review article

Petroleum exploration and production in France

Charles Lamiraux[1] and Alain Mascle[2]

Introduction

Exploration for and production of hydrocarbons in France are concentrated in two major onshore sedimentary basins of Mesozoic age (Mascle *et al.* 1994; with numerous references; Fig. 1). These two basins, the Aquitaine and the Paris Basins, have been intensively explored for the past 40 years and contain a significant amount of hydrocarbons. They still account for 3% of oil (42 500 bopd) and 9% of gas (281 MMcfpd) for French domestic needs (Fig. 2). This national production represents an annual value of about 4 billion French Francs. A third onshore major basin exists, the South-East Basin, where the first phase of exploration from the 1950s to the 1970s was disappointing. A smaller sedimentary basin is present at the eastern edge of the Paris Basin, the Rhine Graben of Tertiary age, which was intensively explored and is still producing a small amount of oil.

Major sedimentary basins are also present in the offshore area. Whereas two of them, the Gulf of Lions and the Western Approaches basins are almost totally marine, the other two (Bay of Biscay and Channel basins) are the offshore extensions of the nearby onshore area. The first results of exploration in both cases have been unsuccessful, but only a limited number of wells have been drilled. The French overseas territories (French West Indies, New Caledonia, French Guiana, Saint-Pierre et Miquelon) are excluded from the present discussion.

Aquitaine Basin

The Aquitaine Basin (Fig. 3) is a composite area that developed since the Triassic on a heterogeneous Palaeozoic basement, which is generally interpreted as a segment of the southern branch of the Variscan orogeny of Palaeozoic age. Late Carboniferous and Permian troughs up to a few thousand metres thick have developed locally as a result of post-Variscan stress release (Fig. 4). In Mesozoic times, a major hinge line (the 'Celtaquitaine flexure') running from Arcachon in the NW, to Toulouse in the SE (Fig. 1), separated a stable and relatively less subsiding platform to the north-east from more rapidly subsiding basins and intervening highs to the south-west. This latter area is subdivided into two distinct domains (Espitalié & Drouet 1992):

- in the south, the northern edge of the Pyrenees thrust belt and its moderately folded foreland that developed from late Cretaceous to late Eocene times;
- to the west, the Parentis Basin, a rapidly subsiding trough related to the opening of the Bay of Biscay in late Jurassic and early Cretaceous times.

The northern Pyrenees and their foreland

The western half of the French northern Pyrenees and their immediate foreland is the most prolific gas-bearing province in France (Fig. 1) (Le Vot *et al.* 1996). After the initial discovery of Saint-Marcet in 1939, two major gas fields were subsequently discovered in deep and structurally complex traps. The Lacq field, discovered in 1951, has produced about 8.1 tcf since 1957, and is still producing 260 MMcfpd. The Meillon field, discovered in 1966, has produced about 1.9 tcf since 1968, and is still producing 80 MMcfpd. The producing intervals are late Jurassic and Neocomian dolostones, the source-rocks are marine Kimmeridgian marls and limestones. Initial porosities are very low, but highly fractured zones greatly enhance the production. In the same area, six other fields are also currently producing from the same stratigraphic intervals, but also from younger Senonian or older Liassic levels (Fig. 3).

Parentis Basin

The Parentis Basin developed as a rapidly subsiding E-W trending trough as early as Kimmeridgian and until Albian times (Bois & Gariel 1994). Almost 10 000 m of sediment accumulated during this time in the main depocentre, which is located in the offshore area to the west. The basin was subjected to two main compressive events in late Aptian and middle–late Eocene times. These phases created broad anticlinal traps that developed above a detachment surface underlain by middle and late Triassic strata. The Parentis Basin is a major oil producing province, with accumulations in carbonate reservoirs of late Jurassic to Neocomian age (Parentis field), or in Purbeckian and Albian sandstones (Cazaux, Les Arbousiers fields). The source rocks are marine marls and limestones of Kimmeridgian age (Fig. 3). Parentis, discovered in 1954, is the largest field. By the end of 1996 the total production was 211 MMb and the field was still producing about 2750 bopd. Since 1991, three new accumulations have been discovered by Essorep, a subsidiary of

[1]Ministère de l'Economie, des Finances et de l'Industrie, Secrétariat d'Etat à l'Industrie, 120 rue du Cherche-Midi, 75353 Paris 07SP, France, [2]Corresponding author: IFP School, 92852 Rueil Malmaison cedex, France (E-mail: alain.mascle@ifp.fr)

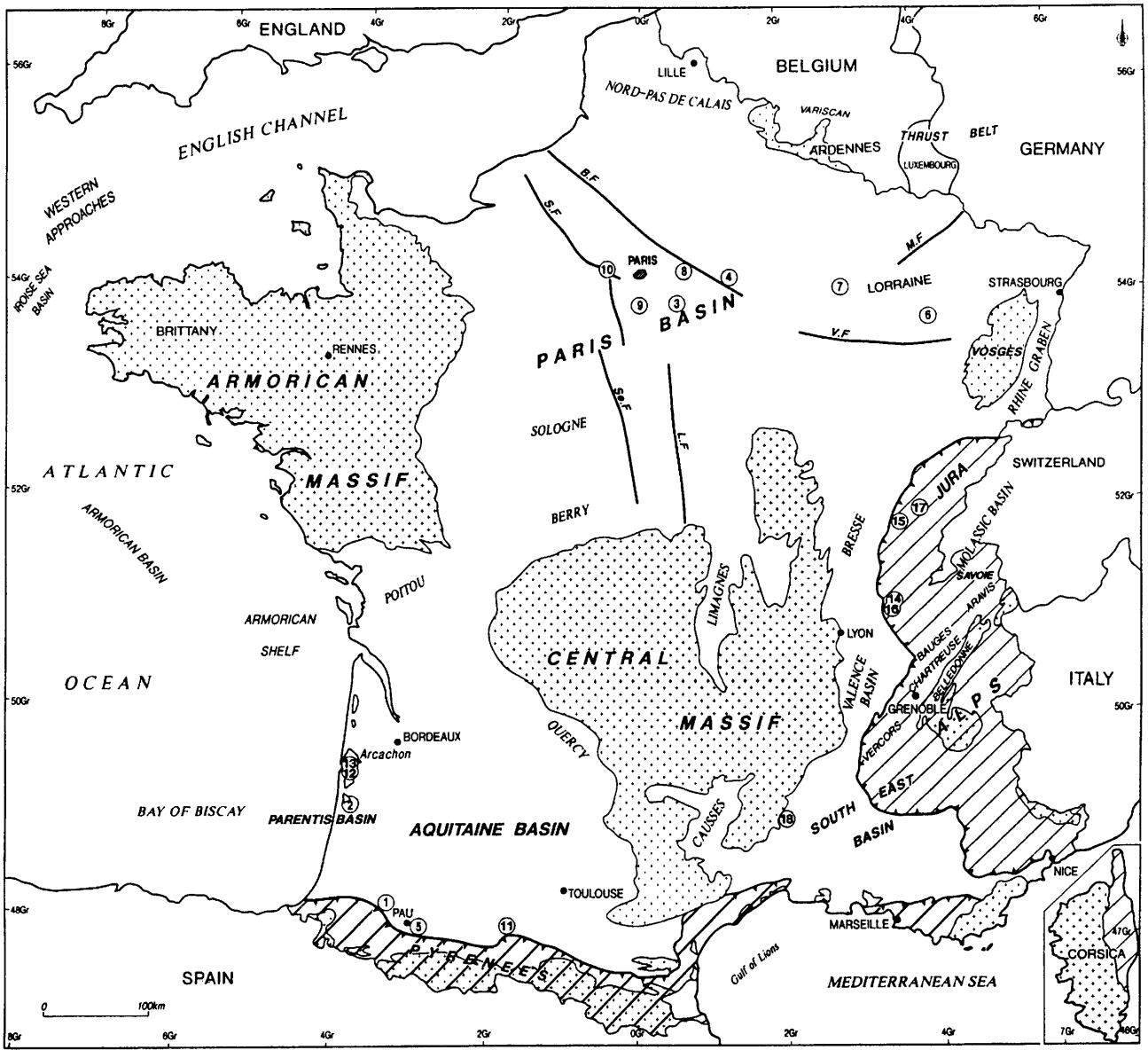
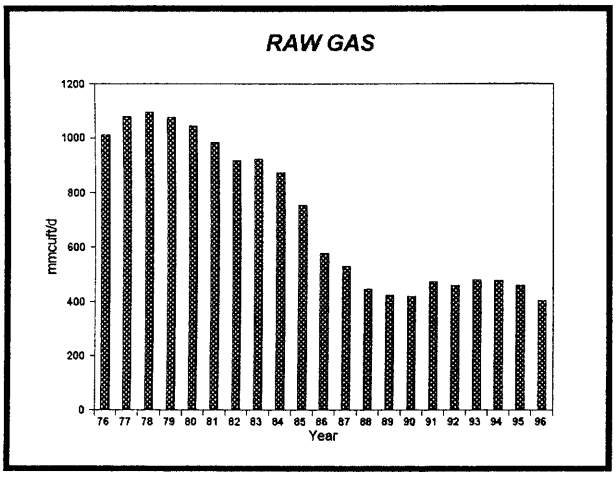


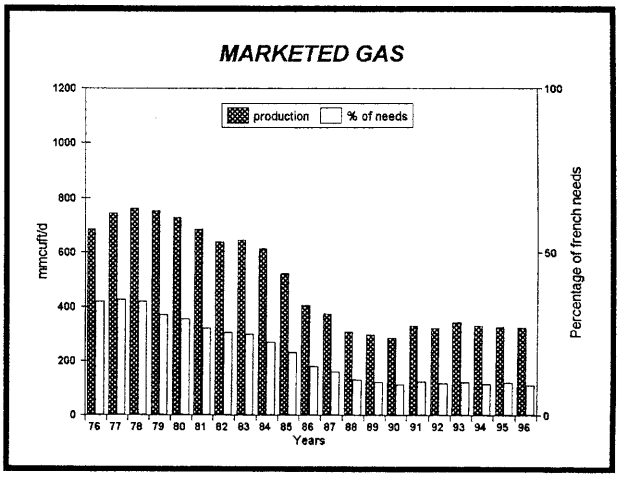
Figure 1 Map of France with the location of the main geographical and geological features (from Mascle *et al*. 1994). B.F., Bray Fault; S.F., Seine Fault; L.F., Loire Fault; V.F., Vittel Fault; M.F., Metz Fault.; 1, Lacq; 2, Parentis; 3, Chaunoy; 4, Villeperdue; 5, Meillon; 6, Forcelles; 7, Trois-Fontaines; 8, Coulommes; 9, Itteville; 10, L'Orme; 11, Saint Marcet; 12, Cazeaux; 13, Courbey; Les Arbousiers and Les Pins; 14, Challeyriat and La Chandelière; 15, Lons le Saulnier; 16, Vaux-en-Bugey; 17, Vallempoulières; 18, Alès Basin; 19, Pointe de Barfleur; 20, Cros de Lagnon; 21, La Vieille Borde.

Exxon. Les Arbousiers (1991) and Les Pins (1994) fields are currently producing about 2250 bopd and 2680 bopd, respectively. The last discovery, Courbey, made in April 1996 in the same area is reportedly comparable in size to the two other fields. The initial production was about 1700 bopd. The other fields (Cazaux, Lugos, Mothes, Lucats) are together producing about 3700 bopd.

Paris Basin

The Paris Basin is a Mesozoic and Tertiary intracratonic basin superimposed on Carboniferous and Permian troughs, and on a Palaeozoic basement which is generally interpreted as the northern branch of the Variscan thrust belt. The more or less circular shape of the Mesozoic outcrops is related to the presence of successive depocentres, often being located just east of Paris, and thinning towards the presently defined basin margins (Perrodon & Zabeck 1991). This shape also results from the uplifts in Tertiary times of the Armorican, Central, Vosges and Ardennes massifs on the western, southern, eastern, and north-eastern borders of the basin, respectively. The subsidence of the basin was controlled by the reactivation of deep major late Variscan faults or arrays of faults, trending NW–SE in the west (Seine and Bray faults for instance), N–S in





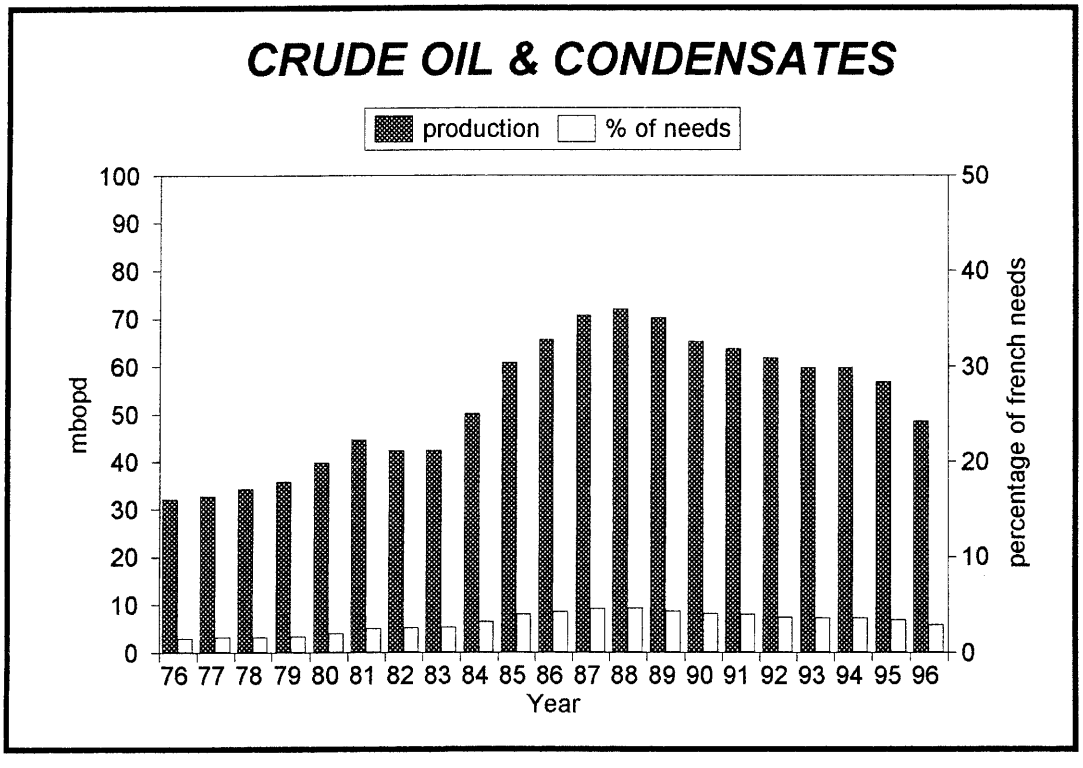


Figure 2 Gas and oil production in France.

the south (Sennely and Loire faults), and E–W to NE–SW in the east (Vittel and Metz faults) (Fig. 1). The tectonic phase that best explains the present distribution and shape of structural traps, was probably the latest Cretaceous-Eocene (Pyrenean) shortening, in conjunction with previous events. The two main hydrocarbon reservoirs encountered so far in the Paris Basin are the late Triassic Chaunoy and Donnemarie sandstones, and the late Dogger (Callovian) oolithic limestones (Figs 3 and 5; Mougenot & Layotte 1996). Smaller accumulations have been found locally in Neocomian and Rhaetian sandstones as well as, more recently, in Hettangian limestones.

The main source rocks are several intervals of marine black marls of Liassic age. The more prolific ones are undoubtedly early Toarcian 'Schistes Cartons' with up to 10% of marine organic matter. It is also believed that the slightly less organic-rich Lotharingian and early Domerian marine marls played an important role in the quantity of oil expelled because of their deeper burial with respect to the overlying Toarcian shales.

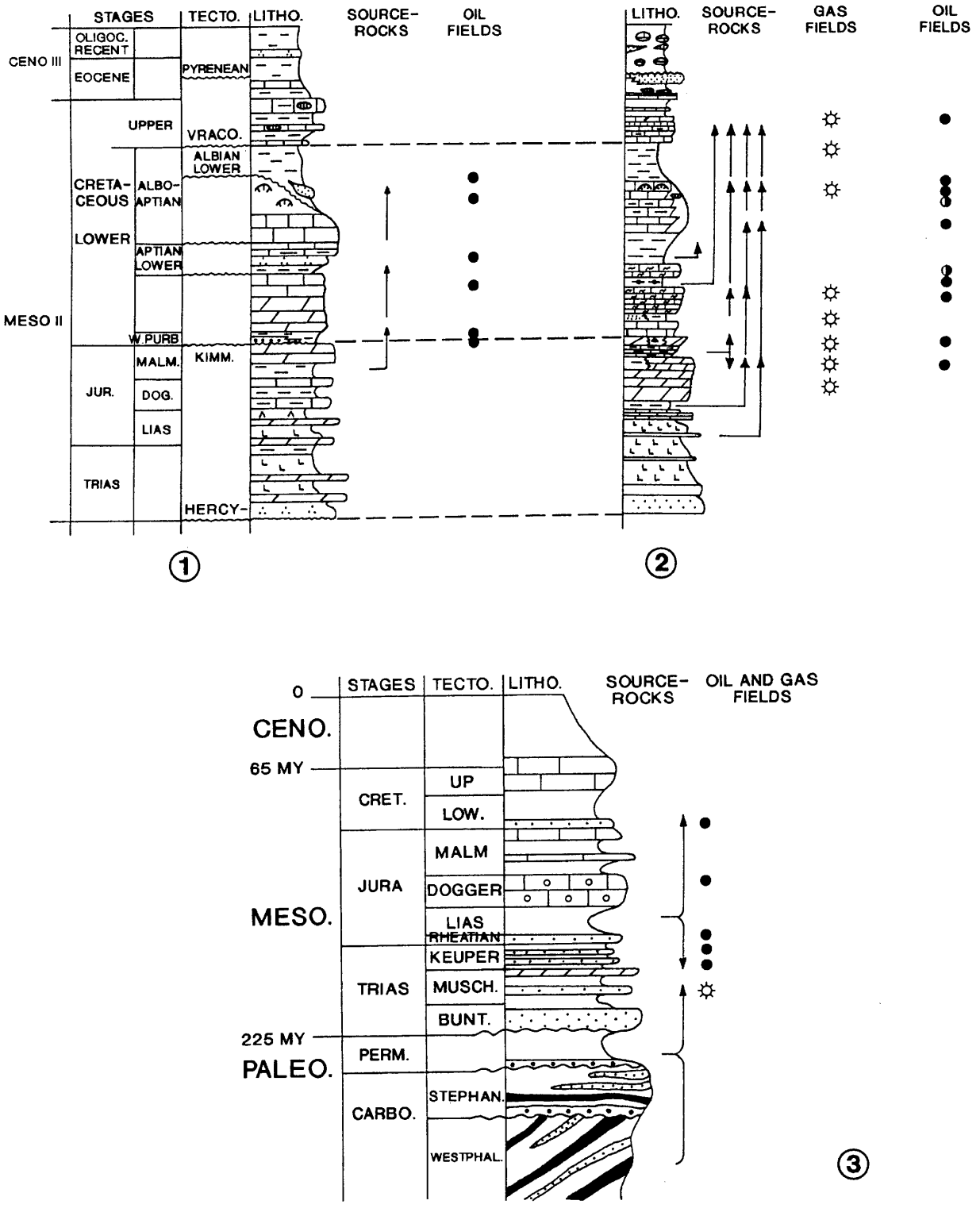


Figure 3 Distribution of main reservoir and source rock intervals. 1, Parentis Basin; 2, Northern Pyrenees; 3, Paris Basin.

In the eastern Paris Basin, there is minor production of hydrocarbons derived from coal seams of late Carboniferous age in Forcelles (oil) and Trois Fontaines (gas) fields. The coal measures belong to the Saar-Lorraine trough, the largest of the French late Carboniferous basins extending far to the north-east in Germany.

Whereas Coulommes was the first oil field to have been discovered as early as 1958, the major developments occurred in

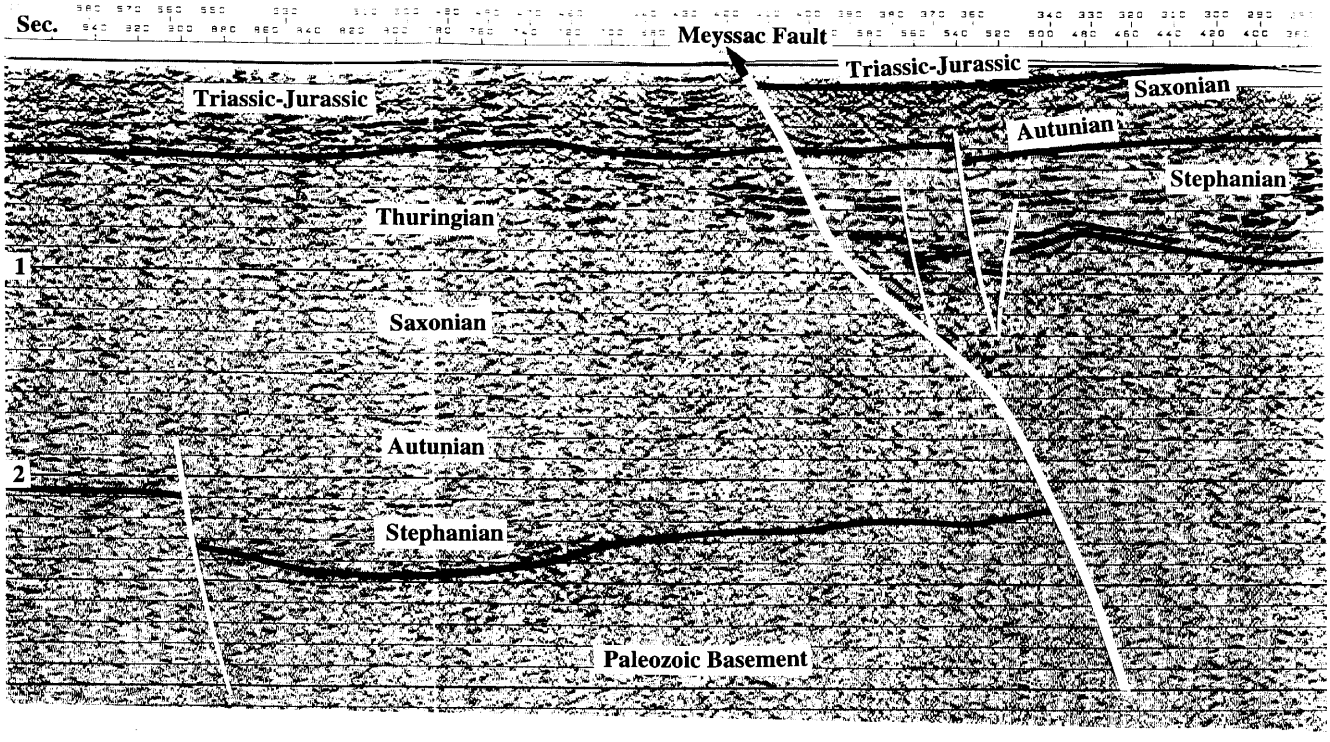


Figure 4 North-eastern edge of the Aquitaine Basin: thick Stephanian-Permian strata concealed below a thin Mesozoic cover. Only a few wells have tested such late Palaeozoic troughs, althought Stephanian–Autunian continental and lacustrine source rocks are locally well developped (from Wosjak *et al*. 1998). Seismic line shot in 1982 and recently reprocessed by IFP and the GéoFrance 3-D research project.

the 1980s with the discovery of two oil fields in the Paris Basin: Villeperdue (1982, Triton/Total) and Chaunoy (1983, Essorep) which are still producing about 3300 and 9100 bopd, respectively.

The last discovery of any significance, the Itteville field (Elf Aquitaine operator), occurred in 1990 and is currently producing 4330 bopd. The latest discovery (La Vieille Borde) was made in March 1996 by an American company, Canyon Energy, in the east of the Paris Basin. Canyon found an accumulation in the Rhaetian sandstones, with initial production about 190 bopd.

The recent oil discovery by the well l'Orme 1 (1990) located west of Paris in a new reservoir (Hettangian), offers support for the idea of long-distance migration from the oil kitchen east of Paris; consequently the western part of the Paris Basin has become a prospective area (Jacquart *et al.* 1995).

The Bresse–Jura–Savoie–Vercors–Valence Basin area

This broad area is made of four structural units that developed in Tertiary times on a Mesozoic platform, which in turn is superimposed on late Carboniferous–Permian troughs (Jacquart & Deville 1996). They are, from west to east: the Bresse and Valence Basin rift grabens of late Eocene–early Miocene age, the Jura late Miocene–Pliocene thrust belt, the Eocene–Miocene Molasse basin and the early Tertiary Bauges–Aravis Subalpine massifs. These merge to the south with the Jura thrust belt to form the Chartreuse and Vercors Subalpine massifs. The Palaeozoic basement reappears in the west as the autochthonous Massif Central, and in the east as the allochthonous Belledonne Massif.

A relatively large number of wells have already been drilled in this general area. The explored structural traps tested have, mostly, been Tertiary horsts and tilted blocks in the Bresse and Valence Basins and the basal part of similar horsts preserved below the main decollement within the late Triassic evaporites in the Jura and Molasse Basins. Complex tectonic sheets have been explored in the Bornes massif (Fig. 6). Most of the oil and gas shows encountered were in early and middle Triassic sandstones and dolomites (recent and significant oil shows have even been reported in the Chaleyriat and La Chandelière wells drilled in 1989). Two prominent source rocks intervals are present, the Autunian (Lower Permian) (types I and III) and in the Toarcian (Lower Jurassic) (type II) strata. No commercial accumulation has been found since the abandonment of the tiny gas fields in the Jura (Valempoulières, Lons-le-Saulnier, Vaux-en-Bugey) which produced from the Triassic, in spite of the large number of wells drilled. For most of the wells drilled before 1980, it is thought that the targets were badly defined because the seismic was often unable at that time to resolve the complexity of the structural traps. It is believed that the next step in evaluating the petroleum potential of these areas will be a better assessment of the relative timing of hydrocarbon generation and migration with respect to the formation of structural traps (as well as stratigraphic traps in the Tertiary basins).

The South-East Basin

The South-East Basin contains the thickest sedimentary package in France with up to 10 000 m of Mesozoic

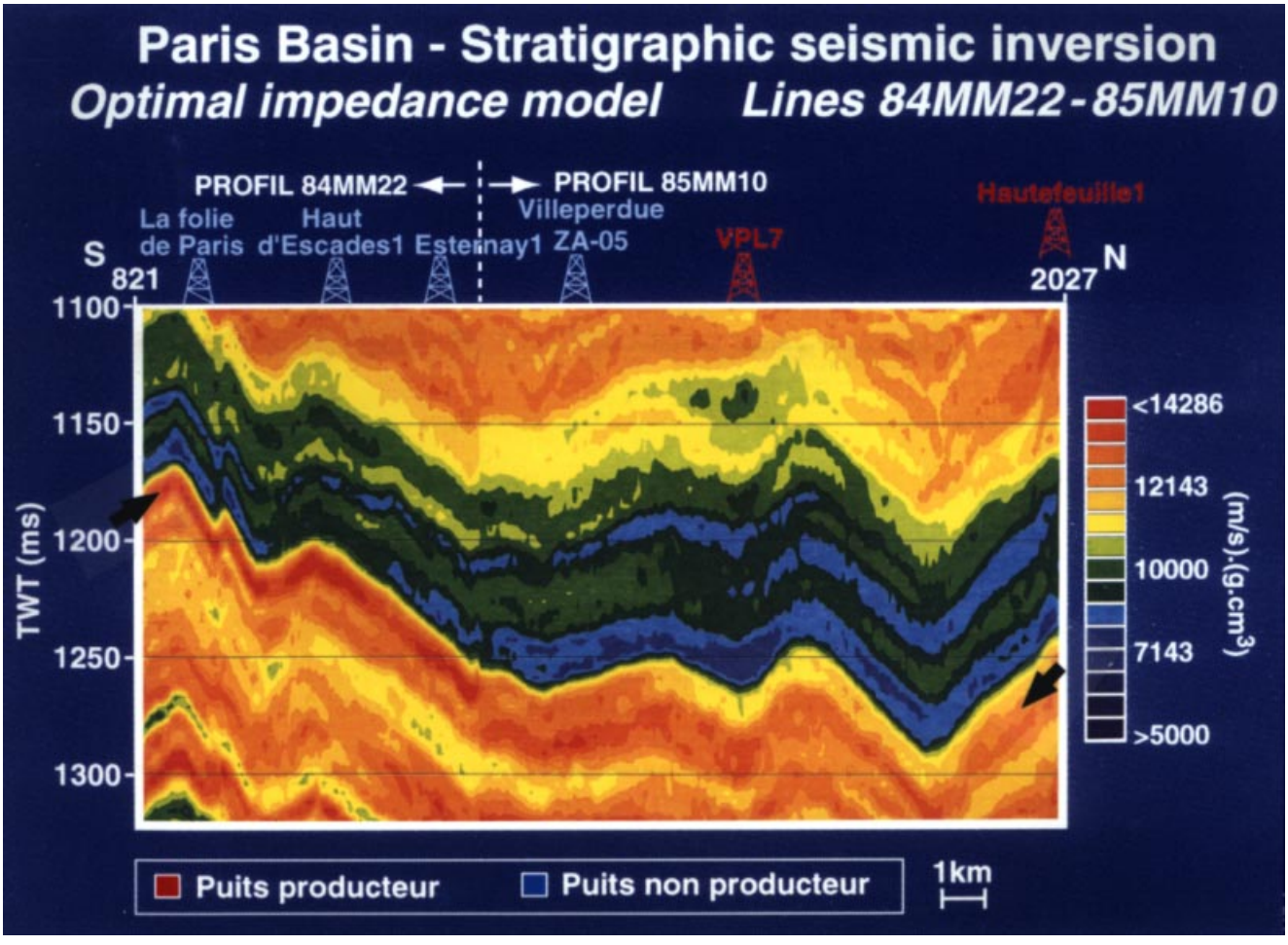


Figure 5 Paris Basin; vicinity of the Villeperdue oil field. Stratigraphic inversion (Interwell software) showing impedance variations in the Callovian calcareous reservoir interval (arrow) linked to variations in porosity (from 13 to 15% on the right (yellow–light orange) to 9–11% on the left (dark orange–red); Bessereau *et al*. (1996). The two producing wells ('puits producteurs') are in red, and the non producing wells ('puits non producteurs') are in blue.

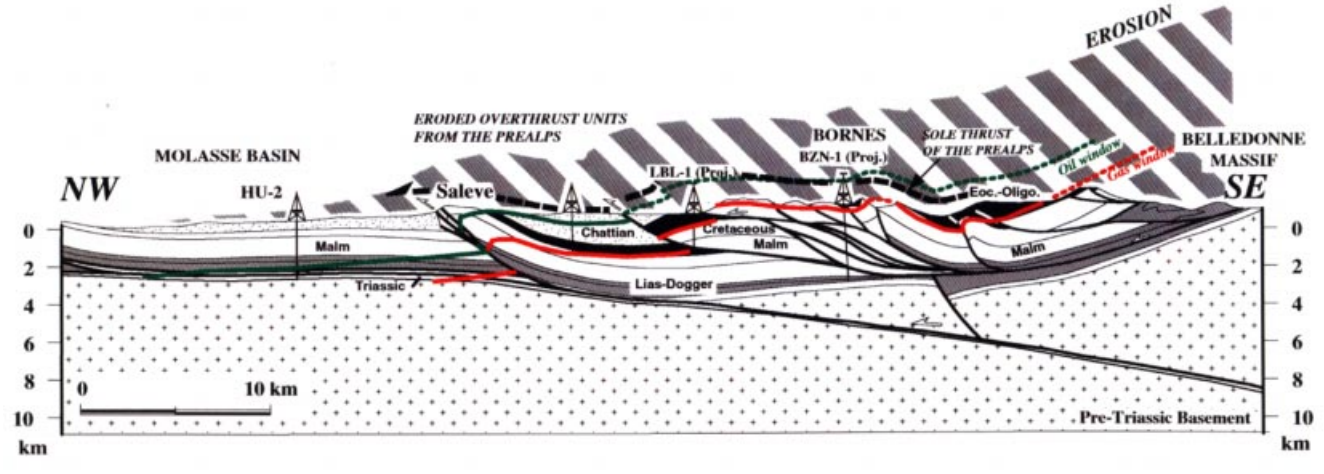


Figure 6 Section across the French Molasse Basin and External Alps (Bornes massif) showing the present location of the oil and gas windows. The main source rock interval is within the Lias (from Jacquart & Deville 1996).

sediments present locally (Mascle *et al.* 1996). Thick late Carboniferous and Permian basins are locally present below, or outcrop at the western or south-eastern edge of the basin. Several major extensional events from Permian to early Cretaceous times led to the subsidence of the deep basins and of the more stable surrounding carbonate platforms. But the present structural complexity results mainly from the superimposition, after the late Cretaceous, of the two major Pyrenean and Alpine compressive events, with an intervening extensional event in Oligocene times. Furthermore, salt diapirism (from the Keuper interval) was locally active throughout Tertiary times, but may have been initiated as early as the Bathonian. The Oligocene extension and subsequent Neogene subsidence were at the origin of rapidly subsiding troughs up to 5000 m thick.

Over the area as a whole possible plays include several intervals in the Triassic and Jurassic section with poor primary porosities but with fracturation or karstification, and Oligocene sandstones or limestones in the corresponding troughs (Deville *et al.* 1994). Mature source rocks are known to occur in at least five stratigraphic intervals: coal measures and oil shales of Stephano-Autunian age, black shales of late Liassic age, silty black shales ('Terres Noires') of Bathonian–Oxfordian age, late early Cretaceous black marls and Oligocene bituminous shales. Although numerous oil and gas shows have been found, no commercial accumulation has been encountered so far. Significant shows have been obtained at different stratigraphic intervals: oil was tested in late Permian–early Triassic sandstones and Oligocene strata, and gas was tested in Liassic dolostones.

Offshore area

Two types of continental margins may be defined in the French offshore (Lamiraux & Mascle 1995). In the south, the Mediterranean margin is of Tertiary age and is related to the opening of the Provençal oceanic basin in Miocene times, following an initial phase of rifting of Oligocene to lower Miocene (middle Aquitanian) age. The continental shelf is usually narrow, with steep slopes down to the abyssal plain. In the Gulf of Lions, however, a broad continental shelf developed in response to the clastic input from the Rhone River and Delta in Pliocene and Pleistocene times.

In the west the continental margin is of Cretaceous age and related to the accretion of oceanic floor in the Bay of Biscay from late Aptian to Campanian times, following the initiation of rifting as early as the late Jurassic. The continental shelf widens from south to north, and three segments can be distinguished:

- The southernmost segment faces the Aquitaine Basin and includes the offshore extension of the Parentis Basin;
- The central unit is located along the coasts of Poitou and Brittany and the sedimentary cover on the continental shelf is thin and of little interest. A relatively thick and unexplored sedimentary prism has, however, developed deeper on the continental slope and rise and is known as the Armorican Basin;
- The northern segment faces the Western Approaches where deep Triassic and Jurassic NE–SW trending basins developed prior to the opening of the Bay of Biscay. Further east, the Channel Basins may be regarded as the offshore prolongation of the Paris and London Basins to the south-east and north-west, respectively.

Gulf of Lions

The Gulf of Lions is a structurally complex area, as deep Oligocene–early Miocene NE–SW trending grabens are superimposed on a concealed segment of the Pyrenean thrust belt of late Cretaceous to Eocene age (Vially & Trémolières 1996). The first exploratory wells were located on the shelf and encountered a thick Neogene cover of poor reservoir and source rock quality lying directly on Palaeozoic basement highs, with occasionally a few intervals of Oligocene or Mesozoic age sediments.

Between 1982 and 1985, four additional wells were drilled, including two wells in deep water on the upper slope of the margin. All of them have been unsuccessful. The only positive results obtained so far in this Mediterranean area are from a few hundred kilometers to the south on the Ebro Delta (Spain). Four fields (Amposta, Casablanca, Montanazo and Dorada with recoverable reserves of $\approx$ 250 MMbo) are producing oil trapped on palaeo highs and in fractured and weathered carbonates sealed by a few thousand metres thickness of Neogene sediments. There is still a possibility that similar plays have remained untested in the Gulf of Lions. A recent and complete reassessment of the potential of the continental shelf of the Gulf of Lions opens the possibility of renewed exploration. A new license was granted in June 1996 to Elf Exploration-Production. It aims to explore Oligocene grabens in which synrift clastic aprons can be expected and could provide stratigraphic traps.

Bay of Biscay

The exploration of the marine western extension of the onshore Parentis Basin started as early as 1966 and had slowed down considerably by the end of 1983 after 24 unsuccessful wells had been drilled. Two significant oil shows however, have been encountered in late Barremian limestones and early to middle Jurassic limestones. The most significant was oil tested in an early Cretaceous reservoir at Antares, which was appraised by a well in 1995 and proved to be non-commercial.

Plays are probably more difficult to define than the ones already proven onshore. The distribution and quality of reservoirs is believed to change rapidly from the northern and southern edges of the basin to the much more rapidly subsiding central depocentre (Bois & Gariel 1994). The very thick late Jurassic to Albian sedimentary infill probably also resulted in the different timing of hydrocarbon generation and migration. The structure of the basin is complicated by halokinesis of Triassic salt.

To the south, the sedimentary cover is much thinner ('Seuil des Landes') and also to the north (Armorican shelf) where more risky late Palaeozoic plays could still be defined.

It should be remembered that, at the southern edge of the Bay of Biscay and in Spanish waters, the small and structurally complex (as part of the Pyrenean thrust belt) Gaviota gas field is producing from a late Cretaceous carbonate reservoir with source rocks of possibly late Carboniferous age.

Western Approaches

The French side of the Western Approaches is better known as the Iroise Sea Basin. The first stage of exploration was completed in the mid 1980s with the drilling of 13 wells but without any significant result except for minor oil and gas shows in Purbeckian and Liassic to Dogger intervals in two wells (Deronzier *et al.* 1994). However, at the same time, the partly onshore Wytch Farm oil field was discovered in southern England, with production expected to reach about 100 000 bopd at the beginning of 1996. At the same time, the Kinsale Head and Ballycotton gas fields in the southern Irish offshore area were also developed with reported reserves of 1.4 Tcf and 73 Bcf, respectively.

It is thus believed that significant amounts of hydrocarbons could be present in French waters in untested structural or stratigraphic traps. The first structures initially drilled were broad inverted anticlines, whereas the Wytch Farm field has shown that the major oil accumulations are located in Jurassic tilted blocks with the main phase of hydrocarbon generation predating the Oligocene inversion event. Mature source rocks are present in the early Liassic interval, but show great lateral variation in both thickness and quality. Reservoirs are developed locally in early Triassic (the main reservoir at Wytch Farm), Callovian and Purbeckian sandstones. Good sandy reservoirs in Wealdian and Albian strata (producing horizon at Kinsale Head) are unfortunately not efficiently sealed.

A re-evaluation of the petroleum potential should be made in the near future, but will require high quality seismic to delineate subtle traps, to map the distribution or organic-rich early Liassic intervals, and to evaluate the amount of erosion following the two inversion events of Aptian and Oligocene age. In April 1996, an offshore well, Pointe de Barfleur, was drilled in the Channel by Hunt Oil. The well was unsuccessful, but interest remains in the French Western Approaches where Ranger Oil recently made an application for an exploration permit.

Coalbed methane

There has been a growing interest of late in coalbed methane exploration, following, and particularly as a consequence of work in the United States. This still unconventional way to produce gas is linked to the possibility that coal can retain very large amounts of adsorbed methane. Numerous coal-bearing basins are present in France, some of them still being mined. Most of these basins are of Carboniferous–Autunian age. They are related to late stages of shearing and stress release at the end of the Hercynian Orogeny. They show great variety in size, structural complexity and coal content. The two largest are the Lorraine and the Nord-Pas de Calais basins.

To date, 11 wells have been drilled in France, two in the Alès Basin and nine in the Lorraine Basin. No significant results have been obtained so far due to the difficulty in implementing the technology of gas recovery, there is no doubt that more wells and tests are needed to demonstrate the economic potential of coalbed methane in France.

Exploration and production terms and conditions

The exploration and production of oil and gas in France now benefit from advantageous legal and fiscal policies. The amendment of the Mining Code in 1994 has significantly simplified the procedure for obtaining exploration permits, by reducing application time from two years to less than one year. Likewise, the tax sytem for oil and gas ensures a more equitable arrangement, even going so far as to subject the companies only to corporate tax for their offshore activities. The Hydrocarbon Conservation Board (SCGH) is in charge of keeping and filing all French petroleum data, such as well logs, seismic survey data base, regional reports etc. Due to its experience and expertise, SCGH staff assist the companies in any request for data. Applications for licensing may be filed with the French administration at any time, and there are no licence or acreage fees.

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