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Early Cretaceous syn-rotational extension in the Organyà basin—New constraints on the palinspastic position of Iberia during its rotation

Zhihong Gong *, Douwe J.J. van Hinsbergen, Reinoud L.M. Vissers, Mark J. Dekkers

Department of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands

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ABSTRACT

In this study we interpret the paleo-stress pattern in the Organyà Basin (southern Pyrenees, northern Spain) as inferred from the anisotropy of magnetic susceptibility (AMS) of 39 sites distributed over the entire basin. Combined with information from other Cretaceous Iberian basins, such analysis adds to constrain kinematic reconstructions of the Cretaceous rotation of Iberia allied with the opening of the Bay of Biscay and the northward propagation of the North Atlantic.

The Organyà Basin is an inverted Cretaceous basin in the hanging wall of the Bóixols thrust. The lithologies are mainly weakly deformed pelagic and hemi-pelagic limestones and marls which recorded the Aptian 35° counterclockwise rotation of Iberia. Three types of AMS fabrics could be distinguished, all representing typical intermediate and tectonic fabrics. EW magnetic lineations dominate in the eastern part of the basin and are related to crustal shortening during the Pyrenean orogeny. This interpretation is consistent with structural cross-sections across the basin showing more intense shortening in the east. In the central part of the basin, approximately NS oriented magnetic lineations are observed, interpreted as the original extensional direction during basin foundering. So, in line with results from previous studies, AMS can still unveil the original extensional direction in an inverted sedimentary basin, something which may be difficult to reconstruct from geological data alone. The original extension direction in the Organyà Basin is perpendicular to the Bóixols thrust bounding the basin to the south.

Correction for the Aptian rotation of Iberia leads us to infer a NE–SW oriented extension direction at the onset of the rotation of Iberia. This extension direction is inconsistent with current plate kinematic reconstructions of the Cretaceous rotation and motion of Iberia. We therefore suggest that, during the opening of the Bay of Biscay and related Iberian rotation, Iberia was in a much more westerly position than assumed in current models, and that the rotation of Iberia was followed by dominantly eastward translation with respect to southern France, prior to N–S convergence and shortening in the Pyrenees since the latest Cretaceous.

1. Introduction

The anisotropy of the magnetic susceptibility (AMS) of weakly deformed rocks in sedimentary basins has been shown to be a sensitive proxy of either paleo-stress or low-strain trajectories (Jelínek, 1977; Hirt et al., 1993; Tarling and Hrouda, 1993; Borradaile and Henry, 1997; Soto et al., 2007). Many previous studies have documented the usefulness of AMS in detecting subtle fabrics, developed even in virtually undeformed sedimentary rocks that do not show any macroscopic evidence of deformation such as brittle mesostructures (Borradaile and Hamilton, 2004; Cifelli et al., 2005; Soto et al., 2007). As a result, the AMS of inverted basin sediments may preserve kinematic and dynamic information on the extensional history of the basin fill (van Hinsbergen et al., 2005; Soto et al., 2007). The AMS analysis of weakly deformed basin sediments thereby provides a strong tool to infer the initial kinematics of inverted basin-bounding normal faults, i.e., to reveal whether these faults were essentially oblique (transtensional) or purely extensional, whilst such early-stage fault kinematics can often no longer be inferred from the reactivated and overprinted basin margin structure.

There are several inverted sedimentary basins exposed in the northern part of the Iberian Peninsula. These basins mainly formed during an Aptian to early Albian phase in which Iberia rifted and rotated counterclockwise (CCW) away from Europe allied with opening the Bay of Biscay to the North and progressive ~E–W spreading and northward opening of the Atlantic Ocean to the West (Carey, 1958; Bullard et al., 1965; Sibuet et al., 2004; Gong et al., 2008b). The basins were inverted along their basin-bounding faults during the latest Cretaceous to middle Miocene compression, leading to the Pyrenean fold-and-thrust belt (Muñoz, 1992; Muñoz et al., 1992; Golonka, 2004). Among these inverted northern Iberian basins are the Basque–Cantabrian basin in the northwest, and the Central

* Corresponding author.
E-mail addresses: gong@geo.uu.nl, z.gong@geo.uu.nl (Z. Gong).

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Pyrenean Basin including the Organyà Basin in the southern Pyrenees (Fig. 1).

In a recent AMS and structural study of the Basque–Cantabrian basin, Soto et al. (2007) have shown that the pre-inversion extension direction in present-day coordinates was NE–SW, perpendicular to a major NW–SE trending, inverted basin-bounding normal fault, the Rumaceo fault. The Organyà Basin in the southern Pyrenees to the east has a comparable geological history of Aptian–Albian extension and late Cretaceous and younger inversion (García-Senz, 2002).

Different plate kinematic evolution models (Carey, 1958; Srivastava et al., 1990a, 2000; Sibuet and Collette, 1991; Olivet, 1996; Sibuet et al., 2004) have been proposed for the opening of the Bay of Biscay and the consequent palinspastic positions of the Iberian plate with time. There are some important inconsistencies between these reconstructions that essentially arise from the inferred positions of the various rotation poles. On the other hand, whilst the kinematics of the opening of the Bay of Biscay and allied rotation of Iberia is still under discussion, most workers agree on the amount of rotation of Iberia with respect to Eurasia: ~35° CCW (Carey, 1958; Bullard et al., 1965; Van der Voo, 1969; Choukroune, 1992; Sibuet et al., 2004; Gong et al., 2008b).

A possible way to test the reliability of the rotation poles used in plate kinematic reconstructions of Iberia is to use coeval tensional directions of the paleo-stress field on the north Iberian margin at the onset of the ~35° CCW Iberia rotation during the Aptian (Gong et al., 2008b). With this aim in mind, we present below the results of an AMS study of the Organyà Basin to (1) validate the conclusions of van Hinsbergen et al. (2005) and Soto et al. (2007) that AMS can convey information on the pre-inversion tectonic directions; (2) to investigate whether the magnetic fabrics in the Organyà Basin can in all likelihood be related to the Aptian–early Albian extension or, alternatively to a younger overprint during the late Cretaceous and younger inversion history and (3) what the angular relationship is between the extension directions inferred from the AMS fabrics and the inverted basin-bounding normal fault now exposed as the Bóixols thrust. We then proceed to place the results of this study in the context of existing plate kinematic reconstructions describing the rifting and rotation of Iberia and contemporaneous opening of the Bay of Biscay and the Atlantic Ocean.

2. Geological setting

In the early Jurassic, opening of the South and Central Atlantic involved breakup of the Pangaea supercontinent into Laurasia and Gondwana (Scotese, 2001; Torsvik et al., 2008). At that stage, the Iberian Peninsula together with Eurasia formed part of Laurasia. During the Cretaceous, progressive breakup and spreading of the North Atlantic Ocean led to separation of the Iberian microplate from Eurasia and Africa along the Azores–Gibraltar plate boundary in the South and the North Pyrenean Fault Zone in the North (Srivastava et al., 1990b; Olivet, 1996; Vergés et al., 2002; Sibuet et al., 2004). During this breakup process, the triangular Bay of Biscay opened leading to ~35° CCW rotation of Iberia (Carey, 1958; Bullard et al., 1965; Van der Voo, 1969; Choukroune, 1992; Sibuet et al., 2004; Gong et al., 2008b). Recently, Gong et al. (2008b) have confined the amount and age of the Cretaceous Iberian rotation with respect to Eurasia to 35° CCW during the Aptian. During this rifting episode, the Pyrenean extensional basins formed on the margins of Iberia and Eurasia. During and/or after the rotation of Iberia, transtensional rifting along the southwestern Eurasia margin resulted in Albian–Turonian alkali-basaltic magmatism and low-pressure high-temperature metamorphism, and in the Albian exhumation and emplacement of upper mantle slices in pull-apart basins presently exposed in the North Pyrenean Zone along the North Pyrenean Fault (Montigny et al., 1986; Vissers et al., 1997; Lagabrielle and Bodinier, 2008).

Northward motion of Africa since the late Cretaceous eventually led to closure of the Pyrenean extensional basins and collision between Iberia and Eurasia, which culminated in the Pyrenean orogeny (Golonka, 2004). N–S contraction lasted from late Santonian–Campanian to middle Miocene times (Muñoz, 1992) and inverted the pre-Santonian extensional structures.

The syn-rotational rifting along the northern Iberian margin resulted in several extensional sedimentary basins including the Basque–Cantabrian Basin, the North Pyrenean Basin and the Central Pyrenean Basin (García-Senz, 2002; Gibbons and Moreno, 2002). These basins experienced several pulses of extension followed by inversion and subsequent flexural subsidence during the Pyrenean orogeny. The Central Pyrenean Basin became detached along an underlying Triassic evaporite horizon and transported some 100 km southward onto the Iberian foreland, whilst the North Pyrenean Basin was fragmented and thrusted northward onto the European foreland (Choukroune and the ECORS Team, 1989; Muñoz, 1992; Beaumont et al., 2000; Rosenbaum et al., 2002). Compression started in late Santonian–Campanian times and progressively led to the development of a typical foreland fold-and-thrust belt, with inversion of the rift-related normal faults including the Bóixols fault (García-Senz, 2002).

The Organyà Basin forms part of the Central Pyrenean Basin and is exposed in the hanging wall of the Bóixols thrust (Fig. 1). The basin was subjected to Berriasian–middle Albian extension and rifting, followed by inversion and shortening during the Pyrenean Orogeny (Juárez et al., 1998; Dinarès-Turell and García-Senz, 2000; García-Senz, 2002; Gong et al., 2008a). The detailed geological structure of the Organyà Basin has been elegantly illustrated by García-Senz (2002) in a number of longitudinal and transverse cross-sections (Fig. 2). The internal structure of the Organyà Basin is dominated by the asymmetric Santa Fé syncline, which has a thick northern limb and a thinner southern limb (Fig. 2). The wavelength and amplitude of this fold increases from east to west, in proportion to the thickening of the Cretaceous series. The dominant structure exposed reflects the compressive deformation whilst the structure at depth reveals the presence of normal faults related to the previous extensional stage (García-Senz, 2002).

Around 4.5 km of hemi-pelagic to pelagic Cretaceous sediments were deposited in the Organyà Basin (Fig. 2). The formations have been very well dated using biostratigraphy (Becker, 1999; Bernaus et al., 1999, 2000, 2003; Bernaus, 2000). The early stages of rifting lasted around 20 Myr and resulted in the deposition of Berriasian–Barremian and earliest Aptian platform carbonates, in a depositional environment interpreted as coastal lagoonal (García-Senz, 2002). The net subsidence was apparently balanced by sediment influx such that throughout the series (Prada Fm.) shallow platform carbonate conditions were maintained. During the Barremian–early Aptian, represented by the transition from the Prada limestones into the Aptian Cabó marls, subsidence rates increased and the net sedimentation rate approximately doubled. Conditions became coastal-marine whilst a higher influx of detrital material suggests increasing topography. In the areas that remained coastal, in the South of Organyà Basin, syn-rift unconformities have been recognized. A hiatus occurs in the upper Albian coinciding with a general rise of the northern Iberian plate (Hiscott et al., 1990). The stage of most intense rifting, reflected by the accelerated subsidence in the Organyà Basin during the Aptian, has been shown to coincide with the counterclockwise rotation of Iberia (Gong et al., 2008b).

3. Sampling and methods

Thirty-nine sites (336 oriented cores yielding at least one standard-sized paleomagnetic specimen) covering the entire Organyà Basin, were drilled using a portable gasoline-powered drill and oriented with a magnetic compass (Fig. 1, Table 1). One specimen from each core was processed for the present AMS study. The anisotropy of the low-field magnetic susceptibility was determined with a KLY-3S AC susceptometer (AGICO, Brno, Czech Republic). It operates at a frequency of 875 Hz with a r.m.s. field of 300 A/m and has a sensitivity level of 3×10^{-8} SI for a standard-sized specimen. The anisotropy is determined by rotating the sample in three perpendicular planes while the magnetic moment in the applied field is monitored, allowing the calculation of the principal axes of the susceptibility tensor according to the procedures described in Jelínek (1977). This involves calculation of a tri-axial ellipsoid with principal axes K_{max}, K_{int} and K_{min} describing its shape and properties. We express the magnetic fabric by the parameters P' (the corrected anisotropy degree, $P' = \exp\sqrt{2\left[(\eta_{max}-\eta_m)^2+(\eta_{int}-\eta_m)^2+(\eta_{min}-\eta_m)^2\right]}$ with $\eta_{max} = \ln K_{max}$, $\eta_{int} = \ln K_{int}$, $\eta_{min} = \ln K_{min}$ and $\eta_m = \eta_{mean} = \sqrt[3]{\eta_{max}\cdot\eta_{int}\cdot\eta_{min}}$) proposed by Jelínek (1981), the shape parameter $T(2(\eta_{int}-\eta_{max}-\eta_{min})/(\eta_{max}-\eta_{min})$ varying between prolate (−1) and oblate (+1)), the magnetic lineation L (K_{max}/K_{int}) and the magnetic foliation F (K_{int}/K_{min}). To verify whether the differences between the estimated principal susceptibilities as compared to measuring errors are sufficiently meaningful to consider the specimen as anisotropic, the F-test is used (Jelínek, 1977). It compares the measurement variance (reduced to 9 positions) to the derived parameters (5 degrees of freedom). In this study, an F-distribution on 5 and 9 degrees of freedom with a level of 95% significance ($F_{5,\ 9;\ 95} = 3.4817$; Jelínek, 1977) is used to evaluate measurement quality. Only the individual samples with an F-test statistic above 3.4817 are considered to be reliable and used for further analysis.

4. AMS results

Most of the specimens yielded technically reliable results: 308 out of 336 passed the F-test criterion, so they are instrument-technically correct. In the case of low susceptibility values combined with low AMS values, like in the present study, there still may be considerable directional spreading over individual sites, however. This is related to the composite nature of the AMS that reflects contributions from the magnetic minerals and the paramagnetic matrix they can vary within a site even in seemingly homogeneous lithologies. Therefore, the AMS interpretation is always based on a fair number of specimens to average out local spatial variation. Twenty five out of thirty nine sites, from the Berriasian to the Aptian (Fig. 3), gave a sufficient number of reliable specimens (at least 6) useful for interpretation (Supplementary Figs. 1–4). The site mean susceptibility ranges from 4×10^{-6} SI to 1287×10^{-6} SI (Table 2). There is no clear relationship between mean susceptibility and the AMS ellipsoid parameters.

Irrespective of lithology and stratigraphic position, most of the sites (Table 2) have low values for the lineation L of <1.02, with one exceptional site (OR14) yielding values of up to 1.05. Similarly, foliation values F are in most of the cases <1.03; however, the same exceptional site gave values of up to 1.05. In addition, there is no clear trend in oblateness versus prolateness of the AMS ellipsoids with lithology or stratigraphic position.

When plotted on a per-site basis (Fig. 4), three main types of AMS fabrics can be distinguished that we relate to an increasing tectonic imprint on the originally sedimentary fabric (in bedding-corrected coordinates). In line with AMS studies from other Iberian basins (Soto et al., 2007), a purely sedimentary fabric has not been retrieved from the Organyà Basin. We recognize a Type 1 AMS fabric with the lowest tectonic signature (Fig. 4a–e) which has the minimum susceptibility axis K_{min} (sub)vertical in bedding-corrected coordinates, i.e., K_{min} is oriented perpendicular to the bedding. K_{int} and K_{max} are nicely clustered, with K_{max} approximately N–S oriented, although some are oriented NW–SE or NE–SW. We will address this in the discussion below. Note that the shapes of the AMS ellipsoids are either prolate or oblate (Table 2). Eighteen of the twenty five AMS sites, mostly from the Cabó and Senyús marls and two (OR49 and OR72) from limestone sites, belong to Type 1. Site OR72 shows larger within-site dispersion than the other sites of this type.

What we label as a Type 2 AMS intermediate fabric (Fig. 4f–h) has well grouped K_{max}, while K_{int} and K_{min} occur in a girdle perpendicular to K_{max}. This type is dominated by prolate AMS ellipsoids with $T<0$ in all of the pertinent sites (Table 2). The magnetic foliation is lost at the scale of the site (Aubourg et al., 2004). Two marl sites (OR33 and OR61) and a remagnetized limestone site (OR 68) belong to this group. This type of magnetic fabric is generally considered to result from the early stages of layer-parallel shortening (Tarling and Hrouda, 1993).

Type 3 AMS fabrics (Fig. 4i, j) are characterized by predominantly oblate ellipsoids, with K_{min} well grouped and almost parallel to the bedding, while K_{max} and K_{int} are less clustered. In this case, the positions of K_{min} and K_{int} are usually interchanged with respect to those of Type 2 and a newly formed magnetic foliation is developed highly oblique to the bedding (Bakhtari et al., 1998; Aubourg et al., 2004). Three marl sites (OR40, OR42 and OR46) and one limestone site (OR14) belong to this group.

Finally, site OR48 from the Cabó marls and site OR 53 from the Prada limestone have a poorly defined AMS fabric (Fig. 4k, l). The fabric obtained from site OR 48 (Fig. 4k) is transitional between Type 2 and Type 3, and is characterized by prolate ellipsoids with K_{min} reasonably well grouped while K_{max} and K_{int} show a girdle perpendicular to K_{min}. The magnetic fabric in Fig. 4l shows the results from an unsuccessful site (OR 53).

All of the AMS fabrics obtained from the Organyà Basin sediments are interpreted as either tectonic fabrics or as fabrics intermediate between a purely sedimentary and a tectonic fabric. The tectonic overprint is considered to gradually increase from Type 1 to Type 3. In the next section we address the tectonic interpretation of the AMS results.

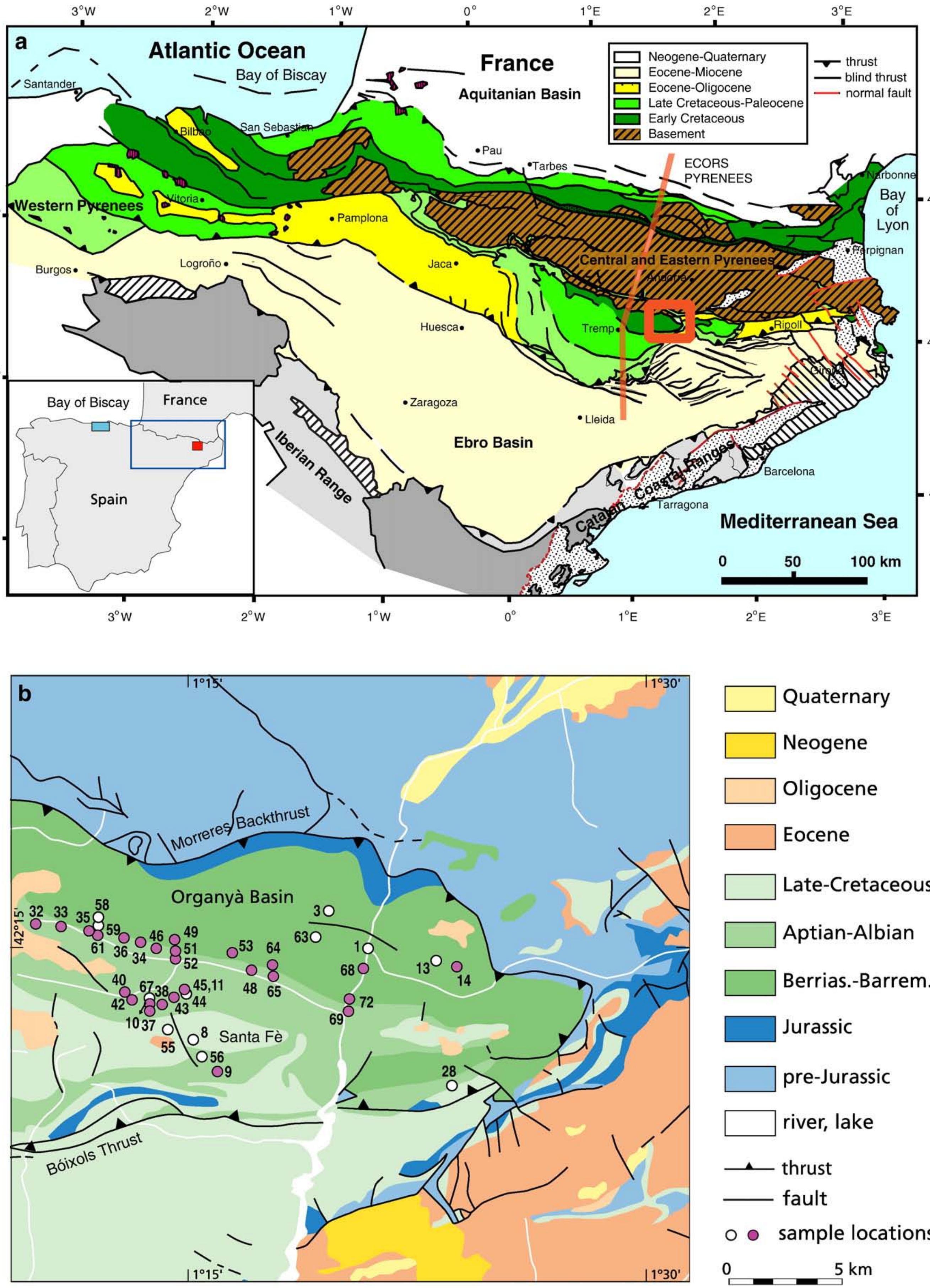
5. Discussion

5.1. Deformation history of the Organyà Basin

The magnetic lineations recorded by the AMS fabrics in the lower Cretaceous pre- and syn-rift sediments of the Organyà Basin show two dominant directions, i.e., N–S and E–W. NE–SW and NW–SE oriented lineations may be transitional between these two endmembers (Fig. 5). A plot of the azimuth of the lineation versus stratigraphy (Fig. 3) shows that the lineation direction in the Organyà Basin does not systematically vary with lithology or age. The geographic distribution, however, of these lineations (Fig. 5) does show a distinct trend, with E–W lineations being dominant in the east, N–S lineations dominant in the western–central part of the basin, and NE–SW or NW–SE lineations that seem to be confined to the northern and southern marginal regions of the basin.

The E–W trending lineations in the eastern part of the Organyà Basin are in line with the large-scale deformational structure of the basin illustrated by García-Senz (2002): the N–S cross-sections (Fig. 2) across the basin strongly suggest that the strain accommodated by the Organyà Basin fill increases from west to east. The E–W trending lineation can thus straightforwardly be interpreted to result from (late Cretaceous and Cenozoic) N–S contraction and basin inversion. As outlined previously in this paper, and as illustrated in Fig. 2, the late Cretaceous–Cenozoic contraction and inversion was for

Fig. 1. (a) Geological map of the Pyrenees modified after Vergés et al. (2002). Red and blue solid rectangles in inset map show locations of respectively the Organyà and Basque–Cantabrian basins. (b) Detailed map of the Organyà Basin showing locations of sampling sites (purple and white dots indicate successful and unsuccessful sites, respectively). Site numbers correspond to those reported in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)


a
Atlantic Ocean
Bay of Biscay
France
Aquitanian Basin
Santander
San Sebastian
Bilbao
Vitoria
Western Pyrenees
Pamplona
Pau
Tarbes
ECORS PYRENEES
Central and Eastern Pyrenees
Andorra
Narbonne
Bay of Lyon
Perpignan
Burgos
Logroño
Jaca
Huesca
Tremp
Ripoll
Girona
Zaragoza
Lleida
Ebro Basin
Iberian Range
Catalan Coastal Ranges
Barcelona
Tarragona
Mediterranean Sea
Neogene-Quaternary
Eocene-Miocene
Eocene-Oligocene
Late Cretaceous-Paleocene
Early Cretaceous
Basement
thrust
blind thrust
normal fault
0 50 100 km
Spain
3°W 2°W 1°W 0° 1°E 2°E 3°E
43° 42° 41°
b
1°15' 1°30'
42°15'
Morreres Backthrust
Organyà Basin
Santa Fè
Bóixols Thrust
Quaternary
Neogene
Oligocene
Eocene
Late-Cretaceous
Aptian-Albian
Berrias.-Barrem.
Jurassic
pre-Jurassic
river, lake
thrust
fault
sample locations
0 5 km

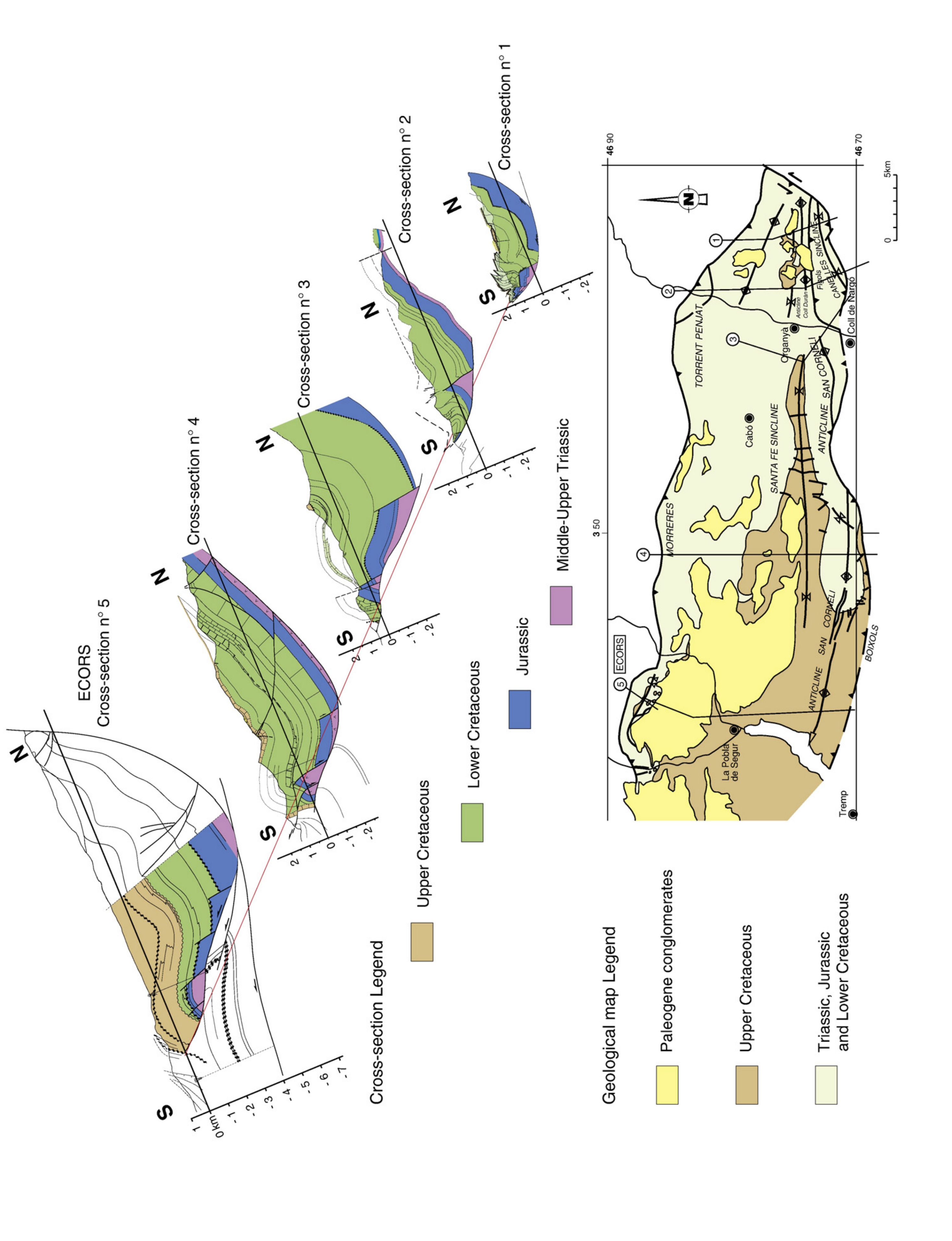

ECORS
Cross-section n° 5
Cross-section n° 4
Cross-section n° 3
Cross-section n° 2
Cross-section n° 1
S
N
Cross-section Legend
Upper Cretaceous
Lower Cretaceous
Jurassic
Middle-Upper Triassic
Geological map Legend
Paleogene conglomerates
Upper Cretaceous
Triassic, Jurassic and Lower Cretaceous
TORRENT PENJAT
MORRERES
SANTA FE SINCLINE
ANTICLINE SAN CORNELI
BOIXOLS
CANELLES SINCLINE
Coll de Nargó
Organyà
Cabó
La Pobla de Segur
Tremp
ECORS
5km
0
46 90
46 70
3 50

Table 1
Sample sites in the Organyà Basin (locations shown in Fig. 1), with GPS positions (in UTM coordinates, georeference: ED50), lithostratigraphic units, age, lithology (L = limestone; M = marl; ML = marly limestone), and bedding plane orientation given as strike and dip).

Site	GPS (N)	GPS (E)	Unit/Formation	Age	Lithology	Strike/dip
OR08	*4674362*	*355777*	*Santa Fe*	*Cenomanian*	*Light L*	*268/29*
OR28	*4671112*	*364194*	*Lluçà*	*Aptian–Albian*	*Dark M&ML*	*251/96*
OR55	*4674578*	*355247*	*Lluçà*	*Aptian–Albian*	*Dark M*	*77/40*
OR56	*4674384*	*355887*	*Lluçà*	*Aptian–Albian*	*Dark M*	*276/43*
OR09	4673823	356638	Font Bordonera	Aptian	Dark M	267/45
OR10	4676608	353783	Senyús	Aptian	Dark M	103/47
OR11	4676651	354627	Senyús	Aptian	Dark M	104/65
OR37	4676149	353474	Senyús	Aptian	Dark M&ML	107/39
OR38	4676146	353737	Senyús	Aptian	Dark M	94/45
OR40	*4676609*	*353688*	*Senyús*	*Aptian*	*Dark M*	*108/43*
OR42	4676502	353673	Senyús	Aptian	Dark M	106/45
OR43	4676657	354225	Senyús	Aptian	Dark M	96/41
OR44	*4676651*	*354627*	*Senyús*	*Aptian*	*Dark M*	*105/48*
OR45	4676634	354604	Senyús	Aptian	Dark M	103/53
OR67	*4676613*	*353782*	*Senyús*	*Aptian*	*Dark M*	*97/43*
OR32	4679374	350548	Cabó	Aptian	Dark M	110/45
OR33	4679420	350608	Cabó	Aptian	Dark M	111/44
OR34	4678412	352887	Cabó	Aptian	Dark M	96/50
OR35	4679435	350663	Cabó	Aptian	Dark M	107/50
OR36	4679145	352279	Cabó	Aptian	Dark M	98/47
OR46	4678324	353738	Cabó	Aptian	Dark M	104/48
OR48	4677654	356981	Cabó	Aptian	Dark M&ML	97/41
OR51	4678088	355021	Cabó	Aptian	Dark M	114/51
OR52	4678226	354979	Cabó	Aptian	Dark M	111/43
OR61	4679114	351293	Cabó	Aptian	Dark M	95/45
OR64	4677510	358140	Cabó	Aptian	Dark M	106/50
OR65	4677405	358088	Cabó	Aptian	Dark M	109/49
OR69	4676084	362557	Cabó	Aptian	Dark M	103/51
OR49	4678686	354971	Prada C	Barremian–Aptian	Dark L	111/57
OR53	*4678016*	*356794*	*Prada C*	*Barremian–Aptian*	*Dark L*	*109/42*
OR58	*4679986*	*351233*	*Prada C*	*Barremian–Aptian*	*Dark L*	*116/50*
OR59	*4679914*	*351326*	*Prada C*	*Barremian–Aptian*	*Dark L*	*118/54*
OR72	4676280	362699	Prada C	Barremian–Aptian	Dark L	105/65
OR13	*4678521*	*363736*	*Prada B, A*	*Barremian*	*Dark L*	*98/42*
OR14	4678273	365704	Prada B, A	Barremian	Dark L	296/18
OR68	4677635	363525	Hostal Nou	Valanginian	Dark L	110/60
OR01	*4678605*	*363464*	*Barranc de la Fontanella*	*Berriasian*	*Light L*	*106/46*
OR03	*4679885*	*361263*	*Barranc de la Fontanella*	*Berriasian*	*Dark L*	*97/56*
OR63	*4679700*	*361298*	*Barranc de la Fontanella*	*Barremian*	*Dark L*	*91/57*

Unsuccessful sites shown in italics.

an important part localised along a decollement in the underlying Triassic evaporites. In the east of the basin, the largely E–W trending Bóixols thrust changes orientation to a NE–SW trend which, during inversion, must have induced a strong component of transpression leading to strain partitioning between motion along the decollement and shortening of the overlying sediments. The resulting larger shortening strains in the east are obvious from the structural cross-sections of García-Senz (2002) and confirmed by our AMS data.

The N–S oriented magnetic lineations, however, obtained from the center of the basin in the western part of the study area, are parallel to the inversion-related contraction direction and are therefore likely not related to this event. Because these directions are orthogonal to the Bóixols thrust—shown by strong contrasts in stratigraphic thicknesses across the fault to be an inverted lower Cretaceous normal fault (Muñoz, 1992; García-Senz, 2002)—it seems most likely that these lineations reflect the (syn-depositional) extension direction during basin foundering.

We noted above that some of our K_{max} directions are NW–SE or (in a smaller number of cases) NE–SW (Fig. 5). We consider these directions as being intermediate between the N–S (syn-sedimentary extension related) and E–W (late Cretaceous contraction related) directions. There are strong structural geological and stratigraphic arguments showing that the presently E–W trending thrust fault initiated as a normal fault and that there has been basin inversion and folding with E–W trending fold axes (Fig. 2). We use these geological arguments to infer the origin of the N–S and E–W trending AMS directions that represent to a certain extent endmember situations. Additionally we would like to test whether extension occurred oblique to the Bóixols inverted normal fault. We feel it unlikely that the intermediate directions represent such oblique extension, first because they do not show any preferred alignment but instead seem more or less evenly spread between N–S and E–W, whilst the N–S trending magnetic lineations in the basin center are strongly aligned, and secondly, because towards the thrusted northern (and, in one site, southern) margin, away from the least deformed basin center, the AMS lineations become intermediate. Likewise, the lineations show intermediate orientations towards the east, and eventually become oriented E–W parallel to the fold axes.

At this point we can make three inferences. First, the original extension direction is still preserved in the inverted basin centre, which probably means that virtually all contraction during late Cretaceous and Cenozoic inversion was accommodated by motion along the basal decollement, with only passive folding of the overlying basin sediments. Secondly, the pre-inversion extension direction we find in the Organyà Basin supports the notion of van Hinsbergen et al. (2005) and Soto et al. (2007) that studying the AMS of inverted basins allows recognition and reconstruction of the original extension direction in an inverted basin. Thirdly, analogous to the results obtained by in the Basque–Cantabrian basin, the N–S extensional direction in the Organyà Basin interpreted from the AMS fabrics is oriented perpendicular to the Bóixols inverted normal fault, suggesting that the syn-depositional extension direction during early Cretaceous rifting (i.e., during at least the early stages of rotation of Iberia; Gong et al., 2008b) was also perpendicular to the main basin-bounding fault. To obtain the pre-rotation extension direction, we therefore correct for the 35° counterclockwise rotation of Iberia with respect to Eurasia, thus restoring a NW–SE orientation of the Bóixols inverted normal fault, with an associated ~NE–SW oriented extension direction. This direction thus marks the extension direction in the Organyà Basin at the early stages of the rotation of Iberia and the opening of the Bay of Biscay.

5.2. Plate tectonic implications

In this paper we show that during the Cretaceous Iberian counterclockwise rotation as documented by Gong et al. (2008b) the Organyà Basin underwent extension. This calls for a position of the basin at the margins of the opening Bay of Biscay. However, an extensional setting of the Organyà Basin (and the South Pyrenean Basin in general) during the rotation of Iberia conflicts with current plate kinematic reconstructions as discussed below, and indicates that the inferred position of Iberia with respect to Europe during the Cretaceous may need revision.

Current plate kinematic reconstructions describing the rotation and motion of Iberia with respect to Europe mainly differ in the estimated locations of the associated Euler poles, and in the consequent pre-rotation position of Iberia with respect to Eurasia. There are in essence

Fig. 2. Oblique projection of five cross-sections across the Bóixols sheet, modified after García-Senz (2002), illustrating the change in structural geometry of the Organyà Basin from west to east suggesting higher shortening strains in the eastern part of the basin. The red line connecting the cross-sections indicates the Bóixols thrust. Locations of sections are shown on the map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

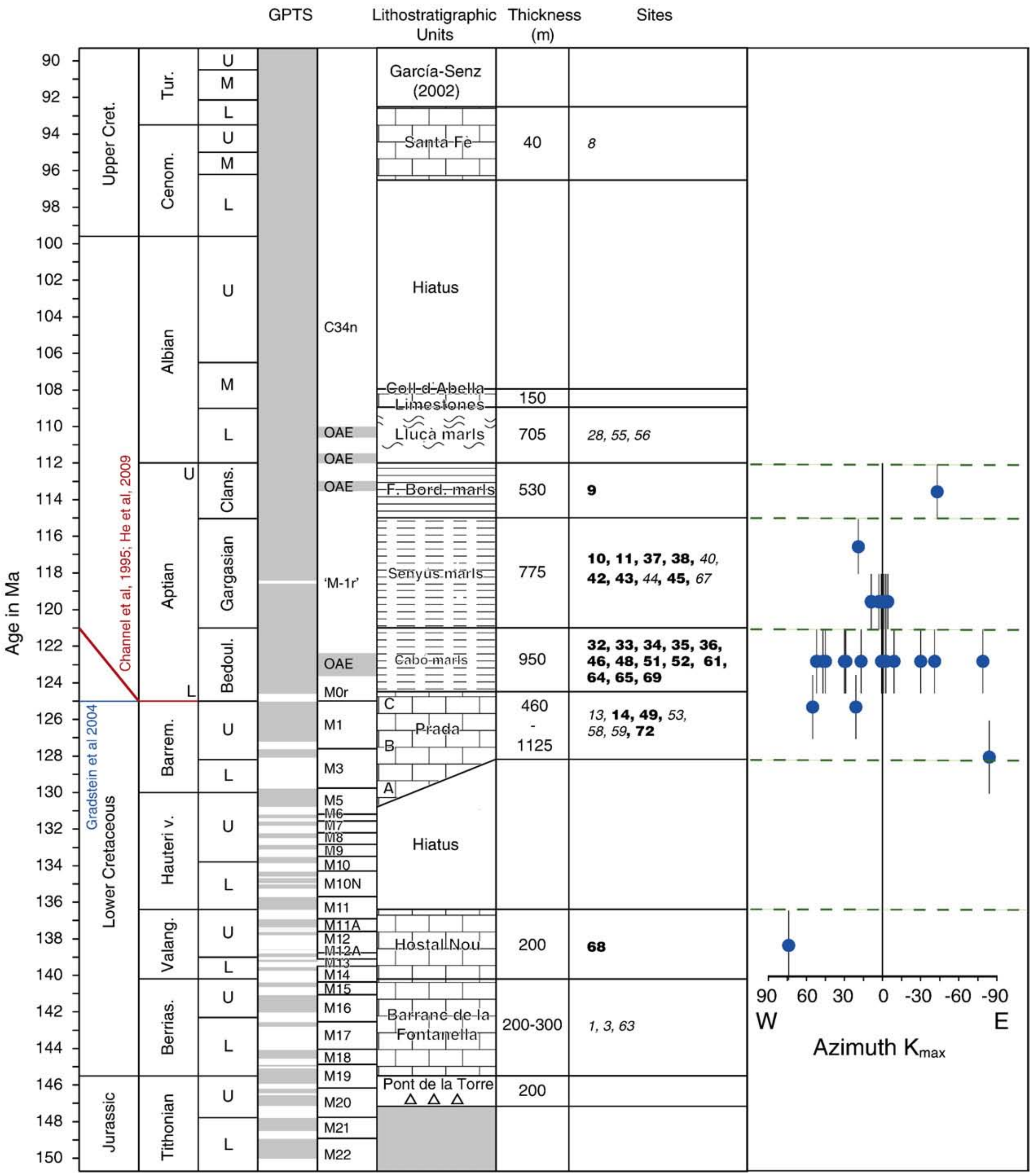


Fig. 3. Stratigraphic column showing the lithology of the Organyà Basin, with lithostratigraphic units and formation thicknesses after García-Senz (2002). Geological and geomagnetic polarity time scales (GPTS) after Gradstein et al. (2004) are shown on the left. The age of M0 marks the oldest age for the onset of the rotation of Iberia (Gong et al., 2008b). These authors used the age given by Gradstein et al. (2004) of 125.0 ± 1.0 Ma. This age has recently been heavily debated in literature. The age given by Channell et al. (1995) of 120.6 was recently confirmed by He et al. (2008) who found 121.2 ± 0.5 Ma. ~121 Ma is thus a more likely age for the onset of rotation of Iberia, and associated extension. Grey (white) indicates normal (reversed) polarity. Chron nomenclature follows CK92 (Cande and Kent, 1992). Graph to the right shows azimuthal direction of the magnetic lineation (K_{max}) versus lithology (time). Successful sites in bold, unsuccessful sites in italics. Blue solid dots indicate site mean azimuthal directions from successful sites. Vertical bars indicate inferred age errors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

two competing end-member models: Srivastava et al. (2000) propose a scissor-type opening model for the Bay of Biscay based on its ocean floor magnetic anomaly pattern and that of the central Atlantic, whereas Olivet (1996), mainly on the basis of geological data, suggests a left-lateral strike-slip opening model (Fig. 6).

The first model (Srivastava et al., 2000), which is based on the fit of anomaly M0 identifications across the North Atlantic and Bay of Biscay and constrained by maintaining the direction of motion between the plates along the Azores–Gibraltar fracture zone, infers a total reconstruction pole for the motion of Iberia with respect to Eurasia located in the Bay of Biscay north of Gijon (Fig. 6a). The second model (Olivet, 1996) assumes a total reconstruction pole in northwestern France, i.e. far north of Iberia, to account for a dominant left-lateral strike-slip component in the motion between Eurasia and Iberia inferred from geological data, with Iberia moving in a southeasterly direction prior to chron A33o (Fig. 6b).

Table 2
AMS parameters from the successful sites in the Organyà Basin.

Sites	N	K_m ($\times 10^{-6}$SI)	K_{max}	K_{int}	K_{min}	St. errors	L	F	P	P'	T
OR9	9	10.50	1.0091	1.0083	0.9826	0.0029	1.0008	1.0261	1.0269	1.0132	0.9425
OR10	8	71.39	1.0051	0.9998	0.9951	0.0007	1.0053	1.0047	1.0100	1.0043	−0.0598
OR11	8	82.99	1.0033	1.0009	0.9959	0.0003	1.0024	1.0051	1.0074	1.0033	0.3633
OR14	7	4.62	1.0446	0.9960	0.9553	0.0128	1.0451	1.0457	1.0929	1.0393	0.0072
OR32	9	519.63	1.0076	1.0005	0.9919	0.0017	1.0070	1.0087	1.0158	1.0069	0.1077
OR33	8	409.70	1.0091	0.9970	0.9938	0.0010	1.0121	1.0033	1.0154	1.0070	−0.5755
OR34	10	473.99	1.0124	1.0043	0.9833	0.0007	1.0080	1.0214	1.0296	1.0132	0.4535
OR35	7	576.03	1.0099	1.0051	0.9850	0.0001	1.0047	1.0205	1.0253	1.0116	0.6244
OR36	9	608.83	1.0095	0.9999	0.9906	0.0016	1.0096	1.0094	1.0191	1.0083	−0.0068
OR37	10	34.87	1.0066	1.0011	0.9924	0.0016	1.0055	1.0088	1.0143	1.0063	0.2254
OR38	9	23.01	1.0094	0.9979	0.9927	0.0051	1.0116	1.0053	1.0169	1.0075	−0.3737
OR42	10	42.95	1.0069	0.9982	0.9949	0.0012	1.0086	1.0034	1.0120	1.0054	−0.4395
OR43	11	81.96	1.0042	0.9994	0.9964	0.0007	1.0048	1.0030	1.0078	1.0034	−0.2285
OR45	11	152.67	1.0092	0.9979	0.9929	0.0011	1.0113	1.0050	1.0164	1.0073	−0.3856
OR46	9	615.01	1.0098	1.0049	0.9854	0.0005	1.0049	1.0198	1.0247	1.0113	0.6028
OR48	11	907.68	1.0053	0.9995	0.9952	0.0005	1.0058	1.0044	1.0101	1.0044	−0.1385
OR49	6	644.02	1.0070	0.9980	0.9950	0.0014	1.0091	1.0030	1.0121	1.0055	−0.4968
OR51	8	1286.67	1.0141	0.9947	0.9912	0.0016	1.0195	1.0035	1.0231	1.0107	−0.6930
OR52	11	714.47	1.0108	0.9989	0.9902	0.0018	1.0119	1.0088	1.0208	1.0090	−0.1495
OR61	8	410.05	1.0087	0.9974	0.9939	0.0024	1.0114	1.0035	1.0149	1.0067	−0.5315
OR64	8	659.34	1.0071	1.0029	0.9900	0.0013	1.0043	1.0130	1.0173	1.0078	0.5033
OR65	9	473.99	1.0093	1.0045	0.9862	0.0006	1.0048	1.0185	1.0234	1.0107	0.5827
OR68	7	42.70	1.0107	0.9979	0.9915	0.0019	1.0128	1.0064	1.0193	1.0085	−0.3314
OR69	19	119.46	1.0237	1.0124	0.9639	0.0008	1.0112	1.0503	1.0621	1.0282	0.6314
OR72	20	28.77	1.0086	1.0033	0.9881	0.0024	1.0053	1.0154	1.0208	1.0093	0.4839

N = number of specimens (F-test > 3.48); K_m = mean susceptibility; K_{max}, K_{int} and K_{min} denote normed principal susceptibilities; St. errors = Standard Error for K_{max}; $L = K_{max}/K_{int}$ (magnetic lineation); $F = K_{int}/K_{min}$ (magnetic foliation); $P = K_{max}/K_{min}$ (the degree of AMS); P' denotes the corrected anisotropy degree; T denotes the shape parameter (Jelinek, 1981).

Both of the reconstructions fit the shape of the continental margins of the northern and southern Bay of Biscay and also the geomorphological features located between Iberia and its adjacent plates. However, Sibuet et al. (2004) argue that the model of Srivastava et al. (2000) fits the M0 better and provides a more robust reconstruction. Sibuet et al. (2004) have proposed a stage pole for Iberia with respect to Eurasia for the period M0–A33o located in the eastern Bay of Biscay at 44.35° N, 4.30° W, 37.21° (Fig. 6a).

Counterclockwise rotation of Iberia around this stage pole would, however, inevitably lead to compression in the Organyà Basin. This inconsistency between the marine geophysical data and the geological evidence for coeval extension in the Pyrenen realm was also noted by Sibuet et al. (2004), who therefore suggested that the Pyrenean basins developed in a backarc setting above a north-dipping slab of subducting Neotethys oceanic lithosphere separating the Pyrenean realm from Iberia. Gong et al. (2008b), however, have shown that the Aptian sediments in the Organyà Basin did record the Iberian rotation, hence that the basin must have formed part of Iberia. The Olivet (1996) reconstruction, on the other hand, poses some problems as well, as this model implies roughly NNW–SSE oriented extension in the Pyrenean domain, which is clearly inconsistent with the restored NE–SW oriented extension direction based on our AMS data and associated normal fault orientations in the Organyà Basin. In addition, the total reconstruction pole in the Olivet (1996) model has a rotation angle of about 27° which, in view of the inferred pole position in northern France, results in an even smaller vertical axis rotation of Iberia close to 25°, i.e., significantly less that the 35° of Aptian CCW rotation documented by paleomagnetism (Gong et al., 2008b).

Albeit on different aspects, it follows that both models for the kinematics of Iberian plate motion are at variance with the geological data from northeastern Iberia, which calls for a further analysis aiming to circumvent such inconsistencies. A detailed plate kinematic reconstruction for the Iberia rotation lies beyond the scope of this paper, but the geological data from the Organyà Basin do allow some inferences on the position of Iberia relative to the rotation pole.

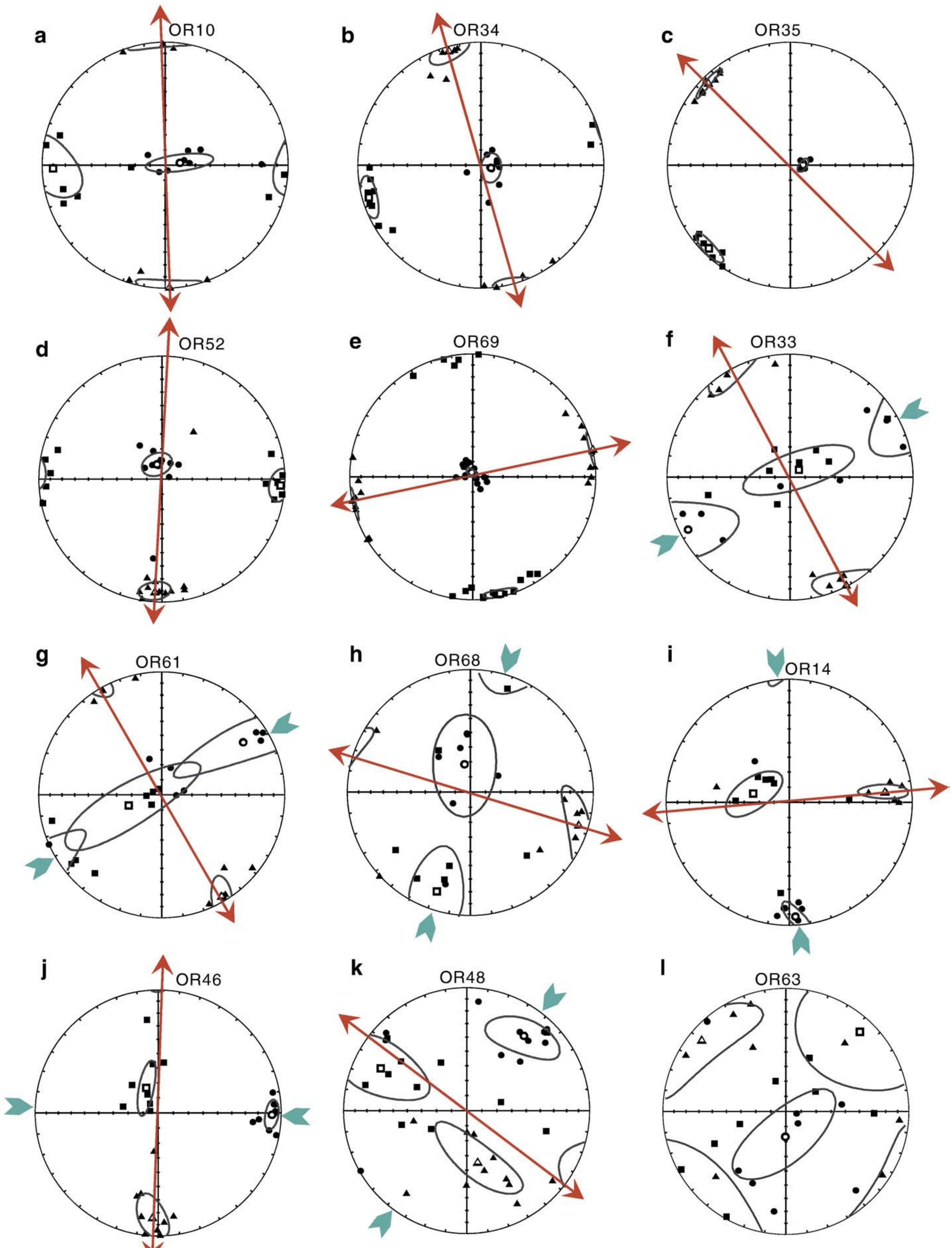
The fact that the northeastern Iberian basins, at the onset of rotation, experienced NE–SW oriented extension (rotating to more N–S directed syn-rotational extension) shows that the whole of the Iberian continent must have lied west of the rotation pole. In any other case, counter-clockwise rotation would lead to compression between (parts of) Iberia and southwestern Europe. It follows that either the stage pole inferred by Srivastava et al. (2000) and Sibuet et al. (2004) is erroneous and should be located further (south)east, or Iberia during its rotation was located much further to the west.

It seems highly unlikely that the location of the stage pole inferred by Sibuet et al. (2004) is dramatically incorrect, as its position is straightforwardly derived from the patterns of magnetic anomalies. We interpret this to imply that at the onset of the Aptian Iberia was located west of the pole suggested by Sibuet et al. (2004). On the other hand, the position of Iberia at the end of the Cretaceous Normal Superchron (the A33o position of Iberia, inferred by Srivastava et al., 2000 on the basis of the A33o and younger anomalies), fits remarkably well with current shortening estimates in the Pyrenean domain of around 165–175 km obtained from restored sections including ECORS (Muñoz, 1992; Beaumont et al., 2000; Rosenbaum et al., 2002). The inferred A33o position of Iberia should, therefore, be essentially correct.

It follows that Iberia must have undergone a significant eastward translation during the early Cretaceous, as also suggested by and implicit in the model of Olivet (1996). There is geological evidence that following the rotation of Iberia, and prior to A33o, there was eastward translation of Iberia with respect to France: the rift-related normal faults in the Organyà Basin are unconformably sealed by Cenomanian strata (Fig. 2), which is fully consistent with increasing localization of the Iberian motion during the Late Cretaceous along the left-lateral wrench faults of the North Pyrenean Zone (Peybernès and Souquet, 1984; Choukroune, 1992; Lagabrielle and Bodinier, 2008).

At this stage it may be argued that a scenario involving rotation of Iberia in a westerly position followed by eastward translation should in all cases violate the constraints imposed by the sea-floor anomaly data. There are, however, two aspects of the plate tectonic reconstructions which lead us to suggest that this problem can be solved.

First, the stage pole proposed by Sibuet et al. (2004) to describe the Cretaceous rotation of Iberia with respect to Eurasia is a finite stage pole relating the position of Iberia at chron M0 to that at chron A33o. We emphasize that most of that period coincides with the Cretaceous Normal Superchron, or the Cretaceous Quiet Zone in sea-floor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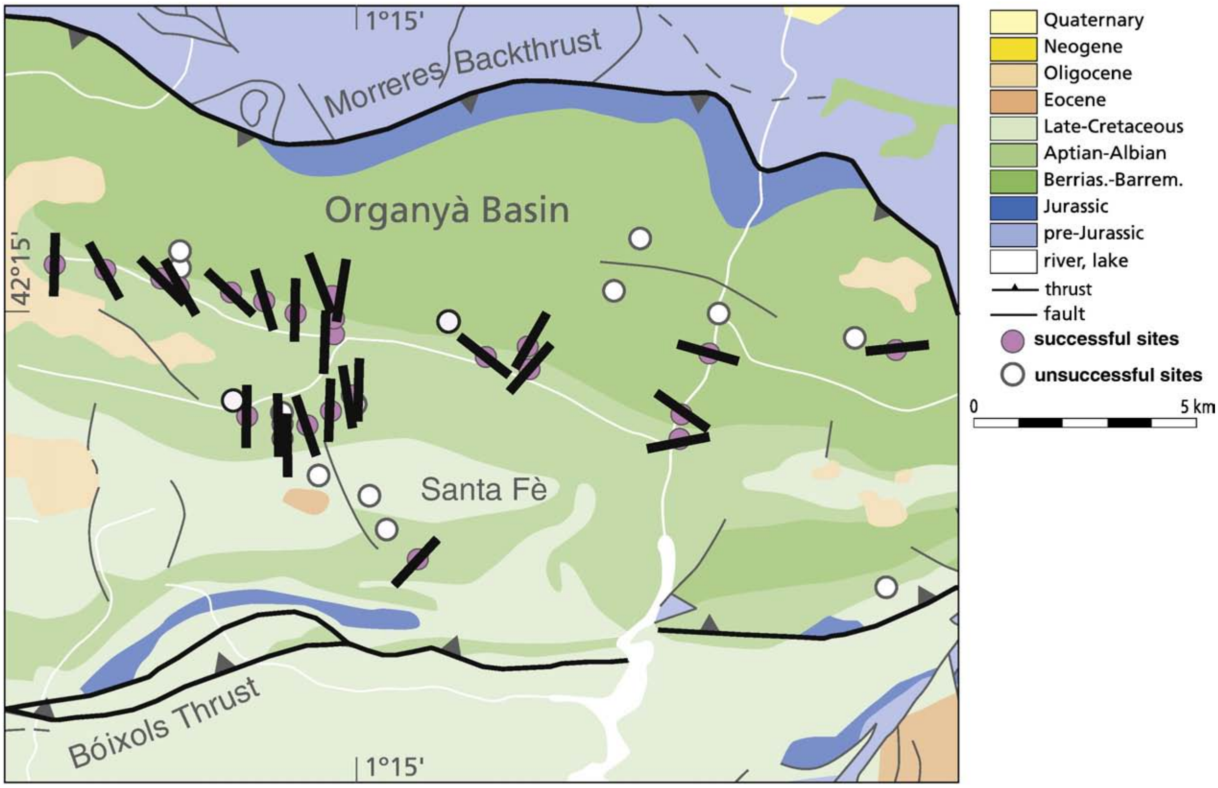

Fig. 5. Orientation of the magnetic lineation (K_{max}) after tectonic correction, as a function of position in the Organyà Basin. E–W lineations are dominant in the east, N–S lineations predominate in the western and central part of the basin, and NE–SW and NW–SE lineations tend to occur in the northern and southern marginal regions of the basin.

anomaly terminology (i.e. ~121–85 Ma; Channell et al., 1995; Gradstein et al., 2004; He et al., 2008). The study by Gong et al. (2008b) clearly confines the rotation of Iberia to the Aptian (~121–112 Ma; Channell et al., 1995; Gradstein et al., 2004; He et al., 2008). Hence, the kinematics of Iberian motion for the M0–A33o interval may well have involved different substages that combine into the net M0–A33o stage pole, obviously without any anomaly record whatsoever in the ocean floor until chron A33o, except of course for the slightly (4 Myr) older A34 anomaly. Note that Sibuet et al. (2004) likewise recognize that the Iberian paleomagnetic data may well serve to refine the kinematic model for the M0–A33o interval.

A second aspect concerns the assumption made in plate kinematic reconstructions that plates are rigid and do not deform. In the case of Iberia, however, there are at least two pieces of evidence suggesting that significant deformation may have affected the northern and western margins. First, a major EW-trending structure exists along the northwestern and northern margin of Iberia which seems to merge eastward with the North Pyrenean Zone. This structure was clearly active during Cenozoic NS-directed shortening since A33o (Sibuet et al., 2004) and accommodated limited subduction of the oceanic Bay of Biscay underneath Iberia (Boillot, 1984; Sibuet et al., 2004). In view of the geological evidence in the North Pyrenean basins for major motions along the North Pyrenean Fault during the late Mesozoic it seems perfectly possible that this discontinuity north of the Iberian margin was already active at that time as well. Secondly, marine studies of the western Iberian margin focussing on the Iberia–Newfoundland breakup history have provided evidence for a complex breakup process involving at least two stages, i.e., a first Tithonian–Barremian (i.e., pre M0) stage leading to mantle exhumation and, notably, a second stage of extension dated as latest Aptian, reflected by at least five 10 km-scale half graben structures (Péron Pinvidic et al., 2007). Although quantitative data on the magnitude of this late Aptian stretching phase are lacking, these data suggest that the Iberian mainland was effectively stretched away from the M0 anomaly.

The above qualitative inventory shows that a scenario involving a more westerly position of Iberia during its rotation followed by eastward motion may be viable. A thorough quantitative plate kinematic analysis is needed, however, to fully reconstruct the position of Iberia during its rotation such that both sea-floor data and Iberian geology-derived constraints are satisfied.

6. Conclusions

Our AMS study in the weakly deformed Cretaceous sediments of the Organyà Basin demonstrates the existence of three types of intermediate to tectonic magnetic fabrics that in all likelihood reflect increasing strain. There is a marked trend in the orientation of the magnetic lineation depending on the position in the basin. In the eastern part of the basin, lineations are oriented E–W which we interpret as the result of a compressional overprint formed during basin inversion and shortening since Campanian–Maastrichtian times. In the western part of the basin, where the regional shortening was largely accommodated by decollement along the underlying Triassic evaporates, N–S directed lineations dominate suggesting NS extension. This N–S extension direction is oriented perpendicular to the inverted Bóixols fault bounding the Organyà Basin to the south, and

Fig. 4. Stereoplots (equal area, lower-hemisphere projection) showing representative AMS data after tectonic correction. Maximum, intermediate and minimum principal anisotropy axes are indicated by respectively triangles, squares and circles. Solid symbols show individual directions, open symbols are mean directions, with 95% confidence zones indicated. Red and blue arrows represent inferred extension and compression directions. (a–e) Examples of Type 1 fabrics with K_{min} perpendicular to bedding. (f–h) Examples of Type 2 fabrics with clustered K_{max}, and K_{int} and K_{min} tending to spread over a girdle. (i,j) Examples of Type 3 fabrics, with clustered K_{min} almost parallel to bedding. (k) Example of transitional fabric. (l) Example of unsuccessful fabric. For further interpretation and discussion see text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

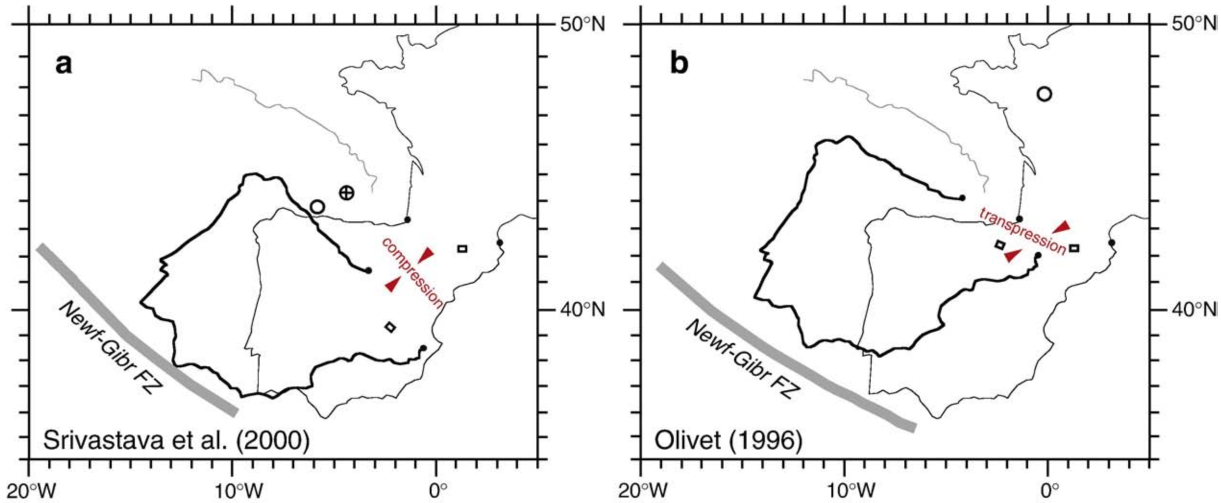

Fig. 6. Reconstructed positions of Iberia at M0 times according to the two main endmember kinematic models of Srivastava et al. (2000) and Olivet (1996), modified after Sibuet et al. (2004). Open circles denote total reconstruction poles for Iberia with respect to Eurasia, small rectangles show approximate positions of the Organyà Basin. (a) Kinematic model of Srivastava et al. (2000), with total reconstruction pole (43.85° N, 5.83° W, −44.76°) of Sibuet et al. (2004). Circle with cross denotes M0–A33o stage pole (44.35° N, 4.30° W, 37.21°) adopted from Sibuet et al. (2004). Rotation of Iberia around this stage pole inevitably leads to NE–SW oriented compression in the Pyrenean realm as indicated by arrows. (b) Kinematic model of Olivet (1996), with total reconstruction pole located in NW France (47.79° N, 0.22° W, −26.81°). This model leads to transpression in the Pyrenean domain with a roughly NE–SW directed component of shortening indicated by arrows.

likely represents the original extension direction during rifting and basin foundering. The NW–SE and NE–SW oriented lineations tend to occur in the marginal parts of the basin and are considered to be transitional.

Correction for the Aptian 35° CCW rotation of Iberia brings the NS lineations into a NE–SW orientation, suggesting that the prevailing stretching direction in the basin during the early stages of opening of the Bay of Biscay and allied rotation of Iberia was NE–SW. This result is inconsistent with current plate kinematic models for the rotation of Iberia such as proposed by Olivet (1996), Srivastava et al. (2000) and Sibuet et al. (2004), that imply either transpression or compression in northeastern Iberia during rotation. We conclude that in order to satisfy the geological constraints of its northeastern margin, Iberia must have had a position somewhere west of the rotation pole. Given that the rotation pole for the opening of the Bay of Biscay proposed by Srivastava et al. (2000) and Sibuet et al. (2004) is likely correct, it follows that Iberia must have been translated with respect to this pole prior to its A33o position as reconstructed by Srivastava et al. (2000). Geological evidence indicates that between the Aptian rotation and the Campanian and younger N–S contraction and formation of the Pyrenees, Iberia moved eastward along the North Pyrenean Zone. A detailed analysis is needed to refine the Cretaceous plate kinematics of Iberia in accordance with ocean floor anomalies and Iberian geological constraints.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tecto.2009.03.003.

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