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AEROMAGNETIC SURVEY OF SOUTH-WESTERN EUROPE

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—The results of a precise and homogeneous aeromagnetic survey covering the Bay of Biscay, France, and the North Western Mediterranean are presented. The results suggest that the Bay of Biscay and the Mediterranean basin were created since the Triassic by drift of the adjacent continents. Indications are given about the times and geometries of opening of these basins. The implications of these results on the Mesozoic and Cenozoic tectonic history of South-Western Europe are important. —

1. Introduction

The Mesozoic and Cenozoic tectonic history of South-Western Europe is controlled in a large part by the structural history of the Bay of Biscay and the Western Mediterranean Sea. These two areas may be oceanic structures created by drift of the adjacent continents since the Triassic, as suggested by recent research on the plate tectonics of the Atlantic Ocean. Thus, one would expect that they be characterized by a magnetic pattern completely different from the pattern over the surrounding continents. In this case, the oceanic magnetic pattern would be dependent upon the geometry of opening of the ocean and the epoch at which it opened. Alternatively, the Bay of Biscay and the western Mediterranean may represent foundered portions of continents, in which case one would expect the magnetic pattern to be essentially continuous across the continental margins.

In this paper, we report the main results of an aeromagnetic survey covering the Bay of Biscay, France, and the North Western Mediterranean sea. It is planned to extend this survey towards the South and then the West. We show that the results support the first hypothesis and provide important data for the plate tectonic history of this area. A detailed interpretation will be published elsewhere [1]. The anomaly maps* and the methods of measurement and data reduction have been described in an earlier paper [2].

We will first briefly describe the methods used in reducing and interpreting the data. We will then describe the distribution of the magnetic sources and examine in more detail the Bay of Biscay and the Western Mediterranean.

2. Data and data reduction

Since 1964, 140 000 km of aeromagnetic tracks have been flown over the Bay of Biscay, France, and the North Western Mediterranean as a part of a systematic survey of South Western Europe. The homogeneity

* Maps are sold by Bureau de Recherches Géologiques et Minières (Direction du Service Géologique National), B.P. 818, 45, Orléans-La-Source, France.

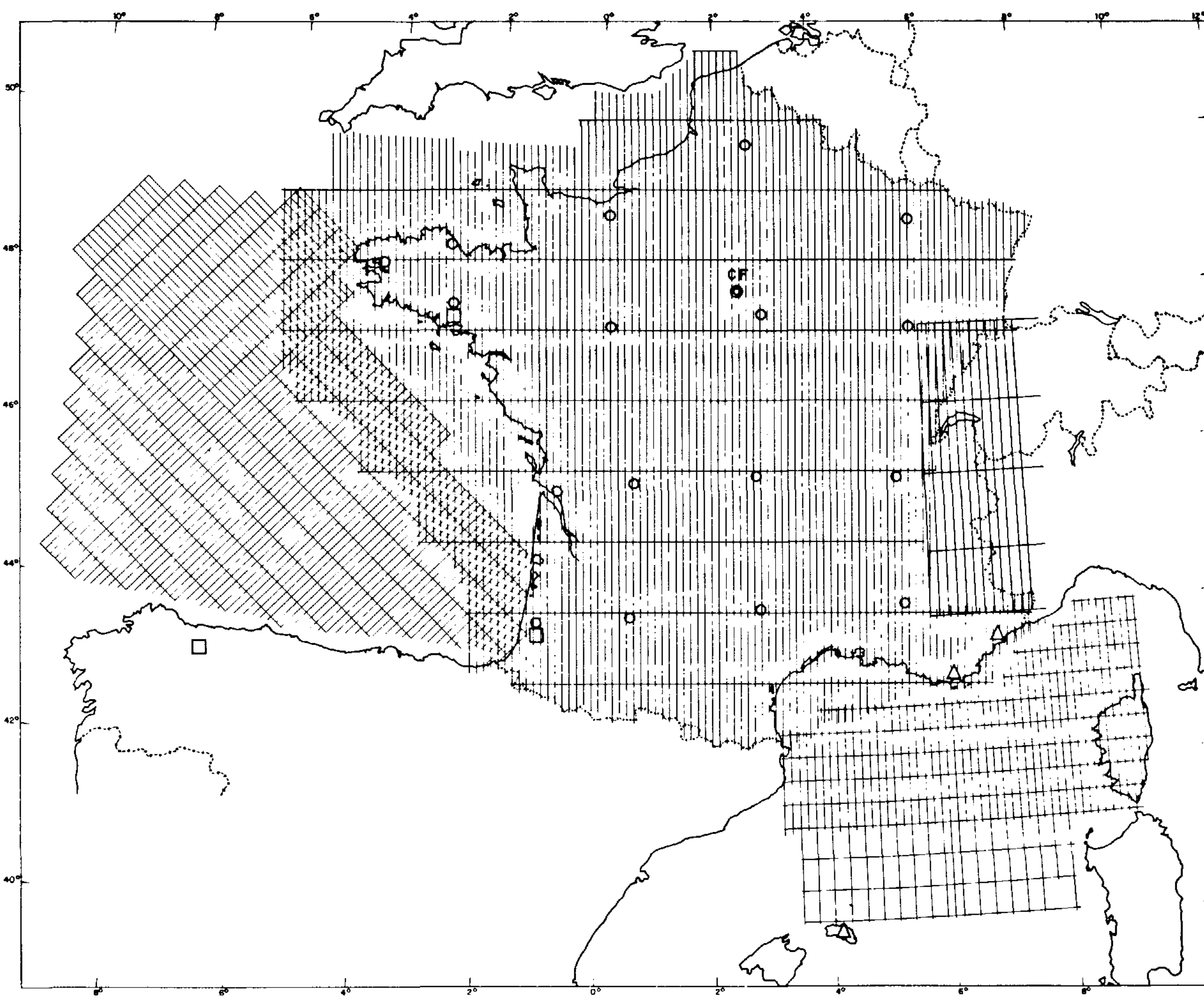

Fig. 1. Track chart; circles, triangles and squares are the reference stations for zones I, II and III of fig. 2; double circle is the base station of Chambon-la-Forêt.

and precision of this survey are excellent. The two main objectives were to give a description of the global magnetic field within the World Magnetic Survey and provide informations on the structure of the crust and upper mantle within the Upper Mantle Program. These imposed tight constraints on the absolute precision of measurement and the density and homogeneity of the flight plan.

Fig. 1 is a flight line chart of the survey, which was realized in three stages between 1964 and 1969. The flight altitude was 500 m over the Bay of Biscay survey, and 3000 m otherwise except over the Alpine zone (5000 m). A spacing of 10 km was adopted between the lines, which were oriented NE–SW over the Bay of Biscay to be perpendicular to the trends of the anomalies, known from shipboard measurements [3]. The spacing between tie-lines is closer over the sea (40 km) to allow a better correction of the magnetic diurnal variation. The positions were determined to better than 50 m and the altitude to better than 30 m. Measurements of the Earth's field total intensity F were made every second with an optically pumped

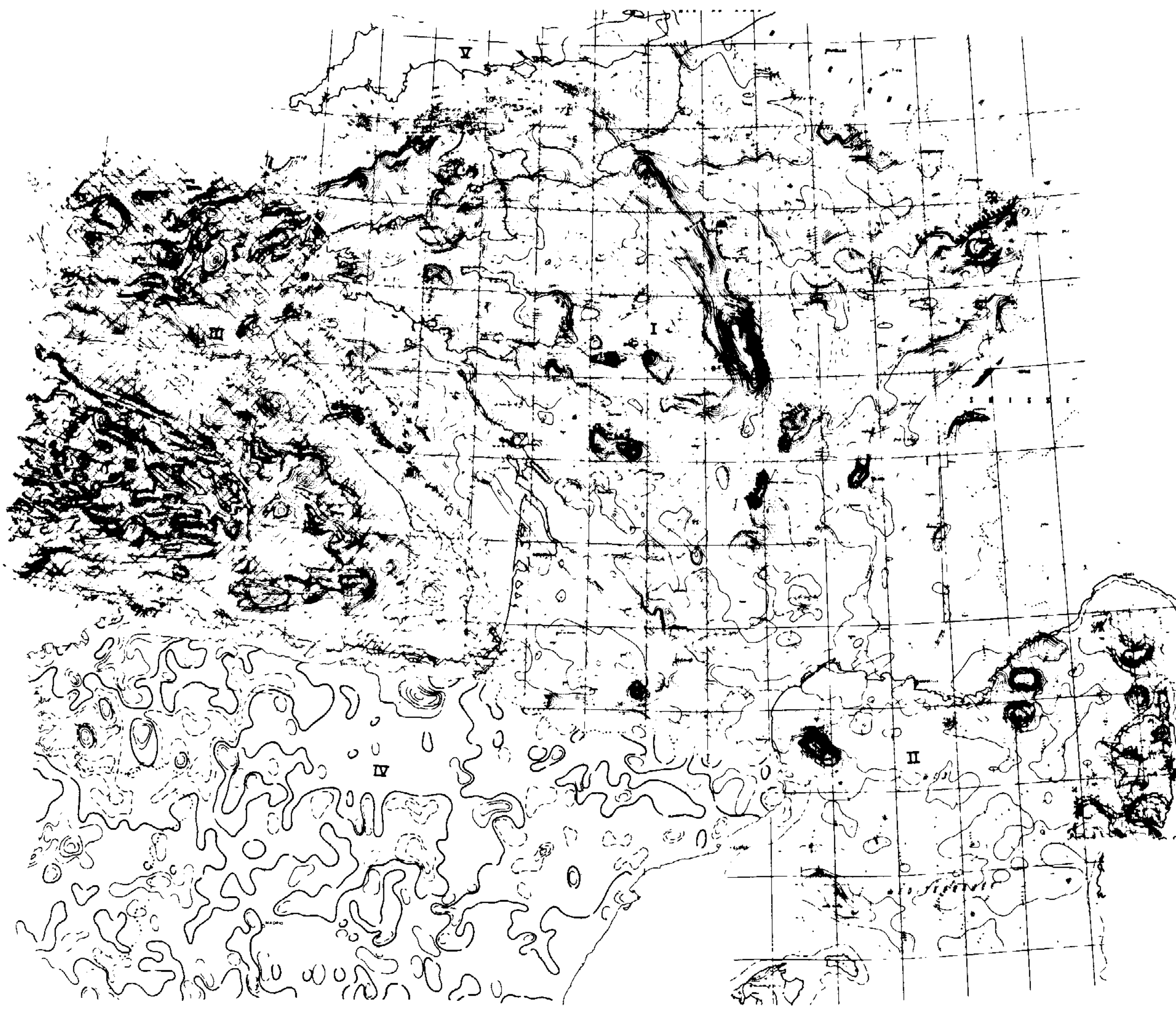

Fig. 2. Magnetic anomaly map. I and II. France and North Western Mediterranean surveys, 3000 m, CNRS-IPG Paris; III. Bay of Biscay survey, 500 m, CNRS-IPG Paris; IV. Spain map from H and Z ground measurements I.G.C. Madrid; V. Great Britain survey, 300 m, Ordnance Survey. I, II and III, 10 γ spacing; IV and V, 50 γ spacing. Negatives are dashed.

magnetometer and corrected for temporal variations with the help of records from fixed stations regularly distributed as shown in fig. 1. The values at each point were reduced to the annual mean $\bar{F}$ 1964,5 for the first part of the survey over France, $\bar{F}$ 1966,5 for the part over the Mediterranean and $\bar{F}$ 1969,5 for the part over the Bay of Biscay. The absolute precision of the reduced values is 3 to 4 gammas in general and 7 gammas over the Bay of Biscay.

The anomalies of the total intensity field over France and the Mediterranean were obtained by removal of a normal field computed by fitting by least squares a second order polynomial *. Over the Bay of Biscay, the IGRF was taken as the normal field.

* Le Mouël has shown that the difference between the second and third order fit does not exceed 4 to 5 gammas anywhere [9].

Fig. 2 is a map of the magnetic anomalies over South-Western Europe. In addition to the survey described above, the anomalies over Spain have been obtained from ground measurements of H and Z by the Instituto Geografica y Cadastral of Madrid, and the anomalies over the northern part of the Channel from an aeromagnetic survey at a height of about 300 m, compiled by the Geological Survey and published by the Ordinance Survey, Chessington, Surrey, 1965.

3. Numerical interpretation techniques

In order to arrive at a structural interpretation of oceanic areas on the basis of magnetic anomalies, it is necessary to determine the pattern of distribution of anomalies, their possible linearity and the major faults which may disrupt them. Instead of trying to compute various parameters concerning individual anomalies, it is often more efficient to use numerical transformations of the distribution of measured anomalies.

In particular, this distribution is distorted with respect to the distribution of the sources by the non verticality of the present field and of the magnetization vector of the sources. It is to eliminate or at least to attenuate this distortion that Baranov introduced in 1957 [4] the transformation which is called reduction to the pole. In this transformation, one computes what the distribution of anomalies would be if both the present field $\mathbf{v}$ and the magnetization vector $\boldsymbol{\gamma}$ were vertical. One has to assume that the direction of magnetization of the sources is known and uniform over the whole zone (however slight variations can be taken into account). In practice, one is led to assume: either that this magnetization is entirely remanent and that its average orientation may be deduced from paleomagnetic data, or that it is entirely induced. Intermediate hypotheses can be made provided one assumes a constant ratio of remanent to induced magnetization, which is hazardous.

One can attempt to test the validity of the assumption made concerning the dips of the magnetization vectors. Let us consider a distribution of anomalies $A(x,y)$ produced by a random distribution of sources of uniform direction of magnetization and its autocorrelation function C for vector $\boldsymbol{\tau}$.

$$C(\boldsymbol{\tau}) = A(x,y) \times A(-x,-y)$$

x and y being the cartesian coordinates in the horizontal plane. Curves of equal value of C in the xy plane have approximately the shapes of ellipses whose small axis has a direction intermediate between the projections of $\mathbf{v}$ and $\boldsymbol{\gamma}$ on the horizontal plane. When $\mathbf{v}$ and $\boldsymbol{\gamma}$ are vertical, these curves become circles*.

In nature, the distribution of the magnetic sources is not random but has a definite pattern. Part of the correlation is due to this pattern. However, while this part predominates at large values of τ, its effect is generally quite small at small values of τ where the effect of the non verticality of $\mathbf{v}$ and $\boldsymbol{\gamma}$ predominates. We will consequently limit our test of the validity of the reduction to the pole to small values of τ.

As vertical derivatives result in a better resolution of the sources, it is often useful to compute derivatives of order K of the anomaly reduced to the pole**.

The reduction to the pole eliminates or attenuates the anomalies which are edge effects produced by the dip of the magnetization vector. One can then more easily estimate the distribution of polarities of magnetization on the transformed map. Provided the regional field has been properly removed and the zones considered have enough homogeneity, one can obtain qualitative estimates of this distribution by computing its histogram. If the anomalies are mostly due to induced magnetization, there will be a predominance of sources of positive polarity. Areas covered by small negative anomalies will in general be much larger than those covered by large positive anomalies. If the anomalies are mostly due to remanent magnetization, as in the Vine and Matthews model [6], there will

* See, for autocorrelation functions of anomalies due to simple magnetic models, A.Spector and B.K.Bhattacharyya [5].

** The derivative of order K of the anomaly reduced to the pole is a linear operator whose gain can be expressed as follows

$$G(\rho,\theta) = \rho^K \frac{\cos J_{a1}}{\cos J_1} \frac{\cos J_{a2}}{\cos J_2} e^{i(J_{a1}+J_{a2})},$$

where ρ and θ are polar coordinates in the Fourier transform plane, θ being counted from the magnetic East, J_1 is the complement of the dip of the present magnetic field vector, J_2 the complement of the dip of the source magnetization vector, and J_{a1} and J_{a2} are the apparent dips of these two vectors in the vertical plane having θ as a trace.

probably be as many sources of positive as of negative polarity. Heirtzler et al. [7] have shown that, during the last 80 my, there has been about as much time when the geomagnetic field has a positive polarity as a negative polarity. Thus, an asymmetrical histogram indicates a predominance of sources of one polarity whereas a symmetrical histogram indicates a probable equality between sources of positive and negative polarity and is compatible with a distribution of anomalies according to the Vine and Matthews model.

Having obtained the areal distribution of the sources, one can obtain a global estimate of the average depth of the sources within zones which appear homogeneous. Two of these techniques will be used here.

(i) We will compute a magnetized topography corresponding to a given distribution of anomalies by a method proposed by Hahn [8]. For each average depth of this magnetic layer, there is a minimum value of the magnetization below which the calculation is not possible [9]. This minimum value grows first slowly with depth until one reaches a limit depth beyond which it grows quasi-exponentially. This limit depth can be considered an estimate of the maximum possible depth of the upper surface of the sources.

(ii) We will also compute the autocorrelation function (a.c.f.) of the observed (or transformed) distribution of anomalies and compare it to theoretical a.c.f. associated with random distributions of prismatic sources with vertical walls. This type of source is similar to those responsible for the anomalies in the Vine and Matthews model and in this case gives a unique solution if the thickness and width of the prisms is properly chosen.

4. Distribution of magnetic sources

A rapid inspection of fig. 2 confirms that the anomaly patterns over the Bay of Biscay and over the North Western Mediterranean are quite different from the anomaly pattern over the adjacent continent. If one takes into account the height of measurement over the magnetic basement, the anomalies have amplitudes several times larger over the Bay of Biscay, the South-Western Channel and the North-Western Mediterranean than over the adjacent continent. It is not possible to consider the patterns of anomalies in these zones to be the continuation of the patterns of anomalies over the adjacent continents. This makes very tenuous the hypothesis that foundered continents, which are the structural prolongations of the adjacent continents, exist below these bodies of water.

4.1. *France*

We will not give here a geological interpretation of the magnetic anomalies over France. Note, however, the most obvious anomaly, which is the Parisian Basin anomaly extending NNW–SSE over 450 km from the middle of the English Channel to the Massif Central. It forms with the anomaly occupying the axis of the Channel a 90° angle whose apex is truncated by E–W lineations visible on the British map. Computations made by Le Mouël [9] suggest that it is caused by an igneous intrusion 10 km wide and 5 to 6 km deep, having an average susceptibility of 2×10^{-3} emu. This set of anomalies, which has a total length of about 1000 km, is a major structural feature of South-Western Europe, yet it is poorly understood geologically. Near the apex, Lapierre et al. [10] describe faults which are parallel to the anomalies which were already active at the Jurassic Cretaceous boundary and then in the Lower Tertiary. Similarly, above the Parisian Basin anomaly, faults along the anomaly have been active at least since Jurassic [11]. Note also that the southwestern prolongation of the Channel anomaly ends in a zone of strong linear anomalies similar to those over the Bay of Biscay.

It seems logical to attribute the whole system to a common cause. Wide linear igneous intrusions are best explained by an episode of extension, which, in this case, should be Jurassic or older and may be related to the extension which should have accompanied the opening of the Bay of Biscay. The history of subsidence of the Parisian Basin and probably also of the Channel syncline, begins at the end of Triassic times. This is the time at which the separation between Africa and North America began, according to deep sea drilling results (see Ewing et al. [12]).

4.2. *Bay of Biscay*

Figs. 2 and 8 show that the magnetic pattern over the Bay of Biscay is greatly different from the magnetic pattern over France or Spain. A zone, with well defined magnetic lineations, is fringed toward the North and East by a magnetically quiet zone which extends

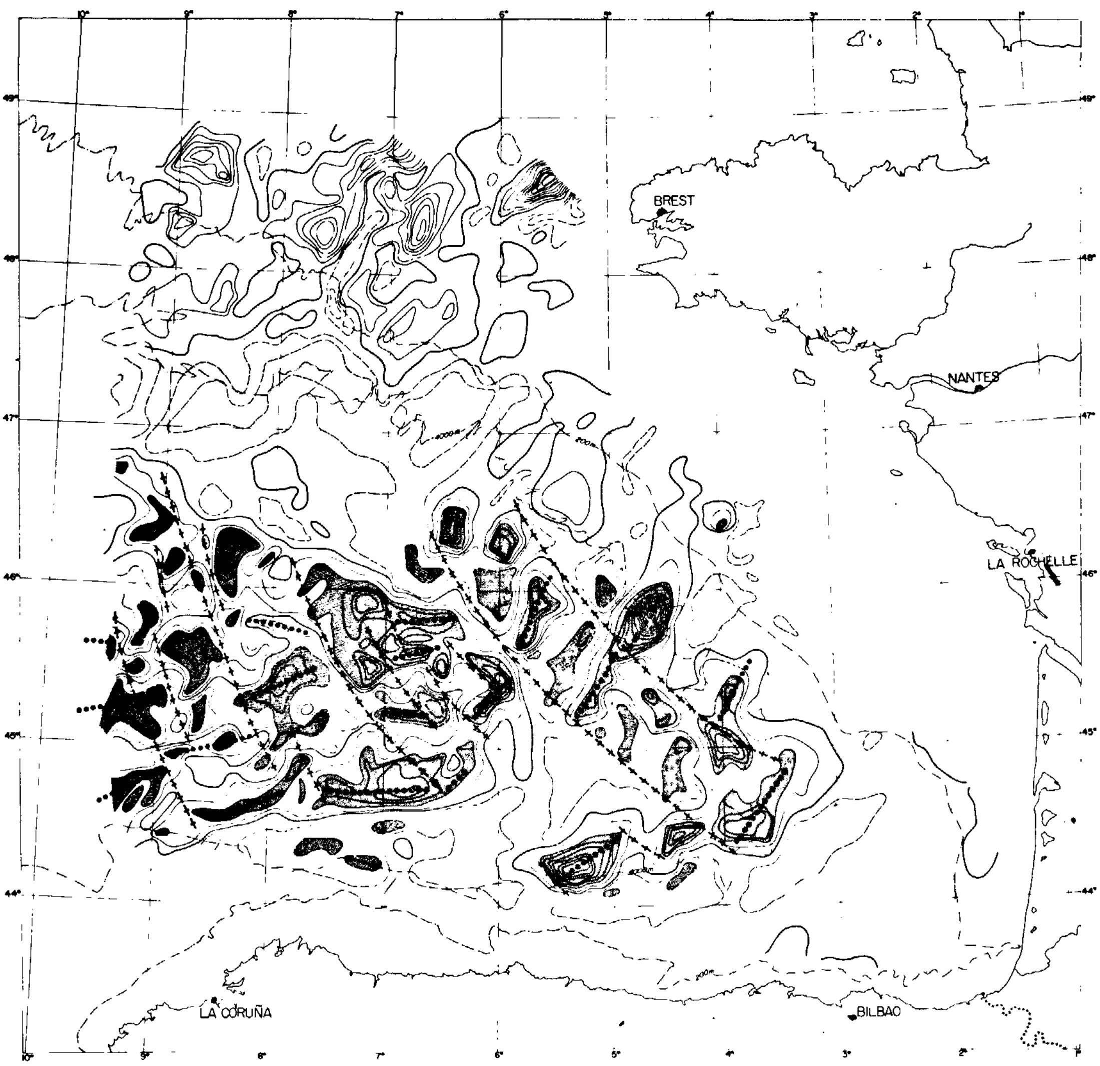

Fig. 3. Map of the anomalies reduced to the pole over the bay of Biscay. Magnetization parameters: $I = 25°$, $D = 25°$ E. 50γ spacing. The anomalies of intensity > 100γ are gray; - - - - are negative isograms; dotted lines are axes of anomalies; + lines are lines of disruption of anomalies.

to the edge of the Armorican shelf. These lineations are entirely within the limits of the isobath 4000 m. Their similarity with the magnetic lineations over the South-Western Channel has been noted above.

Recent geological and geophysical studies indicate that the Bay of Biscay already existed as a deep sea gulf at the end of the Cretaceous and suggest that the Bay was created in Middle Mesozoic time [13]. Similarly, paleomagnetic data suggest that the Iberian peninsula rotated away from Europe between Triassic and Upper Cretaceous time, probably during lower Cretaceous [14, 15]. This would imply a dip much smaller than the present one for the remanent magnetization of the oceanic basement created during this time, as the Triassic magnetic pole is near 45°N, 140°E and the Cretaceous pole near 60°N, 165°E [15].

We have consequently computed the reduction to the pole of the anomalies over the Bay of Biscay with

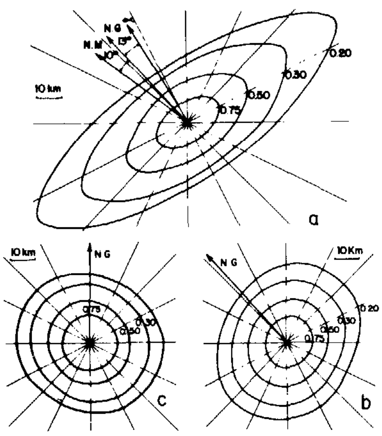

Fig. 4. Normalized auto-correlation functions (see text) (a) initial anomalies of Bay of Biscay; (b) anomalies reduced to the pole of Bay of Biscay; (c) anomalies reduced to the pole of the Mediterranean.

an inclination I of 25° and a declination D of 25°E for the magnetization vector instead of the present inclination of 65° and declination of 10°W. Fig. 3 shows the resulting map of the transformed anomalies. That this choice of parameters is reasonable is shown in fig. 4, using the test described earlier. The curves of equal value of the normalized autocorrelation function of the initial distribution of anomalies have roughly the shape of ellipses (fig. 4a), whereas the a.c.f. of the anomalies reduced to the pole is nearly radial (fig. 4b). Actually, the best values of D and I, according to this test, seem to be D = 13°E and I = 25°. However, somewhat different parameters would not significantly affect this conclusion. The important point is that when the magnetic sources were created, the magnetic pole must have been at a lower latitude close to a Mesozoic position rather than to its present position. This is another indication that the Bay of Biscay was created during Mesozoic times. This conclusion has important implications for the exact configuration of the distribution of magnetic sources, as large changes are produced by this reduction to the pole, due to the very low dip of the field. Most anomalies are displaced northward (by several tens of km for some of them), and large anomalies which exist on the initial map, and are in fact edge effects, disappear on the reduced map.

Another important result is obtained by the study of the distribution of polarities of magnetization. Using a best fit normal field over the Bay of Biscay*, the histogram of the distribution of the values of the anomalies was computed for the triangle of large anomalies, west of 6°W: this histogram is nearly symmetrical, which means that there are about as many negative as positive anomalies. This is shown graphically in fig. 5a. In comparison, over Northern France (fig. 5b) and Southern France (fig. 5d) the distribution is typically asymmetrical. The simplest explanation for this difference is that there are about as many positive as negative magnetic sources in the Bay of Biscay whereas this is not true over the adjacent continent. This result can be explained if the dominant magnetization in the Bay of Biscay is remanent and if there were about as many intervals of reversed and normal polarities during the period when the magnetic sources were put into place. On the contrary, on the continent, the dominant magnetization is probably induced.

Seismic refraction measurements have shown that the structure of the crust in the deep part of the Bay of Biscay is typically oceanic [16]. Seismic reflexion measurements show that the acoustic basement, which lies at a depth of about 7 km within the triangle of anomalies west of 6°W is the top part of the oceanic basement with a velocity of 5 km/sec [13]. It is important to know whether the magnetic sources lie within this layer or within the deeper 6.7 km/sec layer. An estimate of the depth to the upper surface of the magnetized basement is suggested by the technique first described (Hahn's topography). The exponential increase in the value of the magnetization begins near 7.5 km below sea level (fig. 6a). At this level, the corresponding magnetization is of the order of 1400×10^{-6} emu cgs, which is reasonable. The second technique confirms this estimation of the average depth to the upper surface of the sources (fig. 7a).

Thus, these results are compatible with the formation of the pattern of magnetic sources in the Bay of Biscay by the Vine and Matthews mechanism some time during the Mid-Mesozoic. In this case, the pattern of lineations should be a clue to the geometry of

* The best fit normal field is defined by a second order polynomial. Its difference with the IGRF is about 150 gammas to the east and 90 gammas to the west.

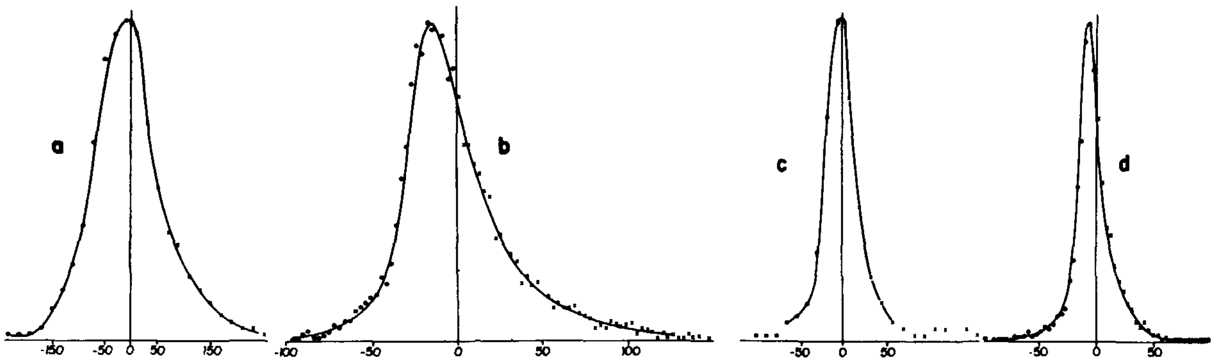

Fig. 5. Histograms of the values of the anomalies. (a) Internal zone of Bay of Biscay; (b) Northern France; (c) deep zone of Western Mediterranean; (d) Southern France. The ordinates are normalized; the scale of the abscissas and the sampling are different according to the area (50 means 50γ).

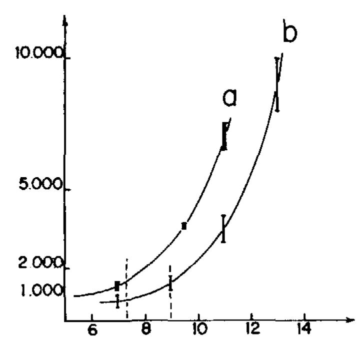

Fig. 6. Minimum magnetization in 10^{-6} emu cgs as a function of the depth of the magnetized topography in km (see text). (a) Internal zone of Bay of Biscay; (b) deep zone of North Western Mediterranean sea.

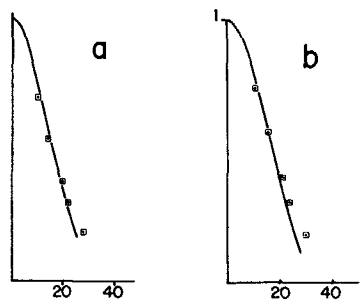

Fig. 7. (a) Bay of Biscay. ▫ experimental values of the mean a.c.f. of the anomalies reduced to the pole; solid curve, theoretical a.c.f. for vertically magnetized square prismatic bodies; horizontal dimensions: 37 × 37 km; depth to the top: 7 km; depth to the base: 9 km (below sea-level). (b) Deep zone of North Western Mediterranean sea. ▫ experimental values of the mean a.c.f. of the anomalies reduced to the pole. Solid curve: theoretical a.c.f. of vertically magnetized square prismatic bodies; horizontal dimensions: 25 × 25 km; depth to the top: 9 km; depth to the base: 13 km (below sea-level). The horizontal dimensions of the prisms are chosen after examination of the maps of the anomalies or of their derivatives. Their vertical dimensions from seismic refraction results.

opening according to the plate tectonic hypothesis. In particular, major disruptions in the pattern of lineations may correspond to fossil transform faults and define the geometry of opening of the Bay. It has generally been assumed that this opening occurred about a pole somewhere along the Pyrenees. Thus, as noted by Le Pichon [17], the pole being so close, transform faults, which are small circles about this pole, should have strong curvatures and enable us to define accurately the location of this pole. In fig. 3, major lines of disruption of anomalies have been indicated. Clearly, this very detailed survey excludes the possibility of a pattern of transform faults centered on a Pyrenean pole. Rather, if the lines of disruption of anomalies are transform faults, they indicate that the pole of opening should lie in a northeasterly direction from the Bay.

With such a pole, the differential motion between Europe and the Iberian peninsula progressively changes from an opening parallel to the lines of disruption of the magnetic anomalies in the Bay to pure strike-slip along the Pyrenees, probably along the North-Pyrenean fault [18]. This resolves the apparent contradiction between the date of opening of the Bay, which is certainly pre-Cenozoic, and the date of the main compressive phase in the Pyrenees, which is Lower Cenozoic. With a pole in the Pyrenees, the opening of the Bay and the compression in the Pyrenees would have been contemporaneous. Le Pichon et al. [13] have shown that a pole of relative motion between Europe and Iberia near 50°N, 3.3°E gives a satisfactory account of the structure of the Bay, its margins and the adjacent continent. They have shown that one of the major zones of disruption of anomalies, between 46.5°N, 9°W and 44.7°N, 8°W has a very strong topographic expression in the basement and is a major structural line in the Bay. They have also pointed out that, if the position of the pole is correct, before the opening of the Atlantic, the Iberian peninsula was situated much farther West than was proposed by Bullard et al. [19].

We will not discuss here in detail the implications of this hypothesis and the reader is referred to Le Pichon et al. [13]. An important problem, however, is recognition of the geometrical mechanism by which

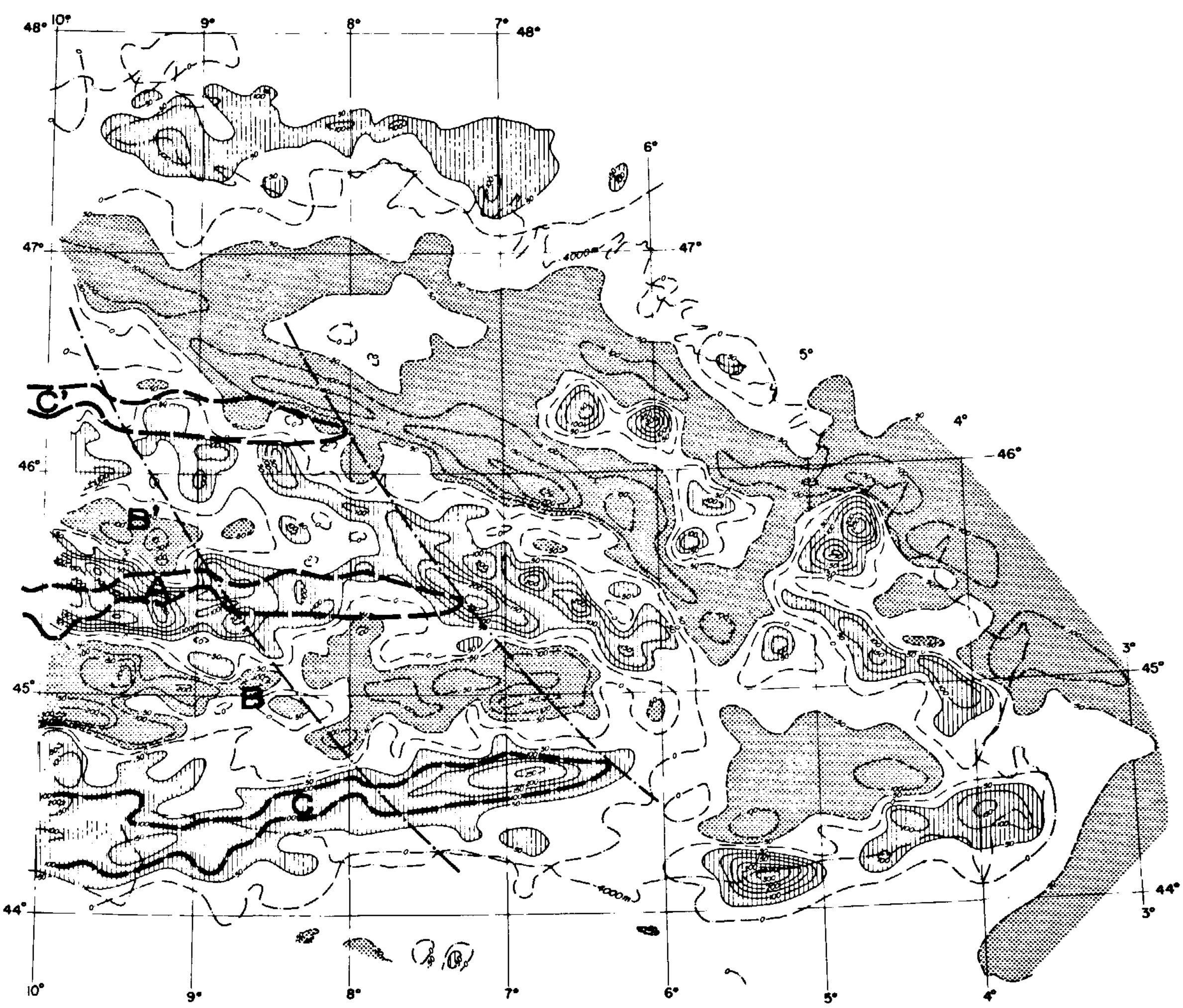

Fig. 8. Details of the magnetic anomalies within deep part of the Bay of Biscay. Anomaly *C* has been rotated by 6.6° and 13° about the 50°N 3.3°E pole. Note how the measured anomalies can be interpreted in terms of two positives (*C*, *C'*) and two negatives (*B*, *B'*) symmetric with respect to *A*. Dash-dot lines are small circles about the 50°N 3.3°E pole.

the pattern of anomalies was produced. Reflexion studies [13] have shown that the pre-Eocene sedimentary layer in the Bay of Biscay has been affected by a strong tectonic phase of vertical disruption. This phase has considerably changed the topography of the basement, creating a deep oceanic trench North of the Spanish margin and increasing the subsidence of the basin at the foot of the French continental slope. The limits of the internal magnetic triangle (fig. 8) probably date from this period. They are the result of faulting with a total throw of one to several kilometers which downdrops the basement from 7.5 km within the triangle to 9 to 11 km outside of it. It is thus difficult to know how much the Mesozoic magnetic pattern has been affected by this tectonic episode.

However, one can test whether the rotation of Le Pichon et al. [13] can account for the pattern of anomalies within the internal triangle. This pattern (fig. 8) is characterized by five main anomalies, three positives, C, C' and A, and two negatives, B and B'. Fig. 8 shows that if one applies to C a rotation of 6.5° about the 50°N 3.3°E pole, it comes on top of A; another rotation of 6.5° puts it slightly north of C'. Thus the anomalies B and B', C and C' can be considered symmetrical with respect to A within this rotation, as would be required by the Vine and Matthews model and A would correspond to the anomaly which was formed last. However, the small number of inversions involved makes it unlikely that one will be able to identify these anomalies which are probably of Upper Mesozoic age.

4.3. *North-Western Mediterranean*

Fig. 2 shows that the deep part of the North-Western Mediterranean is covered by anomalies which have an amplitude of about 100 gammas peak to peak (that is 140 gammas at sea level). This zone of anomalies is surrounded by very large quasi-circular anomalies over Sardinia, Corsica, the continental margins of the Gulf of Genoa, of Provence, of the Gulf of Lion and between the Baleares Islands and Spain. In contrast, the anomalies over Southern France are very small (over the Alps, the Rhone Valley and the Languedoc) and the field there is featureless.

The anomalies reduced to the pole have been computed, assuming that remanent and induced magnetizations are along the same direction (fig. 9). This hypothesis, which was made on the basis of a probable Cenozoic age for the basin, is justified in fig. 4c where the shape of the normalized a.c.f. of the anomalies reduced to the pole is nearly radial. Of course, it is possible to account for this fact by assuming that the magnetization is entirely induced. But a Mesozoic age for the basin is excluded if remanent magnetization is dominant, as the magnetic latitude then was much lower.

The study of the distribution of polarities of magnetization shows that there are as many positive as negative magnetic sources in the deep part of the Basin (fig. 5c) and suggests that the remanent magnetization is dominant. This is very different from the situation over the margins or over Southern France (fig. 5d) where positive sources clearly dominate. Again, the simplest explanation is in terms of an opening of the deep basin according to the Vine and Matthews mechanism.

Seismic refraction measurements [20] give a structure of the crust which is quite similar to that of a typical oceanic crust. The 6.6 to 5.8 km/sec crustal layer lies at a depth of 8 to 9 km below 4 km of 4.9 to 4.1 km/sec material. Seismic reflexion measurements [21] show that below 1.5 km of unconsolidated sediments there are about 500 m of salt (6 my old) underlain by at least two to three km of stratified sediments. This suggests that the 4.9 to 4.1 km/sec layer is not igneous but sedimentary in origin and that the total thickness of sediments is 5 to 6 km. The average rate of sedimentation down to the salt layer is 25 cm/1000 yr or 250 m/my. This is comparable to the present rate of sedimentation which ranges between 5 and 35 cm/1000 yr. Thus, if the average rate of sedimentation during the Plio-Pleistocene is representative of the average rate of sedimentation prior to 6 my ago, this very large thickness may have been deposited during the last 30 my.

An estimate of 9 km for the depth of the magnetic sources in the abyssal part of the basin is obtained by the two techniques described earlier (fig. 6b and 7b). Thus, one can conclude that the average depth of the magnetic sources coincide with the upper surface of the 6.6 to 5.8 km/sec layer.

Fig. 9 is a map of the second vertical derivative of the anomalies reduced to the pole. This derivation is possible because of the rather large wave length of the

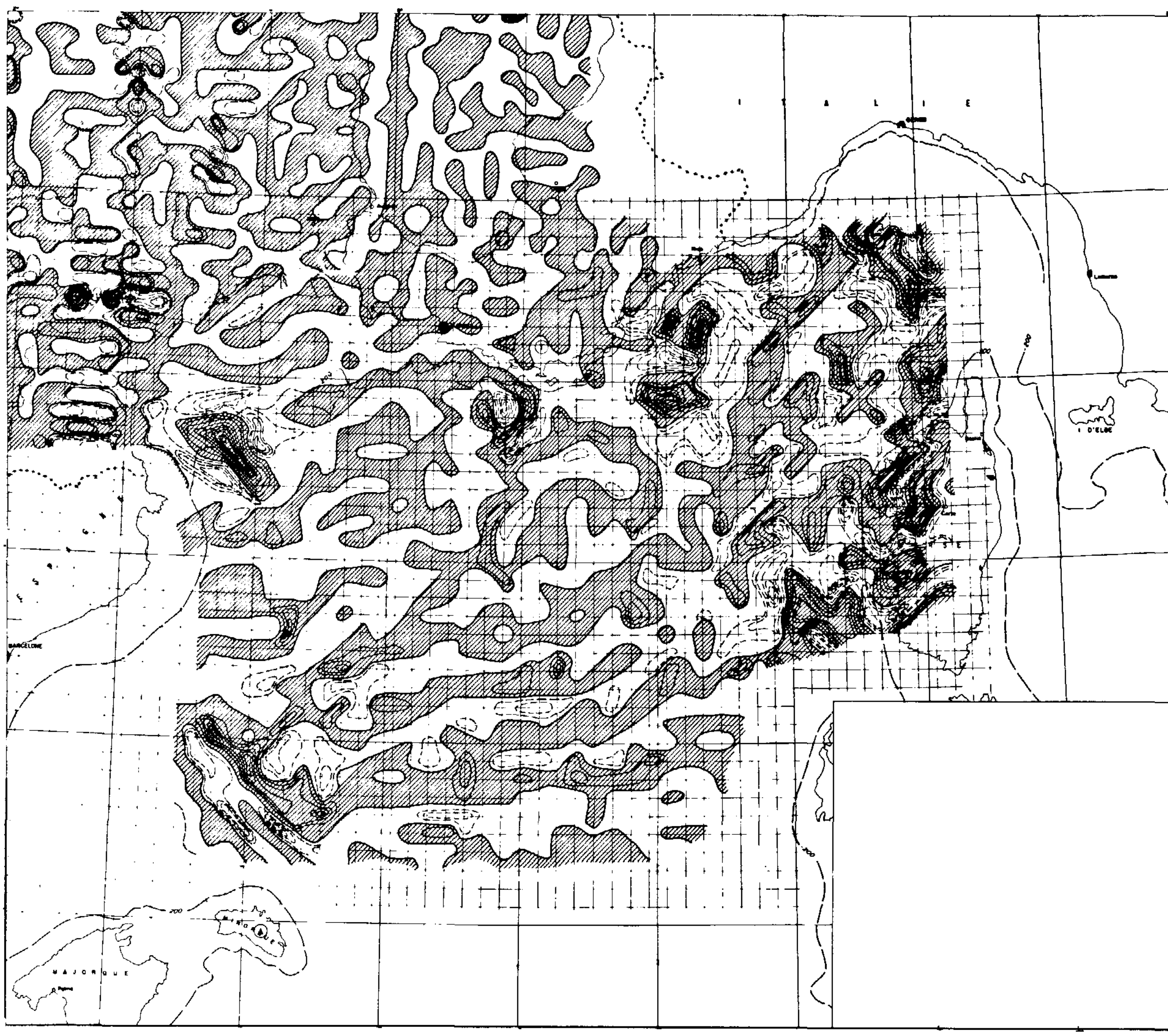

Fig. 9. Map of the second vertical derivative of the anomalies reduced to the pole over the North Western Mediterranean; 10γ spacing; positives are hachured; magnetization along present field $I = 58°$, $D = 4°$W.

measured anomalies and the great height over the magnetic basement (12 km: 3 km of air, 3 km of water, 6 km of sediments). This derivative defines more closely the outlines of the magnetic sources. The main feature of this map is the existence of linear fan-shaped anomalies which have their apex at a large positive anomaly above the island of Minorca (a careful examination of fig. 2 reveals the same pattern of anomalies but more subdued).

The large NW–SE anomaly near Minorca probably corresponds to a basement ridge with an average depth of 4 to 5 km below sea level. A basement ridge has been found there during a recent seismic reflexion survey of the Centre Océanologique de Bretagne. Fig. 9 suggests that this ridge plays an important structural role but its exact signification is not clear. It may correspond to a major fracture zone. Over Southern France, the anomalies are very small (a few gammas) and the pattern there is not significant.

The main result of this survey is the finding that magnetic lineations do exist over the North Western Mediterranean Sea, and that they seem to be confined to the abyssal part (deeper than 2500 m). It is tempting to attribute the lineations to a Middle Cenozoic 'sea floor spreading' episode and the large quasi-circular anomalies surrounding them to igneous intrusions during the early stage of disruption. However, the significance of the magnetic pattern in terms of geometry of opening is not clear. It does not seem possible to relate it to a single rotation of the whole block Corsica--Sardinia away from Southern France [23, 24]. The extension of the survey toward the South is necessary to interpret it further. Note that the great depth of the magnetic sources (12 km below the plane) explains the small amplitudes of the anomalies (100 gammas peak to peak). It is the excellent precision of this survey which allowed us to make this interpretation. Note also that if one takes the limit between continental and oceanic crust at the limit of the approximately linear anomalies, this limit seems to extend largely below the present 2000 m contour. This is important when attempting to reconstruct the relative positions of the continents before their disruption.

5. Conclusions

The precision and homogeneity of the aeromagnetic survey covering the whole of the Bay of Biscay, of France and of the North Western Mediterranean enabled us to use numerical techniques to obtain global estimates of the depth to the magnetic sources and the approximate direction of their remanent magnetization. The technique of reduction to the pole enabled us to obtain a more precise configuration of the magnetic sources, by removing the distortion due to the inclination of the magnetization vectors. The main result is that the Bay of Biscay and the North Western Mediterranean Basin are characterized by linear distributions of magnetic sources of both polarities, which were probably put into place by the Vine and Matthews mechanism. However, a mid-Mesozoic opening is suggested for the Bay of Biscay whereas the opening is probably much more recent in the Western Mediterranean. The geometry of opening of the Bay of Biscay cannot have been a rotation about a pole within the Pyrenees. The pole of rotation must be much farther North, near 50°N, 3°E, which produces strike-slip, and not compression, along the North Pyrenean Fault. The geometry of opening of the North-Western Mediterranean cannot be determined yet. Finally, it is suggested that the two major perpendicular magnetic anomalies occupying the axes of Parisian Basin and the British Channel Syncline were the results of igneous intrusion along faults produced by extension in the early stage of opening of the Atlantic in Triassic times. This was the initial cause of the subsidence related to these two zones.

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