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

J.A. Winchester, The PACE TMR Network Team (contract ERBFMRXCT97-0136)*[,1]

School of Earth Sciences and Geography, Keele University, Keele, Staffs ST5 5BG, England, UK

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Abstract

Multidisciplinary studies of geotransects across the North European Plain and Southern North Sea, and geological reexamination of the Variscides of the North Bohemian Massif, permit a new 3-D reassessment of the relationships between the principal crustal blocks abutting Baltica along the Trans-European Suture Zone (TESZ). Accretion was in three stages: Cambrian accretion of the Bruno–Silesian, Lysogory and Malopolska terranes; end-Ordovician/early Silurian accretion of Avalonia; and early Carboniferous accretion of the Armorican Terrane Assemblage (ATA). Palaeozoic plume-influenced metabasite geochemistry in the Bohemian Massif explains the progressive rifting away of peri-Gondwanan crustal blocks before their accretion to Baltica. Geophysical data, faunal and provenance information from boreholes, and dated small inliers and cores confirm that Avalonian crust extends beyond the Anglo-Brabant Deformation Belt eastwards to northwest Poland. The location and dip of reflectors along the TESZ and beneath the North European Plain suggest that Avalonian crust overrode the Baltica passive margin, marked by a high-velocity lower crustal layer, on shallowly southwest-dipping thrust planes forming the Heligoland–Pomerania Deformation Belt. The "Variscan orocline" of southwest Poland masks two junctions between the Armorican Terrane Assemblage (ATA) and previously accreted crustal blocks. To the east is a dextrally transpressive contact

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* Corresponding author. Tel.: +44-1782-583184; fax: +44-1782-715261.

E-mail address: j.a.winchester@esci.keele.ac.uk (J.A. Winchester).

[1] The PACE TMR Network comprises: J.A. Winchester, P.A. Floyd, Q.G. Crowley, M.A.J. Piasecki (School of Earth Sciences and Geography, Keele University, Staffs ST5 5BG, UK); M.K. Lee, T.C. Pharaoh, P. Williamson, D. Banka (British Geological Survey, Kingsley Dunham Centre, Keyworth, Notts NG12 5GG, UK); J. Verniers, J. Samuelsson (Universiteit Gent, Laboratorium voor Paleontologie, Krijgslaan 281/S8, B-9000 Gent, Belgium); U. Bayer, A.-M. Marotta, J. Lamarche (GeoForschungsZentrum, Telegrafenberg, D-14473 Potsdam, Germany); W. Franke, W. Dörr, P. Valverde-Vaquero (Institut für Geo-wissenschaften, Justus Liebig Universitat, Senckenbergstr. 3, D-35390 Giessen, Germany); U. Giese, M. Vecoli (Institut für Geologische Wissenschaften, MLU Halle-Wittenberg, Domstrasse 5, 06108 Halle/Saale, Germany); H. Thybo, M. Laigle, M. Scheck (Geological Institute, Copenhagen University, Oster Voldgade 10, DK-1350 Kobenhavn K, Denmark); H. Maluski, D. Marheine (ISTEM.CNRS, Laboratoire de Géochronologie-UMR5567, Place Eugene Bataillon, 34095 Montpellier, France); S.R. Noble, R.R. Parrish, J. Evans, H. Timmerman, A. Gerdes (NERC Isotope Geoscience Laboratory, Kingsley Dunham Centre, Keyworth, Notts NG12 5GG, UK); A. Guterch, M. Grad (Instytut Geofyzyki, Ks Janusza 64, 01-452 Warsaw, Poland); S. Cwojdzinski, Z. Cymerman, W. Kozdroj (Polish Geological Institute, ul Jaworowa 19, 53-122 Wrocław, Poland); R. Kryza, P. Alexandrowski, S. Mazur (Institute of Geological Sciences, ul. Cybulskiego 30, 50-205 Wrocław, Poland); and V. Štedrá, J. Kotková (Czech Geological Survey (CGU), Klarov 3/131, 118 21 Prague 1, Czech Republic). Authors collaborating closely with the PACE Network: Z. Belka (Institut für Geologische Wissen-schaften, MLU Halle-Wittenberg, 06108 Halle/Saale, Germany), F. Patočka (Institute of Geology, Czech Academy of Sciences, Rozvojová 135, 165 02 Prague 6, Czech Republic) and V. Kachlík (Department of Geology and Palaeontology, Charles University, 128 43 Prague 2, Czech Republic).

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with the Bruno–Silesian and Malopolska blocks, accreted in the Cambrian, while to the north is a thrust contact with easternmost Avalonia, deeply buried beneath younger sedimentary cover. In the northeast Bohemian and Rhenohercynian Massifs Devonian "early Variscide" deformation dominated by WNW and NW-directed thrusting, records closure of Ordovician–Devonian seaways between detached "islands" of the ATA and Avalonia.

Keywords: East European Craton; Avalonia; Bruno–Silesia; Armorican Terrane Assemblage

1. Introduction

The southwest margin of the East European Craton, the Trans-European Suture Zone (TESZ), is the most prominent crustal feature of Europe. Originally defined by Berthelsen (1993) as a collage of crustal blocks that separates the >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 (Gee and Zeyen, 1996) to be a broad zone incorporating the major shear zones forming the margin of the EEC, including the Teisseyre–Tornquist Zone in Poland and the Thor Suture west of Denmark. It is marked by a major geophysical anomaly, separating the strongly magnetized East European Craton from the contrasting weakly magnetized crustal blocks to the southwest. Despite being everywhere concealed beneath thick sedimentary cover, it is traceable from the Black Sea coast of Romania to the mouth of the River Oder on the Baltic Sea, and thence westwards passing south of Denmark. Seismic reflection data from numerous traverses have played an important role in locating other crustal boundaries, which are less distinct. Their locations were determined by coupling the interpretation of seismic reflection data with geological and geochronological studies of Palaeozoic rocks which crop out in the northern Bohemian Massif, samples obtained from boreholes in southern Poland, northeastern Germany, the Baltic Sea and eastern North Sea, and maps of geophysical potential fields.

This paper aims to collate the geological and geophysical evidence for the sequence of collisions which produced the present configuration of crustal blocks in Central Europe, account for the series of oceanic openings and closures which caused them and explain the mechanisms controlling the repeated rifting of crustal blocks from the Palaeozoic Gondwana margin.

2. Brief summary of previous work

The outline structure of central Europe north of the Alpine–Carpathian Front and west of the approximate course of the TESZ has been known for many years. Evidence has come both from geophysical compilations and from geological information provided by deep boreholes and outcrops of Palaeozoic and older rocks across Central Germany and in the Bohemian Massif. As a result, several principal crustal blocks have been distinguished (although their individual geological histories have not always been well established) and have been shown on recent compilations (e.g. Pharaoh, 1999). Apart from the main EEC (which during much of the Early Palaeozoic constituted the independently moving palaeocontinent of Baltica) to the northeast of the TESZ, the principal crustal blocks recognized include the following.

(a) Eastern Avalonia. Precambrian and early Palaeozoic basement is exposed in Central England and Belgium, and this block was thought to extend eastwards beneath later cover rocks across northern Germany as far as Poland.

(b) Armorica, or, with recent recognition that it may not have comprised a single crustal block, more recently termed the Armorican Terrane Assemblage (ATA, e.g. Franke, 2000; Tait et al., 2000). 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. Here, several different crustal blocks have been recognized, though their relations to each other have been far from clear. Of these, four have become widely recognized as distinctive: Saxothuringia, Teplá–Barrandia, Moldanubia and Bruno–Silesia (also termed Moravia in the literature). Bruno–Silesia was recognized to have a completely separate geological history (see below), 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.

(c) Bruno–Silesia and, partly exposed in the Holy Cross Mountains, the Łysogory and Małopolska terranes. Thought to have late Proterozoic "Cadomian" and, by inference Gondwanan affinities, Bruno–Silesia was considered by Moczydlowska (1997) to be a possible eastward extension of Avalonia. By contrast, the Łysogory and Małopolska terranes were interpreted as fragments of Baltica (Dadlez, 1996; Pharaoh, 1996) because their Ordovician faunas have Baltican affinities. However, recent recognition of late Proterozoic "Cadomian" basement in the Uralides of the EEC (Glasmacher et al., 1999) has complicated the picture because the presence of late Proterozoic basement can no longer be taken as conclusive proof of a Gondwanan origin for crustal blocks in the area.

In the extant voluminous literature on many aspects of the geology of this complex area, individual geological complexes which cross territorial boundaries are given different names in the different countries. In this paper, we have, for example, adopted the Polish spelling of the Karkonosze Complex and the Izera gneiss, while recognizing that the Czech spelling of the same names is equally valid. The distinctive and differing geological histories of these discrete crustal blocks are summarised in simplified form in Table 1.

The results of collaborative work within the PACE network have clarified the following aspects of European basement geology, as described below.

Table 1
Schematic representation showing the different geological histories of the principal crustal blocks accreted to the EEC during the Palaeozoic

Time	Crustal block			
	ATA	Avalonia	Bruno–Silesia	EEC
Neoproterozoic (543 Ma)	Panafrican (Cadomian) deformation and ACM magmatism	Panafrican (Cadomian) deformation and ACM magmatism	Panafrican (Cadomian) deformation	Panafrican (Cadomian) deformation on Uralide margin only; Rifting from Gondwana
Cambrian (490 Ma)	Transtension		Rifting from Gondwana Małopolska docked Lysogory docked with EEC	Passive margin sedimentation
Ordovician (443 Ma)	Plume-influenced magmatism; rifting from Gondwana	Rifting from Gondwana; magmatism in E England Convergence with EEC	Passive margin sedimentation	Passive margin sedimentation
Silurian (418 Ma)		Collision in NW with Laurentia to form Laurussia Acadian orogeny "early" MGCH magmatism in S-separation of "Franconia"		
Devonian (362 Ma)	Saxothuringian HP metamorphism—closure of Saxothuringian seaway	Postorogenic granites	Jeseniky Mts magmatism Adjustment of Bruno–Silesia against Avalonia	
Carboniferous (290 Ma)	"late" MGCH magmatism: tectonic superimposition on Silurian MGCH magmatism as part of Collision with Laurussia Variscan orogeny Postorogenic granites			

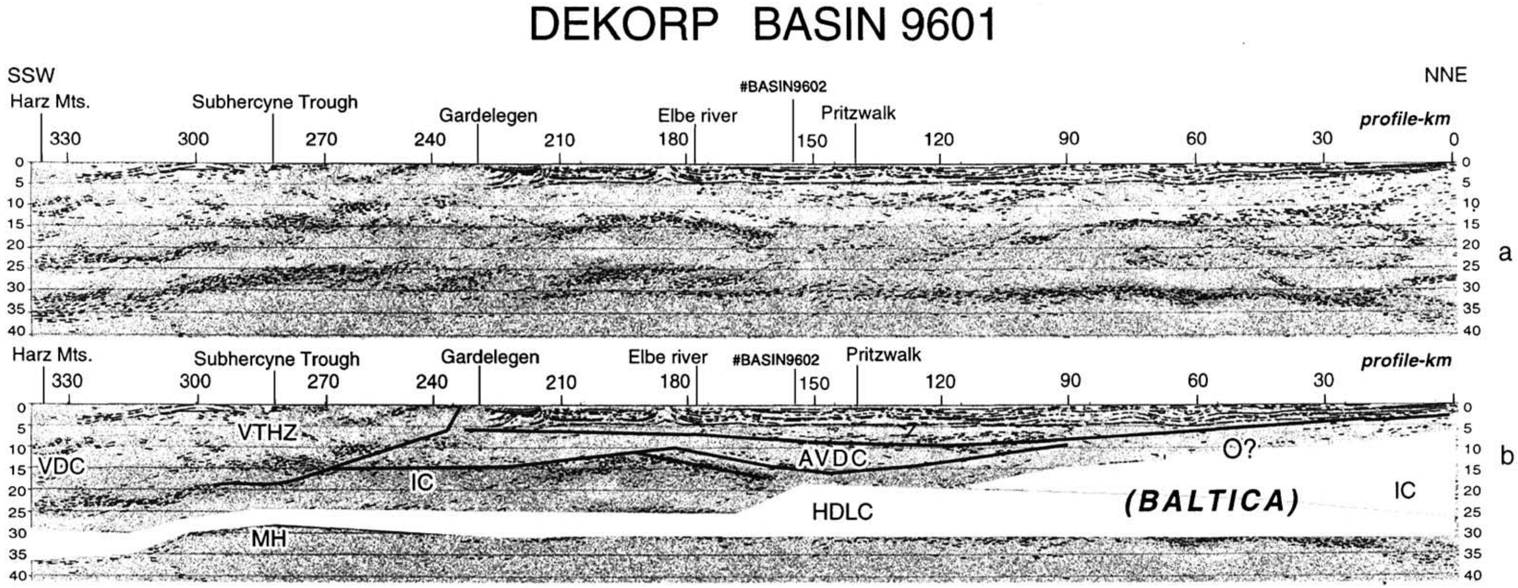


Fig. 1. (a) Line-drawing superimposed on explosion seismic data and vibroseis profile DEKORP BASIN9601, depth-migrated, reduced colour intensity. (b) Interpretation with: O = position of the interpreted 'O-horizon' reflector as possible base of paleozoic deposits; AVDC= Avalonian dense crust; IC = intermediate crust; HDLC = high-density lower crust; MH = Moho; VTHZ = Variscan thrust zones; VDC = Variscan deformed crust. DEKORP BASIN 96 seismic profile (adapted from DEKORP-BASIN Research Group, 1998; Bayer et al., 1999), illustrating shallow-dipping Baltic Crust overridden by a wedge of Avalonian basement.

3. The present geometry of the Trans-European Suture Zone

Seismic traverses (including normal incidence and wide-angle reflection seismics) in the North Sea (BIRPS, MONA LISA), Germany (DEKORP BASIN 96) (Fig. 1) and Poland (POLONAISE) all show that a high-density basement, linked with that of the EEC, extends with progressive attenuation some 150 km to the southwest of the Tornquist–Teisseyre Line (DEKORP-BASIN Research Group, 1998; Guterch et al., 1999; Bayer et al., 1999, 2002). This indicates that the TESZ is not a steep feature, as originally inferred, but dips southwest at a shallow angle—perhaps no more than 20°—so that Baltican crust extends as far southwest as the Elbe Line (Fig. 3) in Germany (Thybo, 1990).

Likewise, in Poland, while the sub-Permian location of the Baltica margin for much of its length runs approximately parallel to the Teisseyre–Tornquist Line, seismic lines from the POLONAISE '97 profiles (Guterch et al., 1999) confirm that its attenuated edge at the base of the crust aligns with the Krakow–Lubliniec Zone (KLZ), the southeast continuation of the Elbe Line, sometimes also called the Cracow Fault (Fig. 3). This coincidence may have governed the location of, and later movements along, the KLZ. Further to the northwest, the continuation of this suture bends westwards, passes south of Denmark and, traversing the southeast North Sea (here known as the Thor–Tornquist Suture; Berthelsen, 1998; Pharaoh, 1999) curves northwest to meet the Iapetus Suture at a triple point junction 300 km east of the Scottish coast (Pharaoh, 1999). It is probably no coincidence that for about 200 km the mid-North Sea rift is superimposed on the course of the Thor Suture, suggesting that basement structure controlled the location of the former feature.

4. The affinities of the Proterozoic basement beneath the southern North Sea and northern Germany

The affinity of the crystalline basement extending east from the coast of England across the southern North Sea and northern Germany has been the subject of much speculation in recent years because it 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 southeast margin of the Rhenish Massif and the 560 Ma Ecker Gneiss in the Harz Mountains (Baumann et al., 1991) may be the only exposed Cadomian basement in this crustal block. Existing seismic traverses across the North Sea (e.g. BIRPS MOBIL 7; Lee et al., 1993) do not image well the internal structure of this easternmost part of Avalonia. However, a seismic traverse (Fig. 2) shows that its internal crustal structure is very different from that of the Anglo-Brabant Deformation Belt southwest of the Dowsing South Hewett Fault Zone because the latter has many highly reflective middle crustal shear zones (Lee et al., 1993). As a result of this recent work, revisions have become necessary to the previous compilation map and a new map has been constructed (Fig. 3) which takes account of the following germane information.

(a) Exposures show that Avalonian basement in Central England, which typically consists of Late Proterozoic intrusive, volcanic and sedimentary rocks (e.g. Thorpe et al., 1984; Pharaoh and Gibbons, 1994; Strachan et al., 1996), was affected by end-Proterozoic/pre-Lower Cambrian deformation ("Cadomian" or "Pan-African" event). Because this area has been so little affected 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."

(b) Evidence from boreholes in eastern England shows that the Midlands Microcraton is bounded to the northeast by a deformation belt of Late Ordovician age associated with voluminous calc-alkaline magmatism (André et al., 1986; Pharaoh et al., 1987). The southern end of this belt is exposed in the Brabant Massif of Belgium and, hence, it is referred to below as the Anglo-Brabant Deformation Belt (ABDB).

(c) The presence of the ABDB questions whether the basement further east, northeast of the Dowsing South Hewett Fault Zone–Lower Rhine Lineament, is also part of Avalonia. With crust which is relatively thin and of constant thickness, it seems unlikely to be a detached piece of Baltica or Laurentia. However, exposures of the Wartenstein Gneiss, in the south Hunsrück at the southeast margin of the Rhenish Massif (Fig. 3) and the Ecker Gneiss in the Harz

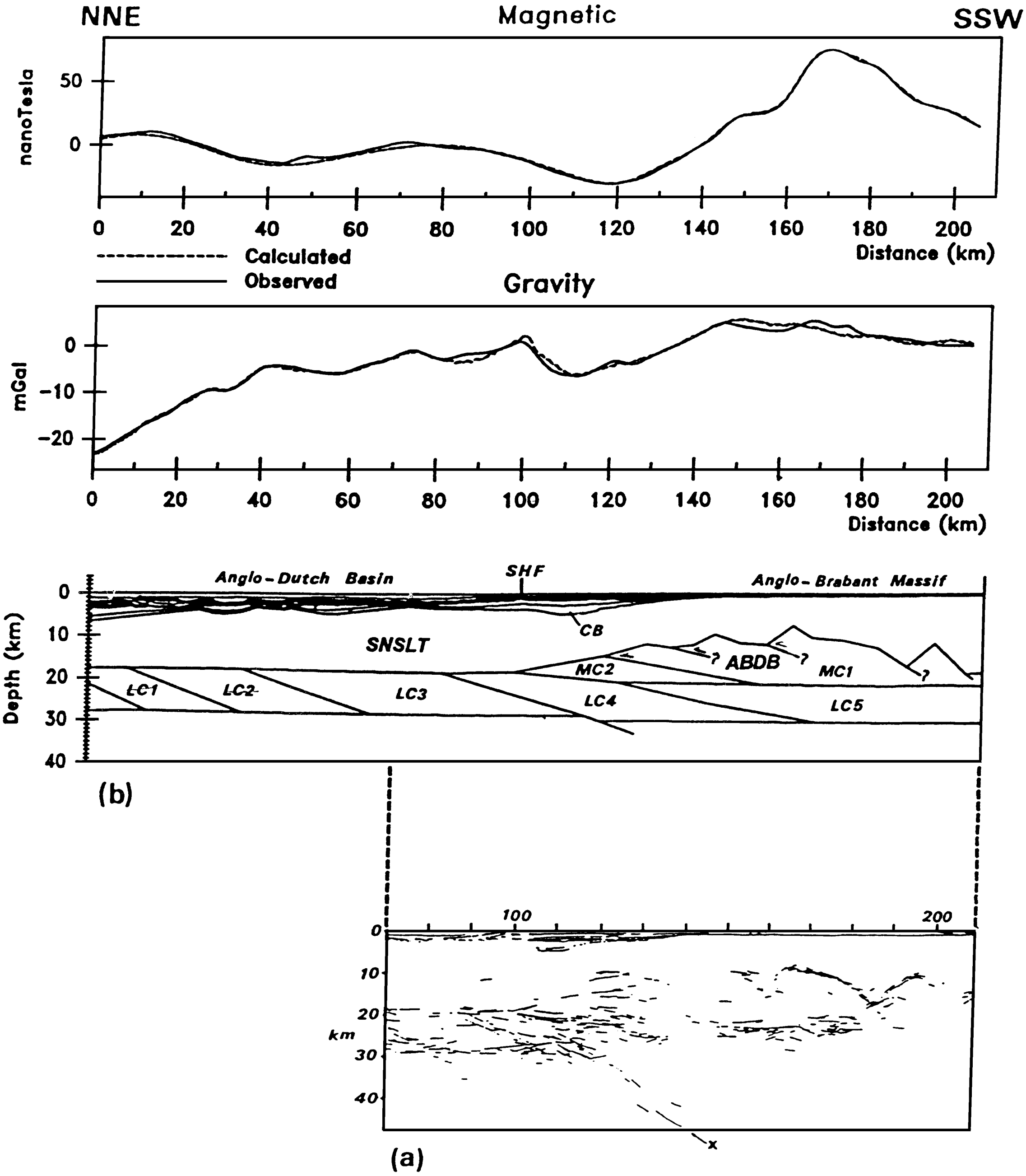


Fig. 2. A seismic traverse across the South North Sea (adapted from the southern part of the BIRPS MOBIL 7—from Lee et al., 1993). (a) Depth-migrated line drawing of the main reflectors. × indicates a possible mantle reflector. (b) Combined gravity/magnetic model constrained by the seismic data. SHF = Dowsing South Hewett Fault Zone; CB = Carboniferous Basin; ABDB = probably imbricated upper crustal rocks of the Anglo-Brabant Deformation Belt (density 2.78 Mg m^{-3}, susceptibility = 0.0 SI); SNSLT = South North Sea–Luneberg Terrane; MC1 = mid-crustal magnetic body (density 2.79 Mg m^{-3}, susceptibility = 0.02 SI); MC2 = separate segment of mid-crustal body (density 2.81 Mg m^{-3}, susceptibility = 0.005 SI). LC1/LC2/LC3/LC4 = lower crust beneath the SNSLT and margin of the ABDB (density 2.98 Mg m^{-3}, susceptibilities = 0.015, 0.005, 0.015 and 0.01 SI, respectively); LC5 = lower crust beneath the ABDB (density 2.95 Mg m^{-3}, susceptibility = 0.005 SI).

Mountains (Fig. 3), yield typically "Cadomian" ages, at the southeastern extremities of this block, thereby suggesting that it too is another piece of Gondwana-derived crust. However, as so many pieces of crustal basement in both Avalonia and the Variscides of Central Europe appear to record end-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.

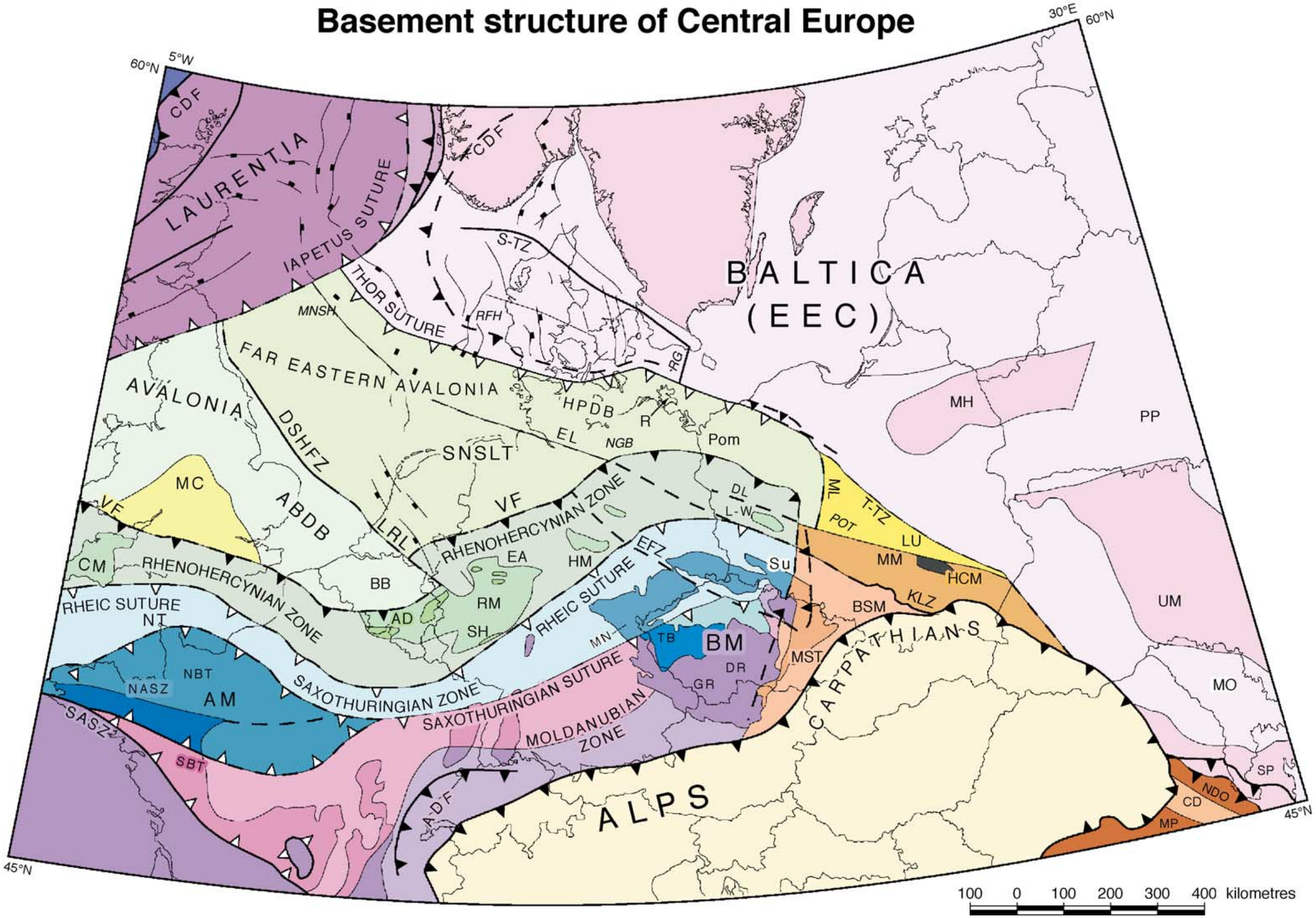
(d) The timing of convergence of this block with Baltica is provided by fossil evidence and sediment provenance data obtained from the G14 borehole, north of the Caledonian Deformation Front close to Rügen Island (Fig. 3). In the cores, sediments with clear Gondwanan fossil associations and Cadomian 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 southwest margin of the EEC (Samuelsson et al., 2001) proves that an uplifted area was being eroded in latest Ordovician time (specifically late Pusgillian to Rawtheyan–Early/Middle Ashgill; Vecoli and Samuelsson, 2001). 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 northeast 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 convergence 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.

(e) The timing of this convergence corresponds quite closely to when Avalonia approached 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. It, therefore, seems likely that the North Sea basement was indeed an extension of Avalonia. Hence, the general name "Far Eastern Avalonia" for this area of crystalline basement seems apt.

(f) The extent of "Caledonide" deformation along the margin with the EEC is very poorly known. Hard evidence is very scarce. Opinion has been divided as to whether there was a 600-km wide mobile zone, extending right across the North Sea to merge with the ABDB, or whether another stable Avalonian block—the so-called Southern North Sea Terrane (Franke, 1995; Pharaoh et al., 1995) or Luneberg Terrane (Berthelsen, 1993) separates the ABDB from the deformation belt at the contact with the EEC. The presence of the Wartenstein Gneiss in the south Hunsrück, apparently lacking a "Caledonian" overprint, and the absence of indications of a "Caledonian" event in Ordovician shaly sequences in the Ebbe and Remscheid anticlines, situated well to the east of the ABDB, in the northeast Rhenish Massif (Gruppenbericht, 1981), both argue for the presence of another stable Avalonian block beneath the southern North Sea, incorporating both the vaguely defined Southern North Sea and Luneberg Terranes: which we here refer to (Fig. 3) as the Southern North Sea–Luneberg Terrane (SNSLT).

(g) The presence of the stable SNSLT beneath the southern North Sea means that it separates the ABDB from the deformation belt along the margin of the EEC. To distinguish the geographic location of the latter deformation belt, it is referred to below as the Heligoland–Pomerania Deformation Belt (HPDB).

(h) If the SNSLT was also part of Avalonia, why did the ABDB, an apparently intra-Avalonian mobile belt, accompanied by voluminous magmatic activity, develop at all? Exposures in the Brabant Massif of Belgium show that, in contrast to the Midlands microcraton of Central England, where the Lower Palaeozoic succession is thin, an enormous thickness of Lower Cambrian turbidites has been deposited (De Vos et al., 1993). This suggests that basin formation in this area was initiated long before the (Ordovician) rifting of Avalonia away from Gondwana. It may, therefore, record an earlier failed rift arm, which later acted as a zone of weakness within the Avalonian microplate. Indeed, the SNSLT may even have been temporarily detached from East Avalonia, accounting for evidence that some subduction occurred (André et al., 1986; Pharaoh et al., 1993, 1995) leading to the collision of these two blocks in the late Ordovician. Hence, the ABDB appears to mark a zone of basement weakness that was deformed both when Avalonia converged with Baltica and Laurentia starting in the Late Ordovician (Shelvian or Taconic phase of deformation) and again in the Acadian deformational phase (Pharaoh, 1999): in the Brabant Massif field evidence


Basement structure of Central Europe
60°N
5°W
30°E
60°N
45°N
45°N
CDF
LAURENTIA
IAPETUS SUTURE
CDF
S-TZ
BALTICA
(EEC)
THOR SUTURE
MNSH
RFH
RG
FAR EASTERN AVALONIA
AVALONIA
HPDB
R
MH
PP
DSHFZ
EL
NGB
Pom
SNSLT
MC
ABDB
VF
VF
DL
L-W
ML
T-TZ
POT
LU
RHENOHERCYNIAN ZONE
LRL
EA
HM
EFZ
Su
MM
HCM
CM
RHENOHERCYNIAN ZONE
BB
RM
KLZ
BSM
UM
RHEIC SUTURE
NT
AD
SH
RHEIC SUTURE
MN
TB
BM
DR
GR
MST
CARPATHIANS
NBT
NASZ
AM
SAXOTHURINGIAN ZONE
SAXOTHURINGIAN SUTURE
MOLDANUBIAN ZONE
MO
SASZ
SBT
ADF
ALPS
SP
NDO
CD
MP
100 0 100 200 300 400 kilometres

shows that deformation occurred between the earliest Early Devonian (mid-Lochkovian) and the early Middle Devonian (mid-Eifelian) (Van Grootel et al., 1997).

(i) The lack of major volcanism in the 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.

5. Magmatism and orogenesis in the northern Bohemian Massif

In the northern Bohemian Massif Silurian–Early/Middle Devonian ages, confined to high-grade metamorphic rocks in the Góry Sowie Block (GSB) (402 Ma; Brueckner et al., 1996; O'Brien et al., 1997) and the Münchberg klippe (395–390 Ma; Kreuzer et al., 1989; Stosch and Lugmair, 1990), may record local tectonothermal and, hence, collisional activity between migrating platelets of the ATA. These dates are historically and collectively termed Eo-Variscan elsewhere in Hercynian Europe (e.g. Faure et al., 1997; Shelley and Bossière, 2000). Subsequent HT/MP metamorphism in the GSB, well-constrained by U–Pb monazite ages (Van Breemen et al., 1988; Bruecker et al., 1996; Timmermann et al., 2000), is contemporary with HP/LT metamorphism determined by ^{40}Ar–^{39}Ar dating (Maluski and Patočka, 1997) along the contact zone of the Saxothuringian and Teplá–Barrandian blocks between 380 and 365 Ma in the West Sudetes.

Subsequently "Variscan" tectonic exhumation of deeply buried crustal slices (353–350 Ma) occurred with 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–Late Carboniferous (Marheine et al., 2000), a timing supported by the age of deposition in adjacent intramontane basins. 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 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 northwest (Baranowski et al., 1990; Kachlík and Patočka, 1998; Collins et al., 2000), (c) the decrease of Ar–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. This is supported by field evidence, as pre-Late Devonian unconformities are known in the central West Sudetes (Hladil et al., 1998; Kryza et al., 2000), and Late Devonian coarse-grained clastic sedimentary fills derived from exhumed metamorphic complexes to the east were deposited in accretionary wedge-floored syntectonic basins. These processes, which started in pre-Late Devonian times in the central West Sudetes (e.g. Hladil et al., 1998) continued into Tournaisian times both in the northwesternmost frontal parts of the West Sudetic orogenic wedge, where mélanges formed in the Kaczawa Complex (Collins et al., 2000). Although often por-

Fig. 3. A revised map showing the distribution of crustal blocks and Palaeozoic deformation belts in Central Europe. Key to abbreviations: ABDB, Anglo-Brabant Deformation Belt; AD, Ardennes; ADB, Anglo-Dutch Basin; ADF, Alpine Deformation Front; AM, Armorican Massif; BB, Brabant; BM, Bohemian Massif; BSM, Bruno–Silesian Massif; CBT, Central Brittany Terrane; CD, Central Dobrogea; CDF, Caledonian Deformation Front; CM, Cornubian Massif; COF, Capidava–Ovidiu Fault; DL, Dolsk Line; 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, Lysogory Unit; L-W, Leszno–Wolsztyn High; MH, Mazurska High; ML, Moravian Line; MM, Malopolska Massif; MN, Münchberg Nappe; MNSH, Mid-North Sea High; MO, Moldavian Platform; MP, Moesian Platform; MST, Moravo–Silesian Terrane; NASZ, North Armorican Shear Zone; NBT, North Brittany Terrane; NDO, North Dobrogea; NGB, North German Basin; PCF, Peceneaga–Camena Fault; Pom, Pomerania; POT, Polish Trough; PP, Pripyat 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; UM, Ukrainian Massif; VF, Variscan Front.

trayed as a displaced fault-bounded block, recent results from the GSB are not inconsistent with other parts of the West Sudetes. While HP 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), it was also affected by the regional HT/MP metamorphism at around ca. 380 Ma, with later minor stages around 370 Ma (Timmermann et al., 2000).

Pre-400 Ma "Caledonian" events outside northwest Europe, therefore, seem to be almost entirely limited to the Anglo-Brabant and Heligoland–Pomerania deformation belts (Fig. 3). In the latter Baltican Lower Palaeozoic, passive margin shelf sediments were folded, thrust and eventually overridden by high-density crust interpreted as Avalonian basement (see above). There appears to have been little other than anchizone metamorphism associated with these movements.

In the northern Bohemian Massif, extensive Palaeozoic bimodal magmatism occurred. Early, mainly acidic, calc-alkaline magmatism of Cambro–Ordovician age (e.g. Philippe et al., 1995; Hammer et al., 1997; Korytowski et al., 1993; Kröner et al., 1994) was interpreted by some as evidence for an arc or active continent margin tectonic setting (e.g. Oliver et al., 1993; Kröner and Hegner, 1998). However, the lack of supporting geological evidence for an arc edifice at the time made others suggest that the chemical characteristics of the intrusions were inherited from extensive melting of the calc-alkaline Cadomian basement (Kryza and Pin, 1997; Aleksandrowski et al., 2000; Floyd et al., 2000). Subsequent dominantly basic magmatism is 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, 2000; 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 northwest Spain (e.g. Peucat et al., 1990), and the Massif Central (Briand et al., 1991, 1995) and Massif des Maures (Briand, personal communication) in France. Floyd et al. (2000) also suggested that plume-induced magmatism can not only explain the amount of heat needed to melt substantial volumes of lower crust to produce the major granitoid bodies, but also provides a 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.

6. Affinities of the Bruno–Silesian, Łysogory and Małopolska blocks

Three distinct crustal blocks are distinguished; in sequence away from the Baltica margin, these are the Łysogory Block, Małopolska Block and Bruno–Silesian Block (Fig. 3). Currently, the original affinities of these blocks are disputed, but while Proterozoic rocks, generally considered to display a Cadomian affinity (Finger et al., 2000), are only exposed in the latter crustal block, the Cambrian sequence on the Małopolska Block has been interpreted as an accretionary wedge to the Bruno–Silesian Block. If so, the two blocks have always been closely linked.

Initially, the presence of a Cadomian-type basement, with evidence of end-Proterozoic deformation, was taken as evidence of a Gondwanan as opposed to Baltican origin because, at the time, it was supposed that Cadomian deformation had not affected Baltica. However, the discovery of widespread end-Proterozoic deformation along the Uralide margin of Baltica showed that the presence of Cadomian deformation was not continent-specific. Furthermore, the existence of a late Proterozoic orogenic belt along the Uralide 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. 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) do not now prove a specifically Gondwanan origin for this crustal block.

Careful study of the faunal assemblages shows that the Early Cambrian brachiopod faunas of the Małopolska block mostly show Gondwanan affinities with only a single Baltican species, *Westonia bottnica*, present. During the Middle Cambrian progressive introduction of Baltican brachiopod species (Jendryka-Fuglewicz, 1998) and the ingress of sediment derived from Baltican sources, indicates that the Małopolska Block was by then adjacent to Baltica. Late Cambrian docking is recorded by the Sandomierz Phase of deformation (Belka et al., 2000). However, the absence of calc-alkaline volcanic rocks in the Cambrian succession of the Małopolska Block argues against it having had a tectonically independent existence: it seems likely that displacement relative to adjacent continents may have involved major strike-slip movement.

Ordovician faunas, well documented in the southern part of the Holy Cross Mountains (Dzik et al., 1994), show essentially Baltican affinities, confirming that accretion of the Małopolska and Bruno–Silesian blocks to Baltica was complete by the end of the Cambrian. In the Łysogory Block, Middle to Upper Cambrian rocks contain fossils absent from Baltica. Inarticulate brachiopods include forms with Gondwanan affinity (Jendryka-Fuglewicz, personal communication) and trilobite trace fossils are identical to those from Gondwanan and peri-Gondwanan microplates (Seilacher, 1983). However, clastic material in the Cambrian succession of the Łysogory terrane was derived both from Baltic and Gondwanan sources, suggesting that neither continent was distant (Belka et al., 2000). Timing of the docking of the Łysogory terrane with Baltica is, therefore, still controversial, but appear to be later than the Małopolska Block.

All these blocks accreted to Baltica far earlier than any part of Avalonia: indeed, before Avalonia actually rifted away from Gondwana, so they cannot be considered as part of Avalonia. There must, therefore, be a tectonic junction which we have termed the Moravian Line (Fig. 3) between these blocks and the easternmost portion of Avalonia buried beneath the thick sedimentary rocks of the Polish Trough.

7. Was there displacement of the Bruno–Silesian, Łysogory and Małopolska blocks relative to the EEC after initial accretion?

Palaeomagnetic and structural data (Lewandowski, 1993; Mizerski, 1995) suggest dextral strike-slip displacement of the Małopolska Block along the southwest margin of the EEC. Provenance of clastic material, sedimentary history and palaeomagnetic data (Nawrocki, 1999; Belka et al., 2000) show that final amalgamation of the Małopolska and Łysogory blocks was attained during the late Silurian. New palaeomagnetic data (Nawrocki, 1999) do not confirm that rotation of the Małopolska Block occurred at this time. Hence, a northwestwards displacement of the Bruno–Silesian and Małopolska blocks may explain how, while they were apparently already attached to Baltica before the docking of the Łysogory Block, they are now located “outside” the latter in their position along the margin of the EEC.

8. The western boundary of the Bruno–Silesian and Małopolska blocks (Moravian Line)

Attempts have been made to trace the western junction of these blocks beneath the thick sedimentary cover of the Polish Trough. Because of the thickness of Mesozoic and Tertiary sedimentary cover rocks, this has proved difficult and controversial. However, information on the timing of docking of the various crustal blocks with Baltica, particularly Avalonia, Łysogory, Małopolska, Bruno–Silesia and the ATA, shows that there has to be a series of junctions between them—i.e. there is no continuity between them. The problem is to trace these junctions beneath such thick cover, below the depth to which boreholes penetrate and, hence, only seismic profiles help here. Relevant data include the following.

(a) Both the POLONAISE ’97 1 (Fig. 4) and TTZ profiles (Grad et al., 1999) show a clear mismatch of mid-crustal structure at 150 km, which is north of the exposed part of the Moravian Line (Fig. 3). This suggests that the Moravian Line continues northward beneath thick cover of younger rocks. The POLONAISE ’97 1 section (Fig. 4) also shows the Moravian Line junction does not penetrate the lower crust: other northeast–southwest trending POLONAISE ’97 sec-

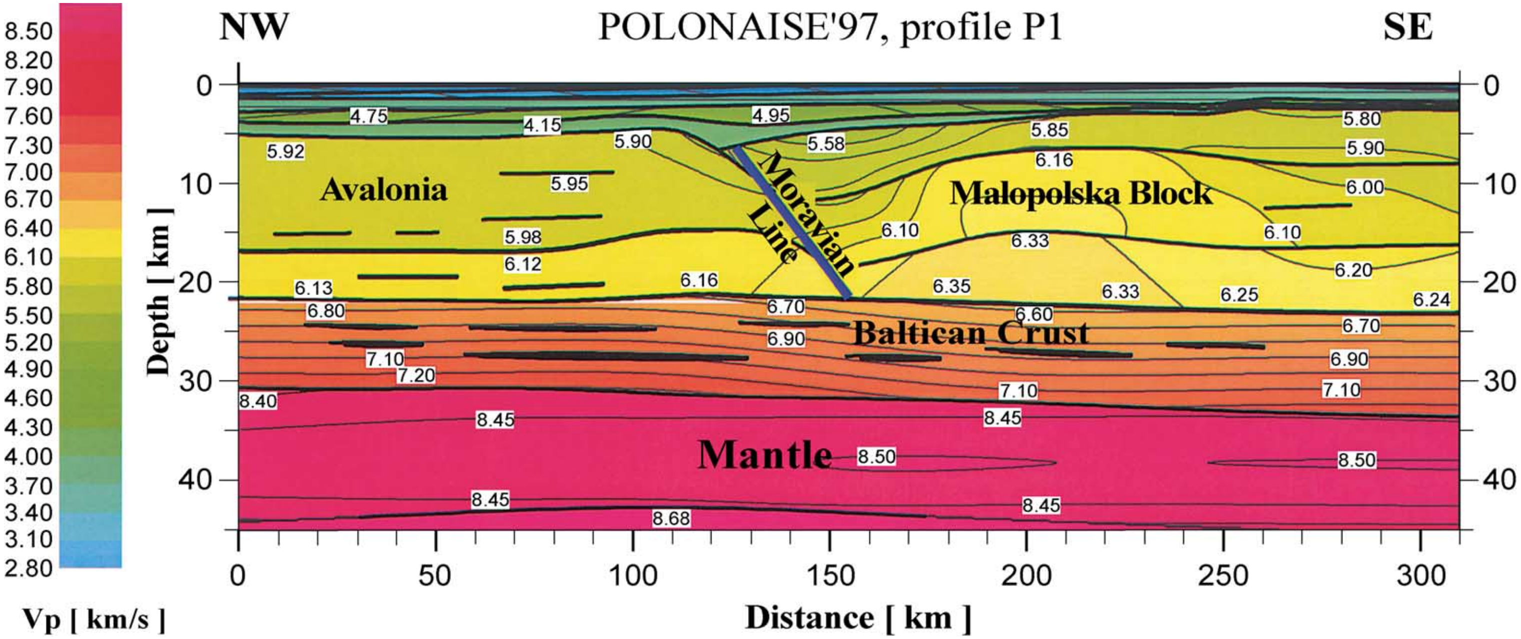


Fig. 4. Profile P1 from POLONAISE ’97 (adapted from Grad et al., 2002), showing the mid-crustal differences between Avalonian crust to the NW and that of the Małopolska Block to the SE seismic profile where it crosses this line (AG). Note that both these crustal blocks overlie thinned Baltican lower crust.

tions intersecting with section POLONAISE ’97 1 show that the lower crust is the thinned extension of Baltican crust underlying crust relating to both Avalonia and the Małopolska Block (Guterch et al., 1999). Compared to POLONAISE ’97 1, the mid-crustal break illustrated in the TTZ profile (Grad et al., 1999) is displaced eastwards: this suggests that dextral displacement of the Moravian Line by strike-slip faulting occurred between the two profiles: this is tentatively placed along the Dolsk Line (Fig. 3).

(b) Where exposed, structures along the Moravian Line show highly oblique (dextral sense of shear) complex overthrusting to the east in the early Carboniferous between 350 and 330 Ma (Schulmann and Gayer, 2000), consistent with northward convergence of the ATA.

9. The northern junction of the Armorican Terrane Assemblage

Following the interpretation of Franke (2000), the northern junction of the ATA approximates to the northern phyllite zone in Germany, as it contains a complex protolith association which includes both metamorphosed equivalents of the Rhenohercynian shelf sequences to the north (Franke, 2000) and Ordovician pelites containing cold water microfloras (Reitz et al., 1995) with affinities to the ATA. 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 Emsian successor basin, the Rhenohercynian ‘successor ocean’ (Franke, 2000). This apparently developed on the south side of the Rheic Ocean, at locations now marked by isolated outcrops and penetrated by boreholes (Oncken et al., 1995a,b) in a narrow belt between the Northern Phyllite and the Mid-German Crystalline High (MGCH). On collision, this was 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 (Franke, 2000). South of the Rheic Suture, the MGCH marks the position of mid-Carboniferous renewed arc magmatism (Oncken, 1997), reflecting convergence and eventual collision of the ATA with the Old Red Continent on the other side of the Rheic Ocean. The DEKORP BASIN 9601 seismic profile and related lines show that the ATA basement has overridden the Avalonian margin at a shallowly south-dipping angle in Germany, with north-directed overthrusting affecting the underlying rocks (DEKORP-BASIN Research Group, 1998; Bayer et al., 1999). Small magnetic highs seem to indicate a continuation of the volcanic centres within the MGCH eastwards into Poland as far as a point just northeast of the Leszno–Wolsztyn High (Fig. 3) corresponding to the location of the Moravian Line.

10. Closure of the Rheic Suture

Compared to the timing of metamorphism linked to the closure of the Saxothuringian Seaway (380–365 Ma), the metamorphism which followed the closure of the Rheic Suture is late (350–330 Ma). This suggests that the ATA had already started to amalgamate in what might have been a series of small orogenic events before its collision with the Old Red Continent. As it approached the ORC, subduction was south-dipping beneath the leading edge of the ATA, leading to the formation of an arc edifice (volcanic rocks of the MGCR) with its associated oceanic back-arc basin—the Rhenohercynian ‘successor ocean.’ Subduction of this backarc basin occurred in the Carboniferous, with northward obduction of small ophiolitic fragments on to the northern side of the Rheic Suture (Franke, 2000).

11. Is there a Variscan Orocline beneath the Polish Trough?

The junction of the Rheic Suture and Moravian Line at almost 90° (Fig. 3) counters previous ideas about a “Variscan Orocline.” However, north-directed thrusting along the Rheic Suture, coupled with east-directed thrusting along the “Moravian Line” has produced the appearance of such an orocline, at least in terms of the compressional geometry—hence, the original theory. But this really masks a moulding of the ATA to the ORC continental margin, with near-orthogonal convergence along the Rheic Suture and dextral shearing along the Moravian Line, as also recorded where this junction is exposed in the northeast Bohemian Massif (Schulmann and Gayer, 2000).

12. Extensions to the Variscides

Still unanswered is the question of whether the ATA included crustal blocks which converged with the ORC further east and were, thus, accreted to the south 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 do occur further east, south of the Bruno–Silesian block, and are found in inliers of basement in the Carpathians, such as the Tatra Mts. Here, metamorphic rocks containing amphibolites with similar chemistry to those in the West Sudetes (Gawęda et al., 2000) are cut by postmetamorphic 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, as is the possibility of a link between the Moesian Platform and the Bruno–Silesian blocks. According to Dudek (1980), the Bruno–Silesian block continues under the Carpathians to the southeast, 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 southeast Europe.

13. Conclusions and summary

Collating all these disparate investigations has provided the following.

(a) A geotectonic explanation for repeated rifting of crustal blocks from the Gondwana margin.

(b) A time sequence of the accretion of the various crustal blocks to Baltica to form pre-Alpine Europe. Three main Palaeozoic accretion events occurred: Cambrian accretion of the Bruno–Silesian, Malopolska and Lysogory blocks; Late Ordovician–Early Silurian accretion of Avalonia; Early Carboniferous accretion of the ATA.

(c) An illustration of the shallow dip angle of many sutures bounding Baltica and, possibly related, an explanation of the oblique closure shown by many accretions.

(d) A revision of the location of the Baltican margin west of Denmark (Fig. 3).

(e) Evidence to support the likely Avalonian affinities of the SNSLT and the extent of its bounding deformation belts.

(f) A suggested trend for the northward extension of the Moravian Line beneath the thick sedimentary cover in the Polish Trough (Fig. 3).

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