PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Mesozoic-Tertiary Evolution of the Aquitaine Basin [and Discussion]

R. Curnelle, P. Dubois, J. C. Seguin, D. Whitaker, D. H. Matthews, D. G. Roberts, Peter Kent, A. S. Laughton and M. M. Kholief

Phil. Trans. R. Soc. Lond. A 1982 **305**, 63-84
doi: 10.1098/rsta.1982.0026

Phil. Trans. R. Soc. Lond. A **305**, 63–84 (1982)

Printed in Great Britain

The Mesozoic–Tertiary evolution of the Aquitaine Basin

By R. Curnelle, P. Dubois and J. C. Seguin

Société Nationale Elf Aquitaine (Production), Boussens, 31 360 *St Martory, France*

The Aquitaine Basin, situated in southwest France, with an area of about 60 000 km^2, has the form of a triangle which opens towards the Atlantic (Bay of Biscay) and is limited to the north by the Hercynian basement of Brittany and the Massif Central, and to the south by the Pyrenean Tertiary orogenic belt. Beneath the Tertiary sequence (2 km thick, and which outcrops over much of the basin) a Mesozoic series, up to 10 km thick, rests generally on a tectonized Hercynian basement but locally it covers narrow (NW–SE-trending) post-orogenic trenches of Stephano-Permian age.

The Mesozoic history can be subdivided into four major structural–sedimentary episodes:

(1) during a Triassic taphrogenic phase a continental–evaporitic complex developed with associated basic magmatism;

(2) throughout the Jurassic, a vast lagoonal platform developed, initially (Lower Lias) as a thick evaporitic sequence followed by a uniform shale–carbonate unit, indicating a relative structural stability;

(3) the end of the Jurassic and the Lower Cretaceous saw a fragmentation of this platform, due to an interplay between the Iberian and European tectonic plates, resulting in an ensemble of strongly subsident sub-basins;

(4) during the Upper Cretaceous and until the end of the Neogene, the evolution of the Aquitaine Basin was influenced by the Pyrenean orogenic phase, with the development, towards the south, of a trench infilled by flysch which, from the Upper Eocene, is succeeded by a thick post-orogenic molasse complex.

The main hydrocarbon objectives in the basin are situated in the Jurassic platform (e.g. the Lacq giant gas field) and the Cretaceous sub-basins (e.g. the Cazaux and Parentis oil fields).

To date, production has been about 4×10^7 m^3 of oil, and about 15×10^{10} m^3 of gas since the first gas discovery (St Marcet) in 1939.

1. Introduction

The Aquitaine Mesozoic–Tertiary basin is situated in southwest France and has the form of a triangle of 60 000 km^2, which opens towards the Atlantic (Bay of Biscay) and is limited to the north by the Hercynian basement of Britanny and the Massif Central and to the south by the Pyrenean Tertiary orogenic belt (figure 1).

Beneath the Tertiary cover (on average about 2 km thick) exists a Mesozoic sedimentary sequence which can reach a thickness of up to 10 km, and which rests generally on a metamorphic and tectonized Hercynian basement. Locally the Mesozoic section covers several NW–SE-trending post-orogenic grabens of Stephano-Permian age.

The pre-Tertiary substratum only outcrops on the flanks of the basin. All the present knowledge of the deeper parts of the basin has resulted from the search for hydrocarbons which began after the commercial discovery of gas at Saint-Marcet in 1939. Since then over 10 000 km of reflexion seismic profile have been shot and over 1000 wells drilled, the deepest of which is Lannemezan 1 with a final depth of 6900 m. All this work, realized mainly by Elf Aquitaine and by Essorep, has resulted in the discovery of about 20 economic hydrocarbon accumulations,

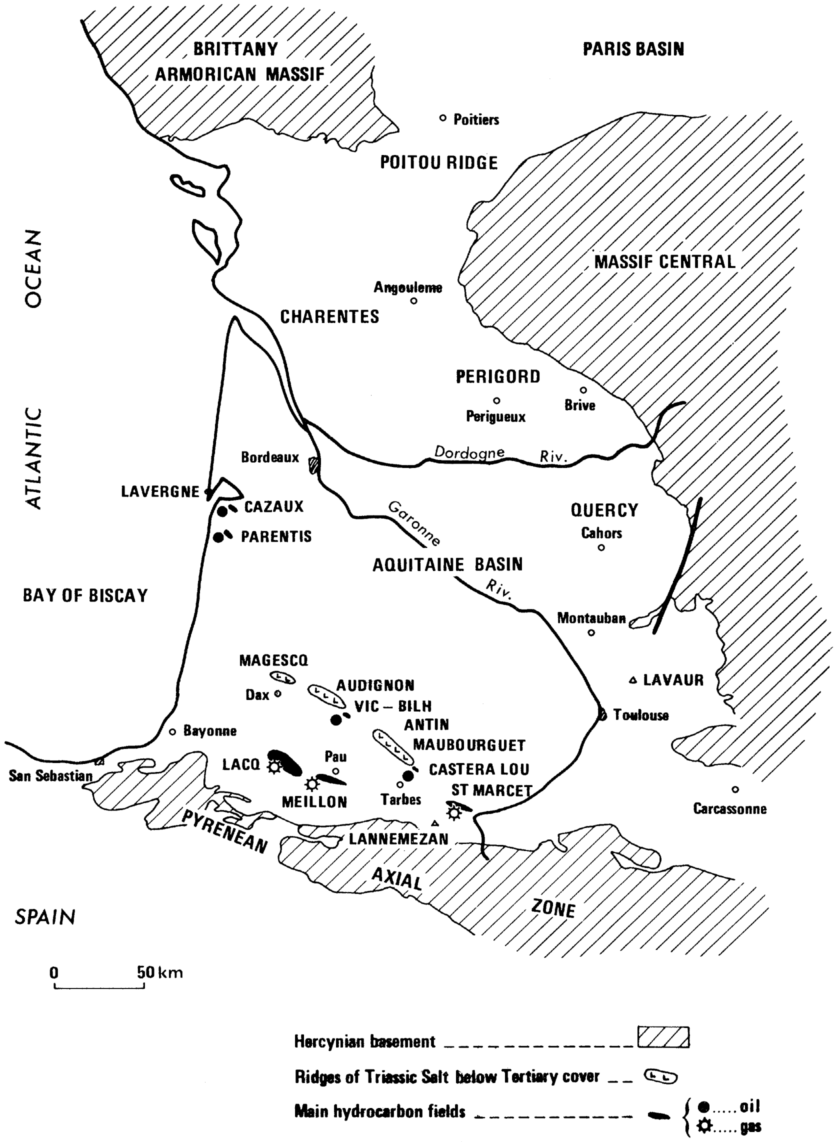

FIGURE 1. Location map.

the most important of which are the giant gas fields of Lacq and Meillon, and the oil fields of Parentis and Cazaux.

2. THE BASEMENT

The make-up of the pre-Mesozoic basement is only partly known, having been reached by only 70 wells; thus the sub-crop map (figure 2) remains very hypothetical. However, the geometry of the base-Mesozoic can be followed, albeit intermittently, from seismic reflexion data. It reaches its maximum burial of 8–10 km along the axis of the Parentis Basin and along the frontal edge of the Pyrenean orogenic belt.

The basement can be divided into two units:

(*a*) *Hercynian basement*, which seems to be of regional extent; it is composed of crystalline Precambrian, with sedimentary series of Cambrian to Carboniferous age with plutonic and

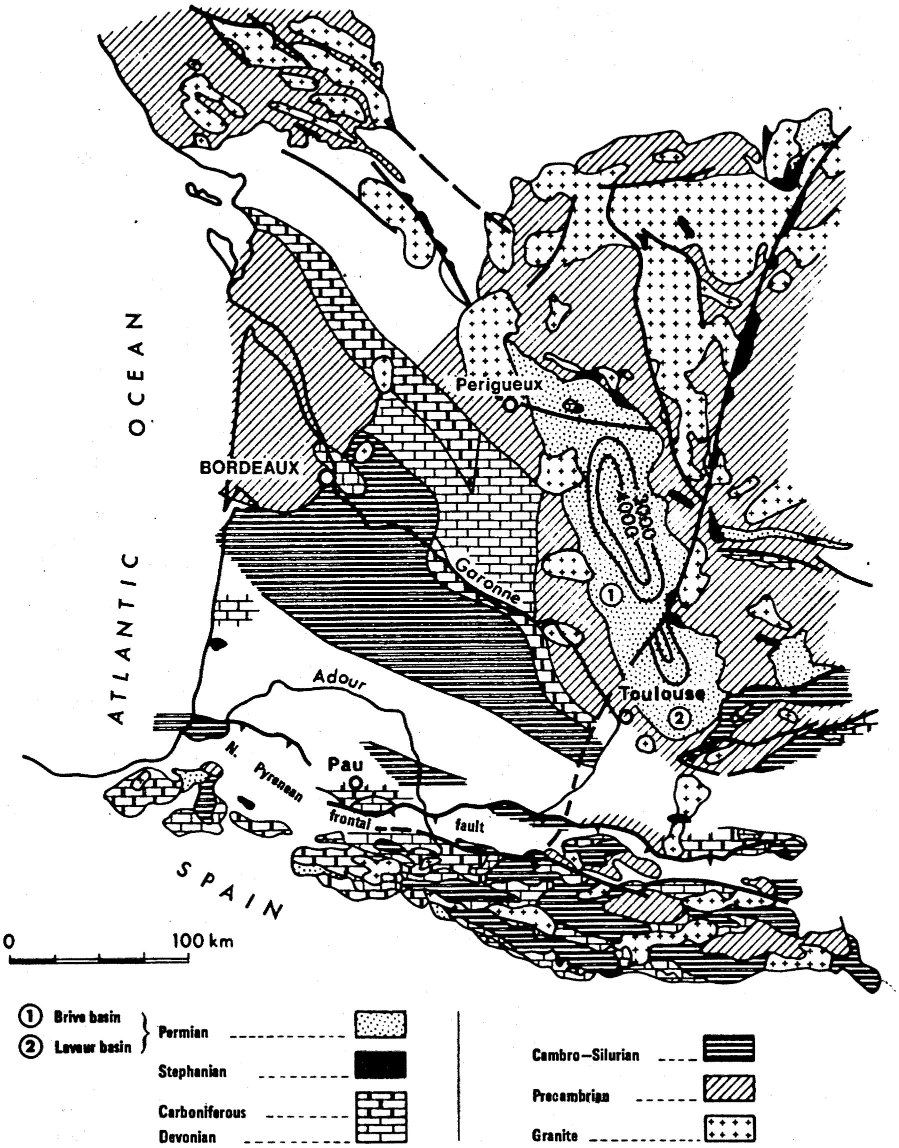

FIGURE 2. Subcrop at the base of the Mesozoic (older than 230 Ma).

hyperbyssal intrusives and also volcanic units; all have been deformed and metamorphosed during the various phases of the Hercynian orogeny.

(*b*) *Stephano-Permian* deposits of sandstone and shales that sometimes reach a considerable thickness in narrow graben, which developed after the main Hercynian orogenic phase. The best developed of these graben is that of Lavaur-Brive, situated to the north of Toulouse, which contains more than 3 km of sediment; it seems that other graben occur beneath the central part of the Aquitaine basin but their geometry is unknown.

3. The major episodes of Mesozoic sedimentation

After the beginning of the Mesozoic, the Aquitaine Basin developed by subsidence as a vast depressed area, the present limits of which are between the Armorican (Brittany) and Central

Massifs and the Pyrenean axis. It seems probable that the southern limit during the Mesozoic extended beyond the present Pyrenees and somewhat onto the Iberian block.

The variations in facies and thickness during successive phases of the basin's evolution are summarized in figures 2 to 11.

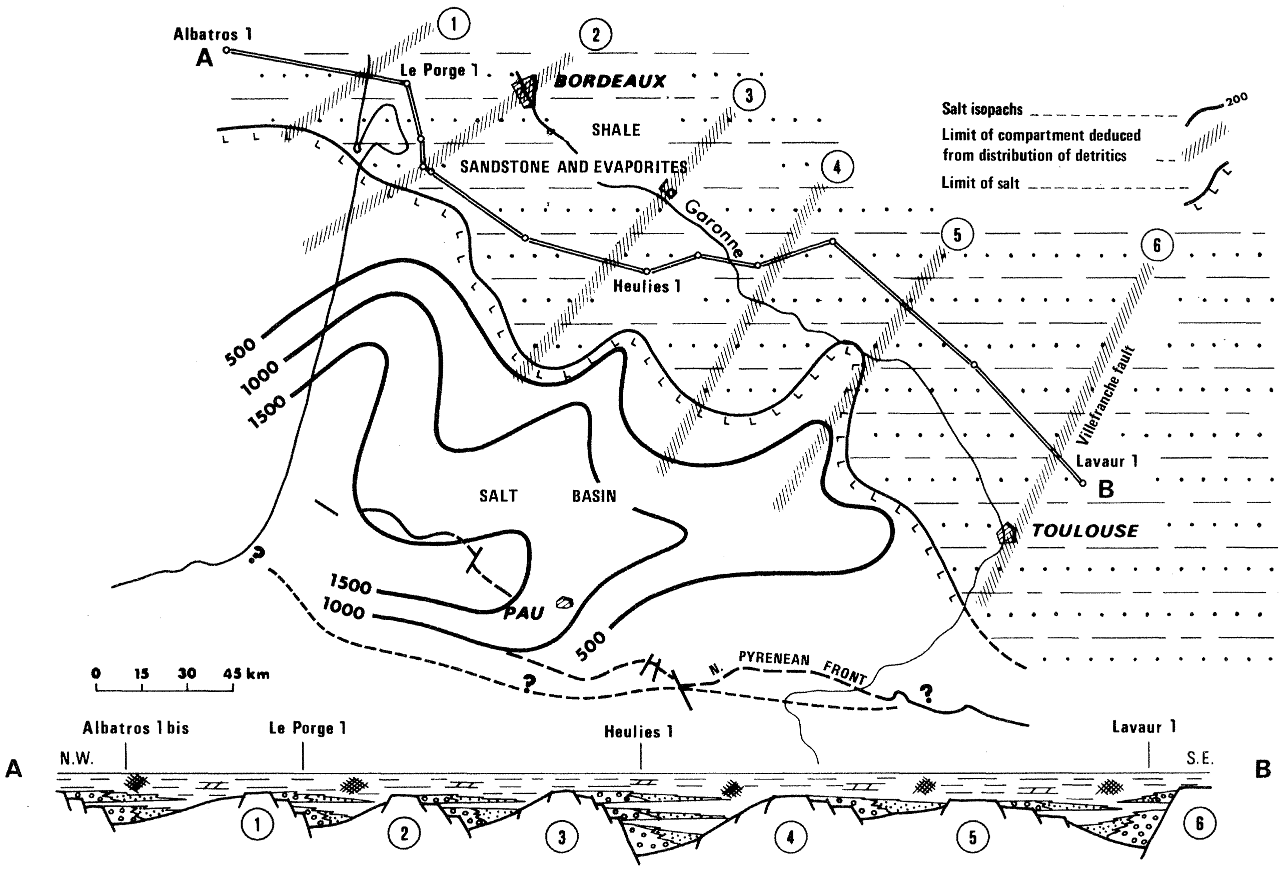

Figure 3. Triassic sedimentation zones (220–195 Ma).

(a) *The Trias* (*figure* 3)

Knowledge of the Trias is rather imprecise owing to three factors: (1) the small number of wells that have traversed it, (2) the almost total lack of good palaeo-dating (rendering difficult any correlation of the reduced series at the edge of the basin with the thick basinal series), and (3) difficulties of identifying the Trias on seismic lines.

The following three palaeogeographic units can be distinguished.

(i) A central basin, defined by the extension of halite deposits. Two main lithological units occur. The first mainly detritic unit comprises, after local development of sands at the base, a silt and evaporitic shale sequence, which can vary in thickness from 0 to 500 m. The environment is interpreted as alluvial cones developing close to active relief, passing laterally into an alluvial plain with fluviatile channels (braided stream) and finally a sabkha–playa environment. The geometry of these deposits, probably a function of tilted fault blocks, is poorly defined. The age is imprecise, the greater part is Lower Triassic, though the lower member could be of Permian age.

The upper unit comprises a number of evaporitic sequences – dolomite, anhydritic shales, anhydrite and halite – in a total thickness of more than 1500 m; the unit may have an accumulated salt thickness of up to 600 m. Within this unit are numerous intercalations of 'ophite' (basaltic lava flows or intrusions, or both). The lower sequences, which are richer in carbonate, are assigned to the Muschelkalk, whereas the top of the series is of Keuper age.

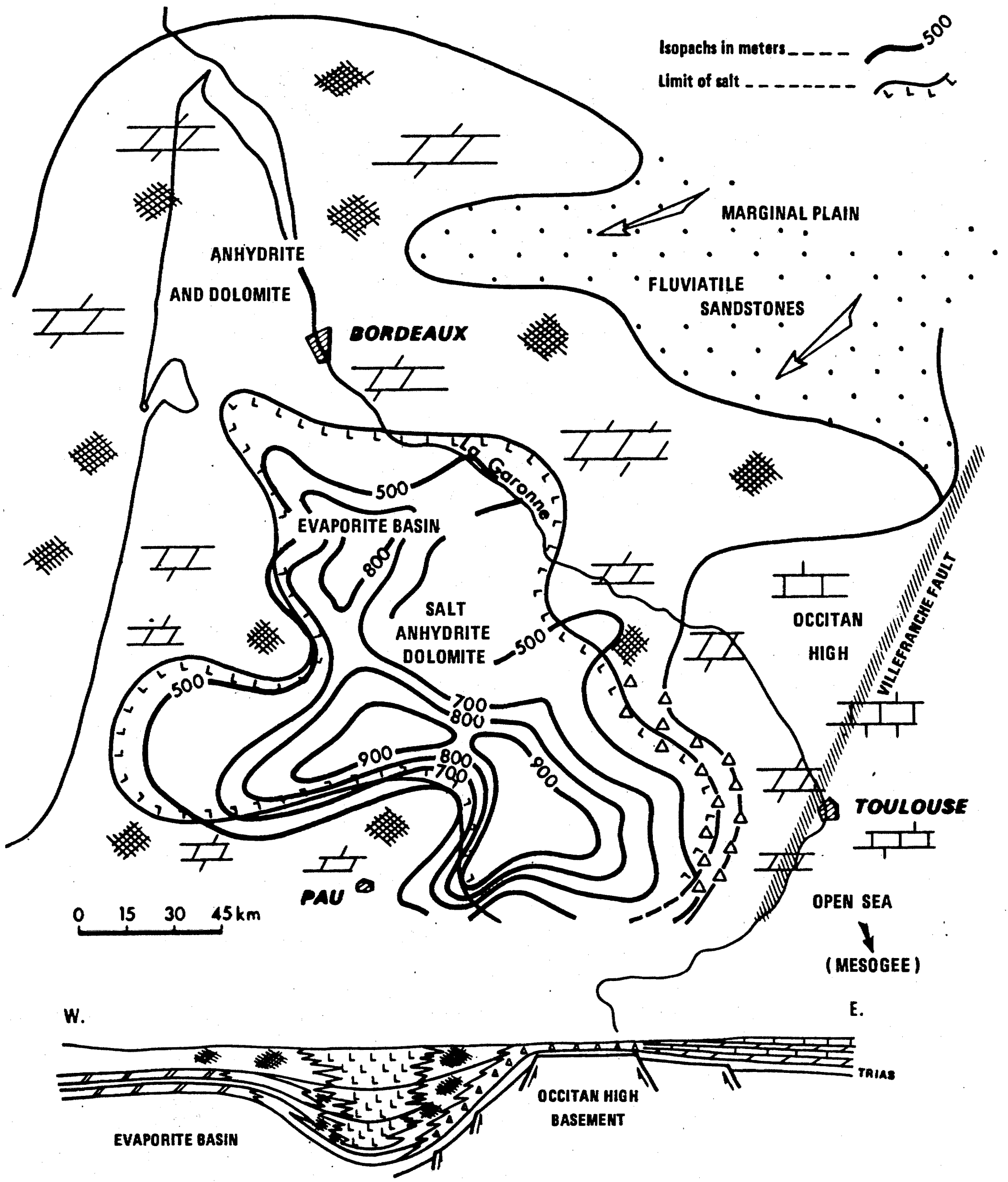

Figure 4. Lower Liassic sedimentation zones (195–190 Ma).

(ii) A wide northern border on which are found the same types of deposits as above – sandstones, silts, carbonates and evaporites – but, with considerably reduced thickness (100–300 m) and salt being absent. The sedimentation corresponds to similar alluvial fan, flood plain and sabkha environments, but developed in a series of small graben as indicated in the section on figure 3. The age is mainly Keuper, at least for the upper parts of the sequence.

(iii) The sedimentation of the Pyrenean zone remains poorly studied. In general the series, which consists of basal detritics with thin evaporites above (perhaps a result of tectonic thinning), leaves the supposition that the Pyrenean axis showed a tendency to be a high, thus limiting the basin within Aquitaine during the Trias.

(*b*) '*Basal Lias*' – *Rhaetian–Hettangian* (*figure* 4)

The sedimentation remained argilo-evaporitic with carbonates, resembling the end-Trias deposits and thus rendering any simple limit to the Trias difficult. For example the basal unit, the Dolomite of Carcans, is dated Middle Rhaetian in the south and Hettangian in the north. However, the distribution of facies indicates that a new pattern of sedimentation had been established with a polarity markedly different from that of the Trias:

(i) to the east, the Occitan high, aligned north–south along the Villefranche fault, is covered on its western margin by thin breccias and detritics, whereas to the east the facies becomes that of a carbonate platform of restricted marine environment (i.e. towards the Mesogean sea);

(ii) to the west, a tectonic basin containing evaporites in dolomite–anhydrite sequences at the edge and dolomite–anhydrite–halite sequences in the centre, reaches thicknesses of 800–900 m.

The Occitan high separated the tectonic basin to the west upon which was to be located the Jurassic Aquitaine shallow-marine platform, from the Mesogean sea to the east.

(*c*) *Jurassic–Neocomian*

During this long period the sedimentation was mainly shale and carbonates in a shallow marine environment, with only very local detritics, thus indicating a planification and retreat of the basin limits. At the same time what is now the Aquitaine Platform gently subsided over the 75 Ma with a maximum thickness of only 2 km. In detail, however, the depocentre changed frequently as a function of the palaeobathymetry and the subsidence. These changes took place on a topography of very low amplitude thus quite rapid changes of facies took place both laterally and vertically.

The various facies developed are as follows:

(i) open marine or external platform facies: shales with mudstone micritic carbonates (with characteristic fauna of ammonites, echinoderms, brachiopods) in numerous coarsening-up, infilling or regressive cycles (Klupfelian sequences);

(ii) barrier or littoral-fringe facies forming a limit between the external and internal platform: bioclastic, oolitic and reefal carbonates and constructed reefs (large-scale coarsening-up sequences);

(iii) confined marine facies on the internal platform protected by the littoral barrier: mudstone carbonates with benthic fauna, often laminated or with lagoonal varves, cut by tidal channels infilled with oolites or bioclasts. These carbonates pass laterally into evaporitic deposits with evaporitic breccias and continental deposits of shales with lignites often showing palaeosols and indications of emersion. The distribution of these various facies in time and space gives the following palaeogeographic evolution.

Lower Lias: progressive submersion of the evaporitic basal Lias by bioclastic and oolitic limestones.

Middle and upper Lias: the Aquitaine Platform was completely submerged and covered by ammonitic marls of external platform facies. The Atlantic and Mesogean oceans are linked over the Occitan High.

Middle Jurassic – Oxfordian (figure 5): re-establishment of the Occitan High with reappearance of internal platform deposits and even indications of emersion (lignites). On the western fringe of the High, an oolitic offshore bar with occasional constructed reefs developed (the formation of Meillon and Saint-Marcet). This barrier was continuous in a N–S sense from Pau to Perigord. Further west open marine conditions persisted in a Marl–limestone facies with ammonites.

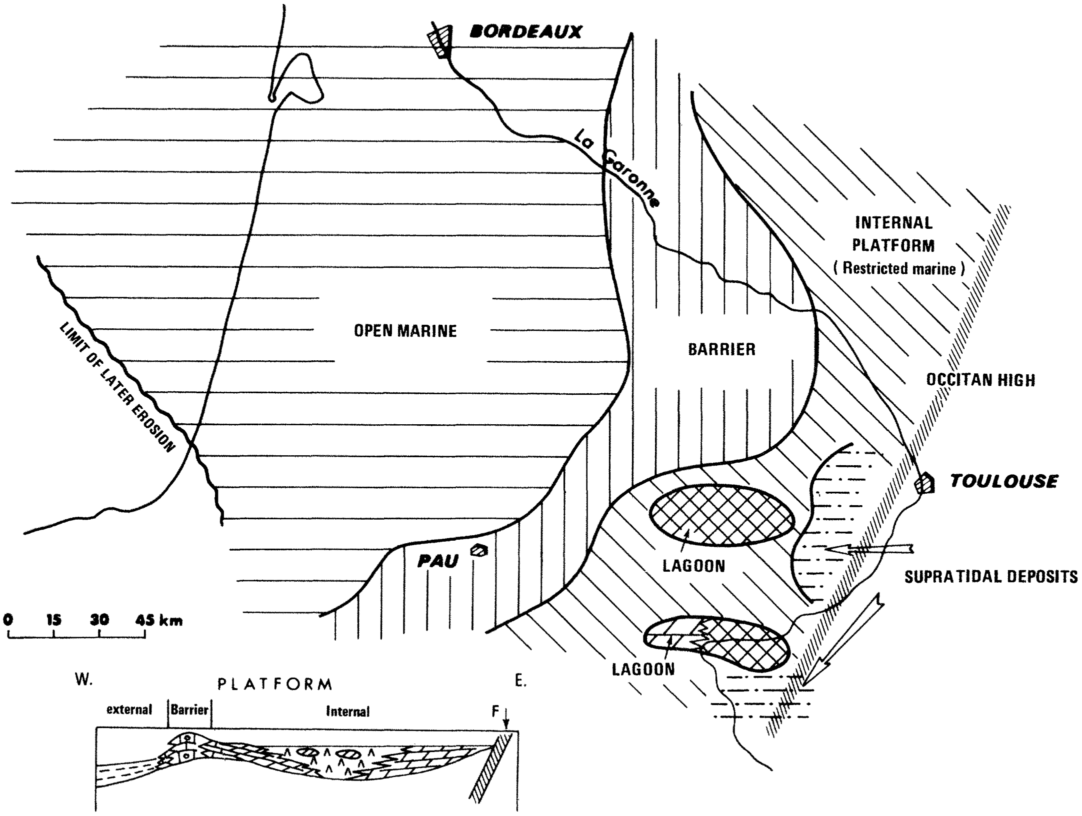

Figure 5. Middle Jurassic – Oxfordian sedimentation zones (170–140 Ma).

Kimmeridgian: the Occitan High was again submerged, with deposition of open marine facies composed of shaly limestone with ammonites. This was the last time that there was a connection between the Atlantic and the Mesogean oceans through the Aquitaine basin. Within the basin three depocentres developed with WNW–ESE trends: the Parentis sub-basin and the Mirande and Arzacq troughs.

Portlandian–Purbeckian (figure 6): the Occitan High reappeared and a calcareous offshore bar, which was locally reefal (in the Charentes region), migrated westwards as far as the present Bay of Biscay. The open marine environment persisted only to the northwest in the Parentis sub-basin. At the end of the Jurassic almost the entire Aquitaine platform was covered by the 'Dolomite de Mano' Formation deposited in a lagoonal platform environment. However, in the depocentres of Mirande and Arzacq thick calcareo-evaporites with anhydrites developed passing into sedimentary breccia ('Brèche de Garlin') at the edges of the basins.

Neocomian–Barremian (figure 7): this period saw the first uplift and erosion of the margins of the basin since Liassic times, with development of fluviatile sands both on the southern flank and deltaic sands to the north. Over the rest of the area shale–carbonate internal-platform facies, similar to that of the end of the Jurassic, persisted. During the Barremian, Aquitaine was a vast and very shallow lagoon. Beneath this landscape the Mirande and Arzacq sub-basins collected considerable thicknesses (up to 800 m) of fine algal limestone with characean algae ('calcaire à Annelides') and some beds with an evaporitic or sabkha tendency.

On the edge of the Parentis sub-basin one sees the change to a littoral environment with deposition of limestone and detritics. Within the basin, an open marine environment developed with siltstone and limestones into which, on the northern flank, are intercalated several thick deltaic units.

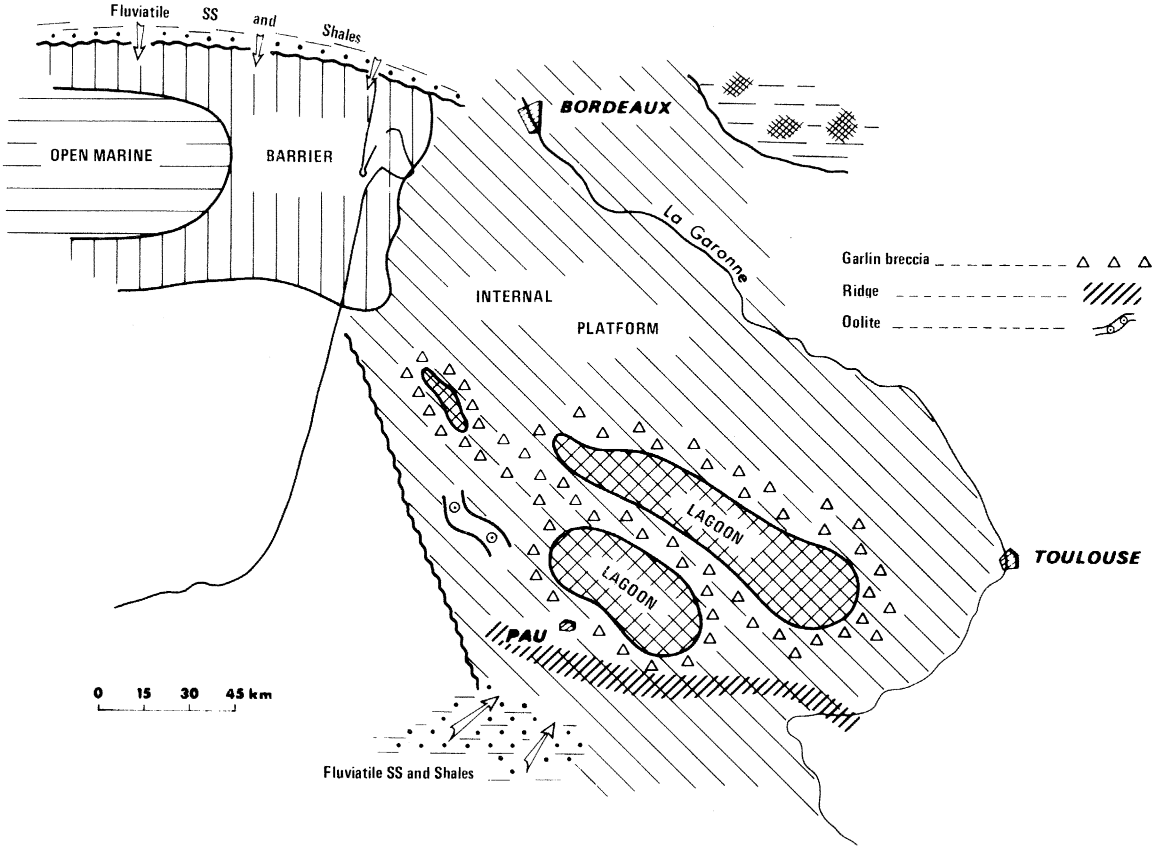

FIGURE 6. Sedimentation zones of the Portlandian–Purbeckian (140–135 Ma).

(*d*) *The Aptian–Albian and Upper Cretaceous*

From the Aptian onwards, the Aquitaine Platform, which had existed since the Lias, was completely modified by the development of two strongly subsiding zones, the sub-basin of Parentis to the north, and the North Pyrenean Basin complex to the south (itself divided into two sub-basins). The main basins were separated by an east–west-trending high, the Central Aquitaine platform. The basins and high all trend E–W (figures 8 and 9), and were to influence the sedimentation until the Senonian.

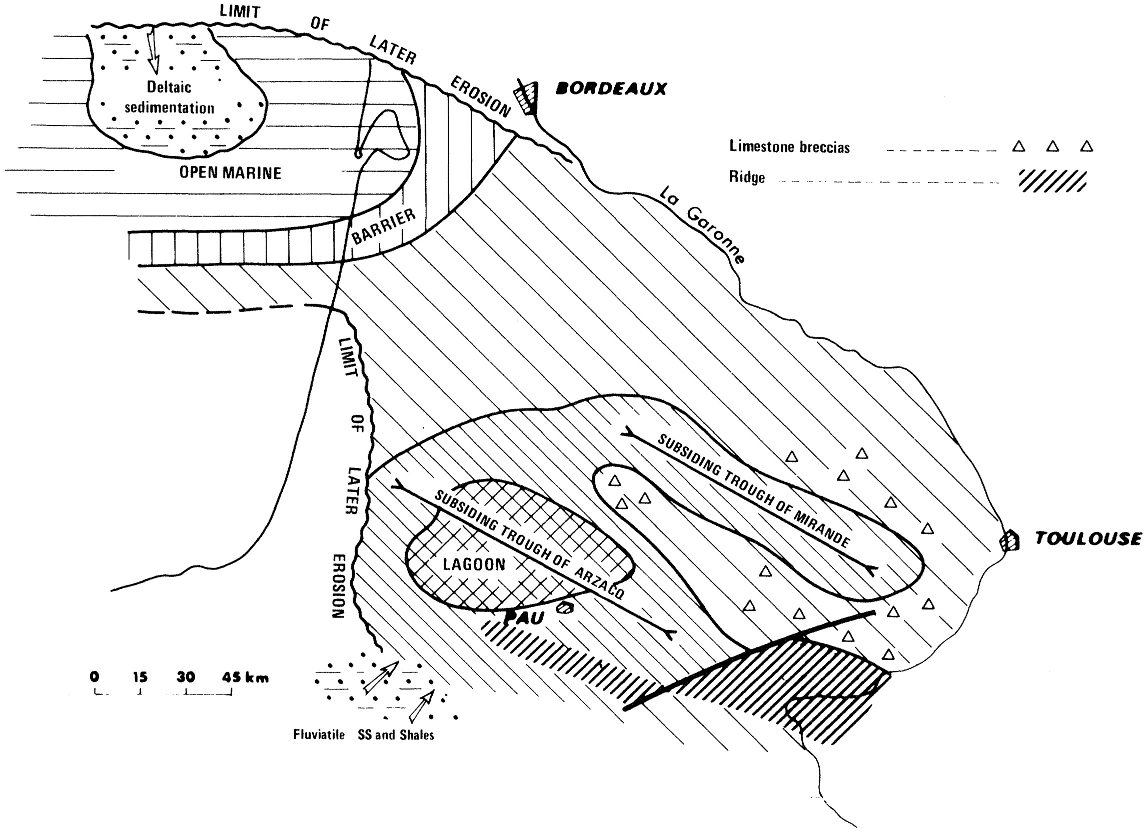

FIGURE 7. Neocomian–Barremian sedimentation zones (135–115 Ma).

(i) *The Parentis sub-basin*

This is a narrow trough that began to subside slightly in the Upper Jurassic. Subsidence continued slowly through the Neocomian–Barremian but during the Upper Aptian and Albian it accelerated. Despite a very high sedimentation rate (more than 2.5 km in 10 Ma), the subsidence outstripped the sedimentation, and the water depth continued to increase to a maximum of about 2 km at the end of the Albian. Along the margins of the basin, submarine canyons, which cut down to the Upper Jurassic, acted as conduits for detritic material that resedimented at the break of slope in lobes with grain or debris flow channel deposits that are separated by interlobe deposits of hemipelagic shale with thinly bedded turbiditic silty 'Bouma' units. The shelf edge, which was cut by the canyons, was a bioclastic offshore bar with more or less continuous bioconstructed reefs.

The Upper Cretaceous had much the same palaeogeography but sedimentation conditions were modified:

the differential subsidence was much reduced;

the whole of the Aquitaine margin was transgressed, causing a retreat of the zone of detritic deposition, and thus very little carbonate sediment reached the trough until the middle of the Senonian;

after the Middle Senonian the borders of the basin started to uplift, initiated a regressive and infilling cycle with a sedimentary (carbonate and siliceous detritic) prism prograding towards the centre of the basin. This cycle was not completed until during the Lower Tertiary.

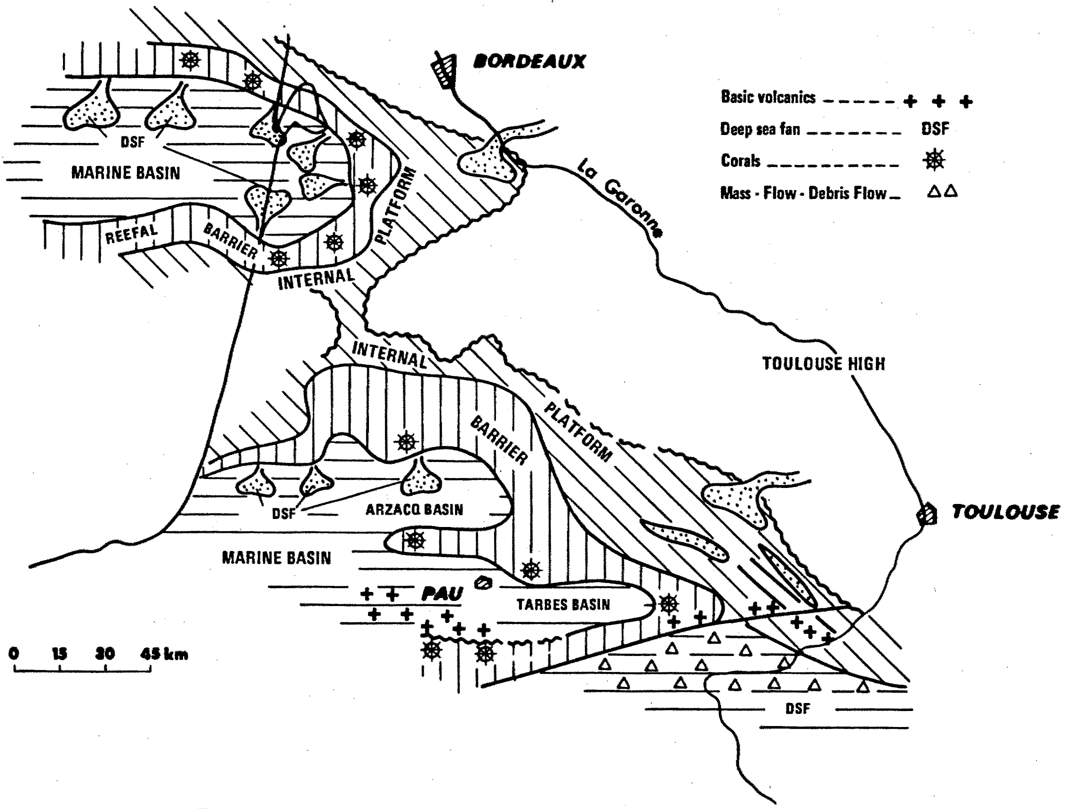

FIGURE 8. Aptian–Albian sedimentation zones (110–100 Ma).

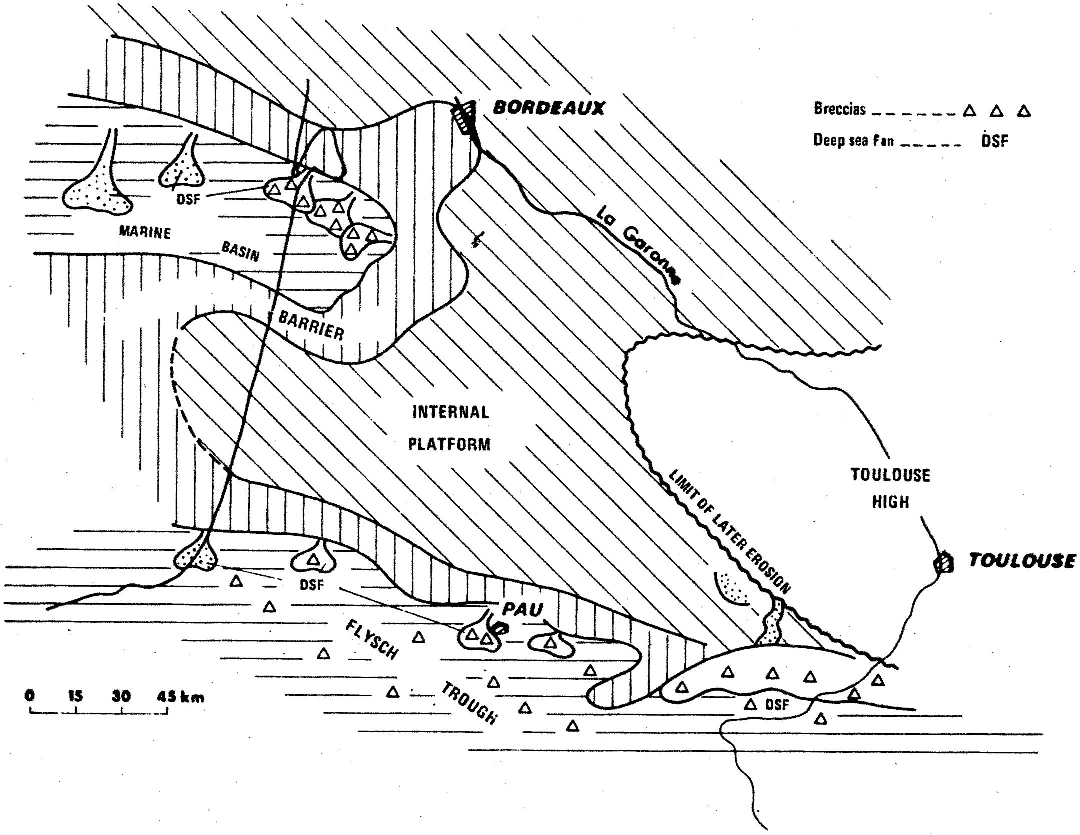

FIGURE 9. Lower Senonian sedimentation zones (85–80 Ma).

(ii) *The North Pyrenean Basin complex*

The North Pyrenean subsidence zone has a structural and sedimentary evolution very much more complex than that of the Parentis sub-basin. It is situated in a relatively narrow zone between the Central Aquitaine Platform and the Pyrenean axis. The latter remained a border high throughout the Aptian–Albian–Upper Cretaceous.

Several stages in the tectono-sedimentary evolution can be distinguished.

The Albo–Aptian taphrogenic phase of basin fragmentation seems to have developed either as a simple wide subsiding basin (Basin of Arzacq) or as narrow strongly subsiding troughs with deep palaeobathymetry (Comminges and Basque basins).

The Basin of Arzacq is filled with almost 3.5 km of open marine sediments, silty marl-with-spicules and limestones in thick coarsening-up regressive sequences. The basal unit, the Sainte-Suzanne Marl, dated Lower Aptian by ammonites, marks the first marine sedimentation in this region since the Kimmeridgian.

The narrow Comminges and Basque troughs of flysch are filled, in the south, with 2–3.5 km of fan deposits and to the north with shales and carbonates with many slumps, olistoliths and fan deposits.

The Albo–Aptian basins and troughs are separated by ridges on which the section is very thin and in shallow-water facies or the section is absent either by erosion or lack of sedimentation. Constructed reefs occur on the northern flanks towards the Central Aquitaine Platform, limiting the marine basins from the internal platform.

This taphrogenic phase is completed by basic and ultrabasic volcanic extrusions related to the ENE–WSW and WNW–ESE fault system.

Merging phase of the various Albian troughs (except the Basin of Arzacq). Gradually by Cenomanian–Turonian times the Albian troughs just to the north of the Pyrenean axis merged to form one simple trough, the Flysch Trough, which extends from the Ariège westwards to the Bay of Biscay. Its geometry is well known. This trough was strongly subsident, accumulating up to 4.5 km of turbidite – submarine fan deposits in very deep water. The fans were fed from canyons that cut into the northern flank of the Aquitaine basin and also the north Iberian margin. On the margins occur thick slumped or resedimented units that pass up-slope into external platform limestone, often with patch-reefs.

Migration phase of the Flysch Trough. From the Turonian to the end of the Maestrichian the Flysch Trough was displaced progressively, with the northern margin retreating about 30 km towards the north during this period. This movement was the result of compressive synsedimentary tectonics with associated folding and thrusting successively covered by the sedimentation.

Syn- and post-tectonic infilling of the Flysch Trough. The infilling was achieved by rapid lateral and frontal prograding units, which pass up into shallow-water detritics through lagoonal to continental facies. This regressive sequence is diachronous, taking place at the end of Cretaceous times in the east (Ariège–Comminges) and towards the end of the Eocene in the west (Arzacq–Basque region).

(iii) *The Central Aquitaine Platform*

Between the northern and southern sub-basins the high zone or Central Aquitaine Platform which is a vestige of the old Jurassic platform, has also (where it remains) a thin but relatively complete section, indicative of a low subsidence rate. Much of this platform was emergent at the Albo-Aptian notably along the 'Les Landes' Ridge – Toulouse High. This high suffered significant erosion with the removal of much of the Lower Cretaceous section and part of the Jurassic. On the northern side of this axis, during the Albo-Aptian, sand–shale littoral facies occur, whereas on the southern flank are supratidal to infratidal carbonates.

At Cenomanian–Turonian times the Central Aquitaine Platform was again drowned and covered as far as the edge of the Massif Central by marine facies shale and limestone and chalk, all very fossiliferous and thin (200–300 m). This episode represents the last great marine transgression in the Aquitaine Basin.

From the beginning of the Senonian onwards, the shorelines, often picked out by reefs, regressed towards the northern and southern marine basins. Behind them followed internal platform deposits, rich in Hippurites, then supratidal and continental shales and sands that progressively spread out from the Landes high, which again emerged at the end of the Cretaceous.

(iv) *Cretaceous salt tectonics*

The break-up of the Jurassic platform triggered the movement of Triassic salt over the whole of the Aquitaine Basin. This movement caused considerable syn-sedimentary effects in all the sedimentary regions, whether in the basins or on the central platform.

The results of the halokinesis are as follows.

Salt walls that grew during the Albo-Aptian created rim synclines with thick sediments. These synclines migrated laterally at the same time as the walls increased in amplitude. The summits of the ridges are often eroded and both local and generalized piercement took place; the best examples are in the Parentis sub-basin and in the Arzacq Basin.

Salt diapirs, more or less cylindrical and, by definition, piercing, are concentrated in the region of Dax and on the 'Les Landes' ridge.

Diapiric anticlines, either symmetrical or in the form of a factory roof, are related to the major fractures. The crests are often eroded and the rim synclines show syn-sedimentary thickening.

The main salt movement ended in the Albian, since a number of Triassic cap-rocks are covered by Albian series; but locally the movement continued into the Upper Cretaceous and often in the Tertiary there was intense reactivation.

The halokinetic phase had considerable impact on the Lower Cretaceous sedimentation. Also, the lithological and rheological changes as a result of the diapiric movement greatly influenced the geometry of the structures created or modified by the later Pyrenean tectonics. Thus the Cretaceous salt tectonics represented a very important stage in the geological history of Aquitaine.

(v) *Summary of the Mesozoic sedimentation*

The sedimentation throughout the Trias to the Upper Cretaceous, over the greater part of the Aquitaine Basin, was in limestone–shale and evaporitic facies typical of platform development and thus is analogous to all the great platform basins related to the Mesogean sea.

4. Mesozoic structural evolution of the Aquitaine Basin

The changes in palaeogeography throughout the Mesozoic often reflect the stages in the structural development during this period. Briefly one can summarize this development in four stages: (*a*) initiation of the basin in the Trias, (*b*) establishment of the Aquitaine Platform during the Jurassic, (*c*) break-up of this Platform at the end of the Jurassic and during the Lower Cretaceous, (*d*) development of the Pyrenean orogenic system during the Upper Cretaceous.

(*a*) *The initiation of the Triassic Aquitaine Basin* (*figure* 10)

Since the geometry and facies of the early stages are poorly known at present, the initiation of the Triassic phase of the Aquitaine Basin is little understood. The picture of the basin is confirmed only at the Upper Trias with a large rift that subsided between WNW–ESE-trending faults, and extended out into what is now the Bay of Biscay. This rift is infilled with evaporitic playa-type deposits. The presence of considerable volumes of ophitic volcanics confirms the crustal nature of the bounding faults.

This simple basin development was preceded by a series of poorly known narrow fault-controlled troughs trending NE–SW infilled mainly with detritics of uncertain Permian to lower Trias age. This zone extends as far as the Armorican and Central Massifs.

The relation between these two stages remains to be established, as is an understanding of the mechanism for the opening of the Upper Trias salt basin. The choice remains between a simple separation or rifting between the Iberian and European plates (if already differentiated) or alternatively an effect of stretching related to shear within the European plate.

(*b*) *The establishment of the Aquitaine Platform during the Jurassic* (*figure* 11)

The Jurassic palaeogeography, with its isopachs trending N–S, which replaced the generally E–W Triassic trends, indicates the establishment of a new structural régime.

The whole of Aquitaine was a more or less submerged platform that tilted towards the west away from the Occitan High, where, by the end of the Lower Lias, an open marine environment was established. The more subsident zones on this platform trend N–S, i.e. parallel to the facies zones.

This structural topographic arrangement seems to be the result of an E–W extension régime which can be ascribed to an early but feeble opening of the Atlantic, to the north of the fault separating the Iberian and European plates.

(*c*) *The break-up of the Aquitaine Platform at the end of the Jurassic and the Lower Cretaceous* (*figure* 12)

Between the Kimmeridgian and the Cenomanian a series of important events resulted in a change in sedimentary trends, from N–S 'Atlantic' to E–W 'Pyrenean'. This change can be followed through three successive stages.

(i) *Kimmeridgian*

In an open marine environment, the isofacies lines remain N–S but the isopachs mark the appearance of E–W trending sub-basins, e.g. Parentis, Arzacq and Mirande.

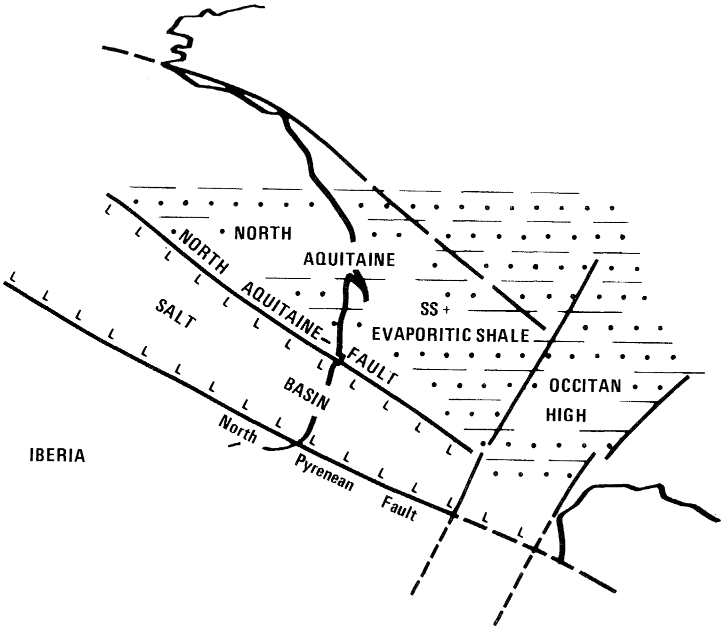

Figure 10. Tectonic and palaeogeographic sketch of Upper Triassic basin.

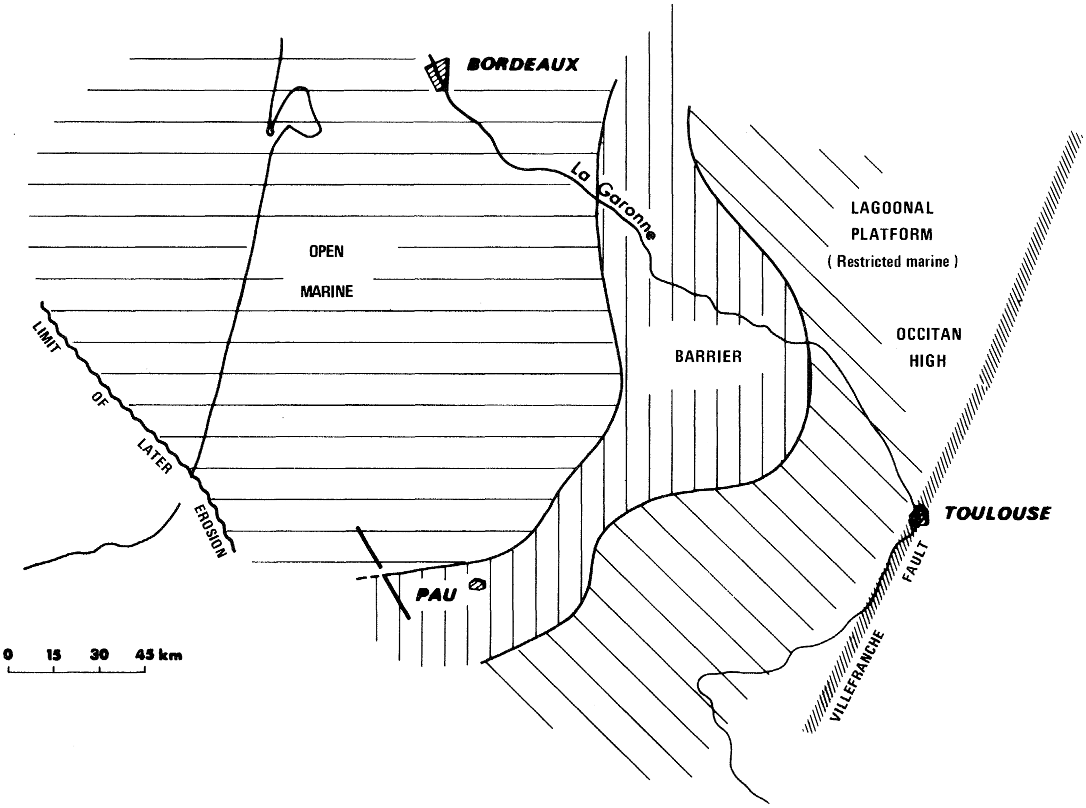

Figure 11. Geometry of basin in Middle Jurassic to Oxfordian.

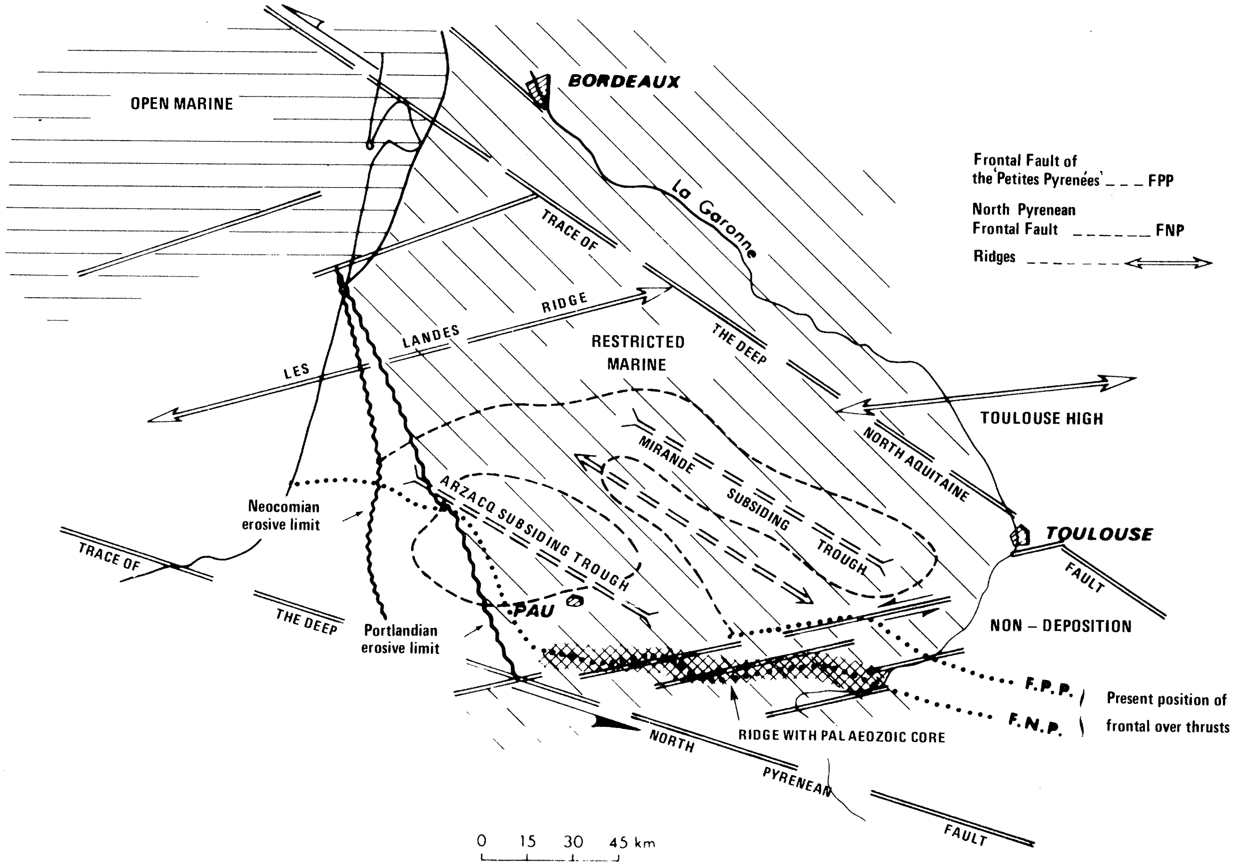

FIGURE 12. Tectonic and palaeogeographic sketch map of the Portlandian to Neocomian.

(ii) *Portlandian to Barremian*

The open marine environment was restricted to the Parentis sub-basin while the rest of Aquitaine was uplifted, with resultant emergence and erosion of the northern and southern flanks. However, towards the south of the region the Arzacq and Mirande sub-basins persisted, receiving either an evaporitic-sabkha or restricted marine sedimentation.

At the same time two structural systems progressively developed, firstly, ENE–WSW trending anticlines of which the main ones are the 'Les Landes' ridge, a wide high on which was triggered intense halokinesis of Triassic salt, and a series of high amplitude anticlines *en echelon* with the north Pyrenean border fault, which were eroded penecontamporaneously to their Hercynian basement cones; and secondly, WNW–ESE trending salt ridges with penecontemporaneous salt extrusion, e.g. Antin – Maubourguet and Audignon ridges (figure 1).

(iii) *Albo-Aptian* (*figure* 13)

The process of break-up reached its greatest mobility with structural amplitude reaching 4 km.

The palaeography was dominated by ENE–WSW trending structures:

a series of *en echelon* sub-basins – Parentis, Tarbes, Comminges – with a maximum rate of subsidence greater than 1 km Ma^{-1} and also a high rate of sedimentation, accumulated several kilometres of either flysch or silt–shale in a deep-sea environment, indicating considerable palaeobathymetry and also steep depositional dips;

a series of high ridges separating the sub-basins, the most important of which is the 'Les Landes' ridge which is *en echelon* with the Toulouse high.

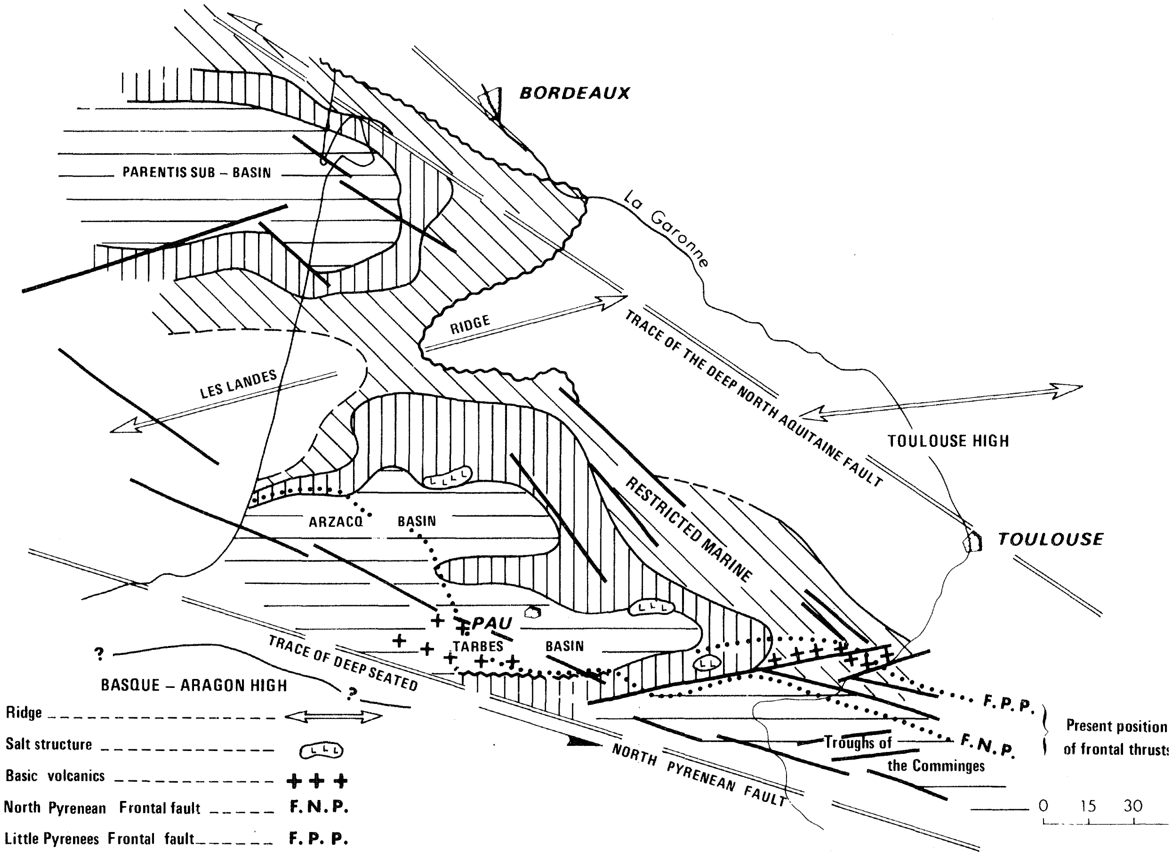

Figure 13. Tectonic and palaeogeographic sketch map of the Albian.

The dislocations that controlled these structures were of crustal magnitude, at least for the southern sub-basins, where ultrabasic volcanics occur and also where metamorphism with growth of diopside occurs in a narrow band the length of the Pyrenees.

All the above movements (Kimmeridgian to Albo-Aptian) have been grouped into a single tectonic phase, the pre-Cenomanian phase. This tectonism is mainly taphrogenic with tilted fault blocks and basins subsiding in regions of intense fracturing of the Aquitaine Platform. These movements again triggered the halokinesis of Triassic salt.

In the zone close to the eventual Pyrenees this phase is expressed, at least locally, by compression, which created *en echelon* anticlines and by development, again locally, of a penetrative schistosity.

Generally, the dislocation of the Aquitaine Platform seems to have followed a logical sequence that can be explained by a system of sinistral shears that affected the intracontinental segment of the European plate between the crustal Pyrenean fault zone and the deep north Aquitaine fault.

Within this segment the resultant ENE–WSW secondary shears controlled the Albo-Aptian basinal and anticlinal trends and also the halokinetic ridges. The opening of the sub-basins seems to have been in a system of pull-apart or rhomb-graben, which are either very large (Parentis and Arzacq) or very small (trenches of the Comminges). This shear system has been interpreted as a result of interactive shear between the Iberian and European plates. However, with the present knowledge of the palaeogeography (i.e. the position of isopachs on either side of the Pyrenees) one is unable to quantify the interplate movement.

(*d*) *The pre-Pyrenean evolution during the Upper Cretaceous*

This evolution has two phases: the development of the Flysch Trough with an E–W trend, and the start of the Pyrenean compression.

(i) *Development of the Flysch Trough*

After the Cenomanian–Turonian, the various Albian troughs along the edge of the Pyrenees (Basque region, Tarbes, Comminges) coalesced into a single E–W-trending unit, the Flysch Trough. As its name implies, this trough is filled with a very thick flysch sequence deposited in a deep marine environment.

The original geometry of the Flysch Trough, i.e. before the Pyrenean orogeny, has been obtained by analysis of the magnetic anomalies observed in the Atlantic near the Bay of Biscay. Anomalies 33/34 (figure 14) indicate that 80–85 Ma B.P., i.e. during the Upper Cretaceous, a triple junction developed with one of its arms trending E–W into the Bay of Biscay and in continuation with the Flysch Trough. It thus seems probable that the trough developed under the tensional régime associated with this arm. Superposition of the American and European anomalies 33 show that the Flysch Trough was considerably wider during the Upper Cretaceous than at present. The later reduction in width, of the order of between a third and a half, was the result of the rotational squeeze of the Pyrenean orogeny, the magnitude of which diminished from the east towards the Bay of Biscay.

(ii) *The start of the Pyrenean compression* (figure 15)

The first Pyrenean compressional phase started in the Middle Senonian and continued through to the end of the Upper Cretaceous. The average compressional direction was N 20° and the effects varied from one structural régime to another.

Aquitaine Platform, frontal to the Flysch Trough. The Pyrenean compression caused a progressive low-amplitude arching of the Aquitaine Platform, thus joining the Toulouse and 'Les Landes' highs to form a miogeanticline which separated the Parentis sub-basin from the Flysch Trough. Shorter wavelength compressive, often asymmetric, anticlines developed on the old salt ridges and on the Albo-Aptian fault-block highs. All these structures trend E–W and are cut by NW–SE and NE–SW trending dextral and sinistral strike-slip faults. During this phase the salt was reactivated and it injected into the cores of the anticlines and sometimes along the strike-slip faults.

The Flysch Trough. The deformation was increasingly intense towards the south where in the more extremely deformed zones an Upper Senonian penetrative schistosity developed. The tectonics were syn-sedimentary with the front part of thrust blocks being taken up in the Upper Cretaceous flysch, at the same time as the trough was being tightened and filled.

Another effect of the increased deformation taking place on the southern flank of the Flysch

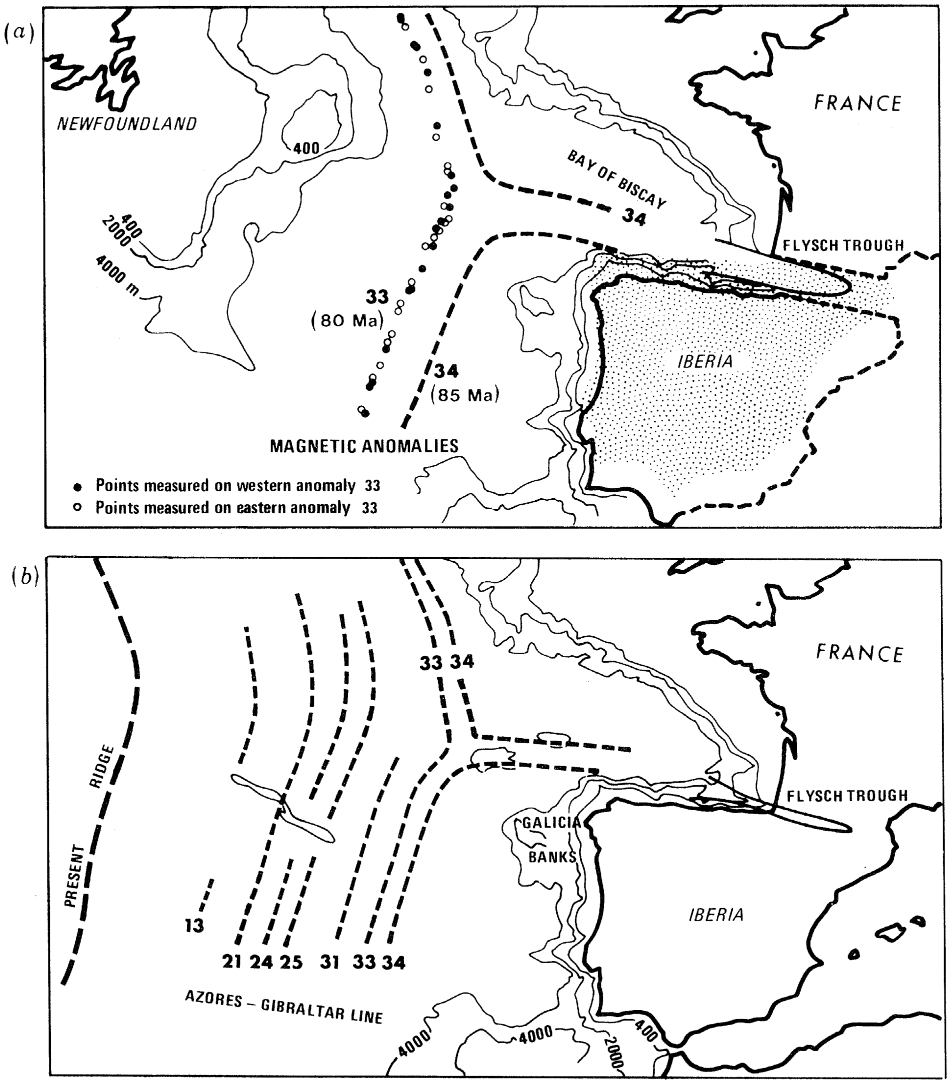

Figure 14. (*a*) Situation at Upper Cretaceous before the Pyrenean (modified from Boillot & Capdevila 1974); (*b*) present situation.

Trough was a migration throughout the Turonian–Maestrichtian of both the axis and the northern flank towards the north.

5. Tertiary and Quaternary structural evolution

The Pyrenean compression, which began in the Senonian, continued throughout the Lower Tertiary with final closure of the Flysch Trough migrating progressively east to west. This closure, with infilling facies changing from marine to continental fluvio-lacustrine, took place at the end of the Cretaceous in the eastern Pyrenees, at Middle to Upper Eocene in the Tarbes Basin and in the Oligocene in the Bay of Biscay (figure 15).

With the start of the uplift of the Pyrenees, during the Oligocene and Neogene, a thick series of fluvio-deltaic sediments (or Molasse) developed in the form of vast alluvial fans. Along the southern border of the Aquitaine Basin, where the Molasse oversteps onto eroded folded

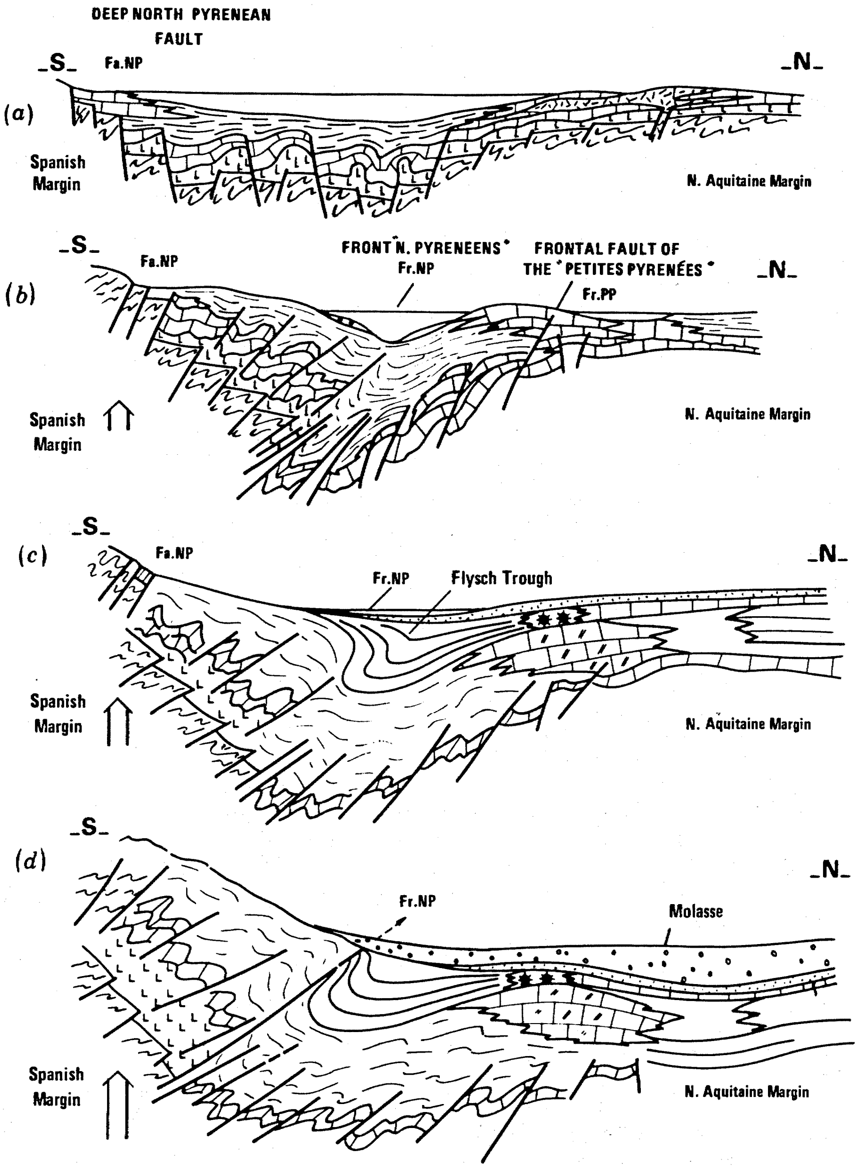

FIGURE 15. Evolution of the flysch troughs: (*a*) Albian–Cenomanian–Turonian (Comminges Zone); (*b*) Maestrichtian–Dano/Montian (Comminges Zone); (*c*) Eocene (Tarbes Basin); (*d*) Molasse Basin (Neogene of the Tarbes Basin).

Mesozoic rocks, the Molasse in its turn was gently flexed and folded, indicating waning N–S Pyrenean compression throughout this period.

The Plio-Quaternary saw the epeirogenic uplift of the entire Pyrenean chain, lifting Oligocene and Neogene erosion surfaces to an altitude of 2.5–3 km which were then dissected by deep-cutting rivers. These developed huge dejection cones of fan-glomerate (e.g. Lannemezan) on the northern flanks of the Pyrenees. The morphology of the Pyrenees was only slightly affected by the Pleistocene glaciation.

The Neogene to Recent post-orogenic sedimentation built out from the Pyrenees in a prograding system and caused a progressive regression of the coast from the east to the west and northwest. The continuation of this process formed the present-day continental shelf of the Atlantic.

6. Conclusions on the structural evolution of the Aquitaine Basin

The analysis of the evolution of the Aquitaine Basin throughout the Mesozoic and Tertiary shows that the overall structural régime was controlled by the opening of the Atlantic and the interaction of the series of faults limiting the Iberian and European plates.

After an initial Triassic separation there followed a series of interactions: separation, transform movements and variable compressive contact. The relative simplicity of this sequence of events is now masked by a great variety of structuro-sedimentary complexities.

In contrast to the complicated Mesozoic evolution, the relatively simple end Cretaceous – Tertiary phase was entirely dominated by the N–S Pyrenean compression which emplaced the Pyrenees of today with its erosion products infilling the present-day Aquitaine Basin.

The contribution to the knowledge of this basin made by the search for hydrocarbons over the last 40 years has been considerable. The future development in this direction – improved seismic techniques, more deep wells – can only improve our understanding of the geology of southwest Europe.

Bibliography (Curnelle *et al.*)

Anon. 1973 *Bull. Soc. geol. Fr.* (7) **15** (1).
Anon. 1978 *Bull. Soc. geol. Fr.* (7) **20** (5).
Arents, J. *et al.* 1975 In *IXe Congrès Int. Sédimentologie, Nice*, thème V, pp. 13–17.
Bertrand, L. 1940 *Bull. Servs Carte géol. Fr.* **204**, 205–282.
Boillot, G. & Capdevila, R. 1974 In *2è Réunion Sci. Terre, Pont-à-Mousson*, p. 59.
Bouroulec, J. & Deloffre, R. 1969 *Bull. Centre Rech. Pau – SNPA* **3** (2), 287–328.
Bouroulec, J. & Deloffre, R. 1970 *Bull. Centre Rech. Pau – SNPA* **4** (2), 381–429.
B.R.G.M., ELF r.e., ESSO-REP & S.N.P.A. 1974 *Géologie du Bassin d'Aquitaine.* Mém. B.R.G.M.
Casteras, M. 1933 *Bull. Carte – géol. Fr.* no. **189** (515 pages.)
Choukroune, P. *et al.* 1972 *Earth planet. Sci. Lett.* **18**, 109–118.
Choukroune, P. *et al.* 1973 *Bull. Soc. géol. Fr.* **15**, 600–611.
Choukroune, P. 1974 Thèse Doct. Sci. Nat., Montpellier. (276 pages.)
Curnelle, R., Dubois, P. & Seguin, J. C. 1980 In *26e Congrès Géol. Int., Bull. Cent. Rech. Explor. – Prod. ELF-Aquitaine, Mém.* no. 3, pp. 1–78.
Debroas, E. J. & Souquet, P. 1976 *Bull. B.R.G.M.* (2) **1** (4).
Delfaud, J. 1969 Thèse Doct. Sci. Nat., Bordeaux. (5 volumes.)
Dubar, G. 1925 *Mém. Soc. géol. Nord* **9** (1). (322 pages.)
Dubois, P. & Seguin, J. C. 1978 *Bull. Soc. géol. Fr.* (7) **20** (5).
Editions Technip 1971 *Histoire structurale du Golfe de Gascogne.*
Feuillee, P., Villanova, M. & Winnock, E. 1973 *Bull. Soc. géol. Fr.* (7) **15** (1).
Ferragne, A. & Vignueaux, M. 1978 *Bull. B.R.G.M.* (2), sect. 4, no. 2, pp. 35–142.
Le Pichon, X., Bonnin, J. & Sibuet, J. C. 1970 *C.r. hebd. Séanc. Acad. Sci., Paris* **271**, 1941–1944.
Mattauer, M. 1968 *Revue géogr. phys. géol. dyn.* (2) **10** (1).
Peybernes, B. & Souquet, P. 1975 *Bull. Soc. Hist. nat. Toulouse* **111**, 204–210.
Peybernes, B. 1976 Thèse Doct. Sci. Nat., Toulouse. (459 pages.)
Schoeffler, J. 1971 Thèse Doct. Sci. Nat., Bordeaux.
Souquet, P. 1971 In *96e Congr. Soc. Sav. Toulouse.*
Souquet, P. *et al.* 1977 *Géol. Alpine* **53** (2).
Williams, C. A. 1973 *Nature, Lond.* **244**, 86–88.
Williams, C. A. 1975 *Earth planet. Sci. Lett.* **24**, 440–456.
Ziegler, P. A. 1981 In *Petroleum geology of the continental shelf of north-west Europe*, pp. 3–39. London: Institute of Petroleum.

Discussion

D. Whitaker. How well explored are the Cretaceous submarine canyons and deep-water fans in the Parentis and southern basins? Could the canyons be clearly defined morphologically, and if so, do hydrocarbons occur in their sandy fills? How well are the fans delimited, and what is the nature of their reservoir rocks (e.g. sandy channel fills)?

R. Curnelle. There is a considerable amount of detrital material filling all the channels. Their base is eroded into the rocks below and has often exposed Barremian rocks, sometimes even rocks as old as Jurassic. In some areas the channels can be followed on the seismic sections. The channel sands often form reservoirs for hydrocarbons.

D. H. Matthews, F.R.S. What do we know about the relation between Pyrenean deformation in the south of the Aquitaine Basin and the formation of the North Spanish trough?

D. G. Roberts. The North Spanish Trough continues north of Gallicia bank and then stops. The seismic reflexion shows that the thrusting that formed the North Spanish Trough continues into the Atlantic, and presumably continues along the Azores Biscay Rise in a manner which is not yet clear. Spain must have moved westward, as well as northward, relative to France during this period of thrusting to produce the observed structures. These observations suggest that the Pyrenees were produced by a combination of shortening and right-handed strike-slip movement.

Sir Peter Kent, F.R.S. The North Pyrenean fault is generally believed to be a strike-slip fault, but is the North Aquitaine also a strike-slip structure?

R. Curnelle. The North Aquitaine is also a shear fault. Extension in the basin occurred during Albian times and continued during the Upper Cretaceous. The normal faulting is associated with widespread strike-slip movement on both right- and left-handed fault systems. The resulting disruption makes the geometry of the Albian and later movements difficult to reconstruct. This tectonic style is rather different from that further west on the northern margin of the Bay of Biscay, described earlier by Dr Roberts.

A. S. Laughton, F.R.S. The subsidence in the Aquitaine Basin was as rapid as 250 $\mathrm{m\,Ma^{-1}}$ during the Albo-Aptian. How does the timing and the rate of this subsidence compare with the results obtained from leg 48 of the D.S.D.P. further to the northwest?

D. G. Roberts. We believe that the history of the Aquitaine Basin is very similar to that of the region to the northwest where holes were drilled during Leg 48. The amount of subsidence is, however, difficult to determine because Hole 400A did not penetrate to the pre-Albian section.

M. M. Kholief. What is the oil potential of the Aquitaine Basin and is it confined to these submarine deltaic fans or are other depositional facies important? Also, what is the relation between the structural style of this basin and the hydrocarbon traps?

R. CURNELLE. The total reserves in place are about 2.4×10^8 t of oil and about 3.5×10^{11} m^3 of gas. The estimated amounts that are recoverable are 6×10^7 t of oil and 2.8×10^{11} m^3 of gas.

There are two source rocks in the Aquitaine Basin. In the Parentis Basin the main source is a sapropel of Kimmeridgian age. Elsewhere it is a black shale formed during a period of restricted circulation during the Barremian, which is associated with evaporites. Most of the oil reservoirs were deposited at the same time as the source rocks.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES