 - Permeability = 2.1 D,
 - Permeability coefficient = $5.5 \cdot 10^{-5}$ m/s,
 - Porosity = 16%;
- **Reservoir fluid:**
 - Temperature = 78°C,
 - Salinity = 21 g/l,
 - Pressure = 173.5 bar;
- **Operating conditions:**
 - Average injection flow rate = 250 m³/h,
 - Average injection temperature = 48°C.

Since thermal aspects are evidently important in a geothermal system, the model also had to take into account heat transfer between the fluid, cap rock, and bedrock. The possibility of considering thermal transfer is proposed as an option in the MARTHE software, and this option was activated in the present simulations.

The geochemistry of the system (fluid and minerals) was chosen to be representative of the Dogger aquifer. A “typical” mineralogical composition of the reservoir was chosen as follows:

- Calcite (95% in mass);
- Dolomite (2.5 % in mass);
- Quartz (2.5 % in mass).

We determined our initial composition of the reservoir fluid from speciation calculations at 78 °C conducted with EQ3/6 (Wolery, 1995) using analytical data from previous BRGM studies of the Dogger aquifer. From these preliminary calculations, we derived the total concentrations of each of the 11 elements taken into account in the “Gestco” SCS that are necessary to initialise our coupled calculations. Table 15 shows the calculated composition of reservoir water obtained from the EQ3/6 initial speciation, assuming that this water is equilibrated with respect to the mineral phases described above (*i.e.* calcite, dolomite, and quartz).

Chemical element	Concentration (mol/kgw)
Hydrogen (not in H ₂ O)	3.496 10 ⁻³
Oxygen (not in H ₂ O)	5.051 10 ⁻²
Aluminium	2.801 10 ⁻⁶
Calcium	2.327 10 ⁻²
Carbon	5.441 10 ⁻³
Potassium	2.795 10 ⁻³
Magnesium	1.269 10 ⁻²
Sodium	3.176 10 ⁻¹
Sulphur	8.762 10 ⁻³
Silicon	5.372 10 ⁻⁴
Chloride	3.713 10 ⁻¹

Table 15 - Elemental composition of reservoir fluid (Dogger aquifer) used as initial geochemical condition.

The calculated pH of this water is 6.25, consistent with *in situ* values measured. The calculations were performed on a mesh composed of 35 grid cells. As a result of the spatial variability of the velocity field (maximum velocity in the vicinity of the two wells and minimum at an intermediate distance between the two wells), we considered cells of variable section (S_{grid} , normal to the flow). This results in the velocity at the centre of each grid cell (V_{grid}) being equal to the local “true” velocity (V_{true} , estimated with the analytical solution). The section of each grid cell was then calculated according to the following law:

$$S_{grid} = Q_{inj}/V_{grid} = Q_{inj}/V_{true}$$

where Q_{inj} is the constant injection flow rate in the stream tube (1% of the total injection flow rate of 250 m³/h). The cells corresponding to the highest velocities (close to the wells) thus have the smallest sections, as illustrated in Figure 27.

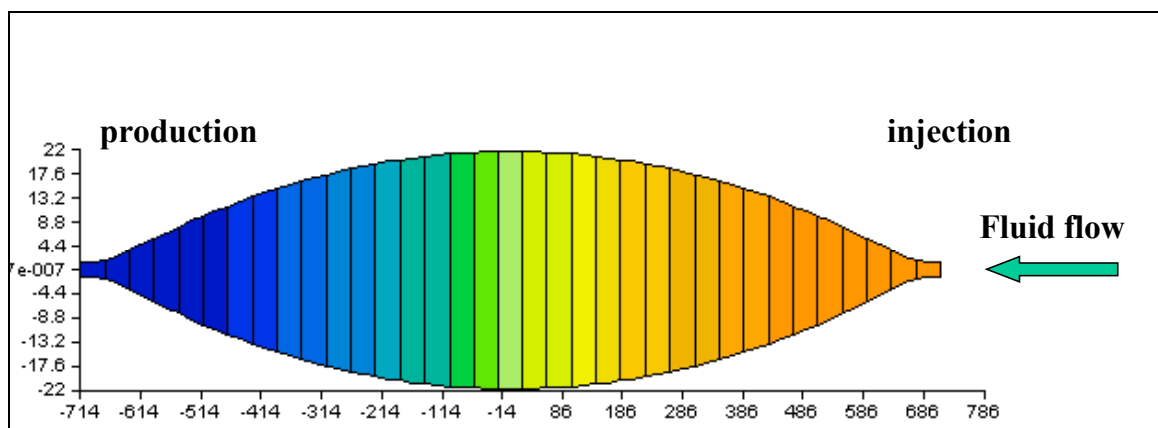


Fig. 27 - 1D-mesh used for simulations (horizontal section of the considered part of the Dogger aquifer, plan view).

The total duration of each simulation was 20 years with a time step varying from 1 day to 1 month. The number of grid cells and the value of the time step are a compromise between required accuracy and the total duration of computation time. Typically, when

the simulations were performed with a constant time step of 1 day (which is the case for the calculations presented here), total computation time was as much as 40 hours.

The scenario planned in the framework of this project consisted in trying to inject as much CO₂ as possible in order to verify the geochemical impact on the system. For this purpose, and regardless of technical feasibility, we first tried continuous injection, throughout the entire simulation period, of water whose composition was similar to that of the reservoir, but enriched under a 200 bar pressure of CO₂. In all the simulations, our working hypothesis was that CO₂ remained entirely dissolved in the aqueous phase because our model cannot accommodate reactive multiphase flow. The limitation for the maximum quantity of CO₂ to be dissolved in the injection solution was given by the following condition, to be verified at all time steps and in every grid cell of the modelled domain:

$$P_{CO_2} = f_{CO_2}/\gamma_{CO_2} < P_{tot}$$

where P_{CO_2} is the CO₂ pressure, f_{CO_2} and γ_{CO_2} are respectively the CO₂ fugacity and fugacity coefficient, and P_{tot} is the local total pressure of the water phase. This condition must be verified in order to be consistent with our initial assumption of that no gaseous CO₂ is actually present in the system.

The first results concerning the changes of CO₂ fugacity over time at various distances from the injection well (Fig. 28) clearly show an inconsistency with the hypothesis of the absence of a gas phase: in this pressure and temperature range, a reasonable order of magnitude of the CO₂ fugacity coefficient is about 0.5 bar⁻¹ (Duan *et al.*, 1992), so that the fugacity peaks observed in Figure 28 would lead to a CO₂ pressure of more than 280 bar, much greater than the local pressure of around 170 bar.

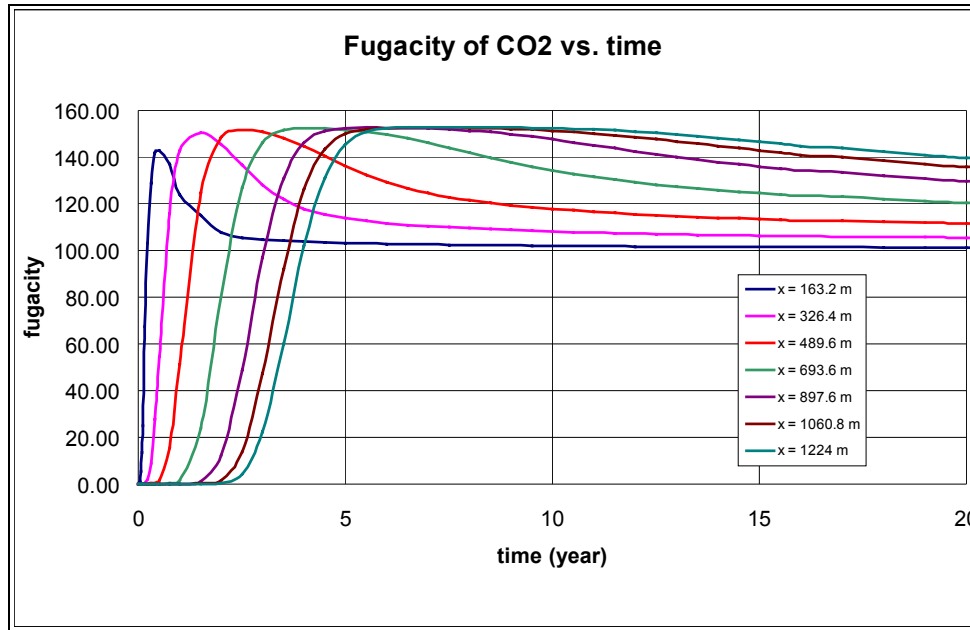


Fig. 28 - Fugacity vs. time at various observation points (x = distance from the injection well). P_{CO_2} in the injection water is 200 bar ($f_{CO_2} \approx 100$).

We thus carried out a series of simulations using a “trial and error” technique in order to obtain a maximum CO₂ initial pressure in the injection water without reaching CO₂ fugacities in the system giving rise to an excessively high CO₂ pressure.

It was ultimately found that injection water enriched under a pressure of 100 bar of CO₂ led to an acceptable value of CO₂ fugacity (Fig. 29). In this configuration, the maximum P_{CO_2} value is about 160 bars, thus remaining below the local fluid pressure of 173 bar, i.e. CO₂ in the gas phase cannot appear. This injection water thus has the same elemental composition as that of the Dogger aquifer, except of course for O and C, due to the high CO₂ content (about 0.92 mol/kgw) and its pH of 3.6 is typical of aggressive water. The principal results obtained with this configuration are illustrated in Figures 29 to 39.

It is seen in Figures 30 and 31 that a significant quantity of CO₂ is effectively stored as calcite and dolomite after 240 months of CO₂ injection in areas located at a distance from the injection, well beyond 50 m for calcite and beyond 250 m for dolomite. We observed significant calcite and dolomite dissolution in the vicinity of the injection well, resulting in an increase in porosity (Fig. 38) in the related area of the studied domain. This could possibly have had an impact on the geomechanical stability of the well basement itself, but most of all it has a direct link with the mass balance of carbon actually stored as mineral in the aquifer. The origin of this intensive dissolution is easily understandable when injecting acidic water into an aquifer composed primarily of calcite, but anticipating the extent and intensity of the precipitation process occurring immediately downstream is less straightforward. This over-saturation leading to a precipitation of carbonates is primarily the result of excess calcium and magnesium originating from the dissolution zone and transported to areas where the fluid was initially equilibrated with respect to the carbonates considered. The pH and fluid-temperature profiles shown in Figures 37 and 39, respectively, are relatively flat after 240 months in the area of interest (the first 250 m downstream from the injection point) and thus do not suggest a pH or thermal effect necessarily inducing precipitation. In order to be conclusive on the origin of this precipitation process, however, it would be necessary to carry out further calculations, e.g. a purely theoretical scenario not taking into account thermal effects, with all other parameters and conditions being equal.

Considering the total quantities of carbon stored in minerals, Figure 32 suggests that mineral trapping is negligible due to this important dissolution occurring around the injection point. The negative part of the curve of Figure 32 is roughly five times that of the positive part, leading to the conclusion that instead of trapping, we observe carbon release due to mineral dissolution. Figure 35, however, shows that after a period of about 6-8 years, the concentration of dissolved CO₂ appears to have reached a steady state and the shapes of the curves are close to that of typical non-reactive tracer breakthrough curves. Nevertheless, upon closer inspection, the zoomed view of these curves (Fig. 36) shows that a genuine steady-state has not yet been reached, and that the CO₂ concentration decreases with distance from the injection well. This suggests that some CO₂ is mineralised somewhere along the stream tube (also see Fig. 34).

Consequently, and in order to be able to conclude on these two contradictory conclusions, it should be considered that Figure 32 represents concentration variations. On the other hand, the volume of the grid cells is far from being constant all along the tube (see Fig. 27). In order to establish a consistent mass balance of the stored carbon, it is thus necessary to take into account the volume of each grid cell. Provided

that the grid step is constant along the flow axis, the correct variable to consider for estimating the mineralised mass of carbon is the relative mass of carbon per unit of length, obtained by multiplying the calculated concentration of Figure 32 by the section (perpendicular to the flow axis) of each corresponding grid cell. The obtained results are shown in Figure 33, where we can estimate that the total area of positive variations (precipitation) is slightly greater than that of negative variations (dissolution). To obtain a quantitative net balance of total carbon stored after 240 months of injection, it is necessary to evaluate the integral of the curve in Figure 33. This calculation was carried out by applying the Simpson algorithm, resulting in a positive integral value of 8.86×10^6 moles of carbon, confirming that some carbon storage occurred within the stream tube. Compared with the 4×10^8 moles injected in the stream tube for this 240 month period, we can estimate a trapping “efficiency” barely more 2%, which is far from being satisfying in terms of storage capacity.

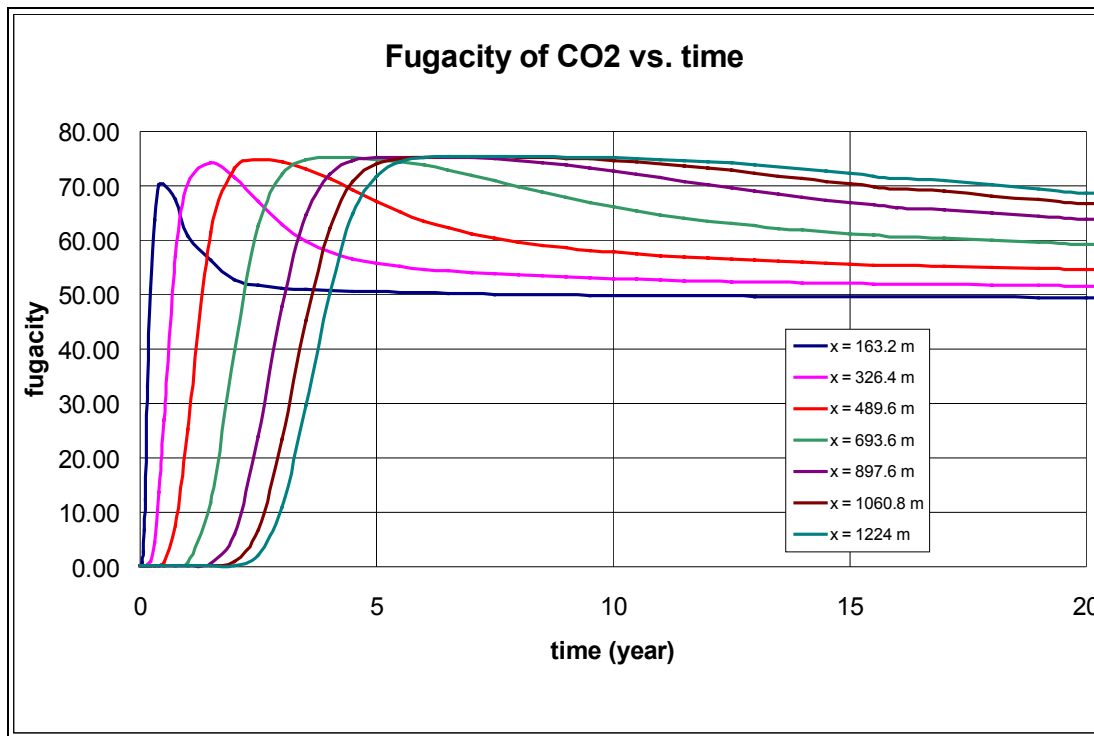


Fig. 29 - Fugacity vs. time at various observation points (x = distance from the injection well). P_{CO_2} in the injection water is 100 bars ($f_{CO_2} \approx 50$).

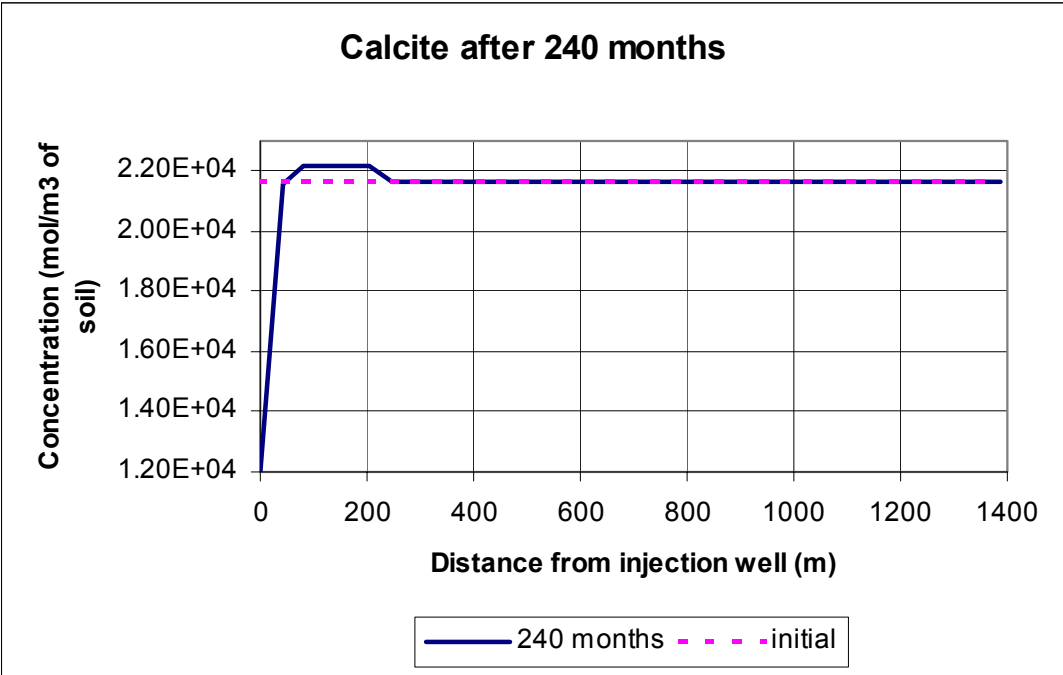


Fig. 30 - Profile of calcite quantities along the aquifer after 240 months of injection.

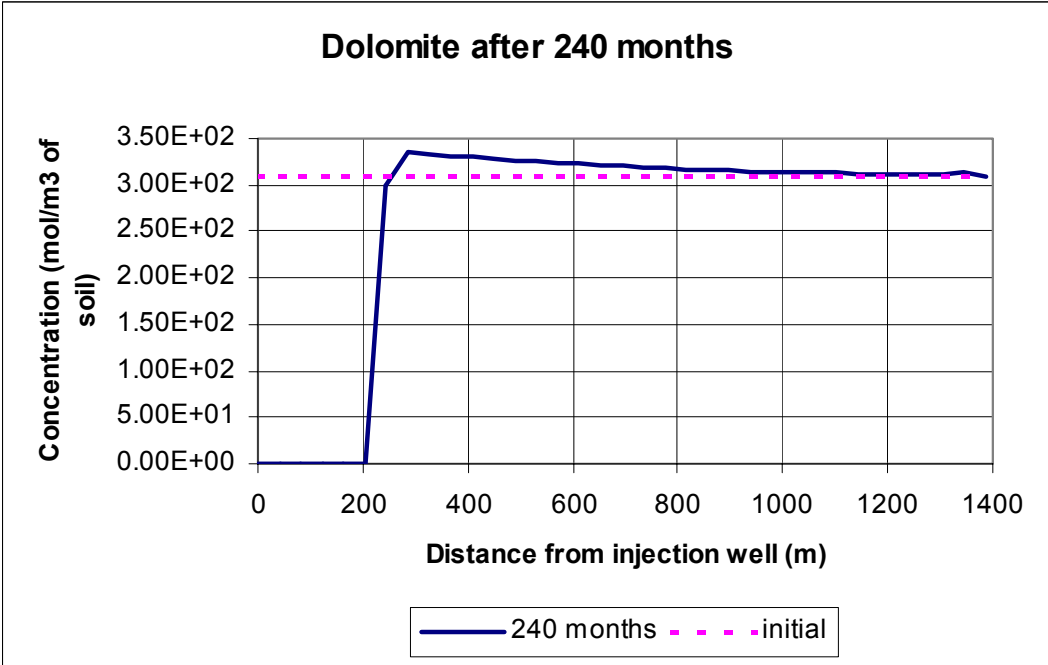


Fig. 31 - Profile of dolomite quantities along the aquifer after 240 months of injection.

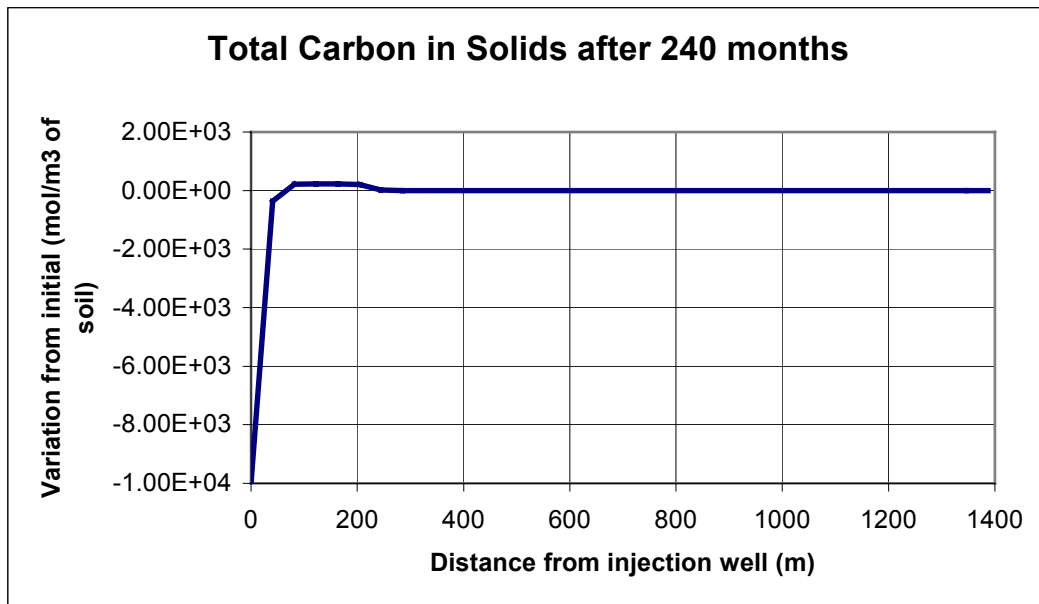


Fig. 32 - Variation of total carbon in solids from initial values: profile along the aquifer after 240 months of injection.

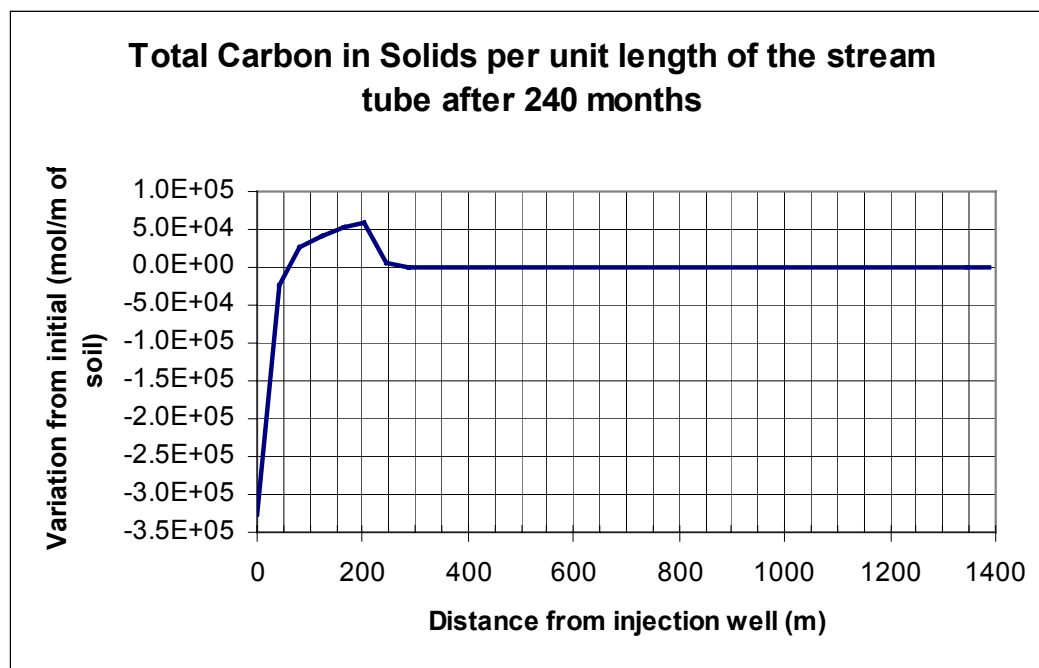


Fig. 33 - Variation of total carbon in solids per unit length of the stream tube compared to initial values: profile along the stream tube after 240 months of injection.

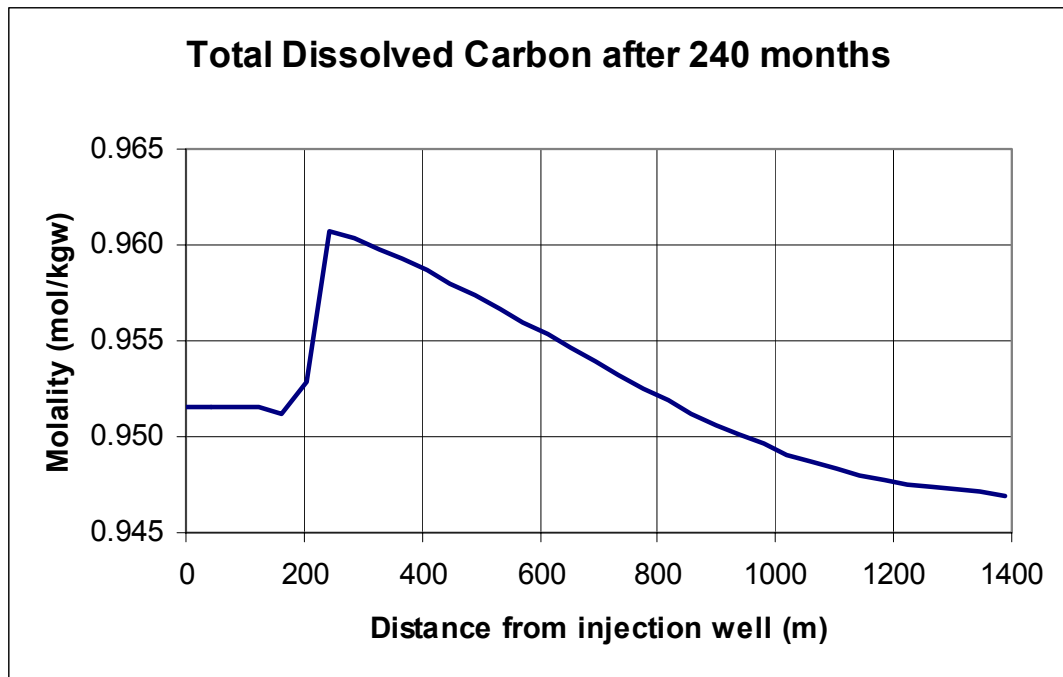


Fig. 34 - Profile of total dissolved carbon along the aquifer after 240 months of injection.

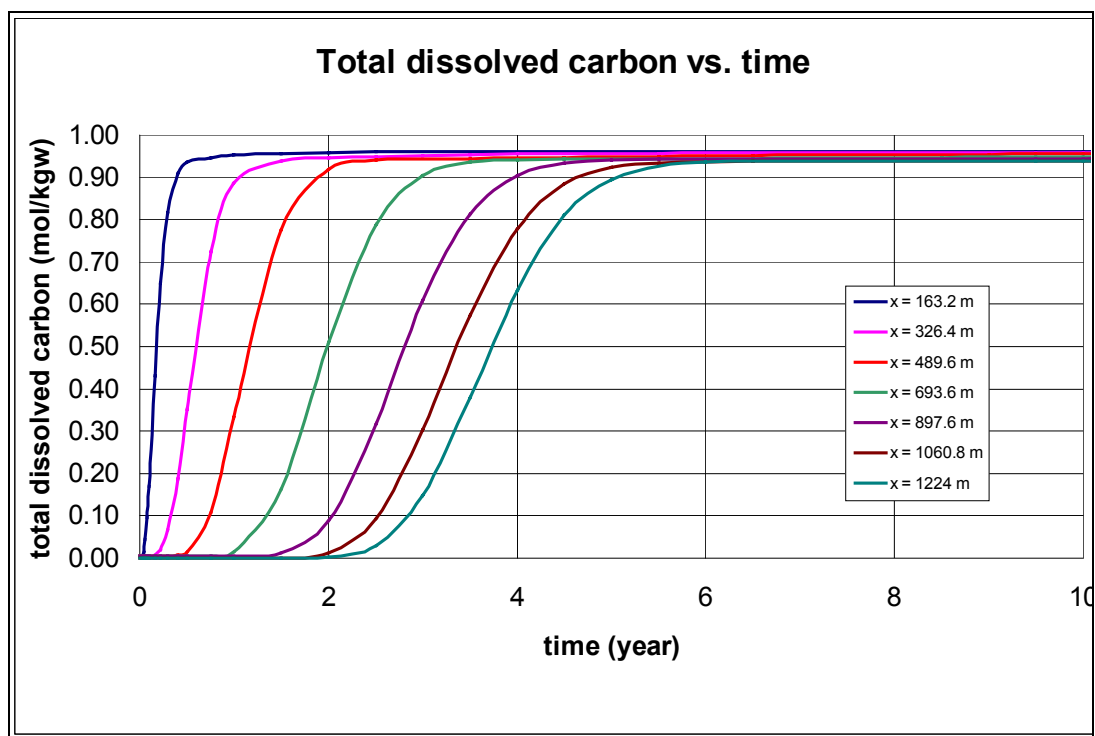


Fig. 35 - Breakthrough curves of dissolved carbon at various observation points (x = distance from the injection well).

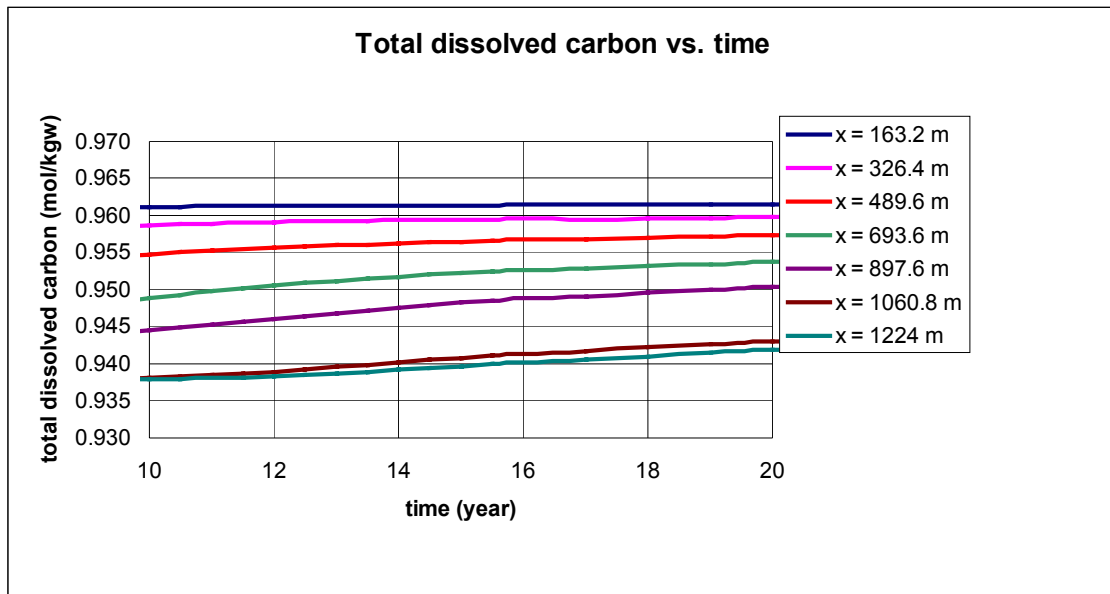


Fig. 36 - Zoomed view of breakthrough curves of dissolved carbon at various observation points (x = distance from the injection well).

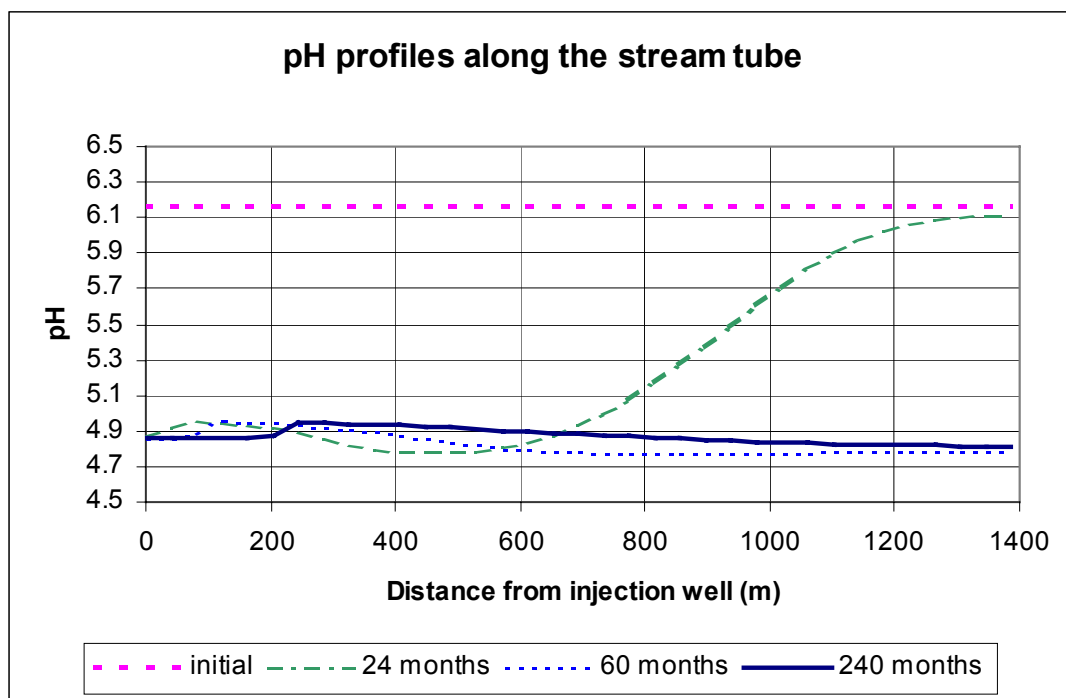


Fig. 37 - pH profiles along the aquifer after 24, 60, and 240 months of injection.

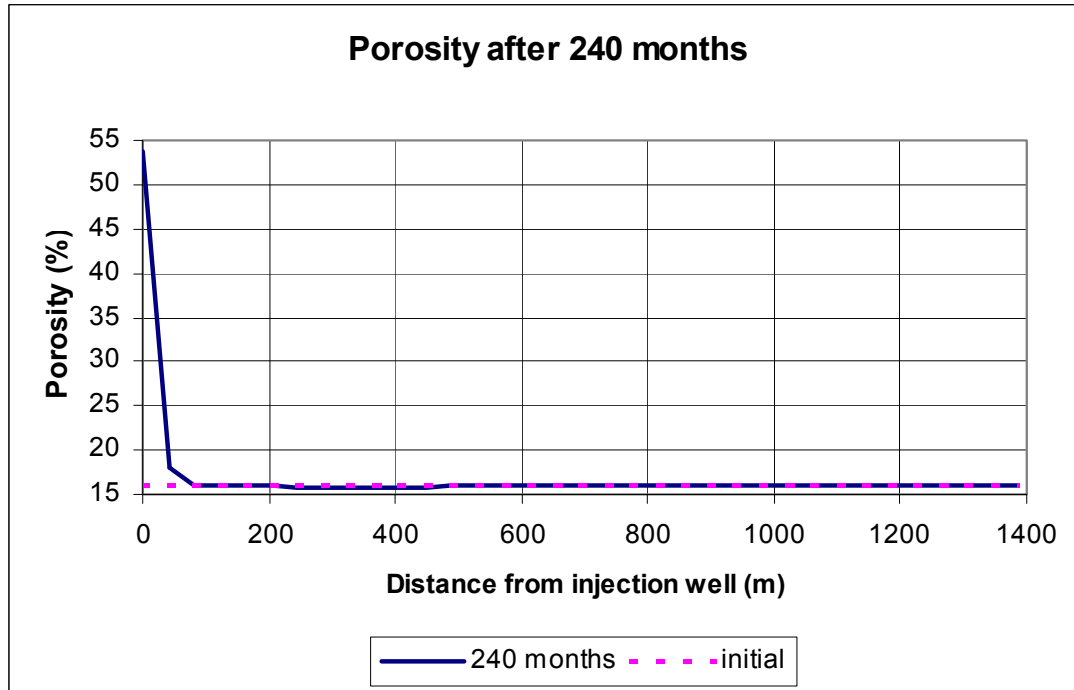


Fig. 38 - Porosity profile along the aquifer after 240 months of injection.

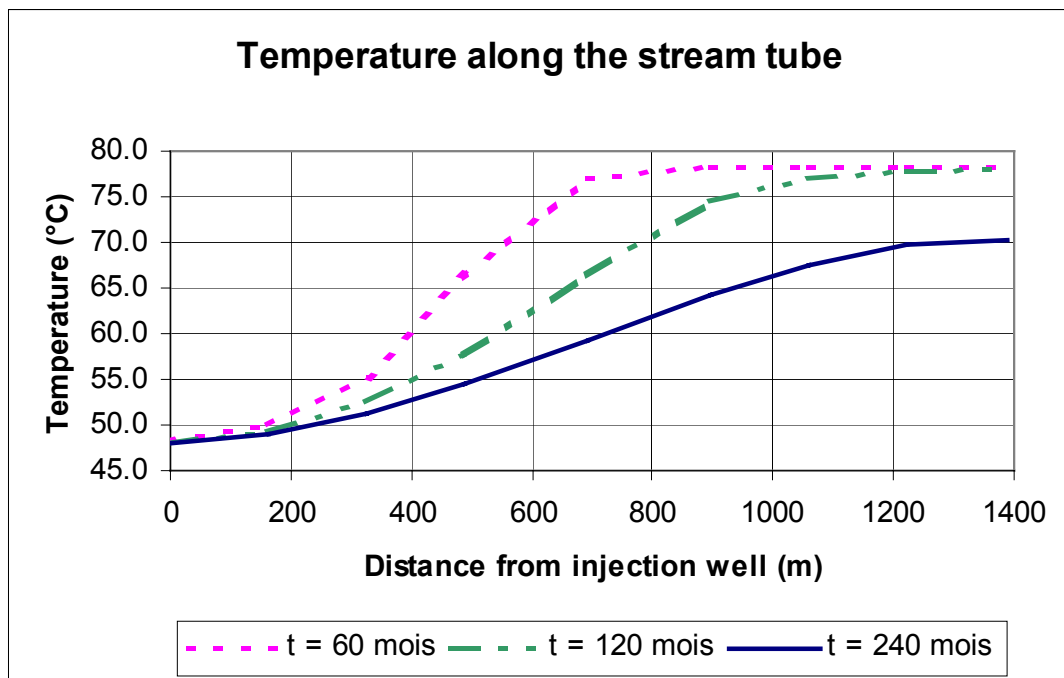


Fig. 39 - Temperature profiles along the aquifer after 60, 120, and 240 months of injection.

4.1.5. Conclusion

The first conclusion we can draw is that, in the scenario we have chosen to consider (i.e. injecting as much dissolved CO₂ as possible at depth), our geothermal doublet in the Dogger aquifer of the Paris Basin does not behave as an efficient CO₂ trapping system. It is to be noted, however, that we voluntarily adopted the “worst case” conditions with the model used the stream tube having the shortest path between the two wells of the doublet and thus providing the shortest transfer time. Further calculations extended to the entire 2D domain would be required to estimate orders of magnitudes of the quantities of CO₂ that could be trapped. Nevertheless, and considering the relatively high rate of dissolved CO₂ injected in this scenario (900 t of CO₂ per year injected in the stream tube considered here, equivalent to a total amount of 0.09 Mt of CO₂ injected per year in the complete doublet system), it appears that the geochemical trapping capacity of the investigated part of the Dogger aquifer is not sufficient to qualify it as a “CO₂ storage” process. This is because less than 400 t of CO₂ was trapped at the end of a 20 year injection period, while more than 17,000 t were released at the production well.

Before attempting to draw any definitive conclusion on the storage capacity of this geothermal doublet, it is necessary to carry out further simulations, i.e. (1) studying other stream tubes, or better the entire doublet system in 2D; and (2) modifying injection strategy (lower CO₂ concentrations in the injected water, injections in successive short periods instead of continuous injection, etc.) in order to remain in the ranges of dissolved CO₂ concentrations that are more consistent with the maximum mineral trapping capacity of the reservoir. In these cases, however, and assuming that it would be technically and economically feasible, it would be necessary to compare the amount of CO₂ possibly stored using these scenarios with the actual CO₂ emissions in the Paris Basin in order to determine if it could have any favourable environmental impact.

4.2. GEOTHERMAL ENERGY OPERATIONS IN THE PARIS BASIN

If it appears that, from a purely theoretical point of view, the capacity of CO₂ precipitation in the Dogger reservoir remains limited although insufficiently characterized and that the acidification of the solution in which CO₂ will be dissolves, risk to question the safety of the well (strong increase in porosity around the injection well), it remains that the injection of limited quantities of dissolved CO₂ or of quantities much larger but in supercritical form are the only realistic options that must be kept.

4.2.1. Introduction: geological context

The Paris Basin is characterised by a stratified Mesozoic and Cainozoic sedimentary succession overlying a crystalline basement. Basin subsidence during the sedimentary deposition increased the thickness of the layers in the centre of the basin. Thus, the sedimentary succession reaches its maximum thickness of 3200 m about 50 kilometres east of Paris. Among the beds, some are porous and permeable and contain a sheet of water whose temperature increases with depth according to a geothermal gradient of 3-4 °C per 100 metres.

In the Ile-de-France region, the sheet of water in the Dogger limestone layer (Middle Jurassic) presents the most favourable temperature and productivity characteristics for geothermal utilisation. Its depth varies between 1500 and 2000 metres, temperature between 56 and 85 °C, and salinity (in equivalent NaCl) between 6.5 and 35 g/l.

The urbanisation of the land above the geothermal reservoir has enabled its use for district heating and domestic hot water production (Ignatiadis *et al.*, 1998).

4.2.2. History of geothermal energy in the Paris Basin

The first geothermal use of the Dogger aquifer in the Paris Basin dates back to 1969 at Melun l'Almont, but it is only since the two oil crises (1973 and 1979) that geothermal energy has undergone genuine development.

From 1980 to 1986, the authorities supported energy savings and the use of renewable energies, leading to about 100 geothermal wells being drilled into the Dogger aquifer. This represents about 50 doublets in the Paris Basin (Figs. 40 and 41).

In 1986, the counter oil crisis reduced the costs of fossil-fuel energies. It marked the end of geothermal energy development and led to financial difficulties for existing debt-ridden operations, resulting from high interest rate loans. Corrosion/scaling phenomena in the casings aggravated the technical and financial situations of the operations. Between 1987 and 1989 a dozen exploitations among the most affected stopped production.

Research was started in 1989 to resolve the technical problems. This led to the use of preventive and curative treatments against corrosion. Financial solutions were also found to help operators reimburse their loans. However, no new geothermal operations were created and investments were used to maintain and optimise existing operations.

Since 1994, operating companies have tried to render their heat networks profitable by grafting fuel- or gas-fired cogeneration systems onto the geothermal units. This has resulted in a reduction of the geothermal energy contribution to thermal energy delivery, i.e. from 75 to less than 50%. At the same time, pumping-assisted geothermal operations migrated towards an artesian production mode.

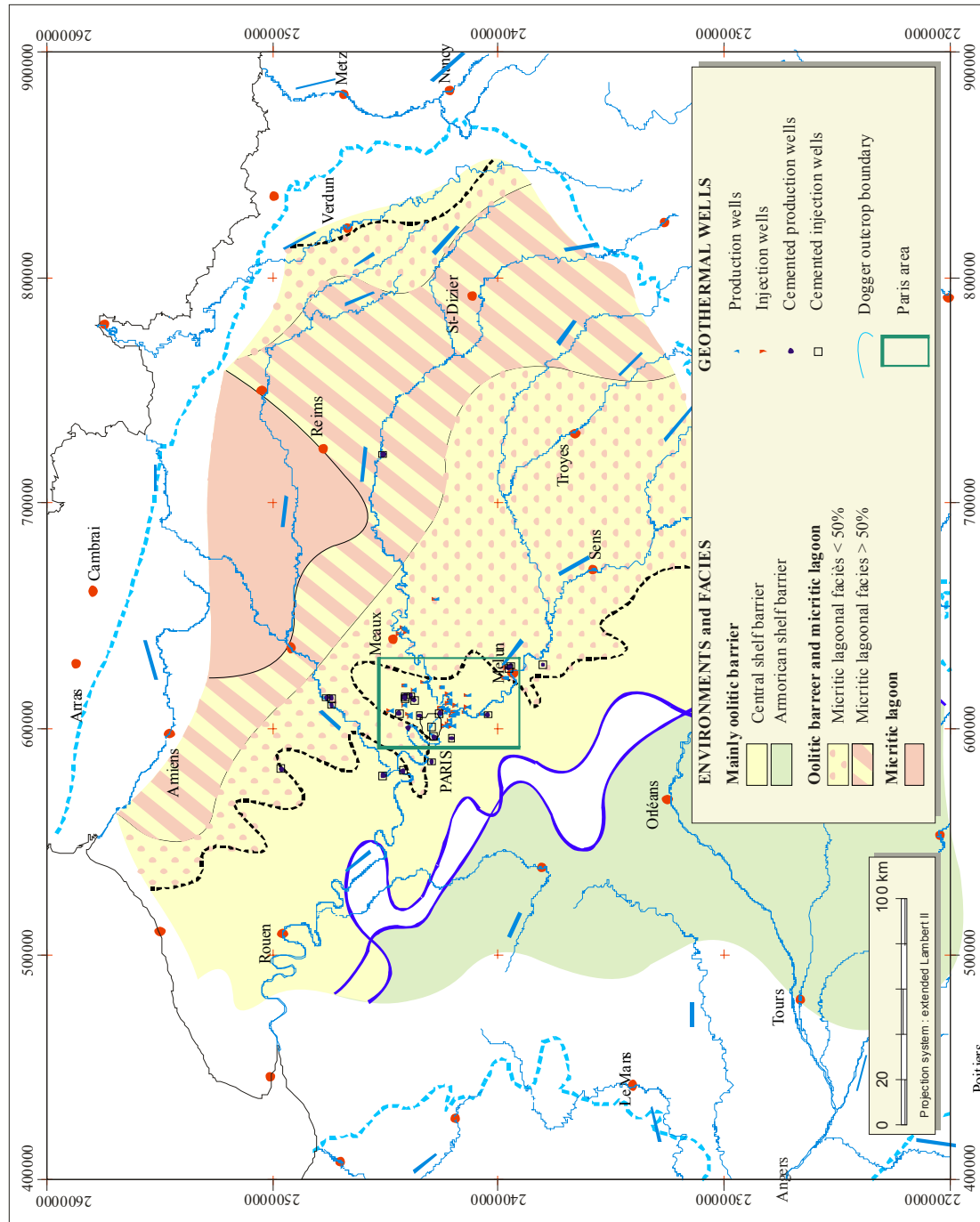


Fig. 40 - Geothermal wells in the Paris Basin.

Today, 34 geothermal doublets in the Dogger aquifer heat 140,000 dwellings via 29 district heating networks.

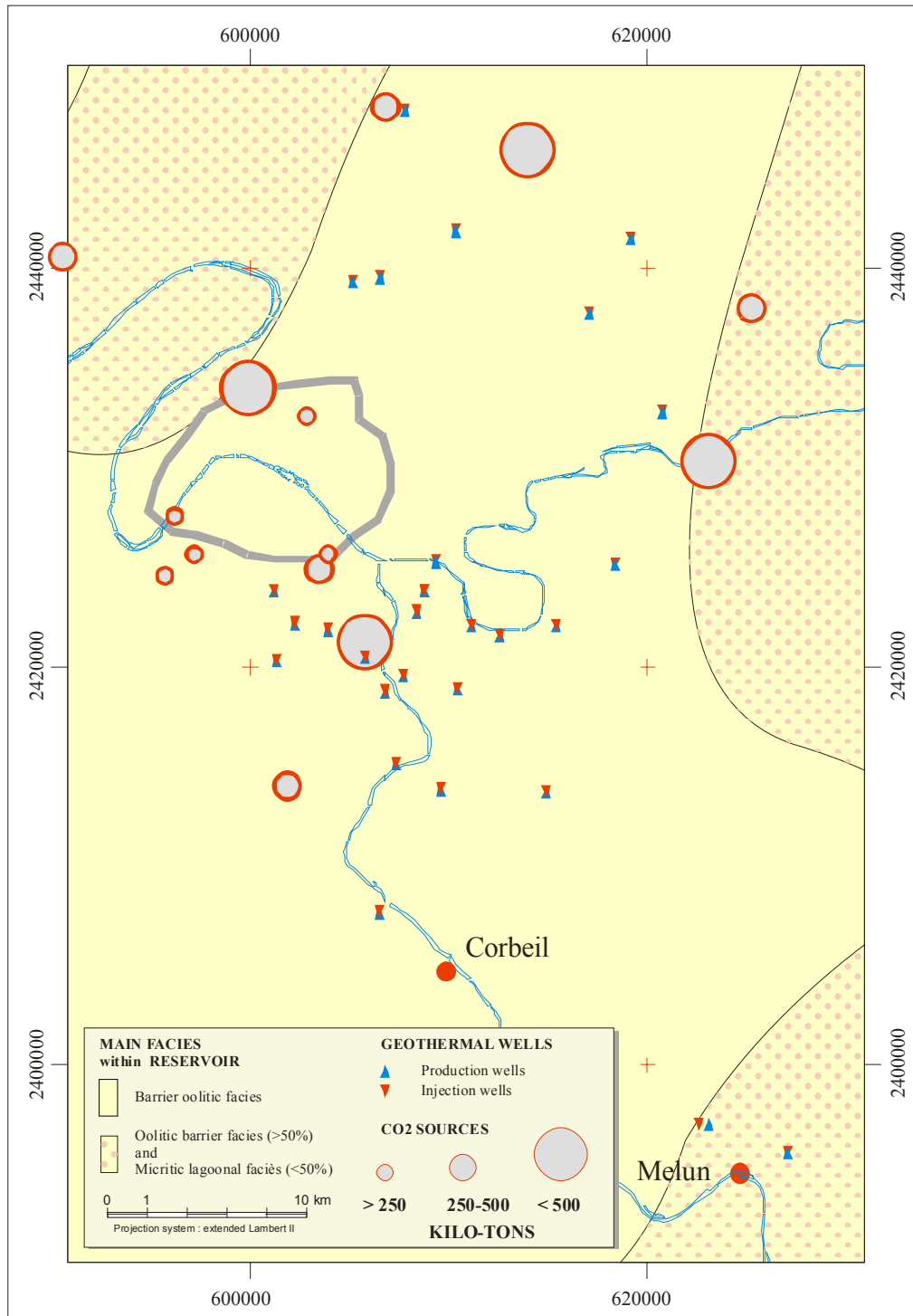


Fig. 41 - Geothermal wells of the Paris area.

4.2.3. Characteristics of the geothermal operations in the Paris Basin

The high salinity of Dogger aquifer water and its high corrosive capacity has imposed a new operating concept: the geothermal doublet involving the re-injection of water into the aquifer after having yielded its calories to a distribution network. This operating mode not only avoids rejecting a polluting fluid on the surface, but also preserves the natural hydrostatic pressure inside the Dogger aquifer.

a) The geothermal loop

Water pumped from the Dogger aquifer circulates in a geothermal loop (Fig. 42), which comprises:

A **doublet** composed of 2 wells —a production well and an injection well— with carbon steel casings (API H 40 to N 80 with predominance of grade K 55). The distance between the injection point and the pumping point in the reservoir at the bottom of the two wells is approximately 1 kilometre to minimise the thermal impact of cold water injection.

This distance between the two wells in the reservoir is obtained with various configurations:

- two straight wells: the wellheads are on two different sites;
- a straight well and a deviated well: the wellheads are on the same site;
- two deviated wells: the wellheads are on the same site.

The **pipe connecting the two wells**, which is generally of K 55 carbon steel. In the case of a doublet with two straight wells, buried pipe in composite material can be used.

An **extraction pump**: this is installed in the production well if the local operating and hydrogeological conditions provide insufficient pressure at the wellhead, thus preventing an artesian production. The pump controls the production flow rate and maintains the pressure higher than the bubble point pressure of the fluid, thereby preventing its degassing. Production in most of the doublets (26 of 34) is by **pumping**, which ensures flow rates between 200 and 300 m³/h (period of heating) and 80 and 150 m³/h (summer period where geothermal energy is used for domestic hot water). The remainder (8 of 34) relies on an **artesian production** in which the operating flow rate is lower and constant, around 100 m³/h and up to 220 m³/h for the most artesian (Bonneuil).

A **degasser**, if the production mode is artesian (Fig. 43) which separates gases from the water phase at a pressure lower than the bubble point pressure. These gases are then recovered and re-injected down the injection well using various techniques (Venturi, etc.). They can also be burned or evacuated directly to the atmosphere via a chimney.

A **filter** located before the thermal exchanger to retain any particles resulting from the reservoir or corrosion deposits.

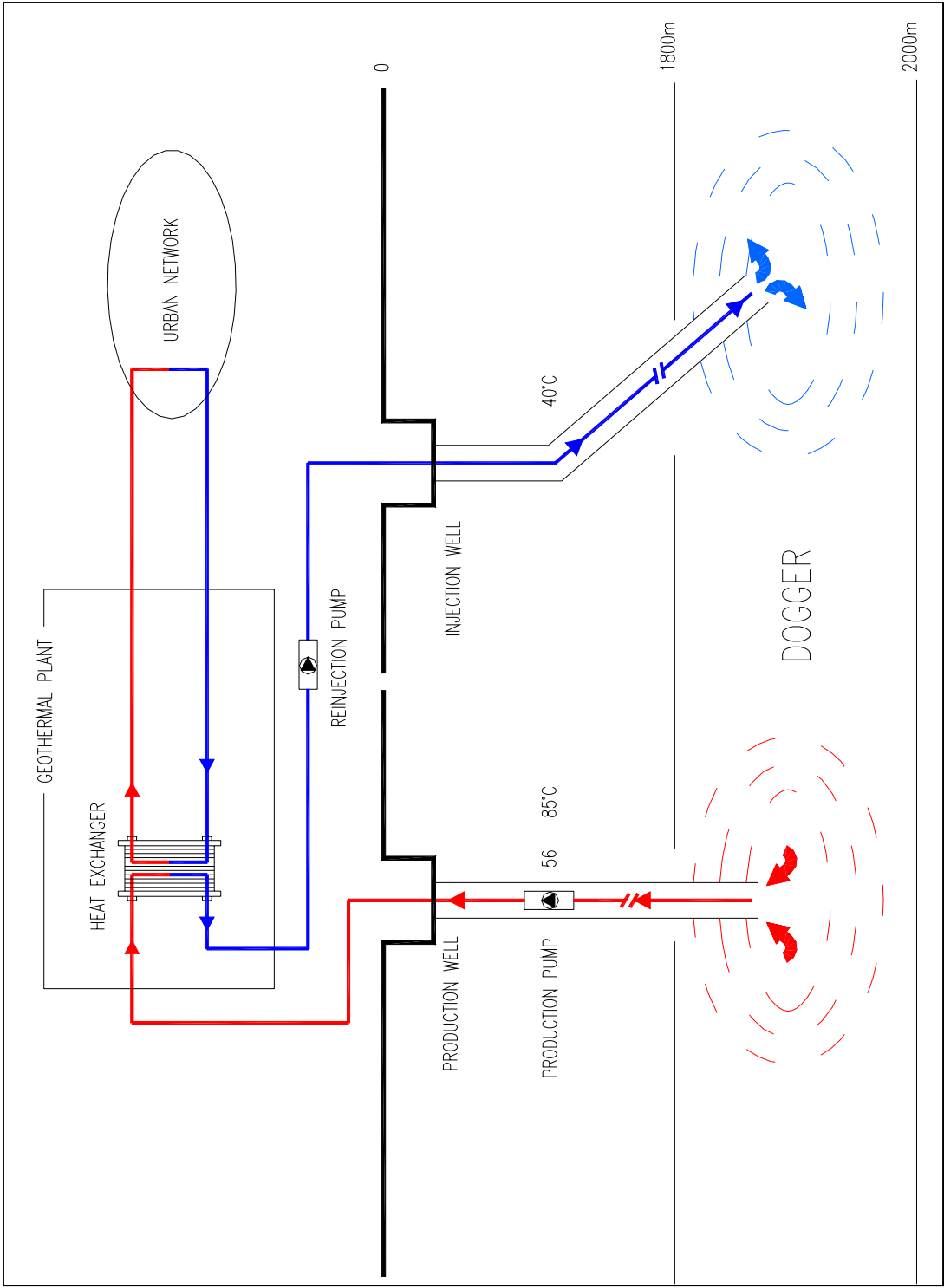


Fig. 42 - Diagram of a geothermal doublet – pumping-assisted production type.

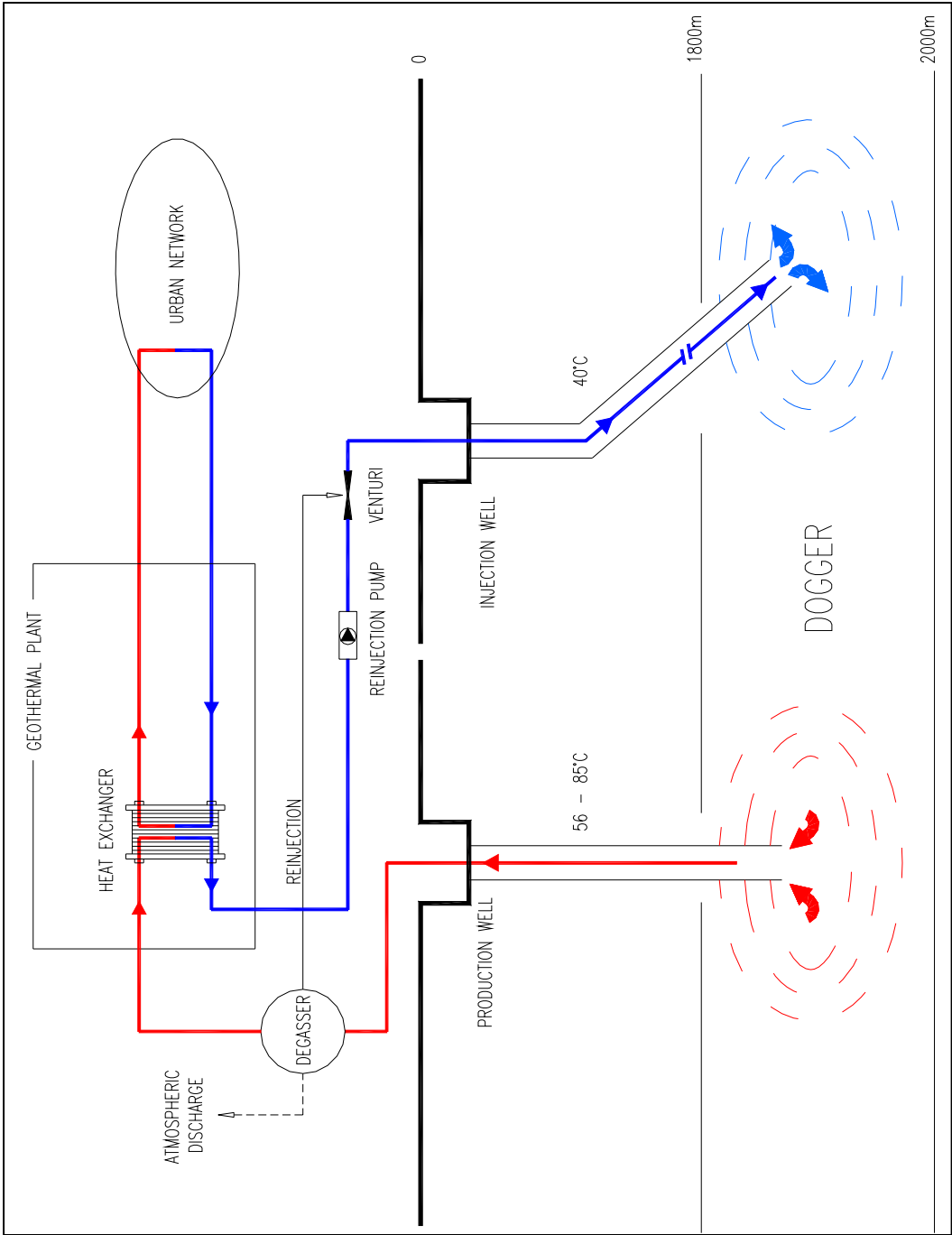


Fig. 43 - Diagram of a geothermal doublet – Artesian production type.

A **stuffing pump** located before the heat exchanger in order to overcome pressure losses in the unit operating in artesian production mode.

A **heat exchanger** with titanium plates in order to resist the chemical aggressiveness of geothermal water.

A **re-injection pump** located after the exchanger in order to increase the pressure to 15 to 20 bars to enable re-injection of the geothermal water in the aquifer.

The geothermal loop is the circulation loop of the town water heated by the geothermal fluid in the heat exchanger. It includes (Fig. 44).

Pipes to transport treated water circulating in closed circuit under a pressure of 10 to 16 bar at a temperature lower than 110° C. The pipes are made of pre-insulated steel or epoxy resin.

Sub-stations composed of one or several exchangers to ensure heating and/or domestic production of hot water for 30 to 200 dwellings.

Rescue contribution ensuring the requirements not covered by the geothermal system (rarely large enough to cover more than 50% of needs at -7 °C) and the totality of the requirements in the event of the geothermal system being temporarily unavailable. It is composed of one or more oil- or gas-fired boiler plants, intended to operate for only a limited number of hours.

Cogeneration systems enabling the combined production of heat and electricity. These operate with a gas turbine or gas or oil engine during 5 months of the year (November 1 to March 31) during which time electricity is repurchased at a fixed price.

b) Assessment of CO₂ emissions from geothermal operations

Table 16 lists the quantities of CO₂ emitted by extra energies and existing cogeneration units associated with each doublet currently in operation.

Extra boiler plants provide an average of 15% of the network heat and account for a mean annual emission of 1500 tonnes of CO₂ per doublet. Nearly half the heat networks (14 of 29) are fed by a cogeneration system, which provides an average 30% of the network heat and is the principal source of CO₂ emission, with an annual average of 7600 tonnes per unit.

Overall, annual CO₂ emissions resulting from use of extra fossil energy (heavy oil, domestic heating oil, natural gas) accounts for 47,000 tonnes and those resulting from cogeneration units 107,000 tonnes.

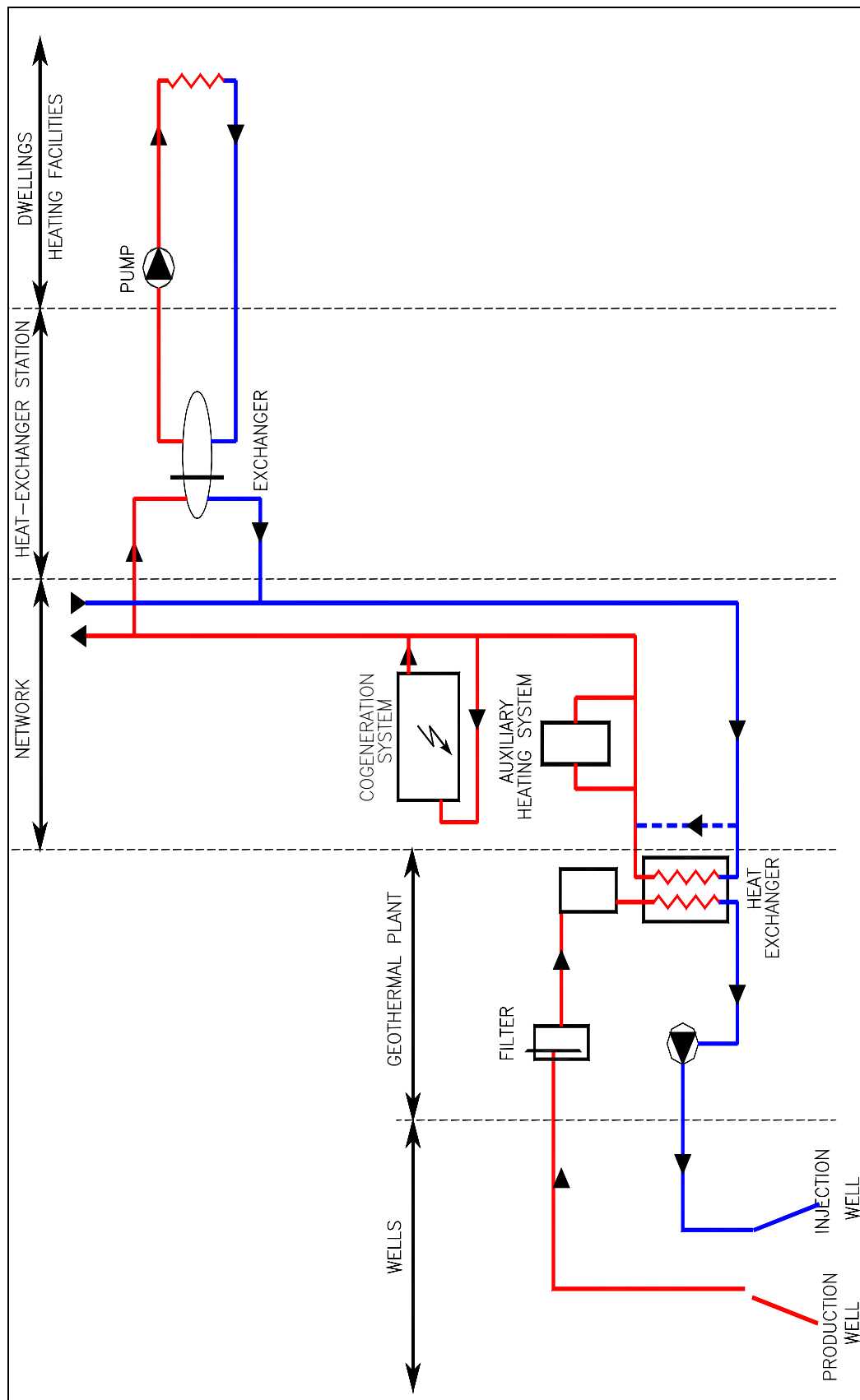


Fig. 44 - General diagram of a geothermal heating plant.

WELLS		Geothermal exploitation										
		Production type	Injection pressure bars	Production temperature (°C)	Max. flow rate m³/h	Min. flow rate m³/h	Average flow rate m³/h	Annual water volume produced (m³)	Annual thermal energy (MWh)	Thermal power MWt	Needed coverage (%)	
1	Le Mée-sur-Seine	artesian	23	72	135		100	893 000	25000	4.5	40	
2	Chevilly-Larue	pumping	20	74	290							
3	et L'hay les Roses	pumping										
4	Fresnes	Pompe	20	74	290					27	62	
5	Melun l'Almont	artesian		73	245		160	1 420 000	28 700	9	47	
6	La Courneuve Nord	pumping	21	58.5	160	80	110	953 975	21 000	5	75	
7	La Courneuve Sud	pumping	22.5	57	180	80	95	833 475	12 500	3.7	37	
8	Meaux Collinet	artesian	19	76	165		90	800 300	6800	5.9		
9	Meaux BV1	artesian	14	77	155		95	820 000	23600	5.7		
10	Meaux BV2	artesian	11.5	77	105		67	590 000	16400	3.9		
11	Meaux hôpital	pumping	16	75	230	120	130	1 123 600		8.5		
12	Alfortville	pumping	12.5	73.5	290	85	156	1 364 000	50 000	10.5	85	
13	Chelles	artesian		69	250		125	1 093 000	28500		74.5	
14	Clichy-sous-bois	artesian	13		75		75	657 000	16 060	2.5	34	
15	Champigny	pumping	12	78	290		250	2 190 000	55 000	11	67	
16	Sucy-en-Brie	pumping		78	190	120			25000	8.5	90	
17	Thiais	pumping		76	250				41 290		86	
18	Bonneuil	artesian	15	78	280		215	1 883 400	42000	11	62	
19	Ris-Orangis	pumping	14	72	190	90	125	1 100 000	20 400	6	90.5	
20	Coulommiers	pumping	7.1	83	180		138	1 207 898	24 600	7	94	
21	Cachan 1	pumping	35.5	69	175		105	924 750	15174		25	
22	Cachan 2	pumping	17.5	68	180		110	960 000	28150		47	
23	Maisons-Alfort 1	pumping	20	73	300		210	1 860 000	40000		67	
24	Maisons-Alfort 2	pumping	20	74	250		135	1 200 000	24000		44	
25	Epinay-Sous-Sénart	pumping	21	74	250		185	1 630 000	49 000		73	
26	Villiers-Le-Bel	pumping	12	65	220		145	1 260 000	11500	8	32	
27	Vigneux	pumping		75	230				38 580	11.5		
28	Blanc-Mesnil	pumping	26	70	190		146	1 280 000	25000		80	
29	Tremblay	pumping	24	73			187	1 634 000	45 800		90	
30	Orly Nouvelet	pumping		62			180	1 600 000	23200		28	
31	Orly Gazier	pumping		62			75	660 000	18 600		22	
32	Montgeron	pumping	22	71			100	876 000	18900		83	
33	Villeneuve-Saint-Georges	pumping		76	240		140	1 220 000	129 000		70	
34	Créteil	pumping	10.5	77	280		240	2 100 000	56000		71	

Table 16 - Operating conditions of several geothermal doublets in the Paris Basin (part 1).

	WELLS	Extra energy				
		Type	Thermal power MWt	Annual thermal energy (MWh)	Required coverage (%)	Annual CO ₂ emission (t/year)
1	Le Mée-sur-Seine	fuel oil + gas	18.4	8 000	13	1 400
2	Chevilly-Larue	fuel oil + gas	30	74+2,250	2	8 300
3	et L'hay les Roses					
4	Fresnes	fuel oil+ gas		300 +16,800	28	1 170
5	Melun l'Almont	heavy gas oil	31	10 000		3 000
6	La Courneuve Nord	natural gas	16.5	8 200	20,3	526
7	La Courneuve Sud	natural gas	17,7	6 200	18	398
8	Meaux Collinet	fuel oil+gas	28 + 2*8	21 000	10	1 300
9	Meaux BV1					
10	Meaux BV2					
11	Meaux hospital					
12	Alfortville	fuel oil + gas	15+20	8 800	15	2 270
13	Chelles					
14	Clichy-sous-bois	gas		8 400	17	1 665
15	Champigny	gas	30	12 000	15	2 472
16	Sucy-en-Brie	fuel oil + gas	12	3 000	10	770
17	Thiais	fuel oil +gas	1 + 15	6 700	14	1 200
18	Bonneuil	gas	14	25 700	38	4 700
19	Ris-Orangis	fuel oil		200	10	36
20	Coulommiers	fuel oil + gas		215+950	4.5	230
21	Cachan 1	fuel oil + heavy gas oil + gas		12 500	20	2 800
22	Cachan 2					
23	Maisons-Alfort 1	gas	26+10	9 000	15	2 170
24	Maisons-Alfort 2	fuel oil	22	1 650	3	650
25	Epinay-Sous-Sénart	gas		18 000	27	3 300
26	Villiers-Le-Bel	fuel oil	11	1 000	3	180
27	Vigneux					
28	Blanc-Mesnil	gas		6 000	20	1 100
29	Tremblay	gas		6 700	10	1 200
30	Orly Nouvilet	fuel oil + heavy gas oil		35,900+5,800	50	2 400
32	Orly Gazier					
32	Montgeron	gas		3 700	17	680
33	Villeneuve-Saint-Georges	heavy gas oil + gas		3,200+115	7	618
34	Crétail	fuel oil + heavy gas oil + gas		8,200+200+100	29	1 600

Table 16 - Operating condition of several geothermal doublets in the Paris basin (cont.).

	WELLS	Cogeneration							CO ₂	Surface equipment			
		Type	Electrical power	Thermal power	Annual utilisation time	Thermal production (MWh)	Needed coverage (%)	CO ₂ emission (t/an)	Total CO ₂ emission (t/an)	Reinjection pump	Degasser	Gas management	Max. pressure (bars)
1	Le Mée-sur-Seine	3 gas engines	9,3	9	5 months	29 500	47	8 800	10 200	2 pumps	1	Atmospheric emission	40
2	Chevilly-Larue	gas turbines	9,6	20	5 months	44 800	36	9 600	18 500				
3	et L'hay les Roses												
4	Fresnes	4 gas engines	7,5	8.2	5 months	15 250	25	4 500	5 670	1 (150 kW)			
5	Melun l'Almont (2-4)	2 gas engines	4,28	4.89	5 months			5 200	8 200		1	Atmospheric emission	
6	La Courneuve Nord	No							526				40
7	La Courneuve Sud	2 gas engines	4,05	4.8	5 months	16 400	47	1 944	2 342				40
8	Meaux Collinet		30	34.5	5 months	112 600	60	30 000	31 300	1 pump	1	reinjection by Venturi system	25
9	Meaux BV1												
10	Meaux BV2									1 pump	1	reinjection by Venturi system	16
11	Meaux hopital		8		5 months			7 400	7 400				25
12	Alfortville	No							2 270				
13	Chelles										1	combustion	
14	Clichy-sous-bois	5 gas engines	6,7	8		23 045	49	5 800	7 465		1	reinjection by Venturi system	
15	Champigny	3 gas engines	5,8	6.3	5 months	15 000	18	4 500	6 972				40
16	Sucy-en-Brie	No							770				
17	Thiais	No							1 200				50
18	Bonneuil	No							4 700				
19	Ris-Orangis	No							36				
20	Coulommiers		6		22 days	425	1,5	5 900	6 130				
21	Cachan 1	gas engine	8,6	9.6	5 months	4 800	8	1 400	4 200				
22	Cachan 2												
23	Maisons-Alfort 1-2	heat buying							2 170				
24	Maisons-Alfort 3-4	gas turbine	5,2	9.2	5 months	29 000	53	12 000	12 650				
25	Epinay-Sous-Sénart	No							3 300				
26	Villiers-Le-Bel	gas	6,5	7.3	5 months	22 500	6,5	6 700	6 880				
27	Vigneux	No											
28	Blanc-Mesnil	No							1 100				
29	Tremblay	No							1 200				
30	Orly Nouvelet (1-2)	No							2 400				
31	Orly Gazier (3-4)												
32	Montgeron	No							680				
33	Villeneuve-Saint-Georges	2 gas engines	4,1	4.9	5 months	11 300	23	3 400	4 018		1	reinjection by Venturi system	
34	Créteil	No							1 600				

Table 16 - Operating conditions of several geothermal doublets in the Paris Basin (cont.).

4.2.4. Development prospects of geothermal operations in the Paris Basin

Considering the energy independence that geothermal energy ensures and the resulting environmental impact (reduction of CO₂, NO_x, SO₂, and dust emissions), the authorities could take measures to support the creation of new operations in the near future. Moreover, without significant support by the authorities, traditional public investors will hesitate to launch new operations.

In this context, the principal development of geothermal energy operations in the Paris Basin is an **extension of existing heat networks**, in particular towards "low temperature" users. Optimising the profitability of these networks will involve their design (in user cascade), regulation of the sub-stations, and the connection of new users to take into account the thermal-energy contributions resulting from cogeneration. This development potential is currently estimated at 30,000 dwellings.

4.2.5. New generation geothermal operations

The 15 years of operation of the first-generation doublets has taught us lessons for the design of future doublets, which could be optimised by:

- increasing well diameter to obtain higher flows with lower electric consumption. Installation of simple or double completion in the injection wells could simultaneously enable **geothermal operation and injection of CO₂**;
- supporting artesian operations to decrease both investment and, more importantly, operating costs. This type of operating mode implies the installation of a degasser and a treatment or re-injection system for gases arising from degassing the geothermal water (CH₄, N₂, CO₂);
- using composite materials to avoid problems of corrosion-scaling on casings and to avoid anti-corrosion treatment of the water (currently only one well is coated with a composite material).

4.3. OIL AND GAS INDUSTRY EXPERIENCE IN CO₂ INJECTION

4.3.1. The Underground Injection Control (UIC) programme of the U.S. Environmental Protection Agency (EPA)

The Underground Injection Control (UIC) programme of the U.S. Environmental Protection Agency (EPA) defines some requirements for Class I wells, defined as wells dedicated to municipal or industrial waste (including hazardous waste) below the deepest underground sources of drinking water (Tsang *et al.*, 2000). Among the five classes of injection well established in this programme, Class 1 is the most relevant for CO₂ injection into brine aquifers such as the Dogger aquifer of the Paris Basin.

A typical Class I injection well constructed according to UIC requirements has at least two casing strings: a surface casing designed to protect underground sources of drinking water, and a long-string casing extended to the injection zone. These casings must be cemented in order to prevent movement of fluid into or between strategic aquifers. Ideally, wells are equipped with injection tubing set on a packer located above

the injection zone to prevent backflow of injected waste into the well. Materials used in well construction must be resistant to the proposed injected waste and to fluids that may form. Before a well is put into operation, the effectiveness of the cementing programme must be verified by logging the well, i.e. lowering electrical sensors into the well that measure variables such as temperature, noise and particle emissions. Similarly, the integrity of the tubular system of the well must be verified by pressure tests.

For the correct operation of Class I wells, the EPA regulates injection pressure to ensure that the well and confining formations are not damaged. The regulations require the maximum injection pressure specified to be set below the fracture pressure of the injection zone, which ensures that the confining zone cannot fracture. Injection pressure, injection volume, and flow rate must be continuously monitored, since any change in the relationship between these variables could indicate downhole problems. The tubing-casing annulus must be filled with fluid with an applied positive pressure. Continuous monitoring of this pressure is required to detect leaks in the tubing, packer, or long-string casing. If a pressure change indicates a leak, the well must be shut down and further tests conducted to verify the cause of the pressure change. The well must remain shut down until all problems are resolved. A simultaneous failure of at least two of these elements would be necessary for waste fluid to escape the injection well; the conditions under which both failures could lead to contamination of a strategic aquifer are unlikely.

Finally, the EPA has determined that correct plugging and abandonment of the wells is important to ensure that injected wastes cannot return to the surface when injection has terminated. Regulations require the operator to submit a plugging and abandonment plan as part of the permit application. This plan must identify the number of plugs and the method of their placement in the well.

4.4. CO₂ INJECTION WELL ENGINEERING ASSESSMENT OF THE U.S. DEPARTMENT OF ENERGY PROGRAMME

A project to study the engineering feasibility and costs of sequestering CO₂ in deep saline reservoirs was completed in 2000 as part of a U.S. Department of Energy programme (Anonymous, 2002). The components of the CO₂ sequestration system considered in this programme were capture of CO₂ from flue gas, preparation of CO₂ for transport (compression and drying), transport of CO₂ through a pipeline and injection of CO₂ into a suitable aquifer.

The design of the carbon dioxide injection wells is based on the UIC programme concerning Class I wells. The operating pressure at the top of the well is determined by considering the pressure required at the bottom of the well to force CO₂ into the injection zone, the pressure increase in the pipe due to the height of the CO₂ column, and the pressure loss due to flow in the pipe. The reported rate of pressure rise with depth in most reservoirs ranges from 0.105 to 0.124 bar/m with some sites having gradients as high as 0.23 bar/m (Hendriks and Blok, 1993). Moving CO₂ into the aquifer requires raising the gas sufficiently above the *in situ* pressure to provide a driving force, but not so high as to risk hydrofracturing the injection interval. Typically the CO₂ injection pressure is about 9 to 18% above the *in situ* pressure (Hendriks and Blok, 1993). The weight of the CO₂ column in the injection tubing provides some of the

required pressure. This pressure contribution depends on the density of CO₂ at the pressure and temperature conditions in the injection tubing. The results of calculations to determine wellhead pressure for various depths are listed in Table 17.

Depth (m)	CO ₂ pressure at wellhead (MPa) [bar]	CO ₂ specific gravity at wellhead	CO ₂ pressure at injection point (MPa) [bar]	CO ₂ specific gravity at injection point
1000	7.50 [74]	0.71	14.7 [145.1]	0.77
2000	12.8 [126.4]	0.83	29.5 [291.2]	0.87
3000	18.7 [184.6]	0.83	44.2 [436.3]	0.91

Table 17 - Wellhead pressures and specific gravities for different CO₂ injection depths.

The requirement for injection pumps depends on the depth of the injection zone. For sites shallower than about 1500 m, pipeline pressure should be sufficient to allow injection.

The design of wells used to inject supercritical CO₂ from the surface down into the deep saline aquifer is based on three or more concentric casings extending to various depths as follows:

- exterior surface casing;
- intermediate protective (long-string) casing(s);
- injection tubing (hangdown tube).

The exterior surface casing is designed to protect underground sources of drinking water in shallow aquifers through which the well passes and to reduce the corrosion potential by preventing contact between the water and the intermediate protective casing. The exterior surface casing extends from the surface to below the deepest underground sources of drinking water and is cemented from the shoe to the surface.

The injection tubing extends from the surface down to the top of the injection zone. The injection tubing should be designed to be removable to facilitate well maintenance if needed. The discharge end of the injection tubing is equipped with a backflow preventer (packer) to prevent CO₂ escape in the event of a well casing failure.

The estimated cost for drilling an injection well into a deep saline aquifer with a capacity of 1500 metric tonnes CO₂ per day is \$645/m (costs adjusted to the year 2000). Annual operating costs for the injection system are determined by estimating utility consumption, analytical needs and predicted labour costs to operate and maintain the system. An electrical cost of \$0.065/kWh is expected for injection pumps (when needed) and other additional power consumption for other loads such as smaller pumps, instruments and lighting. Maintenance materials are assumed to be 4% of the initial material cost. Labour requirements are assumed to be 2 maintenance workers, 11 operators, 0.5 full-time equivalent each for quality assurance (QA) and health and safety (H&S) support and 1 for a supervisor. Labour costs are assumed as \$30/h for maintenance workers and operators, \$50/h for QA and H&S support personnel, and \$70/h for the supervisor. Based on CO₂ samples collected from 3 points every week, analytical requirements are estimated at \$200 per analysis and underground drinking-water samples from 20 wells quarterly at a cost of \$300 per analysis.

4.5. CO₂ INJECTION INTO THE DOGGER AQUIFER OF THE PARIS BASIN USING GEOTHERMAL WELLS

4.5.1. Current state of geothermal injection wells in the Dogger aquifer

a) Configuration of the existing injection wells

- **Types of injection well**

The geothermal injection wells were designed for operating conditions with the following mean parameters:

- fluid-injection temperature between 40 and 65 °C;
- fluid-injection flow rate between 80 and 300 m³/h.

When the wells were designed these conditions imposed limitations on casing size. In order to limit injection pressures to an acceptable level, the diameter of the injection casing cannot be less than 7" (159.4 mm).

Historically, the first geothermal doublets (drilled between 1979 and 1984, and known as first generation) were built according to the following architecture (technical cross-section in Fig. 45):

- surface casing with a diameter of 13 3/8" (339.7 mm) set at approximately 650 metres and cemented from shoe to surface;
- intermediate casing with a diameter of 9 5/8" (244.5 mm) set at approximately 1100 metres and cemented from shoe to surface;
- production casing with a diameter of 7" (177.8 mm) set at the top of the Dogger reservoir (around 1900 m) and cemented from shoe to surface;
- the Dogger aquifer drilled with a diameter of 6" (152.4 mm) or 6 1/4" (158.75 mm);
- direct injection via the 7" casing without completion¹.

This well design would fulfil the following technical criteria:

- injection casing diameter at least 7";
- optimal protection of the upper aquifers, in particular protection by a double casing (9 5/8" and 7") of the strategic Albian-Aptian reservoir.

This category encompasses the "first generation" wells (1979 to 1983) for which injection is via a casing with an external diameter of 7", and also those originally equipped with a 9 5/8" casing and later relined to a 7" diameter.

¹ Completion, a term used in the oil industry, includes removable equipment of the wells intended to avoid contact of the fluid used and the permanent equipment (not removable and thus irreparable in case of damage to the well).

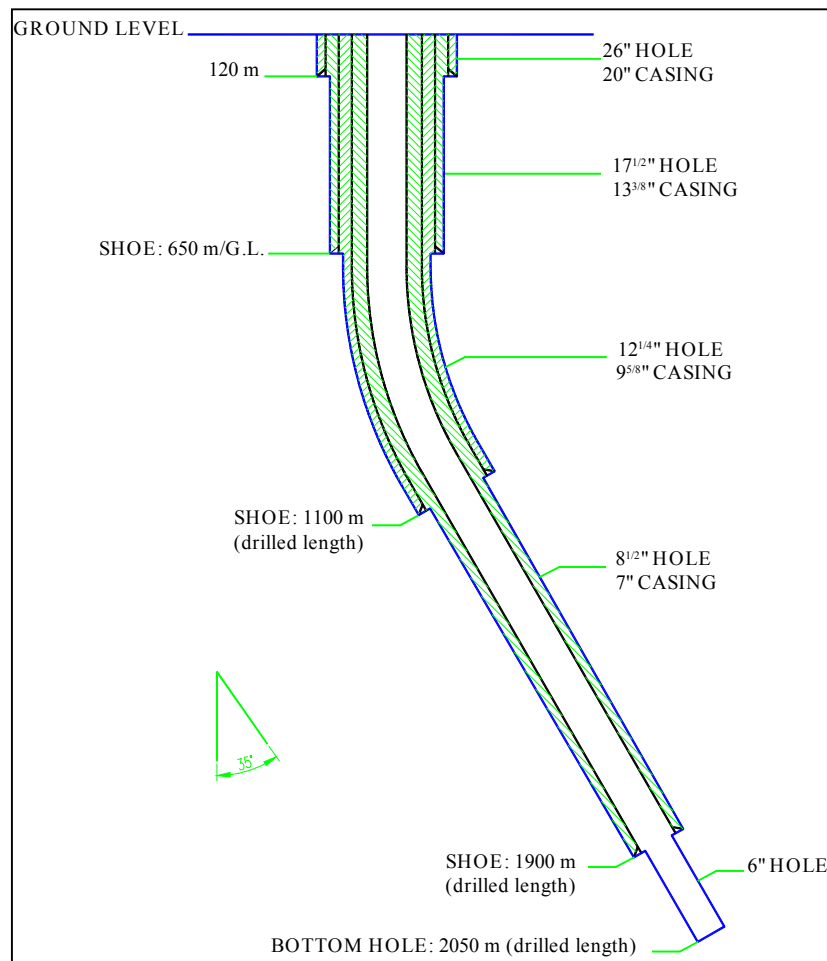


Fig. 45 - Injection well with 7" production casing and no completion.

This concern with protecting the Albian-Aptian by two casings and two cementings was also dictated the specificity of geothermal drillings in the Dogger aquifer of the Paris basin, namely the absence of completion. This feature (compared to the oil well) is explained by the high flow rates used, which can reach and even exceed 300 m³/h. Both production and injection, with this configuration, are carried out directly through the casing. The absence of completion requires good control of corrosion phenomena and also well-cemented production and injection casings.

A second generation of injection well, which has existed since 1984, is characterised by a simplified architecture, in which the principal modification concerns the prolongation of the intermediate casing down to the top of the aquifer. The intermediate casing thus becomes an injection column, as shown in the diagram of Figure 46:

- surface casing with a diameter of 20" (508 mm) set at approximately 30 m and cemented from shoe to surface;
- intermediate casing with a diameter of 13 3/8" (399.7 mm) set at approximately 400 metres and cemented from shoe to surface;
- production casing with a diameter of 9 5/8" (244.5 mm) set at the top of the Dogger aquifer and cemented from shoe to surface;

- Dogger aquifer drilled with a diameter of 8 1/2" (215.9 mm);
- direct injection via the 9 5/8" casing without completion.

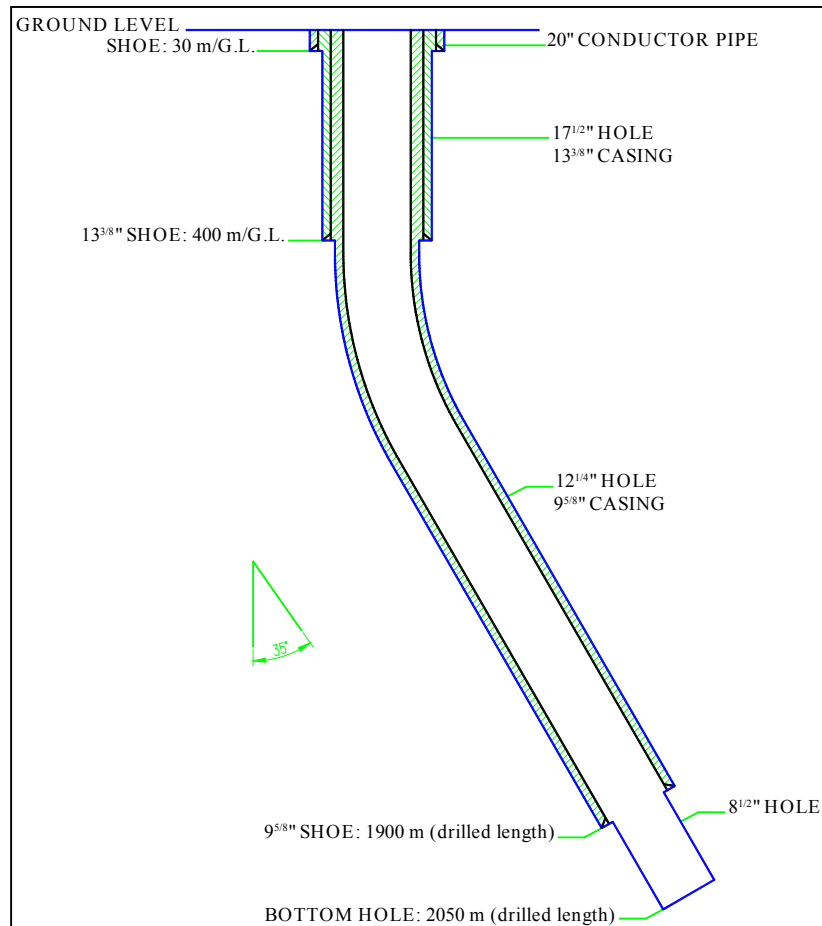


Fig. 46 - Injection well with 9 5/8" production casing and no completion.

This architecture presents:

- the advantage of a larger injection-casing diameter than the first generation. It provides a better injection regime since pressure losses in the casing are inversely proportional to the internal diameter raised to the 5th power;
- the disadvantage of increasing the risk of contamination of the upper aquifers, in particular the Albian-Aptian aquifer, protected by only one casing and one cementing.

To complete the inventory, it is advisable to mention several atypical geothermal installations that are exceptions to the above classification:

- a doublet equipped with a fibreglass completion in the production well (well PM4 of Melun l'Almont drilled in 1994);
- a doublet equipped with cemented fibreglass casings (Villeneuve Garenne installation, closed in 1994);

- symmetrical doublets each equipped with a 13 3/8" diameter pumping chamber at an approximate depth of 900 m and an injection casing with a diameter of 9 5/8".

- **Metallurgy**

With the exception of only one well equipped with fibreglass-coated carbon steel, all geothermal injection wells are equipped with grade API H 40 to N 80 carbon steel casings (minimal yield stress between 40,000 and 80,000 psi, i.e. 276 and 552 MPa), with a predominance of grade K 55.

These steel grades were selected for their greater resistance to hydrogen sulphide embrittlement in view of the presence of H₂S in solution in the Dogger aquifer water.

On the other hand, these "normal" carbon steels (according to the American Petroleum Institute) whose minimal yield stress is between 276 and 552 MPa (grades API H40 to N80) are considered by the oil industry as unsuited for production water containing CO₂ and whose pH can be in the range of 2.5 to 6.5. **This therefore excludes direct injection of CO₂ in its dissolved form into geothermal water at the head of injection wells that are not equipped with removable injection tubing.**

b) State of current injection wells

After several years or even months of operation of certain installations, disorders appeared that resulted in the simultaneous phenomena of corrosion and scaling of the injection casings.

Treatment systems were implemented in almost all the production wells. Injection of a corrosion inhibitor (filming amine) in the shaft bottom enables the entire geothermal loop to be treated, including the injection well.

It can be considered that the current mean corrosion level of injection wells in service is between 30 and 40%. In other words, residual thickness of the metal is about 60 to 70% and close to 50% in some wells. Furthermore, pitting due to localised corrosion can affect up to 60% (80% in some wells) of the wall thickness of the injection tube.

4.5.2. Adapting current geothermal injection wells to CO₂ injection

Two dominant factors that exclude the possibility of directly injecting CO₂ in any form via the injection well, whether diluted in geothermal water or simultaneously injected in gaseous or supercritical form, are (1) significant corrosion of the injection-well casings that have been in service for an average of 17 years, and (2) a grade of carbon steel that is incompatible with acidic carbonated water. It is thus necessary to consider a completion for the well before any injection of CO₂.

a) Well completion

The adaptation of current injection wells involves installing a completion, which may be simple or double. In the case of adapting the first-generation wells, the most technically and economically feasible scenario would be a simple completion.

In this configuration, CO₂ is injected through a removable injection column specifically dedicated to CO₂ injection. The geothermal water is injected via the annular space between the inner tube and the injection casing.

Figures 47 and 48 show technical cross-sections of injection wells equipped with a 7" and 9 5/8" casing, respectively, plus a simple completion for CO₂ injection.

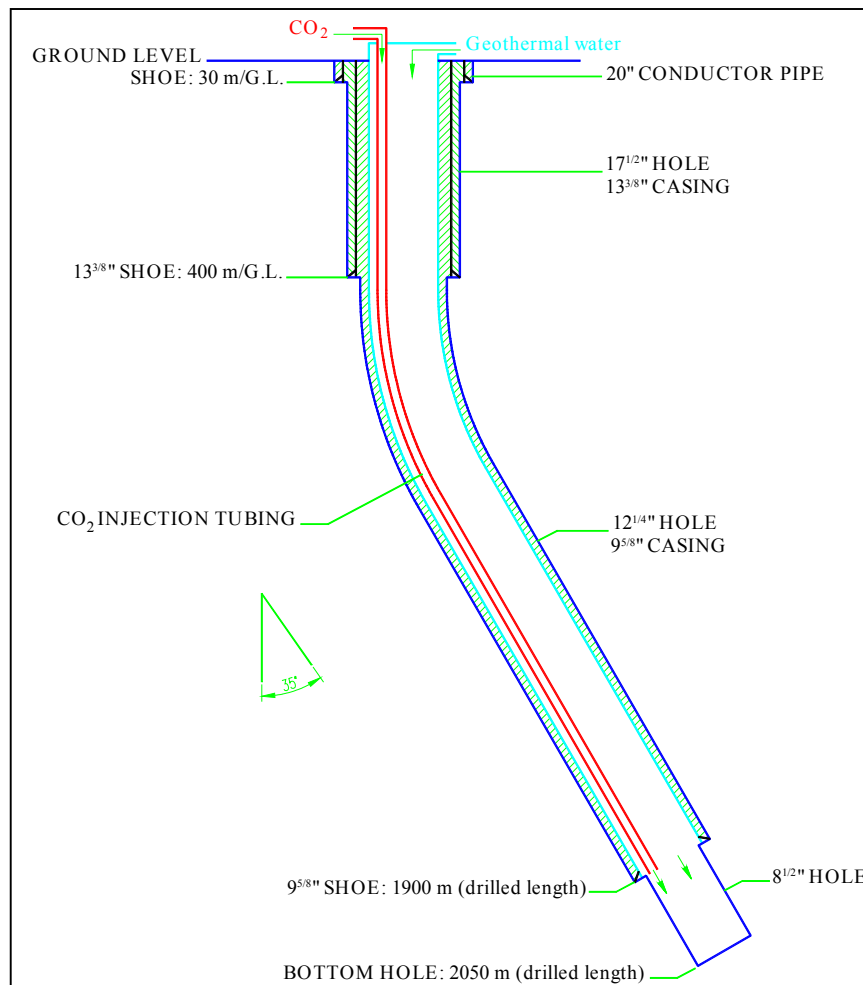


Fig. 47 - Injection well with 7" production casing and single completion.

The following technical questions require responses:

- at what open-hole level should the CO₂ injection tubing shoe be positioned to minimise risks related to CO₂ contact with the lower part of the 7" casing, as well as its cementing, and also those related to dissolution of the formation near the shoe of the 7" casing?
- should the injection tubing be equipped with an anchor device located at the foot of the injection casing? If so, this device must be designed to leave open the passage for the geothermal fluid;
- if the available space allows it, can the use of continuous (coiled) tubing be considered and, if so, what are the operational requirements?

- what metallurgy should be chosen for the CO₂ injection tubing?

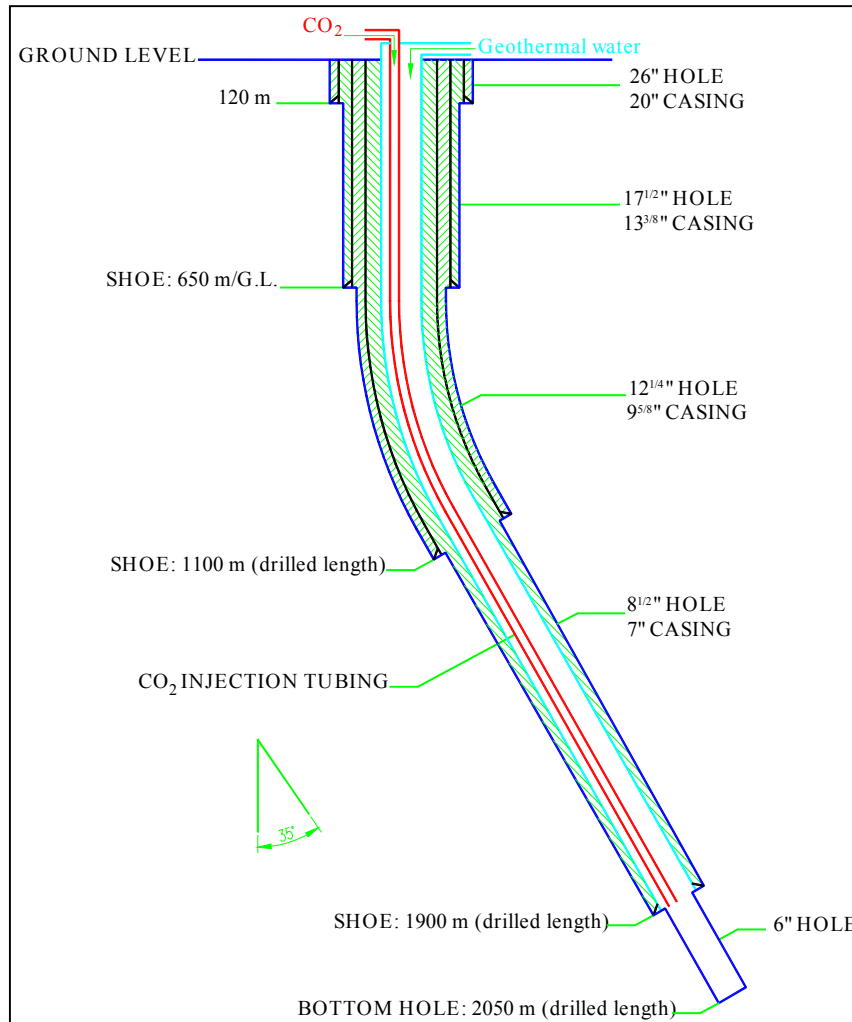


Fig. 48 - Injection well with 9 5/8" production casing and single completion.

The diameter of the injection tubing is of utmost importance because of obvious geometric considerations. The installation of a completion in the well will reduce the geothermal operating diameter and thus:

- with equal injection pressure, reduce operational flow rate;
- at equal operational flow rates, increase injection pressure and operating costs.

b) Effect of the presence of a completion on the operation of existing doublets

The two types of injection well currently used for geothermal operations are to be considered: those equipped with 7" diameter casings and those equipped with 9 5/8" diameter casings.

- **Injection wells equipped with 7" diameter production casings**

Injection of CO₂ in dissolved form

The largest completion that could be run into an injection well equipped with a 7" (26 lb/ft nominal weight) production casing would be a 5" outside diameter type tubing. In the case of a highly deviated well (more than 45°) special couplings would be required due to the low tolerance between the 7" inside diameter and the coupling outside diameter.

Injection of CO₂ in supercritical form

In the case of a single completion installed in a 7" diameter injection well, the CO₂ injection tubing will have to have a small external diameter. Because of the size of the tubing coupling (the outside diameter [OD] of the coupling is 0.5" [12.7 mm] to 1" [25.4 mm] larger than that of the tubing), it is preferable to use tubing with externally flush connections or continuous coiled tubing that can be installed and removed without the need for heavy equipment. Such tubes exist in the following diameters:

Outside diameter	Inside diameter
1" (25.4 mm)	19.86 mm
1 1/4" (31.75 mm)	26.21 mm
1 1/2" (38.1 mm)	32.56 mm
1 3/4" (44.45 mm)	38.91 mm
2 3/8" (60.33 mm)	53.98 mm
2 7/8" (73.03 mm)	64.14 mm

From a practical installation standpoint, it is not possible to consider a diameter greater than 2" for a continuous tube. Any larger and it would be necessary to consider the use of "conventional" tubing with couplings.

Figure 49 gives the pressure loss induced by the presence of an injection tube of four different external diameters ranging between 1" and 3 1/2", according to the operation flow rate in the case of an injection well of diameter 7". The graph shows that only the pressure loss induced by the presence of a tube of external diameter 1" could possibly be acceptable. This must however be studied on a case by case basis according to the operation conditions of the geothermal doublet.

- **Injection wells equipped with a 9 5/8" diameter production casing**

Injection of CO₂ in dissolved form

The largest completion that could be run into an injection well equipped with 9 5/8" (40 lb/ft nominal weight) production casing would be a 7" outside diameter type tubing.

Injection of CO₂ in supercritical form

Figure 50 gives the pressure loss induced by the presence of an injection tube of three different external diameters ranging between 2 3/8" and 3 1/2", according to operation flow rate in the case of a 9 5/8"-diameter injection well. The graph shows that the pressure loss induced by the auxiliary injection tube in a 9 5/8"-diameter well is much lower than in the case of the 7"-diamater injection well. The choice of the external

diameter of the auxiliary injection tube will depend on the operating conditions of the doublet and the quantities of CO₂ to be injected. Considering the pressure losses induced by this tube as a function of operating flow rate, an external diameter up to 2 7/8" seems possible.

4.5.3. Conclusion on the feasibility of CO₂ injection in current geothermal wells

The corrosion state of the current injection wells casings imposes the use of a completion for injecting CO₂. The most technically and economically feasible scenario would be a single completion type to inject CO₂ in dissolved or supercritical form.

Analysis of the observations made on many workover operations during the last five years enables the following points to be confirmed:

- in the case of leakage from the completion used for injecting CO₂ in dissolved or supercritical form, the corrosion state of the permanent injection casing would not prevent CO₂ escape in the event of injection tubing failure. Therefore, the complete security of the injection system could not be guaranteed and the risk of contamination of strategic subsurface aquifers would be too high.
- the residual thickness of the injection casing wall will not allow any increase of pressure required for the simultaneous injection of geothermal water and supercritical CO₂, which would be injected at a pressure of around 100 bars at the wellhead.
- the poor quality of the cementation of the current injection casings (circulation of geothermal water has already been observed in the annulus) and the type of cement used could not prevent CO₂ escape and resist the chemical aggressiveness of the CO₂.

These technical arguments definitively exclude any possibility of injecting CO₂ in whatever form (dissolved or supercritical) via the current geothermal injection wells.

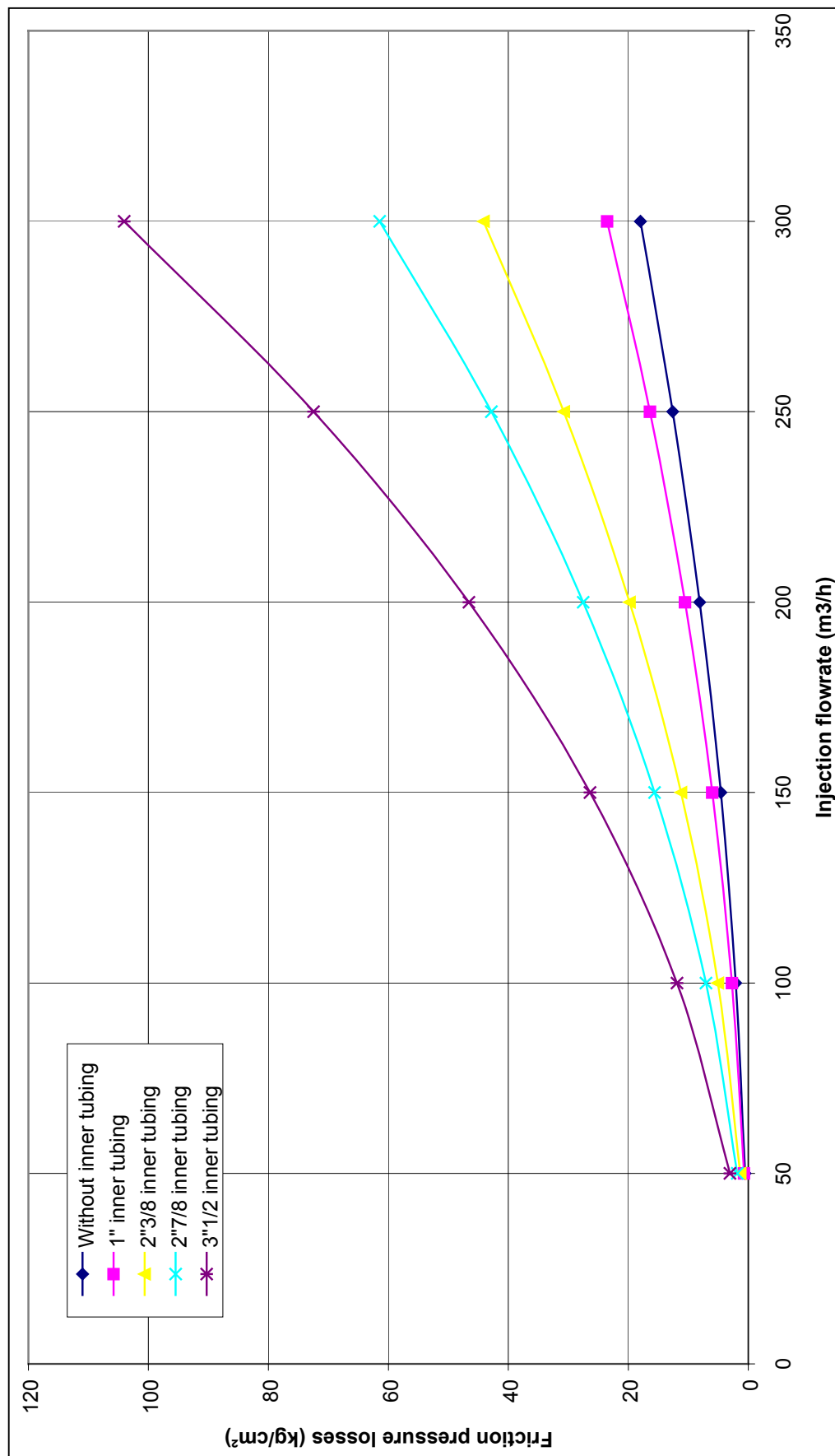


Fig. 49 - 7" injection well: effect of an inner tubing on injection pressure.

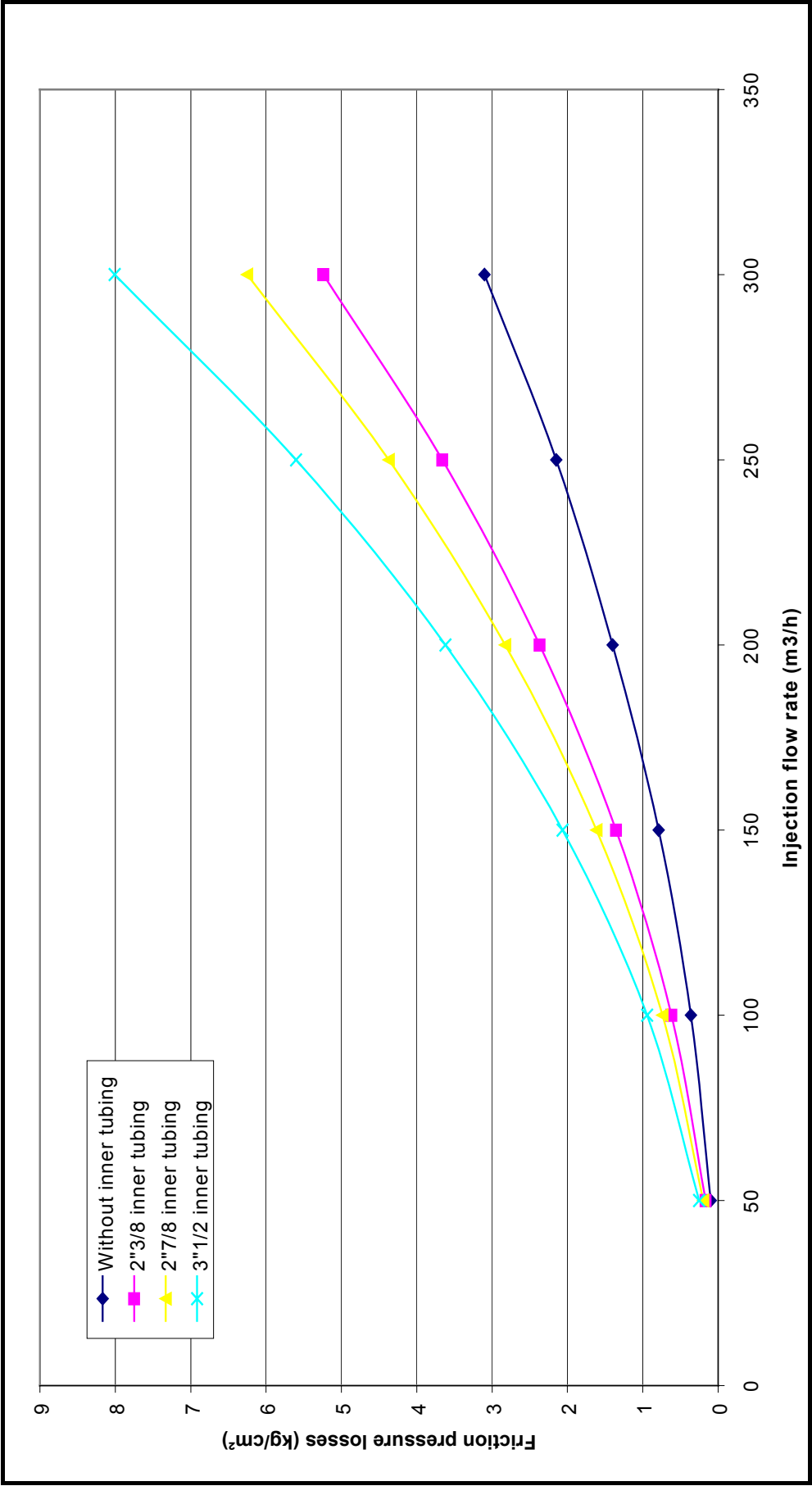


Fig. 50 - 9 5/8" injection well: effect of an inner tubing on injection pressure.

4.6. DESIGN OF FUTURE GEOTHERMAL INJECTION WELLS FOR THE COUPLING WITH CO₂ INJECTION

4.6.1. Technical approach

a) Material aspects of CO₂ injection

Carbon-steel CO₂ pipelines have been widely used in EOR projects where CO₂ and water are injected separately and extensive drying of the CO₂ has been used. Drying to below 100 ppm water is usual when the CO₂ is reasonably clean; if the water content is higher, water may precipitate and cause corrosion of the carbon steel. Consequently, stainless steel with a minimum chromium concentration of 13% is preferred for wet CO₂ injection. However, the investment cost for stainless steel is 3.5 to 4 times higher than for carbon steel.

If the injected CO₂ is dissolved in water, such as geothermal water that contains dissolved H₂S and chloride, this will increase the corrosion phenomena due to the formation of carbonic acid that occurs when injecting pure geothermal water. A carbon-steel injection tubing steel will then have to be considered as being consumable; it will become a removable completion that will have to be replaced regularly (for instance every five years). Corrosion-resistant materials, such as fibreglass for non-metallic materials or duplex (22% Cr), super-duplex (25% Cr) or super-austenitic steels (28% Cr) for metallic materials, may also be used for the injection tubing. However, the investment costs for these materials are respectively 3, 12, 14 and 16 times higher compared with carbon steel.

Furthermore, the long-term integrity of the casing cement under reservoir conditions with CO₂ present is of concern to the European bodies that are interested in stocking large quantities of CO₂ in underground reservoirs.

b) Injection of CO₂ in dissolved form

The dissolution of CO₂ in the geothermal water at the injection wellhead will induce:

- a lower pH due to the formation of carbonic acid;
- a higher pressure due to the increased partial pressure of the CO₂.

The scenario of injecting CO₂ dissolved in geothermal water at a concentration of 10 g/l (i.e. 13 metric tons per year for an annual average geothermal flow rate of 150 m³/h) has been considered as technically and economically acceptable for geothermal exploitations.

Dissolving 10 g/l of CO₂ in the geothermal water at the wellhead induces an increase of the partial pressure of CO₂ by 12 bar and a decrease of the pH by around 2 units (from 6.5 to 4.3). Considering that the bubble pressure (pressure under which the water degasses) is 10 bar on average, the 12 bar increase of the partial pressure of CO₂ will mean a minimum exploitation pressure of around 22 bar to ensure that the CO₂ remains dissolved in the geothermal water. In order to avoid any serious corrosion phenomena or hydrodynamic problems, it is very important that the geothermal exploitation keeps a monophasic fluid in the injection tubing. In addition, the pH

decrease to a value of about 4.3 seriously increases the risk of corrosion; here the scenario considered to be the best technical and economic compromise consists in using a removable carbon-steel tubing. The replacement hypothesis is based on an operational life of five years.

Future geothermal doublets could be dimensioned to take into account the required CO₂ flows to be injected. The diameter of the injection casing, which is governed more by economic factors than technical, could be increased to 13 3/8", with a technical cross section as follows (Fig. 51):

- surface casing of 30" diameter set and cemented at 30 metres;
- intermediate casing of 20" or 18 5/8" diameter set and cemented at 400 metres;
- production casing of 13 3/8" set and cemented at 1900 metres.

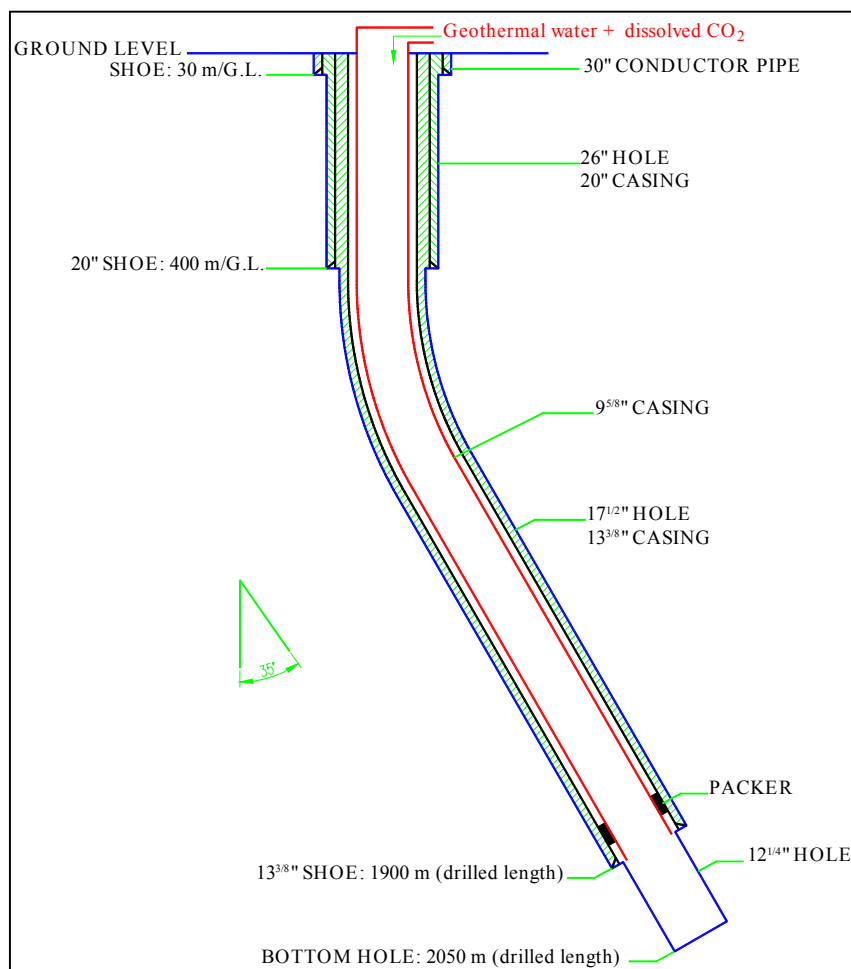


Fig. 51 - Injection well with 13 3/8" production casing and single completion.

The CO₂ injection could be carried out directly in the well provided that the casing material has been adapted to the chemical aggressiveness of the fluid.

- **Injection of CO₂ in supercritical form**

Although injecting CO₂ into a deep saline aquifer is an emerging technology with a short application history, most of the design and operation procedures for CO₂ handling systems can be based on accepted practices used for hazardous liquids and gases in the oil and gas industry, and particularly those developed from EOR (Enhanced Oil Recovery) experience.

In these operations the CO₂ is injected in supercritical form (the critical point of CO₂ being at a pressure of 73.82 bar and a temperature of 31.04 °C), which is the state of CO₂ in the Dogger aquifer at a depth below about 800 m. The injection of CO₂ in supercritical form avoids the adverse effects arising from the separation of CO₂ into liquid and gas phases in the injection zone. The CO₂ compression, cooling and dehydration required to achieve supercritical form must be carried out prior to injection; this is also necessary to overcome the in situ pressure of the Dogger formation. Also, injection equipment must be available at the injection site to accept pressurised CO₂ from the pipeline.

The injection of supercritical CO₂ and geothermal water could be carried out separately by a double completion. In this case, the well will be equipped with two removable injection columns, one for geothermal water, and the other for CO₂ (Fig. 52).

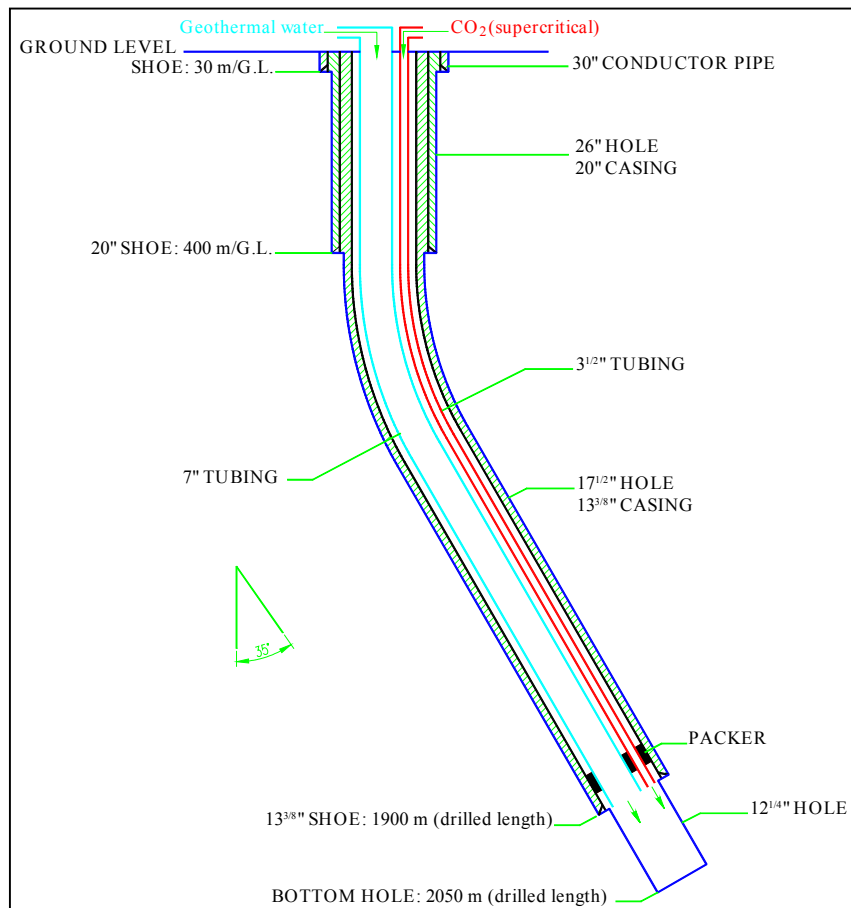


Fig. 52 - Injection well with 13 3/8" production casing and dual completion.

The dimensioning of the two columns must take into account the following factors:

- dimension of injection casing (permanent well equipment);
- geothermal water flow rate;
- CO₂ flow rate.

Table 18 shows various geometrically possible tubing configurations within a 13 3/8" casing, it being understood that the smallest "Tube 1" is intended for the CO₂ injection and that "Tube 2" is intended for the geothermal water injection.

Tube 1 \ Tube 2	7" EFC	7" SC	7 5/8" EFC	7 5/8" SC	8 5/8" EFC	8 5/8" SC	9 5/8" EFC
3 1/2" EFC							
2 7/8" SC							
2 7/8" EFC							
2 3/8" SC							
2 3/8" EFC							
2" CT							
1 3/4" CT							
1 1/2" CT							
1 1/4" CT							
1" CT							

EFC: external flush coupling

SC: standard coupling

CT: coiled tubing

Table 18 - Possible combinations for a double completion.

It can be seen from Table 18 that the combination enabling the maximum supercritical CO₂ injection while maintaining an acceptable diameter for geothermal water injection is the 3 1/2" EFC for Tube 1 (CO₂ injection tubing) and the 7" EFC for Tube 2 (water injection tubing).

The technical cross section of a geothermal injection well dedicated to supercritical CO₂ injection could thus be as follows (Fig. 52):

- a surface casing of 30" diameter set and cemented at 30 metres;
- an intermediary casing of 20" or 18 5/8" diameter set and cemented at 400 metres;
- a production casing of 13 3/8" diameter set and cemented at 1900 metres;
- an injection tubing of 7" diameter for the geothermal water injection;
- an injection tubing of 3 1/2" diameter equipped with a non-return valve;
- a well-bottom anchor device (packer) to isolate the two tubings and prevent any leakage of geothermal water or CO₂ in case of failure of the well production casing.

Particular attention should be paid to the choice of materials (couplings between tubes, thread lubricants, tightness, elastomer, etc.) which will have to be adapted to the chemical aggressiveness of the CO₂. The selection of the material for the supercritical CO₂ injection tubing will depend on the purity of the CO₂. In our case, we consider that the CO₂ is dry enough to use a carbon steel injection tubing that will be replaced regularly (anticipated tubing life of five years).

The considered technical scenario is based on an injection of supercritical CO₂ at a wellhead pressure of around 100 bar, which imposes the same pressure level for the injection of the geothermal water. Under these conditions, and according to the literature (Anonymous, 2002), up to 500 metric tons of CO₂ per day may be injected in the 3 1/2" tubing.

Under these conditions, 180 kt/an could be injected into a geothermal well. This value multiplied by the number of geothermal doublets, would allow the injection of 6,120 kt/an. It correspond to the quasi totality of the industrial CO₂ emission in Paris area (8 Mt/an).

4.7. ECONOMIC APPROACH

4.7.1. Investments costs

The realisation of a geothermal doublet located in the southern suburbs of Paris and comprising one production well equipped with its own inhibitor injection system (bottom-hole injection) and one injection well – both wells equipped with 9 5/8" production casings (see Fig. 50) – requires an investment of about EUR 3.5 million. This amount includes EUR 2.9 million for the wells and EUR 0.6 million for the surface equipment.

Adjusting the features of a new doublet to cater for CO₂ injection will require additional investment cost for the injection well only. This additional investment is related to:

- the increased size of the production casing, from 9 5/8" diameter to 13 3/8" diameter;
- the installation of removable completion, with a single completion in case of dissolved CO₂ injection (Fig. 51) and a dual completion in case of supercritical CO₂ injection (Fig. 52);
- the well head modifications.

The investment is estimated at:

- EUR 4 million for a doublet dedicated to the injection of dissolved CO₂;
- EUR 4.3 million for a doublet dedicated to the injection of supercritical CO₂.

a) Operating costs

For a "pure" geothermal doublet, the operating costs can be broken down into:

- fixed costs, such as maintenance of the geothermal loop, reserve for equipment renewal and management expenses;
- and proportional expenses made up mainly of the electrical consumption of the organs necessary to operate the loop (in particular the submersible production pump and the injection pump) and the treatment systems.

For a "CO₂ injection" geothermal doublet, a yearly sum should be allocated for the replacement of the injection-well completion. Here we have considered a 5-year

frequency for the completion renewal in both CO₂ scenarios, i.e. dissolved and supercritical.

b) Assessment of the costs for each scenario

- **“Pure” geothermal doublet**

- investment: EUR 3.5 million;
- term of the loan: 15 or 20 years;
- interest rate: 6%;
- annual geothermal production: 55,000 MWh;
- annual operating costs: EUR 0.47 million broken down into:
 - maintenance of the geothermal loop: EUR 0.31 million, including:
 - exploitation: EUR 0.05 million per year,
 - follow up, inhibitors: EUR 0.05 million per year,
 - submersible pump (total warranty): EUR 0.21 million per year,
 - specific electricity: EUR 0.16 million on the basis of 2000 MWh annual consumption.

- **Geothermal doublet combined with CO₂ injection in dissolved form**

- investment: EUR 4.0 million;
- term of the loan: 15 or 20 years;
- interest rate: 6%;
- annual geothermal production: 55,000 MWh;
- annual production costs: EUR 0.63 million broken down into:
 - maintenance of the geothermal loop: EUR 0.31 million, including:
 - exploitation: EUR 0.05 million per year,
 - follow up, inhibitors: EUR 0.05 million per year,
 - submersible pump (total warranty): EUR 0.21 million per year,
 - provision for completion replacement (injection well): EUR 0.06 million per year,
 - specific electricity: EUR 0.26 million on the basis of 3200 MWh annual consumption.

- **Geothermal doublet combined with CO₂ injection in supercritical form**

- investment: EUR 4.3 million;
- term of the loan: 15 or 20 years;
- interest rate: 6%;
- annual geothermal production: 55,000 MWh;
- annual production costs: EUR 1.04 million broken down into:
 - maintenance of the geothermal loop: EUR 0.31 million, including:
 - exploitation: EUR 0.05 million per year,
 - follow up, inhibitors: EUR 0.05 million per year,
 - submersible pump (total warranty): EUR 0.21 million per year,

- provision for completion replacement (injection well): EUR 0.075 million per year,
- specific electricity: EUR 0.655 million on the basis of 8000 MWh annual consumption.

c) Calculation of the geothermal cost per MWh

The cost per geothermal MWh, obtained by dividing the total annual cost (i.e. loan repayment and annual operating costs) by the total amount of delivered geothermal MWh, is shown in Table 19.

	Pure Geothermal Doublet	Dissolved CO ₂ geothermal doublet	Supercritical CO ₂ geothermal doublet
Geothermal MWh cost (EUR) 6% - 15 year loan	15.12	18.85	26.82
Geothermal MWh cost (EUR) 6% - 20 year loan	14.11	17.71	25.59

Table 19 - Cost per geothermal MWh for the different scenarios.

These costs can be compared against the costs of fuel and natural gas used for auxiliary heating in the same heating network, i.e.:

- EUR 30.5 / MWh (effective) for natural gas heating;
- EUR 38.0 / MWh (effective) for fuel heating.

Thus geothermal energy remains a competitive heating system even when combined with the simultaneous injection of CO₂ in supercritical or dissolved form.

4.7.2. Conclusion on the feasibility of CO₂ injection in future geothermal wells

a) Injection of CO₂ in dissolved form

The operating conditions (pressure, monophasic fluid) of a geothermal injection well combined with the injection of CO₂ in dissolved form would be close to those of the existing geothermal wells. The technically and economically most acceptable scenario is based on an injection of 10 kg/m³ of CO₂, which represents a total input of 36 tons/day (13,140 tons/year) for an average geothermal injection flow rate of 150 m³/h.

The investment and the geothermal MWh costs would be respectively around 15% and 30% higher compared to a conventional doublet.

The main interest for the geothermal operation would be the possibility of injecting all the CO₂ generated from the use of extra-energy and cogeneration systems (on average 9100 tons/year/doublet).

The main disadvantages would be:

- the expensive injection cost: EUR 100 /ton CO₂ injected;

- the risks of dissolution/precipitation phenomena in the carbonate reservoir, which would compromise the geothermal exploitation of the Dogger aquifer.

b) Injection of CO₂ under supercritical form

Preliminary processing (purification, compression, dehydration) and then transport to the injection site is required for the injection of supercritical CO₂. Added to this is the fact that a double completion is required for injecting the supercritical CO₂ separately from the geothermal water, plus the fact that the injection process needs high pressure and acid-resistant equipment and materials (acid resistant cement grout at the bottom of the well, packers to isolate the annulus, injection tubing with non-return valve).

The investment and the geothermal MWh costs for a geothermal doublet combined with CO₂ injection in supercritical form would be respectively in the region of 25% and 100% higher compared to a conventional doublet.

The supercritical CO₂, whose density and viscosity are lower than those of water, will flow up to the top of the injection zone. The risk of a vertical leakage of supercritical CO₂ through the caprock cannot be excluded and represents the main danger in the urban environment of the Paris area. Furthermore, the risk of gas migration through wells located near the injection zone – for example, the distance between the two bottom holes in a geothermal doublet is only around 1000 metres – is also very high and compromises the total security of the underground sequestration of CO₂ in supercritical form.

The main benefits of injecting CO₂ in supercritical form in conjunction with a geothermal operation, as compared with the injection of CO₂ in dissolved form, are:

- an injection of larger quantities of CO₂ (up to 500 tons/day/well, or 182,500 tons/year/well);
- a lower injection cost: EUR 15.6 per ton of CO₂ injected.

4.8. FEASIBILITY OF CO₂ INJECTION IN THE TRIASSIC AQUIFER

4.8.1. State of the art concerning France's geothermal exploitation of the Triassic aquifer

The Triassic, the deepest sedimentary unit above the basement, comprises clastic sandstone and clay layers. The potential areas that could be used for heating applications in France are located:

- in the southern area of the Loire River, at a depth of about 2000 metres, where the most recent use was for a greenhouse heating project at Saint Denis en Val (Loiret). A first geothermal doublet drilled in the area in the early 1980s yielded very interesting results, with a bottom-hole temperature of 74 °C at a depth of 1500 m, and an operational flow rate of 180 m³/h. However, pressure problems rapidly appeared at the injection well, resulting in a reduction of the operational flow rate and a discharge of the best part of the geothermal water into the Loire River (with a temporary permission of the Administration). The operation was then stopped and the well plugged in 1988;

- in the Paris area, in the Mantes area along the Basse-Seine valley, where the bottom-hole temperature reaches about 80 °C. Two doublets were drilled: one at Cergy Pontoise (Val d'Oise) in 1981 and the other at Achères (Yvelines) in 1982. Unfortunately, the aquifer could not be exploited at Cergy Pontoise due to its low productivity, whilst the doublet at Achères encountered high injection pressures, as at Saint Denis en Val. Development of the Triassic aquifer was thus abandoned in both doublets in favour of the Dogger aquifer.

The injection problems encountered in the Saint Denis en Val and Achères projects put a drastic stop to any exploitation of the Triassic aquifer in France. A major research program has been started by ADEME and BRGM in order to resolve these problems.

4.8.2. Technical aspects concerning injection in the Triassic aquifer

The results of the ADEME / BRGM research programme, combined with those obtained by other European operators in Germany, Denmark, the Czech Republic and Lithuania in the framework of comparable geothermal projects, should revive a certain amount of interest in the potential of geothermal doublets tapping the Triassic reservoir.

From the technical standpoint, it is a question of finding a solution that increases the injection area and reduces the fluid velocity. This could be obtained by:

- increasing the well diameter down to the aquifer;
- drilling highly deviated to horizontal injection wells (Fig. 53);
- drilling a multi-leg (multilateral) well (Fig. 54).

Compared to the Dogger, the completion is notably different at the reservoir level, in that it is equipped with a reinforced with stainless-steel wire-wrap screen (Fig. 53). The injection in the higher part of the well is via the casing itself (as in the Dogger).

All the injection problems mentioned above must be definitively resolved before considering the injection of CO₂ into the Triassic reservoir. The problems related to using these wells for the simultaneous CO₂ injection are roughly the same as those for the Dogger injection wells, with a single removable completion being used to inject CO₂ in dissolved conditions and a dual removable completion being used to inject supercritical CO₂.

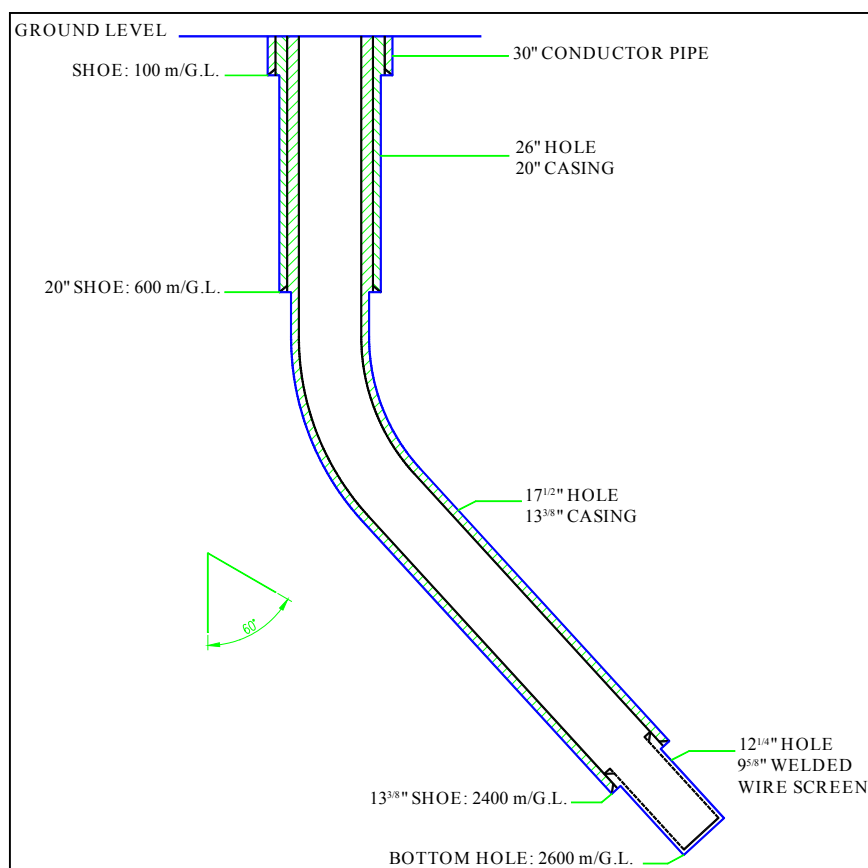


Fig. 53 - Large-diameter injection well for the Triassic reservoir.

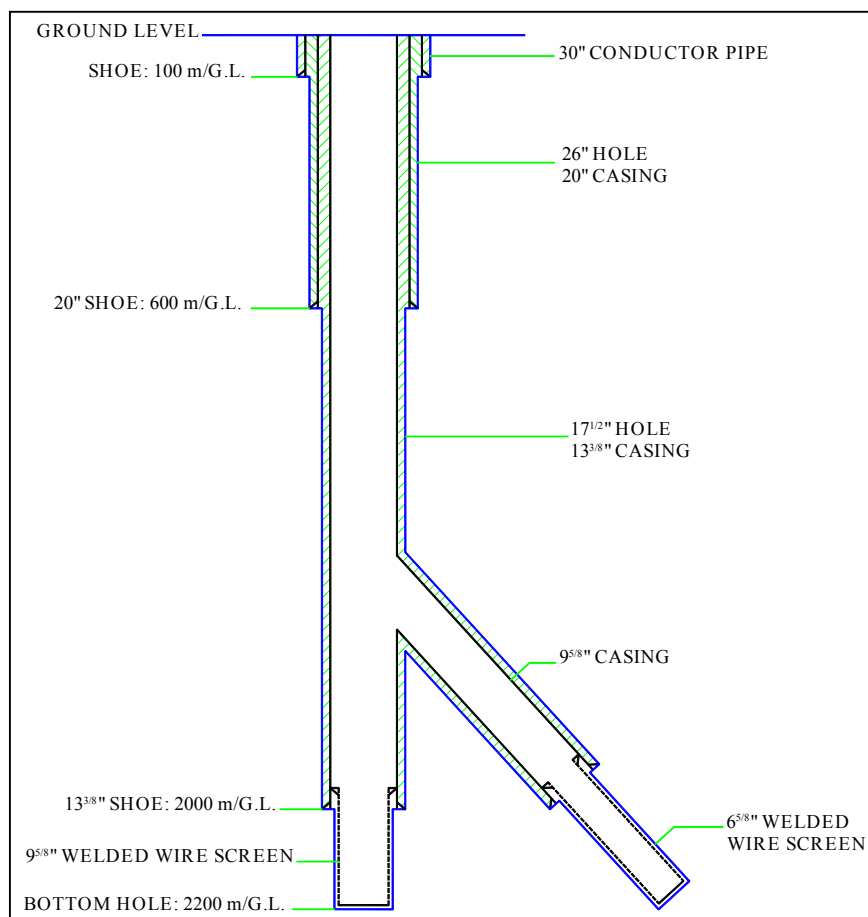


Fig. 54 - Multilateral injection well for the Triassic reservoir.

5. Conclusion

The principal objective of GESTCO is to make a major contribution to the reduction in CO₂ emissions to the atmosphere and so ensuring Europe a continued stable supply of affordable and environmentally acceptable energy. A solution will thus be sought to the problem: *Is geological storage of CO₂ a viable method capable of wide-scale application?* The GESTCO project intends to provide the first documentation that, for emission sources within selected key areas, sufficient geological storage capacity is available.

Within this framework, the BRGM/ANTEA/CFG consortium took care to provide:

- an inventory of the CO₂ emitters in France - localisation and quantification of the principal emissions;
- an inventory of the principal deep aquifers present in the Paris basin - principal characteristics of the aquifers;
- an evaluation of the storage capacities of CO₂ in one of the four principal case-study: low enthalpy geothermal reservoir;
- technical solutions for CO₂ injection in geothermal aquifers;
- evaluation of the cost of CO₂ storage in such an aquifer.

The scenario of CO₂ storage in an exploited low enthalpy geothermal aquifer was retained for the following reasons:

- these aquifers have infrastructures, which would allow the CO₂ injection at lower cost (existing wells and pumping stations);
- the exploitations are located in urban zones, near sources of industrial CO₂,
- the modern geothermal installations are generally of cogeneration type, i.e. they are associated with traditional fuel or gas-fired stations. The first produce heat and the seconds, electricity and heat to mitigate the deficiency of the geothermal installations when the demand for heat is too strong. The storage of CO₂ would then make it possible to produce a completely clean energy.

If the whole of the results obtained makes it possible to be extremely confident on the feasibility of the CO₂ injection in a deep aquifer, in order to reduce the GHG emissions, it appears that many aspects of the problem would need complementary works.

It concerns:

- the difficulty to produce a correct evaluation of the storage capacity for the deep aquifers. This difficulty comes primarily from the fact that these aquifers are little known, little studied and that the methodology for physical parameter interpolation which characterise them, have to be developed;
- uncertainty on the geometry of the possible traps being able to be used for the storage of CO₂ in these deep reservoirs for the same reasons as previously (little known geological objects, very few surveys on these objects);

- the complexity of the modelling of geochemical phenomena to simulate the response of one reservoir to the injection of an aggressive fluid charged of dissolved CO₂;
- the absence of effective and robust modelling tools to simulate the behaviour of diphasic fluids (supercritical water + gas) in a reservoir.

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APPENDIX

Data provided for the construction of the Geographical Information System of GESTCO

Table A: CO₂ emission by administrative region

Name of region	N°	Population	Surface_Km²	Mt CO₂
ILE-DE-FRANCE	11	10660554	11992.08	12.5
CHAMPAGNE-ARDENNE	21	1347348	25544.96	5
PICARDIE	22	1810687	19445.79	4.8
HAUTE-NORMANDIE	23	1737130	12304.07	18.4
CENTRE	24	2371036	39470.56	2.7
BASSE-NORMANDIE	25	1389971	17726.35	1.8
BOURGOGNE	26	1609653	31695.71	3.4
NORD-PAS-DE-CALAIS	31	3959808	12437.61	20.2
LORRAINE	41	2305232	23592.66	21.3
ALSACE	42	1624372	8296.37	4.5
FRANCHE-COMTE	43	1097276	16253.25	2
PAYS DE LA LOIRE	52	3059112	32277.9	7.9
BRETAGNE	53	2795638	27379.14	1.8
POITOU-CHARENTES	54	1595109	25907.99	3.6
AQUITAINE	72	2795830	41836.93	7.2
MIDI-PYRENEES	73	2430663	45450.69	5.6
LIMOUSIN	74	722850	16986.31	1.8
RHONE-ALPES	82	5350701	44691.23	10.8
AUVERGNE	83	1321214	26220.08	1.5
LANGUEDOC-ROUSSILLON	91	2114985	27705.67	2.7
PROVENCE-ALPES-COTE D'AZUR	93	4257907	31682.24	20.1
CORSE	94	250371	8815.64	0.6

Table B: Main industrial CO₂ emission in France

Department	N°	City	N°	Industry	kt CO ₂
BOUCHES-DU-RHONE	13	FOS-SUR-MER	13039	Metallurgy	5315
BOUCHES-DU-RHONE	13	GARDANNE	13039	Centrale thermique	3718
BOUCHES-DU-RHONE	13	LA MEDE	13039	Raffinerie	1398
BOUCHES-DU-RHONE	13	LAVERA	13039	Raffinerie	2032
HAUTS-DE-SEINE	92	ISSY-LES-MOULINEAUX	92040		209
ISERE	38	MONTALIEU-VERCIEU	38247	Cementery	1531
LOIRE-ATLANTIQUE	44	CORDEMAIS	44045	Power station	5253
LOIRE-ATLANTIQUE	44	DONGES	44052	Oil refinery	2064
LOIRET	45	MONTEREAU	45213	Power station	379
MEURTHE_ET_MOSELLE	54	BLENOD-LES-PONT-A-MOUSSON	54079	Power station	3010
MOSELLE	57	CARLING	57123	Power station	4482
MOSELLE	57	FLORANGE	57221	Metallurgy	3166
MOSELLE	57	LA MAXE	57452	Power station	1505
NORD	59	DUNKERQUE	59183	Oil refinery	1288
NORD	59	DUNKERQUE	59183	Metallurgy	7011
PYRENEES-ATLANTIQUES	64	LACQ	64300	Gas production	1061
RHONE	69	FEYZIN	69276	Oil refinery	1234
SEINE-ET-MARNE	77	BRAY-SUR-SEINE	77051		105
SEINE-ET-MARNE	77	CLAYE-SOUILLY	77118		338
SEINE-ET-MARNE	77	GRANDPUITS-BAILLY-CARROIS	77211	Oil refinery	1127
SEINE-ET-MARNE	77	VAIRES-SUR-MARNE	77479	Power station	593
SEINE-MARITIME	76	GONFREVILLE-L'ORCHER	76305	Oil refinery	3118
SEINE-MARITIME	76	LE HAVRE	76351	Power station	4260
SEINE-MARITIME	76	PETIT-COURONNE	76497	Oil refinery	1358
SEINE-MARITIME	76	Port Jérôme	76351	Oil refinery	1503
SEINE-ST-DENIS	93	SAINT-OUEN	93070	Incinerator	893
VAL-DE-MARNE	94	IVRY-SUR-SEINE	94041	Incinerator	470
VAL-DE-MARNE	94	VITRY-SUR-SEINE	94081	Power station	807
VAL-D'OISE	95	CHAMPAGNE-SUR-OISE	95134	Power station	494
VAL-D'OISE	95	CORMEILLES-EN-PARISIS	95176	Minerals	383
VAL-D'OISE	95	LE PLESSIS-GASSOT	95492		263
VAL-D'OISE	95	SAINT-OUEN-L'AUMONE	95572	District heating	123
VILLE DE PARIS	75	PARIS	75119		513
YVELINES	78	FLINS-SUR-SEINE	78238		139
YVELINES	78	GARGENVILLE	78267	Cementery	311
YVELINES	78	LIMAY	78335		144
YVELINES	78	MAISONS-LAFFITTE	78358		339
YVELINES	78	PORCHEVILLE	78501	Power station	152

Table C: Main industrial CO₂ emission by cities in France

City	N°	pop	kt CO ₂	Industry
Fos-sur-Mer	13039	11,601	5,315	Steel metallurgy
Gardanne	13041	17,876	3,718	Power plant
Martigues	13056	42,678	1,127	Oil refinery
Port-de-Bouc	13077	18,801	2,023	Oil refinery
Saint-Mitre-les-Remparts	13098	5,137	1,398	Oil refinery
Bourgoin-Jallieu	38053	22,400	1,531	Cement plant
Donges	44052	6,372	2,064	Oil refinery
Saint-Etienne-de-Montluc	44158	5,750	5,253	Power plant
Pont-à-Mousson	54431	14,642	3,010	Power plant
Florange	57221	11,304	3,166	Steel metallurgy
L Hopital	57336	6,398	4,482	Power plant
Woippy	57751	14,311	1,505	Power plant
Coudekerque-Branche	59155	23,623	1,288	Oil refinery
Dunkerque	59183	70,335	7,011	Steel metallurgy
Orthez	64430	10,159	1,061	Natural gas field
Feyzin	69276	8,520	1,234	Oil refinery
Gonfreville-L'Orcher	76305	10,208	3,118	Oil refinery
Harfleur	76341	9,189	1,358	Oil refinery
Le Havre	76351	195,932	4,260	Power plant
Sainte-Adresse	76552	8,047	1,503	Oil refinery

**Table D: Main industrial CO₂ emission in the North region of France
(Nord - Pas-de-Calais)**

Site	XXXX	YYYY	kt CO ₂	Source
Aniche	665579.83	2600841.52	145	Glass or brick factory
Arques	597566.66	2636963.31	173	Glass factory
Blendecques	595297.05	2635457.99	123	Paper factory
Bouchain	669712.72	2589445.01	115	Power plant
Boulogne	548479.19	2632730.85	349	Steel plant
Boussois	721624.01	2588874.67	322	
Calais	570351.5	2661842.51	104	
Corbehem	651243.05	2593612.68	451	Sugar factory
Dannes	548953.72	2620753.74	347	Cement factory
Drocourt	642012.15	2597828.58	1850	Cokery
Dunkerque	594574.14	2669785.75	1496	Refinery
Dunkerque 1	599685.57	2673047.24	2940	Power plant
Dunkerque 2	599785.57	2673147.24	623	Steel plant
Dunkerque 3	599885.57	2673247.24	140	
Grande Synthe	596329.42	2671947.19	5910	Cokery
Haubourdin	646959.89	2625911.22	108	Waste incineration
Hornaing	672203.58	2597649.51	477	Power plant
Lestrem	624319.01	2626770.67	282	Waste incineration
Lillers	610966.35	2618264.14	135	Sugar factory
Loon-Plage 1	594282.98	2671399.86	750	Steel plant
Loon-Plage 2	594382.98	2671499.86	280	Non ferrous metallurgy
Loon-Plage 3	594482.98	2671599.86	189	
Lumbres	584244.45	2633840.47	469	Cement factory
Madeleine	652189.54	2629021.31	205	District heating
Pont-sur-Sambre	709414.35	2582629.34	478	Power plant
Rety	558826.04	2646922.78	351	
Waziers	654373.12	2600061.94	257	ammoniac plant

Table E: Main industrial CO₂ emission in the Ile-de-France region - France

Site	XXXX	YYYY	kt CO ₂	Source
Vitry-sur-Seine	606000	2421200	807	Power plant
Grandpuits	645000	2399000	640	Refinery
Vaires-sur-Marne	623000	2430250	593	Power plant
Grandpuits	645000	2399000	487	Chemical factory
Ivry-sur-Seine	603700	2424800	470	Waste incineration
Orly	602000	2414000	353	airport
Saint-Ouen	600000	2434000	344	Waste incineration
Saint-Ouen	600000	2434000	313	
Plessis-Gassot	607000	2448000	263	
Saint-Ouen	600000	2434000	246	
Roissy-en -France	614000	2446000	507	Airport
Champagné-sur-Oise	594000	2459300	494	Power plant
Cormeilles-en-Parisis	590800	2440600	383	Mineral Industry
Montereau	644500	2376500	379	Power plant
Maisons-Lafitte	586000	2439000	339	Waste incineration
Claye-Souilly	625200	2438000	338	
Gargenville	562500	2442200	311	
Issy-les-Moulineaux	596000	2424500	209	
Porcheville	558000	2441000	152	Power plant
Limay	556000	2444000	144	District Heating
Flins-sur-Seine	564500	2441800	139	
Saint-Ouen-l'Aumône	583000	2449200	123	
Bray-sur-Seine	666000	2380000	105	
Paris Vaugirard	597500	2425500	125.5	
Paris Grenelle	596500	2427500	127.5	
Paris La Villette	603000	2432500	132.5	
Paris Bercy	604000	2425500	125.5	

Table F: Injection point in the Paris basin aquifers - France

Oil_field	Reservoir	XXXX	YYYY	top reserv	Initial pressure	Initial deep press	Max. thickness	Net thickness	product_a rea	porosity	CO ₂ Reserv dens	CO ₂ _stor_ca pac
Chailly, Brie, Chartrettes Coulommès Marolles en Hurepoix Valence en Brie Villemer Chailly, Brie, Chartrettes Chaunoy Donnemarie St Germain Villemer	Middle Jurassic	658573	2421646	1582	72	171	15	5	23000000	0.15	0.7	12100000
	Middle Jurassic	643577	2432817	1677	75	0	35	35	15000000	0.15	0.7	53100000
	Middle Jurassic	597286	2396400	1378	65	149.3	5	3.5	500000	0.09	0.7	110000
	Middle Jurassic	640694	2382619	1629	73	173.6	25	3.8	1500000	0.08	0.7	319000
	Middle Jurassic	636109	2367326	1435	72	156.9	20	13	12000000	0.14	0.7	15300000
	Upper Triassic	658573	2421646	2136	94	214	60	4	5000000	0.15	0.7	2100000
	Upper Triassic	637000	2384000	2147	100	235	58	25	53000000	0.13	0.7	121000000
	Upper Triassic	657807	2386203	2538	115	265	37	15	10000000	0.11	0.7	11600000
	Upper Triassic	627033	2398177	2145	99	237	67	28	8400000	0.145	0.7	23900000
	Upper Triassic	636109	2367326	2054	88	225	0	2.5	2600000	0.147	0.7	643000
Oil_field	Product Oil 1991	Statement 1991		oil_den sity	Oil factor BO	oil_volume	undergr_oil_vol	CO ₂ _stora _capa				
Chailly, Brie, Chartrettes Coulommès Marolles en Hurepoix Valence en Brie Villemer Chailly, Brie, Chartrettes Chaunoy Donnemarie St Germain Villemer	1680000	closed for economic reason		0.848	1.02	1980000	2020000	1410000				
	1840000	in production		0.86	1.082	2140000	2310000	1620000				
	92000	close in 1986		0.864	1.007	106000	107000	75100				
	103000	in production		0.855	1.039	120000	125000	87600				
	654000	concession		0.868	1.052	753000	793000	555000				
	13000	in production		0	0	0	0	0				
	4370000	in production		0.8399	1.085	5200000	5640000	3950000				
	336000	in production		0.8429	1.16	399000	462000	324000				
	341000	in production		0.85	1.131	401000	453000	317000				
	0	concession		0	0	0	0	0				

Table G: Injection point in the Dogger aquifer - France

Name	Height m	Depth m	Well Radiu s mm	Permeabilit y D	Porosity %	Res Press bars	Res Temp °C	Open	X Lambert	Y Lambert	Z m	ID	Transmissivity Kh	Salinity g/l
ACHERES2	30	-1314	159.4	1.13	0	150.15	60	N	579711.36	2440181.27	23	GACH2	34	0
ALFORTVILLE1	9.4	-1592	215.9	5.6	16.1	0	75.2	Y	606701.39	2419894.7	35	GAL1	52.8	19.4
AULNAY-SOUS-BOIS2	24.1	-1625	159.4	1.51	11.6	181.64	71.5	N	612007.7	2436497.81	56	GAY2	36.4	26.6
AULNAY-SOUS-BOIS4	22.5	-1618	159.4	2.98	20	180.69	70.3	N	612830.64	2439513.69	56	GAY4	67	25.5
BEAUVAIS2	19.2	-1073	159.4	1.26	19	124.81	46.9	N	580548.97	2494138.65	67	GBVS2	24.2	23.8
BONDY1	16.9	-1651	159.4	3.09	17.6	0	65.4	N	611228.18	2435416.07	49	GBO1	52	0
BONNEUIL-SUR-MARNE2	27	-1632	215.9	2.67	20.3	0	79.7	Y	610845.53	2418849.61	35	GBL2	72	24.4
CACHAN-NORD1	7.4	-1438.4	159.4	2.51	14.8	162.69	64.5	Y	599491.32	2421169.26	44	GCDN1	18.5	16.4
CACHAN-NORD2	16.8	-1528	215.9	1.19	14.3	172.32	69.5	Y	599492.24	2421159.18	44	GCDN2	20	16.5
CERGY-PONTOISE2	19.5	-1291	159.4	0.5	20.9	148.51	57	N	577599.31	2449239.2	97	GCY2	9.7	14.8
CHAMPIGNY-SUR-MARNE2	25.9	-1550	215.9	2.24	16.1	173.47	73.9	Y	616653.53	2422427.78	103	GCHM2	58	25.6
CHATENAY-MALABRY1	18.3	-1470	159.4	0.51	0	163.9	67	N	594106.99	2418749.82	160	GCTM1	9.4	0
CHELLES2	19.4	-1655	215.9	1.65	19.9	185.53	70.8	Y	619061.39	2430064.97	40	GCHE2	32	0
CHEVILLY-LARUE1	13.1	-1554	215.9	0.99	10	172.41	75.4	Y	602193.16	2419087.11	93	GCHL1	13	18.2
CLICHY-SOUS-BOIS2	14.8	-1652	159.4	2.29	14.9	184.24	70.4	Y	615334.74	2434990.56	90	GCL2	34	19.4
COULOMMIERS2	14.1	-1842	159.4	3.84	15	211.13	85.2	Y	655941.34	2425246.83	135	GCO2	54.3	30.4
CREIL1	0	-1425	159.4	0	16	165.2	59	N	612202.35	2474053.25	86	GCR1	45.8	26.7
CREIL2	0	-1451	159.4	0	17	167.76	59	N	611994.87	2471935.47	86	GCR2	26.4	27.6
CREIL-LE-PLATEAU2	11.5	-1466	159.4	1.39	18	0	60.4	N	608667.37	2471808.42	31	GCR6	16	28.2
CRETEIL-MONT-MESLY2	23.6	-1621.8	215.9	1.4	15.8	179.85	77.9	N	609419.85	2419217.83	41	GCRT2	33	23
EPERNAY2	9.4	-1378.1	159.4	0.63	13	162.5	60	N	719801.58	2449271.4	173.9	GEPE2	5.9	9.4
EPINAY-SOUS-SENART1	17	-1592.2	215.9	3.15	0	176.05	74.9	Y	613155.9	2410825.54	42	GESE1	53.6	14.9
EVRY2	19.2	-1492	159.4	0.38	14.1	167.8	70.9	N	604510.75	2402892.77	80	GEV2	7.3	12.3
FONTAINEBLEAU2	9.8	-1645	159.4	0.58	10.5	185.54	73.2	N	626662.02	2378439.49	80	GFO2	5.7	7.3
FRESNES1	8.8	-1536.6	215.9	1.21	12.5	0	71.7	Y	599608.64	2417510.78	82.6	GFR1	10.6	13.6
GARGES-LES-GONESSE1	15.7	-1577	159.4	5.25	16.6	176.29	67.7	N	605051.51	2442133.04	60	GGAR1	82.7	29.1
IVRY-SUR-SEINE1	11	-1456	159.4	3.04	15	162.58	65	N	605127.92	2424087.75	32	GIV1	33.5	0
LA-CELLE-SAINT-CLOUD2	30.3	-1266.7	159.4	0.44	12.7	144.01	60.6	N	583744.6	2427549.52	163	GLC2	13.4	0
LA-COURNEUVE-NORD1	27.5	-1616	159.4	1.02	15.4	180.19	56.6	Y	604804.16	2436888.44	35	GLCN1	28	22.8
LA-COURNEUVE-SUD2	24.5	-1612	159.4	1.36	14.6	179.92	57.9	Y	603478.61	2436618.91	35	GLCS2	33.3	23.4
LA-PORTE-SAINT-CLOUD1	22.7	-1408	159.4	1.52	15.8	158.5	61.2	N	594797.03	2426609.27	25	GPSC1	34.5	0
LA-VILLETTE1	16.6	-1587	159.4	1.48	15.6	177.64	57.3	N	604102.55	2433017.94	52	GLAV1	24.5	17.9

Name	Height m	Depth m	Well Radius s mm	Permeabilit y D	Porosity %	Res Press bars	Res Temp °C	Open	X Lambert	Y Lambert	Z m	ID	Transmissivit y Kh	Salinity g/l
LE-BLANC-MESNIL2	17.6	-1619	159.4	4.26	17	180.32	65.6	N	608701.86	2439161.85	47.5	GBMN2	75	28.1
LE-MEE-SUR-SEINE2	23	-1618	159.4	2.2	13.7	0	72.2	Y	620824.01	2394281.54	75.6	GLMS2	50.7	0
L'HAY-LES-ROSES1	5.6	-1526	215.9	3.28	14.4	0	73.2	Y	600555.31	2419315.22	88	GHLR1	18.3	14.9
MAISONS-ALFORT-12	22.1	-1486.7	215.9	2.64	0	167.61	69	Y	607630.08	2422588.87	42.5	GMAS2	58.3	22
MAISONS-ALFORT-22	9.2	-1584	215.9	2.4	16.1	0	72.6	Y	607125.75	2421000.96	32	GMA4	22.2	0
MEAUX-BEAUVAL-12	26.5	-1726	159.4	3	15	194.41	78	Y	643210.95	2439470.38	60	GMX6	79.4	33
MEAUX-BEAUVAL-21	18.6	-1727	159.4	3.59	16	192.77	78	Y	642782.47	2439003.17	55	GMX7	66.6	35
MEAUX-COLLINET2	20	-1718	159.4	3.53	18.5	192.45	77.7	Y	641477.2	2438034.85	50	GMX2	70.5	0
MEAUX-HOPITAL2	30.2	-1710	159.4	1.36	17.5	192.33	75.6	Y	640677.75	2441287.31	46	GMX4	41	0
MELUN-L'ALMONT1	0	-1628.7	159.4	0	0	184.09	71.5	Y	625423.32	2393582.1	77.5	GMEL1	37.5	15.7
MONTGERON1	24	-1564	159.4	1.14	16.9	0	72.5	Y	607863.57	2411081.14	50	GMO1	27.5	0
ORLY-11	8.7	-1586	159.4	6.86	14.1	174.97	76	Y	606037.93	2416843.88	40	GOR1	60	0
ORLY-22	9.8	-1584	215.9	2.27	13.5	0	76	Y	605137.55	2415918.52	47	GOR4	22.2	15.3
RIS-ORANGIS1	14.4	-1513.5	159.4	1.43	15	169.04	71.9	Y	604749.97	2404968.62	80	GRO1	20.6	0
SEVRAN2	14.7	-1640.5	159.4	1.45	14	183.98	70.7	N	613023.46	2436932.94	52.5	GSA2	21.4	23
SUCY-EN-BRIE2	23	-1643	215.9	4.82	14.6	181.32	78.1	Y	613607.06	2419279.58	89	GSUC2	110.8	0
THIAIS2	8.7	-1579	215.9	3	13	0	76.6	Y	604112.17	2417679.42	59	GTHI2	26.2	17
TREMBLAY-LES-GONESSE2	18.9	-1646	159.4	3.07	15.1	182.93	74.2	Y	617512.55	2438793.74	63.4	GTRE2	58	25.7
VAUX-LE-PENIL1	19	-1615	159.4	2.89	0	0	71.9	N	626258.4	2392686.65	80	GVLP1	55	0
VIGNEUX-SUR-SEINE2	7	-1573	215.9	3.44	12.3	173.63	73.5	Y	605672.23	2412338.86	34	GVS2	24.2	13.7
VILLENEUVE-LA-GARENNE1	12.1	-1602.5	159.4	0.55	10.6	178.49	57.5	N	599024.46	2427872.03	29	GVG1	6.7	246
VILLENEUVE-SAINT-GEORGE2	19.2	-1589.6	215.9	3.74	15.2	175.46	76.5	Y	608735.54	2415993.45	34	GVSG2	71.6	17
VILLIERS-LE-BEL-GONESSE2	16.7	-1503.7	215.9	2.57	17.3	170.36	69	Y	605979.28	2445311.14	80	GVLB2	43	27.4

Table H: Triassic Reservoir – Paris basin – France

NAME	ID	XXXX	YYYY	TOP TRIAS	BASE TRIAS	TOP TRIAS	BASE TRIAS	TOP TRIAS	BASE TRIAS	RESERV THICK	EFFIC THICKNESS	PRESS bar	POROSITY %	K mD	TRANSMISS Dm	T °C
Sennely 2	SEY2	588318	2300129	-1182	-1240	-1240	-1318	-1318	-1318	237	0	153				70
Courgivault	CG1	683325	2412341	-2575	-2541	-2722	-2694	-2998	-2961	0	99	250	5.2			111
Brié	BrI19	624987.05	2388040.36	-2123	0	0	0	0	0	0	45	0	9		0.4	96
Tousson	TSN101	607699.82	2373351	-2095	-2325	0	0	0	0	222	128	248	10		0.6	90
Mantes 101		550996.81	2444551	-1320	0	0	0	0	0	27	13	144.5	23		40	49
Arsy	ArY 1	623890.06	2489505.88	-1714	-1812	0	0	0	0	200	0	190	<4%	très faible		72
Achères	AC1	580608.31	2439575	-1906	-1955	0	0	0	0	49	0	0			0.13	72
Coulommès	BH2	646019.34	2435516.77	-2597	-2740	0	0	0	0	190	0	325				100
Feigneux 1		641769	2473323	0	0	0	0	-2220	-2340	121	-57	242	11	300	96	80
Villemer	VM101	632314	2366569	0	0	0	0	0	0	0	20	225	20	1 à 20		88
Saint Germain	SGA1	627985	2397668	-2143	-2342	0	0	0	0	200	67	237	21	20		99
Donnemarie	DOE1	657699	2387715	-2538	0	0	0	0	0	37	15	265	11 à 19	180		115
Chaunoy	CHY1	634432	2396696	-2167	-2232	-2290	-2313	0	0	146	85	235	13	130		100
Chailly	CHY1	622037	2386480	-2136	0	0	0	0	0	60	4	214	15	30		94
Cergy	GCY1	578419.84	2449813.76	-1940	-1973	0	0	0	0	33	22	193	14		3,3-8,9	77
Melleray	GMV1	573796.36	2621160.96	-1436	-1618	0	0	0	0	182	36	143	15	430	15.47	74
Pannes	PAS1	622799.89	2335877.84	-2005	-2112	-2193	-2264	-2303	-2547	0	178	240	0,5-6	2300 à 2600		90

Table I: Dogger Reservoir – Paris basin – France

NAME	ID	XXXX	YYYY	TOP DOGGER	BASE DOGGER	RESERV THICK	EFFIC THICKNESS	PRESS Kg/cm ²	POROSITY %	K mD	TRANSMISS Dm	T °C
Chailly,...	CHY1	622037	2386480	-1582	0	15	5	171	0			0
Coulommès	BH2	646019.34	2435516.77	-1677	-1911	234	0	175	15	0.5 à 19		75
Marolles en Hurepoix		596365	2396256	-1378	-1591	213	3.5	149.3	0	100	3	68
Valence en Brie	VL103	641475	2382635	-1629	0	0	3.8	173.6	0			0
Villmer	VM101	632314	2366569	-1435	0	0	13	156.9	0		0.5	70
Saint-Martin de Bossenay	SMB1	699370	2382220	-1261	-1765	65	0	145	15		0.1	66.5
Mantes 101		550996.81	2444551	-914	-1119	103	0	110	12	1 à 1280	0.3 à 5	56
Pannes	PAS1	622799.89	2335877.84	-1385	-1613	228	0	158	8	0.6 à 2.5	1	59
Montvilliers	MVIL-1	587163	2350141.6	-1454	-1667	27	0	160	0	<0.1	0	60
Tousson 101	TSN101	607699.82	2373351	-1559	-1795	236	106	200	8.5	<0.1		0
Sennely 2	SEY2	588318	2300129	-916.9	-1032	116	0	106	11	<10		55
Achères	AC1	580608	2439575	-1324	-1471	147	0	145	0		2	58.5

Table J: Current gas and underground storage infrastructures – France

Name	Term_Type
BREAL	COMPRESSION STATION
NOZAY	COMPRESSION STATION
MONT	COMPRESSION STATION
MAZEROLLES	COMPRESSION STATION
BRIZAMBOURG	COMPRESSION STATION
CAPTIEUX	COMPRESSION STATION
AUVERS-LE-H.	COMPRESSION STATION
AUROS	COMPRESSION STATION
LAPRADE	COMPRESSION STATION
CHAZELLES	COMPRESSION STATION
MARAIS-VERNIER	COMPRESSION STATION
CHERRE	COMPRESSION STATION
SAINT-ARNOULT-DES-BOIS	COMPRESSION STATION
MONTAUBAN	COMPRESSION STATION
ROQUES	COMPRESSION STATION
ROUSSINES	COMPRESSION STATION
CHATEAUROUX-SAINT-MAUR	COMPRESSION STATION
MERY-S/C	COMPRESSION STATION
PITGAM	COMPRESSION STATION
BARBAIRA	COMPRESSION STATION
SAINT-VICTOR	COMPRESSION STATION
EVRY-GREGY	COMPRESSION STATION
CHATEAU-LONDON	COMPRESSION STATION
AVION	COMPRESSION STATION
ARLEUX-EN-G.	COMPRESSION STATION
TAISNIERES	COMPRESSION STATION
DIERREY-SAINT-JULIEN	COMPRESSION STATION
VINDECY	COMPRESSION STATION
LA BECUDE-DE-MAZENC	COMPRESSION STATION
PALLEAU	COMPRESSION STATION
COURTHEZON	COMPRESSION STATION
SAINT-MARTIN-DE-C.	COMPRESSION STATION
VOISINES	COMPRESSION STATION
BREHEVILLE	COMPRESSION STATION
MORELMAISON	COMPRESSION STATION
ENTRE-DEUX-GUIERS	COMPRESSION STATION
BALDENHEIM	COMPRESSION STATION
LUSSAGNET	UNDERGROUND STORAGE
IZAUTE	UNDERGROUND STORAGE
CERE-LA-RONDE	UNDERGROUND STORAGE
CHEMERY	UNDERGROUND STORAGE
SOINGS-EN-S.	UNDERGROUND STORAGE
SAINT-ILLIERS	UNDERGROUND STORAGE
SAINT-CLAIR-SUR-EPTE	UNDERGROUND STORAGE
BEYNES	UNDERGROUND STORAGE
GOURNAY-SUR-ARONDE	UNDERGROUND STORAGE
GERMIGNY-SOUS-COULOMBS	UNDERGROUND STORAGE
TERSANNE	UNDERGROUND STORAGE
ETREZ	UNDERGROUND STORAGE
MANOSQUE	UNDERGROUND STORAGE
CERVILLE	UNDERGROUND STORAGE
TROIS-FONTAINES	UNDERGROUND STORAGE PROJECT
MONTOIR-DE-B.	LIQUIFIED NATURAL GAS TERMINAL
FOS-SUR-MER	LIQUIFIED NATURAL GAS TERMINAL
	NATURAL GAS FIELD
	NATURAL GAS FIELD
	NATURAL GAS FIELD
	NATURAL GAS FIELD
	NATURAL GAS FIELD
	NATURAL GAS FIELD
	NATURAL GAS FIELD

