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Inversion tectonics of the northern margin of the Basque Cantabrian Basin

MANUEL GÓMEZ[1]; JAUME VERGÉS[1] and CARLOS RIAZA[2]

Key words.– Inversion tectonics, Subsidence analysis, Thermal modelling, Western Pyrenees, Basque-Cantabrian Basin.

Abstract. – The northern margin of the Basque-Cantabrian Basin was analysed combining stratigraphic and structural data from both surface and subsurface together with reflectance of vitrinite data from oil wells. The use of cross-section balancing techniques in addition to thermal modelling enabled us to reconstruct the tectonic, burial and thermal evolutions of the basin margin as well as those of the Landes High to the N in two different periods. The section restoration at the end of the Cretaceous shows a northern basin margin structure influenced by evaporites related to south-dipping normal faults. The reconstruction in middle Eocene times yielded up to 1 800 m of Paleocene-middle Eocene deposits on top of the basin margin. Subsequent tectonic inversion related to the Pyrenean compression led to the north-directed thrusting of basement units and to the formation of thrust slices or inverted folds in the cover along the northern margin of the basin. Tectonic subsidence analysis together with maturity data provided evidence that oil was generated in the basin during the late syn-rift and post-rift stages in the Late Cretaceous and became overmature during the period of incipient inversion after 55 Ma. In the autochthonous Landes High, the oil was generated after the tectonic inversion period 37 Ma.

Inversion tectonique de la marge nord du Bassin basque-cantabrique

Mots clés.– Inversion tectonique, Analyse de la subsidence, Modélisation thermique, Pyrénées Occidentales, Bassin Basque-Cantabrique.

Résumé. – La bordure du Bassin basque-cantabrique a été analysée en combinant des données structurales de surface et de subsurface avec des données de réflectance de vitrinites en puits. L'utilisation des techniques d'équilibrage de coupes et de modèles thermiques a permis de reconstruire les évolutions tectoniques, thermiques et l'enfouissement de l'extrémité du bassin ainsi que du plateau des Landes au nord, à deux époques différentes. La restauration des coupes à la fin du Crétacé montre une structure de la bordure du bassin fortement influencée par la présence d'évaporites liées aux failles normales à regard sud. La reconstruction a l'Eocène moyen met en évidence 1 800 m de dépôts allant du Paléocène à l'Eocène moyen au sommet de la bordure du bassin. Postérieurement l'inversion tectonique liée à la compression pyrénéenne a conduit au charriage d'unités de socle vers le nord et à la formation de chevauchements ou des plis dans la couverture sédimentaire sur la bordure septentrionale du bassin. En outre, l'analyse combinée de la subsidence tectonique et des données de maturité indique que la formation du pétrole a commencé dans l'allochtone à l'étape finale du syn-rift et post-rift pendant le Crétacé supérieur et à l'autochtone après la phase d'inversion au Tertiaire à partir de 37 Ma.

INTRODUCTION

The Basque Cantabrian Basin, located in the northern margin of Spain, is a Mesozoic extensional basin which was inverted during the Pyrenean orogeny in Paleogene times (fig. 1). From Triassic to Albian times, the extension was associated with the formation of the North Atlantic [Le Pichon *et al.*, 1971; Montadert *et al.*, 1979; Ziegler, 1988]. This extension was particularly intense during the Aptian-Albian interval owing to transtensive movements related to the counterclockwise rotation of Iberia during the formation of the Bay of Biscay [Montadert *et al.*, 1979; García-Mondéjar, 1996; García-Mondéjar *et al.*, 1996]. In this transtensional context, the subsidence was especially severe in the eastern part of the Basque Cantabrian Basin along the western branch of the Basque Arch. The onset of the Pyrenean orogeny led to the inversion of the thick early Cretaceous basin above the Keuper (Triassic) evaporitic level. The stratigraphy and sedimentology of the Mesozoic succession have been documented by García-Mondejar [1989]. The large-scale geometry of the inverted basin has been described by Cámara [1997]. However, the detailed evolution of this inversion tectonics has not yet been fully explained because of the relatively deep level of erosion affecting this inverted margin and because of the poor quality of the available seismic data. The lower Cretaceous rocks outcropping on the northern margin of the basin and imaged at the Cormorán-1 borehole present a high level of maturity of organic matter. These values contrast with the moderate values of the autochthonous platform deposits lo-

[1]Institute of Earth Sciences "Jaume Almera", CSIC, Luís Solé i Sabarís, s/n, 08028 Barcelona, Spain
[2]Repsol YPF, Paseo de la Castellana 278-280, 28046 Madrid, Spain
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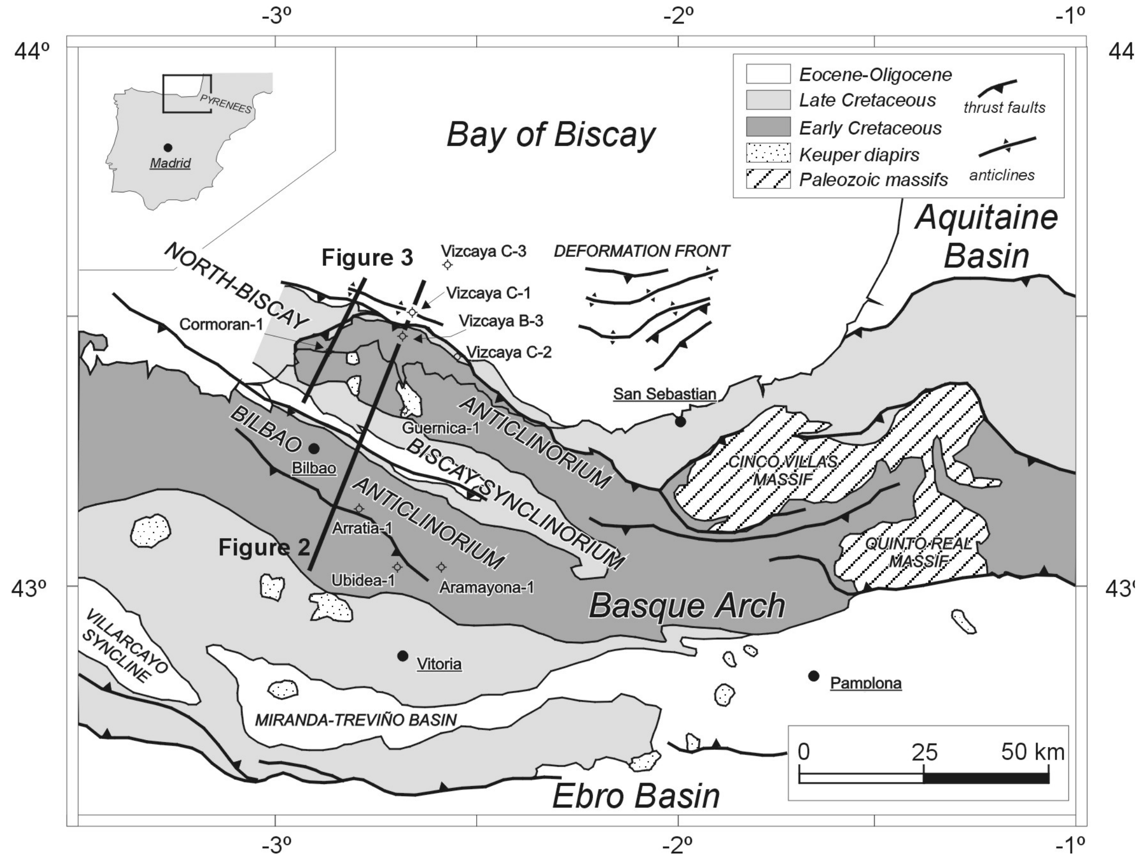

FIG. 1. – Simplified structural map of the NE Basque-Cantabrian Basin with the location of cross-sections and oil wells.
FIG. 1. – *Carte structurale simplifiée du Nord-Est du Bassin basque-cantabrique avec la localisation des coupes et des puits.*

cated to the north of the northern inversion front, which was a structural high during the Cretaceous.

The aim of this paper is to reconstruct the geometry of inversion tectonics of the northern margin of the Basque-Cantabrian Basin by integrating a balanced and a restored section with a backstripping analysis constrained by thermal and maturity data. Thermal modelling enable us to constrain the burial and exhumation of the northern margin of the basin. The two stages of restoration are (1) late Cretaceous, close to the transition from post-rift sag basin to foreland basin, and (2) the end of the middle Eocene close to the onset of the northern margin inversion [Soler *et al.*, 1981; Cuevas *et al.*, 1999].

THE BASQUE-CANTABRIAN BASIN STRATIGRAPHY

The study area is located on the northeastern side of the Basque Cantabrian Basin. This region is characterized by the change in the folding trend, from ENE-WSW to the east and WNW-ESE to the west, outlining the Basque Arch which approximately parallels the coastline (fig. 1). Two rifting episodes are recorded in the pre-inversion stratigraphy of the Basque Arch : the early Triassic and the late Jurassic-early Cretaceous [e.g., García-Mondéjar, 1996].

The syn-rift stratigraphy corresponding to the early Triassic rifting consists of red continental clastics, evaporites and carbonates that crop out in the eastern branch of the Basque Arch, overlying and surrounding the Paleozoic massif of Cinco Villas [García-Mondejar, 1989]. The upper Triassic Keuper facies crop out to the west, forming diapirs aligned in a NW-SE direction. These alignments suggest the position of pre-existent faults at depth [Serrano *et al.*, 1994; García-Mondéjar, 1996; Cámara, 1997].

The post-rift stratigraphy above the Keuper consists of early to middle Jurassic platform carbonates, which are uncommon in the study area. The second syn-rift period embraces the late Jurassic and early Cretaceous infill (154-96 Ma), which was characterized by the presence of continental clastic sequences and carbonates infilling fault-bounded basins [Ramírez del Pozo, 1971; Pujalte, 1977; Pujalte, 1981; Rat, 1988]. The Aptian-middle Albian interval was characterized by the deposition of fluvio-deltaic and shallow marine siliciclastic sediments, carbonate platforms and muddy intraplatform sequences known as the Urgonian Complex [Rat, 1988; García-Mondejar, 1989]. Continued extension accompanied by the development of left-lateral strike-slip structures after the opening of the Bay of Biscay was coeval with the deposition of fluvial, shallow marine and siliciclastic flysch sequences (the Supra-Urgonian Complex, upper Albian-lower Cenomanian in age) [García-Mondejar, 1989]. During the late Cretaceous there was deposition of carbonatic flysch sequences (Cenomanian-Santonian) and siliciclastic flysch deposits (Campanian-Maastrichtian) under the influence of the opening of the Bay of Biscay [Mathey, 1987]. Submarine volcanism took place in the area during the Cretaceous especially in late Albian times [García-Mondéjar *et al.*, 1996]. These rocks crop out in the northern limb of the Biscay Synclinorium and are probably related to the faults of the early Cretaceous rifting period [Cámara, 1997] and/or to major crustal scale faults [Azambre and Rossy, 1976].

During the Maastrichtian-early Eocene, the onset of compressive movements related to the Pyrenean contraction led to the uplift and folding of the sedimentary infill. Concomitantly, around the Biscay Synclinorium a deep flysch trough developed, being infilled with fluvial, shallow-marine and thick turbidite sequences with an eastern provenance [Mathey, 1987; Pujalte *et al.*, 1989; Pujalte *et al.*, 1993].

GEOMETRY OF INVERSION TECTONICS

Present geometry of the inverted basin

In this section, we describe the present onshore and offshore geometry of the northern margin of the Basque-Cantabrian Basin. We focus our attention on the western part of the Basque Arch, characterised by the existence of NW-SE trending structures.

The structure of the Basque-Cantabrian inverted basin was determined by the construction of a regional, 55-km long, SSW-NNE balanced section (fig. 1), which was restored to the top of the Cretaceous (fig. 2). The balanced section was constrained by two offshore exploratory oil wells and by published maps and sedimentological data from onshore [García-Mondéjar, 1985; Mathey, 1987; Robador and García-Mondéjar, 1987; García-Mondejar, 1989; Robador *et al.*, 1991; Pujalte *et al.*, 1993; EVE, 1994]. Furthermore, a second cross-section located 12 km towards the NW shows the Cormorán-1 oil well and provides additional tectonic information on the basin inversion (fig. 3).

The offshore structure is characterised by a set of north-directed thrust faults. The propagation of these thrusts results in the formation of the North Biscay Anticlinorium, whose structure varies along the strike. To the SE, a highly overturned fault propagation anticline made up of lower Cretaceous sediments and cored by Keuper evaporites developed (fig. 2). These lower Cretaceous sediments show a significant reduction in thickness across the anticlinorium, being thicker in the upright section of the forelimb (1 400 m) and thinner in the overturned section (620 m). The associated tight syncline to the north is cored by Paleocene rocks located on top of thin upper Cretaceous platform sediments. To the NE, the frontal structure consists of a set of imbricated thrusts detached in

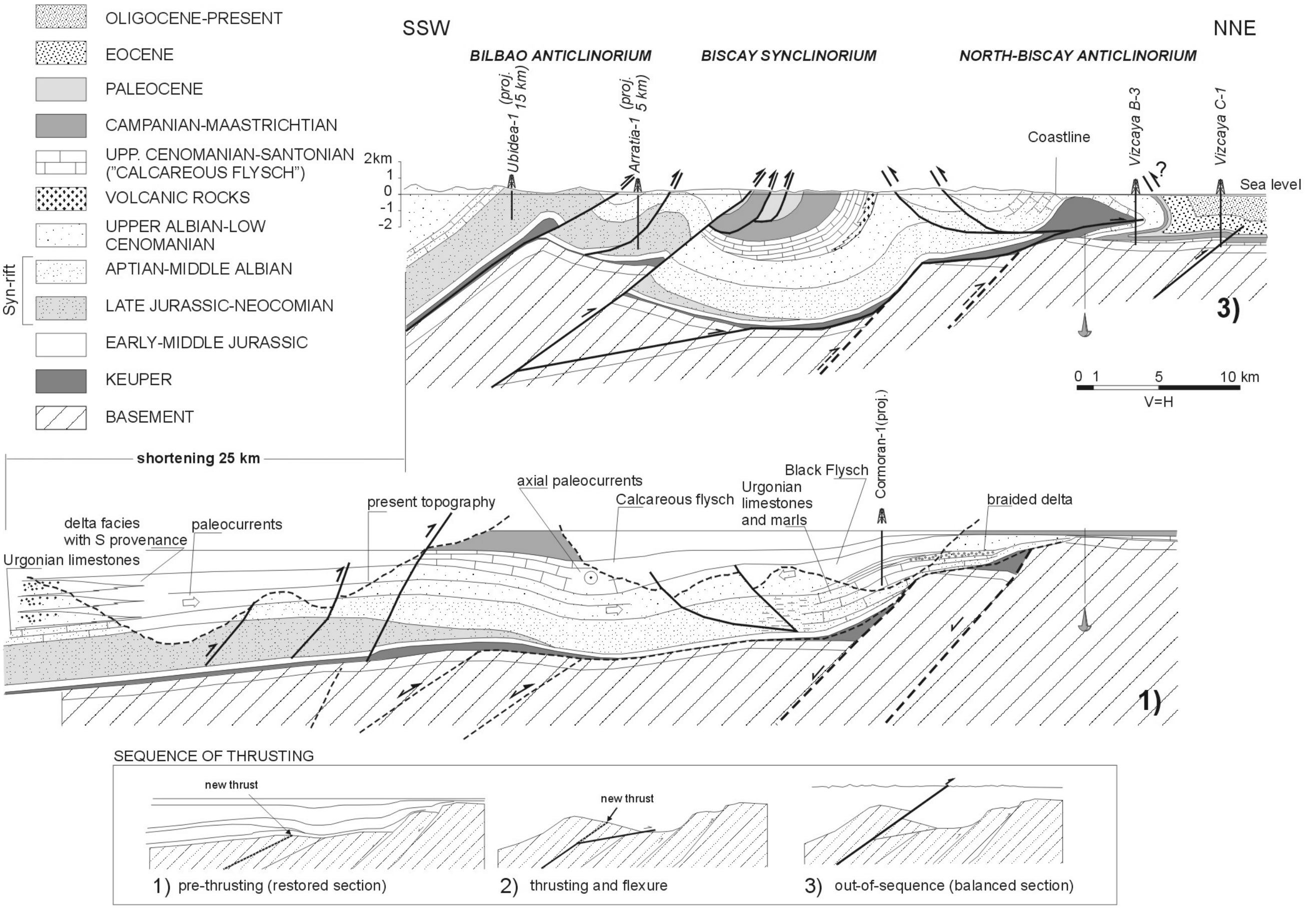

FIG. 2. – Balanced section and section restored to the top of the Cretaceous across the inverted NE Basque-Cantabrian Basin. The restored section shows schematically the sedimentology and paleocurrents of the upper Cretaceous units. The location of the normal faults was deduced from the geometry of the restored section in agreement with regional data (see fig. 1 for location). The sketch in the lower part of the figure shows the thrusting sequence.
FIG. 2. – *Coupe équilibrée et restaurée à la fin du Crétacé à travers le Bassin basque-cantabrique inversé. La coupe restaurée montre schématiquement la sédimentologie et les paléocourants des unités du Crétacé supérieur. La localisation des failles normales a été interprétée a partir de la géométrie de la coupe restaurée et des données régionales (cf. fig. 1 pour la localisation). Le schéma de la partie inférieure de la figure montre la séquence des chevauchements.*

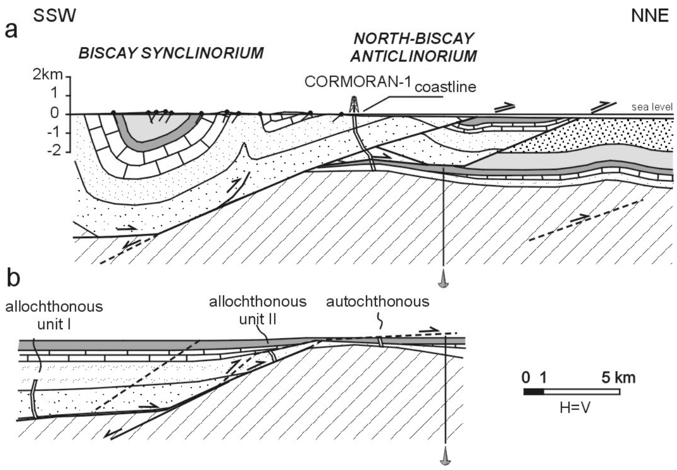

FIG. 3. – Balanced section across the Biscay Synclinorium and the North Biscay Anticlinorium offshore. This section shows the Cormorán-1 borehole (see fig. 1 for location and fig. 2 for legend).
FIG. 3. – *Coupe équilibrée a travers le synclinorium de Biscaye et l'anticlinorium de Nord Biscaye en mer. Cette coupe montre le sondage Cormorán-1 (cf. figure 1 pour la localisation et figure 2 pour la légende).*

the Keuper evaporites overthrusting basinal lower Cretaceous rocks on top of upper Cretaceous platform sediments (fig. 3).

Along the regional section, the back limb of the North Biscay Anticlinorium crops out to the south of the NE prolongation of the Guernica diapir, where up to 1 500 m of evaporites were drilled in the Guernica-1 borehole (fig. 1 for location). In the section, the core of the Biscay anticlinorium was infilled with Keuper evaporites based on surface and subsurface information. To the south, the section shows the increasing thickness of the Cretaceous units, reaching a maximum (up to 7 500 m) in the Biscay Synclinorium. In this region a number of volcanic and volcanoclastic layers are interbedded with Cenomanian sediments (fig. 2).

The Bilbao Anticlinorium, located to the South, is affected by an intense axial plane cleavage [Cámara, 1997], and is cored by late Jurassic-Neocomian thick sedimentary sequences. The presence of these sediments is evidenced by 2 exploration oil wells located to the SE of the regional section (fig. 1 for location). These wells imaged about 2 000 and 3 000 meters of Neocomian rocks [Lanaja *et al.*, 1987]. The thickness of these units diminishes progressively to the north, before petering out in the northernmost part of the structure (fig. 2). The geometry and thickness of the upper Jurassic-Neocomian unit and the reduced thickness of the underlying lower Jurassic and Keuper sediments (as pointed out by Soler *et al.* [1981]) imply the presence of the basement in a relatively shallow structural position. The involvement of the basement in the structure of the area has been deduced from field data [e.g., Cuevas *et al.*, 1999] and also inferred from geophysical data that suggest the NE-directed thrusting of Cretaceous intrusives together with lower crustal rocks [Aller and Zeyen, 1996]. In contrast to Cámara [1997], who interpreted significantly thicker Keuper and late Jurassic-Neocomian units, the sections in figure 1 and figure 3 show that the basement is involved in the thrust system.

According to our interpretation, a main thrust carrying basement rocks propagated the deformation to the north, forming the Bilbao Anticlinorium-Biscay Synclinorium pair. A new basement thrust moved to the north transporting the basin margin and forming the frontal structure (fig. 2 and fig. 3). Onshore, under the frontal lower Cretaceous a frontal fault-related anticline developed, which trends parallel to the regional structures. The Vizcaya C-1 well imaged this anticline showing the involvement of the basement in the reverse faulting (fig. 2).

The minimum shortening calculated in the SE sector of the study area is about 25 km and was mainly produced by the overthrusting of the basement units (fig. 2). This amount of shortening does not take into account the deformation produced by the intense cleavage described in the Bilbao Anticlinorium and is thus a minimum value as pointed out by Cámara [1997]. In front of the structure the deformation was accommodated mainly by the overturned anticline related to the Guernica diapir, which had developed during the extensional period [García-Mondéjar, 1987]. The contrasting style of deformation in the frontal part of the two sections (highly overturned fold vs. north-directed thrust imbricates) could have been attributed to (1) differences in the pre-inversion geometry of the basin which are common in pull-apart settings [e.g., McClay and Dooley, 1995], and (2) to the long-lived Guernica diapir. Diapirs in this context are preferential sites for accommodating shortening during compression, inducing the formation of highly sheared folds at the basin margins in transpressive settings [e.g., Brun and Nalpas, 1996].

Restored section at the end of the Cretaceous

The geometry of the northern Basque-Cantabrian Basin at the end of the Cretaceous was determined by the restoration of the regional cross-section (fig. 2). This restoration was undertaken by bed-length balance using the top of the Maastrichtian stratigraphic sequence as the reference.

The application of this method of restoration to the study area poses a number of problems :

a) uncertainties in the geometry of the present-day section attributed to the exhumation of part of the section and also to the absence of good quality subsurface data;

b) the existence in the present-day section of a large volume of evaporites hampers the area balance of the restored section;

c) the strong lateral variations in the thickness of the lower Cretaceous units (mainly Urgonian and Supra-urgonian, Aptian-lower Cenomanian units) complicate the construction of a palinspastic section valid for the whole study area.

In an attempt to minimise these problems, we used published additional sedimentological information to constrain the restored basin and we interpreted a significant accumulation of Keuper evaporites attached to the former normal faults, assuming diapirism during the extension.

After pinning the structure in the foreland, the northern margin of the Basque-Cantabrian Basin was positioned by restoring the overturned limb of the North Biscay Anticlinorium to its pre-inversion situation. The geometry of the lower Cretaceous units and the presence of coarse delta facies in the margin suggest that the margin was active, at least, during the Aptian-lower Cenomanian interval. To the south, the thick Cretaceous depocenter coincides with the location of the present Biscay Synclinorium. To the south of the basin margin, the complete Jurassic and

Cretaceous cover attains a thickness of approx. 5000 m. The thickness is about 3 500 m for the lower Cretaceous units and 4 000 m for the upper Cretaceous units along the main frontal flysch trough. This thickness is evidenced by the outcropping geometry of the upper Cretaceous units in the northern limb of the Biscay Synclinorium. The exact thickness of these units is difficult to estimate due to internal folding, and therefore the thickness represented in the restored section should be considered as a minimum. The maximum thickness for the upper Cretaceous units attains 2 500 m for the upper Cenomanian-Santonian unit and 1700 m for the Campanian-Maastrichtian unit [EVE, 1994].

The Cormorán-1 well was projected 12 km to the SE, parallel to the structures, in the balanced section. The restoration allowed us to locate the well stratigraphy in the reconstructed basin margin, resulting in an additional thickness of approx. 1,000 m of upper Cenomanian-Campanian sediments on top of the measured 2,400 m of Aptian-lower Cenomanian infill (fig. 2b). These upper Cretaceous sediments must be thinner than in the centre of the basin because of the situation of the stratigraphic section close to the basin margin. Soler *et al.* [1981] pointed out the existence of 750 m of upper Cretaceous in the North Biscay Anticlinorium, a value close to the 1,000 m projected in the restored section from the well data.

Further south, the restored section shows the incipient uplift and folding of the basement and lower Cretaceous infill, giving rise to a gentle anticline. The thinning towards the anticline crest of the syntectonic beds and the change in the direction of the paleocurrents (from approx. N-S during Albian-Cenomanian to approx. E-W during Maastrichtian-Eocene) provide evidence of folding activity [Pujalte *et al.*, 1989; Robles *et al.*, 1989; Pujalte *et al.*, 1993; EVE, 1994]. The formation of this anticline during the late Cretaceous can be related to the early stages of Pyrenean compression [Rat, 1988; Pujalte *et al.*, 1989; Pujalte *et al.*, 1993; EVE, 1994]. The late Jurassic-Neocomian and lower Cretaceous successions are thicker to the south of the anticline than in the north. These units include platform and deltaic deposits sourced from the south, indicating the presence of an active southern margin [Robles *et al.*, 1989]. This tectonic inversion is, however, younger than inversions determined in the southern part of the Basque-Cantabrian Basin during the early Cretaceous [Malagón *et al.*, 1994].

THERMAL EVOLUTION

Before the application of backstripping techniques, a thermal analysis based on vitrinite reflectance data was carried out to constrain a possible thermal evolution for both the northern margin of the Basque-Cantabrian Basin and the autochthonous Landes High and also to constrain the thickness and age of the stratigraphic reconstructed section of this northern margin. Maturity modelling is based on the linear relationship between depth and vitrinite reflectance (Ro) found in basins largely unaffected by major unconformities, young dip-slip faults and localized igneous activity. The percentage of vitrinite reflectance (%Ro) increases with depth and/or duration of burial, reflecting the response of the sedimentary section to the paleoheat flow [Dow, 1977]. The Genex^{TM} software calculates the increase in vitrinite reflectance, using a correlation curve between the given reflectance and the modelled transform ratio. This ratio is the amount of petroleum generated by primary cracking (which increases with temperature) with respect to the maximum amount generated in a complete petroleum evolution, the primary cracking being the transformation of kerogen to petroleum [Beicip-Franlab, 1998].

Northern margin of the Basque-Cantabrian Basin

The Cormorán-1 borehole cuts the inverted basinal deposits overthrusted on top of the platform deposits (see cross-section of figure 3). The reflectance of vitrinite shows very high %Ro values varying from 1.4 % in the shallow part of the section to 4 % at 2 400 m of depth (fig. 4). The thermal modelling described in this section was performed by varying the values of heat flow and/or the thickness of the section.

As a first step, we used the present-day stratigraphic sequence from the Cormorán-1 borehole as depicted in figure 4, imposing a minimum constant value of heat flow at the bottom of the basement of 64 mWm^{-2}, which is relatively low for extensional basins, and a maximum constant value of 76 mWm^{-2}. Using these parameters that correspond to the present-day heat flow in the Cantabrian Basin [Marzán, 2000] the calculated profile of %Ro does not fit the observed values of vitrinites.

Subsequently, we used the same heat-flow parameters and the restored cross-section data at the end of the Cretaceous to complete the stratigraphic column of the northern border of the Basque-Cantabrian Basin. An upper Cretaceous unit (late Cenomanian-Campanian) approx. 1 000 m thick and a Tertiary unit (Paleocene and early to middle Eocene) 1 870 m thick were extrapolated from the restored section and from the nearby Vizcaya C-1 borehole. The new maturity curve does not fit the observed values of vitrinite reflectance, especially in the lower part of the curve as shown in figure 5.

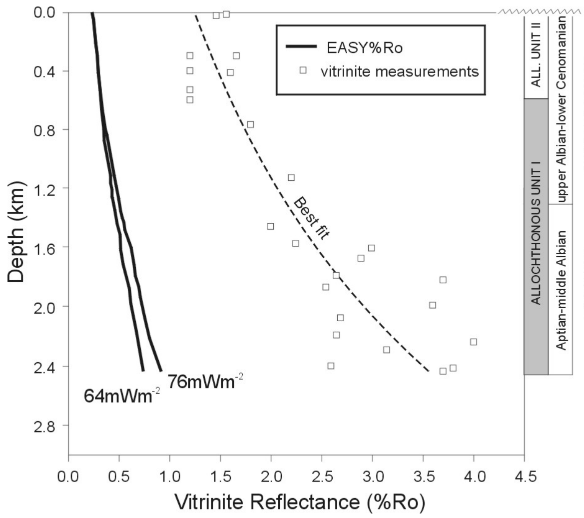

FIG. 4. – Plot reconstructing the reflectance of vitrinite distribution of the Cormorán-1 borehole. The overthrusted tectonic slice constituted by upper Albian-lower Cenomanian rocks (Supra-Urgonian) was restored to the top of the allochthonous Albian deposits. Calculated % Ro is for constant heat flows of 64 and 76 mWm^{-2}, equivalent to the present-day heat flow.

FIG. 4. – *Diagramme montrant la distribution de la réflectance des vitrinites dans le sondage Cormorán-1. L'écaille tectonique chevauchante constituée de roches de l'Albien supérieur, Cénomanien inférieur a été restaurée au sommet des dépôts allochtones albiens. Le %Ro a été calculé pour deux flux de chaleur de 64 mWm-2 et 76 mWm^{-2}, correspondants au flux de chaleur de l'actualité.*

With these constant values of heat flow, the only way to fit the observed data is to add a substantial thickness (between 3 000 and 4 000 m) of Tertiary pre-inversion sediments on top of the reconstructed section. This is unlikely in this region since the amount of Paleocene-Eocene sediments offshore only attains 2 000 m (Vizcaya C-1 borehole).

In the following steps the reconstructed section was kept constant up to the middle Eocene and a variable heat flow was introduced in accordance with the tectonic evolution of the basin. It is usually possible to adjust the heat flow of a rifted region by defining the duration and magnitude of the extension period (stretching factor). However, the Paleogene inversion of the Basque-Cantabrian Basin towards the north and south makes it difficult to estimate the late Jurassic-middle Albian rifting stretching factors. Regional data assembled by Vergés and García Senz [2001] indicates three main periods of tectonic evolution for the area : (1) rifting and strike-slip development from 120 to 93.5 Ma, (2) thermal relaxation from 93.5 to 55 Ma and (3) thrusting, foreland development and a final quiescent period from 55 Ma to the present. During the rifting and pull-apart development, a significant amount of heat flow between 80 mWm^{-2} and 90 mWm^{-2} was used (100 mWm^{-2} is a typical value for strike-slip settings [Allen and Allen, 1990]) and during the final stage of the development the present-day value of 64 mWm^{-2} was employed. In the interval the heat flow was progressively relaxed from 80-90 at 93.5 Ma to 64 mWm^{-2} at 55 Ma (fig. 6). The thermal maturity shows the best fit, especially with the lower part of the observed vitrinite reflectance data using 85 mWm^{-2}.

The calculated initial heat flow is essential for producing the very high reflectance of vitrinites encountered in the Cormorán-1 borehole and in the lower Cretaceous rocks outcropping in the region. This is consistent with the emplacement of volcanic rocks in late Albian times, coeval with an important crustal thinning in the Basque-Cantabrian basin [Azambre and Rossy, 1976; García-Mondéjar *et al.*, 1996]. An important NW-SE magnetic anomaly, parallel to the main structures of the area, suggests that the presence of the volcanic rocks is a regional feature [Aller and Zeyen, 1996]. The thermal calculations were made on the assumption of an additional reconstructed stratigraphy based on the regional geology that includes upper Cretaceous to middle Eocene rocks. However, the upper vitrinites are difficult to match; they are located in a different tectonic slice, close to the major normal fault bounding the basin (fig. 3). When restored, this tectonic slice is positioned above deep basin deposits. The apparently higher %Ro of these vitrinites may be due to the original basin location of the rocks affected by a slightly different heat flow history.

The heat flow history as well as the reconstructed stratigraphic section determined from the thermal model of the Basque-Cantabrian Basin forms the basis for the backstripping analysis and geohistory discussed below.

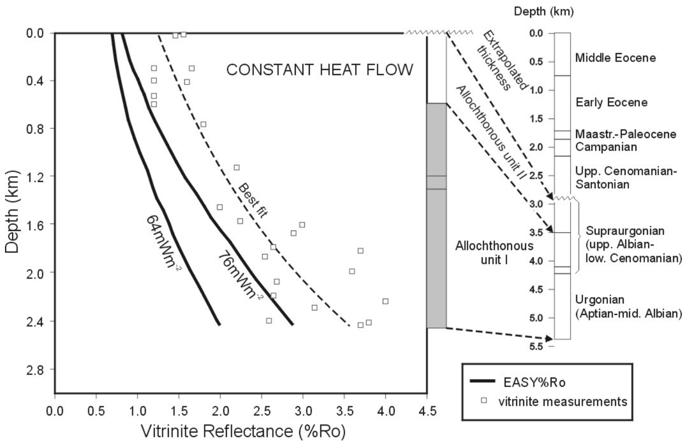

FIG. 5. – Plot showing the thermal model using the reconstructed stratigraphic sequence from the lower Cretaceous to the middle Eocene, and constant heat flows of 64 and 76 mWm^{-2}, equivalent to the present-day heat flow.

FIG. 5. – *Diagramme montrant le modèle thermique tiré de la séquence stratigraphique reconstruite du Crétacé inférieur à l'Eocène moyen et des valeurs de flux de chaleur constants de 64 mWm^{-2} et 76 mWm^{-2}, correspondants au flux de chaleur de l'actualité.*

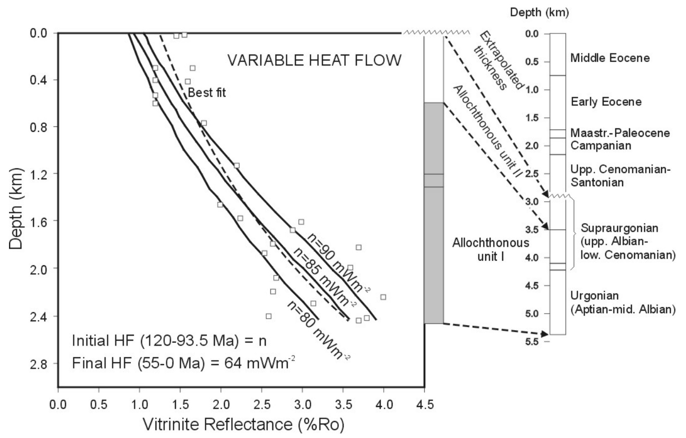

FIG. 6. – Plot showing the thermal model using the reconstructed stratigraphic sequence from the lower Cretaceous to the middle Eocene, 3 stages of heat flow (as discussed in the text), and different values of heat flow (between 80 and 90 mWm^{-2}) for the first stage (rift and pull-apart evolution).

FIG. 6. – *Diagramme montrant le modèle thermique tiré de la séquence stratigraphique reconstruite du Crétacé inférieur à l'Eocène moyen, 3 étapes de flux de chaleur (comme discuté dans le texte) et de valeurs différentes du flux de chaleur (entre 80 et 90 mWm^{-2}) pour le premier stade (évolution en rift et en pull-apart).*

Autochthonous Landes High

Three boreholes, located in the Landes High to the north of the Basque-Cantabrian Basin inversion front, show reflectance of vitrinite data sampled in the lower part of the boreholes in the basement Carboniferous coals. The three wells (Vizcaya B-1, Vizcaya C-1, and Vizcaya C-3 in fig. 1) display reduced Cretaceous thicknesses (between 200 and 400 m) unconformably overlying Paleozoic and Triassic sediments with slightly different %Ro values varying from 0.72 to 1.22. The deepest well is the Vizcaya C-3 cutting the most complete upper Cretaceous and Cenozoic stratigraphy of the Landes High. In this well, 500 m of eroded Triassic-Jurassic sediments were estimated by extrapolation from the more complete Aulesti-1 well. Interestingly, the thermal analysis of the three wells indicate a good fit with a constant heat flow of about 68-70 mWm^{-2}, thereby indicating that this amount can be used for geohistory.

RECONSTRUCTED STRATIGRAPHIC SECTION AT THE END OF THE MIDDLE EOCENE : BURIAL AND EXHUMATION

The results of the thermal analysis and the regional data allow us to reconstruct a complete stratigraphic sequence for the northern boundary of the Basque-Cantabrian Basin. This sequence includes approx. 1 000 m of upper Cretaceous sediments, about 1 000 m of Paleocene-early Eocene infill and about 800 m of middle Eocene deposits on top (fig. 7). The inclusion of these middle Eocene sediments in the northern margin of the basin assumes that the inversion of the marginal area post-dated this age. However, an older age of deformation has been documented in the inner part of the inverted basin [Pujalte, 1989; Robles *et al.*, 1989; Pujalte *et al.*, 1993]. The onset of Pyrenean-related compression accelerated the growth of an earlier, basement-involved Bilbao Anticlinorium, resulting in an increase in the tectonic subsidence and in the generation of a frontal trough in the centre of the basin. This led to a thick accumulation of flysch deposits in front of the anticline [Mathey, 1987; Rat, 1988; Robles *et al.*, 1989] (fig. 7). The assumed pre-tectonic latest Cretaceous to middle Eocene units were considered constant in thickness in the 2 selected wells but slightly thicker in the vicinities of the growing anticline.

With increasing shortening, the basin margin was uplifted and eroded and the lower Cretaceous rocks were exposed. A subsidence analysis performed in this scenario yielded information on the main pre-inversion tectonic events, which is difficult to deduce in the present highly eroded section.

BACKSTRIPPING ANALYSIS

Subsidence analyses were performed in two stratigraphic sections located in the northern margin of the Basque-Cantabrian Basin and in the more stable Landes High to the North.

The stratigraphic sequence in the northern basin margin is based on the reconstruction of the Cormorán-1 well (fig. 7); and the northern section is based on the Vizcaya C-3 borehole, located 20 km offshore aligned with the regional section (see fig. 1 for location). The Vizcaya C-3 well attains a depth of 4 150 m, imaging 100 m of Carboniferous sediments at its base. This Paleozoic basement is unconformably overlain by upper Cretaceous limestones made up of 104 m of Cenomanian and 384 m of Santonian to Maastrichtian deposits, these two units being separated by an unconformity. The upper Cretaceous rocks are unconformably overlain by 760 m of middle and upper Eocene marls and limestones and by a 2 220 m thick unit of Oligocene marls. Finally, on top of the section, 324 m of sediments which were assigned to Miocene to recent, complete the stratigraphy.

The subsidence analysis was performed by means of the backstripping method [Steckler and Watts, 1978] based on the decompaction of sediments, paleobathymetric estimations and assuming local isostasy. The utilized algorithm calculates the decompaction of sediments using porosity-depth relationships based on the following equation, 1/(z)=Lz+1/(0); where z is the given depth, L is the compaction factor, (0) is the surface porosity and (z) is the porosity at depth z. In the case of some lithologies, the algorithm uses empirical porosity-depth relationships based on different published sources [BEICIP-FRANLAP, 1998]. The average porosity of a given formation results from the porosities of the different lithologies composing the formation.

The paleowater depth estimations were obtained from the literature and from the facies analysis for the northern Basque-Cantabrian Basin [Robador and García-Mondéjar, 1987; Robles, 1988; García-Mondejar, 1989; Robador *et al.*, 1991; EVE, 1994]. In the case of the Landes High, we used the paleobathymetric estimations of Brunet [1997] although they correspond to a section located approx. 100 km to the north in the Parentis Basin. In the northern Basque-Cantabrian Basin the Urgonian sediments (Aptian-middle

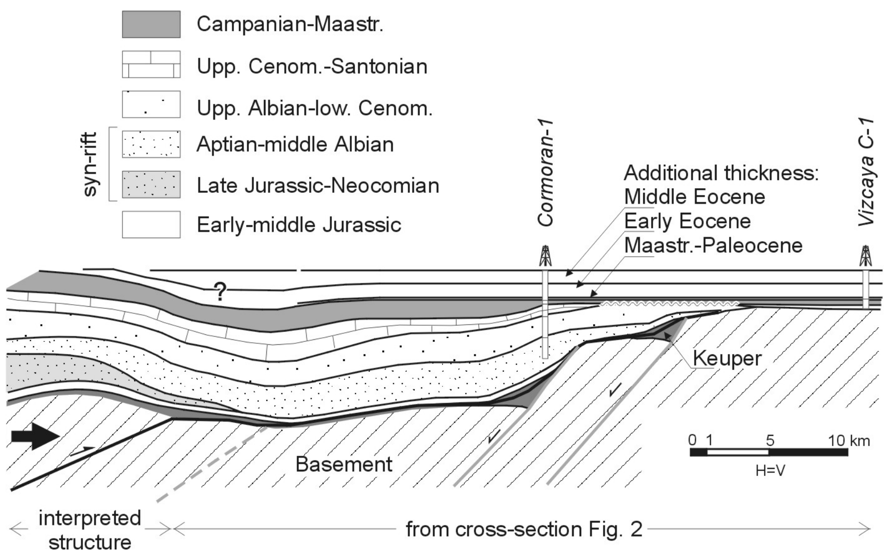

FIG. 7. – Reconstruction of the northern margin of the Basque-Cantabrian Basin using the results from the thermal modelling.
FIG. 7. – *Reconstruction de la marge nord du Bassin basque-cantabrique à partir du modèle thermique.*

Albian) have been interpreted to be deposited at a depth not exceeding 200-300 m [García-Mondejar, 1989]. However, we used a conservative water depth of 150 m for this period, taking into account the marginal situation of these sequences. Given the fact that the Supraurgonian unit (upper Albian-lower Cenomanian) records a deepening of the basin, from fan delta facies to turbidites, we progressively increased the water depth from 50 to 250 m for this interval. For the upper Cretaceous and lower Tertiary units we considered a paleobathymetry of 200 m, bearing in mind that the sedimentation took place in relatively deep troughs [García-Zarraga and Rodríguez-Lázaro, 1991]. We slightly decreased the paleowater depth for the middle Eocene unit, taking into account the presence of contemporaneous coarse sediments in the basin [EVE, 1994].

In the Landes High, we assigned a paleobathymetry close to sea level for the Cretaceous, assuming that various unconformities determined for this period were produced in a shallow water context. The younger unconformity has been dated to 65 Ma (between Maastrichtian and middle Eocene). From 65 Ma to the present we assumed a fairly constant paleowater depth equivalent to that of the present day one (306 m).

The eustatic variations were not taken into account in the backstripping calculations owing to software limitations. However, their impact on the tectonic subsidence are relatively small. A sea-level curve of the Bay of Biscay shows a sea level rise from approx. 75 m at the start of the Aptian to 150 m in the Santonian-Campanian interval [Brunet, 1997]. The same curve shows a progressive sea level fall from the late Cretaceous to the present. The paleobathymetric estimations for the Cretaceous indicate a shallowing of the basin from Aptian to middle-late Albian times (120-105 Ma). The eustatic variation for the same period results in a deepening from 75 m to approx.110 m, suggesting that the correct subsidence is slightly smaller than the one calculated. From middle-late Albian to lower Cenomanian times (105-97 Ma), the facies indicators suggest an increase in the paleobathymetry whereas the sea-level curve varies from approx.110 m to 150 m. The impact of sea level fluctuations would result in a slightly stronger tectonic subsidence than that calculated for this interval (a maximum of few tens of meters).

The subsidence curves display a well-differentiated subsidence history for the Basque-Cantabrian Basin and its continuation to the N into the Landes High (fig. 8). The northern margin of the basin shows a well-marked period of subsidence during the early Cretaceous and the lower part of the late Cretaceous from approx.120 to 85 Ma. The intensity of this subsidence event is, however, variable showing an early phase of moderate subsidence rate (120 to 95 Ma), followed by a sudden increase in the rate of tectonic subsidence (95 to 85 Ma), and ending with a moderate rate of subsidence (fig. 8). These events can be related to the major geodynamic processes which occurred in the region during the opening of the Bay of Biscay. The early phase of moderate subsidence can be associated with rifting, whereas the rapid subsidence phase can be linked to the formation of pull-apart basins during the transtensional motion of the Iberian plate. The duration of this rapid period of subsidence lasted for approx. 10 m.y. in this region. The slow rate of tectonic subsidence (85-55 Ma) could be a consequence of the transtensional tectonics as demonstrated by the regional data [e.g., Vergés and García Senz, 2001]. To the E of this locality, the onset of this moderate phase corresponds to short phases of basin inversion within the general strike-slip movement between the Iberian and European plates.

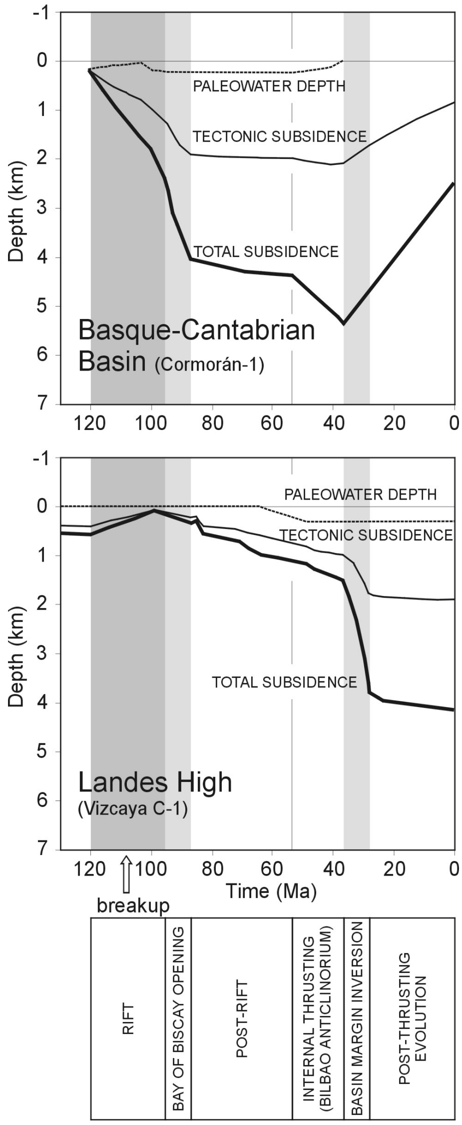

FIG. 8. – Subsidence analysis of the northern margin of the Basque-Cantabrian Basin and of the Landes Platform High.
FIG. 8. – *Analyse de la subsidence de la marge nord du Bassin basque-cantabrique et du plateau des Landes.*

After the Cenomanian-Santonian unconformity, at ~85 Ma, the tectonic subsidence was fairly constant and slow coinciding with the post-rift stage of the Basque-Cantabrian Basin. This subsidence pattern was interrupted by the onset of a slightly faster tectonic subsidence period during the early Tertiary at approx. 55 Ma, which lasted for approx.15 m.y. before the end of basin subsidence at about 37 Ma. The tectonic subsidence ended at ~40 Ma although the basin still subsided until 37 Ma, when uplift of the basin occurred by thrusting.

As discussed above, the Landes High displays a different vertical motion history. Uplift was the predominant process occurring at this rifted margin during both the early moderate basin subsidence stage and the early part of the rapid basin subsidence stage. This uplift culminated near the end of the rapid basin subsidence period linked to the pull-apart setting at approx. 100 Ma. This age roughly coincides with compressive events determined in the Mauléon-Lacq Basin and follows compressive events in the Organyà Basin in the southeastern Pyrenees [Berástegui *et al.*, 1990; Vergés and García Senz, 2001]. From late Albian to middle Eocene times the tectonic subsidence was slow and fairly constant ending with a stable period of several million years. This period preceded the onset of an abrupt increase in tectonic subsidence characterized by very high rates (fig. 8).

The geometry of the Landes High subsidence curve shows a period of continuous tectonic subsidence from the late Cretaceous (100 Ma) to the late Eocene (37 Ma) followed by a period of accelerated subsidence that lasted until the late Oligocene (28 Ma) (fig. 8). This subsidence pattern triggered the scarce and discontinuous deposition during the Cretaceous and early Tertiary (100-37 Ma), which contrasts with the rapid sedimentation in the late Eocene-early Oligocene interval (37-28.5 Ma) during the development of the foreland basin [Cámara, 1997]. From the late Oligocene to the present the subsidence did not undergo significant variations, the curve showing an almost horizontal trend.

TIMING OF DEFORMATION

The tectonic inversion of the northern margin of the Basque-Cantabrian Basin has been dated as Eocene [Soler *et al.*, 1981; Cuevas *et al.*, 1999], latest Eocene-Oligocene [Derégnaucourt and Boillot, 1982; Rat, 1988] and late Cretaceous-Eocene [Cámara, 1997]. The data presented in this work can help to clarify this important chronology of deformation, and its relationship to oil generation and migration.

The analysis of the tectonic subsidence of the northern side of the Basque-Cantabrian Basin and the southern part of the Landes High not only provides the timing of Tertiary inversion but also the progression of this deformation. During the early Eocene, at ~54 Ma the northern side of the thick Mesozoic Basque-Cantabrian Basin underwent a noticeable increase in tectonic subsidence after a long period of slow post-rift subsidence. This increase can be associated with the onset of significant compressional tectonic deformation affecting the southern and central regions of the basin. The NE directed Bilbao Anticlinorium, which involves basement units, represents the most suitable structure that led to an increase in the tectonic subsidence towards the foreland (fig. 2 and fig. 7). This tectonic event lasted for about 14 m.y. and then, after a short quiescent period characterized by continuous deposition, the northern boundary of the basin was inverted above a NE directed thrust system. This inversion resulted in an uplift of the whole region after 37 Ma.

By contrast, the southern side of the Landes High was characterized by a significant increase in tectonic subsidence at 37 Ma in response to the tectonic inversion of the marginal areas of the northern Basque-Cantabrian Basin. The Landes High acted during this period as a foreland basin receiving most of its terrigenous supplies from the Pyrenean Range to the E. This foreland period lasted for about 8.5 m.y., ending at 28.5 Ma. From 28.5 Ma to the present, the Landes High has remained stable with low sedimentation rates.

In the Landes High, part of the increase in the subsidence was due to the considerable amount of upper Eocene and Oligocene deposits imaged by the offshore wells. These deposits are relatively poorly dated in the Vizcaya C-3 borehole. Although we do not have solid arguments to support a different dating, the internal thrusting in the Oligocene sediments and the markedly reduced section of the Miocene to Plio-Quaternary deposits on top suggest that the presence of about 2,000 m of Oligocene deposits is an overestimation. In such a case, the tectonic subsidence determined in this study would be a maximum.

The correlation of these two areas of the Basque-Cantabrian region suggests a clear shift in the tectonic activity migrating from the centre of the basin inversion of the Bilbao anticlinorium to its northern margin along the North-Biscay anticlinorium. Further deformation migrated towards the Landes High where small-displacement basement thrusts affect the lower part of the cover succession (fig. 2 and fig. 3).

The two contrasting subsidence evolutions and tectonic chronologies in the northern Basque-Cantabrian Basin and the Landes High offer a number of possibilities for hydrocarbon exploration. On the basis of subsidence analysis and vitrinite data, we present the hydrocarbon maturity geohistory of the two studied sections (fig. 9).

In the northern Basque-Cantabrian Basin the two periods of significant burial (1) in the late Cretaceous, with an elevated heat flow, and (2) in the early Eocene led to the generation of hydrocarbons at 100 Ma and to their overmaturity before Tertiary uplift. In the Landes High the generation of hydrocarbons started after the main period of subsidence and rapid sedimentary infill (37 Ma). This generation was partially coeval with the final stages of the growth of the foreland structures. It should be pointed out, however, that most of the oil in the upper Cretaceous and Eocene successions generated (and continues to generate) after the development of the thrust-belt.

CONCLUSIONS

A new balanced and restored section from the Bilbao anticlinorium in the S to the Landes High in the N based on surface and subsurface data shows the present structure of the inversion tectonics of the northern margin of the Basque-Cantabrian Basin.

The restored section at the end of the Cretaceous shows the post-rift geometry of the basin and the mild inversion of the ancestral Bilbao anticlinorium.

The shortening calculated from large structures is 25 km (33 %). This figure must be considered as a minimum owing to the significant tightening of folds and the widespread existence of a strong axial plane cleavage. The shortening resulted in the formation of thrust-slices or overturned folds cored by evaporites along the northern basin margin and the sedimentary cover. The geometry of the evaporitic bodies in the pre-inverted basin could influence the style of frontal deformation.

Thermal modelling indicated that the best fit of the vitrinite data is obtained by combining a variable heat flow in concordance with the major tectonic episodes in the re-

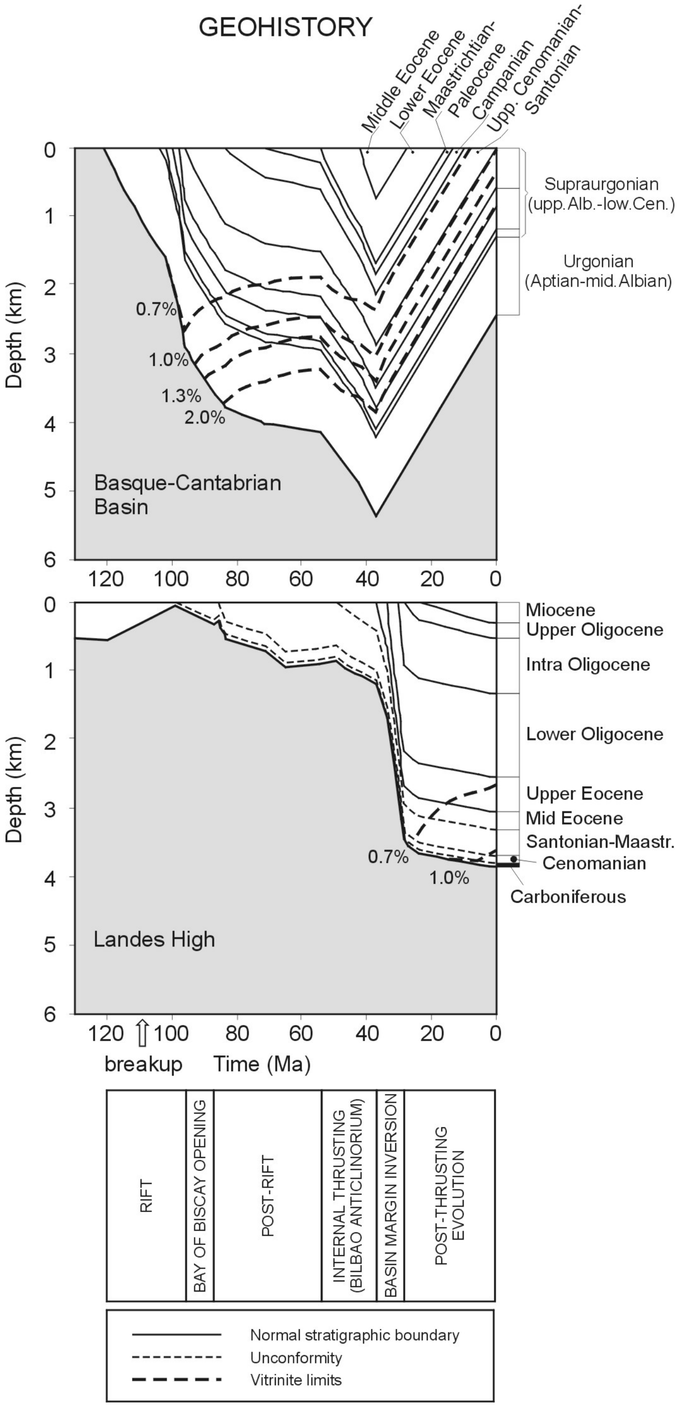

FIG. 9. – Geohistory and hydrocarbon maturity of the northern margin of the Basque-Cantabrian Basin and of the Landes Platform High. The isoreflectance curves to define the evolution of oil and gas windows through time are represented. %Ro < 0.7 : immature; 0.7 < %Ro < 1 : oil window; 1 < %Ro < 1.3 : peak oil generation; 1.3 < %Ro < 2 : condensate and wet gas zone; 2 < %Ro : dry gas zone.
FIG. 9. – *Histoire géologique et maturation des hydrocarbures de la marge nord du Bassin basque-cantabrique et du plateau des Landes. Dans le diagramme sont représentées les lignes d'isoréflectance : %Ro < 0.7 : immature; 0.7 < %Ro < 1 : fenêtre à huile; 1 < %Ro < 1.3 : production maximum d'huile; 1.3 < %Ro < 2 : zone à gaz condensé; 2 < %Ro : zone à gaz sec.*

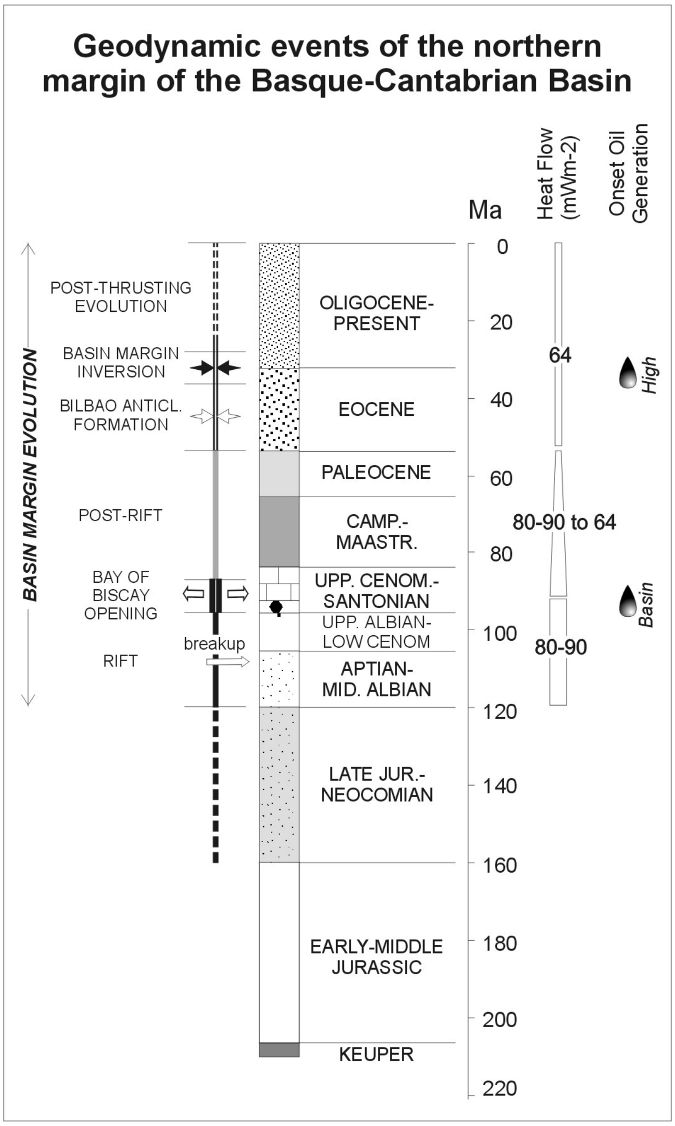

FIG. 10. – Geodynamic events for the northern margin of Basque-Cantabrian basin deduced from the subsidence analysis including proposed heat-flow values and timing of oil generation from Aptian to the present.
FIG. 10. – *Evénements géodynamiques pour la bordure nord du Bassin basque-cantabrique déduites de l'analyse de la subsidence incluant les valeurs de flux de chaleur proposées et la chronologie de la génération du pétrole de l'Aptien à l'actuel.*

gion, and the addition of approx. 1,800 m of Paleocene-middle Eocene deposits on top of the basin margin (fig. 10).

Tectonic subsidence modelling in combination with hydrocarbon maturity analysis suggests that oil generation started during the Mesozoic lattermost rift stage in the basin. Subsequently the basin underwent a thermal relaxation period, a stage of subsidence related to basement-involved folding in the hinterland and a final period of thrusting and exhumation. These processes led to the overmaturity of the lower Cretaceous outcropping sediments. In contrast, in the Landes High the oil generated after the Tertiary basin inversion and foreland basin development commenced at 37 Ma, resulting a present-day oil window which embraces upper Cretaceous to upper Eocene sediments.

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