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Pomeranian Caledonides (NW Poland), fifty years of controversies: a review and a new concept

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The results of a half-century investigations of the Pomerania-Rügen Caledonides are reviewed. Fifty years ago there were two rival hypotheses based exclusively on analyses of gravity and magnetic data. One of them assumed the presence of the so-called Circum-Fennosarmatian Caledonides, the second one claimed that the Precambrian craton of the eastern Europe extends far to the west reaching northern Germany and Pomerania. As time passed, more new facts from boreholes and seismic refraction and reflection studies accumulated. New hypotheses appeared, namely the concepts of an aulacogen and a major strike-slip fault, now merely of a historical importance. In spite of the new data the principal dilemma remains the same until present. Some investigators believe that the East European Craton (Baltica) extends far to the south-west reaching the Elbe-Odra Line, others assume the presence of the Caledonian deformations in Rügen and Pomerania which are regarded — according to modern concepts — as a manifestation of terrane tectonics. The latter group of hypotheses is supplemented by the author with the model of proximal terranes detached from the craton margin farther to the south-east and then re-accreted. The hypothesis is based on an analysis of differences in crustal structure in northern Germany and western Poland, and on the concept of a counter-clockwise rotation of Baltica during the Ordovician, proved by palaeomagnetic data.

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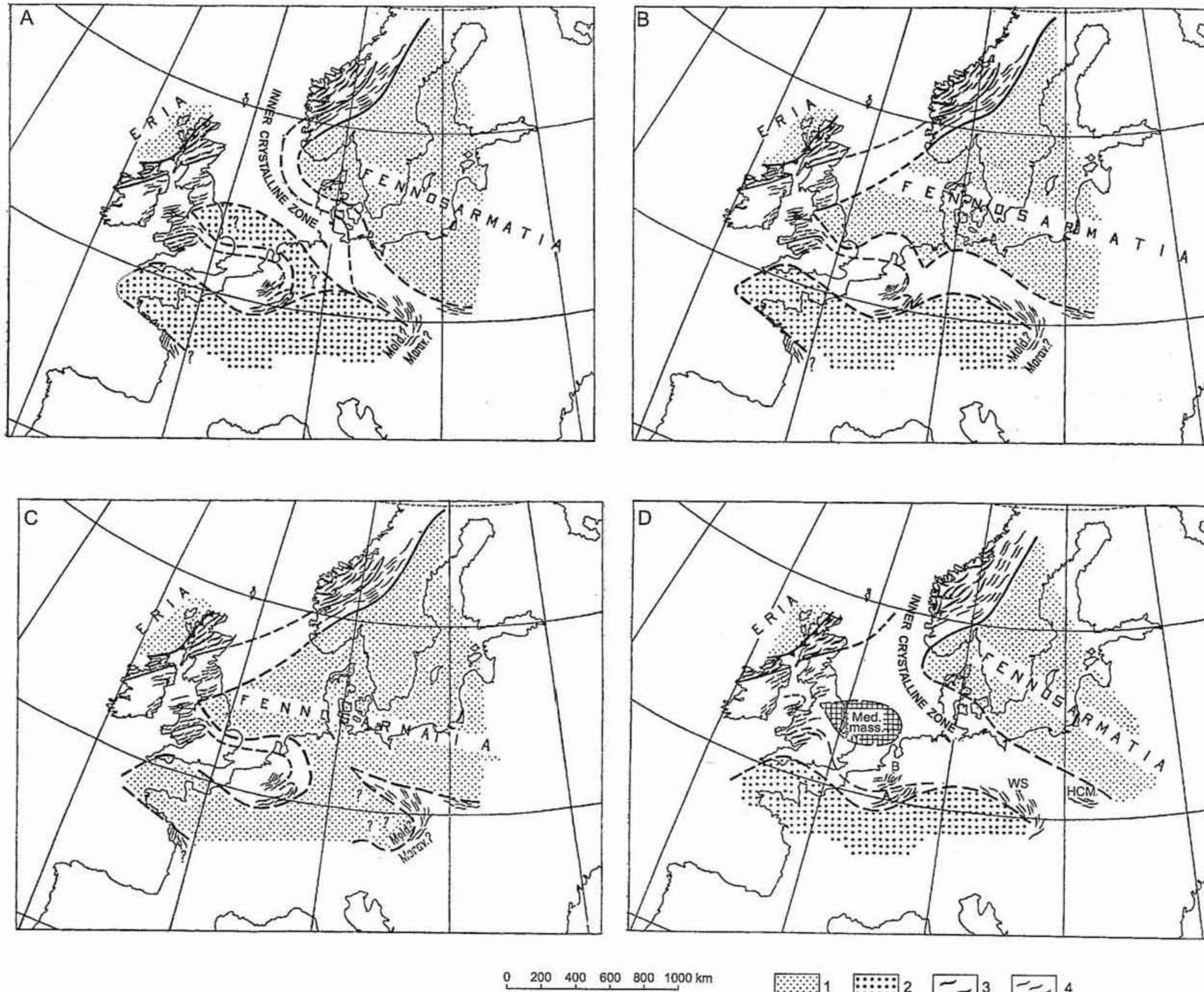
INTRODUCTION

One of the key tectonic problems of the central Europe is the location and development of the southwestern margin of the East European Craton and the existence or non-existence of a Caledonian deformation belt along this boundary. This question was debated since the turn of the centuries, commencing with the papers by Wawrzyniec Teisseyre and Alexander Tornquist, and first contrasting views expressed by Edward Suess and Emil Haug. It became particularly hot, however, during the second half of the century with the appearance of new facts obtained from geophysical investigations and deep boreholes.

Ten years ago, political changes in the central Europe facilitated a considerable increase of scientific contacts between geological communities of central and western Europe. This promoted an increasing interest devoted by Western European investigators to the geological problems of the areas east of Elbe river, and thus to an intensification of a research and multiplication of interpretational concepts. In view of the "round anniversary" and at the turn coming next of the centuries it appears pertinent to remind — most of all to the younger generation of scientists — how the early discussions developed and how interpretations changed. It is the more so important that Polish papers, although commonly including English summaries, were often neglected by some Western scientists. It is worth considering that many present concepts have their roots in the more distant past, that not everything started ten years ago, and that many early ideas and controversies are still alive. It is also timely to summarize the state of our knowledge and to outline possible interpretations, even if they are still divergent. The subject of the present paper is the central, Pomeranian part of the East European Craton margin, with some necessary references to neighbouring areas, mainly Rügen and the adjoining Baltic off-shore.

PREVIOUS STUDIES: 1950–1990

Discovery of a line dividing Europe into a stable eastern and more mobile western part, by Wawrzyniec Teisseyre and


A
B
C
D
ERIA
FENNOSARMATIA
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Mold.?
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1
2
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4

Alexander Tornquist at the turn of 19th and 20th centuries, was of fundamental importance for the question considered here. This line defined the southwestern boundary of the East European Platform (= Craton). It is not surprising that later this line was named after these two investigators. This notion persisted until present with its initial form "Tornquist Line" or "Tornquist Zone" (TZ) subsequently modified to "Teisseyre-Tornquist Zone" (in short T-T Zone)[1] and, lastly, divided into two segments: northwestern (Sorgenfrei-Tornquist Zone) and southeastern one (Teisseyre-Tornquist Zone).

First geotectonic reconstructions after 1950 referred to the earlier mentioned debates on a location of the Precambrian Platform boundary. They were based on regional gravity and magnetic measurements, supported by a general knowledge about a structure of younger members of sedimentary cover. These reconstructions aimed at connecting very distant exposures of Caledonian age deformations including the main belt of the Scandinavian-British Caledonides on one hand and smaller regions in Brabant-Ardennes area and in the Holy Cross Mts., on the other hand. These connections were best presented by von Gaertner (1950, 1960) who considered essentially two possibilities. The first one (Fig. 1A) assumed that the platform boundary runs along the Tornquist line, with an adjoining belt of the Caledonian folding (so-called Circum-Fennosarmatian Caledonides) linked in the substrate of the North Sea with the Norwegian Caledonides (Stille, 1950, 1951). The second possibility (Fig. 1B) assumed that the East European Craton (EEC) extends across Denmark and northern Germany to the Netherlands and central England (Szatskij, 1946; Bogdanov, 1964, 1968; Szatskij and Bogdanov, 1961). This interpretation included the assumption that the so-called East Elbe Massif existed in the basement of the North German Lowlands (later on variously labelled: North German or Netherlands North German Massif, Lüneburg Massif). This massif was thought to be characterised by a shallow Precambrian basement, as deduced from strong gravity and magnetic anomalies. Presently, one does not attribute much importance to these anomalies, as they may be explained by magmatic bodies within Upper Palaeozoic strata (*cf.* Ziegler, 1990). However, some authors still believe that this area is an intramontane massif (Hoffmann, 1990) or a separate terrane (Brause *et al.*, 1994).

The first interpretation (Fig. 1A) assumed a direct link between the Holy Cross Mts. and Norwegian Caledonides, and a separate position of the Ardennes Caledonides. In the second interpretation (Fig. 1B) it was assumed that the Ardennes Caledonides are linked with the Holy Cross Mts. To the two above interpretations von Gaertner added a third one showing no connection between the Ardennes and the Holy Cross Mts. (Fig. 1C) and a fourth one (von Gaertner, 1960, second variant — see Fig. 1D), that is closest to some recent opinions, which assumed direct links between all the three branches, with the London Massif forming a median massif.

Watson (1977), Kvale (1977), Khain (1977) and Sturt *et al.* (1980) also suggested that EEC extended as far as central England.

In Poland, during this first stage of investigations several variants of the location of the T-T Zone were proposed (Pawłowski, 1947; Dąbrowski, 1957; Skorupa, 1959; see Fig. 2). Initial reconstructions by Polish (Sokołowski and Znosko, 1959, 1960) and German scientists (Kölbel, 1959) favoured a large extension of the EEC towards the west. Soon, however, the same investigators changed their opinions, after taking into account the results of boreholes in Rügen. Kölbel (1963) extended the belt of Caledonian deformations to the NW, terminating it in a dead-end fashion in Rügen area. On the other hand, Znosko (1962) referring to the concept of the Circum-Fennosarmatian, Caledonian Belt, developed and improved this concept in several papers (Znosko, 1963, 1964*a, b*, 1965, 1966, 1974, 1979, 1986). At first, he linked the Rügen and Pomeranian Caledonides directly with the Norwegian Caledonides through the northern Jutland.

First important corrections were introduced to these models due to the results of boreholes in the Danish area (Sorgenfrei and Buch, 1964; Sorgenfrei, 1966). It appeared that in the substrate of southern Jutland the Mesozoic is underlain by Precambrian rocks. They bound from the south the Danish Basin where weakly deformed Lower Palaeozoic deposits in epicratonic development occur. The described basement elevation was later referred to as the Ringköbing-Fyn High (RFH). Now it became impossible to trace the presumed Caledonian belt directly across northern Jutland towards southern Norway. Instead, it had to follow the roundabout way to the south of the RFH.

It was only in the early sixties — when first deep boreholes were drilled in the northern Rügen area (Fig. 3) — that it became evident that intensely deformed Ordovician sediments are unconformably overlain by Triassic sediments. Initially, deformation of these Ordovician rocks was regarded as "germanotype" and of Variscan age (Franke, 1967*a, b*; Jaeger, 1967; Albrecht, 1967). Slightly later, apparently under the influence of Soviet advisors, some German geologists interpreted the Rügen Zone as forming part of a Caledonian fold belt (Busch *et al.*, 1974; Glushko *et al.*, 1974, 1976).

Almost at the same time the first deep boreholes were drilled in Poland, both at the margin of the Precambrian Platform (Lębork — Dadlez, 1967*b*), as well as in the Koszalin–

[1] This proposal referred to the priority of Teisseyre (Znosko, 1971) whose paper, however, was published in Polish only and therefore was less accessible (*cf.* Norling, 1981).

Fig. 1. Relations between Caledonian foldings after von Gaertner: **A** — 1950, first variant, **B** — 1950, second variant, **C** — 1950, third variant, **D** — 1960, second variant

1 — Foreland, 2 — Hinterland, 3 — Early Caledonian folds, 4 — Late Caledonian folds; B — Brabant Massif, HCM — Holy Cross Mountains, Med. mass. — Median massif, Mold. — Moldanubian, Morav. — Moravian, WS — Western Sudetes

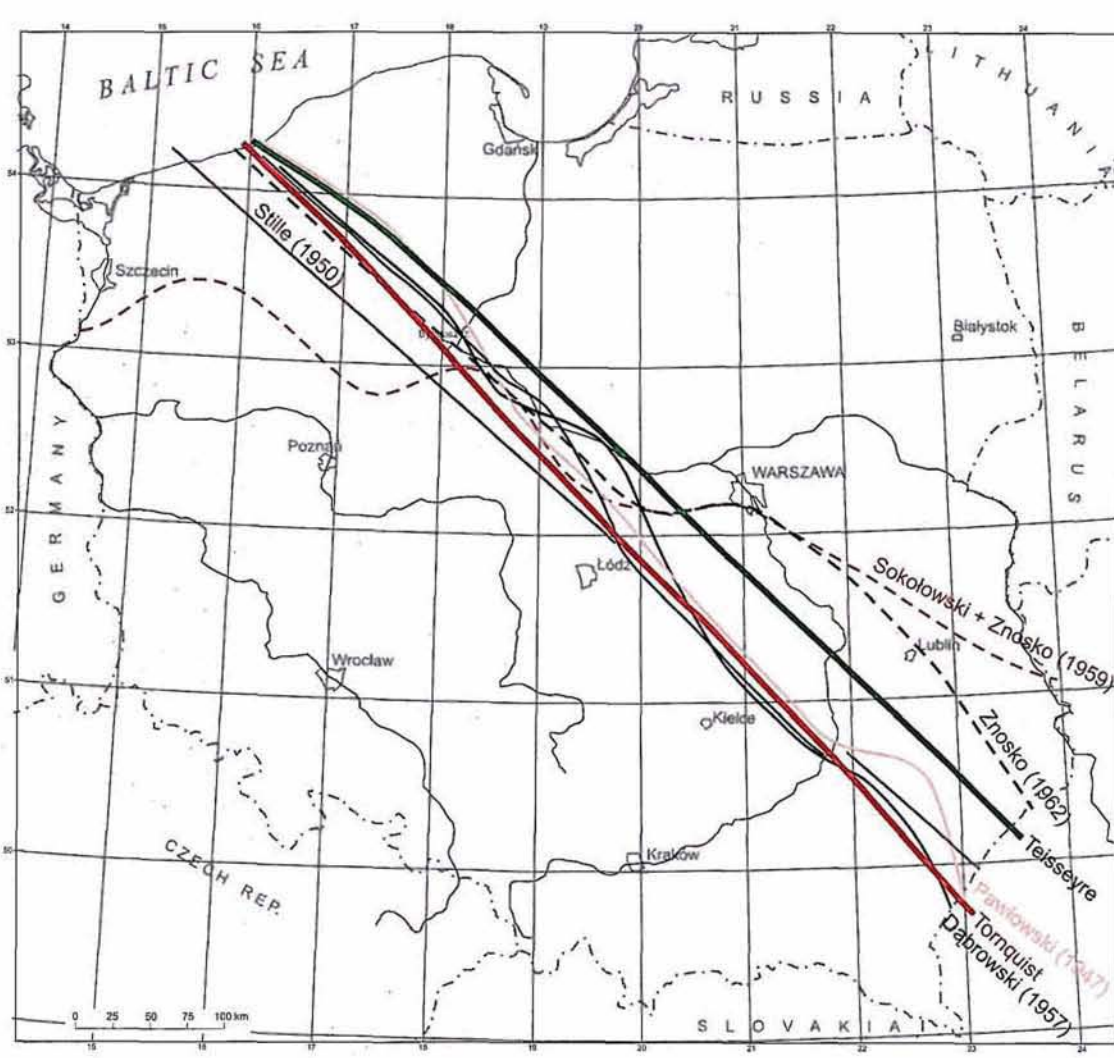


Fig. 2. Teisseyre-Tornquist Zone according to the early concepts

Chojnice Zone (Dadlez, 1967*a*, *b*)[2]. The former found flat-lying Lower Palaeozoic, including the Silurian with mudstone intercalations deposited from turbidity currents and interpreted as a distal flysch sourced from the south and west (Jaworowski, 1966, 1971). The wells in the Koszalin–Chojnice Zone encountered as a rule thick, strongly deformed Ordovician and Silurian series separated from the overlying Devonian or Zechstein deposits by a distinct angular unconformity. These observations revealed a substantial contrast between both the areas reflecting a consistent relationship between a fold-belt and its foreland.

Seismic refraction studies conducted in the seventies (Młynarski, 1982) revealed a distinct horizon with velocities exceeding 6 km/s, related to the top of the consolidated Precambrian basement, that was inclined to SW and reached depths on the order of 7 to 8 kilometers near the Koszalin–Chojnice Zone. To the SW of this zone, refractive horizons are less distinct, disrupted and display velocities lower than 6 km/s.

In Rügen investigations were soon supplemented by deeper boreholes though their results were not published, as they were classified as "top secret". It was only after re-unification of Germany when results of these wells became accessible (i.a. Franke, 1990; McCann, 1996*b*).

Drilling projects in Poland, in the Koszalin–Chojnice Zone, were considerably accelerated during the sixties and seventies. General compilations of well results were published by Dadlez (1974, 1978), providing strong evidence for Caledonian deformations (Znosko, 1962, 1965; Dadlez, 1967*a*, 1974; Teller and Korejwo, 1968; Modliński, 1968). Initially also Pożaryski (1964) joined the above listed authors. The Pomeranian folded Caledonides were then regarded — according to the theory of

[2]This is the zone of tectonically disturbed Mesozoic, distinctly contrasting with the area of weak deformations adjoining from the north-east. *Ca.* 20 km to the NE of this zone the Caledonian Deformation Front is assumed basing on the borehole data (Fig. 3).

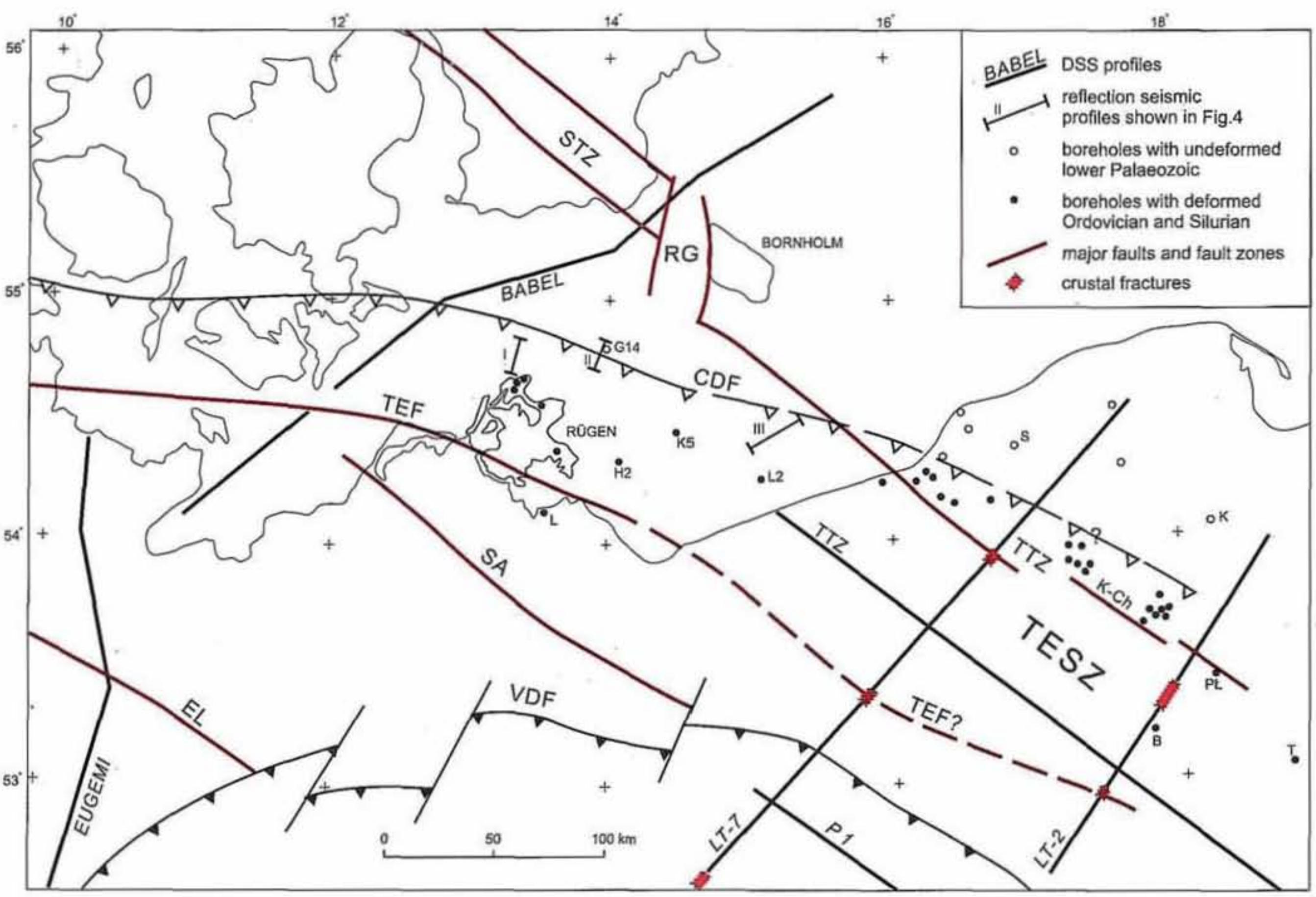


Fig. 3. Locality map with major tectonic features (after various sources)

CDF — Caledonian Deformation Front, EL — Elbe Line, K–Ch — Koszalin–Chojnice Zone, RG — Rönne Graben, SA — Stralsund-Anklam Fault, STZ — Sorgenfrei-Tornquist Zone, TEF — Trans-European Fault, TESZ — Trans-European Suture Zone, TTZ — Teisseyre-Tornquist Zone, VDF — Variscan Deformation Front; key boreholes: B — Bydgoszcz IG 1, K — Kościerzyna IG 1, L — Loissin, T — Toruń IG 1, PŁ — Polskie Łąki IG 1, S — Słupsk IG 1

geosynclines — as a belt of externides that developed from a miogeosyncline. A Caledonian eugeosyncline and a belt of internides was expected farther to the south, i.a. in the Sudetes. At one time it was assumed that the Caledonian belt bifurcated in the Holy Cross Mts. area with one branch extending to the NW, to Pomerania and the other — to the west, to the Sudetes (Znosko, 1964*a*, *b*). This view was shared by Krebs (1978) who was the first to coin the name "North German-Polish Caledonides".

The hypotheses assuming the existence of the Circum-Fennosarmatian branch of Caledonides were opposed for a long time by more stabilistic approaches despite the well-known strong tectonic deformations in Pomerania and Rügen. Worth mentioning is here the view that the East European Platform was rimmed to the south-west by a so-called pericratonic depression (Bogdanov, 1964, 1968). Also Pożaryski (1968) began to share this opinion slightly later, maintaining that the pericratonic depression was "paratectonically" deformed during the Early Palaeozoic. Later on, the same author (Pożaryski and Kotański, 1978) put forward a hypothesis of two Caledonian aulacogens existing in the Early Palaeozoic: Rügen–Piła and Koszalin–Chojnice, with a mantle plume located at the point of their convergence, i.e. precisely under Rügen. Similar view was adopted for a long time by German geologists (e.g. Franke, 1977; Franke *et al.*, 1989*a*, *b*) who discerned in this zone either the "Danish-Polish marginal platform trough" (Danisch-Polnische Tafelrandsenke = pericratonic depression) or the "Tornquist aulacogen". Apart from the lack of evidence of a mantle plume, the aulacogen concept raised objections, as aulacogens are by definition intra-cratonic features whereas the discussed structure is located at the cratonic margin.

Approximately at the same time, it was proposed that an "orogenic" triple junction occurred in the substrate of the North Sea (Zwart and Dornsiepen, 1978; Strömberg, 1981), the two main branches of which correspond to the Iapetus suture that is associated with the main Caledonian belt whereas the third branch that was not fully developed (failed arm?) followed the Tornquist Line. At this time the model of the mutual interplay of three continental plates, Laurentia, Baltica and Gondwana, has developed and later supplemented by the concept that microcontinents were detached from Gondwana and accreted to the northern continents.

Very important for further improvements of geotectonic models were the results of boreholes drilled in central and southeastern part of the North Sea and near the Danish-German state boundary. They revealed beneath Mesozoic or Upper Palaeozoic strata (including the Lower Devonian) the occurrence of rocks with various grade of metamorphism, from phyllites to crystalline schists and gneisses, that yielded isotopic ages — investigated using Ar/Ar and K/Ar methods — ranging between 400 and 450 Ma (Frost *et al.*, 1981; Ziegler, 1981, 1982). These occurrences confirmed the direct connection of the Norwegian Caledonides with the Rügen-Pomeranian ones along the southern flank of the Ringköbing-Fyn High.

Until the eighties, tectonic models for the area were analysed in terms of the geosynclinal theory. Plate tectonic concepts were applied with a considerable delay but when they appeared it was an extreme approach from the beginning. Brochwicz-Lewiński *et al.* (1981*a, b*) claimed that from the Early Ordovician to Early Devonian a great transcontinental sinistral strike-slip fault produced a total displacement on the order of 1500–2000 km along the margins of the Laurentia and Baltica plates. This fault was supposed to be responsible for detaching the southwestern corner of Baltica resulting in the above estimated separation of formerly linked Proterozoic elements of Sweden and Dobrogea. This concept was criticised by Znosko (1982) from the regional geology viewpoint, by Dadlez (1983) with emphasis on general plate kinematics and by Bergström (1984) with regard to palaeobiogeographical arguments.

Pegrum (1984*a, b*) assumed a late Caledonian sinistral transform fault with a displacement of *ca.* 500 km which transected the Iapetus Ocean separating two branches of the main Caledonian belt with an opposite vergence, namely: the Irish-Scottish and Norwegian Caledonides. This fault was supposed to continue to the south-east controlling deformations in the Rügen-Pomerania segment. This concept, based i.a. on a comparison of the Precambrian basements of the Ringköbing-Fyn High and northeastern Poland, i.e. two completely different units, does not seem to be substantiated.

Slightly earlier, Ziegler (1978, 1982, 1984) presented the first plate tectonic model for the area under discussion, proposing the concept of two continental plates, Laurentia and Baltica, and two oceanic plates, Iapetus and Prototethys. The last mentioned plate incorporated microcontinents detached from Gondwana, that drifted to the north and successively converged and collided with Laurentia and Baltica. This author maintained in principle his concept in the following papers (Ziegler, 1989, 1990), in addition conceiving the North German-Polish Caledonides as a symmetric orogen, thrusted both to the north onto Baltica as well as to the south. In the hinterland of the Pomeranian externides, the internides were thought to occur, deeply buried beneath the axial part of the North German Mesozoic basin.

Berthelsen (1984) traced the origin of the Caledonian deformation belt back to a much older, Late Proterozoic transform fault, active along the southern margin of the Laurentia-Baltica plate. The margin was converted in the latest Proterozoic and Early Palaeozoic into a passive margin whose sedimentary cover was subsequently folded and thrusted onto the Baltica margin due to dextral transpressional accretion of a Cadomian continent. This concept was later expanded in successive papers (Berthelsen, 1992*a, b*) by defining the so-called fold-and-thrust belt. The same author put forward a hypothesis of an indentation of the cratonic crust between the underlying Avalonian crust and overlying fold-and-thrust belt in the collisional zone (*cf.* BABEL..., 1993). The model of a fold-and-thrust belt was also later adopted by Dadlez *et al.* (1994), who questioned, however, the criteria defining the Pomerania Terrane (see below).

During the eighties there was an increasing agreement in the Western Europe as to the concept of an Avalonia microcontinent that was detached from Gondwana during the Ordovician and accreted to the northern continents during the Silurian. It comprised the peri-Atlantic tectonic units of the Appalachians from Maine to Newfoundland, while in Europe — southern England, Ardennes and Brabant Massif. Subsequently, the concept was expanded farther to the east while at the same time Avalonia was arbitrarily divided into Western (American) and Eastern one (European). Between the latter and the Baltica plate there was the Tornquist Ocean or Sea (Cocks and Fortey, 1982). Its closure led to a development of the North German-Polish Caledonides. It is worth stressing that the concept of the East Avalonia is very close to the earlier concept of the intramontane London Massif.

As evident from the above, the concept of a mobile Caledonian deformation belt occurring in Pomerania and Rügen was debated in Poland since 1962. It was repeatedly modified, it used to be questioned, but finally, nearly thirty years later, in the decade of 1980–1990, it gained a wide support.

RECENT VIEWS: SINCE 1990 TO PRESENT

At the turn of the eighties and nineties in geotectonic interpretations of the discussed area the concept of tectonostratigraphic terranes appeared with reference to the Avalonia terrane. Strangely enough, the pioneers in this field were the former ardent opponents of mobilistic models. In view of limited subsurface control there was a relatively free-choice approach to defining terranes. Thus, e.g. Pożaryski (1990, 1991; Pożaryski *et al.*, 1992) distinguished in the Polish territory the following terranes: Pomeranian, Łysogóry, Małopolska Massif and Upper Silesian, whereas Franke (1993, 1994) added to those, in the area from the North Sea to the Holy Cross Mts., the Southern North Sea, Southern Jylland, Radom–Kraśnik, Cracovides, and — moreover — closer undefined Sudety and Cadomian-Caledonian terranes in the substrate of the Polish-German Lowlands. Dadlez *et al.* (1994) questioned the criteria defining the Pomerania Terrane and the terrane character of the Łysogóry Region, at the same time assuming that the Małopolska "Massif" may be a proximal terrane detached from the EEC margin farther to the south-east and subsequently re-accreted. Recently, Aleksandrowski (1998), using the Sudety area as a starting point, distinguished in western Poland the Neoproterozoic Wielkopolska Terrane and Caledonian

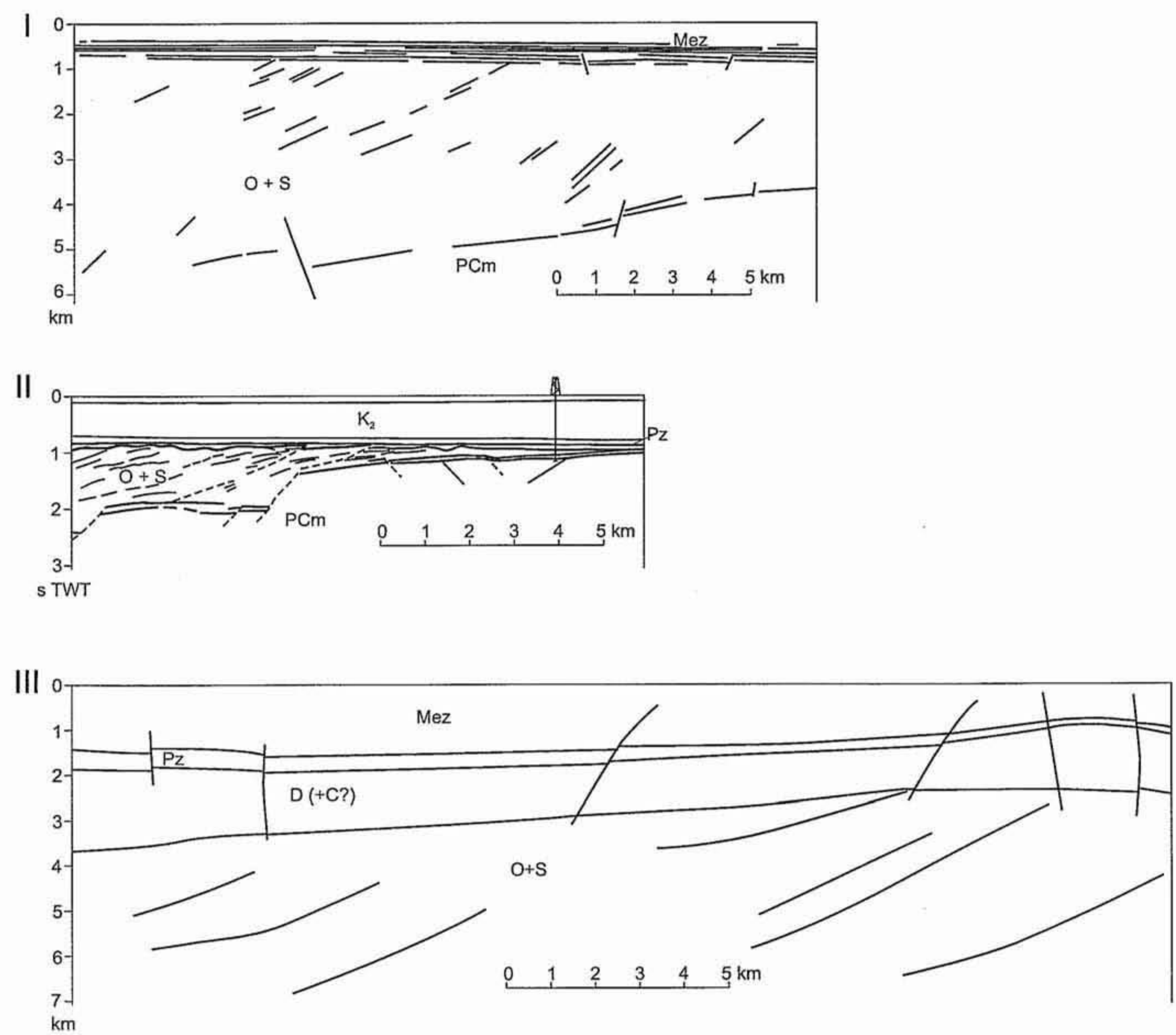


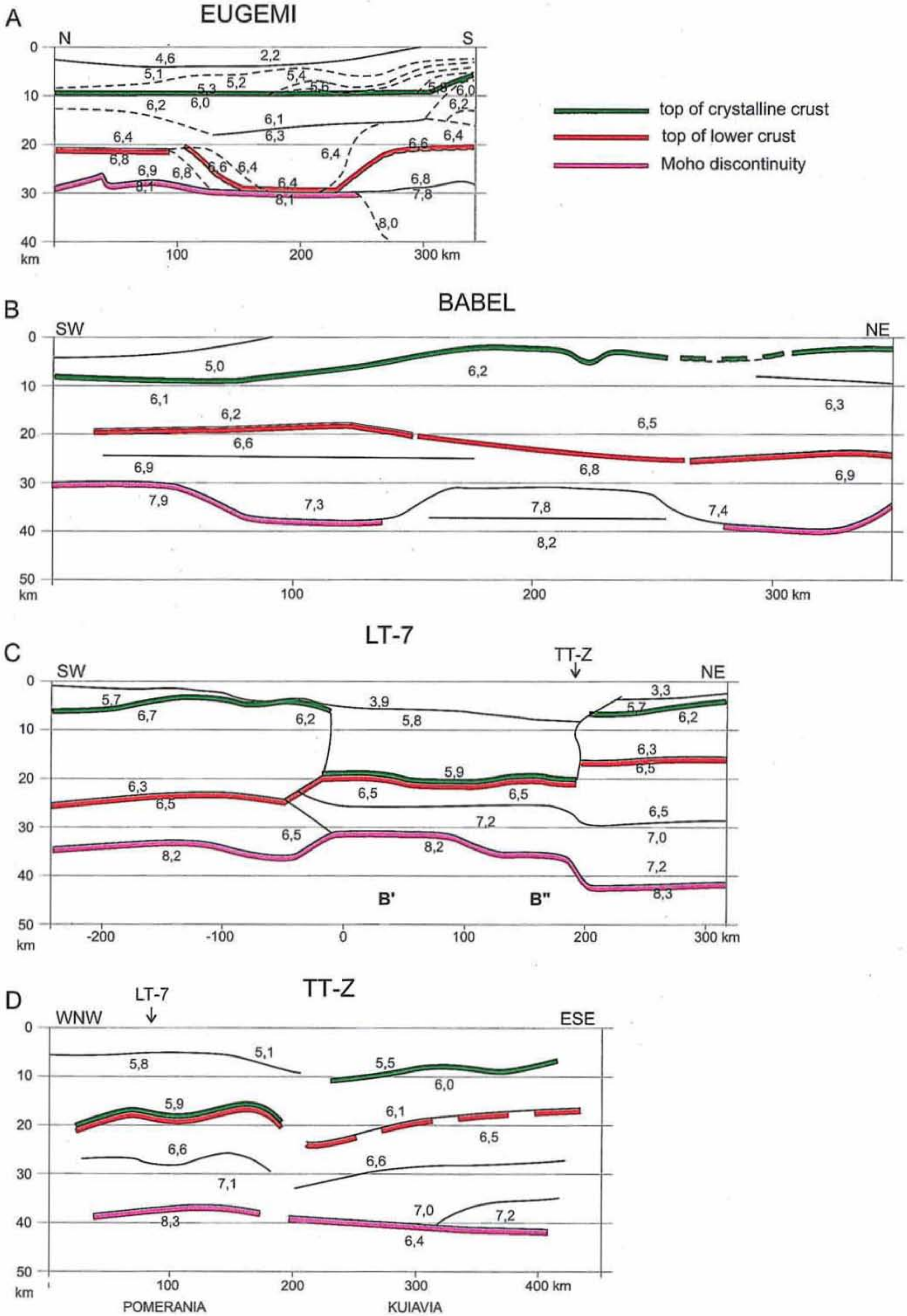
Fig. 4. Reflection seismic profiles north and east of Rügen; for location see Fig. 3

I — German sector of the Baltic Sea north of Rügen after Piske *et al.* (1994); II — German sector north-east of Rügen after Schlüter *et al.* (1997); III — Polish sector; K_2 — Upper Cretaceous, Mez — Mesozoic, Pz — Zechstein, D — Devonian, C — Carboniferous, O+S — Ordovician and Silurian, PCm — Precambrian

Pomerania Terrane, without explaining, however, the criteria underlaying such a subdivision. Lastly, Unrug *et al.* (1999) developed a concept of terranes in southern Poland accepting i.a. that the Małopolska Terrane represents a fragment of East Avalonia, deformed in the Caledonian times due to a sinistral transpression. The Łysogóry Terrane is supposed to had been deformed as late as in the Variscan times.

Seismic reflection profiles in the Baltic off-shore area, both in the German (Piske *et al.*, 1994; Schlüter *et al.*, 1997) and Polish sectors, revealed a zone of southward inclined reflections (Figs. 3 and 4); these are regarded as being related to Lower Palaeozoic series that were thrusted upon the epicratonic cover. Below, the top of the crystalline basement is recorded. A minimum extent of the thrust can be estimated at several tens of kilometres. These observations confirmed the concept developed by Znosko (1969) thirty years ago. The lateral continuation of this thrust zone can be found to the west of Jutland (MONA LISA..., 1997).

Investigations of a deep crustal structure (DSS — deep seismic sounding) have been carried on in Poland since the sixties though their synthetic results were published only much later (Guterch *et al.*, 1986). Methodology of the early investigations was relatively poor and did not allow to gain insight into e.g. the internal distribution of seismic velocities in the crust. The


A
EUGEMI
N
S
top of crystalline crust
top of lower crust
Moho discontinuity
B
BABEL
SW
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C
LT-7
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B'
B"
D
TT-Z
WNW
LT-7
ESE
POMERANIA
KUIAVIA
km

first profile, applying modern methods, yielding a complete set of data on a velocity pattern (LT-7 — Fig. 5C) was shot in the early nineties (Guterch *et al.*, 1994; Dadlez, 1997). Slightly earlier, similar profiling was conducted in the framework of the EUGENO (EUGENO-S..., 1988) and EUGEMI Projects (Aichroth *et al.*, 1992) — forming components of the long EUROPEAN GEOTRAVERSE — as well as along the BABEL Profile (BABEL..., 1993; Thybo *et al.*, 1994) crossing the Baltic Sea between Rügen and Bornholm. All these profiles revealed a relatively simple structure of the Precambrian crust of the East European Craton and a very complex patterns of crustal blocks with different velocities distribution and boundaries of crustal layers in the Phanerozoic Europe (see below). With the beginning of the international research programme EUROPROBE the name TESZ (Trans-European Suture Zone) was coined for this zone, the name suggesting that we are dealing with a collisional suture[3].

Meissner *et al.* (1994) used the results of deep reflection seismics, mainly of the DEKORP Programme, in order to define the features of the crystalline crust, the differences between its particular blocks and the boundaries of the Avalonia microcontinent. Unfortunately, the results of reflection profiles in eastern Germany and western Poland (Horst *et al.*, 1994; DEKORP-BASIN..., 1999; Młynarski *et al.*, 2000) are ambiguous and thus inconclusive. In turn, Królikowski and Petecki (1997) performed gravity modelling in Pomerania, detailing the relationships between anomalies and crustal thicknesses and postulating the presence of basic intrusives in the upper crust. Preliminary results of most recent DSS profiles of POLONAISE Program were published in 1999 (Grad *et al.*, 1999; Jensen *et al.*, 1999; Środa *et al.*, 1999).

As stated above, results of boreholes that encountered highly deformed Lower Palaeozoic deposits were summarized by Dadlez (1978). This summary needs to be supplemented (Fig. 3) with the wells Bydgoszcz IG 1, Toruń 1 and Polskie Łąki IG 1, and with boreholes from the Baltic Sea off-shore area, both in the Polish (Dadlez, 1995, pl. IX) and German sectors (Rempel, 1992). The Bydgoszcz IG 1 borehole encountered below the Middle Devonian steeply inclined (30–75°) shales of probably the Late Silurian age. The Toruń 1 well encountered a thick series of deformed Silurian and Ordovician below the Zechstein. Dating of the deformation age of this section was subject to different interpretations (Dadlez, 1982; Pożaryski *et al.*, 1992). The Polskie Łąki IG 1 well encountered below the Middle Devonian the Caradoc sediments dipping 35–40°. Off-shore wells L2 and H2 encountered — again below the Devonian — the Ordovician shales with variable dips (10–60°), and the K5 well revealed shales of the same age and with similar variable dips (35–90°), that are most probably in faulted contact with the Upper Carboniferous strata. It is also necessary to correct the results of the Gościno IG 1 well (Czermiński, 1967; Dadlez, 1967*a, b*) that did not bottomed in metamorphosed Lower Palaeozoic sediments but in strongly lithified Devonian deposits (see also Pożaryski, 1975, p. 84).

In summary, between Rügen and Toruń more than 30 boreholes have penetrated tectonically deformed Ordovician and Silurian rocks that are discordantly covered by the Devonian or Zechstein deposits. The width of the deformed zone is at least 30 km in an off-shore area, and probably not less than 60 km at the 18° meridian.

The old Rügen boreholes and the nearby Loissin well (Fig. 3) were re-investigated during recent years with modern methodology, both with respect to their biostratigraphy (Servais, 1994), provenance of detrital material (Giese *et al.*, 1994) and characteristics of tectonic deformations (Katzung *et al.*, 1993; Franke and Illers, 1994). In addition to proving the compressional style of deformations (reversed strata, presence of several overthrusted slices) and finding initial cleavage and anchimetamorphism in lower structural horizons, also partial transport of sediments from Avalonian directions and their volcanic arc provenance were evidenced. The described acritarchs also confirm an Avalonian provenance. The interpretation of the above facts is compatible with a deformation of the Rügen Ordovician in conjunction with collision of East Avalonia with Baltica.

In the foreland of the deformed Caledonian belt in Poland also new boreholes were added (e.g. Słupsk IG 1 and Kościerzyna IG 1 — Fig. 3), whereas in the Baltic Sea — G14 well was drilled (Franke *et al.*, 1994; McCann, 1996*a*). The most important result of these wells is the observation that turbidite intercalations appear earliest close to the deformed belt, and later at more distant localities (see also Jaworowski, 2000). This Wenlock-Ludlow progradation clearly evidences the location of the source area to the south-west and its progressive uplift facilitating continued sediment supply. These siliciclastic sequences were deposited as distal flysch fans in a deeper water flexural foreland basin.

Of great importance are also the developing palaeobiogeographic and palaeomagnetic studies. First of all, they outlined quite precisely the boundaries of Avalonia and enabled a reconstruction of the break-up of the Late Proterozoic Rodinia megacontinent, as well as an Early Palaeozoic drift of Avalonia and Baltica and mutual relationships between them (Cocks and Fortey, 1982; Torsvik and Trench, 1991; Torsvik *et al.*, 1991, 1992, 1996; Trench and Torsvik, 1992; Lewandowski, 1997, 1998; MacNiocall *et al.*, 1997). There is a tendency to extend Avalonia also across the Polish territory, although the eastern terrane boundary is debatable. E.g. Cocks *et al.* (1997) question the large extent of Avalonia, reaching as far as Rügen, and conclude that its northeastern boundary follows the Elbe Line. Palaeomagnetic research in Poland (Lewandowski, 1987, 1993, 1994; Nawrocki, 1993) could not directly contribute to solving

[3]The TESZ is commonly erroneously identified with the T-T Zone. The former is a crustal block (or rather assemblage of blocks) up to 100 km wide, whereas the latter, according to the traditional historical definition, is a linear fault zone bounding the TESZ from the north-east (see also Dadlez, 1993).

Fig. 5. DSS profiles: A — EUGEMI Profile after Aichroth *et al.* (1992), B — BABEL Profile after Thybo *et al.* (1994), C — LT-7 profile after Guterch *et al.* (1994), D — TTZ profile after Grad *et al.* (1999); for location see Fig. 3

6,1 — seismic velocities (V_p) in km/s

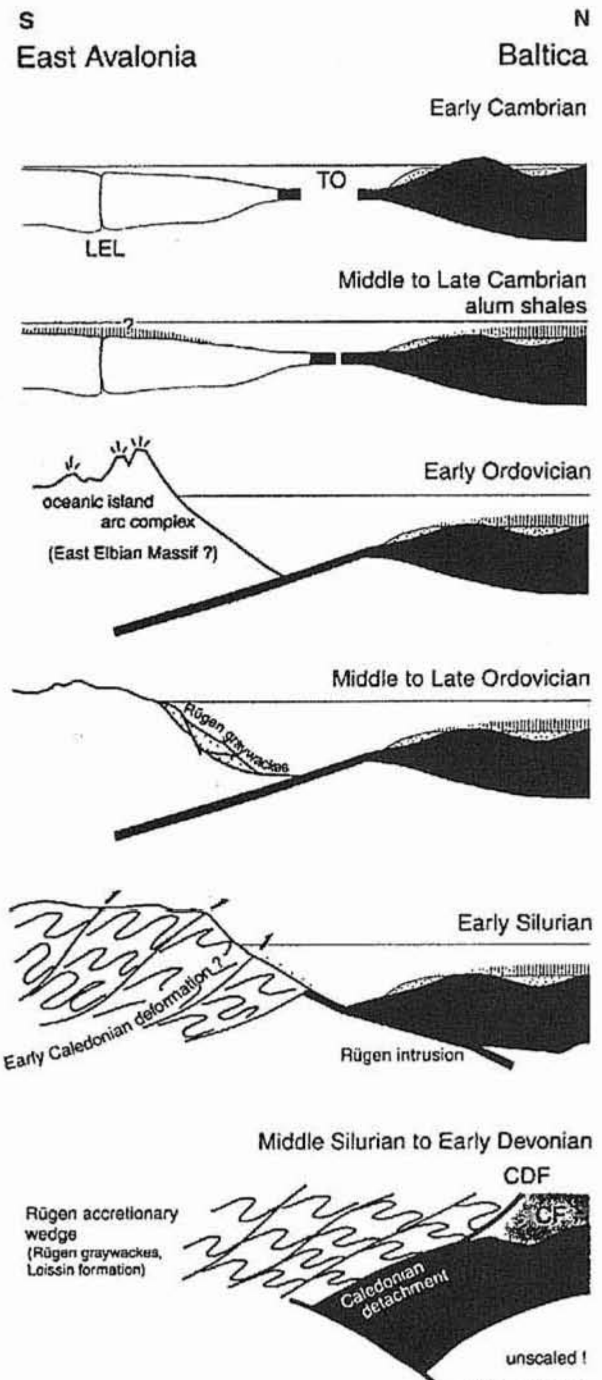

Fig. 6. Subduction in the Tornquist Ocean after Hoffmann and Franke (1997) and Hoffmann *et al.* (1998)

ABS — Avalonia-Baltica Suture; CDF — Caledonian Deformation Front; CF — Caledonian Foredeep, LEL — Lower Elbe Line; TEF — Trans-European Fault; TO — Tornquist Ocean

problems discussed as they were conducted in outcrop areas of southern Poland; however, they allowed for indirect conclusions.

Revived were also the older concepts that postulate that the Caledonian internides are exposed in the Sudetes. Oliver *et al.* (1993) and Johnston *et al.* (1994) propose that the Tornquist Ocean suture is located in the Sudetes along the Intra-Sudetic Fault.

Recently, Tanner and Meissner (1996) presented two models. The first one locates the Tornquist Ocean suture near the Caledonian Deformation Front in Pomerania, thus in line with prevailing opinions. The second model assumes that it is located much farther to SW, as far as the Elbe Line. A similar extreme position is taken by Berthelsen (1998) who precludes the existence of the Caledonian deformation belt east of Odra river. He claims that in Poland the suture between Baltica and Avalonia is deeply concealed beneath Variscan thrusts and that the TESZ (erroneously named TTZ by him — see the footnote 3) is in fact an intraplate pseudosuture resulting from a Variscan reworking of cratonic crust. It is worth pointing out that the above interpretation is, as a matter of fact, a return to the concept of a pericratonic depression. With regard to this, the following question remains: according to the above concept a modified Baltica crust is covered by a "deformed foredeep fill" of considerable width (more than 200 km). Do analogies of such a case exist in the foreland of any other orogen?

An opposite view is presented by Cymerman (1998), based on investigations of the Góry Sowie Massif in the Sudetes, that is regarded by him as the only Caledonian relic in this region. He assumes that the massif represents part of the Caledonian volcanic arc which rimmed Baltica during the Early Palaeozoic, then collided with Avalonia and subsequently was incorporated into the Sudetic orogen during Variscan obduction processes, together with a fragment of the Tornquist oceanic crust. From the above concept it follows univocally that there existed Avalonia to the north of the Sudetes.

DISCUSSION

1. It is obvious that the information on the tectonic position of the Lower Palaeozoic in the substrate of the German-Polish Lowlands can only be provided by boreholes. Geophysical studies alone, most of all seismic ones, can give only indirect indications. So far, wells that encountered strongly deformed Lower Palaeozoic series are located along a belt between Rügen and Toruń, that is 400 km long and on average merely 20–30 km wide (Fig. 3). Outcrops of the folded Lower Palaeozoic in the Holy Cross Mts. are located in the prolongation of this belt to the south-east, at a distance of *ca.* 250 km. To the south-west of this belt the top of the Lower Palaeozoic is down-faulted and located at depths that will remain inaccessible for boreholes for a long time. In this area, that covers *ca.* 40 000 km^2 of the Polish territory, resolution of reflection seismic data usually does not reach beneath the Zechstein due to the screening effect of salt deposits. Pioneering profiles with an extended recording time gave very poor results, and moreover exclusively from the lower crust, both in the German Basin (Horst *et al.*, 1994) and in the Polish one (Młynarski *et al.*, 2000). The most recent German profile (DEKORP-BASIN..., 1999) is slightly better in that respect but also does not provide full answers to some questions. In particular, there is a lack of univocal data about the location of the top of the upper crystal-

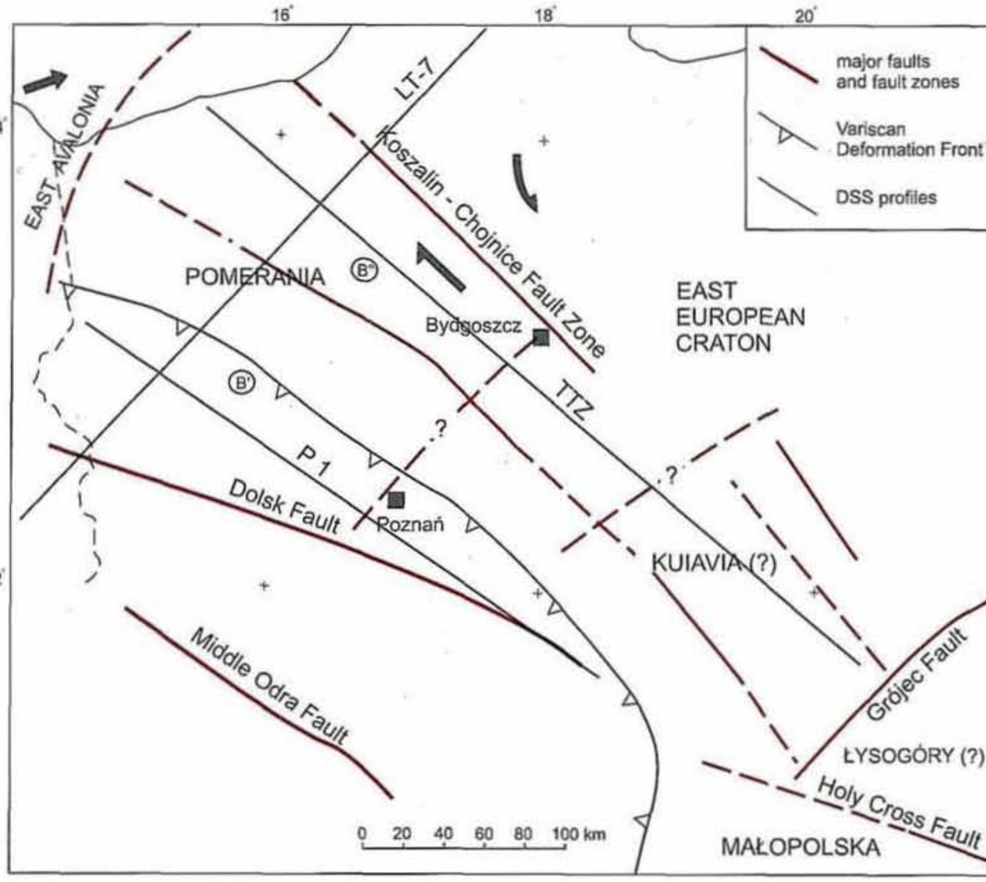

Fig. 7. Approximate locations of supposed proximal terranes: Pomerania and (?)Kuiavia

line crust and Palaeozoic sequences between it and the bottom of the Zechstein. This gap is thus filled with merely single DSS profiles and older refraction survey, the latter being difficult to interpret and correlate.

2. The DSS profiles, although located far away from each other, reveal, however, substantial differences in thickness and vertical velocity distribution in the crystalline crust directly to the south of the East European Craton margin (Fig. 5). Thus, in the German EUGEMI Profile (Aichroth *et al.*, 1992) north of the Elbe Line the crystalline crust is less than 30 km thick and can be divided into an upper layer (down to a depth *ca.* 20 km) with velocity V_p = 6.0–6.4 km/s, and a lower layer — 6.8–6.9 km/s (Fig. 5A). In the same profile farther to the south, under the depocenter of the North German Basin, the crust thickens (up to 30 km); its lower high velocity layer disappears and upper layer, with velocities of 6.0–6.4 km/s, extends down to the Moho discontinuity (Fig. 5A). At the southern termination of the BABEL A Profile (BABEL..., 1993) the crust is 30 km thick and is composed of two layers. The upper layer extends to the depth 20 km and is characterised by velocities 6.1–6.2 km/s, whilst the lower layer has velocities in the 6.6–6.9 km/s range (Fig. 5B). The crust studied in the LT-7 profile in Poland (Guterch *et al.*, 1994; Dadlez, 1997) distinctly contrasts with these data. In this profile the crust shows three layers (Fig. 5C) with the upper layer (down to 20 km) characterised by exceptionally low velocities 5.8–5.9 km/s. Two other layers, the middle one with velocity *ca.* 6.5 km/s and the lower one with velocity 7.2 km/s display in the block B'' thicknesses about 7 and 10 km, respectively, while the Moho discontinuity was found at a depth of *ca.* 35 km. Farther from the craton (block B') the Moho rises to a depth *ca.* 31 km at the expense of the lower crystalline crust thinning here to *ca.* 5–6 km. Velocity values given above for the middle and lower layers are surprisingly similar to those for respective layers in the neighbouring craton but their thicknesses are much lower.

Of all these data the most significant are: (1) the lack of a high velocity lower crust beneath the axis of the German Basin; (2) occurrence of the upper crustal layer with anomalously low velocities as well as the appearance of lower layers with velocities characteristic for the craton in the Polish territory; (3) overall thickness of the crust beneath the axis of the Polish Trough being larger than below the German Basin.

As may be judged from the results of the most recent TTZ profile (Grad *et al.*, 1999) the layer with anomalously low velocities extends to SE as far as the central part of the country (Fig. 5D — the Pomerania unit). East of the Bydgoszcz (18°)

meridian there is a relatively rapid change of the crustal structure. The low velocity layer disappears, being replaced by the upper layer with velocities 6.0–6.1 km/s and thickness of more than 10 km, rather typical for the cratonic crust. Two other layers with velocities 6.5–6.6 km/s (middle) and 7.0–7.2 km/s (lower) extend farther to SE. Their thickness slightly increases, to 10 and 15 km, respectively, while the Moho discontinuity lowers to *ca.* 40 km and more. A similar change in crustal structure, although not that sharp, occurs in the profile P1 parallel to the above described line, at the Poznań (*ca.* 17°) meridian (Jensen *et al.*, 1999). Thus, in central Poland east of the Poznań–Bydgoszcz line (in the Kuiavia unit) a thickness of the crystalline crust and internal pattern and thicknesses of its layers approach the features of the cratonic crust even more. The latter crust is characterised by the following parameters: the upper layer (V_p = 6.2–6.3 km/s) has a thickness of 6–8 km, the middle one (*ca.* 6.5 km/s) — 13–14 km, and the lower one (7.0–7.2 km/s) — *ca.* 13 km, while the Moho is located at a depth of *ca.* 40 km (Środa *et al.*, 1999).

These observed differences in crustal structure between western and central Poland stress the segmentation of the crust across the TESZ; this was already suggested by the distribution of gravity field gradients and deep crustal fractures (Królikowski *et al.*, 1996).

Interpretation of the upper layer with anomalously low velocities in the Pomeranian unit is of a key importance. Along LT-7 line the base Zechstein is located at depths of the order of 3–4 km, whereas the top of the discussed layer — at 6–8 km. The intervening 3–4 km thick interval corresponds to the presumed total thickness of the Devonian, Carboniferous and Rotliegend series. The layer with velocities 5.8–5.9 km/s probably corresponds to Lower Palaeozoic sediments that have a total thickness of 12 to 13 km. This leads to two possibilities (Dadlez, 1997): either we are dealing with Lower Palaeozoic sediments that were deformed and weakly metamorphosed during the Caledonian orogenic cycle, or with a non-disturbed sequence that was deposited on the passive margin of the craton. However, the considerable thickness of this interval speaks against the latter possibility. Its explanation would require assuming a large thickness gradient relative to the marginal part of the craton near the Koszalin–Chojnice Zone where the Lower Palaeozoic may attain thicknesses 5000 metres at most. In the case of a tectonic pile (accretionary wedge) such thicknesses are easier to explain.

3. Results of reflection seismic studies (Piske *et al.*, 1994; Schlüter *et al.*, 1997) imply a high probability of Caledonian slices being thrust far upon the cratonic foreland north and east of Rügen, including also the Polish Baltic sea sector. Minimum lateral displacement along these thrusts is estimated at 30 km, while maximum values are 80–120 km. The latter values result from the paper by Hoffmann and Franke (1997) who claim — citing electric conductivity data — that the autochthonous cratonic basement may extend south-westwards to the Stralsund-Anklam fault zone (Fig. 3). Farther to SE, in the Polish onshore areas, seismic evidence of thrust sheets is lacking. This may result from a lack of modern seismic profiles in the discussed zone or from a change in the character of tectonic contact: instead of the oblique collision of Avalonia with Baltica a strike-slip accretion may had occurred here.

When considering the problem of the Caledonian Deformation Front (CDF) and the associated flexural foreland basin, the following aspects should be taken into account. First, the Pomeranian Caledonides may not reveal features of a typical orogen in an orographic sense because they were composed mainly of the Ordovician and Silurian shales which — due to their low degree of lithification — were probably quickly eroded. The same reason may had led to a lack of a typical foreland basin with molasse sediments. Moreover, the CDF was probably strongly eroded prior to the Devonian transgression, and thus its present position may have shifted to the south relative to its original position[4].

The problem of thrusts leads to a further question of presumed subduction zone (Fig. 6). In the cross-section transecting Rügen, Hoffmann and Franke (1997) and Hoffmann *et al.* (1998) assumed an earlier (till the Late Ordovician) activity of a subduction zone inclined to the south beneath the Avalonia microplate, and a subsequent subduction with an opposite direction, i.e. beneath Baltica. To support their interpretation they refer i.a. to the pattern of reflecting horizons in the BABEL Profile (BABEL..., 1993) and moreover — in the case of the southerly subduction — to the presence of anorthosite xenoliths in the Lower Rotliegend basalts of the central part of the German Lowlands. However, it should be noted that: (1) the above reflecting horizons can be attributed to the crustal fabric of the Precambrian Baltica, and (2) there is no evidence of the northward subduction related magmatism north of the CDF.

4. Results of palaeomagnetic studies indicate that the Baltica plate was undergoing during the Ordovician to Silurian a counter-clockwise rotation exceeding 90°. In other words, the East European margin trended NE–SW during the Early Ordovician, whereas by the end of Silurian was NW–SE oriented. In tandem with this rotation Baltica was displaced from higher (60°) to lower (30°) latitudes on the southern hemisphere. During the same time Avalonia drifted northwards (towards the equator) while undergoing variable rotation, and finally collided obliquely with Baltica under a left-lateral transpressional regime.

5. The scarcity of geophysical and borehole data for the discussed area opens a vast field for speculations. In view of these limited constraints the present author feels free to contribute to the group of proposed terrane models and to put forward additional working hypothesis assuming accretion of proximal terranes that were detached from the EEC farther to the south-east (present Dobrogea–Black Sea area?) and were subsequently re-accreted (Fig. 7). The proposal refers to the idea put forward earlier with regard to the Małopolska Terrane (Dadlez *et al.*, 1994). The latter is regarded as a proximal terrane because of considerable depositional and palaeobiogeographical similarities with the EEC and, at the same time, different diastrophic evolution. What are the arguments supporting the hypothetical

[4] It is necessary to stress here strongly that it is not justified to identify the CDF with the subsurface fault TEF (e.g. Hoffmann and Franke, 1997; McCann, 1996*b*). CDF represents the front of thrusts and as such is a shallow feature that was modified by erosion, whereas the TEF is a deep-seated element defining the root zone of these thrusts, corresponding to the Tornquist Ocean Suture at deeper crustal levels.

existence of similar terranes farther to the north-west, i.e. in the discussed area?

a) Variability of the seismic velocities (V_p) in the crystalline crust of the basement of the German-Polish Lowlands suggests a presence of several crustal blocks. If we agree that the crustal structure in the German part is typical for the East Avalonia, its development east of Odra river is completely different. It follows that Avalonia does not extend to the east beyond Odra.

b) Similarity of seismic velocities in the Polish segment to the velocity pattern in cratonic lower and middle crystalline crust, together with observed large differences in thicknesses of its particular layers leads to supposition that this a reworked cratonic crust. This would not necessarily mean, however, that it represents a marginal part of the EEC in autochthonous position. This can be as well a cratonic crust of allochthonous proximal terranes which, similarly to the Małopolska Terrane, were detached from the EEC farther to the south-east and re-accreted again. Their crust may have been thinned, as commonly happens to continental crystalline crust along the passive margin, and/or modified (as in the Małopolska Terrane) by the earlier pre-Arenig diastrophism. Between Avalonia and the Małopolska Terrane at least two such terranes can be distinguished (Fig. 7) in the Pomeranian segment (blocks B' and B'' — Dadlez, 1997). Similarities of the crust in the Kuiavian segment to the cratonic crust are so striking that one cannot exclude the autochthonous character of this block. In fact, it is located in line with the Łysogóry Block, presently assumed to occupy an autochthonous tectonic position (Dadlez *et al.*, 1994). This question remains still open, however, and the allochthonous origin of the Łysogóry and Kuiavia blocks should not be rejected.

c) Counter-clockwise rotation of Baltica during the Early Palaeozoic may had caused right-lateral shearing stresses along its margins which induced the detachment of crustal slivers from the EEC and their transport along its margin to the NW. There, they docked as they met the East Avalonia which was then wandering from the opposite direction and collided with Baltica under conditions of a left-lateral transpression.

CONCLUSIONS

1. When considering the above discussed tectogenetic models of the investigated area one can — for reasons given above — exclude the concepts of the aulacogen and transcontinental strike-slip fault zones.

2. Although our knowledge is considerably broader now than it was 50 years ago, we are still in a similar position having the choice between several models and no unquestionable evidence to prove any one of them. Just like in earlier times, the problem boils down to an answer to the question: "...where is the southwestern margin of the East European Craton located?" or, defining the problem in a more modern fashion: "...what is the location of the suture which separates Baltica from the Avalonia microplate or from analogous microplates located farther east?". There exist at least three rival concepts of the tectonic evolution of the considered area:

— strongly depressed passive margin of the Baltica plate with markedly reworked crust;

— active margin of the Baltica plate along which the Caledonian fold-and-thrust belt developed;

— assemblage of tectonostratigraphic terranes.

3. In the framework of the latter concept the present author proposes still another version envisioning proximal terranes detached from Baltica farther to the south-east and subsequently re-accreted to this plate. This hypothesis is based on observed variability of the crustal characteristics in the foreland of Baltica as well as on the concept of its Early Palaeozoic rotation.

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