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BAY OF BISCAY AND PYRENEES *

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– The different hypotheses proposed for the creation of the Bay of Biscay are reviewed. New geological and geophysical data collected in the last two years in the Bay and in the Pyrenean domain give new insight into the tectogenesis of the Pyrenees. Geological data of the Pyrenean area provide tight constraints on the hypothesis of formation of the Bay. The most probable hypothesis is an opening by rotation of the Iberian Peninsula around a pole of rotation situated near Paris, which resulted in strike-slip motion along the North Pyrenean fault during the Upper Mesozoic. A progressive westward migration of the pole initiated in the late Cretaceous blocked the motion along the fault and led to the main Eocene tectogenetic Pyrenean phase. –

1. Introduction

The structure of the Bay of Biscay is largely oceanic [1]. Its formation therefore implies a relative motion of the Europe and Iberia plates, as suggested earlier [2–4]. The only possible boundary between the two plates corresponds to the present location of the Pyrenees. Consequently, any hypothesis about the formation of the Bay of Biscay must be in agreement with the structural evolution of the Pyrenees.

A very large volume of geological and geophysical data collected in the Bay of Biscay and the adjacent continents has been published recently [1]. Yet, there is no agreement on the mode of formation of the Bay of Biscay and at least five different hypotheses have been presented. This paper will summarize the main pertinent geological facts and verify the compatibility of the proposed hypotheses with the structural framework of the Pyrenean domain. Structural data, acquired in the last two years, will be presented. They give new insight into the tectogenesis of the Pyrenees.

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2. Main facts and their immediate consequences in the Bay of Biscay

Within the Bay of Biscay, three main structural domains can be recognized: a central triangular deep part, deep marginal basins on each side, and continental margins (fig. 1).

From seismic refraction results [5, 6] and from the lineated pattern of magnetic anomalies [7, 8], the structure of the deep central part is oceanic. The acoustic character of the substratum is also typical of an oceanic layer 2 [9]. West of the Bay, N-S magnetic anomalies 31 and 32, against which the E-W Biscay magnetic lineations end, are continuous (fig. 1). This suggests that most of the Bay existed at the time of anomaly 32 (76 my), that is in the Campanian [10, 11]. Results of the two JOIDES drill holes 118 and 119 have shown that Paleocene marine sediments exist within the central part of the Bay [12]. Correlations of seismic reflection results with cores' stratigraphy indicate the presence of a rather thick sedimen-

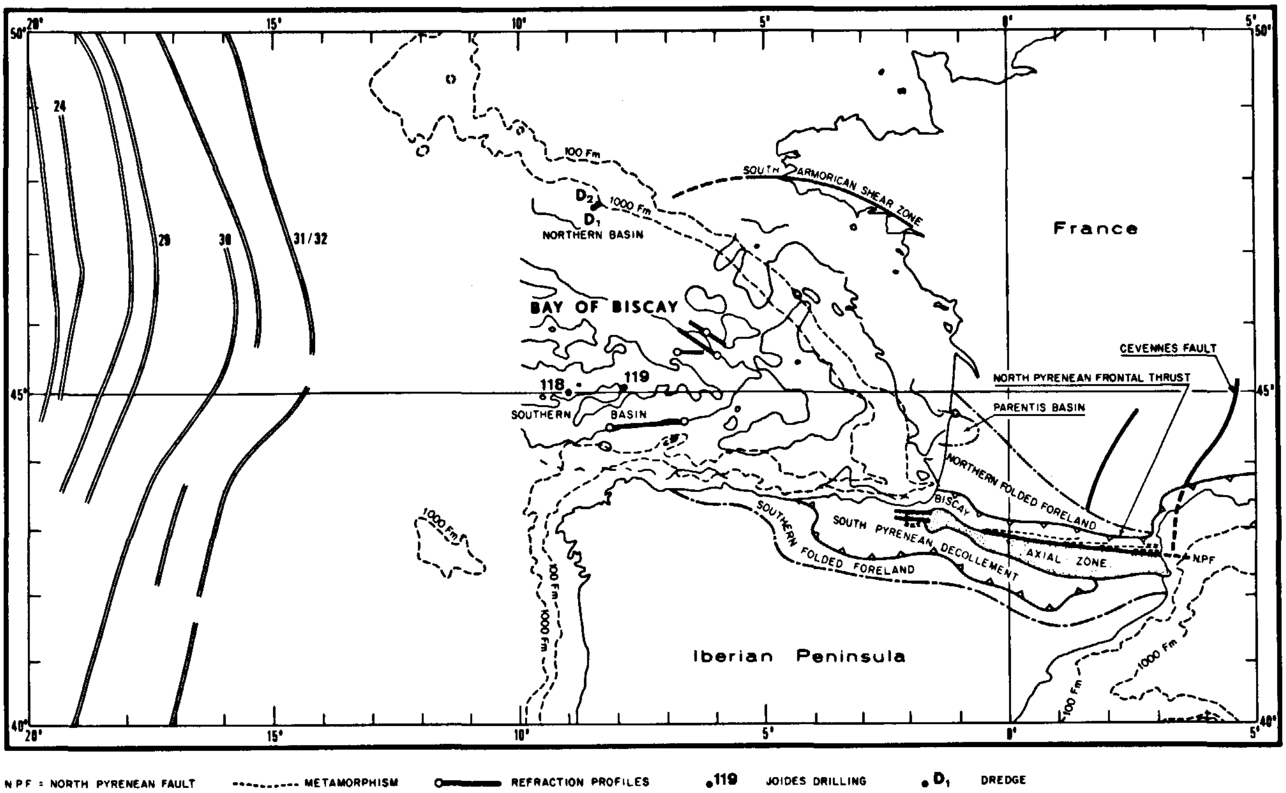

Fig. 1. General location map of the Bay of Biscay and the Pyrenean domain. Magnetic anomalies reduced to the pole after Galdeano [57]. See text for further explanation.

tary sequence below the Paleocene throughout the central part of the Bay. The probable age of the base of the sedimentary sequence is Upper Cretaceous if continuous sedimentation at a rate similar to the average rate during the Cenozoic is assumed or Lower Cretaceous if the sedimentation was very slow ("red clay" type) [9, 13]. Thus, at least the main portion or the central deep part of the Bay was created before the Paleocene but most probably after the Jurassic. On the basis of a detailed seismic reflection survey Sibuet et al. [9] and Montadert et al. [13] have both concluded that the central part of the Bay was affected by a minor tectonic phase during the Upper Eocene, with vertical tectonics and some igneous intrusions.

The nature (oceanic or foundered continent) of the deep marginal basins, which contain 5 to 6 km of sediments, is still controversial. The absence of magnetic lineations is notable [14]. Seismic reflection results indicate an increase in age of the base of the sedimentary filling from the central deep part to the continental margins. Diapirs which may be due to evaporites, are present [9, 13]. There is a striking asymmetry between the northern and southern basins. The northern basin has only been affected by subsidence, whereas the southern basin has been affected by tectonics, probably due to a limited overriding of the deep sea floor by the Spanish continental margin in Eocene time and later [9, 13]. Corings and dredgings on the Armorican continental slope have revealed that the continental margin began to subside approximately at the limit of the Jurassic and the Cretaceous. Neritic Lower Cretaceous (Aptian-Albian) sediments are now found at a depth of 3000 m. (D_1 and D_2 in fig. 1 [9]). Seismic reflection results also indicate a general monoclinal flexure of the continental margin during the deposition of the sedimentary sequence. To conclude, there is strong evidence for a large amount of subsidence of the continental margins and adjacent deep basins during the Cretaceous. This subsidence continued during the Cenozoic.

Important results on the continuation of the geological structure of the Armorican peninsula to the west onto the continental shelf [15–17] have been recently obtained from seismic reflection, rock coring and gravity studies on the continental shelf. A major late Hercynian shear zone (< 290 my), the South Armorican shear zone [18], extends up to 5.5°W cutting across the main Armorican structural units. The gravity pattern on each side of the shear zone is different. The amount of horizontal displacement along the shear zone may reach hundreds of kilometers. If such a large displacement has taken place all predrift reconstructions of continents, based on continuity of Hercynian belts across the Bay of Biscay, are suspect unless the displacement is restored [17].

3. Main facts and their immediate consequences in the Pyrenean domain

The main structural zones outlined in the Pyrenees [19–21] are shown schematically in fig. 1.

To the south of an axial zone made of Hercynian material, the South Pyrenean Mesozoic and Cenozoic series has been transported toward the south over large distances without any large plastic deformation [22].

To the north of the axial zone, the North Pyrenean zone contains the deep structural level of the belt. The Mesozoic series is intensely deformed and has been locally affected by syntectonic mesozonal metamorphic transformations [23, 24]. An important characteristic of this zone is the presence of a pattern of deep near-vertical E-W faults, the most prominent of which is the North Pyrenean fault, which already existed in Late Hercynian times (~290 my) [25–27] and along which the Cretaceous subsidence and the maximum post-Cretaceous deformation have been localized. Actually, this major fault may be considered to have determined the general rectilinear trend of the Pyrenees [27] and to have largely guided their structural evolution. This structural evolution will be summarized next with the series of sketches of fig. 2.

3.1. *Mesozoic movements of subsidence and distension**

The first significant movements of subsidence along Pyrenean trends occurred during the Trias and the Infra-Lias (190 to 225 my). They were accompanied by the deposition of large thickness of evaporites. A less subsident epicontinental marine basin persisted during the Lias and the Jurassic (136 to 190 my). At the end of the Jurassic, a general regression took place. During the Lower Cretaceous, the subsidence rate greatly increased within limited basins or troughs, mostly in the Parentis basin and in the North Pyrenean trough. During the Middle and Upper Cretaceous, an active continuous subsidence continued within narrow troughs which became filled by flysch sediments locally of Wildflysch type. The subsidence rate was always greater to the West than to the East.

Volcanic activity within the North Pyrenean zone and synsedimentary movements of the major North Pyrenean faults are two significant geological phenomena related to these movements of subsidence.

Tholeiitic basalts (often called "ophites" in the French geological literature) were erupted during the Trias [33] (190 to 225 my) and basaltic tuffs and flows during the Lias and the Infra-Lias (172 to 190 my). Peridotitic massifs made of lherzolite are found along the general trend of the North Pyrenean fault. In the Western Pyrenees, they are Cenomanian (94 to 100 my) or pre-Cenomanian as eroded fragments have been found within Cenomanian strata [34]. In the Eastern Pyrenees, they are Albian (100 to 106 my) or Post-Albian as Albian sediments have been clearly metamorphosed at their contact (unpublished observation of P.C., 1971). If the intrusion of the lherzolitic massifs occurred at the same time all along the North Pyrenean trough, it would indicate that such intrusion occurred in Albian-Cenomanian times. Volcanic activity of Upper Cretaceous age occurred within the North Pyrenean trough. These volcanics consist of undersaturated flows of syenitic composition [35], tholeiites near Lourdes and submarine alkali basalts in the Biscay Pyrenees [36, 37].

The pattern of predominantly vertical faults, with a dominant E-W trend like the North Pyrenean fault

*** Paleogeographic maps for different periods during the Mesozoic have been published [19, 20, 28–32].**

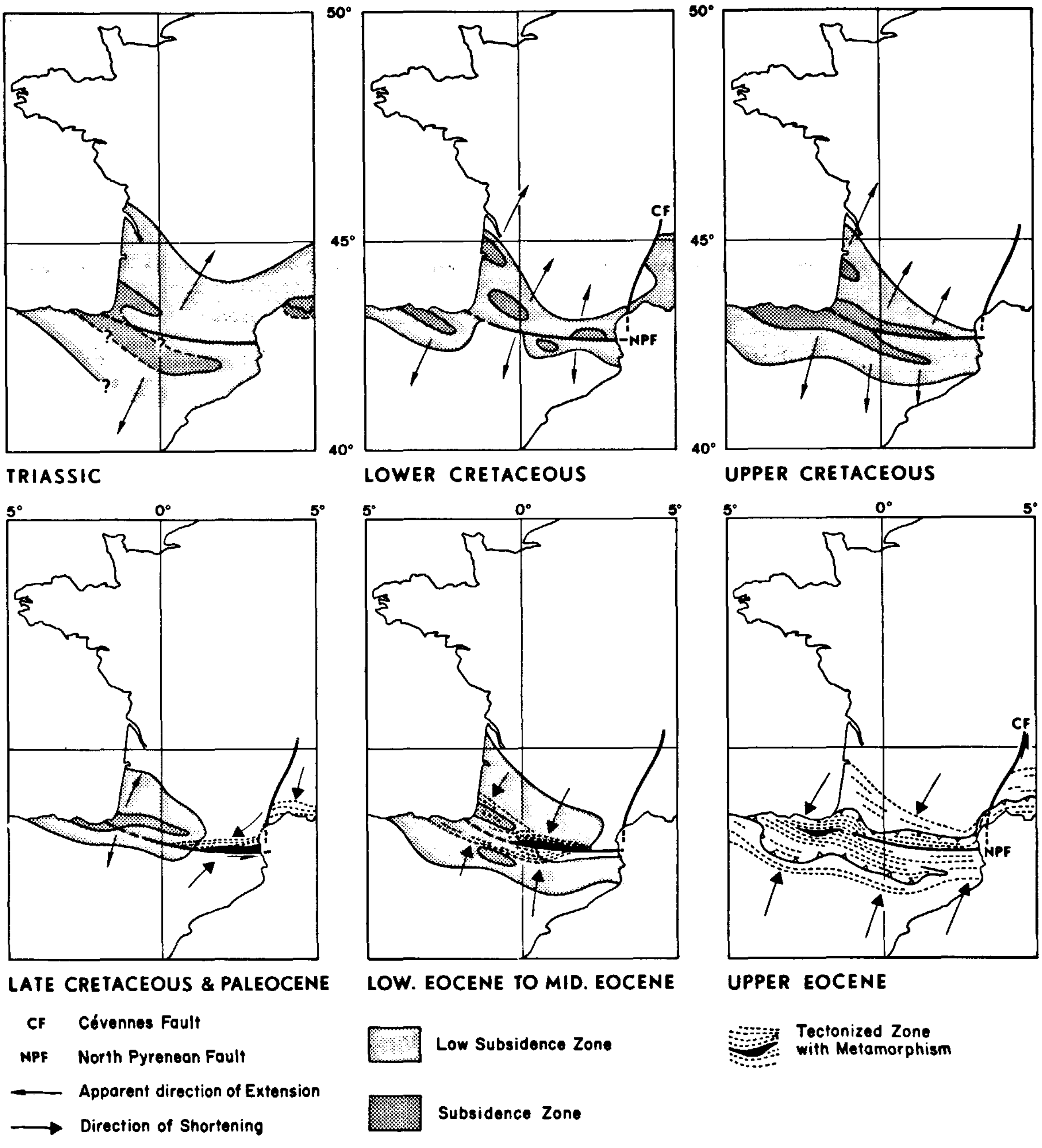

Fig. 2. Schematic diagrams showing the evolution of subsidence and the tectogenesis within the Pyrenean domain. There is no palinspactic reconstruction.

and a minor N-S trend, such as the Cevennes Fault [38] was active during the Jurassic and even more during the Cretaceous. The vertical movements along these faults are the origin of the earlier false hypothesis of a pre-Cenomanian folding phase within the Pyrenees [39]. These movements resulted in stratigraphic wedges, in disappearance of series on the topographic highs, and in abrupt lateral variations of facies

[27, 31, 40, 41]. Vertical offsets reach several thousands of meters locally, especially along the North Pyrenean fault.

The presence of synsedimentary normal faulting and of mostly basic or ultrabasic activity, within the most actively subsiding North Pyrenean zone, leads the authors to believe that the subsidence was associated with a significant distension, that is an apparent N-S extension of this part of the Pyrenean domain.

3.2. *Post-Cretaceous tectogenesis*

It had previously been proposed that there were two well-defined tectogenetic phases within the Pyrenean domain, at the end of the Cretaceous and during the Upper Eocene [19, 21, 42]. Recent results suggest that the deformation began at the end of the Cretaceous in the Northeastern Pyrenees and that it progressively extended westward, before the whole Pyrenean domain was affected at the end of Eocene times [43]. The main facts which lead to this notion of a time and space progressive tectonic phase are the following:

Syntectonic metamorphism of the Northeastern Pyrenees is of Late Cretaceous age [24, 42] (< 65 my). It is localized within a very narrow zone along the North Pyrenean fault. In this zone, the deformation is characterized by synmetamorphic folds with axes which become near-vertical close to the fault. The geometry of the folding and the nature and direction of the slicken sides on the fault planes indicate that there was a left lateral motion along the North Pyrenean fault during the Late Cretaceous compressive phase [43]. In contrast, at the same time (from the Cretaceous to the Eocene), there was in Biscay (Westernmost part of the Pyrenees) rapid subsidence and continuous sedimentation, without any angular unconformity. The metamorphism described in Biscay by Lamare [44], and which is of a type similar to the Eastern Pyrenees' metamorphism, is post-Ypresian, as it is contemporaneous of the tectonic which affects the Ypresian (49 my) of this region.

The Pyrenean domain was submitted to compression during most of the Eocene. On the southern flank of the Pyrenees, synsedimentary nappes were emplaced as early as the Lower Eocene and during all the Eocene [45]. This emplacement of nappes in a strongly subsident South Pyrenean basin can be interpreted as the result of a compression within a region further north, that is the present axial Paleozoic zone. Consequently, one is led to assume that the shortening of the axial zone of the Central Pyrenees had begun during the Lower Eocene to end during the Upper Eocene. In the Northwestern Pyrenees, oil exploration has revealed angular unconformity within the Lutetian (45 to 49 my) and even the Ypresian (49 my) over gentle folds which affect the base of the Eocene [46, 47].

To summarize, whereas the present Pyrenees are roughly cylindrical [19, 48], this cylindricity is apparently the global result of many shortenings of different ages across different traverses. The end of the Cretaceous within the Northeastern Pyrenees, most of the Eocene within the Central Pyrenees, and the Upper Eocene within the whole Pyrenean domain are periods of compression, presumably due to a net shortening between the Iberia and Europe plates (fig. 2). However, whereas left lateral movements along the North Pyrenean faults occur during the late Cretaceous tectogenesis, this is not true of the Eocene during which the direction of deformation are not compatible with a left lateral motion along E-W faults [21]. Finally, during the Oligocene and the Miocene, late compressive movements have weakly affected the external domains in the northern parts of the belt (frontal thrust of the Orthez region and Marginal Spanish Sierras).

4. Main proposed kinematic patterns of opening of the Bay of Biscay

Four of the principal hypotheses which have been proposed to explain the formation of the Bay and which are still debated are schematically shown in fig. 3. The fifth one [19] will be presented together with the fourth one [53]. In the following, these hypotheses will be briefly discussed in the light of the facts presented above, especially those which concern the Pyrenean domain.

4.1. *The scissors-opening of the Bay (fig. 3A)*

The first and most obvious hypothesis explains the formation of the Bay by an opening analogous to the movement of scissors with a pole of rotation somewhere along the Pyrenees [2–4, 49–51]. Carey [49]

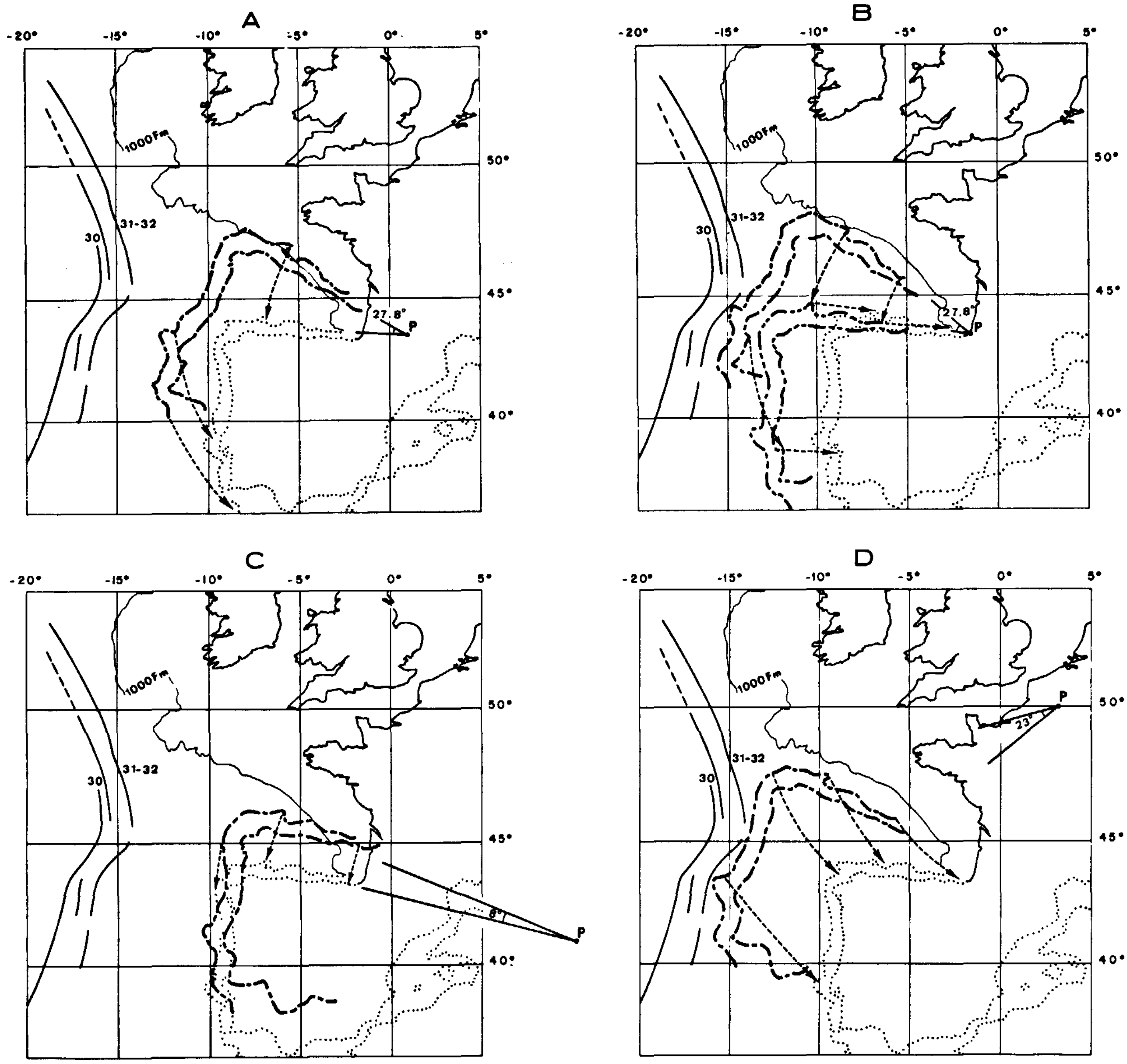

Fig. 3. Schematic diagrams corresponding to the four main hypotheses of opening of the Bay. See text.

points out that the opening would explain the compressive formation of the Pyrenees, if the pole of rotation is situated just west of the mountain belt. This implies that the formation of the Bay is exactly contemporaneous of the Pyrenean tectogenesis and that the geometry of shortening varies extremely rapidly along the Pyrenees. Shortening varies between 0 near the pole to up to 200 km, depending on the extract position of the pole (see fig. 3A). There are three major objections to this hypothesis. The formation of the Bay is mostly pre-late Cretaceous at a time when there was only extension within the Pyrenean domain. The very large variation in the rate of shortening along the Pyrenees is hard to reconcile with the approximate global cylindricity of the Pyrenees [27]. Finally, the preopening reconstruction leaves a gap west of Portugal [51].

4.2. *The two phases opening (fig. 3B)*

Bacon and Gray [52] propose a solution which apparently overcomes the previous difficulty by assuming "that the rotation about a pole at the western end of the Pyrenees left Iberia in a position (relative to Europe) several hundred km to the west of its present one". Then "a pre-Cretaceous west to east movement of Iberia of some hundreds of km" restores Iberia to its present position. In plate tectonic terms, the Bay opens in Jurassic or earlier times by a rotation about a pole near the present western end of the Pyrenees, followed by a Late Jurassic rotation with a pole much farther north, which resulted in E-W left lateral strike-slip along the North Pyrenean fault and the North Spanish trench. They assume that there is in Jurassic times an oceanic area east of Iberia and consequently south of the Pyrenees and that an active consuming plate boundary (trench-cordillera system) is present along the present location of the Pyrenees. This consuming plate boundary would have absorbed 200 to 300 km of oceanic plate in the Eastern Pyrenees and a much larger amount farther east. As discussed earlier, Jurassic times are marked by slow subsidence and by some distension. There is no volcanism of calc-alkaline type or tectonic evidence of such a Jurassic consuming plate boundary anywhere. It would be equally difficult to assume that such an active plate boundary existed in Trias or Cretaceous times. In addition, it is geologically unlikely that a large oceanic area existed east of Iberia and south of France in Mesozoic times. Rather, it is probable that Corsica and Sardinia were connected to Iberia and would consequently have been situated somewhere south of the Pyrenees. Finally, the North Spanish trench is offset by about 80 km from the North Pyrenean fault and the geometry of the episode of strike-slip motion is consequently difficult to accept.

To summarize, the whole Mesozoic era is a period of subsidence and limited distension within narrow troughs, with basic and ultrabasic activity and without any evidence, whether volcanic or tectonic, that an active consuming plate boundary existed anywhere. Consequently, the hypothesis seems rather improbable, especially in view of the fact that it implies a pre-Cretaceous age for the opening of the Bay.

4.3. *The Corsica pole of opening (fig. 3C)*

Montadert and Winnock [30] propose that the Bay is only the westernmost end of a zone of tension which probably extended all the way to Provence, with a rotation not exceeding 10–20°. In plate tectonic terms, the pole of rotation is on the eastern extension of the axis of the Pyrenees, somewhere near the southern end of Corsica. Consequently, the opening of the Bay in Mesozoic times is accompanied by more limited extension east of it in the Pyrenean domain. However, pushing the pole farther east has two drastic consequences. First, the angle of rotation diminishes (8° in fig. 3C) and the edges of the continents have a large angular mismatch. Second, the amount of extension diminishes linearly to the east and is still a minimum of 150 km in the Aquitaine basin, even if one considers only the deep central part of the Bay as oceanic. The resulting preopening reconstruction in fig. 3C is clearly impossible and should be rejected.

4.4. *The Paris pole opening (fig. 3D)*

Le Pichon et al. [53] propose that the opening occurred in one single rotation, with a pole near Paris, thus resulting in opening within the Bay and in simultaneous left-lateral strike-slip along the North Pyrenean fault in the pre-late Cretaceous and mostly in post-Jurassic times (although the beginning of break-up probably occurred in the Triassic as it has been also proposed by Mattauer and Seguret [19]). This hypothesis was partly based on an interpretation of the aeromagnetic map of the Bay of Biscay [8]. The hypothesis was developed in a series of papers [54–56]. The finite rotation about the Paris pole is equivalent to the composition of the two rotations of Bacon and Gray [52].

The major problem with this hypothesis (and of course also with the Bacon and Gray's hypothesis) is the apparent absence of continuity of the North Pyrenean fault in the Western Pyrenees [19]. This has led Mattauer and Seguret [19] to propose a modification of the hypothesis. They first noted that the Cretaceous phase of distension was more developed to the west than to the east, which implies a limited amount of anticlockwise rotation not exceeding, in their opinion, 7 or 8°. They noted further that the Late Cretaceous tectonic phase in the Northeastern Pyrenees occurred while subsidence continued to the west. This fact also implies a small amount of rotation about a pole situated halfway through the Pyrenees. The total Mesozoic rotation may possibly explain up to one half of the opening of the Bay of Biscay. Mattauer and Seguret propose that the other half had been produced previously, during a Triassic phase of opening, by rotation about a pole near Paris. They point out that there cannot be any geological evidence either for or against large-scale left lateral displacement during the Triassic.

As reported earlier, since the publication of this article, recent discoveries by workers from the Montpellier laboratory show that the Late Cretaceous eastern orogenic phase is restricted to a narrow band on each side of the North Pyrenean fault, and that there is evidence for left lateral motion along the fault at this time. In addition, these discoveries suggest that the evidence obtained from surface cartography and oil exploration does not disprove the existence of major E-W strike-slip faults in the western area. Rather, synsedimentary and (or) pre-Upper Middle Cretaceous strike-slip faults may well be present in this area, as will be shown now.

Below the Middle and Upper Cretaceous strata, which are very thick in this region, the Jurassic and lower Cretaceous substratum has a highly irregular repartition [31]. This repartition may be explained by synsedimentary activity of Cretaceous faults. It is remarkable that one of these faults is marked by the presence of lherzolite bodies along its trend. Eroded blocks of lherzolite have been found in the Cenomanian strata in the Oloron Sainte Marie region. The presence at the surface of ultrabasic rocks suggests that it is a major fault which acted while or just before sediments were being deposited. The synsedimentary nature of the faulting could be the major difficulty in the detection of the horizontal component of movement along these faults. To give a modern analogy, we suggest that the western part of the North Pyrenean system was similar to the part of the San Andreas system between the gulf of California and the Transverse Ranges.

We briefly mention another argument which has been advanced against this hypothesis: the approximate continuity of the Jurassic neritic facies on each side of the Pyrenees [30]. There is no reason to deduce from this apparent paleogeographic continuity a structural continuity and consequently the validity of the argument is not accepted.

On the contrary, it seems that many structural facts can be explained within the framework of the hypothesis of a Cretaceous rotation about a pole near Paris: in particular the coincidence of the narrow sedimentary troughs, the deep zone of major faulting and the hypothetical transform faulting region and the occurrence of left lateral movement of unknown amplitude along the North Pyrenean fault during the Late Cretaceous phase. However, it is difficult to think of possible structural geological markers on each side of the fault which could be used to establish independently the amount of displacement which has occurred along it.

5. Conclusion

The hypothesis of a Cretaceous opening of the Bay of Biscay with simultaneous pure shear along the North Pyrenean fault can account for the geological and geophysical data within the Bay and the continental domain. This hypothesis, while still quite schematic, gives a coherent frame in which the geological facts concerning the evolution of the Pyrenean domain can be integrated. Conversely, these facts suggest that the model should be somewhat modified. While the shear faulting is the major phenomenon, a variable much smaller N-S component of movement which induces extension or compression depending on the location and the period has to be assumed [19].

During Cretaceous times, the distension implies that the large shear, in the hundreds of km along the North Pyrenean fault system was accompanied by a N S extension of a few km, thus explaining the subsidence of the troughs. The increasing subsidence toward the west shows that the N-S extension increased toward the west. During the late Cretaceous synmetamorphic tectonic phase of the Northeastern Pyrenees, which is associated with left lateral shears, the shear ceases to be the dominant phenomenon and a component of N-S compression appears to the east.

This compression progressively extends to the west. By lower-Middle Eocene, there is no more shear but only compression and by Upper Eocene, the collision of the Iberia and Europe plates is essentially terminated. This evolution can be interpreted as due to the progressive migration from east to west of the pole of rotation with respect to the near Paris position, which corresponds to pure shear. The movement of opening of the Bay ceased when the migration of the pole led to pure compression along the whole North Pyrenean fault system.

From the paleomagnetic results Zijderveld and Van der Voo [57] and Stauffer and Tarling [58], indicate a post-Kimmeridgian (< 146 my) to pre-Upper Cretaceous rotation of Iberia with respect to Europe, which is compatible with our hypothesis. However, the results are difficult to interpret and are apparently still quite controversial.

The kinematics of this opening can best be tested by a closely spaced magnetic survey west of the Iberian peninsula [56]. A more accurate interpretation of the aeromagnetic map of the Bay, with a one km spacing instead of a 10 km spacing between data points, has already given some confirmation of the validity of the proposed kinematic pattern [59].

Acknowledgments

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