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The Variscan plate tectonic evolution: an improved "Iapetus model"

by *Joachim Neugebauer*[1]

Abstract

Paleomagnetic, faunal, and facies data do not support the concept of an ocean within the European Variscides (= Hercynides). Therefore, a Variscan plate tectonic model is proposed with an ocean outside the European Variscides. The Caledonides, Variscides, and Alleghenides are considered as one single mega-orogen, all originating from one ocean, the Iapetus. The "Iapetus model" interprets the Variscan orogen as a result of a "mega-shear" combined with crustal shortening between Gondwana on one side and Laurentia-Fennosarmatia on the other side of the orogen. The mega-shear occurred after the closure of the main ocean and affected a "Mediterranean Sea type" area between the two continents, termed here the "Variscan Sea". It included several basins of thinned continental crust for the most part. The Variscan tectonic evolution is interpreted as being dominated by ensialic shearing and thrusting, the Carboniferous magmatism as syncollisional. Starting with the restoration of Pangaea, maps of a tentative Permian to Ordovician paleogeography and crustal shortening are presented. Based on a map of the distribution of Variscan (Carboniferous) metamorphism on a Pangaea configuration, as well as on paleomagnetic and facies data, a variant of the model favoured by the author postulates a final strong rotation of Gondwana during the Carboniferous leading to the Alleghenian orogeny.

Keywords: Plate tectonics, mega-orogen, Iapetus model, paleogeography, Caledonides, Variscides, Alleghenides.

1. Introduction

After two decades of resistance, it is now generally accepted that the Variscides (Hercynides) are to be explained by principles of plate tectonics involving an ocean. However, the proposed plate tectonic models are strongly controversial. One group of authors (e.g. ZIEGLER, 1986, IGCP 233, Oviedo 1986) follows the concept of exotic (suspect) terranes as first developed for the Cordilleras orogen on the west coast of North America (CONEY et al., 1980). A second group favours "classic" plate tectonic solutions and eliminates one or two Devonian / Carboniferous oceans within the area of the European Variscides (MATTE, 1986, LEEDER, 1987, and many others). Both concepts have in common the problem of finding evidence for true oceans within the Variscides. Some rocks found in the unmetamorphic realm and even more in the metamorphic center of the Variscides are interpreted as remnants of Paleozoic oceans or indicators of Paleozoic subduction zones (e.g. FRISCH et al., 1984, MENOT et al., 1988). Nevertheless, problems arise from the geologic setting (e.g. missing of oceanic and continental slope sediments, subduction related magmatites, etc.) and from the interpretation of data, (e.g. the uncertainty of Paleozoic U/Pb ages derived from zircons of polymetamorphic rocks, see discussion on p. 316.

A third solution of the problem, the one presented here, assumes that the Variscides are not the product of a separate ocean, but the by-pro-

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duct of the Caledonian cycle. After the closure of the main ocean and the formation of the Caledonides, an unconsolidated rest of a former continental margin continued to exist between two main continents (Laurussia and Gondwana). This area of the later Variscides consisted of ridges and basins with thinned continental crust (patches of oceanic crust are possible and in one case even probable). According to this model, the Early Devonian paleogeographic situation for the Variscides was in some respects comparable to the recent Mediterranean Sea (Fig. 11). However, the "Paleozoic Mediterranean Sea", termed "Variscan Sea" (not ocean!) here, was predominantly underlain by continental lithosphere.

The basins and ridges of the Variscan Sea were compacted by further convergence of the main continents involved and a dextral megashear into the Variscan orogen. Later on, continual shearing to the west and the elimination of a rest of the Iapetus (SW Iapetus) led to the Alleghenian orogeny of the Central and Southern Appalachians and finally to the formation of the mega-continent Pangaea. An essential feature of the model is that the Iapetus was not only the ocean of the Caledonides, but also of the Variscides and Alleghenides, all belonging to one mega-cycle. Therefore I shall call this concept the "Iapetus model" of the Variscan plate tectonic evolution.

BADHAM (1982) published a draft of the plate tectonic model of the Variscides described above. A more elaborated model was presented by NEUGEBAUER (1987a,b) orally. Due to the ambiguity of some data, details of the model can be varied and thus the "Iapetus model" sometimes includes more than one possible explanation.

The reconstruction starts with the restoration of the late Permian Pangaea (i.e. after the Variscan and Alleghenian orogenies) and regresses in time. The plate motions are reversed stepwise on the basis of a true geographic map. Essential parts of the following contribution are: 1. the distribution of Variscan metamorphism in a Pangaea reconstruction, and 2. semi-quantitative preliminary estimates of Variscan crustal shortening. The reconstruction uses the three main continents involved as a rigid framework. Their assumed motions based on paleomagnetic, facies, and tectonic data, limit both amounts and directions of the tectonic transport within the Variscides.

2. Paleotectonic data

2.1. THE LATE PERMIAN PANGAEA (Fig. 1)

During the Late Permian, all continents were integrated into the megacontinent Pangaea. Based on the magnetic anomalies of the Atlantic, reconstructions of the circum-Atlantic part of Pangaea (Fig. 1) proposed by different authors agree on the positions of North America, Greenland, the Rockall plateau, Europe, Iberia, and Africa relative to each other. Furthermore, the positions of the Adriatic plate, Corsica-Sardinia, the Alborean-Kabylian, and the Peloritanian-Calabrian microcontinents can be located from the development of the Mediterranean Sea.

Details of the reconstruction can be varied. The contact of Africa and North America in Fig. 1 is slightly closer than that of EMERY and UCHUPI (1984, fig. 384), but still leads to a good match of the boundaries "continental / oceanic crust" (EMERY and UCHUPI, 1984, plates) of the continents involved. For clarity of representation, the continental hinges are shown in Fig. 1 instead of the boundaries being used for the reconstruction. The position of the Adriatic plate in principle agrees with the one proposed by DERCOURT et al., 1985 (though a closer position to Sicily was chosen for this model); this places the Adriatic plate into regions of thin oceanic type crust of both the Ionian Sea and the most eastern Mediterranean Sea. The Triassic paleomagnetically indicated northern direction of the Adriatic plate is parallel to that of Africa in this model (Fig. 1, data from SOFFEL, 1978). The positions of the other microcontinents mentioned are based on REHAULT et al. (1987).

The front of the Caledonides, Variscides, and Alleghenides (see Fig. 1) separates the cratonic parts of Laurentia (North America), Fennosarmatia (Europe) and Gondwana (Africa, etc.) from the triangle of the mega-orogen. The reconstruction shown in Fig. 1 proposes an ocean in the east (the Permian-Triassic Paleotethys, see ŞENGÖR, 1985) in agreement with most other authors. The distribution of marine Permian (North Anatolia, Taurides, Greece, Sicily, Tunisia, Yugoslavia, eastern Southern Alps, Hungarian Bükk Mountains) corroborates the southern part of the depicted Paleotethys, but not its northern part (broken lines in Fig. 1). One of the possible explanations is an

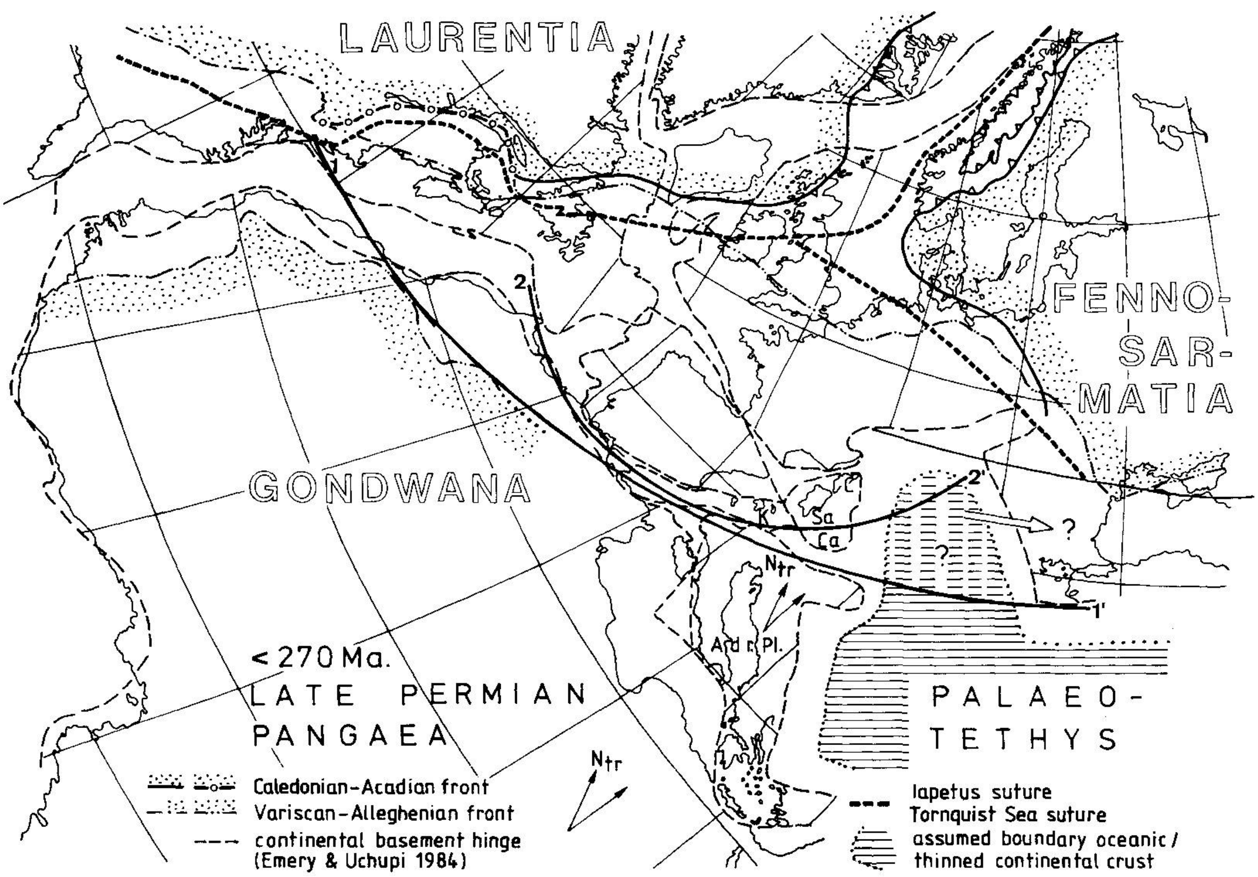

Fig. 1 Late Permian Pangaea: main continents, suture lines, and the Paleotethys.
Ntr: Triassic north; Adr. Pl.: Adriatic Plate; Ca: Calabrian-Peloritanian Massif; C–Sa: Corsica-Sardinia; K: Kabylian Massif. Arcs 1–1′ and 2–2′: discussed shear zones. For further explanation, see section 2.1.

origin of the northern part by Jurassic extension (arrow in Fig. 1, see consequences in 3.1.).

Two oceanic sutures (heavily dashed lines) and two possible main shear zones (thick arcs 1-1' and 2-2') depicted in Fig. 1 are discussed later. The overlap of some microcontinents over these zones can be avoided by a slight change in the boundaries of the continents and microcontinents. These boundaries were not the same as the depicted recent boundaries due to crustal extension during rifting and crustal shortening during collision. For the same reason, the boundary "oceanic crust/thinned continental margin" is schematically fixed at some distance from the boundaries of the continents and microcontinents in all figures.

Two uncertainties in the restoration of Pangaea have important consequences: 1. The edges of Ireland, Rockall Bank, and southern Greenland fit so tightly in Fig. 1 that the suture between Newfoundland and Ireland is nearly a straight line. This version is also proposed in many publications (e.g. DEWEY and SHACKLETON, 1984). A less tight restoration of the Rockall Bank section of the North Atlantic (e.g. HAWORTH, 1983, NEUGEBAUER, in preparation) would result in a bend of the suture line between Newfoundland and Ireland. The consequence of the bend is a discontinuous tectonic evolution of both regions leading to a later closure of the Iapetus in the Newfoundland section. This would mean an Early Devonian (Acadian) instead of Late Silurian (Caledonian) time of orogeny in Newfoundland (the age of that orogeny in Newfoundland - Late Silurian or Early Devonian? - is weakly defined. RODGERS, 1982, p. 234). 2. Iberia could be rotated slightly clockwise and moved westward from its position in fig. 1. This would support the favoured "model of strong rotation" (section 3.2.).

2.2. THE MAIN ARGUMENTS (Figs. 2, 3, and 4)

The main reason for developing the Iapetus model of Variscan plate tectonics is that evidence for oceans is insufficient within the Variscides. When the tectonic sutures of the nonmetamorphic Variscides are compared with true oceanic sutures, the lack of relicts of Paleozoic oceanic crust, oceanic sediments, and subduction related magmatism and metamorphism is striking (see BEHR et al., 1984, p. 33, data review of MATTE, 1986a, and figs. 5, 8, 10, 11).

Some authors assume that the relicts are camouflaged in the central metamorphic zone. They interpret eclogites, amphibolites, orthogneisses, etc. as Paleozoic ophiolites, arc magmatites, etc., based on Early Paleozoic zircon U/Pb ages (e.g. FRISCH et al., 1984, MENOT et al., 1984, 1988). Although this would solve the problem of the missing Variscan ocean, the ages obtained have to be interpreted carefully. Studies with the SHRIMP ion microprobe show that polymetamorphic zircons, having undergone three or more high-temperature events, often show an external zone of zircon, grown during the last high grade metamorphic event (cf. KRÖNER et al., 1987). Due to this "double zircon", the concordia intercepts derived from the analyses of zircon fractions may be too low. Remnants of Cadomian (or older) oceans, back arc basins, and arc magmatites may be an alternative interpretation of the eclogites, amphibolites, and gneisses concerned if the apparently Paleozoic zircon ages in reality are rejuvenated Cadomian ages.

Calc-alkalic magmatism of the "magmatic arc" type appears in Early Carboniferous time (e.g. in the Black Forest and Vosges, HOLL and ALTHERR, 1987). I follow the traditional view that this magmatism is syncollisional and due to ensialic thrusting, with evidence from facies and tectonic progradation. Such type of magmatism is difficult to distinguish from magmatic arcs by geochemical criteria (cf. HARRIS et al., 1986).

I do not wish to discuss all arguments dealing with the complex question of a camouflaged ocean in and outside the central metamorphic zone. The pertinent arguments are incorporated into the Iapetus model (i.e. the

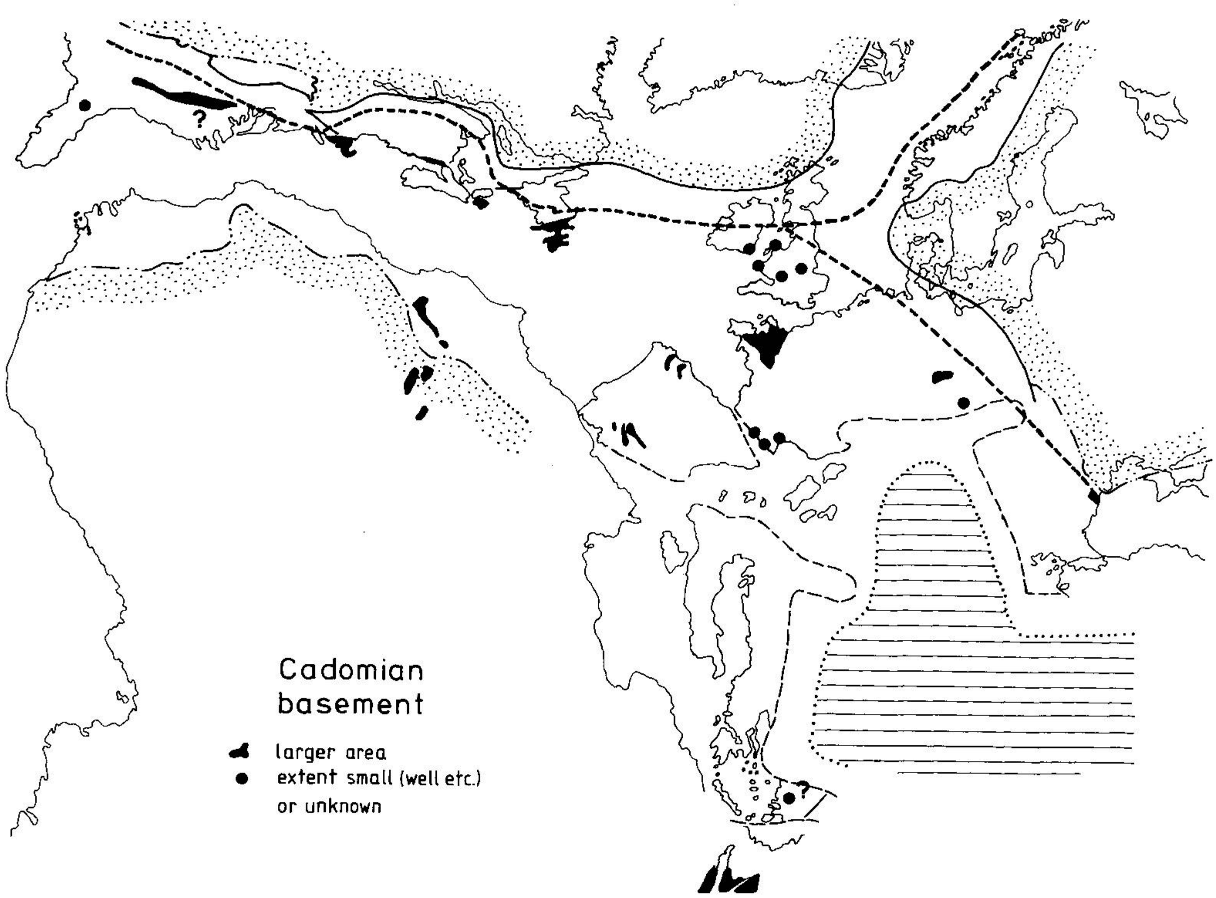

Fig. 2 Distribution of Cadomian age basement belonging to the Gondwana plate.
Data basis: ZWART and DORNSIEPEN (1980), Tectonic Map of Africa 1:10000000 (1968), ZIEGLER (1982: London Platform), SUK et al. (1984: Brunovistulikum), SECOR et al. (1986b: Tallahassee/Suwannee terrane in Florida), uncertain: (?).

Lizard ophiolite, the Late Silurian/Early Devonian glaucophane-schists of the Ile de Groix, Fig. 11, etc.).

Because evidence for Paleozoic oceans within the Variscides is not convincing, I present a plate tectonic solution placing the great ocean outside the Variscides sensu strictu. This ocean was closed before the "Variscan era" (Devonian-Carboniferous) and only a relict of one of its continental margins including marginal basins (altogether called the "Variscan Sea") was shortened to become the Variscan orogen. Evidence in favour of this model is given by paleomagnetic, facies, and faunal analyses, published by various authors (sources: see captions).

The oceanic suture lines in Figs. 2, 3, and 4 allocate areas of the mega-orogen to the three main continents. All Variscan areas belong to Gondwana forming part of its wide continental margin during the Ordovician.

In Fig. 2 the Cadomian (=Panafrican) basement is restricted to Gondwana and its margin while Laurentia and Fennosarmatia have older basement at their margins (localities of Cadomian basement mainly after ZWART and DORNSIEPEN, 1980, other sources see captions). Ordovician paleomagnetic latitude data (fig. 3) derived from paleomagnetic inclinations support the allocation of the different parts of the continental margins (data from PERROUD et al., 1984, and DEUTSCH, 1984). The data indicate that Laurentia and Fennosarmatia were located near the equator whereas Gondwana and the areas allocated to its margin lay near the South pole (BONHOMMET and PERROUD, 1986). Gondwana was separated from the other two continents by a wide ocean, as seen by the differences of latitudes of 20–30°.

LEWANDOWSKI (1987) reports Ordovician high latitude values (60°) for the Holy Cross mountains, east of the Barrandium (36°) and east of the suture line shown; these values contradict the faunal evidence and are not depicted in Fig. 3.

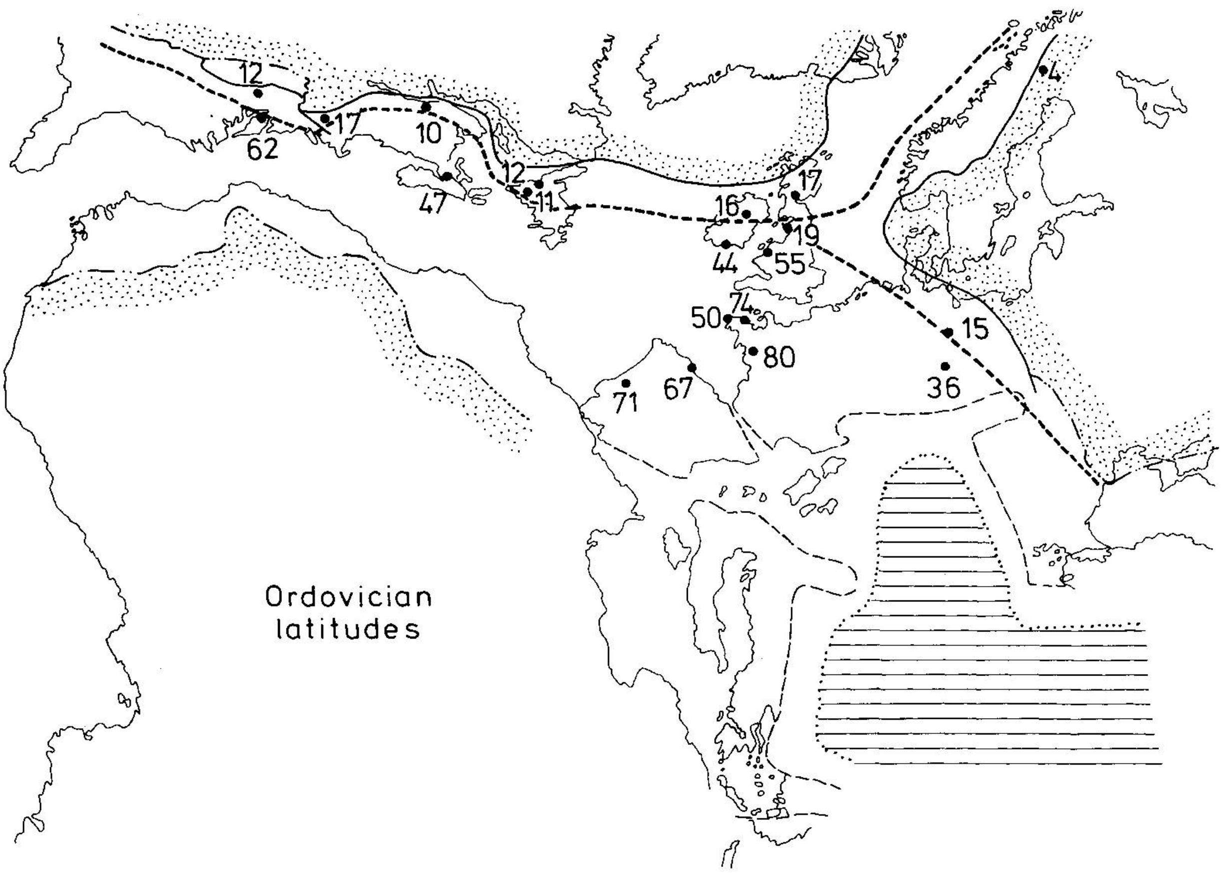

Fig. 3 Ordovician latitudes and the plate boundaries (suture lines).
Cf. locations of the same data in Fig. 13. Latitudes according to paleomagnetic data of PERROUD, VAN DER VOO and BONHOMMET (1984) and DEUTSCH (1984).

2.3. FAUNA AND FACIES

Faunal and facies analyses shown in Fig. 4 also support the positions of the suture lines. COCKS and FORTEY (1982) and many other authors distinguish three faunal provinces in the Late Cambrian and Early Ordovician. The Gondwana province is characterized by clastic facies which are believed to belong to areas of high latitudes. This interpretation is supported by the occurrence of Late Ordovician glacial sediments both in North Africa and on the Gondwana margin reaching as far as the Armorican Massiv and Thuringia (cf. Fig. 13 and HAMBREY, 1985; CAPUTO and CROWELL, 1985; VAN HOUTEN and HARGRAVES, 1987). Carbonate sediments (COCKS and FORTEY, 1982) and evaporites (ZHARKOV, 1981) both indicators of a warm climate, are found on Laurentia and Fennosarmatia.

Fauna provincialism ended in the Late Ordovician and faunal exchange continued into the Silurian indicating that all three continents were close together since the Late Ordovician (COCKS and FORTEY, 1982, VANNIER et al., 1987). Some authors describe "cosmopolitan faunas" for the Silurian, (e.g. BRUTON, 1986; COCKS and FORTEY, 1982), whereas others find some faunal differences. ILIESCU and TAUGOURDEAU (1981) distinguish a "northern" and a "southern province" of Chitinozoa, the latter being characteristically Gondwanian. There is one area in which the two faunas mix: the Moldanubian platform. Fig. 12 shows the first contact of the two continents in this area.

Opinions diverge on faunal differences during the Devonian. COCKS and FORTEY (1982) report new differences between the British Isles + Fennosarmatia + Laurentia on the one hand, and Saxothuringia + North Armorica + Iberia on the other. They assume a new Devonian "Rheic ocean" between these two areas. Without doubt, basins deepen and extend in the region discussed at least during the Middle Devonian. On the other hand, YOUNG (1987) reports evidence for a close affinity of verte-

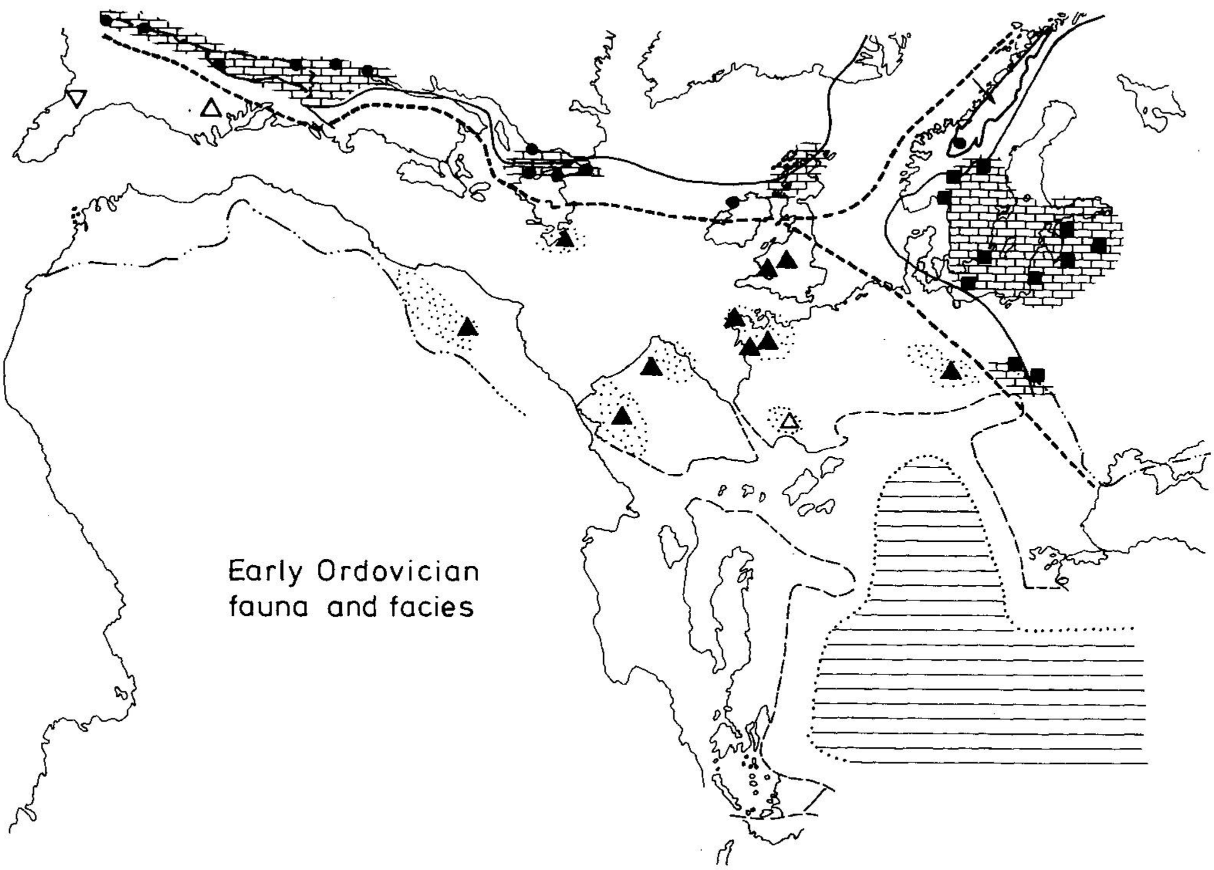

Fig. 4 Early Ordovician (Arenig) fauna and facies defining three continents (concept and locations after COCKS and FORTEY, 1982).
Full Symbols: Early Ordovician fauna; facies symbols: Early Ordovician carbonates and clastics. Additional open symbols (upright and inverse triangles): Cambrian and Silurian "exotic" faunas (SECOR et al., 1986a; SUPPE, 1985). Arrow (Scandinavia): nappe transport.

brate faunas of Gondwana and Laurussia (Laurentia + Fennosarmatia) during the Middle and Late Devonian. Therefore, the differences of the faunas (ostracodes) may be due to the change from a tropically humid to an arid climate (cf. Fig. 11).

Further to the south, in the area between the Saxothuringian zone and cratonic Gondwana, any paleomagnetic, climatic or faunal evidence for a Paleozoic ocean is missing. From the discussion above follows that all areas up to and including England, Wales, and Southern Ireland as well as the Barrandian belong to the margin of Gondwana during the Ordovician.

2.4. FURTHER DISCUSSION OF THE THREE SUTURE LINES (Fig. 5)

Many obducted ophiolites line the suture between Gondwana and Laurentia, as well as the one between Fennosarmatia and Laurentia, leaving no doubt about the oceanic nature of these boundaries (see Fig. 5). Subduction related magmatites are also present along both sutures. However, they are virtually absent along the suture between Gondwana and Fennosarmatia (with the exception of André et al., 1986). A possible explanation is that the thick sediment cover along this boundary of Fennosarmatia shrouds these rocks. I propose an alternative explanation presented in Figs. 12 and 13 with the Gondwana plate moving parallel to this suture during the Ordovician and Silurian.

2.5. CARBONIFEROUS METAMORPHISM ON A RESTORED PANGAEA (Fig. 5)

Carboniferous metamorphism is shown in a simplified manner on the Pangaea reconstruction of Fig. 1. Crustal thickening (especially due to thrusting) or high heat transfer (e.g. by

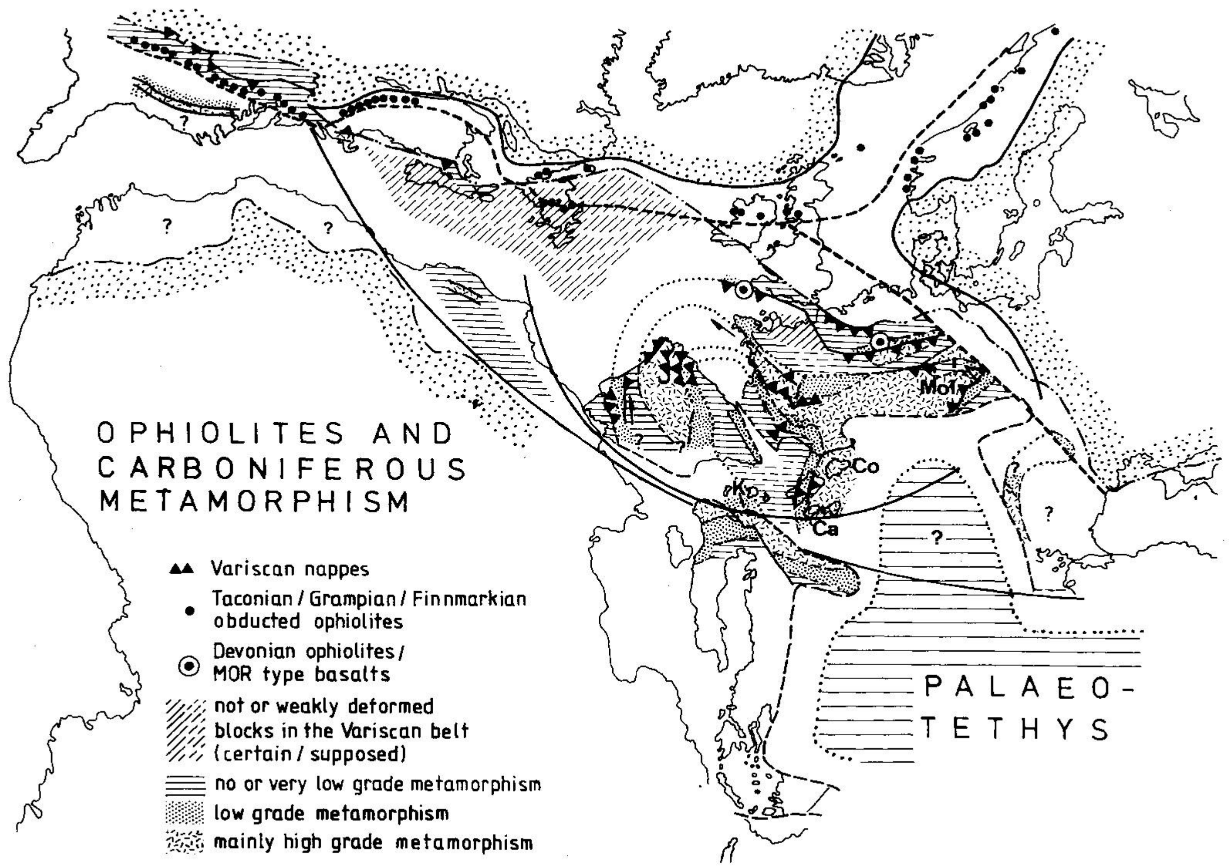

Fig. 5 Early Paleozoic ophiolites, Devonian MORB type basalts, and Carboniferous metamorphism (simplified).
Note the misfit of the metamorphism of the Adriatic Plate. Ca: Calabrian-Peloritanian Massif, Co: Corsica, K: Kabylian Massif, Mol: Moldanubian Massif. Symbols of metamorphism are also used in Figs. 6–9.

plutonism) has to be assumed where Paleozoic sediments are metamorphic. Examples for metamorphism below Variscan thrusts (nappes) are the phyllitic zone below the Giessen nappeLizard nappe (southern Rhenohercynian zone-SW England), the metamorphic zone below the nappe of the Moldanubian Münchberg Massif, and the phyllitic zone below the nappes along the line Sardinia-Montagne Noire-NW Iberia.

Variscan nappes are also reported from the central metamorphic zone (Central Iberian zone, French Massif Central, Bohemian Massif, e.g. MATTE, 1986; RIBEIRO et al., 1964, 1980; BURG et al., 1985; DUBUISSON et al., 1988; BEHR et al., 1984; TOLLMANN, 1982). The Carboniferous metamorphism of this zone is of low pressure/high temperature type (e.g. WEBER and VOLLBRECHT, 1986). The nappe pile resulting from Carboniferous nappe thrusting can therefore not have been very thick. High heat flow and the intensive plutonism of this zone must have contributed to the high grade metamorphism. Strong underthrusting of sediments or low grade metamorphic rocks below the margins of this zone is one possible reason for the intensive plutonism.

The distribution of Variscan metamorphism was shown on a map of the restored Pangaea by VAI (1980) and VAI and COCOZZA (1986). The new map (Fig. 5) differs mainly because of a diverging restoration of Pangaea. It is based on the "Metamorphic Map of Europe, 1:1,5 Mio., Paris 1973", and the map of PAECH (1976). There is still uncertainty on my part about the Variscan age of the metamorphism in the Eastern Carpathians and the Circum Rhodope belt. Carboniferous metamorphism in the Southern Appalachians is reported by DALLMEYER et al. (1986).

The Variscan metamorphism of the Southern Alpine-Austroalpine and West Carpathian area (northern part of the Adriatic plate) does not fit into the pattern of Variscan metamorphic zones shown in Fig. 5. This area fits better near its present position, namely into the gap between Corsica/Calabria (Ca) and the southern Moldanubian Massif (MOL). Fig. 5 clearly demonstrates this discrepancy. I cannot place the Adriatic plate into this gap because this would contradict the current models of alpidic plate motions in the Mediterranean Sea area (cf. section 2.1., DERCOURT et al., 1985, 1986). Another solution is described in section 3.2.

2.6. THE ALLEGHENIAN OROGENY

The Alleghenian orogeny is the result of a strong collision including large décollement nappes in the Southern Appalachians (COOK et al., 1979). The Alleghenian deformations took place mainly in the Upper Carboniferous and the Lower Permian (SECOR et al., 1986a, b); they continued there while crustal shortening practically ceased in Western Europe at the Westfalian/Stefanian boundary. The culmination of orogeny and nappe formation in Europe was in the Viséan/Namurian stages., i.e. before the main collision in the Southern Appalachians. From this results that the last motion of the Gondwana plate during the Alleghenian orogeny has to follow a path which does not strongly affect the Westeuropean regions. The analysis of the Late Carboniferous/Early Permian structures of Europe, Africa and North America indicates a last large westward motion of Gondwana (ARTHAUD and MATTE, 1977) and a westward collision with nappe transport perpendicular to the nappe fronts of the Southern Appalachians.

3. The models

3.1. CARBONIFEROUS MAIN SHEAR ZONES

It is necessary to identify one or several shear zones between Gondwana and Laurussia (Laurentia + Fennosarmatia) along which the westward motion of Gondwana could have taken place. The entire orogenic belt is affected to some degree by such shearing (ARTHAUD and MATTE, 1977), but the main shear zone must be south of the traverse Iberian arc. The structural misfit of the SE end of the Iberian arc and the Adriatic plate are further arguments for such shear zones.

There are two possible locations for the main shear zones both shown in Figs. 5 and 1. The first one, proposed by ARTHAUD and MATTE (1977), BARD et al. (1980), and MATTE (1986), exhibits a large radius and follows well-known structural zones in the North American and North African continental margins and the Variscan Atlas fault (cf. Fig. 1, line 1-1′). The reconstruction using this shear zone is here called the "westward shear model". The second location follows the present continental margins of Newfoundland, North Africa, and the margins of some minor plates (cf. Fig. 1, line 2–2′). This line has a small radius. Because the motion along this shear zone results in a strong rotation of Gondwana of about 30–35°, it is called the "model of a strong rotation" here.

3.1.1. The "westward shear model" (= model 1), (see Figs. 6 and 8)

Fig. 6 shows the reversal of the Gondwana plate motion described by the first model. The amount of the reversed plate motion is restricted by the fit of the Adriatic plate within the Variscan metamorphic zones. The approach has the following disadvantages: 1. The Moroccan Antiatlas region loses contact with the main Gondwana continent. This is not supported by local facies. 2. The ranges of the Moroccan and SW Iberian orogenic zones cannot be reconciled although the zones should be contiguous (better seen in Fig. 8). 3. A part of the Paleotethys remains open E of Corsica/Sardinia (cf. Fig. 1: area with broken hatched signature). This part is artificially closed by a westward translation of the Moesian platform in Fig. 6. Further problems arise through the plate motions of the Acadian orogeny (cf. Fig. 11).

Fig. 8 continues explaining the "westward shear model" and represents the minimum amount of shortening resulting from nappe transport and (other) deformation. Shortening through deformation (folding etc.) is assumed to be about 35–40% of the width of the zone. Arrows are shown where nappes are clear and nappe transport has been added (e.g. Giessen nappe: >60 km [Behr et al., 1984], Lizard thrust: "possibly several hundreds of km" [Shackleton, lecture 1986, Mainz], the nappe of NW Iberia [e.g. Bragança, Morais, etc. units, central Iberian zone]: > 200 km [Geological Map of Iberia, 1:1 Mio, 1981, Martinez-Garcia, 1986]). The amount of nappe transport is often poorly established. Carboniferous high pressure minerals have been described close to

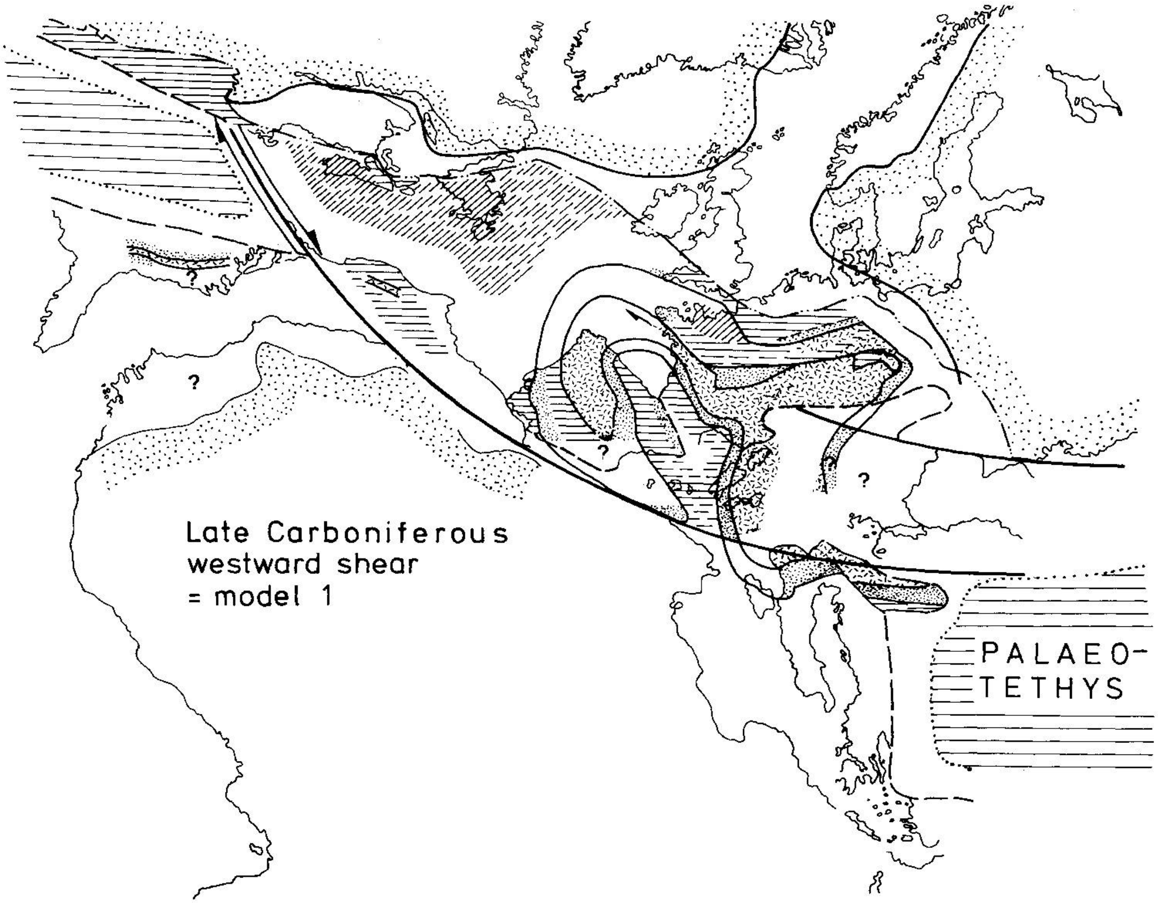

Fig. 6 Late Carboniferous westward shear (model 1).
Note position of Morocco, and the new position of the Adriatic Plate compared to Fig. 5. Arrows: amount of shear. Other symbols as in Fig. 5.

two nappes, (southern Rhenoherzynikum: MASONNE and SCHREYER, 1983); Zelezny Brod unit, Western Sudetes: GUIRAUD and BURG, 1984).

Additionally, two occurrences of Devonian mid-oceanic ridge type basalts are shown in Fig. 8 because they indicate basins and greater extension (Lizard point, DAVIES, 1984; Giessen nappe, GRÖSSER and DÖRR, 1986). The Lahn-Dill syncline (an ensialic basin) contains Lower Carboniferous MORB basalts (WEDEPOHL et al., 1983).

The Early Carboniferous latitudes of Fig. 8 are derived from paleomagnetic inclinations (PERROUD, 1986; AIFA, 1987). They comply both with the central line of Early Carboniferous tropic coals of Russia (STRACHOW, 1961, 1963) and, more or less, with the equator of the paleomagnetic reconstructions of SCOTESE (1984). Note the similar latitudes of the Cantabrian Mountains (southern external zone: 7°) and the Harz (northern external zone: 5°). Upper Viséan to lower Namurian evaporite deposits are known from NW Africa (Rhadames, Tindouf, Illisie, Reggane basins, [ZHARKOV, 1981]), fitting the given latitudes. None of the different paleogeographic data presented in Fig. 8 pleads for the existence of a larger ocean within the European Variscides during the lower Carboniferous.

3.1.2. Carboniferous strong rotation of Gondwana (Figs. 7 and 9)

The "model of strong rotation" (Figs. 7 and 9) assumes that Gondwana began westward rotation after its northwestward motion (and the formation of the Westeuropean Variscides) slowed down. Both shear zone and rotation can be seen in Fig. 1 (zone 2-2′) and Fig. 7, respectively. Due to this rotation, the Adriatic plate was separated from southern Europe and a "gap" was created (Fig. 1: broken hatched

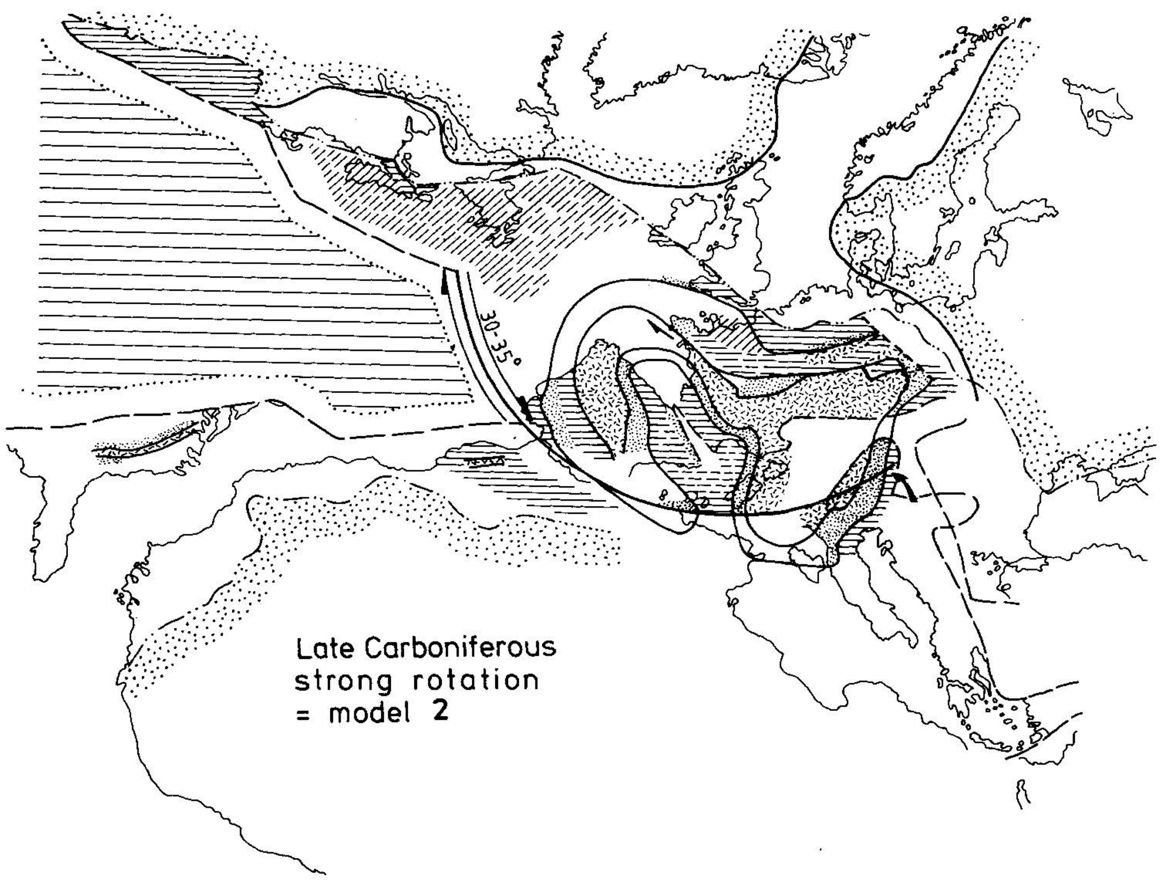

Fig. 7 Late Carboniferous strong rotation (model 2).
Note position of Morocco, and of the Adriatic Plate. Thick short arrow: reversal of Alpidic rotation (MAURITSCH and FRISCH, 1980). Other symbols as in Figs. 5 and 6.

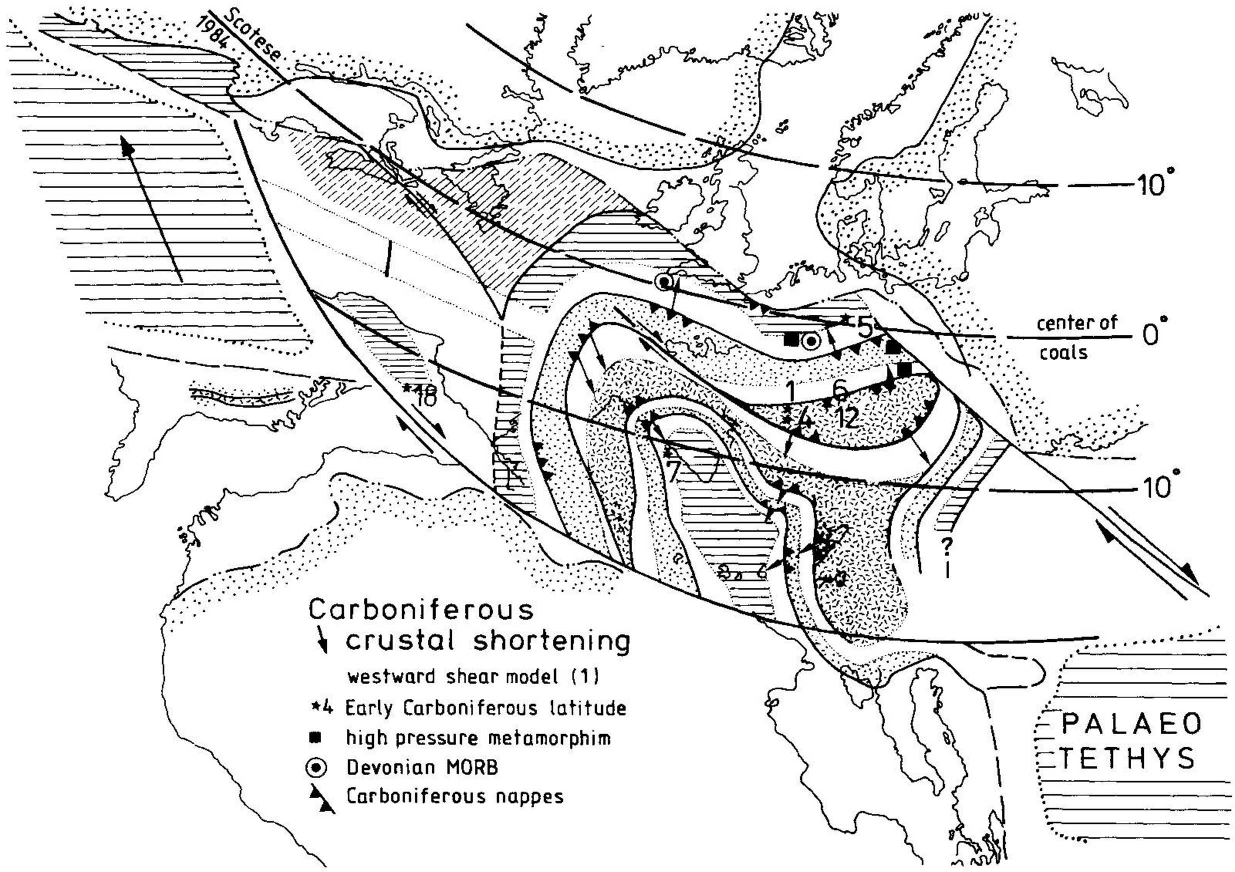

Fig. 8 Tentative reconstruction of Carboniferous crustal shortening applied to model 1.
White zones: assumed amount of total deformation. Long arrow: total shortening = plate convergence. Small arrows mark nappes. Note position of Morocco. Paleolatitudes from PERROUD (1986), AIFA (1987), and BACHTADSE et al. (1983). Other symbols see Figs. 5 and 6. The symbols for metamorphism are simplified within the individual Variscan zones (cf. Fig. 5).

area). A satisfactory explanation cannot be given for the crustal shortening in the SE Variscides without assuming a continent in this gap.

The minimal extensions applied to the continental parts in Fig. 8 (westward shear model) are also valid for the "model of strong rotation" (Fig. 9). The paleogeographic latitudes can be drawn in a similar way except for the African parts (Morocco etc). and the larger ocean in the west.

Although this model leads to a better explanation of the metamorphic zones of the European Variscides (see 2.5. and Fig. 5), it needs further supporting evidence: a rotation of about 30-35° (after a back-rotation of this magnitude, the Adriatic plate meets the European margin [cf. Fig. 7]) should agree with paleomagnetic data. Therefore, the paleogeographic reconstructions of SCOTESE (1984) which integrate the available paleomagnetic data, are presented for the Early and Late Carboniferous here (Fig. 10). The resulting rotation of about 30–35° is the same as that independently reconstructed in Fig. 7. Other arguments include an opening of equal magnitude (30–35°) for the Paleotethys, which seems to be the countereffect of the same rotation, and the direction of convergence in the Southern Appalachians, the Marathon and Ouachita Mountains (details NEUGEBAUER, in preparation).

The data on the climate also seem to fit into this model: the evaporites of the Venezuela, Amazon and South Peruvian basins are all of Late Carboniferous age, no Early Carboniferous evaporites being reported from these areas (ZHARKOV, 1981). Compare the positions of these regions in Fig. 10a and 10b. CAPUTO and CROWELL (1985) and VEEVERS and POWELL (1987) propose a strong migration of the south pole (rotation) during the Carboniferous based on glacial deposits on Gondwana.

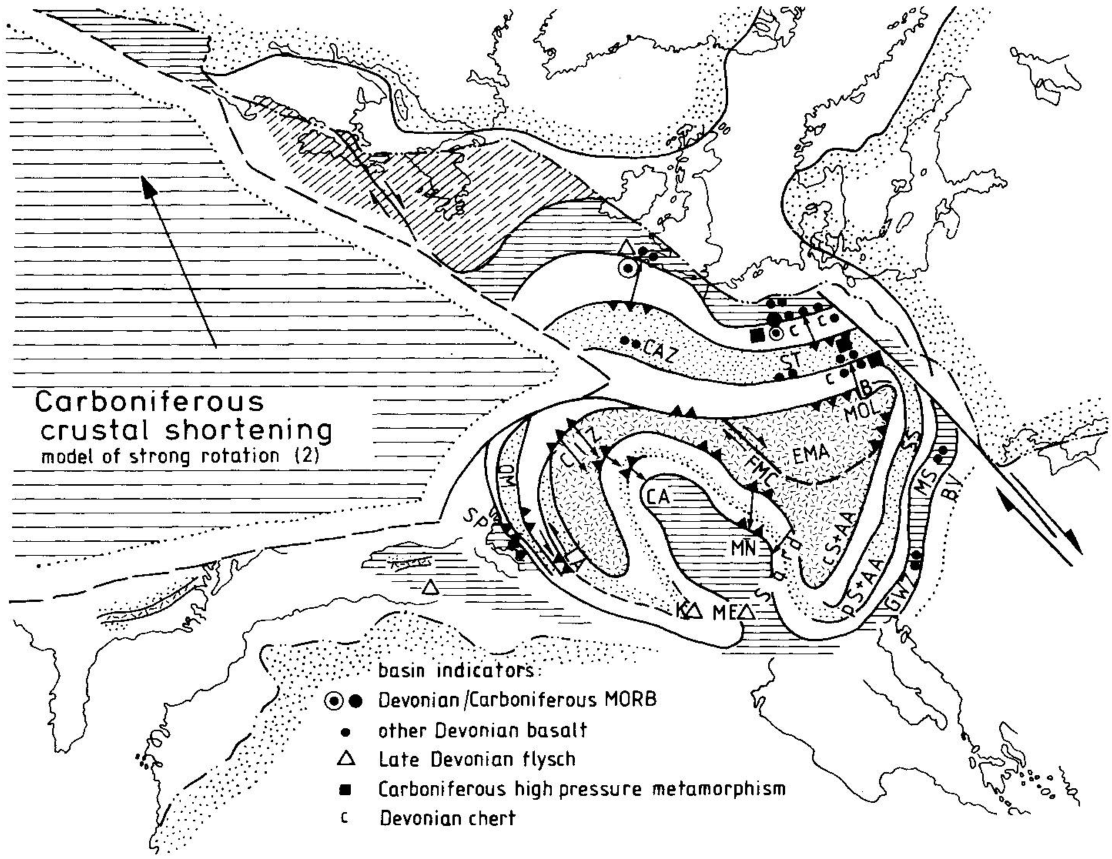

Fig. 9 Tentative reconstruction of Carboniferous crustal shortening applied to model 2.
Note: the Variscan basins are connected to the west with an ocean, the SW Iapetus. Long arrow: total shortening = plate convergence.
B: Barrandian region; BV: Brunovistulikum; CA: Cantabrian Zone; CAZ: Central Armorican Zone; CIZ: Central Iberian Zone; EMA: External Massifs of the Western Alps; GWZ: Northern and Southern Alpine Graywacke Zone; FMC: French Massif Central; K: Kabylian Massif; LA: Lusitanian-Alcudian Zone; ME: Menorca; MN: Montagne Noire; MOL: Moldanubikum; MS: Moravosilesikum; OM: Ossa-Morena Zone; pS+AA: phyllitic Southern Alpine and Austroalpine Zone; cS+AA: high grade metamorphic Southern Alpine and Austroalpine Zone; Sard: Sardinia; SP: South Portuguese Zone; ST: Saxothuringian Zone. Other symbols see Figs. 5 and 6. Symbols of metamorphism are simplified within the Variscan zones (cf. Fig. 5).

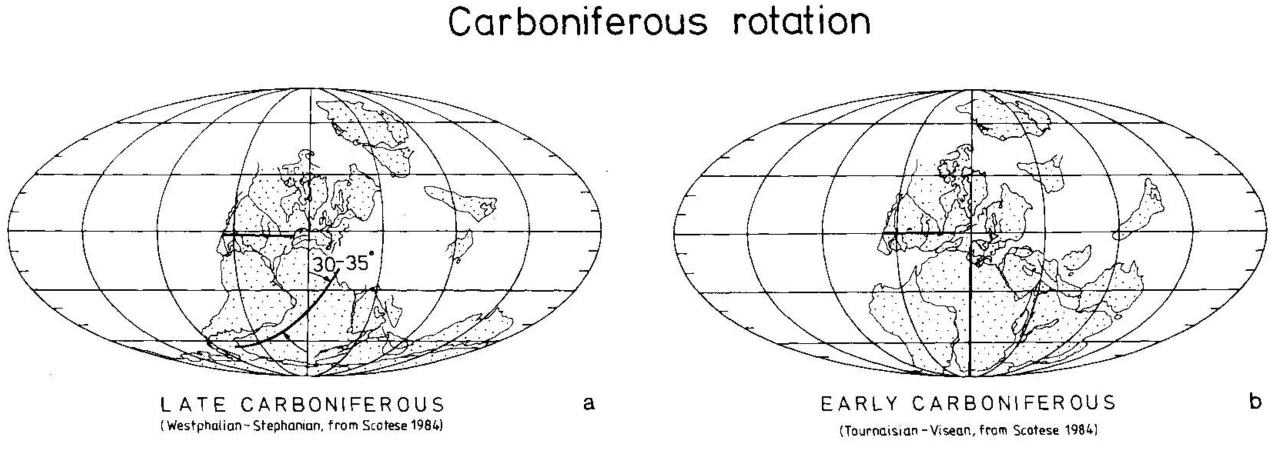

Fig. 10 Carboniferous rotation of 30–35° due to paleomagnetic data.
The same pair of longitude and latitude is marked in Figs. 10a and 10b (paleogeographic base maps evaluating the available paleomagnetic data from SCOTESE, 1984).

4. Paleotectonic evolution in the light of the model of strong rotation

The arguments given above seem to favour the model of strong rotation. We will therefore reverse plate motions starting with the configuration of this model and go back in time from the Carboniferous to the Ordovician.

4.1. CARBONIFEROUS CRUSTAL SHORTENING (MODEL 2; Fig. 9)

The rotation of 30–35° (see 3.1.2.) followed by the Variscan folding and thrusting is reversed in Fig. 9. Some details are changed compared with Fig. 8. A special alternative was chosen which could not be integrated in Fig. 8: the separation of the Saxothuringian-North+Central Armorican zone from the Ossa-Morena zone as well as the separation of the Rhenohercynian zone from the South Portuguese zone. Due to the positions chosen, the main basins are connected with the oceanic realm in the west. This variation avoids an outer continental margin position for the South Portuguese zone.

In addition, Fig. 9 shows some indicators for deeper Devonian basins: 1. sequences dominated by chert in the Devonian (southern Harz, Giessen nappe in the southern Rhenish Massif, Bavarian facies in the lower Münchberg Massif), 2. Devonian extensional basalts, and 3. Devonian flysch (South Cornwall, Menorca, Kabylian-Rif zone, and Antiatlas). Later, zones of greater deformation often developed in the deeper basins.

The reconstruction of Fig. 9 results in a larger oceanic realm west of the European Variscides. The Carboniferous crustal shortening is in the order of 1000 km in both models (Figs. 8 and 9). A strong strike-slip movement has to be assumed along the SW margin of Fennosarmatia.

4.2. LATE AND MIDDLE DEVONIAN (NO FIGURES)

Alkali- and MORB-type basalts of Middle and early Late Devonian age indicate extension and formation of deeper basins in the Rhenohercynian-Cornwall/Lizard zone, in the Saxothuringian-Central Armorican zone, and in the South Portuguese-Austroalpine Grauwacken-Moravosilesian zone (cf. Fig. 9, and HEINISCH et al. [1987] for the age of the Austroalpine basalts). These extensions have been tentatively reversed in Fig. 11. COCKS and FORTEY (1982) favour this extensional event and postulate an expansion to a "Rheic Ocean" because of differences of ostracode faunas; other paleontologic evidence is contrary (cf. section 2.3.). VAN DER VOO (1988) assumes a Late Devonian position of North Africa (Gondwana) near the South Pole, based on a new paleomagnetic pole deduced from measurements in Western Australia (HURLEY and VAN DER VOO, 1987). Thus a wide ocean between Gondwana and Laurentia becomes necessary. This position of the South Pole is contrary both to the Late Devonian paleomagnetic pole of AIFA (1987) determined on Moroccan samples and the Moroccan carbonate facies. Other indications for a large Middle or Late Devonian ocean are missing.

4.2. EARLY DEVONIAN (Fig. 11)

The late Early Devonian (/early Middle Devonian) is the time of the Acadian orogeny in the Northern Appalachians (and Newfoundland?, see p. 315 and RODGERS, 1982, p. 233). The Acadian orogeny was probably induced by a further approach of Gondwana toward Laurentia.

The collision between the Gondwana margin (Nova Scotia) and Laurentia continues in an oblique direction including both the subduction and final closure of the remaining basins NW of Nova Scotia. The curved Laurentia margin necessitates a strike-slip fault between Newfoundland and Nova Scotia (STOCKMAL et al., 1987; KEPPIE, 1982: "gulf fault"). The displacement along the strike-slip fault makes possible an approximation of the amount of convergence during the Acadian orogeny.

It is difficult to compensate the amount of displacement of the strike-slip fault further to the southeast. Two solutions seem possible: 1. a crustal shortening in the Saxothuringian basin + the continuation of the motion along the margin of Fennosarmatia (Fig. 11). 2. a continuation of the strike-slip zone along the "Ligerian line" of AUTRAN and COGNÉ (1980) from the South Armorican zone to the southern Massif Central (not shown in Fig. 11), and then

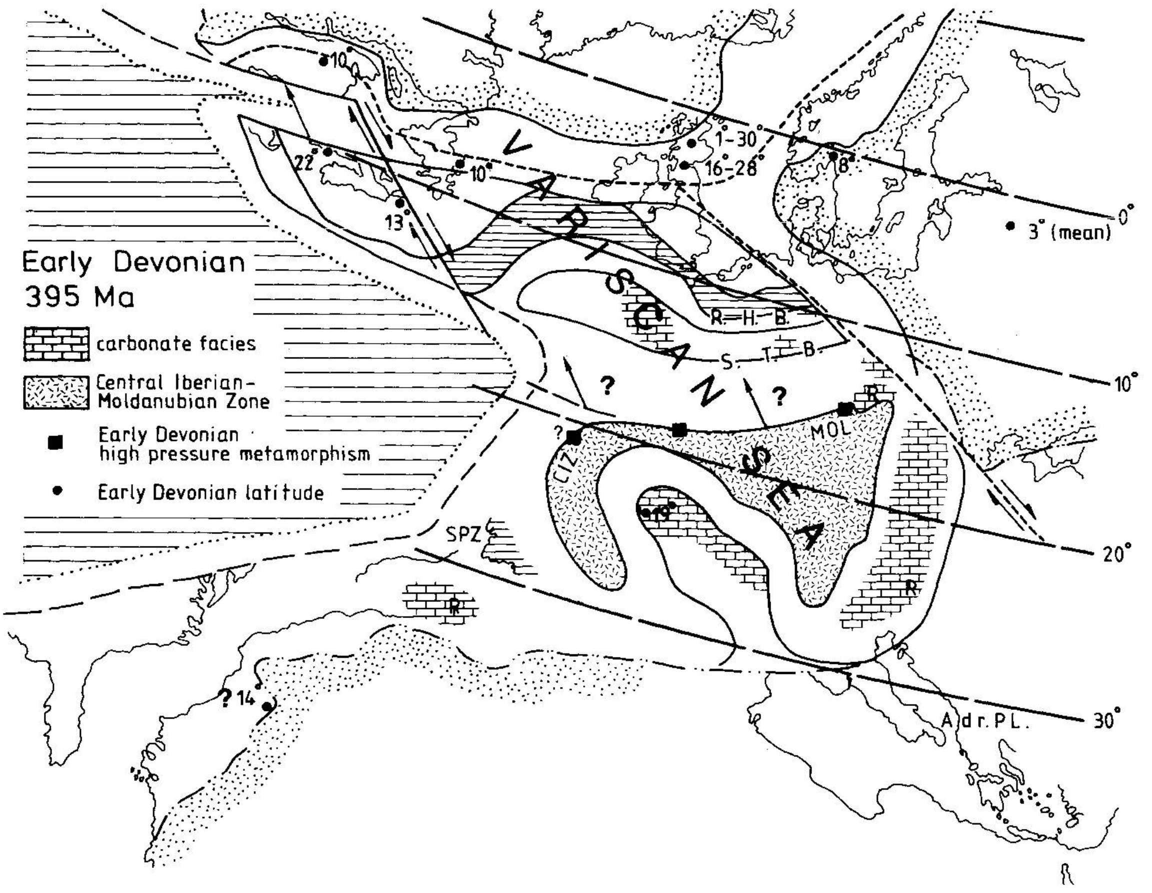

Fig. 11 The Acadian-Ligerian orogeny and Early Devonian paleogeography.
Note closure of the small oceanic basin N of Nova Scotia and the transfer of the movement into the Saxothuringian basin. Arrows: amount of plate convergence. Carbonate facies seems to be restricted to the arid zone. Reefs: Antiatlas (Morocco), Barrandium, and Austroalpine/Southern Alpine. Paleolatitudes from DOUGLASS (1988), KENT et al. (1984), PERROUD and BONHOMMET (1984), and SCOTESE et al. (1985). High pressure metamorphism: see text, section IV.3
CIZ: Central Iberian Zone; MOL: Moldanubikum; R: reefs; R.H.B.: Rhenohercynian Basin; SPZ South Portuguese Zone; S.T.B. Saxothuringian Basin.

further on to Corsica (?) and along the western boundary of the Adriatic plate to the Red Sea (??). Both possibilities would explain the data on which the "Ligerian orogeny" is based (AUTRAN and COGNÉ, 1980; COGNÉ and LEFORT, 1985).

The first possibility is depicted in Fig. 11 and would explain the high pressure metamorphism of the Late Silurian/Early Devonian from the Ile de Groix (Bretagne, AUDREN and TRIBOULET, 1984). There, glaucophane schists indicate subduction to the southeast (tectonic transport to the northwest). Late Silurian/Early Devonian high pressure metamorphism is also known from the Massif Central (PEUCAT and COGNÉ, 1977), from the Münchberg Massif + the northern margin of the Moldanubikum (SCHÜSSLER et al., 1986, WEBER and VOLLBRECHT, 1986), and perhaps from NW Iberia (uncertain age: Ordovician/Silurian?, MARTINEZ-GARCIA, 1986). In Late Silurian/Early Devonian time, obduction of some metamorphic ophiolites (now eclogites) is assumed for the western Massif Central (DUBUISSON et al., 1986) and for NW Iberia (Early Devonian, MARTINEZ-GARCIA, 1986).

Furthermore, Fig. 11 shows the distribution of carbonates during this time and some latitudes derived from paleomagnetic inclinations (for sources of data see captions). Though the paleomagnetic data scatter, they still indicate low latitude positions of Laurussia, Nova Scotia, and Cantabria. These areas lay close to or somewhat south of the equator, while the nearest evaporitic basin (arid zone) to the north was in the Hudson Bay basin (ZHARKOV, 1981). According to this reconstruction, lower Devonian carbonates including reefs reach more than 30°

south of the equator. This and the paleolatitudes from Cantabria to Laurussia indicate that no wide ocean existed within the Westeuropean Variscides at this time.

4.4. THE EARLY SILURIAN

The changes from Fig. 11 to Fig. 12 show the reversal of the Late Caledonian collisions along the main suture line from Newfoundland, Ireland, and Scotland to Scandinavia and Greenland as well as along the SW margin of Fennosarmatia. The latter "collision" between the SW margin of Fennosarmatia and the NE Gondwana zones was probably a strike-slip movement; this would explain both the relatively small tectonic impact and the minor magmatism along this margin. The long time interval between the first faunal exchange and the final collision (Late Ordovician and Late Silurian, respectively) also plead for a strike-slip character of this movement.

The block with the hatched signature (Fig. 12) was relatively rigid during Variscan time (cf. rigid blocks in Fig. 5); it includes SW Newfoundland, Nova Scotia, and the Boston area, i. e. the Avalonia and Meguma terrains of Williams and Hatcher (1982), along with the North Armorican block, and the London Brabant Massif. During the Middle Devonian, southern parts of this block underwent extension. The "Avalonia" block may have extended farther west towards the Southern Appalachians (Williams and Hatcher, 1982, not shown in Fig. 12). Accordingly, the Acadian collision would have continued into the Southern Appalachians (see 4.3.).

4.5. THE MIDDLE ORDOVICIAN

The central and southwestern Iapetus was wide during the Middle Ordovician (Fig. 13). Active continental margins were situated both along Laurentia and northern Avalonia, the

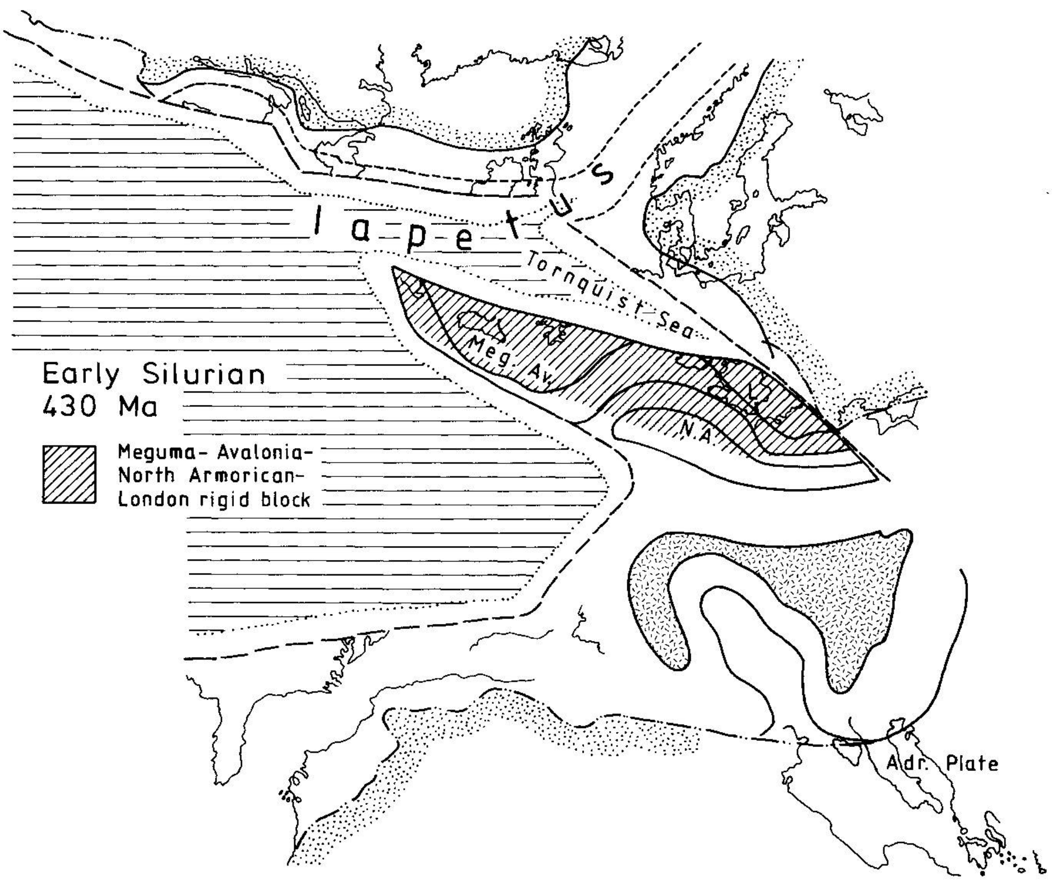

Fig. 12 Early Silurian paleogeography.
The NW Iapetus and the Tornquist Sea are nearly closed. Note the strike-slip movement of the shaded block (Avalonia) along the SW Fennosarmatia margin. Adr. Plate: Adriatic Plate. The lines depict the zones of the former figures.

outermost part of the Gondwana margin. North Africa was located near the South Pole, as late Ordovician glacial deposits of that region prove (van Houten and Hargraves, 1987, Caputo and Crowell, 1985, pole position from Seyfert and Sirkin, 1979, glacial movements from Fairbridge, 1970). The paleomagnetic latitudes of Fig. 3 are shown again. Most of these appear to fit well, taking into account their scattering (high latitude values scatter more due to methodical reasons). An exception of the good fit is the Barrandium (36°) (Andreeva et al., 1965). The locations of late Ordovician tillites in western Europe (open triangles), as well as those of ironstones indicating a (moderately) humid climate, also fit into the general model. There is no indication of a wide ocean between England, Wales, and southern Ireland and North Africa during the Ordovician.

The position of low latitude of Laurentia and Fennosarmatia is furthermore confirmed by carbonate facies (Fig. 4) and by a belt of Ordovician evaporite basins in North America (Zharkov, 1981), which are parallel to the paleolatitudes indicated for Laurentia.

5. Summary and discussion

5.1. SUMMARY OF THE IAPETUS MODEL

The "Iapetus model" presented in this paper considers the Caledonides, the Variscides, and the Alleghenides as being formed by the closure of a single large ocean, the Iapetus, separating three continents: Laurentia, Fennosarmatia, and Gondwana. Subduction of the Iapetus probably began during the Cambrian and led to the obduction of ophiolites in the Early to Middle Ordovician (Dewey and Shakleton, 1984), the western ophiolites being obducted onto Laurentia (Taconian/Grampian orogeny), and the eastern ophiolites onto NW Fennosarmatia (Finnmarkian orogeny, cf. Fig. 5 and Roberts et al., 1985, p. 927).

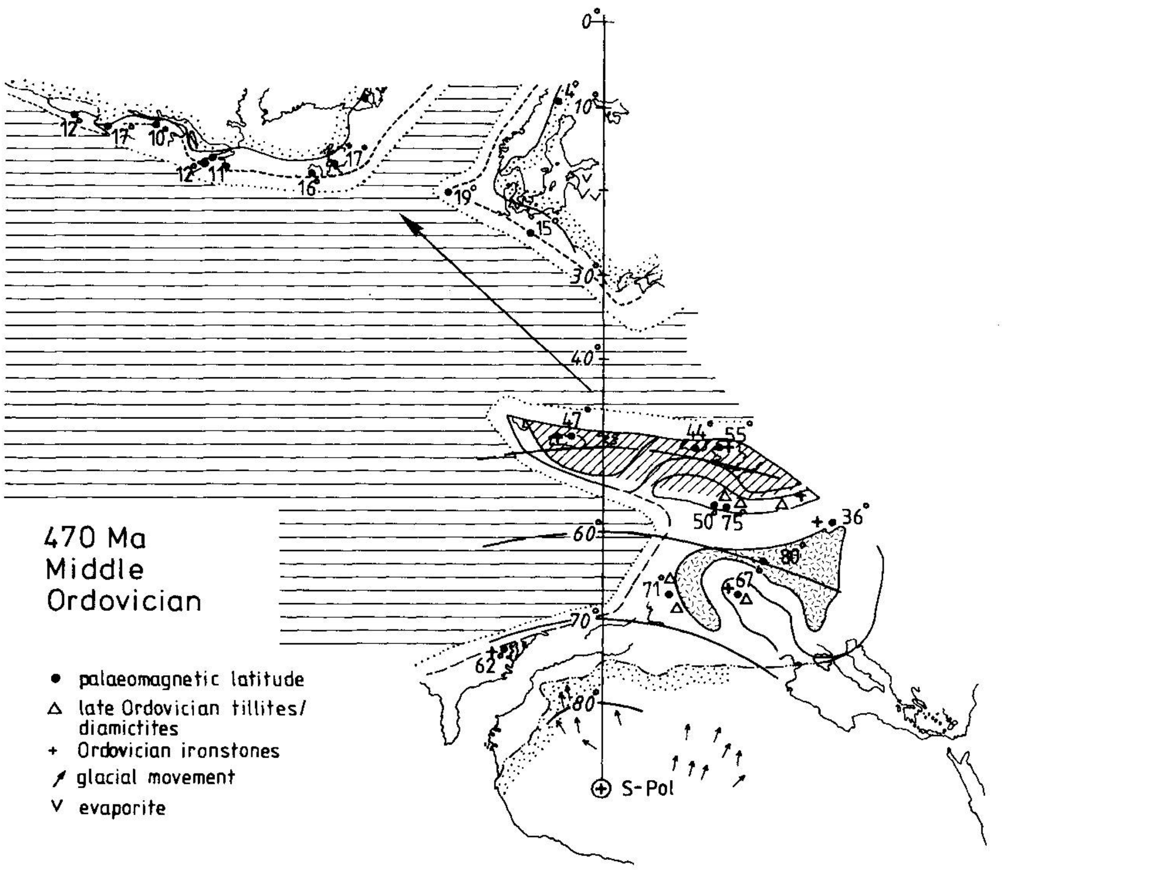

Fig. 13 Middle Ordovician paleogeography and paleolatitude marks.
Note a wide Iapetus in the SW, but a smaller distance between Avalonia (shaded) and the southern cape of Fennosarmatia. The Late Ordovician position of Gondwana may be about 15° more to the northwest: compare the suitable Late Ordovician latitudes of the glacial movements, tillites and diamictites. Arrow: assumed plate convergence, Paleolatitudes from Fig. 3. Shaded area: see Fig. 12.

The model starts in the Middle Ordovician (Fig. 13) while subduction was still active. On account of glacial deposits, paleomagnetic latitudes, and facies described, Gondwana (North Africa) and its wide margin was located near the South Pole, while the other two continental margins were near the equator (Figs. 13, 3, 4). The exact path of Gondwana toward the other continents is unclear, but several arguments support a strike-slip contact and strike-slip movement of Gondwana along the SE margin of Fennosarmatia (Figs. 13, 12 and section 4.4.). The first contact between the three continents had already taken place by the Late Ordovician, accompanied by faunal exchange.

During the Late Caledonian orogeny, the NE Iapetus between Laurentia and Fennosarmatia, as well as the Tornquist Sea, a side-arm of the Iapetus, were closed. Further NW-drift of Gondwana and oblique collision of its northwestern external margin (Avalonia) led to the late Early Devonian Acadian orogeny closing the remainder of the Central Iapetus between Nova Scotia and the northern Appalachians (Fig. 11). The same convergent motion may be compensated more to the "east" by crustal shortening of the Saxothuringian basin indicated by high pressure metamorphism (Fig. 11 and 4.3.).

The paleogeographic situation after the Acadian orogeny was as follows: the ocean of the mega-orogen, the Iapetus, was closed except for its southwestern part; the three cratons formed a triangle with alternating basins and swells in between, which formerly belonged to the Gondwana margin (Fig. 11, 9). This "Variscan Sea" is comparable to a Mediterranean Sea stage.

During the Middle and early Late Devonian, an unexplained interruption of convergence led to the formation of several extensional basins near the northern and southern boundaries of the Variscides (4.2.). In one of the basin centers (Lizard point-southern margin of the Rhenish Massif) MORB type basalts extruded.

In the Early Carboniferous (Fig. 9), further movement of Gondwana towards Laurentia-Fennosarmatia (Laurussia) eliminated the Variscan Sea and formed the Variscides. All deformable crust was shortened (preferentially basins with thinned continental or — if present — oceanic crust). The amount of the crustal shortening is approximately 1000 km according to the model. After the "Variscan collision", Gondwana moved to the west by a rotation along a shear zone. This led to the closure of the rest of the Iapetus and the birth of the mega-continent Pangaea.

Paleomagnetic, faunal, and facies data do not favour an ocean within the European Variscides during Devonian or Early Carboniferous time.

5.2. DISCUSSION

It is apparent from Figs. 1 to 4 that the continental margin of Gondwana was unusually extensive reaching up to the southern British Isles, SW Newfoundland, and Nova Scotia. It contained at least four deeper basins as recognized by facies and extensional magmatism (cf. Fig. 9 and 4.1., 4.2.). This is not a "normal" continental margin, but more of the type of basins and continental ridges observed in the SW Pacific east of Australia (Lord How Rise, etc.). However, little or no oceanic crust is assumed for the centers of the Devonian basins. In addition, the transform fault at the NE side of Gondwana during the Ordovician is comparable to the Alpine transform of New Zealand. If these comparisons are valid, some concepts involving "exotic terranes" are closely related to the Iapetus model.

This model of paleotectonic evolution represents an integration of current plate tectonic concepts for the Variscides. The concept is conventional because it assumes a large ocean as the final basis for such a large orogen, although unconventional as far as proposing a pre-Variscan closure of the main part of the ocean as well as its location outside the Variscan orogen. The model involves an "exotic terrane" concept, but specifies most of the terranes as basins and ridges and an outer arc (Avalonia) at the margin of Gondwana. Furthermore, it is a Mediterranean Sea type concept assuming an "intracontinental geosyncline" (termed here the "Variscan Sea") between the continents after closure of the main ocean. Last but not least, it is a mega-shear model (ARTHAUD and MATTE, 1977, BADHAM, 1982): the mega-shear compacted all marginal basins with thinned continental crust and centers of oceanic crust, eliminated the rest of the Iapetus ocean in the W, and created the mega-continent Pangaea.

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