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Stratigraphy, correlations and palaeogeography of Palaeozoic terranes of Bulgaria and NW Turkey: a review of recent data

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Abstract: Within the Alpine tectonic units SE of the European Variscan Orogenic Belt in Bulgaria and NW Turkey several crustal blocks are identified. Although their contact relations with surrounding units are obscured by Alpine events, the differences in the succession of events, stratigraphy, sedimentology and palaeobiogeographical distribution within them permits recognition of the Moesian, Balkan, Istanbul and Zonguldak Terranes. The Moesian terrane corresponds to the pre-Variscan Palaeozoic and Neoproterozoic rocks of the Moesian microplate in north Bulgaria and south Romania. The Balkan Terrane in Bulgaria incorporates Neoproterozoic and Palaeozoic sequences in the Western Balkanides (part of the Carpathian–Balkan orogen) and another three allochthonous units (Kraishte, Central Balkanides and Strandzhides). In NW Anatolia in Turkey, the Caledonian basement and Ordovician to Carboniferous sedimentary succession are divided into the Istanbul Terrane and the Zonguldak Terrane. With the exception of the Moesian Terrane in the Bulgarian area, they all comprise a Cadomian basement with relicts of oceanic lithosphere, volcanic arc and a continental crust of unknown affinity. Based on characteristic features within their Palaeozoic successions, these terranes are correlated with the main terrane assemblages in Central and Eastern Europe. It is suggested that they all are of peri-Gondwanan origin but behaved independently while drifting towards Laurussia. During the Early Devonian the Zonguldak Terrane docked to Baltica, whereas the others were still at similar palaeolatitudes to the Central European terranes (e.g. Saxo-Thuringian). This was followed by the successive accretion of the Moesian Terrane to Laurussia along the Rhenohercynian suture at the end of Devonian–Early Carboniferous and of the Balkan and Istanbul Terranes between the Early and Late Carboniferous.

The Variscan Orogenic Belt in Europe is characterized by a mosaic of Gondwana-derived crustal blocks or terranes, which were successively accreted to Laurussia during the Palaeozoic. The position of the Palaeozoic terranes in Bulgaria (Balkan and Moesia) and in Turkey (Taurus, Istanbul, Zonguldağ) (Fig. 1) is shown in the palaeogeographical reconstruction of McKerrow & Scotese (1990), although McKerrow & Scotese's suggestion is of rather a Baltican origin of the Istanbul and Zonguldak Terranes.

The purpose of this paper is to review the stratigraphic, sedimentological and palaeogeographical data accumulated recently on the Palaeozoic of the Moesian and Balkan Terranes in Bulgaria (Fig. 2) (as defined by Yanev 1990, 1993, 1997, 2000; Haydutov & Yanev 1996) and the Istanbul and Zonguldak Terranes (Fig. 3) (Göncüoğlu 1997, 2001; Göncüoğlu & Kozur 1998, 1999; Kozur & Göncüoğlu 2000) in NW Turkey. In addition, the palaeogeographical position of the Moesian, Balkan, Istanbul and Zonguldak Terranes during Palaeozoic time is discussed here in the light of the evolution of the Variscan Orogenic Belt and the Trans-European Suture Zone (Berthelsen 1993), where it separates Avalonia–Baltica from the members of the Armorican Terrane Assemblage.

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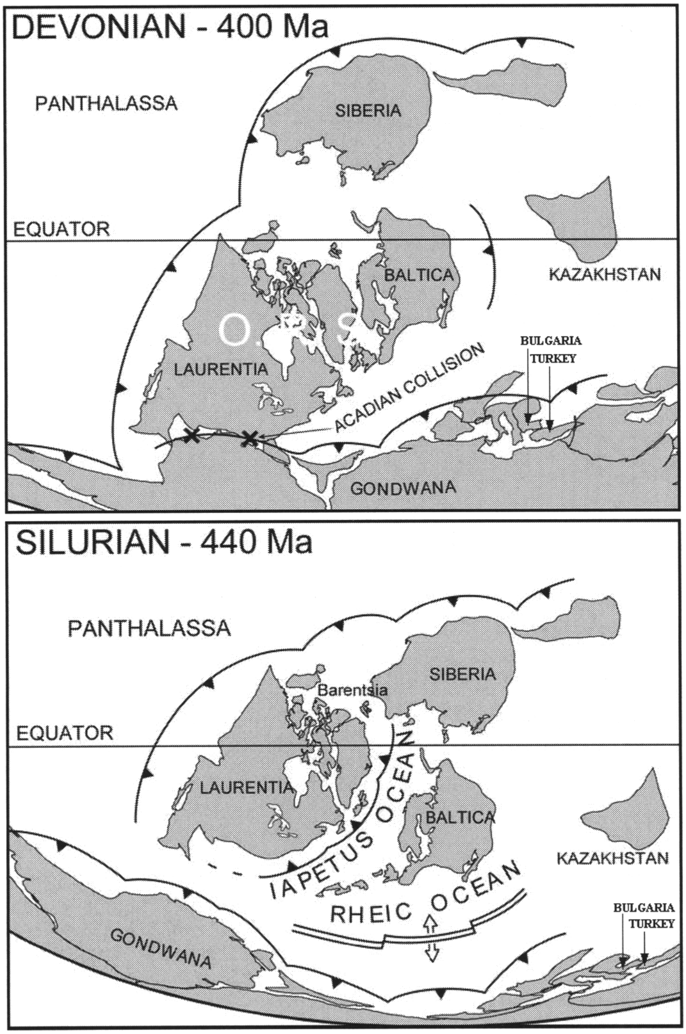

Fig. 1. Palaeogeographical reconstruction of Gondwana, Baltica, Laurussia and peri-Gondwanan European terranes (after McKerrow & Scotese 1990).

In recent years, detailed work has been carried out the geology, palaeogeography and geodynamics of these terranes in Western and Central Europe (e.g. Pharaoh 1999; Franke 2000; Winchester & PACE TMR Network Team 2002). In the west, Avalonia was one of the earliest recognized Gondwana-derived terranes that was already accreted to Baltica at the end of the Ordovician. Recently, it was suggested that this was not restricted to Southern Britain but may well continue towards Central and Eastern Europe (e.g. Moravo-Silesian terrane; Pharaoh 1999) to include some small crustal blocks.

The next group of Gondwanan terranes that were accreted to Baltica–Avalonia later in the Palaeozoic is the Armorican Terrane Assemblage (Franke 2000), which includes several crustal blocks within the Variscan Belt in Central and SE Europe (e.g. Bohemian Massif).

The far eastern part of the Variscan Belt, however, remains relatively less-known to the international community. Being located on the eastern extension of the Variscan Belt and being involved in post-Variscan orogenic events, this region should theoretically include dismembered pieces of the Eastern European Craton and its cover (Baltica-derived terranes), the Avalonian Terrane, the Armorican Terrane Assemblage or other peri-Gondwanan terranes. Regional palaeogeographical reconstructions (e.g. Görür

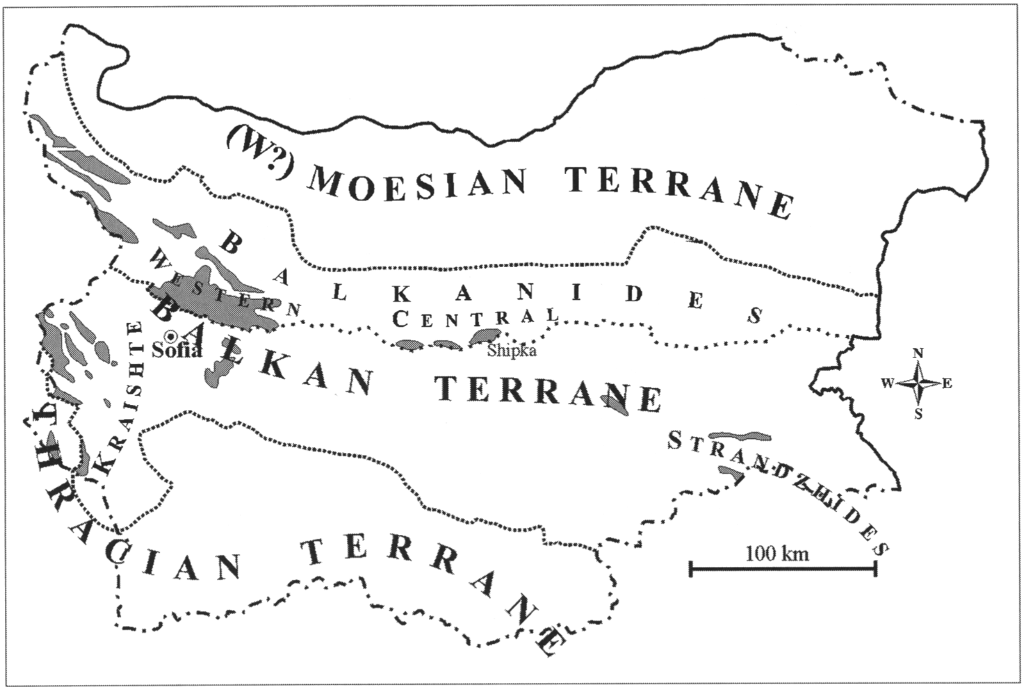

Fig. 2. Geological sketch showing the Palaeozoic terranes and outcrops in Bulgaria.

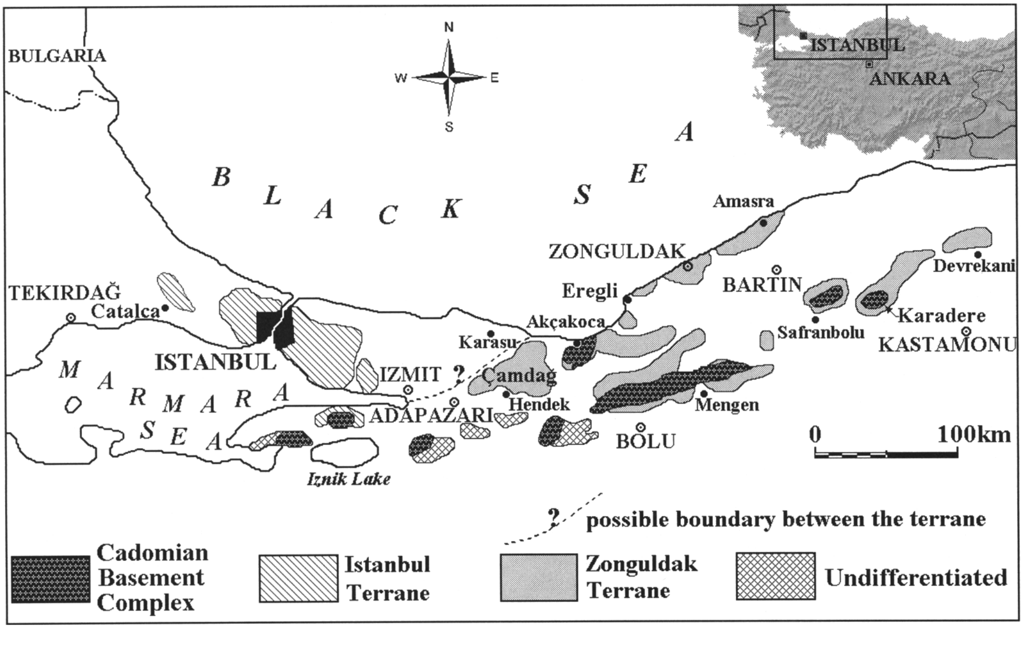

Fig. 3. Geological sketch showing the Palaeozoic terranes and outcrops in NW Anatolia, Turkey.

et al. 1997; Stampfli 2000; Kalvoda 2001; Von Raumer *et al.* 2002) for this area, including the northern part of Balkan Peninsula and NW Anatolia, were mainly based on oversimplified previous work and did not take new data and comprehensive stratigraphical evidence into account, and thus are somewhat speculative.

Moesian Terrane

Stratigraphy and sedimentology

Western and central part of the Moesian Terrane. In the western and central part of the Moesian Terrane, in Bulgaria, the Palaeozoic sediments consist of Upper Silurian to Viséan marine deposits and a Permian continental cover.

The oldest marine sediments are Lower Silurian (Pridoli) and Lower Devonian black shales about 200 m thick with some bivalves and trilobites, and chitinozoans, acritarchs and spores. Palynological evidence supports a latest Silurian and Lochkovian age (Lakova 1993, 2001*a,b*; Steemans & Lakova 2004) with continuous sedimentation across the Silurian–Devonian boundary. There is no record of Pragian to Lower Eifelian sediments.

The Middle Devonian sequence comprises 800 m of dolomitic limestones, calcareous dolomites and micritic limestones, with 60 m of Emsian shales at the base. The Mid-Devonian age is recognized using Foraminifera, brachiopods and conodonts (Spassov *et al.* 1978; Vdovenko *et al.* 1981; Boncheva *et al.* 2002). A slight angular unconformity with clastics (calcirudites) at the base is found at the Emsian–Eifelian and Eifelian–Givetian boundaries in the central part. The Upper Devonian sequence is missing.

The boundary between the Middle Devonian and the Lower Carboniferous is an erosional surface as proved by conodont and sediment data (Boncheva *et al.* 2002). In the west, the Viséan limestones with algae, crinoids and ostracodes, black shales and dolomites overlie Tournaisian limestones. An Early Carboniferous age was proved using conodonts and Foraminifera (Spassov 1977; Vdovenko *et al.* 1981; Boncheva *et al.* 2002). The Lower Carboniferous sequence is about 730 m thick whereas Upper Carboniferous units are missing.

In the central part, 580 m of Carboniferous continental shales, siltstones, sandstones and coal-bearing shales were shown to be Tournaisian to Early Namurian in age by macro- and microflora. These are the only coal-bearing Carboniferous sediments outside the Dobrudgea coal basin in east Moesia (Nikolov *et al.* 1990; Dimitrova 1996). The Westphalian sequence is missing.

With a contrasting lithology and clear discordance, Permian continental clastic rocks cover either Middle Devonian or Viséan–Namurian rocks. The Permian sequence consists of reddish breccias–conglomerates, sandstones and siltstones, 50–800 m thick. These drastic variations in the thicknesses are controlled by the pre-Permian palaeotopography.

Eastern part of the Moesian Terrane. The Palaeozoic section consists of a marine sequence from Ordovician to Viséan (with numerous local discontinuities) covered unconformably by continental Carboniferous and Permian deposits.

The oldest subsurface sediments in the eastern part of the Moesian Terrane in Bulgaria are Ordovician pelitic rocks about 100 m thick. In Romania, the Ordovician sequence, mainly encountered in boreholes, is 750 m thick and dated by palynomorphs (Parashiv & Beju 1974). The overlying Silurian and Lower Devonian units are mainly dark shales and siltstones with minor limestones and marls, up to 2000 m thick. Conodont and graptolite faunas prove the existence of Llandovery and Wenlock Series (Spassov & Yanev 1966). Chitinozoan, acritarchs and spores provide evidence of a Pridolian and Early Devonian age (Lakova 1993, 2001*a,b*; Steemans & Lakova 2004). Locally, thin quartzites and sandstones of possible Emsian–Eifelian age cover the Lower Devonian sequence with shales. In other areas, the Lower Emsian sequence is directly covered by Eifelian carbonate sequences (Spassov 1987; Boncheva 1995).

The Middle–Upper Devonian to Viséan carbonate sequence in the subsurface is subdivided into six informal lithostratigraphic series: carbonate–sulphate, dolomite, banded limestones, intraclastic limestone, organic limestones and clastic limestones (calcirudites). The total thickness of carbonate platform deposits penetrated is 1200–2000 m, thickening from NW to SE. The assumed stratigraphical thickness may be as great as 3000 m. Fossil data on conodonts (Spassov 1983; Boncheva *et al.* 1994, 2000; Boncheva 1995; Yanev & Boncheva 1997) prove Eifelian, Givetian, Frasnian, Famennian and Viséan stages. Spassov (1987) provided macrofossil constraints on the Eifelian age on corals, brachiopods, ostracodes and trilobites. The Upper Viséan, locally developed to the east, is up to 2300 m thick and consists of limestones at the base, followed by dark shales with coal layers and sandstones. The characteristic feature of the carbonate–dolomite sequence in the eastern part

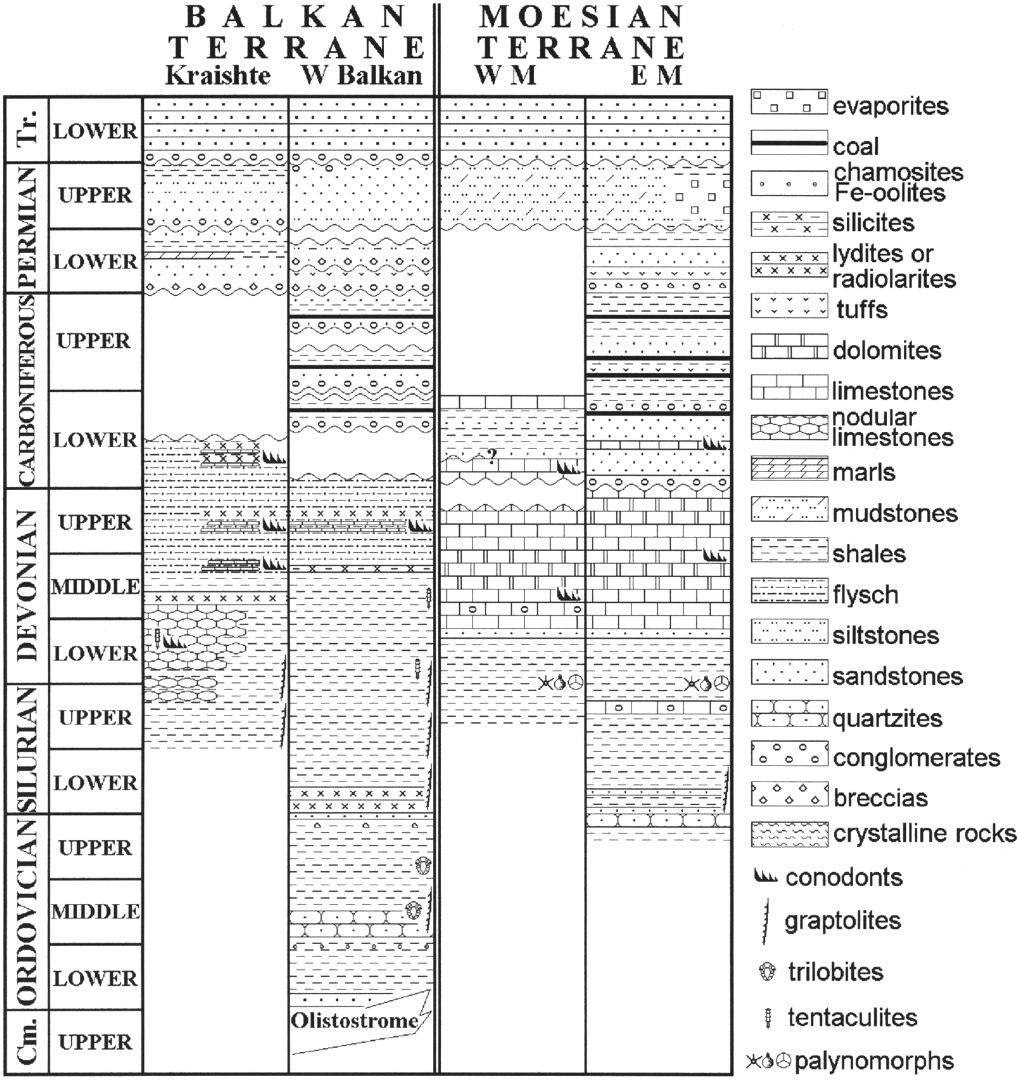

Fig. 4. Generalized stratigraphy of the Palaeozoic in the Balkan and Moesian Terranes in Bulgaria.

of the Moesian Terrane is a dozen widespread unconformities within the Middle Devonian to Permian sequence, as established by sedimentological data and conodont biostratigraphy (Yanev & Boncheva 1995).

In the Dobrudgea Coal Basin, Middle to Upper Devonian carbonates are unconformably overlain by Upper Namurian–Westphalian coal-bearing terrigenous strata (Fig. 4, in the composite column EM of eastern part of Moesia and Dobrudgea Coal Basin). The Tournaisian and Lower Viséan units are missing.

The Permian sequence consists of conglomerates, sandstones, shales and evaporites. The great variations in the thickness of the Carboniferous (0–3000 m) and Permian sequences (0–3500 m) resulted from post-Palaeozoic erosion.

Palaeogeography

Palaeogeographical interpretation and reconstruction of the Moesian Terrane is based on combined biogeographical, palaeoclimatic and palaeomagnetic analysis.

The palaeobiogeographical interpretations are based on palynomorphs from the Upper Silurian and Lower Devonian sequences. The chitinozoan faunas of the Lochkovian and

Emsian in the Moesian Terrane show clear peri-Gondwanan affinities with North Africa, Spain and Brittany (Lakova 1995). Coeval acritarchs show palaeogeographical affinities (Lakova 2001*b*) with Brittany, Spain, North Africa and Southern England. Recently, palaeobiogeographical analysis of Lochkovian spores has revealed affinities with Belgium, Southern Britain and Poland (Steemans & Lakova 2004). The northern position of the Moesian Terrane in the Lochkovian, as indicated by palaeophytogeography, supports the hypothesis of northward drift of Moesia in Ordovician to Devonian times from Gondwana to Laurussia.

The palaeoclimatic interpretations are based on Palaeozoic rocks and minerals indicating specific climatological conditions and zones, and thus palaeo-latitudes (Yanev 1990, 2000). In the Ordovician to Early Devonian the abundance of organic matter in the predominantly shaly sequence and the presence of Fe-oolitic minerals provide evidence of sedimentation in a temperate zone. Anhydrites in the Givetian of the eastern part suggest a transition to an arid zone. The Upper Carboniferous coal-bearing succession indicates deposition in the equatorial zone. These palaeoclimatic interpretations support a northward migration of the Moesian Terrane depositional environment from the southern temperate zone in the Silurian to the southern arid zone in the Late Carboniferous. In the Permian, the presence of reddish clastic deposits, anhydrites and evaporites in the eastern part suggests sedimentation in a northerly arid zone.

The Gondwanan v. Baltican affinities of the Moesian Terrane are a matter of discussion, because of controversial data from Romania. The palaeogeographical distribution of Cambrian trilobites and shelly fauna is shown to be of mixed affinities with Avalonia, Bohemia and Baltica (Iordan 1992). Lower Devonian chitinozoans of East Moesia and possibly West Moesia show Northern Gondwana affinities (Vaida & Verniers 2005). On the other hand, Seghedi *et al.* (2004) interpreted the Eifelian of the Moesian Terrane as part of Laurussia. Obviously, further palaeobiogeographical studies on both benthic and planktonic fossils are necessary to confirm the origin of the Moesian Terrane.

Balkan Terrane

Stratigraphy and sedimentology

Within the Balkan Terrane, two distinct areas of specific stratigraphical and sedimentological development can be recognized: the West Balkan Mountains and the Kraishte region. In addition, allochthonous low-grade metamorphic Palaeozoic rocks occur in the Shipka part of Central Balkanides and in the Strandzhides.

Western Balkanides. In the Balkan Terrane, an island-arc association of cumulates, dykes and pillow lavas metamorphosed to greenschist-facies outcrops in the Western Balkan Mts. Recent isotope-geochronological dating of the ophiolites indicates an age of 563 Ma, confirming a Early Cambrian or Late Proterozoic age of the island arc (Von Quadt *et al.* 1998; Carrigan *et al.* 2003). These ages are similar to Pan-African ages and provide further evidence of a Gondwana origin of the Balkan Terrane. The island-arc complex is transgressively and unconformably overlain by an Arenig olistostromal sequence. Non-metamorphic Middle and Upper Ordovician shales and sandstones with brachiopods and trilobites, in total 2000 m thick, cover the olistostrome sequence. Upper Ordovician glaciomarine diamictites possibly relate to emergence as a result of glaciation (Gutierrez-Marco *et al.* 2003).

Following a continuous transition from the Ordovician, the Silurian sequence represents a pelagic pelitic succession of 300 m lydites, black graptolitic shales and laminated shales–siltstones dated graptolites (Sachanski 1993; Sachanski & Tenchov 1993). The succession of established graptolite zones proves a complete Silurian section and transitional sedimentation across the Silurian–Devonian boundary (Sachanski 1998).

An outcropping 1500 m Devonian succession of shales and siltstones with scarce tentaculites, graptolites and chitinozoans (Lower and Middle Devonian), silicites, siliciclastic ‘pre-flysch’ alternations of shales and lydites (Middle Devonian) is followed by thick flysch deposits with macroflora of Late Devonian to Viséan age. Whereas Lochkovian, Pragian and Emsian rocks were proved by means of fossils, the assignment of the siliciclastic ‘pre-flysch’ alternation to a Mid-Devonian age is based only on its stratigraphical position. The development of flysch sedimentation in a progressively subsiding basin occurred between the Late Devonian and the Viséan (Yanev 2000). Age determination is based of macroflora and on conodonts in single carbonate layers (Boncheva & Yanev 1993).

The continental cover consists of Upper Carboniferous and Permian sediments and pyroclastic rocks, and overlies variegated sedimentary and metamorphic rocks of different ages. Namurian–Westphalian and Stephanian coal-bearing deposits rich in macroflora crop out in isolated basins. Permian reddish siliciclastic rocks 0–3000 m thick accumulated over folded basement including the Upper Carboniferous sedimentary, volcanic and intrusive rocks.

Kraishte region. The oldest Palaeozoic sedimentary rocks in the Kraishte region are Silurian black shales with lydites at the base. The age was proved, using graptolites (Spassov 1963, 1964), as Late Silurian and Early Devonian. The Upper Silurian and Lower Devonian sequence is developed in continuous shaly–carbonate sedimentation. In the central and southwestern parts of Kraishte biogenic limestones are dated, using conodonts and tentaculites (Boncheva 1991; Sachanski & Boncheva 1994), as Lochkovian to Eifelian and Frasnian–Famennian (Spassov 1973). The Lower Devonian sedimentation is a non-rhythmic succession of limestones and shales, the shales being predominant. Characteristic of the Devonian 'pre-flysch' sedimentation is the occurrence of thick folded lydite packets. Olistostromes of Lochkovian and Pragian limestones (Boncheva 1991) occur in the Middle Devonian–Lower Carboniferous and the Upper Jurassic–Lower Cretaceous flysch. The total thickness of the Silurian and Devonian units is hard to estimate because of tectonic displacement and lack of outcrops.

The Middle Devonian to Viséan mainly turbiditic succession about 1500 m thick is represented by clastic rocks with some carbonate and lydites in the upper part (Yanev 1985; Yanev & Spassov 1985). Upper Carboniferous and Lower Permian units are missing. The continental cover is of Upper Permian sandstones, siltstones and scarce breccias–conglomerates about 300–400 m thick.

Palaeozoic succession of Shipka part of Balkanides and Strandzhides. In the Shipka part of the Balkan Mountains several Alpine tectonic slices consist of disturbed Riphean–Cambrian to Devonian low-grade metamorphic rocks that contain an incomplete stratigraphic column. The generalized Palaeozoic section consists of a Riphean–Cambrian metasedimentary formation, an Ordovician quartzite–shale formation, an Upper Silurian–Middle Devonian limestone–shale formation and an Upper Devonian rhythmic flysch sandstone–shale formation (Yanev *et al.* 1995). There are scarce fossil data only from the limestone–shale formation. Several crinoid-bearing horizons in the limestones were proved to be Devonian using crinoids (Kalvacheva & Prokop 1988) and conodonts provide data on the Early Devonian (Yanev *et al.* 1995).

In the Strandzhides, metamorphic rocks up to greenschist facies of probable Palaeozoic age occur as allochthonous units in several Alpine nappe structures. The Palaeozoic succession is overturned and thrust over the Triassic and Jurassic sequences. Three metasedimentary series are recognized (Maliakov 2003). The lower series consists of metaconglomerates, metasandstones, marbles and phyllites, and is more than 600 m thick. Above, metasandstones, phyllites, marbles and metadiabase crop out. The total thickness is 550 m. The conodont fauna from this series indicate an Early Devonian age (Boncheva & Chatalov 1998). This series is covered by 100 m of recrystallized limestones, 350 m of black phyllites and 450 m of grey–green calc-phyllites.

Palaeogeography

Middle Ordovician benthic faunas of the Balkan Terrane in west Bulgaria and eastern Serbia are of Bohemian and North African affinities (Guttierez-Marco *et al.* 2003). The Emsian chitinozoans are of clear Gondwanan affinities. The Carboniferous macroflora (*Cyclostigma*) is characteristic of the humid zone.

Palaeoclimatic interpretations for the Ordovician are based on Fe-oolitic rocks and diamictites, which suggest a depositional environment in the higher latitude humid zone at about 40° S. The Llandovery post-glacial graptolitic black shales were possibly deposited in the cool temperate zone (Yanev 1997). The abundance of diverse macroflora and coal deposition in the Late Carboniferous is characteristic of the equatorial humid zone. The presence of anhydrite matrix in the reddish Permian clastic rocks indicates deposition in an arid climatic zone. Thus, palaeoclimatic interpretations may support a northward migration from a temperate latitude in the Ordovician to the equator in the Permian.

Palaeomagnetic data are available for the Balkan Terrane in Serbia (Milicević 1993, 1994). They indicate a position between 50° and 29° S during the Tremadoc, of 30°–40° S in the Mid-Ordovician and 38° S in the Late Ordovician. In the Early Devonian, the Kucaj Terrane in Eastern Serbian (considered to have the same sedimentary development as the Balkan Terrane) was located at about 16° S. In the Permian, palaeomagnetic data suggest that the position of the Balkan Terrane was at 8–14° N (Nozharov *et al.* 1980; Milicević 1993). However, palaeomagnetic data are better interpreted when combined with palaeoclimatical and palaeofaunal evidence.

Istanbul Terrane

Stratigraphy and sedimentology

The crystalline basement of the Istanbul Terrane is represented by a structural complex including fragments of meta-ophiolites, island-arc volcanic rocks and arc-type granitoids, together with pieces of a continental crust of unknown affinity (Göncüoğlu 1997; Ustaömer & Rogers 1999; Yiğitbaş *et al.* 2004). Recently, Ustaömer *et al.* (2005) determined a new U–Pb zircon age of 571–579 Ma from the arc-type granitoids in the Bolu Massif (Fig. 3).

The lowermost unit of the Palaeozoic succession in the Istanbul area comprises almost 1500 m of fine-laminated siliceous shales with sandy interlayers in its upper part. It is conformably overlain by 750 m of thin- to medium-bedded greenish sandstones alternating with thin-bedded, laminated shales (Gedik *et al.* 2002). None of these formations has yielded fossils, so that an Early Ordovician age assigned to them is arbitrary.

A formation of almost 1000 m thickness of variegated conglomerates, conglomeratic sandstones, arkosic sandstones and pink shales unconformably overlies the earlier formations. These continental clastic rocks are transgressively covered by 50–100 m of quartzarenites and quartzites with conglomeratic intervals. The quartzites do not include any fossils but contain undetermined traces (?*Crusiana*) and vertical vermes tubes (Önalan 1982). Upwards, the quartzites are transitional to a succession with greenish shales, siltstones and sandstones in the lower part and violet–grey and green mudstones with carbonate-rich lenses with brachiopods. Reddish–black bands with oolitic and nodular chamosite and hematite occur both in lower and upper parts of the succession. The thickness varies between 250 and 750 m. The chamositic bands in the lower part yielded early Late Ordovician brachiopods (Sayar 1984) followed by sandstones with Late Ordovician (Villas, pers. comm.) brachiopods. The carbonate-rich upper part includes Telychian brachiopods and conodonts (Haas 1968). No glacio-marine rocks have been observed at this interval as yet. The uppermost part of this formation includes a 70 m band with oolitic chamosites and limestones with conodonts characteristic of the Wenlock.

Upwards, 100 m of sparry, compact and laminated limestones follow, known as 'Halysites Limestones'. These limestones include corals in addition to brachiopods, cephalopods and crinoids. Conodont findings indicate a Late Wenlock to Late Ludlow age. The following 300 m of the succession is characterized from bottom to the top by neritic limestones. The lower part comprises grey to pink stromatolitic limestones, followed by dark grey to black limestones and dolomites. The upper part of the succession is represented by nodular limestones with marly interlayers. This carbonate succession is dated on the basis of brachiopods, corals and conodonts (e.g. Haas 1968), and includes without a significant break the whole Pridoli to Early Emsian succession.

The carbonates are transitional to an almost 800 m alternation of clayey sandstones, limy greywackes and discontinuous bands of limestones, rich in brachiopods, corals, goniatites, bivalves and trilobites, that indicate continuous deposition between late Emsian and early Eifelian. The carbonate succession above consists of limestones of mid–late Eifelian age and nodular limestones with chert bands. Brachiopod and conodont findings from this 'lower nodular facies' indicate a Givetian to early Frasnian age. The following grey to brown silicified shales and cherts with violet nodular limestone and chert intervals, almost 100 m thick, include late Frasnian conodonts and are transitional to 'upper nodular facies', a 75–80 m thick band with nodular limestones and lydite bands. The lower part of this unit includes Famennian conodonts (Çapkinoğlu 2000), whereas the uppermost layers are mid-Tournaisian in age (Göncüoğlu *et al.* 2004).

After an intervening unit of black lydite with phosphate nodules, late mid-Tournaisian in age (Gedik *et al.* 2003), the succession passes into proximal turbidites with plant remains and olistostromal sandstone–conglomerate bands, very rich in detrital white mica and clasts of felsic igneous rocks. This unit is traditionally known as the 'Variscan flysch' in the Istanbul area and is more than 2500 m thick. The flora obtained from the lower half of the formation is Viséan in age (Baykal 1963). The youngest foraminifer age is from reefal limestones within the greywackes and is Late Viséan.

The Palaeozoic rocks of Istanbul are intensively deformed and intruded by Late Permian granitoids (e.g. Görür *et al.* 1997). The lower part of the unconformably overlying red continental clastic rocks has not yet yielded any fossils. However, the middle part is Late Permian in age, so that the orogenic event responsible for the deformation should be of Carboniferous to Permian age.

Palaeogeography

No palaeomagnetic data are available from the NW Anatolian Palaeozoic and the palaeogeographical interpretations are mainly based on biogeographical and palaeoclimatic data. The Ordovician to Silurian benthic faunas of the Istanbul Terrane are of Avalonian and Podolian affinities, as mentioned by Haas (1968). Starting with the Devonian (Emsian and throughout Frasnian), however, brachiopods and trilobites are of clear Bohemian and North African (Morocco) affinities. This affiliation is further supported by Emsian ostracodes indicating faunal relations to Thuringia and Morocco (Dojen *et al.* 2004). The Carboniferous macroflora (*Cyclostigma*) is also found in Bulgaria and Central Europe. The Late Viséan foraminiferal assemblage and the Early Carboniferous development, on the other hand, have been correlated with the Moravo–Silesian (Brunovistulian, Kalvoda *et al.* 2003) zone.

As in the case of the Balkan Terrane, Ordovician siliciclastic rocks comprise Fe-oolitic or chamositic sequences, suggesting deposition in a temperate humid zone at about 40° S. The dominance of reefal limestones during the Devonian as well as the presence of diverse macroflora in the Early Carboniferous is characteristic of the equatorial humid zone, so that, as for the Balkan Terrane, a migration of the Istanbul Terrane from temperate latitudes in the Ordovician to near the equator in Late Palaeozoic times can be assumed.

Zonguldak Terrane

Stratigraphy and sedimentology

To the east of Istanbul, a number of isolated Palaeozoic successions crop out within the Alpine tectonic units (Fig. 3). Göncüoğlu & Kozur (1998, 1999), Kozur & Göncüoglu (2000) and Von Raumer *et al.* (2003) suggested that they represent a distinct terrane (Zonguldak Terrane, Göncüoğlu & Kozur 1999), separate from the Istanbul Terrane. The rationale for this suggestion is that their stratigraphy, starting with lower Middle Ordovician, is completely different from that of the Istanbul Terrane (Fig. 5) and that these differences cannot be explained simply by lateral facies changes. Moreover, a late Early Devonian regional angular unconformity in the Zonguldak terrane together with an accompanying thermal event (Kozur & Göncüoğlu 2000) contrasts with continuous platform-type deposition in the Istanbul Terrane during the same time interval.

The basement of this terrane occurs in the Karadere area, where Chen *et al.* (2002) dated the tonalitic and granodioritic rocks to 570 and 590 Ma using the U–Pb zircon method. Thus, the basement rocks of the Zonguldak and Istanbul Terranes are both related to the Cadomian magmatism, characteristic of Gondwanan or peri-Gondwanan terranes in Central and Southern Europe.

This basement is unconformably overlain by siliciclastic rocks, commencing with Tremadoc shales, followed by a series of laminated shales and siltstones. A 700 m thick quartzite unit with conglomeratic interlayers is conformably covered by black shales with rare limestone layers. Graptolite, acritarch and conodont data from this succession indicate that the succession includes the time-span Early Arenig to Mid-Ludlow (Dean *et al.* 1997, 2000).

Upper Silurian (Pridolian) and Lower Devonian (up to Pragian) rocks are missing. The unconformably overlying succession is of quartzites and oolitic chamosites with a thick packet of carbonates. The lower part of this unit is very rich in neritic fossils and includes Pragian palynomorphs and conodonts. The onset of carbonate deposition here is late Emsian, and it terminated in the late Viséan (Dil & Konyali 1978). The thickness of this shallow–marine limestone-dolomite succession reaches 1200 m. In contrast to the Istanbul Terrane, the carbonates display typical features of reef, lagoon and restricted shelf deposition, and are very rich in corals, brachiopods, bivalves and foraminifers especially in the upper part. This carbonate succession is conformably overlain by shallow-marine sandstones with brachiopods, corals and land plants. Carbonate lenses within them yielded early Serpukhovian conodonts (Göncüoğlu *et al.* 2004).

Upwards, the succession is characterized by a regressive series that grades into floodplain deposits with numerous coal seams of Westphalian age (Kerey 1984). The youngest age obtained from the plants within this 700–1200 m succession of these continental clastic rocks in the Zonguldak area is Stephanian.

The Carboniferous strata here are only slightly deformed and unconformably overlain by Permo-Carboniferous continental clastic rocks.

Palaeogeography

The Tremadoc acritarchs in the Karadere area are known from localities in Avalonia, Baltica and Gondwana, and hence are not indicative for palaeogeographical interpretations. Dean *et al.* (1997) suggested that the Late Ordovician and Silurian fauna were of mainly Avalonian affinities. The Devonian benthic fauna of this zone, on the other hand, is typical of the Rhenohercynian

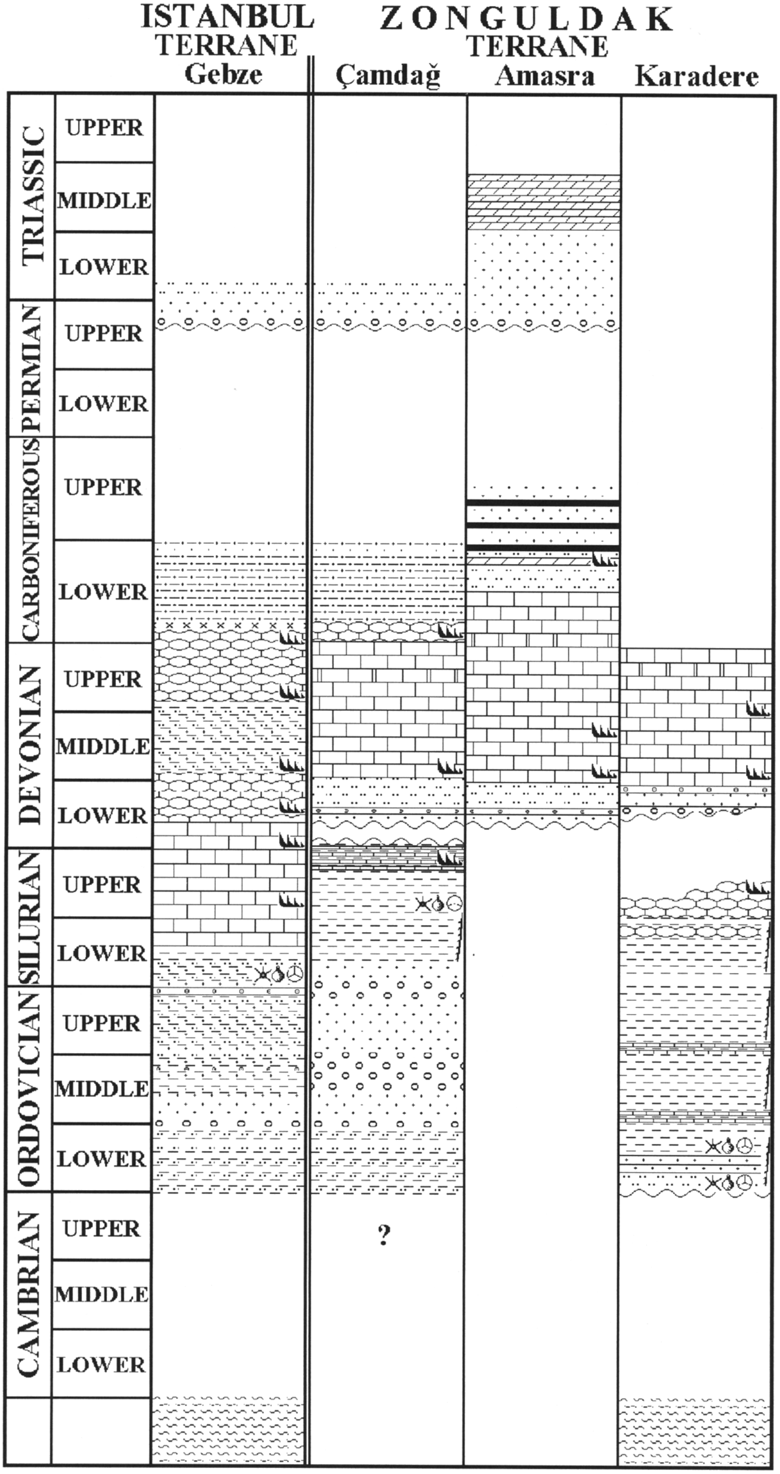

Fig. 5. Generalized stratigraphy of the Palaeozoic in the Istanbul and Zonguldak Terranes in NW Anatolia, Turkey.

in Central Europe and SW England (Tokay 1955). The Late Namurian–Westphalian sediments, fauna and flora in the Zonguldak Coal Basin correlate very well with Moesia, Balkan and other Upper Carboniferous coal basins in Europe deposited under tropical conditions.

Discussion

The brief review of the recent data given above may help to answer the following questions regarding the palaeogeographical setting of the Balkan and NW Anatolian terranes: How do the Palaeozoic terranes of Bulgaria and NW Anatolia correlate with each other? Were these terranes part of Baltica, Avalonia or the Armorican Terrane Assemblage? What was the location of the Bulgarian and NW Anatolian terranes with regard to the Variscan suture zones?

How do the Palaeozoic terranes of Bulgaria and NW Anatolia correlate with each other?

Two of the terranes described, the Balkan and Istanbul Terranes, show striking similarities in their Ordovician to Carboniferous sedimentary development, which may imply their common terrane affinities and origin.

That these two terranes shared the same depositional environments between the Ordovician and Eifelian is expressed in the development of very similar sedimentary successions: shallow-water siliciclastic deposits with brachiopods in the Ordovician, mainly deeper water black shales with graptolites in the Silurian, an alternation of shales and limestones across the Silurian–Devonian boundary, and predominantly carbonates in the Lower Devonian shales, with carbonate or lydite in the Eifelian. However, some differences as a result of bathymetric conditions and local palaeo-relief exist, such as reefal limestone bodies in the Middle Silurian rocks of the Istanbul Terrane, compared with the shaly sedimentation in the Balkan Terrane. After the Givetian, flysch accumulation started in the Balkan Terrane, in contrast to the shallow-marine, chiefly carbonate, sedimentation in the Istanbul Terrane. These contrasting depositional environments, caused by tectonic activity, existed laterally and persisted until the Viséan. The Lower Carboniferous flysch in the Istanbul Terrane developed later than the flysch sedimentation in the Balkan Terrane where it started in the Givetian–Frasnian, whereas during the Late Carboniferous, continental deposits with coal formed in the Balkan Terrane; in the Istanbul Terrane no Carboniferous deposits younger than Viséan are preserved.

An excellent stratigraphical correlation is possible only between the East Moesian and Zonguldak Terranes for the Mid-Devonian–Carboniferous interval. Regarding the pre-Mid-Devonian, concerning striking features of the Zonguldak Terrane such as the deposition of graptolitic shales with pelagic carbonates in Mid-Ordovician to early Late Silurian and the early Mid-Devonian unconformity, these are not common features of all the continental microplates ascribed to Moesia. However, in East Moesia as well as in Dobrudgea similar occurrences were reported (e.g. Seghedi *et al.* 2004) within tectonic intercaletions of the Alpine belt. It is important to note that the Silurian and Devonian chitinozoans in East Moesia are of North Gondwanan affinity (Vaida & Verniers 2005).

Were these terranes part of Baltica or peri-Gondwana (Avalonia and the Armorican Terrane Assemblage)?

The question refers to the classical approach that considers the Moesian, Istanbul and Zonguldak Terranes as part of the Eastern European Craton (or Baltica) throughout their geological history (e.g. Görür *et al.* 1997; Von Raumer *et al.* 2002; Kalvoda *et al.* 2003).

Two lines of evidence are against such an interpretation: the Cadomian affinity of the oceanic lithosphere and the palaeobiogeographical provinciality based on benthic faunas. Both the Eastern Balkan and NW Anatolian terranes are characterized by the presence of Cadomian oceanic lithosphere and arc-type magmatism that lasted until the Early Cambrian. The oldest sedimentary cover of these crustal pieces is Early Ordovician, which would indicate that their amalgamation and hence deformation would have lasted during the Cambrian time. Thus, their Cadomian affinity would imply that they were originally part of Gondwana. The Ordovician trilobite fauna in the Zonguldak Terrane is more akin to that of south Wales (Avalonia) and Bohemia than Baltica (Dean *et al.* 1997, 2000). Consequently, it is unlikely that the Balkan and NW Anatolian Terranes were parts of Baltica.

The Avalonian Terrane is characterized by Pan-African (Cadomian) events of Late Proterozoic age, deposition of siliciclastic rocks during the early Ordovician, and deformation, magmatism and metamorphism related to the 'Caledonian' orogeny as a result of either the

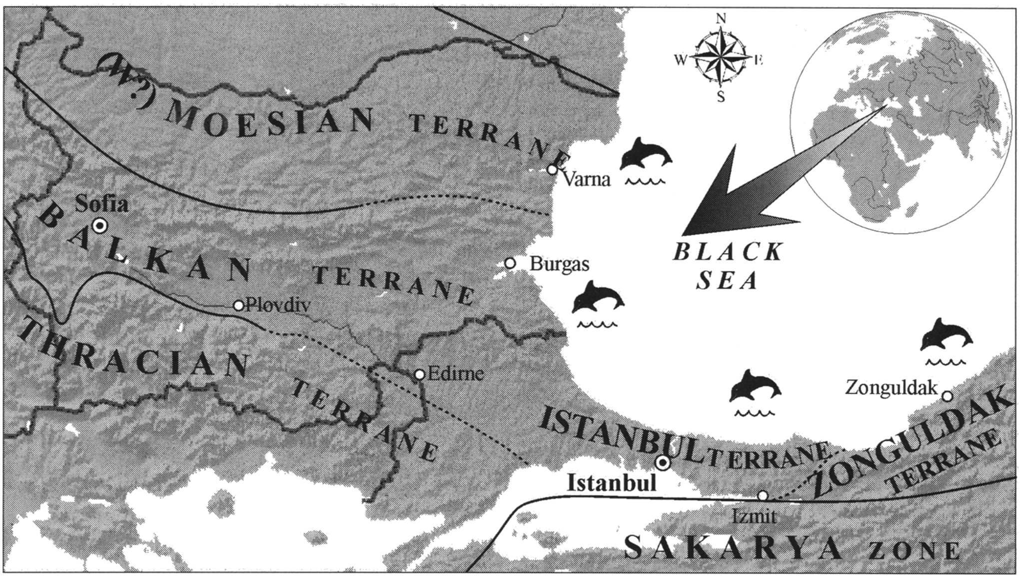

Fig. 6. Schematic map of the relationships between the studied terranes.

Late Ordovician collision with Baltica or the subsequent Late Silurian accretion with Laurentia. All these geological events can be used as important geological criteria to identify the Avalonian terranes. Additionally, distinct zones of faunal provinciality, mainly controlled by global palaeoclimate established for the Ordovician–Silurian period (e.g. Cocks 2001) and the deposition of glacier-related sediments in Gondwana or peri-Gondwana during the end-Ordovician could also be used for palaeogeographical interpretations.

The Ordovician in the Zonguldak Terrane contains trilobites of clear Avalonian (Wales) affinities (Dean *et al.* 2000). The Devonian benthic fauna are the same as in the Rhenohercynian zone (i.e. Avalonian or Armorican Terranes).

In the Balkan Terrane, Mid-Ordovician benthic faunas (trilobites and brachiopods) were found (Gutierrez-Marco *et al.* 2003) that are of North African affinities. The planktonic fossils (chitinozoans and acritarchs) of the Early Devonian in the Moesian Terrane indicate the high latitude of the Armorican Terrane Assemblage and not the low latitude of Baltica (Lakova 1995, 2001*b*).

From the studied terranes, only the Balkan Terrane includes diamictites within the uppermost Ordovician strata representing very important palaeogeographical evidence that it was not part of Avalonia but of Gondwana or Armorica. During the Ordovician and Silurian the terranes studied either comprise abundant organic matter in predominantly shaly sequences or include Fe-oolitic minerals, evidence for deposition in a temperate humid zone. During the Mid-Devonian and Carboniferous, the fauna and flora of the Bulgarian and Turkish terranes suggest a depositional migration from the southern arid zone to the equator.

The palaeomagnetic data for the Balkan Terrane in Serbia further suggest a movement of the terrane from a southern subpolar latitude in the Ordovician to the equator in the Permian.

Even if there are some faunal links to Avalonia, the absence of Shelveian (late Ordovician) and/or Scandian (late Silurian) events in the West Moesia, Balkan and Istanbul Terranes opposes a link with Avalonia. The Zonguldak Terrane and some continental microplates in East Moesia, on the other hand, may have been located in the eastern continuation of Avalonian and Moravo-Silesian terranes. This is due to the fact that especially the Zonguldak Terrane displays a key unconformity of late Early Devonian age, which may correspond to the Acadian event also known in the southern periphery of Avalonia (Pharaoh 1999).

Taking into account the generalized stratigraphical column, the occurrence of palaeoclimatological indicators in the sediments, and the palaeobiogeographical affinities of the benthic and planktonic fauna, it seems very probable that the West Moesian, Balkan and Istanbul

Terranes were more closely linked to the Armorican Terrane Assemblage that includes the Bohemian and Saxo-Thurungian terranes in Europe.

What was the location of the Bulgarian and NW Anatolian Terranes with respect to the Variscan suture zones?

The accretion of Gondwana-derived crustal blocks to Laurussia has resulted in the formation of a distinct orogenic belt: the Variscan Zone. Geodynamic reconstructions (e.g. Franke 2000; Neubauer 2003; Von Raumer 2003) suggest a very complex network with numerous crustal blocks within the Variscan Zone. Obviously, there were several oceanic seaways (e.g. Rheic Ocean, Rhenohercynian Ocean, Saxo-Thuringian Ocean, Palaeotethyan Ocean, etc.) that separated the terranes or terrane assemblages. Of the terranes studied here, only the Zonguldak Terrane includes evidence for a late Early Devonian deformation. This event is frequently observed in the Avalonia-related terranes in central Europe and attributed to the docking of Armorican terranes to Laurussia by the closure of the Rheic Ocean. If this interpretation is confirmed by additional data, the Zonguldak Terrane can be positioned at the eastern edge of the Moravo-Silesian terranes to the south of Laurussia during this period. The uplift and the closure of the Palaeozoic basin during the Late Stephanian was accompanied by weak deformation, but no distinct Variscan metamorphic event is recorded in the basement of the Zonguldak Terrane (Chen *et al.* 2002).

The Moesian Terrane has not been affected by the closure of the Rheic Ocean and its docking to Baltica should be somewhat later, between the Late Devonian and Early Carboniferous Variscan convergence. The striking lithological, faunal and floral similarities in the Tournaisian to Stephanian successions in Zonguldak, Moesia, Donetz, Silesia, the Ruhr, Belgium and Wales can be attributed to their common palaeogeographical location to the north of the Rhenohercynian margin.

Considering the general sedimentological development from the Ordovician to the Late Devonian–Early Carboniferous in the Balkan and the Istanbul Terranes and their correlation with the Saxo-Thuringian or Moldanubian zones of Central Europe, their most probable position was to the south of the Rhenohercynian suture.

In the Bulgarian and NW Anatolian realm the terrane boundaries are covered by Mesozoic–Tertiary successions and complicated by Cimmerian and Alpine deformations. Hence, there are no surface or subsurface data to locate exactly the sutures between these terranes. Moreover, no ophiolite-bearing subduction–accretion prisms of Palaeozoic age have yet been identified along the terrane boundaries. The only ophiolitic material between the Moesian, Balkan and Thracian Terranes in Bulgaria has been proven (e.g. Haydutov & Yanev 1997) to be of Pan-African age. The absence of ophiolitic material suggests that the terranes may have been juxtaposed by wrench-faulting (Kerey 1984) or oblique docking (Göncüoğlu 1997).

Conclusions

Existing data on the Palaeozoic rocks in the eastern part of the Variscan Suture Zone need to be enhanced by further detailed palaeomagnetic and geophysical data, especially in the Turkish part. However, the available data provide a solid starting point for a preliminary geodynamic interpretation. This interpretation is mainly based on stratigraphical, sedimentological, palaeofaunal and biogeographical data for palaeogeography and basin development.

The present data support Yanev's hypothesis of the peri-Gondwanan origin of the Moesian Terrane, its northward migration between Ordovician and Devonian time, the lack of a Scandian unconformity, drifting to the sub-equatorial arid zone in Late Devonian–Early Carboniferous time and accretion to Baltica in the Carboniferous. On the other hand, the Balkan Terrane, also of peri-Gondwanan origin, is very similar to the Saxo-Thuringian Zone and belongs to the late Palaeozoic accreted terranes south of the Rheic Suture. The accretion of the Balkan Terrane to Moesia–Baltica postdates the Early Carboniferous and continued during the Late Carboniferous and Permian. The collision between the terranes was not a coeval event but a polyphase process.

For the Zonguldak and Istanbul Terranes in NW Anatolia, the Late Pan-African–Cadomian crystalline basement and the fossil provinciality for the Early Palaeozoic are considered as important evidence for their peri-Gondwanan origin. After drifting across the Rheic Ocean, the Zonguldak Terrane probably collided with Baltica during the Early Devonian and the Istanbul Terrane accreted to the northern palaeocontinent in the Serpukhovian. As no Palaeozoic oceanic lithologies have yet been identified, their accretion during the Variscan convergence may have involved strike-slip tectonics.

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