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A new model for the Hercynian Orogen of Gondwanan France and Iberia

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Abstract

The Hercynian Orogen of Gondwanan France and Iberia is a collage of disparate terranes separated by faults. Plate reconstructions indicate that the orogen developed during a massive dextral transpression as Laurentia slid along the boundary of Gondwana, and as Laurentia, Baltica, and East Avalonia rotated clockwise to form Pangea. It is proposed, therefore, that the collage is the result of this transpression, and that it is an amalgamation of displaced tectonostratigraphic terranes which represent the dismembering of the Gondwanan shelf, with its stable platform Ordovician–Devonian sedimentary sequence, and the neighbouring Rheic Ocean. Specifically, it is proposed that: (1) the slice of the Gondwanan shelf that now forms north Brittany was displaced dextrally from NW Africa, around Iberia, by more than 2000 km; (2) the ophiolites, oceanic material, and volcanic arcs of south Armorica and the Massif Central represent slices of the Rheic Ocean, displaced dextrally along the Gondwana margin and shuffled in amongst slices of Gondwanan shelf; (3) the convergent component of the transpression is represented by thrusts throughout the region, the Léon Terrane of France, and ophiolite-bearing klippe in NW Iberia. The Ibero-Armorican arc was formed by wrapping the mobile dextral shear belts about a rigid Iberian basement block. The dextral Porto-Tomar Shear Zone represents the more important shearing in Iberia, and the Iberian sinistral shears are interpreted as bookshelf-type structures, subsidiary to the dextral shearing.

1. Introduction

Recently we described the structures of Ile de Groix eclogites and blueschists (Shelley and Bossière, 1999). These rocks probably represent oceanic lithosphere (Ballèvre et al., 1998) subducted to at least 70 km depth (Müller et al., 1995; Bosse et al., 1998), followed by exhumation, during which process the rocks underwent a high extensional strain (Shelley and Bossière, 1999). These events took place in the Silurian and Devonian (Peucat and Cogné, 1977; Peucat, 1986a), but our attempts to reconstruct the plate tectonic setting for that time were beset with the following problems:

1. Groix is part of a south Armorican complex of fault-bound terranes with absolutely disparate geologies (Rolet, 1994). For instance, whilst the oceanic rocks of Groix indicate Silurian–Devonian subduction to depths of at least 70 km, followed by exhumation to shallow depths, the Ancenis area of south Armorica (Fig. 1) exposes a stable platform sequence of sediments ranging in age from Ordovician to Upper Devonian (Robardet et al., 1994).
2. The Ancenis area is not alone. To the north, in north and central Brittany, and to the south, in Aquitaine and the Montagne Noire, stable platform sediments range in age from Cambro-Ordovician through the Devonian with no significant sign of tectonism until the middle–upper Devonian (Robardet et al., 1994).
3. Groix is part of a region that extends through south Armorica into the Massif Central, and which

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exposes metamorphosed lower-middle Paleozoic oceanic volcanics, ophiolites, volcanic arcs, and high pressure metamorphics (e.g. Girardeau et al., 1986; Ledru et al., 1986; Ballèvre et al., 1987; Guiraud et al., 1987; Bodinier et al., 1988; Dubuisson et al., 1989). They have been explained as representing the lower–middle Paleozoic opening and closing of a South Armorican Ocean (Dubuisson et al., 1989). It is, however, difficult to reconcile this ocean with the stable platform sequences to the north and south, and even more difficult to reconcile it with the Ancenis sequence, right in the middle of this oceanic complex.
4. The Gondwanan Paleozoic platform sequence of north and central Brittany is proximal, the southern France sequence distal, yet their relative positions with respect to Gondwana are now the reverse (Robardet et al., 1994).
5. NW France and Iberia were part of Gondwana during the lower–middle Paleozoic. Because of faunal contrasts (Robardet et al., 1994), Gondwana is supposed to have been separated from East Avalonia and Baltica by the Rheic Ocean (Fig. 2). The Carboniferous Hercynian Orogeny represents the closure of this ocean, and the suture is considered to run along the western English Channel, then under the Paris Basin (Robardet et al., 1994). One might have expected this suture to be marked by extensive areas of oceanic crust, volcanic arc and subduction complexes. Although the Lizard ophiolites and the Léon area of NW Brittany may represent some of this expected material, there is very little that is obvious, and in any case, the suture is unexpectedly close to the proximal stable platform Gondwanan sediments of north and central Brittany.

The traditional rather 'fixist' approaches to explaining these geological relationships have not worked. For example, it is simply not credible that the major subduction and exhumation events represented by the Groix eclogites and blueschists did not leave their mark in either the tectonic or volcanic record of

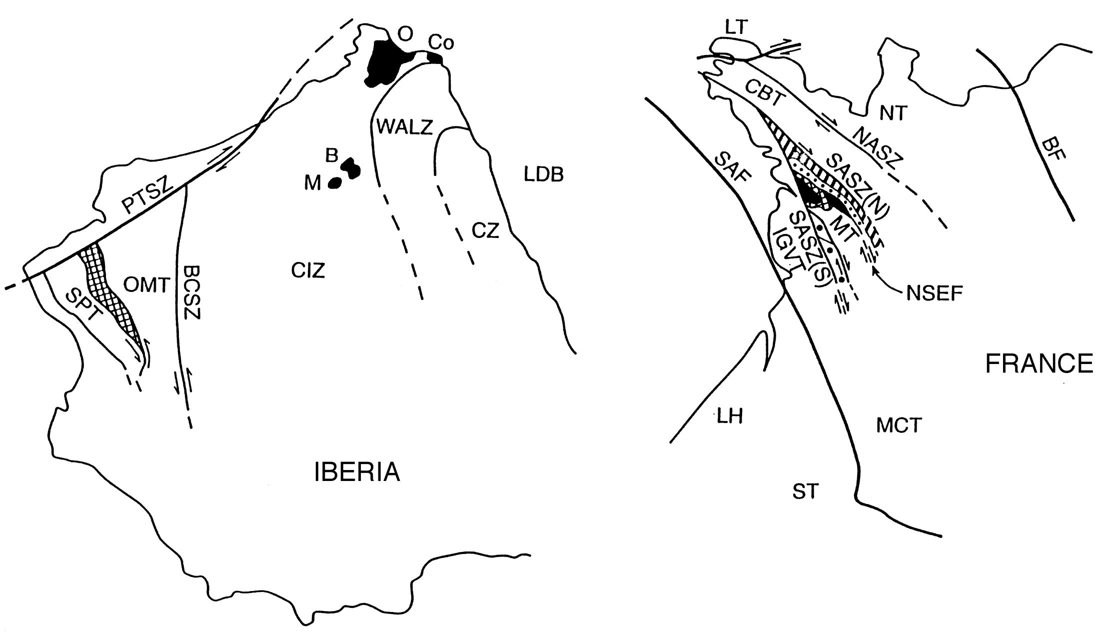

Fig. 1. Tectonostratigraphic terranes of Gondwanan France and Iberia. The relative positions of Iberia and France are after Lefort (1989). In France: BF = Bray Fault and possible suture of the Rheic Ocean; LT = Léon Terrane; NT = Northern Terrane; NASZ = North Armorican Shear Zone; CBT = Central Brittany Terrane; SASZ(N) = Northern Branch of the South Armorican Shear Zone; Thick lines = Lanvaux Terrane; Small dots = Saint Georges-sur-Loire Terrane; NSEF = Nort-sur-Erdre Fault; Blacked area bounded to north by NSEF = Ancenis Terrane; Blacked area cut by SASZ(S) = Champtoceaux Terrane; Cross-hatching = Mauves-sur-Loire Terrane; MT = Mauges Terrane; Big dots = Mortagne Terrane; SASZ(S) = Southern Branch of the South Armorican Shear Zone; IGVT = Ile de Groix-Vendée Terrane; SAF = South Armorican Front; MCT = Massif Central Terrane; LH = Landes High; ST = Southern Terrane. To the east of the Armorican shear zones, and between them and the MCT, the Hercynian structures are buried under post-Hercynian Paris Basin sediments. Much of ST is covered by post-Hercynian Aquitaine Basin sediments. In Iberia: CO = Cabo Ortegal, O = Ordenes, B = Brangança, M = Morais, all representing klippe with ophiolite and other complexes; LDB = Le Danois Bank; CIZ (Central Iberian Zone), WALZ (West Asturian–Leonese Zone) and CZ (Cantabrian Zone) represent Paleozoic sedimentary zones within the Iberian Terrane; PTSZ = Porto-Tomar Shear Zone; BCSZ = Badajoz-Córdoba Shear Zone; OMT = Ossa Morena Terrane; Cross-hatched area = Pulo do Lobo Oceanic Terrane; SPT = South Portuguese Terrane. The eastern part of Iberia is mainly covered with post-Hercynian deposits, though inliers of Proterozoic and Paleozoic material with uncertain affinities occur throughout. The area west of PTSZ exposes post-Hercynian basinal sediments.

adjoining sedimentary sequences. Nor is it credible that the Ancenis Ordovician to Devonian sediments were deposited in their present geological setting within a discrete sinistral pull-apart basin (Diot and Blaise, 1978), given that the Ancenis sequence is the same in most respects as the rest of the greater north Gondwana shelf succession (Robardet et al., 1994).

The purpose of this paper is to address these problems with a new model for the Hercynian Orogen, based on the application of the concept of suspect tectonostratigraphic terranes (Coney et al., 1980; Howell, 1995). There is prima facie evidence for the new model, as described in Section 6, below. But first, in Sections 2–5, we introduce the main geological elements that make up the Hercynian Orogen of Gondwanan France and Iberia, outline the plate tectonic setting of the Hercynian Orogeny, and describe the tectonostratigraphic terranes of Gondwanan France and Iberia. For the most part, this paper represents reinterpretation of a large volume of existing data. However, reference is also made to our recent work on the Ancenis Terrane, which can be interpreted as an exotic duplex in terms of the new model (Shelley and Bossière, 2000).

2. The main geological elements within the Hercynian Orogen of Gondwanan France and Iberia

2.1. The W African Craton

The Pre-Cambrian cratonic areas of Gondwana include the W African craton. Its distinctive isotopic character and ages (ca. 2.0 Ga, 2.8 Ga, and 3.1 Ga) are well established (Nance and Murphy, 1996), and it differs, for example, from the neighbouring Amazonian cratonic area. W African cratonic rocks are known in only two isolated areas of the French–Iberian region, in north Brittany as small areas of 2 Ga gneissic basement (Egal et al., 1996), and from Le Danois Bank, north of Spain, through to the Landes High under the Aquitaine basement (Guerrot et al., 1989; Lefort and Agarwal, 1999). There is no evidence that these rocks directly underlie the rest of Gondwanan France and

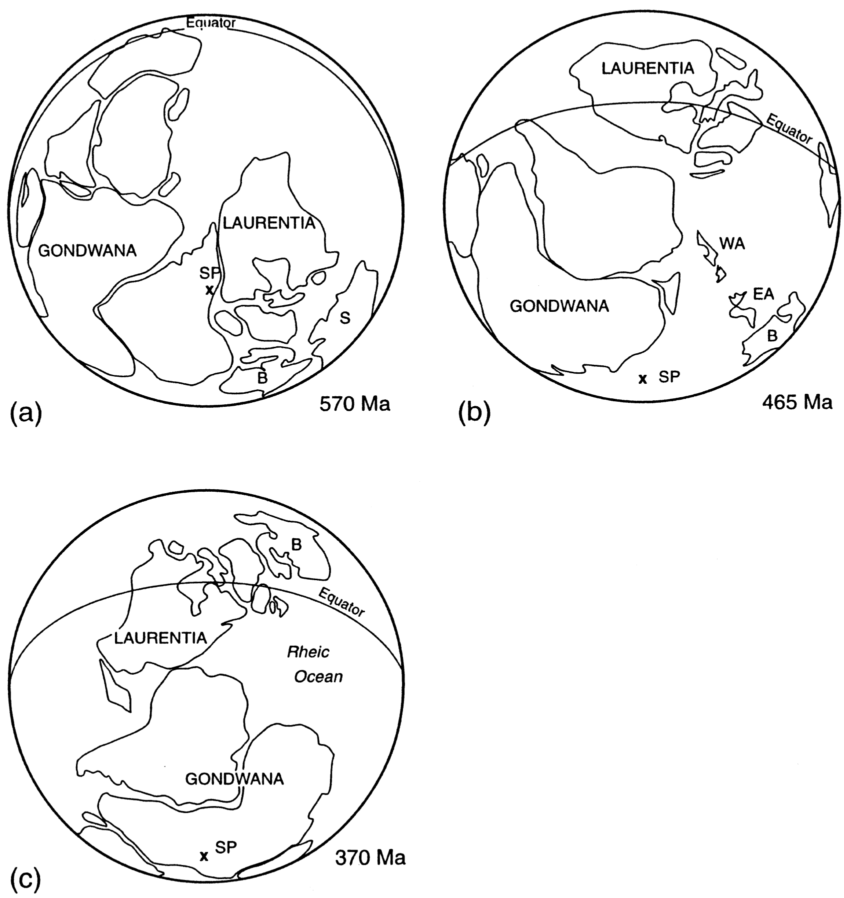

Fig. 2. Positions of the major continental masses, (a) in the late Proterozoic, 570 Ma ago (Dalziel et al., 1994), (b) in the Ordovician, 465 Ma ago (Dalziel, 1997), and (c) in the Devonian, 370 Ma ago (Dalziel et al., 1994). SP = South Pole; B = Baltica; S = Siberia; WA and EA = West and East Avalonia.

Iberia. However, the W African geochemical signature pervades all continentally derived rocks of Gondwanan France and Iberia (Nägler et al., 1995), and this is exemplified particularly by detrital zircons which carry W African cratonic ages (e.g. Vidal et al., 1981; Paquette et al., 1985; Peucat, 1986b; Peucat et al., 1986).

2.2. Cadomian (Pan-African) events

Throughout much of the Orogen there is a basement of late Proterozoic low grade metasediments (in France they are called the Brioverian Schists). The Pan-African metamorphic events were accompanied by the accretion and amalgamation of oceanic/volcanic arc terranes along the Gondwanan boundary. For example, in north Brittany, there are the Saint Brieuc and Saint Malo Terranes, as described by Strachan et al. (1989, 1996), and in Iberia there is the Ossa Morena Terrane, described by Quesada (1990) and Eguiluz and Abalos (1992). The Brioverian rocks, according to Nance and Murphy (1996), have chemistries that indicate mixing of the W African 2-Ga cratonic material with juvenile mantle-derived material. Indeed, the mixing of those two sources accounts for the geochemical signature of the entire Iberian–French Gondwanan region (Nägler et al., 1995).

Transcurrent faulting associated with the Cadomian events was mainly sinistral (Balé and Brun, 1983; Strachan et al., 1996).

2.3. Cambro-Ordovician extension

The end of the Cadomian Orogeny was marked by regional extension, rifting, and volcanism, exemplified in Gondwanan France by Cambrian acid volcanics (Thiéblemont and Cabanis, 1994), and in Iberia, by normal faulting which defines the boundaries between the Central Iberian and West Asturian–Leonese Zones, and which partitioned depositional and volcanic activity throughout the lower Paleozoic (Martínez-Catalán et al., 1992). In Iberia, the voluminous Ollo de Sapo acid igneous rocks, interpreted by Gebauer et al. (1993) as metaplutonic, and emplaced in the early Ordovician (488 Ma), are also probably related to this rifting.

Extension and rifting would have been accompanied by continental thinning and a reduction in continental relief, and terranes such as West and East Avalonia were detached from the main Gondwanan continental mass. According to their geochemical signatures, West Avalonia originated next to the Amazonian craton, and East Avalonia abutted against both the Amazonian and W African cratons (Nance and Murphy, 1996). North Brittany (Cadomia) was adjacent to the W African craton, but whether or not it drifted away from Gondwana during Cambro-Ordovician rifting is discussed below.

2.4. The Ordovician–Devonian stable shelf sediments

Marine sedimentation on the Gondwanan shelf from the Ordovician through the Devonian succeeded the Cambro-Ordovician extension. Robardet et al. (1994) in a review of the French Gondwanan deposits state (p.4): "All the north Gondwanan regions maintained strong sedimentary and faunal affinities throughout the Paleozoic period". Sediments in central Iberia, north and central Brittany, and Normandy, are inner shelf deposits, indicating proximity to emerged land areas, whereas sediments in Montagne Noire and the Pyrenees are outer shelf facies. The Ancenis area has features in common with both types. Many of these areas include red beds at the base of the sequence, coarse Ordovician sands, glaciomarine dropstone deposits in the Ashgillian, a condensed and euxinic Silurian sequence, and Devonian limestones. There is no evidence of major tectonic disturbance until sometime in the Devonian.

2.5. Oceanic and volcanic arc rocks, Eohercynian tectonism and high pressure metamorphism

There are remnants of oceanic crust in many parts of south Armorica and the Massif Central (e.g. Girardeau et al., 1986; Ballèvre et al., 1998) as well as volcanic arcs (e.g. Peucat et al., 1986) and Eohercynian (pre-Carboniferous Paleozoic) tectonism and metamorphism (e.g. Brun and Burg, 1982; Peucat, 1986a; Bosse et al., 1999). The shelf sediments are missing in these areas, so that the Saint Georges-sur-Loire area, for example, immediately north of Ancenis, is characterised by monotonous virtually unfossiliferous siltstones and mudstones of Ordovician to Devonian age (Lardeux and Cavet, 1994), in addition to oceanic volcanics. The arc magmatism and high-pressure metamorphism of oceanic volcanics, as on Ile de Groix (Müller et al., 1995; Bosse et al., 1998), imply subduction-related processes, and these processes were taking place before the Carboniferous Hercynian Orogeny from as early as the Ordovician, as evidenced by subduction-related granitoids in south Armorica (Guerrot et al., 1997), through 422 Ma for the Groix high-pressure metamorphism (Peucat, 1986a), 404 Ma for the 'porphyroids' consisting of ignimbrites and acid volcanics (Peucat et al., 1986), to 360 Ma for the high-pressure metamorphism in the Champtoceaux area (Bosse et al., 1999). The Champtoceaux area of high-pressure and high-temperature metamorphism is thought to have involved thinned continental crust intruded by basic dykes (Ballèvre et al., 1994; Matte, 1998).

Eohercynian tectonism in the south Armorican and

Massif Central areas is most generally characterised by WNW–ESE shortening accompanied by top-to-the-WNW thrusting (Brun and Burg, 1982).

2.6. Hercynian events

The Hercynian Orogeny marks the amalgamation of continental plates to form the supercontinent Pangea. It marks the end of stable shelf sedimentation along the north Gondwanan boundary, and Devonian marine sediments are unconformably overlain by Carboniferous or younger deposits. Many of the Carboniferous sediments are non-marine, and many were deposited in intermontane pull-apart basins (e.g. Rolet et al., 1994).

The orogeny was accompanied by transcurrent and thrust faulting. Gondwanan France is particularly well known for its transcurrent dextral faults (Gapais and Le Corre, 1980), which include the North Armorican Shear Zone (NASZ), the northern and southern branches of the South Armorican Shear Zone (SASZ-N, and SASZ-S), and the Nort-sur-Erdre Fault (Fig. 1). These structures are very profound so that the SASZ can be traced to depths greater than 100 km, and the NASZ to sub-crustal depths (Judenherc et al., 1999). Structures in the north of the SASZ dip southwards, suggesting subduction (Granet, 1999; Judenherc et al., 1999).

In Iberia, Hercynian transcurrent faults (Fig. 1) are either dextral (Dias and Ribeiro, 1993) or sinistral (e.g. Quesada and Dallmeyer, 1994). The relative importance of dextral and sinistral movement is discussed later.

Transcurrent movements were accompanied by convergent movements represented in part by thrusts. More details of these are given in Section 5, below.

3. The general plate tectonic setting

Grand-scale plate movements most relevant to the Hercynian Orogen of France and Iberia involve Gondwana, Laurentia, and Baltica. In the early Paleozoic, Laurentia and Baltica were separated by the Iapetus Ocean, and Gondwanan France and Iberia were bordered by the Rheic Ocean. The Iapetus Ocean closed during the Caledonian Orogeny, Laurentia and Baltica merged, and fragments from the Gondwana margin, such as Avalonia, were caught up in that merger (Keppie et al., 1996). The late Paleozoic Hercynian Orogeny represents the closure of the Rheic Ocean and amalgamation of Gondwana with those continental masses previously affected by the Caledonian Orogeny. During its closure, the Rheic Ocean's boundary with Gondwana is likely to have been an active plate boundary.

A great variety of opinion exists on the changing relationships of oceanic and continental masses in the late Pre-Cambrian and Paleozoic. Perhaps the most comprehensive overviews have been presented by Dalziel et al. (1994) and Dalziel (1997). The dramatic movements portrayed include Laurentia (North America), attached to Australia and Antarctica in the Pre-Cambrian, becoming detached and moving dextrally around Gondwana, and gliding past the northern tip of South America in the Devonian (Fig. 2). Baltica is described as having moved dextrally around Gondwana in advance of Laurentia. A further view of the Laurentia/Gondwana collision is given by Dalla Salda et al. (1998). Other recent presentations of plate movement include Torsvik (1998), whose reconstructions differ from Dalziel's in that he uses what he calls the 'archetypal view' to position continents in relative paleolongitudes, Dercourt (1997), who portrays the French Gondwanan region very much like a modern convergent Pacific boundary all the way through the lower Paleozoic until the closure of the Rheic Ocean, Keppie et al. (1996), who approach the problem mainly from the point of view of terrane capture, and Mac Niocaill et al. (1997) who suggest that Baltica moved away from Gondwana after approaching W Africa in its dextral motion around Gondwana, and that from the early Ordovician into the Silurian the Rheic Ocean widened between Gondwana and Baltica.

We have chosen to use the reconstructions of Dalziel et al. (1994) and Dalziel (1997) because they cover in a consistent way the entire period under consideration, and because their model seems to be based on a true global perspective. From the point of view of this paper, perhaps the most important observation to make is that the closure of the Rheic Ocean to form Pangaea in the Carboniferous involves a massive dextral movement of several thousand kilometres (Fig. 3), and the Dalziel et al. (1994) model is little different from most others in this respect. Fig. 3 shows that the amount of convergence, due to the relative clockwise rotation of Laurentia and Baltica as they docked with Gondwana, was relatively small compared to the dextral shearing. According to these plate reconstructions, the Rheic Ocean was not closed in the traditional orthogonal way. To a large extent, it was swept sideways as Laurentia sheared into place.

4. The tectonostratigraphic terranes of Gondwanan France and Iberia

The concept of suspect tectonostratigraphic terranes derives from the modern Pacific margin where plate boundaries marked by oblique convergence and transcurrent faulting are sites for the displacement and amalgamation of exotic terranes.

Although terrane movements are a microcosm of the grand-scale break-up, displacement, and amalgamation of continental masses, the displacements may be massive, possibly many thousands of kilometres (Howell et al., 1985; Jarrard, 1986). For example, thousands of kilometres of relative movement have been involved in the fragmentation, displacement and amalgamation of terranes in SE Asia during the Cenozoic, as graphically portrayed by Hall (1996), a 2500 km displacement of the Torlesse Terrane of New Zealand, along the eastern margin of Gondwana during the Mesozoic, has been demonstrated by Adams et al. (1998), and > 1000 km orogen parallel displacements of terranes in NW America have been documented by Andronicos et al. (1999).

The plate tectonic setting of the Hercynian Orogeny, described above, indicates oblique convergence and transpression, the same as for those areas in SE Asia and around the Pacific where mega-displacements of terranes are well documented. Therefore, the questions to be addressed here are:

- Is there a collage of Hercynian terranes that can be interpreted as an amalgam of displaced tectonostratigraphic terranes, similar to those of the Pacific and SE Asia?
- If so, what were the displacements?

A primary requirement of the tectonostratigraphic terrane model is that terranes be bounded by faults, and the disparate and faulted nature of French and Iberian Pre-Cambrian/Paleozoic terranes is well established. Rolet (1994), for example, writes: "The Armorican Massif is cross-cut by several major late Carboniferous shear zones which subdivide it into seven geographically distinct zones. Each of these is characterised by its own lithotectonic pile. This explains the striking inhomogeneity of the Armorican Massif....". This is an ideal description of a collection of suspect tectonostratigraphic terranes.

A number of workers have already described French

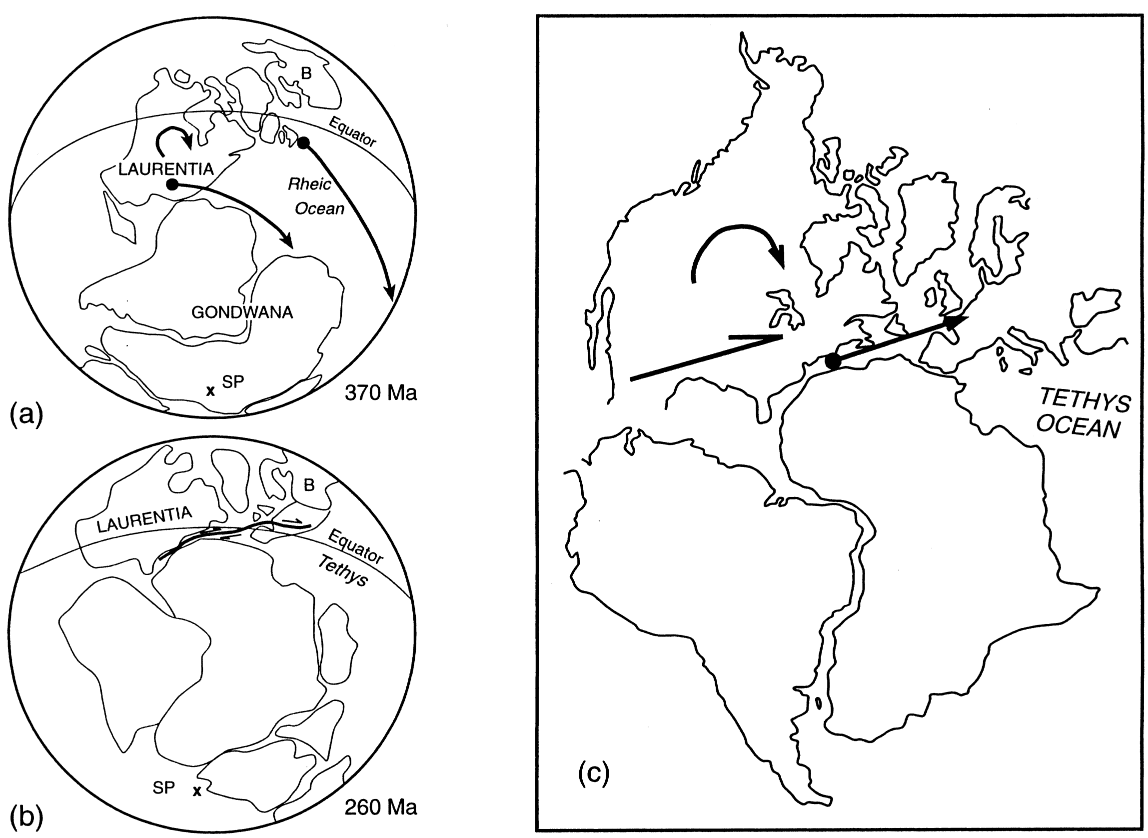

Fig. 3. Laurentia and its dextral shearing along the northern boundary of Gondwana to form Pangea and the Hercynian Orogen. SP = South Pole, and B = Baltica. The Hercynian events took place between 370 Ma and 260 Ma. In (a), the arrows show the several thousand kilometres of dextral movement and the clockwise motion necessary to form Pangea. (b) Schematic of the zone of dextral transpression we suggest was responsible for the development of the Hercynian Orogen. In (c), the filled circle and arrow show how north Brittany may have been translated dextrally from NW Africa to its present site in response to the dextral translation of Laurentia. The necessary clockwise rotation of Laurentia and Baltica, which provided the convergent component of transpression, is also indicated. Plate reconstructions in (a) after Dalziel et al. (1994), (b) after Dalziel (1995), and (c) after Bullard et al. (1965).

and Iberian areas as an aggregate of tectonostratigraphic terranes (e.g. Franke, 1989; Martínez-Catalán, 1990; Quesada, 1991), and some workers, for specific areas, have discussed the allochthonous nature of 'accreted terranes' (e.g. Guerrot et al., 1997). A few have intimated the need for moderate or substantial displacements, so that Balé and Brun (1986) and Le Corre et al. (1990) suggest the Léon region of France has been displaced by between 150 and 400 km, perhaps from the west of Iberia, and Nance and Murphy (1996) place the Cadomian orogenic region of north Brittany southwest of Iberia, adjacent to NW Africa in the late Proterozoic. Despite all this, major lateral displacements have not generally been advocated for Hercynian Gondwanan terranes. Thus, the Hercynian Orogen is usually ascribed to 'convergence' rather than transpression, and the maps and diagrams in the review of pre-Mesozoic geology in France, edited by

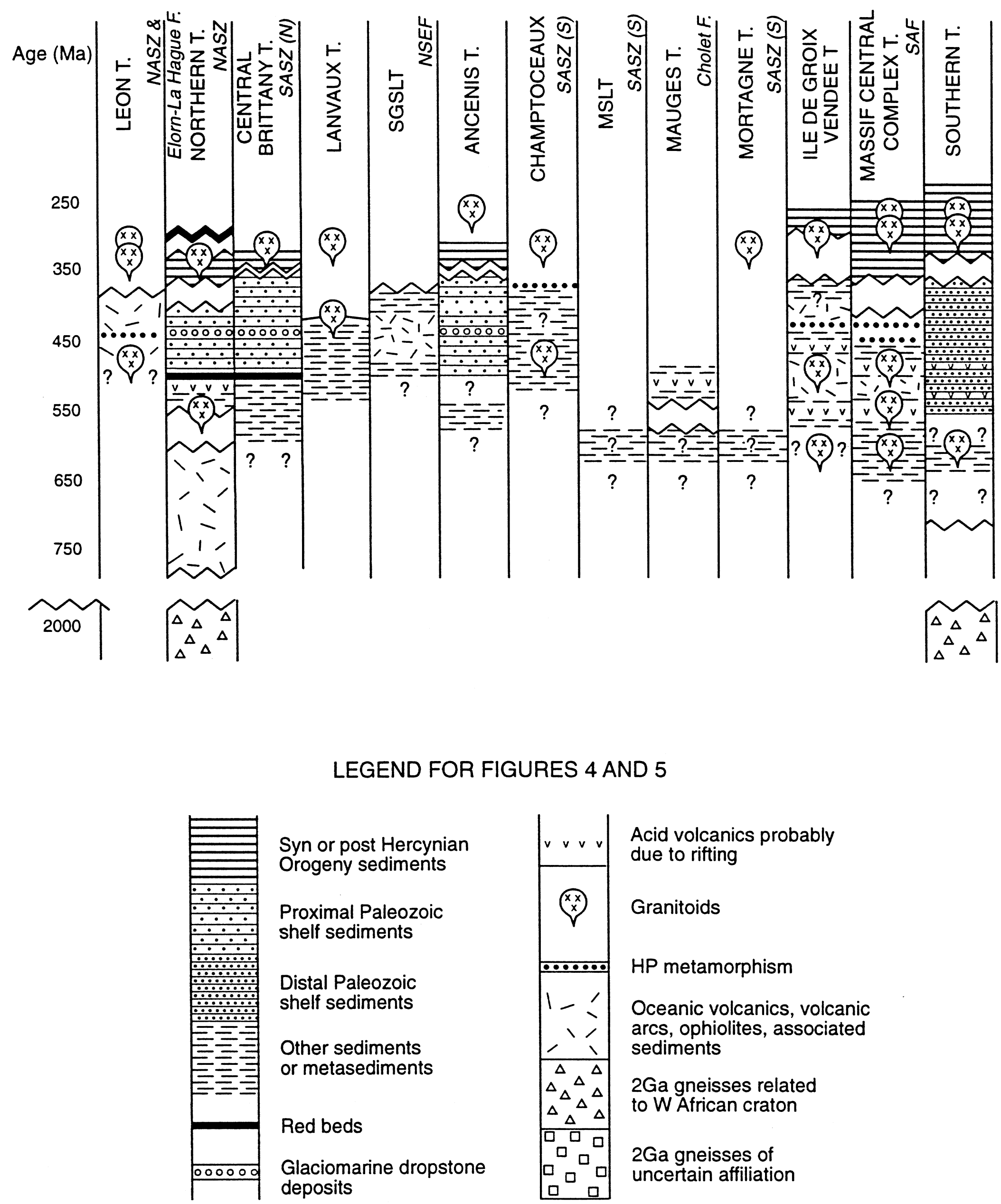

Fig. 4. Diagrammatic sections to show the contrasting geology of the tectonostratigraphic terranes of Gondwanan France. The relationships, inevitably, are generalised. See text for more details. NASZ = North Armorican Shear Zone, SASZ = South Armorican Shear Zone, (N), its northern branch and (S), its southern branch. SGSLT = St Georges-sur-Loire Terrane. NSEF = Nort-sur-Erdre Fault. MSLT = Mauves-sur-Loire Terrane. SAF = South Armorican Front. The key also applies to Fig. 5.

Keppie (1994), and figure 11 in Lefort et al. (1997), portray almost fixed geographies or purely orthogonal movement patterns, such as for the opening and closing of the South Armorican Ocean.

The degree of subdivision of any area into tectonostratigraphic terranes is always a matter for debate, and Howell (1995, p. 97) discusses the problems of 'splitting' or 'lumping together' terranes. The essential prerequisites for splitting are bounding faults and contrasting geological histories either side of the fault. But there are three difficulties, in practice. The first is a matter of scale. Ad absurdum, an exotic block in a mélange qualifies as a terrane. The second problem is that the amount of splitting depends, to some extent, on the geological period one is discussing. For example, the Saint Brieuc and Saint Malo Terranes in north Brittany, described by Strachan et al. (1989, 1996), are important to a discussion of the Proterozoic Cadomian Orogeny (at which time those terranes amalgamated), but they are of little significance to the discussion here, because in the context of the Hercynian Orogeny, north Brittany probably behaved as one terrane. Thirdly, as always in geology, there are the problems of lack of exposure and lack of data.

Here, we subdivide Gondwanan France and Iberia into terranes with contrasting histories in terms of the Hercynian Orogeny. Our descriptions are concise because they are based on existing literature to which we give reference. The exception is the Ancenis Terrane, for which we provide our own observations. The essential elements of the geology in each terrane are summarised in geological columns (Figs. 4 and 5).

4.1. Tectonostratigraphic terranes of Gondwanan France

Rolet (1994) mentions seven distinct 'lithotectonic zones' (equivalent to 'tectonostratigraphic terranes') in Armorica, Piqué et al. (1994, figure 5) has three, and Autran et al. (1994) four. This illustrates the problem, noted above, in deciding to what extent one should 'split' or 'lump'. Here, following the general advice of Howell (1995) to split rather than lump, we define 13 terranes (Figs. 1 and 4).

4.1.1. Léon Terrane

A complex of strongly metamorphosed (eclogite and amphibolite facies) and deformed oceanic and arc material, it includes the granitic orthogneiss of Brest, intruded 466 Ma ago (Le Corre et al., 1990), the Lannilis amphibolites, and eclogitic lenses dated at 440 Ma (Paquette et al., 1987). The Ordovician dates for the eclogites and Brest orthogneiss indicate a Paleozoic protolith, and the metamorphism is probably Eohercynian (Silurian and/or Devonian) because it predates Carboniferous granitoids aged 340, 300, and 290 Ma (Le Corre et al., 1990). Because of its oceanic and volcanic arc nature, and because of the probable Eohercynian metamorphism, Le Corre et al. (1990) suggest the

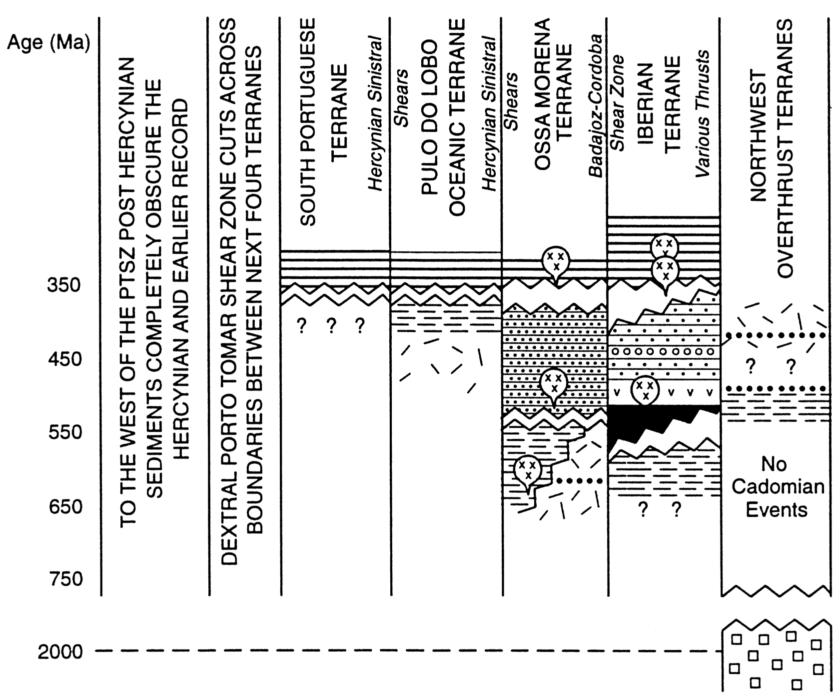

Fig. 5. Diagrammatic sections to show the contrasting geology of the terranes of Iberia. The relationships, inevitably, are generalised. See text for more details. The key for the section is given with Fig. 4.

Léon Terrane represents a displaced part of the south Armorican region.

4.1.2. Northern Terrane

This exposes 2-Ga orthogneiss basement covered by late Proterozoic Brioverian metasediments, strongly affected by the Pan-African Cadomian Orogeny between 580 and 540 Ma ago (Egal et al., 1996). Subduction related arc activity goes back to 750 Ma (Strachan et al., 1996). The central part of the terrane has Brioverian volcanics and marine volcanogenic sediments. To the east there was a platform (Chantraine et al., 1994) on which were deposited Brioverian sediments eroded from the developing Cadomian Orogen to the west, and this platform is cut by numerous plutons emplaced between 615 and 585 Ma. The succeeding unconformable sequence of lower and middle Paleozoic sediments starts in the Cambrian with mainly very shallow water, often tidal, deposits and includes ignimbrites and other acid pyroclastics of Cambrian age. Continental lower Ordovician red beds were followed by a marine trangression in the Arenig, leading to the Ordovician–Devonian marine sequence of shelf sediments. The sequence ends in the Emsian (Lower Devonian), and is unconformably overlain by lowermost Carboniferous fluvial and marine deposits. The unconformity marks the onset of the Hercynian Orogeny.

The boundary that separates the Léon from the Northern and Central Brittany Terranes is described by Balé and Brun (1986) and Le Corre et al. (1990) as a dextral shear which displaced the Léon Terrane between 150 km and 400 km from the southwest during the Carboniferous. Part of this shear zone might now be described as a southern branch of the NASZ, running SW–NE just south of Brest, and the other part to the NE is described as a south dipping synmetamorphic structure characterised by thrusting to the NW (Le Corre et al., 1990).

4.1.3. Central Brittany Terrane

This terrane does not expose 2-Ga Pre-Cambrian basement, and according to Ballard et al. (1986), the Brioverian of the Central Brittany Terrane was not affected by the Cadomian Orogeny or the associated plutonic events. The Brioverian–Ordovician discordance may be due solely to Ordovician extensional faulting. Furthermore, Ballard et al. (1986) suggest that the Brioverian here may be Cambrian, at least in part. The post-Brioverian Paleozoic sequence starts with continental Ordovician red beds. Cambrian acid volcanics are absent. A marine transgression, as in the Northern Terrane, then resulted in stable shelf sediments laid down in a relatively proximal position against the main land mass of Gondwana. Near Brest, the shelf sequence continues through to the Frasnian and Famennian (younger than in the Northern Terrane). The shelf sediments are unconformably overlain by lowermost Carboniferous deposits.

The boundary between the Northern and Central Brittany Terranes is the NASZ. Although it is often shown as passing through Léon to the north of Brest, and this may be where some of the most recent movement has been, we think it more appropriate to describe the main western continuation of the NASZ as being south of Brest, coinciding with the boundary between the Léon and Central Brittany Terranes. The NASZ displaces the Plouaret–Commana plutonic complex (329 Ma) by 15 km (Guillet et al., 1985), and does not significantly displace younger granitoids (291 Ma).

4.1.4. Lanvaux Terrane

The 200-km-long Lanvaux Terrane consists of Silurian granitoids, now orthogneisses, emplaced 415 Ma ago, and sinistrally sheared before the Hercynian (Cogné et al., 1983), and lower Paleozoic and possibly late Proterozoic sediments, with slaty cleavage, ranging in age up to the beginning of the Wenlockian. The sediments differ from the shelf facies in the Northern and Central Brittany Terranes (Lardeux and Cavet, 1994).

The boundary between the Central Brittany and Lanvaux Terranes is the SASZ-N. Syntectonic granitoids were intruded along it about 340 Ma. Granitoid-derived mylonites indicate displacements of the order of 40 km (Jegouzo and Rossello, 1988) post 340 Ma. Immediately north of this fault is the Dinantian St. Julien de Vouvantes fault-bound basin.

4.1.5. Saint Georges-sur-Loire Terrane

This terrane is bound to the north by the Lanvaux Terrane, which is thrust over it, and to the south by the Nort-sur-Erdre Fault and the Ancenis Terrane, described below. It contains N and E-type MORB oceanic volcanics, as well as IAT and BAB (personal communication—Ganne and Bossière). The volcanics are in part Silurian, include pillow lavas, and are metamorphosed up to temperatures between 240°C and 320°C, near the boundary of the greenschist and pumpellyite–actinolite facies (personal communication Ganne and Bossière). The associated sediments are monotonous, mainly unfossiliferous siltstones and mudstones (Lardeux and Cavet, 1994), unlike the shelf sequence in the Northern, Central Brittany, Ancenis, and Southern Terranes. Lefort (1989, p. 55) refers to the offshore Paleozoic Baie d'Audierne rocks, immediately south of the SASZ, south of Brest, as analogous to the St Georges-sur-Loire volcanics.

4.1.6. Ancenis Terrane

Traditionally this has been described as a discrete sinistral pull-apart sedimentary basin, first as a site of marine Ordovician to Devonian sedimentation (Diot and Blaise, 1978), then in the Carboniferous as an intermontane pull apart. The problem with this interpretation is that the marine sediments are the same as the stable shelf sequence, widespread elsewhere: a discrete pull-apart marine basin seems improbable. Shelley and Bossière (2000) show that the intermontane Carboniferous sediments are enveloped in a tectonic mélange of the older marine Paleozoic sediments. We interpret the entire terrane as an exotic duplex, displaced dextrally from afar, with the terrane boundaries representing the deformed boundaries of a dextral Carboniferous pull-apart.

The Ancenis shelf sequence is similar to that elsewhere. Absent, however, are the Cambrian acid volcanics and thick Ordovician sandstones common in other areas of French Gondwana.

The Ancenis Terrane is bound to the north by the Nort-sur-Erdre Fault and Saint Georges-sur-Loire Terrane, and to the south by the unnamed fault that separates it from the Champtoceaux and Mauges Terranes (Shelley and Bossière, 2000).

4.1.7. Champtoceaux Terrane

To the north the Champtoceaux Terrane is bound against the Ancenis Terrane by an unnamed fault, to the east it is faulted against the Mauges Terrane, to the south it is thrust (from NE to SW—Marchand, 1981) over the Mauves-sur-Loire Terrane, and both this and the Champtoceaux Terrane are truncated on the southwestern side by the SASZ-S. The Champtoceaux Terrane bears no similarity to the Ancenis or St. Georges-sur-Loire Terranes to the north, nor to any other terrane it is faulted against. It is made of eclogite and granitic orthogneiss (leptynite) of the eclogite or granulite facies. Timing of granitoid emplacement is thought to be lower Paleozoic (up to upper Ordovician) and the high-pressure metamorphism is 360 Ma (Ballèvre et al., 1994; Bosse et al., 1999). Many of the rocks show evidence of extreme strain with horizontal extension at deep crustal levels. Some boundary faults are thrusts, thought to be Devonian in age (Ballèvre et al., 1994), but the southern boundary is the SASZ-S, clearly of Hercynian age. Ballèvre et al. (1994 p. 185) point out the unique similarity between the lower units of the Champtoceaux Complex and the Malpica-Tuy Unit of northwestern Spain.

4.1.8. Mauves-sur-Loire Terrane

Consisting of micaschists, thought to be Pre-Cambrian, the Mauves-sur-Loire Terrane is overthrust by the Champtoceaux eclogitic and granulitic terrane, and cut off by the SASZ-S. Its relationship to other terranes is completely uncertain.

4.1.9. Mauges Terrane

The Mauges Terrane exposes a Cambrian succession of acid volcanics and volcanogenic sediments (Cavet et al., 1966), unconformable on a basement of Brioverian schists, presumed to be late Pre-Cambrian. The terrane is in fault contact with the Champtoceaux terrane, and all other terranes around it.

4.1.10. Mortagne Terrane

This terrane is characterised by Hercynian granitoids (including the Mortagne Granite dated at 313 Ma) and a complex of earlier orthogneisses and other metamorphic rocks (Lerouge and Quénardel, 1988; Guineberteau et al., 1987). It is bound by the Cholet Fault to the north and the SASZ-S to the south.

4.1.11. Ile de Groix–Vendée Terrane

This coastal region is bound to the northeast by the SASZ-S, the site of syntectonic granitic emplacement around 310–300 Ma (Bernard-Griffiths et al., 1985). The main elements are: Ile de Groix eclogites and blueschists, derived from 500 Ma oceanic volcanics (Bernard-Griffiths et al., 1986), metamorphosed ca. 422 Ma (Peucat, 1986a); blueschists of Bois de Cené (probably the same as Ile de Groix); Ordovician orthogneisses; often severely deformed, metamorphosed packets of lower–middle Paleozoic sediments containing acid volcanics including the probable Cambrian Chataigneraie Ignimbrite, and the volcanic arc ‘porphyroids’ dated at 405 Ma by Peucat et al. (1986). Some metamorphism is of Barrovian type with staurolite-, kyanite- and sillimanite-bearing assemblages. Stretching lineations most commonly trend E–W to NW–SE, and may be related to Eohercynian thrusting from ESE to WNW, though Gapais et al. (1993) show that some stretching lineations are Carboniferous, related to extension on top of a Carboniferous granite (see also Brown and Dallmeyer, 1996).

4.1.12. Massif Central Terrane

The Massif Central Terrane is a complex that probably warrants further subdivision. In common with terranes in south Armorica, excepting the Ancenis Terrane, it does not contain the Gondwanan Paleozoic shelf deposits, and instead exposes a complex of rocks, including oceanic material, affected by Eohercynian events. The terrane is a complex of nappes, thrust from the north. High-pressure metamorphism is recorded in the Silurian–Devonian (Pin and Peucat, 1986). There is no evidence for a 2-Ga Pre-Cambrian basement, but some areas of probable late Proterozoic metasediment are known. A review is given by Ledru et al. (1994), though we note that parts of what is described here as the Southern Terrane (see next) is included by Ledru et al. (1994) under the heading Massif Central.

4.1.13. Southern Terrane

Poorly exposed, and largely covered by Mesozoic and Cenozoic sediments, the Southern Terrane is characterised by lower and middle Paleozoic stable shelf sediments, known from drill hole data in Aquitaine, and exposed in the Montagne Noire area south of the Massif Central, and in the Pyrenees. Proterozoic metasediment and 600 Ma granitoids are present, and basement forming the Landes High under the Aquitaine Basin is probably made of W African cratonic rocks (Lefort and Agarwal, 1999). Cambrian acid volcanics precede the marine Gondwanan shelf sequence. The sequence differs in that it lacks obvious Ordovician glaciomarine sediments, and the sediments are thought to be distal with respect to Gondwana in contrast to the proximal sequences of the Northern and Central Brittany Terranes (Robardet et al., 1994). Carboniferous sediments, the oldest 335 Ma, unconformably overlie the shelf sequence.

The boundary between the Southern and Ile de Groix–Vendée Terranes is obscured by later depositional basins but it is probably a major fault corresponding to the South Armorican Suture or Front (Autran et al., 1994, figure 1). The eastern part of the boundary corresponds with the discontinuity between terranes 3 or 3′ and 4′ in figure 1 of Autran et al. (1994), and it also corresponds to the dividing line between the Central and Southern Regions of granitoid types in figure 19 of Ploquin and Stussi (1994).

4.2. Iberian tectonostratigraphic terranes

The following brief descriptions of Iberian terranes (Figs. 1 and 5) derive mainly from the works of Dallmeyer and Martínez-García (1990), Quesada (1991), Crespo-Blanc (1992), Dallmeyer et al. (1993), and Quesada and Dallmeyer (1994).

4.2.1. Iberian Terrane

The main central mass of Iberia is usually referred to as an autochthon, with a Proterozoic basement and a cover of lower-middle Paleozoic shelf sediments. The Proterozoic is syn-orogenic flysch deposited during the Cadomian Orogeny, and Cadomian metamorphism is weak. The Paleozoic shelf sequences can be subdivided into three belts: the Cantabrian Zone (CZ), the West Asturian–Leonese Zone (WALZ) and Central Iberian Zone (CIZ). In CIZ, the base of the sedimentary sequence is Ordovician. Below that are the Ollo de Sapo acid metaplutonics, emplaced in the early Ordovician (Gebauer et al., 1993). Important breaks in the succession, related to Eohercynian–Hercynian events, usually exist from the Emsian upwards; synorogenic flysch as old as Upper Devonian was deposited in peripheral parts of CIZ, whereas in other more internal parts, non-flysch marine sedimentation occurred during the Lower Carboniferous. In WALZ, the Cambrian is comprised of continental red beds (cf. the Ordovician red basal deposits in parts of Armorica), and the sedimentary sequence continues through into the lower Devonian when it is interrupted by Eohercynian–Hercynian events; the marine platform sequence is overlain unconformably by Upper Carboniferous coal-bearing continental sequences. The boundary between CIZ and WALZ is a normal fault zone, which partitioned depositional and volcanic activity throughout the lower Paleozoic (Martínez-Catalán et al., 1992). An almost complete Paleozoic succession is developed in CZ except in the NE of the zone which was emergent from the late Ordovician to the late Devonian. In CZ, marine sedimentation continued into the Carboniferous, though coal basins become important in the Middle Carboniferous.

4.2.2. Ossa-Morena Terrane

The Ossa-Morena Terrane is separated from the Iberian Terrane to the north by the Badajoz–Córdoba Shear Zone (Quesada and Dallmeyer, 1994). Running WNW–ESE, this is an Eohercynian–Hercynian sinistral shear zone, and it was also a terrane boundary in the Proterozoic (Eguiluz and Abalos, 1992).

The terrane contains oceanic and volcanic arc material of Cadomian age, possibly representing a paired metamorphic belt and subduction towards what is now S or SSW (Quesada, 1990). These rocks were moderately or strongly metamorphosed and deformed during the Cadomian orogeny. The covering Paleozoic strata differ from those of central Iberia in being more distal.

The boundaries between Ossa-Morena Terrane and the other terranes further south are sinistral shear zones running more or less E–W.

4.2.3. Pulo do Lobo Oceanic Terrane

To the south of the Ossa-Morena Terrane, this is made of Ordovician–Silurian oceanic lithosphere (including the Beja–Acebuches Ophiolite), and lower–middle Devonian turbidites (Dallmeyer et al., 1993, figure 5), thought to represent an accretionary prism. It is affected mainly by greenschist facies metamorphism. Both the Pulo do Lobo Oceanic and Ossa-Morena Terranes are overstepped by late Devonian and/or lower Carboniferous flysch.

4.2.4. South Portuguese Terrane

This is usually considered exotic, because it is separated from the main Iberian massif by the Pulo do Lobo Terrane of oceanic material. It exposes only Upper Devonian and Carboniferous rocks, some pre-orogenic shelf type, some syn-orogenic. The nature of its basement is unknown.

4.2.5. Northwest Overthrust Terranes

At Cabo Ortegal, Ordenes, Bragança, and Morais, klippe exist with ophiolites, and on top of those, sheets of variously metamorphosed Pre-Cambrian gneisses and lowermost Paleozoic sediments. Most recently, oceanic lithosphere in the Ordenes Complex has been described by García et al. (1999) as representing subduction-related events and the formation of oceanic crust in the Devonian Rheic Ocean. Clearly exotic, the klippe were thrust over Iberia from the west during the Hercynian Orogeny. Periods of high-pressure metamorphism, at 490 Ma, 420 Ma, and in the Early Devonian, have been recorded by Peucat et al. (1990) and García et al. (1999).

5. Terrane boundaries: the amounts and senses of displacement

5.1. French Gondwanan Hercynian transcurrent faults

Guillet et al. (1985) and Jegouzo and Rossello (1988) have described displacements of 15 and 40 km along the NASZ and SASZ-N, judged from the displacement of syntectonic granites, and Jegouzo and Rossello (1988) suggested approximately 200 km displacement on the SASZ-S on the basis of the width of mylonites derived from syntectonic granites. However, these faults are tectonostratigraphic terrane boundaries, as described above in Section 4, and the total displacement along them may be much greater than directly observed. This is because, by definition, it is not possible to determine directly the amounts of displacement along tectonostratigraphic terrane boundaries or the times of initiation of displacements. It is possible for a terrane boundary fault to have been initiated before any of the rocks presently seen on either side of the fault were formed.

In the case of the NASZ, the 15 km displacement post-dates a 329 Ma granite (Guillet et al., 1985), but given that the orogeny commenced at least 355 Ma, there was sufficient time (at least 26 Ma) for up to 1300 km displacement at modest plate movement rates of 5 cm/y, or 2600 km at faster rates of 10 cm/y. In the case of the SASZ-N, the observed 40 km displacement post-dates 340 Ma granites (Jegouzo and Rossello, 1988); before that there is sufficient time for displacements of 750 km at rates of 5 cm/y, or 1500 km at 10 cm/y. In the case of the SASZ-S, the syntectonic granites are 300–310 Ma (Bernard-Griffiths et al., 1985), allowing up to 4500 km possible movement along the fault.

The duration of the Hercynian Orogeny was at least 50–60 Ma, time sufficient for displacements up to 6000 km. Going back to Fig. 3, one can see that the gross lateral displacement, according to Dalziel's reconstructions, is of the order of 4000–5000 km. The figures above show that time is not a problem in accommodating such a displacement. Clearly the displacement was partitioned amongst several faults, but what is not immediately clear is whether the partitioning was relatively even, or whether there was one or more master faults that accommodated most of the movement.

5.1.1. Displaced fragments of the W African craton

Nance and Murphy (1996) placed the Northern Terrane (Cadomia), with its 2-Ga remnants of the W African craton, next to the W African craton in the late Pre-Cambrian. If this is correct, north Brittany has been displaced dextrally by some thousands of kilometres from that position. It is probable that the displacement occurred after the end of the Devonian because faulting during the Cadomian Orogeny is known to have been sinistral, not dextral (Balé and Brun, 1983; Strachan et al., 1996), and because it places north Brittany in the correct proximal position for receiving its Ordovician–Devonian inner shelf sediments. The alternative, that Cadomia rifted from Africa during Cambro-Ordovician extension, and collided with Armorica during the Hercynian Orogeny, is unlikely given that a rifted fragment of continental crust would have thinned during extension and have been submerged, in which case it would not have been a site of proximal sedimentation.

As noted above, there is a theoretical possibility of as much as 2600 km movement along the NASZ, which bounds the Northern Terrane. More likely, however, is that the displacement was partitioned along several of the Armorican faults.

5.1.2. Sinistral faults in Hercynian France?

Despite the fact of dextral faults, and the plate tectonic setting which indicates massive dextral movements (Fig. 3), some faults in the region have been described as sinistral. Thus, the rhomboidal shape of the Ancenis Carboniferous Culm basin was interpreted as a sinistral pull-apart structure by Diot and Blaise (1978), and the rhomboidal shapes of the Mortagne Granites were interpreted in terms of sinistral pull-aparts that facilitated granite emplacement (Guineberteau et al., 1987). We have now shown in detail why the Ancenis structure is dextral, not sinistral (Shelley and Bossière, 2000): the rhomboidal shape is due to later deformation of the original pull-apart, and the shape is analogous to a *C*–*S* or σ-porphyroclast structure. In the specific case of Ancenis, the SASZ-N was active as a dextral fault at the same time the Ancenis Carboniferous pull-apart was forming, just to the south, and it would be extraordinary if one were dextral, the other sinistral. With regard to the Mortagne Granite, sinistral shearing has been described as weak and only preserved along the E–W-trending sides of the rhomboids. It is known that a stronger dextral shearing both precedes and succeeds the sinistral shearing. The main evidence for sinistral shear is that the main foliation parallel to the SASZ curves into the E–W sides of the rhombs, suggesting sinistral movement. Guineberteau et al. (1987) report, but do not figure, sinistral *C–S* structures. We suggest the rhomboidal shape is bound by the equivalent of *C* and *S* planes. For example, the observed curving of foliation is exactly as would be expected along an '*S*' plane, and it is well known that minor sinistral shear can be expected along the trailing edges of *S* planes, as for example with mica-fish within a dextral system. We note too that some granitoids elsewhere, intruded along stepped dextral faults, occupy rhomboidal spaces similar to the Mortagne Granite (e.g. Gleizes et al., 1998).

Perhaps the most convincing evidence for sinistral shear in the south Armorican region is given by Cogné et al. (1983). Based on asymmetric quartz *c*-axes girdles, they suggest a Silurian granite (415 Ma) was subject to sinistral shear before the later south Armorican dextral shear. Unfortunately, they were not able to constrain the timing of this event, which took place between 415 Ma and 315 Ma.

5.2. Transcurrent faults of Hercynian Iberia

In Iberia, faults which bound the principal terranes, such as the Badajoz–Córdoba Shear Zone, are sinistral. The opposing senses of shearing, sinistral in Iberia, dextral in Armorica, have been linked to development of the Ibero-Armorican arc (Matte and Ribeiro, 1975; Matte, 1986), and this is discussed further in Section 6, below. As is the case for France, one cannot determine magnitudes of displacement along the Iberian terrane boundaries with any certainty.

5.2.1. The Porto-Tomar Shear Zone

Cutting across all the Iberian sinistral shear zones, and across the main terrane boundaries, is the dextral Porto-Tomar Shear Zone (Fig. 1). To the west of this shear zone, the Hercynian Orogen is completely obscured by Mesozoic–Cenozoic basinal deposits, but along the Porto-Tomar Shear Zone itself there are mélanges and tectonic slices of variable metamorphic grade. Paleontological evidence indicates middle to upper Devonian ages for some of the imbricated material.

According to Dias and Ribeiro (1993), the Porto-Tomar Shear Zone was active throughout much of the Devonian as well as the Hercynian. Thus, the shear zone is not simply a late feature cutting earlier sinistral shears. Instead, simultaneous movement on the sinistral shears and the dextral Porto-Tomar Shear Zone indicates the latter is the master fault, and that the sinistral shears it cuts are analogous, perhaps, to S planes or bookshelf-type structures between the master *C* planes. This places a major constraint on the magnitude of movement along the sinistral shears of Iberia during the Hercynian, but it allows the possibility of very large scale movement along the dextral Porto-Tomar Shear Zone.

5.3. Subduction, obduction, and thrusting

The general plate tectonic setting (Fig. 3) suggests the Hercynian Orogen developed during a transpression, and it is common for the convergent and transcurrent components of transpression to be partitioned into separate transcurrent faults and thrusts (Dewey et al., 1998). In Hercynian Gondwanan France, in addition to the dextral shear zones there is much thrusting from the northern sector, as is known, for example, from beneath the Aquitaine basin (Lefort et al., 1997), and in the Montagne Noire (Matte, 1998, figure 5). In some cases, the individual fault zones display elements of both transcurrent and thrust movement, as with the Nort-sur-Erdre Fault (Diot and Blaise, 1978; Marchand et al., 1988). In Iberia, thrusting was mainly to the east and northeast (Matte, 1986; Matte, 1998).

Convergence during the orogeny is also indicated by the obduction of oceanic lithosphere, as in the Northwest Overthrust Terranes of Iberia and the Léon Terrane of France. Subduction may possibly be represented within the orogen itself by the southwards-dipping sub-crustal structures associated with the SASZ (Granet, 1999; Judenherc et al., 1999).

The Ibero-Armorican arc represents a bending of the Hercynian Orogen, either by indentation of a rigid Iberian crustal block (Matte and Ribeiro, 1975; Matte, 1986), or, as discussed in Section 6 below, by the wrapping of Hercynian terranes around a rigid crustal block. In either case, the structure represents one other aspect of the convergence that led to Pangea.

6. A new model for the Hercynian Orogen

Based on the above account of the Hercynian Orogen of Gondwanan France and Iberia, we suggest a prima facie case exists for the following model:

- That the Hercynian Orogen of Gondwanan France and Iberia developed during a massive dextral transpression, as Laurentia sheared along the Gondwanan boundary;
- That the Rheic Ocean between Gondwana and Baltica/East Avalonia was closed as much by being

shifted sideways as by convergence; and,

- That slices of the Gondwanan shelf with its Ordovician–Devonian sediments were displaced dextrally by several thousand kilometres.

A corollary is:

- That the south Armorican and Massif Central oceanic and volcanic arc material represents slices of the Rheic Ocean shuffled in amongst slices of the Gondwanan shelf.

6.1. Discussion of the model

Evidence for massive dextral transpression comes principally from plate reconstructions of the time (Fig. 3). Evidence for transpression within the Orogen is present in abundance, as witnessed by the combination of transcurrent and thrust faults, discussed above in Section 5. It is the norm that convergent plate boundary movements are oblique. Evidence that the Hercynian movements were oblique makes the traditional ideas of orthogonal convergence and orthogonal opening and closing of oceans untenable. With regard to 'closure' of the Rheic Ocean, plate reconstructions (Fig. 3) indicate it involved a major shift of the ocean to the 'east', as well as 'closure' in the conventional sense.

The fact that the orogen consists of disparate fault-bound tectonostratigraphic terranes suggests that slices of the participating plates have been displaced substantially during formation of the Hercynian Orogen. In particular, the presence of proximal Ordovician–Devonian shelf sediments and a 2-Ga basement in the Northern Terrane of north Brittany provides strong evidence for displacement of that terrane by thousands of kilometres from NW Africa. Displacement and shuffling of tectonic slices provide a ready solution for the problem that the proximal shelf facies (of the Northern Terrane) occurs further away from the Gondwana land mass than does the distal facies (of the Southern Terrane).

6.1.1. The Rheic Ocean

It is almost inevitable that shuffling and amalgamation of displaced terranes along the Gondwanan boundary would have involved tectonic slices of the adjacent Rheic Ocean. Others have already suggested that obducted oceanic material in the Hercynian Orogen represents Rheic Ocean (e.g. García et al., 1999). We suggest here that the terranes of south Armorica and the Massif Central, which contain oceanic lithosphere and volcanic arc material, also represent Rheic Ocean, but that in these cases the slices were formed by transcurrent faulting. In such a model, the Eohercynian structures of south Armorica and the Massif Central represent plate movements within the Rheic Ocean, prior to the formation of the Hercynian Orogen. Therefore, we examine again the reconstructions of Dalziel (1997) and Dalziel et al. (1994), shown in Fig. 2, with a view to understanding what the pre-Hercynian movements might have involved. In common with most other reconstructions for the period, the plate movements involve closing of the Iapetus Ocean to form the Caledonide Orogen, movement of Baltica away from Gondwana to form the Rheic Ocean, and dextral movement of Laurentia relative to Gondwana in the late Devonian and Carboniferous to form Pangaea.

For the Ordovician and Devonian we suggest possible plate boundaries (Fig. 6). In particular, it seems necessary to have spreading ridges between Baltica and Gondwana before the Caledonides formed, a southwards-dipping subduction zone to close the Iapetus Ocean (Masson et al., 1999), and, given the passive nature of the north African Gondwana margin from the Ordovician to the Devonian, a series of island arcs within the Rheic Ocean, as shown.

Eohercynian events in south Armorica and the Massif Central include subduction and exhumation of Groix, and a more general metamorphism and WNW–ESE-shortening accompanied by top-to-the-WNW thrusting (Brun and Burg, 1982). If one removes the 40–50° rotation of Armorica that took place during the bending of the Ibero-Armorican arc (Perroud, 1986; Edel, 1987), the WNW–ESE shortening would have been WSW–ENE, which is what one might reasonably predict was taking place within the volcanic arcs of the Rheic Ocean (Fig. 6).

6.1.2. The Ibero-Armorican arcuate structure.

Iberia and Armorica together present an arcuate shape, and this has been interpreted by Matte and Ribeiro (1975), Matte (1986), and Dias and Ribeiro (1994) as the result of a clockwise rotation of Armorica (nearly 90°), and a similar anticlockwise rotation of Iberia due to the pushing of a rigid Iberian block (the indentor) into the mobile Eohercynian–Hercynian belt. Supposed consequences of this indentation were contrasting régimes of faulting in Armorica (dextral) and Iberia (sinistral). The idea is that most structures observed in the Iberian and Armorican Eohercynian–Hercynian belts were formed during this indentation.

The indentor model has been well received in the literature, but there are considerable problems with it. Lefort (1989), for example, observes that the SASZ does not in fact bend towards the south as it is traced westwards, and he notes several geophysical and geological discontinuities in the Bay of Biscay region, which suggest an interrupted rather than continuous arcuate structure.

Lefort (1989) also points to similar Cadomian arcuate structures elsewhere, including Newfoundland, and suggests the shapes are fundamentally Cadomian rather than Hercynian. In support of this, we note that Eguiluz and Abalos (1992) describe the Badajoz–Córdoba Shear Zone as a Proterozoic terrane boundary, and the fact that the terrane contains a Proterozoic paired metamorphic belt (Quesada, 1990) serves to emphasise its fundamentally Cadomian nature. Similarly, the internal zone boundaries within the Iberian Terrane, which later became sites of Hercynian shearing and thrusting, are not fundamentally Hercynian but rejuvenated Cambro-Ordovician extensional faults (Martínez-Catalán et al., 1992). In contrast, in Armorica, generally, the major shear zones are regarded as fundamentally Hercynian, indicating again that the Iberian part of the arc is not simply continuous with, nor a simple mirror image of Armorica.

Lefort (1989) concedes that Hercynian deformation might have tightened any original curved structures, and such a tightening has been advocated on the basis of paleomagnetic data by Ries et al. (1980), Perroud (1986), and Edel (1987). It seems most likely that rotations are 40–50°, not as much as proposed in the indentor model.

Tapponnier et al. (1982) note that the indentor model does not include any consideration of how a layered mobile belt might behave. In the case of the Ibero-Armorican structure, one might envisage terranes as layers, with terrane boundaries accommodating much of the deformation by slip. In such a model, if the terranes were buckled during indentation, would not the relative movements of the terranes be the opposite of that described, sinistral in Armorica and dextral in Iberia?

The more general problem with the existing indentor model is that it seeks only to explain the structure of the arc, not the geological relationships between the constituent terranes. Because it ascribes most Eohercynian and Hercynian structures to the process of indentation, the model, as it exists, requires a fixist approach to terranes, which we suggest is untenable.

According to our model for the Hercynian Orogen, it is perhaps more useful to envisage the Ibero-Armorican arc as a structure formed by dextral shearing around Iberia, and with the convergent components of transpression causing the shear zones to be wrapped around the rigid Iberian mass. This is similar to shear zones, which sweep and wrap around rigid porphyroclasts in a mylonite. In Iberia, the dextral shearing is represented by the Porto-Tomar Shear Zone, as discussed above, and in Armorica by the well known Armorican shear zones. This model is not exclusive of the process of indentation: indeed, convergent components of the transpression probably involved some degree of indentation of the rigid Iberian promontory, synchronous with the dextral shearing.

Our model provides a solution to the question as to

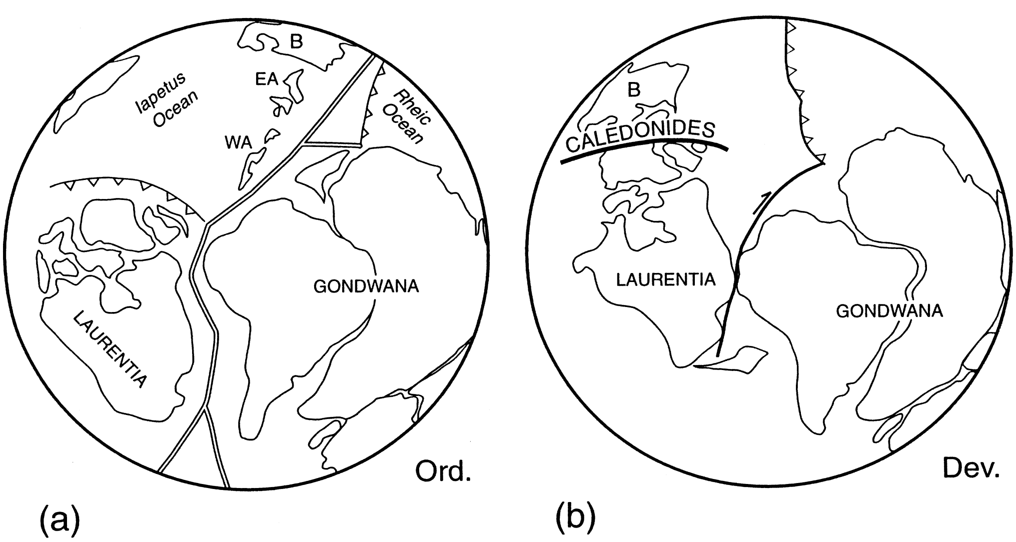

Fig. 6. The distribution of continental masses in the (a) Ordovician and (b) Devonian, according to Dalziel (1997) and Dalziel et al. (1994). These reconstructions have the following features in common with most others for the period: closing of the Iapetus Ocean to form the Caledonide Orogen; movement of Baltica away from Gondwana; dextral movement of Laurentia relative to Gondwana in the late Devonian and Carboniferous to form Pangaea. Possible plate boundaries are shown, and in particular, it seems necessary to have spreading ridges between Baltica and Gondwana before the Caledonides formed, and, given the passive nature of the north African Gondwana margin from the Ordovician to the Devonian, a series of island arcs within the Rheic Ocean, as shown. According to the model proposed here, these island arcs, the associated subduction systems and the ocean crust, were displaced by dextral shear to form much of south Armorica and the Massif Central during the closure of the Rheic Ocean.

why the paleomagnetic data indicate rotations of 40–50°, less than that proposed in the indentor model. If the major structures are the Porto-Tomar Shear Zone in Iberia, and the Armorican shear zones in Armorica, it can be seen from Fig. 1 that rotations of 40–50° are sufficient to straighten the shear zones. According to our model, the E–W to NW–SE structures in the Iberian part of the arc are thrusts and relatively minor sinistral shears along rejuvenated Proterozoic and Cambro-Ordovician faults. They probably represent, for the Hercynian Orogeny, bookshelf-type movements, synchronous with the overriding dextral shear: they are not the Iberian mirror-image equivalents of the Armorican dextral shears.

7. Conclusions

We propose a new model for the development of the Hercynian Orogen of Gondwanan France and Iberia. It involves major displacements and shuffling of tectonostratigraphic terranes along the northern boundary of Gondwana due to a massive dextral transpression as Laurentia slid along that boundary to form the supercontinent Pangea. There is the following prima facie case for the model: the major plate movements have already been proposed in published plate reconstructions of Dalziel et al. (1994) and Dalziel (1997); the disparate fault-bound nature of French and Iberian terranes is well known; the major transcurrent faults of both Iberia and France are dextral; and the dextral shearing was accompanied by convergence, as evidenced by obducted klippe and thrusts throughout the region.

Several long-standing problems are explained by the model. Thus, the 2 Ga basement of north Brittany may be explained by a 2000–3000 km dextral displacement from NW Africa. Such a displacement also explains why the Paleozoic shelf sediments of north Brittany are proximal.

The model provides a solution for the occurrence of oceanic and tectonically disturbed rocks set in amongst the areas of Paleozoic stable shelf sedimentation. Thus, we suggest that the Eohercynian structures and oceanic–volcanic arc terranes of south Armorica represent pre-Hercynian structures and slices from within the Rheic Ocean, shuffled in amongst slices of Gondwanan shelf during the transpression. The WNW–ESE extensions and top-to-the-WNW thrusting are consistent (after undoing rotation of the Ibero-Armorican arc) with subduction-related events along NNW–SSE-oriented arcs in the Rheic Ocean. Thinned continental crustal material involved in these terranes probably represents fragments of Gondwana that drifted into the Rheic Ocean during Cambro-Ordovician rifting. We suggest a new concept for the development of the Ibero-Armorican arcuate structure, that of a dextral shear zone wrapped around the rigid core of Iberia. The sinistral shear zones of Iberia are of lesser importance, as indicated by the master fault status of the synchronous dextral Porto-Tomar Shear Zone. The amount of wrapping is consistent with the 40–50° rotations indicated by paleomagnetic data.

The model also provides at least two possible solutions for the occurrence of distal shelf sediments in localities (southern France) which are now closer to the main Gondwanan land mass than are the proximal deposits of north Brittany. One solution is that the Southern Terrane remained essentially in situ, and that it was always in a distal position relative to the Gondwanan landmass. Another solution is that it was displaced from the Gondwanan shelf, from some distance to the west, and that it was emplaced as a tectonostratigraphic terrane in advance of the terranes to its north.

Finally, we note that the model is supported by geological relationships in northwest Africa. Close to where it is proposed Cadomia was attached to Africa, shelf sediments of late Proterozoic to Carboniferous age directly overly the 2 Ga African craton. Immediately to the north are shelf sediments of lower Paleozoic to middle Devonian age, caught up in Eohercynian and Hercynian movements. Of particular significance are late Devonian–Carboniferous dextral shears that run NE–SW, such as the Western Meseta Shear Zone, and the synchronous sinistral faulting along the Atlas Paleozoic Transform Fault (Piqué et al., 1993). These faults can possibly be seen as analogous to the Porto-Tomar and Badajoz–Córdoba Shear Zones in Iberia. In eastern Morocco, dextral shearing is accompanied by west verging folds dated at ca. 370 Ma (Clauer et al., 1980; Huon et al., 1988). In Algeria, similar relationships exist, though the Paleozoic blocks are caught up in the Alpine fold belt. Dextral shearing in the Grande Kabylie was active well into the Permian on ENE–WSW lines (Bossière and Peucat, 1985, 1986; Peucat and Bossière, 1991).

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