Palaeozoic amalgamation of Central Europe: an introduction and synthesis of new results from recent geological and geophysical investigations

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Abstract: Multidisciplinary studies undertaken within the EU-funded PACE Network have permitted a new 3-D reassessment of the relationships between the principal crustal blocks abutting Baltica along the Trans-European Suture Zone (**TESZ**). The simplest model indicates that accretion was in three stages: end-Cambrian accretion of the Bruno-Silesian, Łysogóry and Małopolska terranes; late Ordovician accretion of Avalonia, and early Carboniferous accretion of the Armorican Terrane Assemblage (**ATA**), which had coalesced during Late Devonian – Early Carboniferous time. All these accreted blocks contain similar Neoproterozoic basement indicating a peri-Gondwanan origin: Palaeozoic plume-influenced metabasite geochemistry in the Bohemian Massif in turn may explain their progressive separation from Gondwana before their accretion to Baltica, although separation of the Bruno-Silesian and related blocks from Baltica during the Cambrian is contentious.

Inherited ages from both the Bruno-Silesian crustal block and Avalonia contain a 1.5 Ga 'Rondonian' component arguing for proximity to the Amazonian craton at the end of the Neoproterozoic: such a component is absent from Armorican terranes, which suggests that they have closer affinities with the West African craton.

Models showing the former locations of these terranes and the larger continents from which they rifted, or to which they became attached, must conform to the above constraints, as well as those provided by palaeomagnetic data. Hence, at the end of the Proterozoic and in the early Palaeozoic, these smaller terranes, some of which contain Neoproterozoic ophiolitic marginal basin and magmatic arc remnants, probably occurred within the end-Proterozoic supercontinent as part of a 'Pacific-type' margin, which became dismembered and relocated as the supercontinent fragmented.

The SW margin of the East European Craton, the Trans-European Suture Zone (TESZ) is traceable from the Black Sea coast of Romania to the mouth of the River Oder on the Baltic Sea, despite being everywhere concealed beneath thick sedimentary cover. Further to the NW the continuation of this suture bends westwards, passes south of Denmark, and, traversing the SE North Sea (here known as the Thor-Tornquist Suture: Berthelsen 1998; Pharaoh 1999) curves NW to meet the Iapetus Suture at a triple point junction 300 km east of Dundee (Pharaoh 1999). It is therefore arguably one of the most prominent lithospheric features of Europe. Originally defined by Berthelsen (1993), as a collage of crustal blocks that separates the more than 850 Ma old Precambrian crust of the East European Craton (**EEC**) from the Variscan and Alpine mobile belts of western Europe, the term TESZ is now understood to be a broad zone incorporating the major shear zones forming the margin of the EEC, including the Teisseyre–Tornquist Zone in Poland, the Sorgenfrei Thrust Zone in Sweden and the Thor Suture west of Denmark (Gee & Zeyen 1996). It is marked by a major geophysical anomaly, separating the strongly magnetized East European Craton from the contrasting weakly magnetized crustal blocks to the SW (Banka *et al.* 2002; Williamson *et al.* 2002).

The EU-funded Training and Mobility of Researchers (TMR) Network 'Palaeozoic Amalgamation of Central Europe' No. ERBFMRXCT97–0136 (PACE) was set up to improve understanding of how central Europe was assembled. Despite the difficulties caused by the extensive post-accretion Mesozoic sedimentary cover the main objective of the study was achieved by collating the geological and geophysical evidence for the sequence of

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collisions which produced the present configuration of crustal blocks accreted to central Europe. The sixteen contributions to this volume record aspects of the multidisciplinary work done, and are listed under five separate subject-related headings: (1) biostratigraphy and provenance evidence; (2) isotopic constraints; (3) petrology and geochemistry; (4) structural evolution; and (5) seismic traverses and deep crustal structure.

Despite several co-ordination meetings of the Network, different shades of opinion remain. It is not the purpose of this volume to minimize debates: indeed it is partly intended to emphasize and focus on the main discussion points so that discussion can continue to be made as broad as possible.

One important debate concerns the continental affinities of the Bruno-Silesian Block together with the possibly associated Łysogóry and Małopolska blocks of the Holy Cross Mountains in Poland. On one hand Cocks (2002) claims that there is no faunal evidence to suggest that these blocks were ever separated from Baltica, and that, since the discovery of late Neoproterozoic ('Cadomian' or 'Panafrican') deformed basement to the Uralides in the east of Baltica (Glasmacher *et al.* 1999), the presence of Panafrican-age detrital muscovites is not proof of Gondwanan affinities. By contrast Belka *et al.* (2000) combined the presence of detrital muscovites with a claim that some Cambrian faunas have an affinity with Gondwana. Both agree that since the end of the Cambrian these blocks were attached to the Baltica margin. This precludes any possibility of them being part of Avalonia, which was still attached to Gondwana in the early Ordovician. Equally clearly any 'Central European Caledonides' should not include the Late Cambrian Sandomierz Deformation (Samsonowicz 1926).

A second debate highlighted is the affinity of basement blocks accreted to the East European Craton, and how they may be distinguished. Many papers continue to be published suggesting that, for example, Avalonian basement underlies parts of the Bohemian Massif (e.g. Finger *et al.* 2000). In this debate establishing the late Ordovician timing of the accretion of Avalonia to Baltica (Vecoli & Samuelsson 2001; Samuelsson *et al.* 2002*a*) is a crucial piece of evidence that the basement of 'Far Eastern Avalonia' (Fig. 1) has Avalonian affinities, although rendered possibly suspect with respect to the main part of Avalonia by the Anglo-Brabant Deformation Belt, characterized by calc-alkaline magmatism (Pharaoh *et al.* 1993). Further evidence concerning the Anglo-Brabant Deformation Belt and the likely basement of Far Eastern Avalonia is provided in this volume by Verniers *et al.* (2002) and Samuelsson *et al.* (2002*b*).

Isotopic evidence from the Bohemian Massif for the timing of ophiolite generation and deformation (Marheine *et al.* 2002; Crowley *et al.* 2002*a*) clearly shows that accretion dates for these crustal blocks is much later than that of Avalonia, and that Devonian and Carboniferous subduction and collision of constituent blocks of the Armorican Terrane Assemblage predated accretion to the Laurussian supercontinent, comprising Laurentia, Baltica and Avalonia. However, as observed by Aleksandrowski and Mazur (2002) individual crustal blocks within the Armorican Terrane Assemblage appear to be continuous for long distances to the west, negating suggestions that separate 'Armorican' and 'Perunican' blocks existed. More focused studies of a single meta-ophiolitic body, the Marianske Lazne Complex, have produced differing conclusions. A dominantly petrological study (Štědrá *et al.* 2002) has produced a different assessment of the margins and affinities of gabbros at the southern margin of the complex than that reached, by means of a mainly geochemical study (Crowley *et al.* 2002*b*), even though authors are common to both papers. Clearly there is scope for more detailed studies of these rocks, as also indicated by a study of the Ślęża Ophiolite (Floyd *et al.* 2002), which reports for the first time on pillow lavas in its discussion of an otherwise well-studied ophiolite.

On the large scale structural interpretations vary widely, usually reflecting the part of central Europe with which the authors are most familiar. Thus, based on considerable knowledge, structural reconstructions provided in this volume by both Aleksandrowski and Mazur, and by Franke and Żelaźniewicz, present widely differing models.

Assistance is also provided by the abundance of seismic traverses. These reveal that, whether below the thick late Palaeozoic–Mesozoic sedimentary cover in the Polish Trough (Grad *et al.* 2002) or further to the NW beneath the south-eastern North Sea (Scheck *et al.* 2002) an important feature of deep Central European geology is the shallow-dipping wedge of Baltican basement which, attenuating steadily, projects far to the SW of its sub-Permian position. This evidence shows that the major suture lines in Central Europe are shallow-dipping. A final survey, further to the west (Sintubin & Everaerts 2002) provides further evidence for the Lower Palaeozoic Anglo-Brabant Deformation Belt in Belgium.

Faced with these debates and the mass of

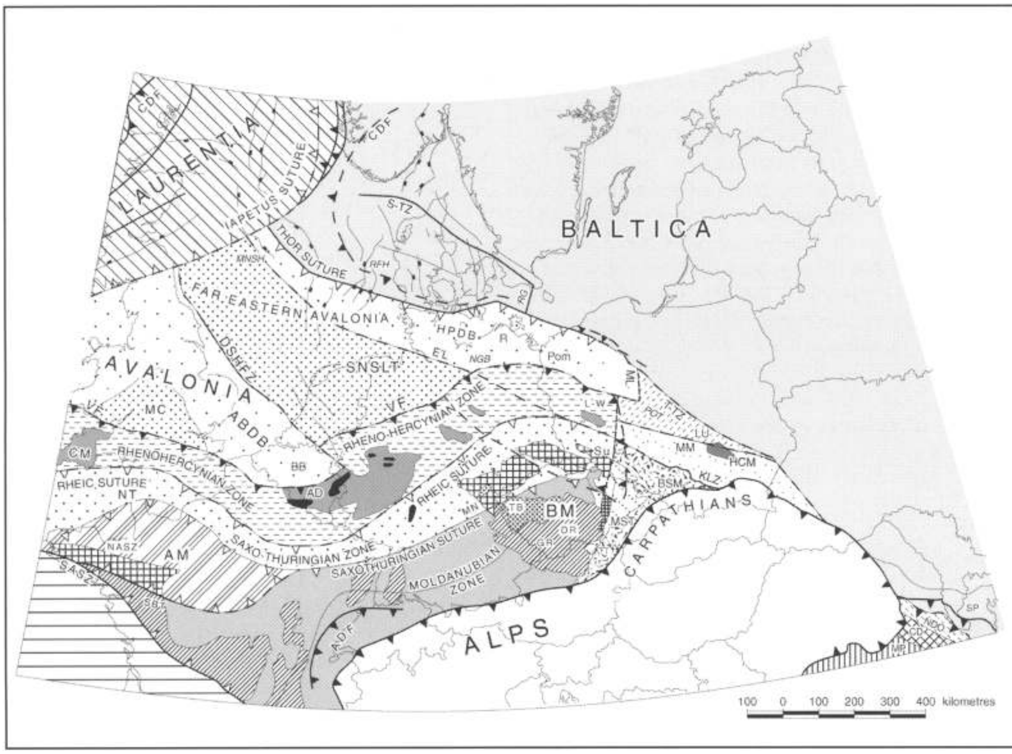

Fig. 1. A map showing the distribution of crustal blocks and Palaeozoic deformation belts in Central Europe. Key to abbreviations: ABDB, Anglo-Brabant Deformation Belt; AD, Ardennes; ADF, Alpine Deformation Front; AM, Armorican Massif; BB, Brabant; BM, Bohemian Massif; BSM, Bruno-Silesian Massif; CD, Central Dobrogea; CDF, Caledonian Deformation Front; CM, Cornubian Massif; DR, Dronsendorf Unit; EA, Ebbe Anticline; EFZ, Elbe Fault Zone; EL, Elbe Lineament; GF, Gföhl Unit; HCM, Holy Cross Mountains; HM, Harz Mountains; HPDB, Heligoland-Pomerania Deformation Belt; KLZ, Krakow-Lubliniec Zone; LU, Łysogóry Unit; L-W, Leszno-Wolsztyn High; MC, Midlands Microcraton; MM, Małopolska Massif; MN, Münchberg Nappe; MNSH, Mid-North Sea High; MP, Moesian Platform; MST, Moravo-Silesian Terrane; NASZ, North Armorican Shear Zone; NBT, North Brittany Terrane; NDO, North Dobrogea; NGB, North German Basin; Pom, Pomerania; POT, Polish Trough; R, Rügen Island; RFH, Rynkøbing-Fyn High; RG, Rønne Graben; RM, Rhenish Massif; SASZ, South Armorican Shear Zone; SBT, South Brittany Terrane; SH, South Hunsruck Massif; SNF, Sveconorwegian Front; SNSLT, South North Sea – Luneberg Terrane; SP, Scythian Platform; S-TZ, Sorgenfrei-Tornquist Zone; Su, Sudetes; TB, Teplá-Barrandia; T-TZ, Teisseyre–Tornquist Line; VF, Variscan Front.

supporting data, much of it new, a co-ordinated summary of the Palaeozoic Amalgamation of Central Europe, reconciling the differences, is needed. In this introduction the lines of evidence cited in the remainder of the volume are brought together in an attempt to explain these processes as part of a more global framework. Compromises have been sought where disagreements appear to be fundamental; hence the suggestion that during the Cambrian the Bruno-Silesian Block may have acted as a 'bridge' between Baltica and the Amazonian part of Gondwana – the Amazonian link indicated by the inherited Proterozoic dates obtained by Friedl *et al.* (2000). It was also necessary to account for the series of oceanic openings and closures which produced the crustal blocks, and to explain the mechanisms controlling their sequential rifting from the Palaeozoic Gondwana margin. This in turn required establishment of a series of global models consistent with the geological histories of these microcontinental blocks, as well as those of the principal continents, and these are explained next.

Major accreted crustal block assemblages

The outline structure of central Europe north of the Alpine-Carpathian Front and west of the approximate course of the TESZ has long been known. Using evidence from geophysical compilations, geological information provided by deep boreholes and outcrops of Palaeozoic and older rocks across central Germany and in the Bohemian Massif, the principal crustal blocks have long been distinguished. Recently summarized (Pharaoh 1999), they include Bruno-Silesia, Avalonia and the Armorican Terrane Assemblage.

Bruno-Silesia and associated blocks

These comprise Bruno-Silesia itself and, partly exposed in the Holy Cross Mountains, the Łysogóry and Małopolska terranes. Further to the SE and apparently sharing a similar Palaeozoic geological history are the Central and Southern Dobrogea terranes and the Moesian Platform of southern Romania, the latter only known from boreholes. Because it contains late Proterozoic magmatic rocks in the sub-Phanerozoic basement, Bruno-Silesia was considered by Moczydlowska (1997) to be a possible eastward extension of Avalonia. At the time, the presence of such rocks, sometimes termed 'Cadomian' in western Europe, or more generally, 'Panafrican', was accepted as an indication of attachment to the southern continents, collectively known as Gondwana. By contrast the Łysogóry and Małopolska terranes were interpreted as fragments of Baltica (Dadlez 1996; Pharaoh 1996), because their Ordovician faunas have Baltican affinities. However, a link between the Bruno-Silesian Block and the Małopolska Block is inferred because the Cambrian sequence on the latter has been interpreted as an accretionary wedge to the Bruno-Silesian Block. If true, the two blocks have always been closely linked. Initially the presence of a Panafrican-type, late Neoproterozoic deformed basement, with evidence of end-Proterozoic deformation, was taken as evidence of a Gondwanan origin, as opposed to Baltican, where, at the time, it was supposed that no Panafrican deformation had occurred. However, the discovery of widespread end-Proterozoic deformation along the Uralide margin of Baltica showed that the presence of Cadomian deformation was therefore not continent-specific. Hence the presence of Cadomian-type basement in the Bruno-Silesian block and the derivation of sediment in the Małopolska Block from a 'Cadomian' source (Belka *et al.* 2000), does not now prove a specifically Gondwanan origin for this crustal block. Furthermore, the existence of a late Proterozoic orogenic belt along this margin of Baltica may indicate that Baltica was still (albeit fleetingly) attached to Gondwana at the end of the Proterozoic, although strong faunal differences between Gondwana and Baltica show it was surely detached by the early Cambrian. However, Belka *et al.* (2000) show that the early Cambrian brachiopod faunal assemblages of the Małopolska block mostly have Gondwanan affinities with only a single Baltican species, *Westonia bottnica*, present, a conclusion disputed by Cocks (2002). With progressive introduction of Baltican brachiopod species and the ingress of sediment derived from Baltican sources during the middle Cambrian (Jendryka-Fuglewicz 1998), the Małopolska Block must at that time have been adjacent to Baltica. Actual docking is recorded by the Sandomierz Phase of deformation in the late Cambrian (Belka *et al.* 2000). However, the absence of calc-alkaline volcanic rocks in the Cambrian succession of both the Bruno-Silesian and Małopolska blocks argues against them having had a tectonically independent existence: it seems likely that displacement relative to adjacent continents may have involved major strike-slip movement, and the conflicting faunal evidence suggests that they acted as a link between Baltica and Gondwana during the Cambrian. In the Łysogóry Block, Middle to Upper Cambrian rocks contain fossils which do not occur in Baltica. Inarticulate brachiopods include forms with Gondwanan affinity (Belka pers. comm.) and trilobite trace fossils are identical to those from Gondwanan and peri-Gondwanan microplates (Seilacher 1983). Ordovician faunas, well documented in the southern part of the Holy Cross Mountains (Dzik *et al.* 1994) show essentially Baltican affinities, confirming that a connection of the Małopolska and Bruno-Silesian blocks with Baltica was established by the end of the Cambrian.

Palaeomagnetic and structural data (Lewandowski 1993; Mizerski 1995) suggest dextral strike-slip displacement of the Małopolska Block along the SW margin of the EEC. Provenance of clastic material, sedimentary history and palaeomagnetic data (Nawrocki 1999; Belka *et al.* 2000) show that amalgamation of the Małopolska and Łysogóry blocks was attained during the late Silurian. However, the presence of Devonian arc-related magmatism in the Jesiniky Mountains suggests that with SE-directed subduction on the NW margin of the Bruno-Silesian Block, its displacement along the

TESZ margin of Baltica may have continued into late Palaeozoic time.

Where exposed, structures along the western margin of the Bruno-Silesian Block are tectonic. They show highly oblique (dextral sense of shear) complex overthrusting to the east (Moldanubian Thrust) in the early Carboniferous between 350–330 Ma (Schulmann & Gayer 2000).

Attempts have been made to trace this junction northwards beneath the thick sedimentary cover of the Polish Trough. Because of the thickness of Mesozoic and Cenozoic sedimentary cover rocks, this has proved difficult and controversial, and depends largely on the results of seismic profiling. Both the Polonaise P1 and TTZ profiles (Jensen *et al.* 1999; Grad *et al.* 1999) show a clear change of mid-crustal structure north of the Moldanubian Thrust, suggesting that it continues northward as a major feature termed the Moravian Line by Winchester *et al.* (2002). In the TTZ profile the mid-crustal break illustrated is displaced eastwards compared to Polonaise P1: this may suggest dextral displacement of the Moravian Line by strike-slip faulting between the two profiles, perhaps along the Dolsk Line (Grad *et al.* 2002).

To the SE a possible link between the Moesian Platform and the Bruno-Silesian blocks has been suggested. According to Dudek (1980), the Bruno-Silesian Block continues under the Carpathians to the SE, presumably as far as the Peri-Pieniny lineament (Carpathian suture). Its southwestern extent is also not reliably constrained, but Dudek (1980) supposed that it extends to the Danube, approximately as far as the Krems-Vienna Line in Austria. Further work is therefore needed to establish the relationship with the Moesian Platform and other crustal blocks in SE Europe.

Avalonia

Precambrian and early Palaeozoic basement exposed in central England, Belgium and western Germany is widely accepted as part of Avalonia, the Palaeozoic microcontinent extending west as far as New England, and best exposed in the Avalon Peninsula of Newfoundland, after which it is named. Avalonian basement in central England, which typically consists of late Proterozoic intrusive, volcanic and sedimentary rocks (e.g. Thorpe *et al.* 1984; Pharaoh & Gibbons 1994; Strachan *et al.* 1996) was, like the Bruno-Silesian Block, affected by end-Proterozoic/pre-Lower Cambrian deformation. Because this area has been affected so little by later movements, and is overlain by a thin early Palaeozoic shallow marine sedimentary sequence succeeded conformably by Devonian terrestrial deposits: the 'Old Red Sandstone', it has sometimes been called the 'Midlands Microcraton' (e.g. Turner 1949; Pharaoh *et al.* 1987).

Boreholes in eastern England reveal that the Midlands Microcraton is bounded to the NE by a Caledonian deformation belt (Pharaoh *et al.* 1987; Noble *et al.* 1993). Late Ordovician calc-alkaline volcanic rocks are present within this belt and extend from eastern England to Belgium (André *et al.* 1986; Pharaoh *et al.* 1991). The southern end of this belt is exposed in the Brabant Massif of Belgium, and hence it has been termed (Winchester *et al.* 2002) the Anglo-Brabant Deformation Belt (ABDB). The deformation belt is inferred to have developed in early Devonian (Acadian) time above a zone of crustal suturing inherited from the late Ordovician soft collision of Avalonia and Baltica.

The presence of the ABDB questions whether the basement further east, NE of the Dowsing – South Hewett Fault Zone – Lower Rhine Lineament (Pharaoh 1999), is also part of Avalonia. Pharaoh *et al.* (1993) suggested that this lineament may separate crusts with differing structures, juxtaposed by late Ordovician subduction, the inferred cause of the calc-alkaline volcanism identified above. In this area the crystalline basement is generally not exposed. Far to the south, the 574 ± 3 Ma Wartenstein Gneiss (Molzahn *et al.* 1998), cropping out in the south Hunsrück at the SE margin of the Rhenish Massif and the 560 Ma Ecker Gneiss in the Harz Mountains (Baumann *et al.* 1991), both lying south of the Variscan Front, may be the only exposures of crystalline basement in this crustal block. The typically calc-alkaline composition and late Neoproterozoic age of these gneisses is broadly comparable to Avalonian basement exposed in central England and hence, despite the presence of the intervening ABDB, the basement of this area is generally linked with that of Avalonia. However, as so many pieces of crustal basement in both Avalonia and the Variscides of Central Europe appear to record late Proterozoic Cadomian deformation, it is the timing of the docking of these individual crustal blocks with Baltica which is most likely to decide their affinities.

Fossil evidence and sediment provenance data obtained from the G14 borehole, north of the Caledonian Deformation Front close to Rügen, NE Germany show that sediments with clear Gondwanan fossil associations and Cadomian mineral ages are first encountered in the Ashgill. The presence of reworked acritarchs of Llanvirn age and peri-Gondwanan affinity in the

Ashgill stratal sequences on the SW margin of the EEC (Samuelsson *et al.* 2002*b*) proves that an elevated area was being eroded in latest Ordovician time. Sediment provenance studies (Vecoli *et al.* 1999) show that the uplifted area was part of the Danish–North German–Polish 'Caledonides' which formed at the NE margin of Avalonia on its collision with Baltica (Berthelsen 1992; Dallmeyer *et al.* 1999). Hence, the timing of closure of the Tornquist Ocean and Avalonia–Baltica collision must have taken place between the middle Caradoc and the Rawtheyan. This interval of approximately 10 Ma was apparently sufficient for the development of the deformation belt separating the North Sea basement from Baltica and its partial erosion. The timing of this collision only slightly predates Avalonian convergence with Laurentia, based on evidence from Atlantic Canada (e.g. Cawood *et al.* 1994), and the onset of Windermere Supergroup sedimentation in the English Lake District (Cooper *et al.* 1993). The basement to the southern North Sea (the Southern North Sea–Luneberg Terrane (SNSLT) of Pharaoh *et al.* (1995) was probably an extension of Avalonia, possibly separated from Avalonia proper by a small, perhaps marginal, oceanic basin. If so, the ABDB was an intra-Avalonian mobile belt, perhaps developed in the Acadian orogenic phase, when Avalonia was moulding itself on to the margins of Baltica and Laurentia.

The lack of significant volcanism in the Heligoland-Pomerania Deformation Belts (HPDB) in either the passive margin sediments on the Baltican side or those on the Avalonian side (with the exception of volcanogenic clasts in sediment which could have originated from ashfall from distant volcanism) suggests that, in view of the earlier rapid northward motion of Avalonia, continental convergence was probably very oblique.

Finally, at the time of Avalonian convergence with Baltica, the Bruno-Silesian and related blocks must have formed a promontory. At the time of convergence, more easterly portions of Avalonia may have been detached and displaced eastwards, lending credence to the accounts that 'Celtic' (e.g. Avalonian) faunas in the Zonguldak Terrane of Turkey (Dean *et al.* 2000; Kozur & Göncüoğlu 1998).

Armorican Terrane Assemblage

The Armorican Terrane Assemblage (*sensu* Franke 2000; Tait *et al.* 2000) is exposed in a series of massifs across much of middle Europe from Spain to Poland. The largest and most significant areas of critical exposure in central Europe are in the Bohemian Massif, west of the Moldanubian Thrust. Here several different crustal blocks have been recognized, though their relations to each other have been far from clear. Of these, three have become widely recognized as distinctive: Saxothuringia, Teplá-Barrandia, and Moldanubia. A fourth crustal block in the Bohemian Massif, Bruno-Silesia, is recognized as having a completely separate geological history and believed to have formed part of a separate microcontinent (see above), but distinctions between the histories of the other terranes have not been fully explored because for a long time it was thought that the palaeomagnetic data from Teplá-Barrandia was typical of the entire massif. Recent work (e.g. Franke 2000; Franke *et al.* 1995) showing division of the Bohemian Massif into independently moving blocks suggests that this is not valid.

Numerous papers provide evidence of the complexity of relationships between independent terranes of the Bohemian Massif (e.g. in the summary provided by Aleksandrowski and Mazur, this volume), but they generally lack evidence of end-Ordovician/early Silurian collision seen in eastern Avalonia, and the Rheic Suture, interpreted to mark the southern margin of Avalonia, is shown on most reconstructions to pass north of the exposed Palaeozoic rocks in the Bohemian Massif (e.g. Franke 1995). Though Early Devonian ('Caledonian', but historically and collectively termed Eo-Variscan elsewhere in Hercynian Europe, e.g. Faure *et al.* 1997; Shelley & Bossière 2000)) metamorphism and magmatism has been recorded locally in the northern Bohemian Massif, it is mostly confined to high-grade metamorphic rocks in the Góry Sowie Block (**GSB**) (Brueckner *et al.* 1996; O'Brien *et al.* 1997) and the Münchberg klippe (395–390 Ma: Kreuzer *et al.* 1989; Stosch & Lugmair 1990) and may record some local tectonothermal and hence collisional activity between migrating platelets of the ATA, with subsequent exhumation. Although often portrayed as an exotic fault-bounded block, recent results from the GSB are not inconsistent with other parts of the West Sudetes. Although high pressure metamorphism was initiated somewhat earlier than further west, as indicated by growth of metamorphic (granulite facies) zircon at 402+0.8 Ma (O'Brien *et al.* 1997), other ages obtained indicate that further high temperature/medium pressure metamorphism occurred around *c.* 380 Ma, with later minor stages around 370 Ma consistent with a more widespread event in the Sudetes (Timmermann *et al.* 2000). Pre-400 Ma metamorphic events outside NW Europe otherwise seem to be almost entirely limited to the Anglo-Brabant and Heligoland-Pomerania Deformation Belts (Winchester *et al.* 2002), where Baltican Lower Palaeozoic passive margin shelf sediments have been folded, thrust and eventually overridden by high-density crust interpreted as Avalonian basement.

Subsequent late Devonian high temperature/medium pressure metamorphism in the GSB is well-constrained by U-Pb monazite ages (van Breemen *et al.* 1988; Bröcker *et al.* 1998; Timmermann *et al.* 2000) and appears to be contemporary with high pressure/low temperature metamorphism along the contact zone of the Saxothuringian and Teplá-Barrandian blocks between 380–365 Ma. In this event the orogenic wedge in the West Sudetes generally propagated from east to west. In the Karkonosze-Izera complex (central West Sudetes) this is shown by: a) early kinematic indicators in mylonitic ductile shear zones (Mazur 1995; Seston *et al.* 2000); b) the decrease in metamorphic grade from garnet zone in the east to chlorite zone in the NW (Baranowski *et al.* 1990; Kachlík & Patočka 1998; Collins *et al.* 2000); c) the decrease of ^{40}Ar–^{39}Ar cooling ages towards the west (Marheine *et al.* 1999); d) diminishing ages of flysch sedimentation onsets towards the west showing that tectonic exhumation was much earlier in the east. In addition, pre-late Devonian unconformities occur in the central West Sudetes between the Kłodzko metamorphic complex and the Bardo Unit (Hladil *et al.* 1998; Kryza *et al.* 2000), while late Devonian coarse-grained clastic sedimentary fills derived from exhumed metamorphic complexes to the east were deposited in syntectonic basins (Aleksandrowski & Mazur 2002). These processes, which started in pre-late Devonian times in the central West Sudetes (e.g. Hladil *et al.* 1998) continued until the Tournaisian in both the northwesternmost frontal parts of the West Sudetic orogenic wedge, where mélanges formed in the Kaczawa Complex (Collins *et al.* 2000), and in the metamorphic core of the complex such as the Orlica-Snieznik area where high pressure metamorphism produced eclogites. This range of dates suggests that a plethora of small-scale collisional events occurred, consistent with jostling of the small platelets of the ATA.

The term 'Variscan Orogeny' has been used to describe the deformation associated with the closure of the Rheic Ocean. However, this closure was complex, and although only younger Early–Middle Carboniferous dates (350–330 Ma) prevailing along the Rheic and Moravian suture lines may relate to final closure, both earlier (from mid-Devonian onwards) and later dates, up to post-Stephanian age, are regularly described as Variscan. In the West Sudetes Carboniferous metamorphism is recorded as well as an earlier Devonian event, and the latter was followed by tectonic exhumation of deeply-buried crustal slices (353–350 Ma) and the superimposition of a greenschist to lower amphibolite facies overprint dated at 345–340 Ma). ^{40}Ar–^{39}Ar dating (325–320 Ma) suggests that metamorphism was complete by the middle to late Carboniferous (Marheine *et al.* 2000), a timing supported by the age of deposition in adjacent intramontane basins. It is these Carboniferous events which are generally considered to reflect the docking of the amalgamated ATA with the Avalonian and Bruno-Silesian margin of the growing Laurussian supercontinent. The range of dates suggests that collision was not a simple process: it probably began earlier where the accreting ATA first impinged on promontories, such as that of the Bruno-Silesian Block, and occurred later further west.

Deformation of the Laurussian margin as a result of this collision produced the only significant late Palaeozoic deformation to affect both Avalonia and Bruno-Silesia: the continuity of this event has led some workers to equate the Rhenohercynian deformation zone with that in Bruno-Silesia. The northern junction of the ATA is generally marked by the Northern Phyllite Zone in Germany. However, ophiolitic fragments assigned to the Giessen-Werra-Südharz Unit (e.g. Franke 2000), which are spatially related to this suture, appear to mark the closure of an early Devonian successor basin, the Lizard-Giessen-Harz 'ocean', which apparently developed on the south side of the Rheic Ocean, and was, on collision, overthrust to the north, so that the ophiolitic fragments resulting from the obduction of this successor basin are now situated within the Giessen-Werra-Südharz/Selke Nappe, north of the Rheic Suture. The Mid-German Crystalline High (**MGCH**) marks the position of both, below the Rheic Suture late Silurian–Devonian arc magmatism on the Avalonian margin, and, now spatially superimposed upon it, but above the south-dipping Rheic Suture, Carboniferous age volcanism (Oncken 1997). Small magnetic highs seem to indicate a continuation of the volcanic centres within the MGCH eastwards into Poland as far as a point just NE of the Leszno-Wolsztyn High, corresponding to the location of the Moravian Line. The metamorphism which followed the closure of the Rheic Suture is Visean (350–330 Ma). As it approached Laurussia, subduction was south-dipping beneath the leading edge of the ATA, leading to the formation of an arc edifice (volcanic rocks of the MGCH?) with its associated oceanic back-arc basin – the Lizard-Giessen-Harz 'ocean'. Subduction of this successor back-arc basin occurred in Devono-Carboniferous time, with obduction of small remaining fragments, now thrust on to the northern side of the Rheic Suture.

Still unanswered is the question whether the ATA included crustal blocks which converged with Laurussia further east, and were thus accreted to the southern margin of Bruno-Silesian Block. Because the latter area is overprinted by the Carpathian/Alpine movements, and basement inliers are well-scattered within the Carpathian arc, further work is needed before this question can be answered. However, rocks apparently subjected to Variscan-age metamorphism, often intruded by mid-Carboniferous post-orogenic granitoids, do occur further east, south of the Bruno-Silesian Block, and are found both in inliers of basement in the Carpathians, such as the Tatra Mountains, and further east: there are for example reports of 'Celtic' (e.g. Avalonian) faunas in the Zonguldak Terrane of northwestern Turkey (Dean *et al.* 2000; Kozur & Göncüoğlu 1998). In the Tatra Mountains, metamorphic rocks containing amphibolites with similar chemistry to those in the West Sudetes (Gawęda *et al.* 2000) are cut by post-metamorphic Variscan granitoid rocks, dated by both ^{40}Ar–^{39}Ar and Rb–Sr methods at 300–330 Ma (Burchart 1968; Janak 1994). If these rocks form part of the European Variscides, the distance of its eastward continuation is uncertain.

In the northern Bohemian Massif extensive bimodal magmatism occurred in the early Ordovician, with bursts of magmatism continuing until the Devonian. Early, mainly acidic magmatism of Cambro-Ordovician age (e.g. Philippe *et al.* 1995; Hammer *et al.* 1997; Korytowski *et al.* 1993; Kröner *et al.* 1994) shows calc-alkaline chemistry, which was interpreted by some as evidence for an arc or active continent margin tectonic setting (e.g. Oliver *et al.* 1993; Kröner & Hegner 1998). Others suggested that the absence of supporting geological evidence for an arc edifice at the time makes it more likely that chemical characteristics of the intrusions were inherited from extensive melting of the calc-alkaline Cadomian basement (Kryza & Pin 1997; Aleksandrowski *et al.* 2000; Floyd *et al.* 2000). Subsequent dominantly basic magmatism was associated with clastic basin-fill metasedimentary rocks, typical of magmatism associated with an extensional tectonic setting. Minor associated felsic volcanic rocks are shown by Sm–Nd systematics and their REE distribution to result from continued melting of continental crust (Furnes *et al.* 1994; Patočka *et al.* 1997, 2002; Dostal *et al.* 2000). Analytical results from the basic rocks, using a database of over 600 full analyses (e.g. Floyd *et al.* 1996, 2000; Winchester *et al.* 1995, 1998), argue that the magmatic range is more likely to result from the interaction of an enriched plume with both asthenospheric and sediment-contaminated lithospheric mantle sources (Floyd *et al.* 2000). Although the volume of magmatism preserved is smaller than younger plume-influenced magmatic provinces, it has widespread correlatives in many parts of Western Europe including the Massif Central (Briand *et al.* 1991, 1995) and Massif des Maures (Briand pers. comm.) in France and from NW Spain (e.g. Peucat *et al.* 1990). Floyd *et al.* (2000) also suggested that plume-induced magmatism can also explain the amount of heat needed to melt substantial volumes of lower crust to produce the major granitoid bodies, and provides one possible mechanism for the fragmentation of the Armorican Terrane Assemblage (ATA) as it separated from Gondwana, and the repeated rifting of crustal fragments from the Gondwana margin, including Avalonia and the ATA.

On the basis of faunal distinctions and putative timing of rifting from Gondwana it has been argued that the Bohemian and Armorican Massifs were on separate microcontinents in the middle of the Palaeozoic: to the former the term 'Perunica' was given. However, the absence of any definitive collision zone between these crustal blocks, and the continuing uncertainty in defining which blocks were rifting apart renders such distinctions putative at best. It is likely instead that the ATA comprised several related crustal blocks (though not as many as indicated in the so-called Hun Superterrane; Stampfli 1996), which migrated towards Baltica *en bloc* after rifting from their former peri-Gondwanan position.

Global Models: the affinities and likely wander paths of the accreted mid-European crustal blocks

Such models are necessarily speculative, as much work remains to be done. In this section a series of sketch models are presented in order to explain how the main crustal blocks became accreted to the TESZ margin of Baltica, and their likely origins. These models do not draw upon the wealth of palaeomagnetic data used by

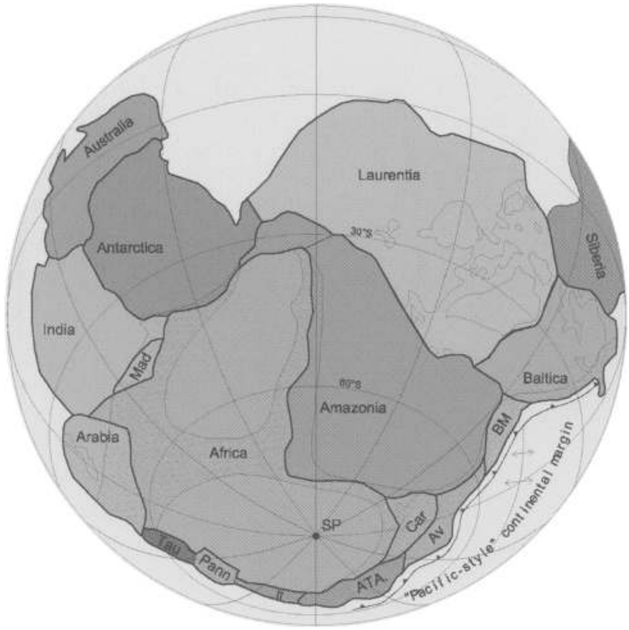

Fig. 2. Schematic reconstruction of the 'Pannotia' supercontinent in the late Proterozoic 600 Ma ago. Stippled areas are those deformed during the Panafrican event. Toothed lines represent areas of arc development or active continental margins Abbreviated microcontinent names are: ATA, Armorican Terrane Assemblage; Av, Avalonia; BM, Bruno-Silesia-Moesia; Car, Carolina; It, Italy; Pann, Pannonia; Tau, Taurus.

others, notably Dalziel (1997) and Torsvik *et al.* (1996). The models presented here are primarily designed to be 'correct' in terms of the likely location of microcontinent derivation and timing of accretion to Baltica.

An initial model (600 Ma) predates the opening of the Iapetus and related oceans and represents the fleeting development of the 'Pannotian' supercontinent (Dalziel 1997) resulting from the continental collisions recorded by the Panafrican orogenic events (Fig. 2). This model shows the main pre-Alpine Central European microcontinents forming an active continental margin (ACM) to the supercontinent, with the Bruno-Vistulian basement and Avalonia both adjacent to the Amazonian craton, based on the presence of inherited 1.5 Ga 'Rondonian' ages obtained from rocks in NE Austria (Friedl *et al.* 2000), Nova Scotia (Nance & Murphy 1994) and central England (Tucker & Pharaoh 1991). Baltica is shown adjacent to Bruno-Vistulia, and the end-Proterozoic magmatic belt extending the length of the Urals, and into the Timanides is shown as an extension of the ACM. However, if the orientation of Baltica at this time was as is claimed by Torsvik & Rehnström (2001), it is possible that Baltica was situated on the opposite side of the Panafrican mobile belt from Amazonia. In such a scenario the belt would represent a collisional zone rather than an ACM. In the opposite direction the ACM extends through the ATA, shown adjacent to the north African craton as it lacks inherited 'Rondonian' ages, and other blocks thought to have separated from their peri-Gondwanan positions later, notably the basements of Italy, the Pannonian blocks, and the Tauride basement of southern Turkey. The presence of late Neoproterozoic minor ophiolitic fragments within this ACM (e.g. Scarrow *et al.* 2001) attests to the obduction of successor basins and suggests that it originally formed a West Pacific-type rather than Andean-type continental margin.

A second model (Fig. 3) represents changes taking place at the end of the Proterozoic. It shows a narrow, but widening Iapetus Ocean, formed by the rifting of Laurentia in the early break-up of the end-Proterozoic supercontinent. Similar rifting of Baltica has occurred, with the Brunosilesia-Moesia crustal block occupying a position between it and peri-Gondwanan terranes. At this stage the Pacific-type margin of the supercontinent remains active, as recorded by voluminous calc-alkaline volcanism.

The third model (Fig. 4) shows an Early Cambrian setting with the Iapetus Ocean now wide,

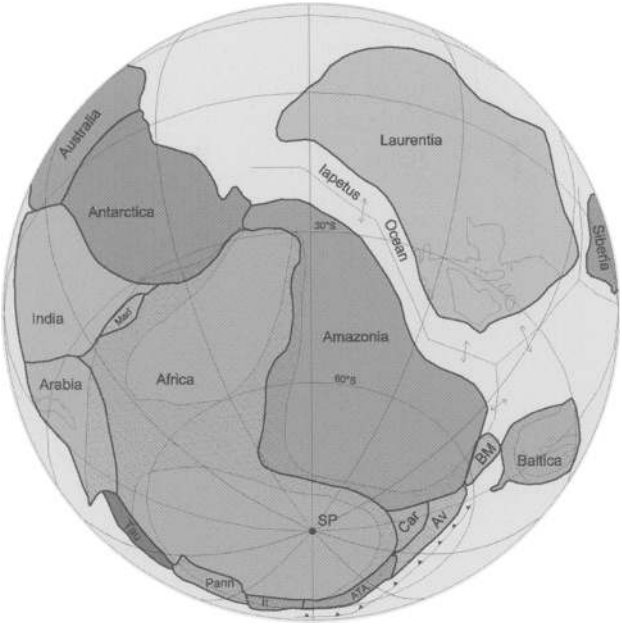

Fig. 3. Sketch reconstruction of continental distribution showing the opening of Iapetus at the end of the Proterozoic at 550 Ma ago. Ornament and abbreviations are as in Figure 2.

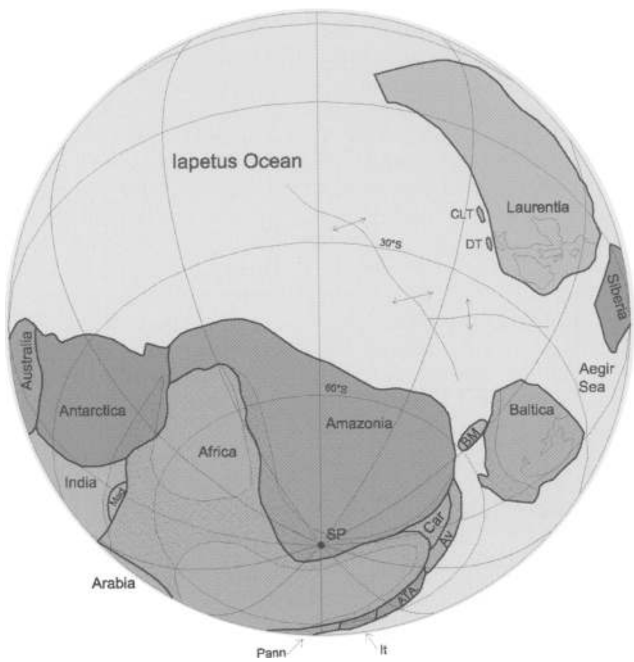

Fig. 4. Sketch reconstruction of continental distribution in the Early Cambrian at 520 Ma ago showing the Iapetus Ocean at its maximum width. Ornament and abbreviations are as in Figure 2. In addition CLT, Chain Lakes Terrane; DT, Dashwood Terrane.

and a cessation of magmatic activity along the Gondwana West Pacific-type margin. Brunosilesia-Moesia continues to act as a bridge between Gondwana and Baltica, and the latter continent remains in middle to high latitudes, as indicated by Torsvik & Rehnström (2001).

The start of the Ordovician Period (Fig. 5) reveals several changes. Rapid closure of the Iapetus Ocean has begun with subduction on both the Laurentian (Taconic Arc) and Gondwana (Gander Arc, off Avalonia) margins. At the same time Brunosilesia-Moesia is now detached from Gondwana and attached to Baltica at a location still far SE of its present position. Avalonia and the ATA remain attached to the Gondwana margin, with shelf sedimentation.

During the Llanvirn Stage (Fig. 6), renewed arc magmatism marks the detachment of Avalonia from the Gondwana margin and its rapid northward migration, narrowing the Iapetus Ocean. At the same time a widening Rheic Ocean is developing between Avalonia and the Gondwana margin, from which the ATA is already separating as a series of linked blocks. Avalonia is also depicted as migrating as more than one block, to allow for the possible presence of ophiolitic material in the Anglo-Brabant Deformation Belt, which would indicate that the evidence for the attachment of the easternmost part of the microcontinent is not secure.

By the early Silurian (Fig. 7), Avalonian docking with the TESZ margin of Baltica is shown, with imminent closure of the relic of the Iapetus Ocean between these continents and Laurentia. Speculatively, the collision of Avalonia with the Bruno-Silesian promontory has detached its easternmost portion, which is now displaced sinistrally: it could potentially form part of the western Pontides, if 'Celtic' faunas do indeed occur there. The ATA is now shown separated from Gondwana, while the Rheic Ocean is already starting to close, with subduction along the southern margin of Avalonia, marking the earlier stage of volcanism in the Mid-German Crystalline High. The new ocean separating the ATA from the Gondwana margin is now the Proto-Tethys Ocean.

By the early Carboniferous (Fig. 8), later, southward subduction, marked by renewed volcanism in the Mid-German Crystalline High, illustrates the final stage in the approach of the ATA to Baltica, also impelled by Gondwanan convergence. Contact has already been made with the Bruno-Silesian promontory, with dextral strike-slip faulting along its western margin, and detachment of the easternmost Variscides, which are displaced eastwards by

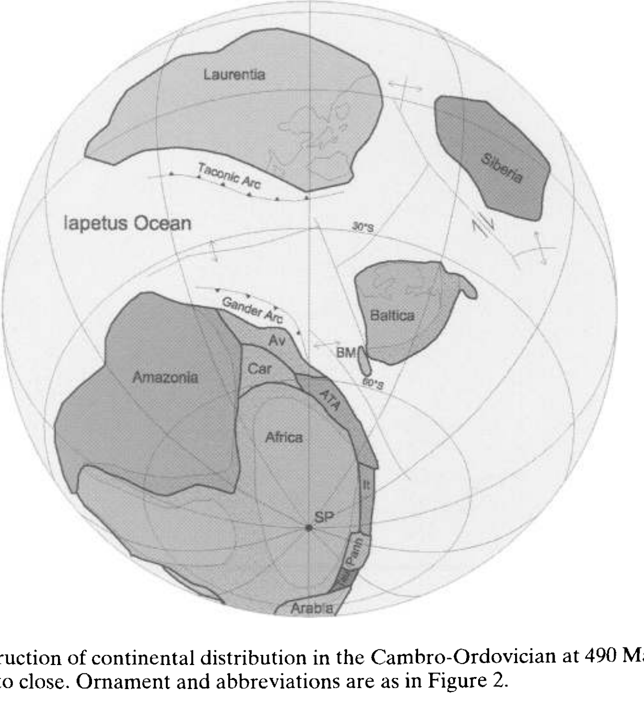

Fig. 5. Sketch reconstruction of continental distribution in the Cambro-Ordovician at 490 Ma ago as the Iapetus Ocean began to close. Ornament and abbreviations are as in Figure 2.

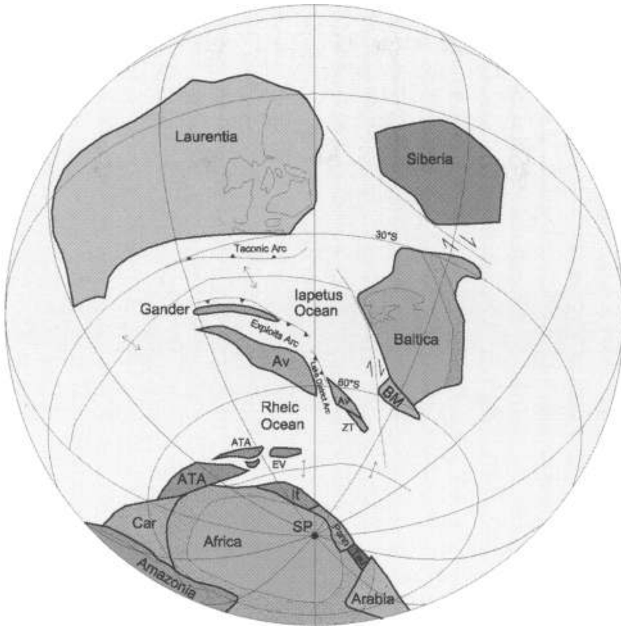

Fig. 6. Sketch reconstruction of continental distribution in the Llanvirn, 465 Ma ago as Avalonia migrated northwards. Ornament and abbreviations are as in Figure 2. In addition EV, Eastern Variscides; ZT, Zonguldak Terrane.

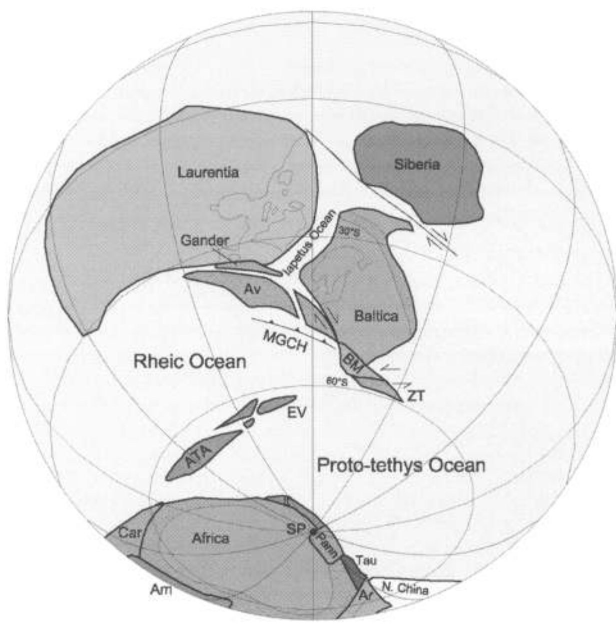

Fig. 7. Sketch reconstruction of continental distribution in the Early Silurian 440 Ma ago showing the accretion of Avalonia. Ornament and abbreviations are as in Figure 6. In addition Ar, Arabia; MGCH, Mid-German Crystalline High.

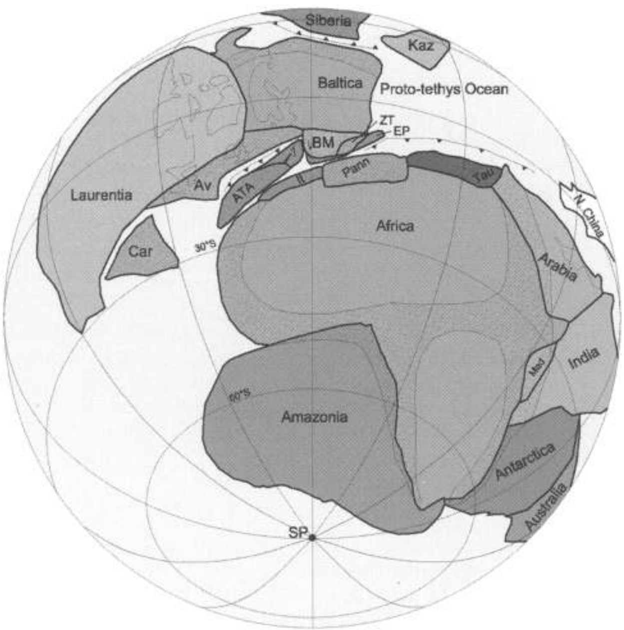

Fig. 8. Sketch reconstruction of continental distribution in the Early Carboniferous 350 Ma ago, as Gondwana and Laurasia converged. Ornament and abbreviations are as in Figure 6. Kaz, Kazakhstan.

sinistral faulting to form the Variscide basement seen in Carpathian inliers and in the Zonguldak and Istanbul Terranes of NW Turkey.

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