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Introduction: geological and geophysical studies in the Trans-European Suture Zone

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1. Introduction

The Trans-European Suture Zone (TESZ) is the boundary between ancient Precambrian lithosphere of the East European Craton (EEC) and the younger lithosphere beneath the latest Neoproterozoic–Palaeozoic mobile belts of western Europe. The former is characterized by a thick crust (*c.* 45 km), low heat flow and a tectono-thermal age of about 3000 to 800 Ma, the latter by a thinner crust (*c.* 30 km), higher heat flow and a tectonothermal age of 560 to 290 Ma. These contrasting types of crust were juxtaposed during the Caledonian and Variscan orogenic episodes. The crystalline basement of the TESZ is largely concealed by sedimentary basins controlled by the reactivation of structures within the suture zone during Permian– Mesozoic extension and Cenozoic inversion. The pre-Permian evolution of the craton and the mobile belts, and the location of the sutures, is inferred from isolated outcrops, hundreds of boreholes and geophysical evidence. Existing seismic data demonstrates that the TESZ is rather narrow and has an expression at all levels of the lithosphere and deep into the asthenosphere. Teleseismic studies have demonstrated that the differences in the velocity structure of the asthenospheric and lithospheric mantle across the TESZ persist to depths of *c.* 400 km (Zielhus & Nolet, 1994).

EUROPROBE's TESZ project is a coordinated multidisciplinary investigation into the nature and history of the fundamental lithospheric boundary which separates southwestern and northeastern Europe (Pharaoh, in Gee & Zeyen, 1996). Deciphering the Phanerozoic tectonic history is fundamental to the understanding of the deep geophysical signature of lower crust and upper mantle and the thermo-mechanical processes that led to the juxtaposition of these contrasting continental lithospheres. Funding for the EUROPROBE programme, provided by the European Science Foundation, is principally used to organize scientific workshops. The papers published in this volume represent a selection of the papers presented at the workshop organized by the Polish Academy of Sciences and Polish Geological Institute in April 1996, and held at Książ Castle in the Sudetes Mountains of Poland.

2. Principal tectonic zones of the Trans-European Suture Zone

For purposes of description, the TESZ and its immediate neighbourhood may be divided arbitrarily into provinces which reflect the present day physiography of the region, the relative importance of the Mesozoic–Cenozoic cover and the superimposition of the younger Alpine–Carpathian orogenic belt in southern Poland.

The East European Craton, exposed in the Baltic (Fennoscandian) and Ukrainian Shields, extends along the entire northeastern side of the TESZ (Fig. 1) and formed during several complex episodes of crustal accretion and reworking through Archaean and Proterozoic time (Gaál & Gorbatschev, 1987). The interior of the craton is covered by a relatively thin, undisturbed epicratonic sedimentary cover of Riphean to Cenozoic age. Thicker, basinal Silurian sequences occupy passive margin foredeeps along its southwestern margin. The Sorgenfrei–Tornquist Zone (STZ), a Carboniferous–Mesozoic graben system long regarded as the southern margin of the Baltic Shield, lies to northeast of the Caledonian-age Avalonia–Baltica suture, also known as the Caledonian Deformation Front (Berthelsen, 1992). Thybo *et al*. (1990), using wide angle refraction data, demonstrated the presence of an abrupt (*c.* 5 km) step in the Moho at the STZ, which is confirmed by preliminary results from the TOR teleseismic experiment (Kind *et al.* 1997, this issue). Towards northern Poland, the STZ and Caledonian Deformation Front (CDF) converge into the Teisseyre–Tornquist Zone (TTZ). Geophysical evidence for the control of deep crustal structure on shallower, younger structures in this region is presented by Thybo (1997, this issue).

The Anglo-Brabant Massif of southern Britain and Belgium comprises juvenile Neoproterozoic crust of 'Avalonian' affinity, formed from accreted oceanic arcs and marginal-basins (Pharaoh & Gibbons, 1994). The early Palaeozoic sedimentary cover is thin on the Midlands Microcraton and much thicker in the Caledonide basins of Wales, eastern England and Belgium. Sedimentary provenance changed from cratonic (Cambrian) to more juvenile, arc-derived

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(Ordovician), reflecting the isolation of Avalonia from more ancient continental provenances by the opening of the Iapetus, Tornquist and Rheic oceans (Thorogood, 1990). Localized Silurian deep water basins were once again fed sediment by ancient cratonic sources, probably Laurentia and/or Baltica (Soper & Woodcock, 1990). Acadian (*c.* 380 Ma) deformation produced a structural arc (Soper, Webb & Woodcock, 1987) wrapping around the Midlands Microcraton (Fig. 1). Van Grootel *et al.* (1997, this issue) provide more detailed constraints on the nature and timing of volcanism, foreland basin development, metamorphism and deformation in the eastern part of the massif.

The Caledonide basement of the southern North Sea is concealed by Devonian and younger strata, thickest beneath the Anglo-Dutch Basin. Interpretation of deep seismic reflection profiles suggests that the basin is floored by (?Avalonian) basement equivalent to that beneath southern Denmark, northern Germany and northwestern Poland (Franke, 1995; Pharaoh, England & Lee, 1995) although further studies of drillhole core are required to confirm this. Basement rocks recording Caledonian deformation (Frost, Fitch & Miller, 1981) have been proven by drilling highs along the northern periphery of the basin but are of uncertain correlation with the onshore Caledonides, e.g. the Southern Uplands. The trace of the Iapetus and Tornquist sutures shown in Figure 1 is therefore rather schematic. The southern edge of the Baltic Shield is delimited by boreholes proving metamorphic rocks with Sveconorwegian affinities.

The position of the Caledonian Deformation Front, the upper crustal expression of the Trans-European Fault, the presumed Avalonia–Baltica suture (Berthelsen, 1992; Franke, 1995), is located using deep boreholes in Denmark, northern Germany and Poland. On and around Rügen Island, such boreholes encounter a thick, deep water Ordovician succession of volcanic arc provenance (Giese, Katzung & Walter, 1994), and possible Avalonian faunal affinity (Servais & Katzung, 1993; Servais & Fatka, 1997, this issue). The latter interpretation is contested by Cocks, McKerrow & van Staal (1997, this issue), who place the eastern limit of Avalonia at the Elbe Line (Fig. 1). Giese *et al.* (1997, this issue) describe the tectonic structures in this zone, which are consistent with the hypothesis that the northern edge of Avalonia (if Servais & Fatka are correct) was thrust over Silurian basinal facies of the Baltica marginal foredeep (Katzung *et al.* 1993).

In central Poland the Caledonian and Variscan basement is largely concealed by the Permian to Mesozoic fill of the Polish Trough, including thick Zechstein salt. Numerous deep seismic sounding (DSS) profiles have been acquired (Guterch *et al.* 1986), and a narrow zone of thinned, anomalous crust with near vertical margins coincident with the Teisseyre–Tornquist Zone (TTZ) has been identified. A new interpretation of the LT-7 profile by Dadlez (1997, this issue) infers the presence of a folded and gently metamorphosed early Palaeozoic basement beneath the trough. Gravity modelling of the DSS profiles presented by Krolikowski & Petecki (1997, this issue) supports the presence of near-vertical crustal discontinuities. Imprecision in the location of the Variscan Front southwest of the trough results in uncertainty as to the affinity of the crust in this region (Dadlez, Kowalczewski & Znosko, 1994).

In southeastern Poland, in the Holy Cross Mountains (HCM), an almost complete early Palaeozoic epicratonic succession, has a provenance mostly in the EEC, but also contains detrital micas from Neoproterozoic sources (Bełka *et al.* 1996). Late Silurian flysch-like sequences continue the foredeep recognized in northern Poland. Faunal (Dzik, 1983) and geological evidence suggest that the southern block of the HCM, the Małopolska Massif (Fig. 1), was minimally displaced from the EEC during early Palaeozoic time (Dadlez, Kowalczewski & Znosko, 1994), whereas palaeomagnetic data confirm proximity, achieved by large-scale dextral rotations, from early Carboniferous time (Lewandowski, 1993, 1994). Numerous deep boreholes penetrate the post-orogenic cover, particularly towards the Upper Silesian coal basin. The Kraków–Lubliniec tectonic zone (KLZ), a narrow (about 0.5 km wide) belt of intense ductile-brittle fold and fault deformation and magmatic intrusion, separating the Małopolska and Upper Silesian massifs, may represent a terrane boundary (Dadlez, Kowalczewski & Znosko, 1994), separating crustal blocks with strongly contrasting early Palaeozoic histories (Buła, Jachowicz & Żaba, 1997, this issue). The Proterozoic basement of the Upper Silesian Massif (USM), only known from deep boreholes, comprises in the southwest metasedimentary and meta-igneous rocks with cooling ages of *c.* 550 Ma and supposed 'Cadomian' affinity, and in the northwest, Vendian phyllites comparable to those of the Małopolska Massif. Overlying Cambrian strata contain trilobites and acritarchs of Acado-Baltican faunal affinity and Iberian aspect (Moczydłowska, 1997, this issue), supporting the view of Dadlez, Kowalczewski & Znosko (1994) that the KLZ may represent a fundamental terrane boundary, along which Baltica and disparate Gondwana-derived terranes were sutured at the end of early Palaeozoic time. The Upper Silesian Massif passes to the southeast beneath the Carpathian overthrust belt of Alpine age.

In the Dobrogea area of Romania, northwest of the Black Sea, in the Moesian Platform, Vendian phyllites are tectonically juxtaposed against a higher grade basement including banded iron formations, comparable to that of the Ukrainian Shield (Kräutner, Muresan & Seghedi, 1988). This evidence suggests that the TESZ emerges intact from beneath the Carpathian Arc, and passes through the Black Sea towards Asia Minor.

The Sudetes Mountains at the northeast margin of the Bohemian Massif (Fig. 1) represent the principal exposure of the Variscide Orogen in Poland (Dallmeyer, Franke & Weber, 1995) with a Neoproterozoic basement which has undergone a variable degree of reworking (Żelaźniewicz & Bankwitz, 1995; Żelaźniewicz, 1997,

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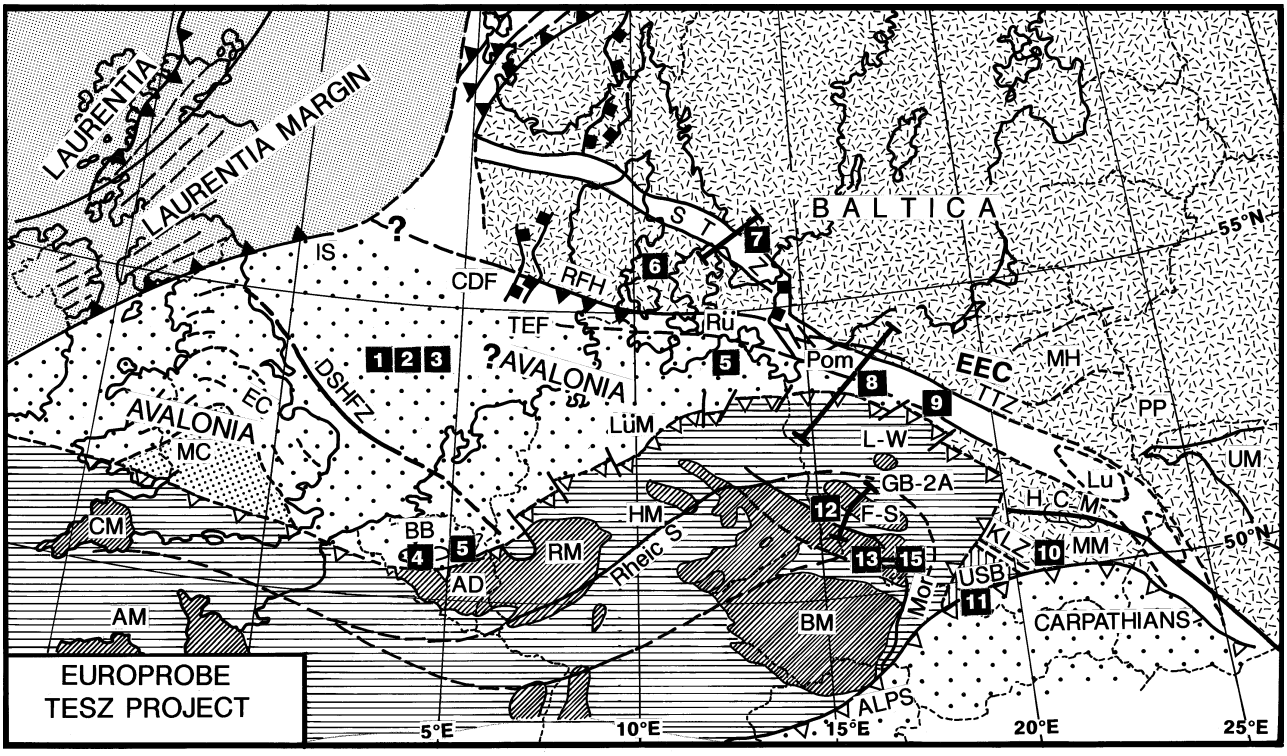


Figure 1. Basement tectonic sketch map of the Trans-European Suture Zone and adjacent areas, slightly modified from A. Berthelsen (EUROPROBE Newsletter no. 5, 1994) and Gee & Zeyen (1996). The Central Polish Trough is located at the position of the letters TTZ on this map. Key: AD, Ardennes; AM, Armorican Massif; BB, Brabant Massif; BM, Bohemian Massif; C, Cadomia; CDF, Caledonian Deformation Front; CM, Cornubian Massif; DSHFZ, Dowsing-South Hewett Fault Zone; EBL; Elbe Line; EC, Eastern English Caledonides; EEC, East European Craton; F-S, Fore-Sudetic Block; HM, Harz Mountains; HCM, Holy Cross Mountains; IS, Iapetus Suture (Avalonia–Laurentia); IS?, uncertain location of Laurentia–Baltica Suture; KLZ, Kraków–Lubliniec Zone; Lu, Lublin Trough; LüM, Lüneburg Massif; L-W, Leszno–Wolsztyn Basement High; MC, Midlands Microcraton; MH, Mazury High; MM, Maopolska Massif; Mor, Moravia; Pom, Pomerania; PP, Pripyat Trough; RFH, Rynkøbing–Fyn High; RM, Rhenish Massif; Rü, Rügen Is; USM, Upper Silesian Massif; STZ, Sorgenfrei–Tornquist Zone; Su, Sudetes Mountains; TEF, Trans-European Fault; TTZ, Teisseyre–Tornquist Zone; UM, Ukrainian Massif.

Approximate geographical coverage of these conference proceedings:
1. Pharaoh, England, Verniers & Żelaźniewicz (pp. 585–90)
2. Cocks, McKerrow & van Staal (pp. 627–36)
3. Servais & Fatka (pp. 617–25)
4. Van Grootel, Verniers, Geerkens, Laduron, Verhaeren, Hertogen & De Vos (pp. 607–16)
5. Giese, Katzung, Walter & Weber (pp. 637–52)
6. Thybo (pp. 597–606)
7. Kind, Gregersen, Hanka & Bock (pp. 591–5)
8. Dadlez (pp. 653–9)
9. Krolikowski & Petecki (pp. 661–7)
10. Buła, Jachowicz & Żaba (pp. 669–77)
11. Moczydłowska (pp. 679–89)
12. Żelaźniewicz (pp. 691–702)
13. Maluski & Patočka (pp. 703–16)
14. Cymerman, Piasecki & Seston (pp. 717–25)
15. Aleksandrowski, Kryza, Mazur & Żaba (pp. 727–39)

this issue). Crustal blocks showing some pronounced contrasts in stratigraphy and metamorphic grade are partly bounded by major ductile shear zones. Although these blocks contain continuous Ordovician–Lower Carboniferous successions (Urbanek *et al.* 1995) there is considerable disagreement as to whether they represent separate terranes sequentially accreted to the margin of Baltica during the Caledonian Orogeny (Oliver, Corfu & Krogh, 1993; Cymerman & Piasecki, 1994) or dismembered parts of larger Variscan tectonic nappe units, as seen further west in Europe (Matte *et al.* 1990; Franke *et al.* 1993). The sharp oroclinal bend of the Variscan Orogen in this region (Fig. 1) further complicates interpretation. The review by Żelaźniewicz (1997, this issue) confirms that the Sudetes have a similar lithotectonic composition and tectonothermal history to the

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Saxothuringian Zone of western Europe. Latest Neoproterozoic ('Cadomian') and Cambrian strata were deformed, metamorphosed and intruded by granitoids in early Ordovician time. Deformation of Hercynian (*sensu lato*) age commenced in late Devonian time, locally concurrent with a phase of blueschist facies metamorphism, and continued into Early Carboniferous time with crustal imbrication under widespread greenschist to amphibolite facies conditions. Subsequently, the orogenic front propagated northwards and the foreland basin of Moravia was deformed. A detailed geochemical and isotopic study by Maluski & Patočka (1997, this issue) constrains the age of blueschist and greenschist metamorphism to 360 and 340 Ma respectively. Cymerman, Piasecki & Seston (1997, this issue) redefine the terranes present within the Sudetes, and suggest an early Palaeozoic (?Ordovician) phase of ocean development prior to the Variscan cycle. Aleksandrowski *et al*. (1997, this issue) present detailed kinematic analyses of several of the most significant Variscan ductile shear zones.

3. The eastern limits of Avalonia and the identity of late Neoproterozoic crust within the Trans-European Suture Zone

One of the most critical problems within the TESZ, and perhaps the key to understanding the evolution of the zone, concerns the identity of the late Neoproterozoic crust incorporated within it. In the western part of the zone, it is likely that the crust originally formed part of the (Ordovician) terrane of Avalonia. Cocks, McKerrow & van Staal (1997, this issue) demonstrate that this terrane can be followed, on the basis of its distinctive mid-Ordovician shelf fauna, for 2000 km through the Appalachian Orogen, from Cape Cod to the type-locality in the Avalon Peninsula, and for another 2000 km across western Europe, certainly to the Elbe Lineament, and perhaps beyond. The maximum exposed width is about 500 km. Undoubtedly the shape of Avalonia has become more elongate as a consequence of transtensional extension on numerous internal shear-zones during the Caledonian Orogeny. The Elbe Lineament, at least its shallow expression, represents a late Variscan, relatively brittle structure, presumably superimposed on earlier orogenic sutures. To the northeast, the faunas of the Rügen area (Servais & Fatka, 1997, this issue) reflect deeper water environments, and are therefore less easily characterized as Avalonian. Clearly further work needs to be done in comparing the latter sequences to certainly Avalonian deep-water sequences, e.g. the Skiddaw Group of the Lake District which may be correlated with the shelf sequences and faunas.

In southern Poland the identity and provenance of late Neoproterozoic crust within the TESZ is presently uncertain. The crust forming the basement to the Avalonia Terrane, typically juvenile Neoproterozoic lithosphere comprising volcanic arcs and marginal basins accreted onto a relatively outboard margin of Gondwana (Pharaoh & Gibbons, 1994), is presumed to die out eastwards, and be replaced by crust originating at some remove along the margin(s) of Gondwana. Many geologists (e.g. see Żelaźniewicz, 1997, this issue; Moczydłowska, 1997, this issue) have historically referred to this crust as being of 'Cadomian' type because of its age, without consideration for its lithotectonic and terrane affinities. In the literature, the term 'Cadomian' is usually used for crust consolidated and stabilized during the latest Neoproterozoic (that is, Pan-African) Cadomian Orogeny, in a belt exposed from Iberia to the Bohemian Massif, although the term has been used in a more general way to include in addition the broadly coeval Avalonian and Monian terranes (D'Lemos, Strachan & Topley, 1990). Even in the Cadomian type area, the northern Armorican Massif of France, the Precambrian is markedly heterogeneous, incorporating old, > 2000 Ma old (Icartian) components as well as much younger, late Neoproterozoic elements (Power & Gibbons, 1994), and it is not easy to to define a 'Cadomian' terrane or crustal type. It is therefore recommended that the epithet 'Cadomian' should be applied with caution to Neoproterozoic crustal elements in central Europe, and certainly not without qualification.

4. Towards a model for the evolution of the Trans-European Suture Zone?

Biostratigraphical and palaeomagnetic evidence suggest that the character of the TESZ was established during the assembly of Pangaea by collision of Russo-Baltica first with Gondwana-derived microcontinents (Avalonia and other component pieces of the present Armorican, Bohemian and Iberian massifs) and then with the Gondwana supercontinent itself (Ziegler, 1990). However, the relationships between Avalonia and Russo-Baltica remain enigmatic, particularly in areas of southern Poland and the Slovak Republic where crust of 'Cadomian' (that is, latest Neoproterozoic) age and affinity possibly underlies Vendian and Cambrian strata which continue into the East European Platform. Faunal provincialism (Cocks & Fortey, 1982) supports the presence of a major ocean (Tornquist Sea) along the southern margin of Russo-Baltica during early Ordovician time, which had closed by the end of Silurian time, an interpretation which is not contradicted by the palaeomagnetic evidence (Torsvik *et al.* 1992). The crust accreted to Russo-Baltica during this period included Neoproterozoic terranes originating from the margin(s) of Gondwana, perhaps from as far away as Florida and Amazonia (Cocks, McKerrow & van Staal, 1997, this issue). The presence of more juvenile early Palaeozoic lithosphere, that is, ophiolitic and volcanic arc material, has been inferred from detrital provenance studies in northern Germany (Giese, Katzung & Walter, 1994) and U–Pb zircon studies in Poland (Oliver, Corfu & Krogh, 1993). More recent geochemical studies (Furnes *et al.* 1994; Floyd *et al.* 1996; Żelaźniewicz, 1997, this issue) cast doubt on the

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presence of volcanic arcs in Poland and favour instead an early Palaeozoic phase of bimodal, intraplate rift-magmatism progressing to the possible formation of small oceanic basins. Either arcs were never present, or they were subsequently removed during the major transcurrent deformational episodes which are likely to have affected this margin of Baltica. Amalgamation of Laurentia, Russo-Baltica and Avalonia to produce Laurussia was completed by mid-Devonian time. Further juvenile crustal material was added during the subsequent development of the Rheic Ocean. Much less certain is the number of different terranes involved in this accretionary mosaic, the identity and affinity of individual terranes, the magnitude of linear displacement and rotation during their transport, the timing of their docking to Russo-Baltica, and the degree of crustal reworking in the Variscan Orogeny, the final climactic collision between Gondwana and Laurussia, which completed the aggregation of Pangaea in late Carboniferous time.

It is hoped that the answers to some of these fundamental questions on the origin of the Trans-European Suture Zone will be provided by the multidisciplinary geological and geophysical studies presently in hand.

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