International Geology Review

Tectonic evolution of the southern margin of Laurasia in the Black Sea region

Aral I. Okay\textsuperscript{ab} & Anatoly M. Nikishin\textsuperscript{c}

\textsuperscript{a} Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey
\textsuperscript{b} Department of Geology, Istanbul Technical University, Maslak 34469, Istanbul, Turkey
\textsuperscript{c} Geological Faculty, Moscow State University, Moscow, Russia

Published online: 19 Feb 2015.

To cite this article: Aral I. Okay & Anatoly M. Nikishin (2015): Tectonic evolution of the southern margin of Laurasia in the Black Sea region, International Geology Review, DOI: 10.1080/00206814.2015.1010609

To link to this article: http://dx.doi.org/10.1080/00206814.2015.1010609

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions
Tectonic evolution of the southern margin of Laurasia in the Black Sea region

Aral I. Okay and Anatoly M. Nikishin

*Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey; Department of Geology, Istanbul Technical University, Maslak 34469, Istanbul, Turkey; Geological Faculty, Moscow State University, Moscow, Russia

(Received 13 March 2014; accepted 19 January 2015)

The Black Sea region comprises Gondwana-derived continental blocks and oceanic subduction complexes accreted to Laurasia. The core of Laurasia is made up of an Archaean–Palaeoproterozoic shield, whereas the Gondwana-derived blocks are characterized by a Neoproterozoic basement. In the early Palaeozoic, a Pontide terrane collided and amalgamated to the core of Laurasia, as part of the Avalonia–Laurasia collision. From the Silurian to Carboniferous, the southern margin of Laurasia was a passive margin. In the late Carboniferous, a magmatic arc, represented by part of the Pontides and the Caucasus, collided with this passive margin with the Carboniferous eclogites marking the zone of collision. This Variscan orogeny was followed by uplift and erosion during the Permian and subsequently by Early Triassic rifting. Northward subduction under Laurussia during the Late Triassic resulted in the accretion of an oceanic plateau, whose remnants are preserved in the Pontides and include Upper Triassic eclogites. The Cimmeride orogeny ended in the Early Jurassic, and in the Middle Jurassic the subduction jumped south of the accreted complexes, and a magmatic arc was established along the southern margin of Laurasia. There is little evidence for subduction during the latest Jurassic–Early Cretaceous in the eastern part of the Black Sea region, which was an area of carbonate sedimentation. In contrast, in the Balkans there was continential collision during this period. Subduction erosion in the Early Cretaceous removed a large crustal slice south of the Jurassic magmatic arc. Subduction in the second half of the Early Cretaceous is evidenced by eclogites and blueschists in the Central Pontides and by a now buried magmatic arc. A continuous extensional arc was established only in the Late Cretaceous, coeval with the opening of the Black Sea as a back-arc basin.

Keywords: Laurasia; Laurussia; Pontides; Caucasus; Black Sea; subduction; accretion; magmatic arcs

Introduction

The geological evolution of the Black Sea region is charted here from the early Palaeozoic to Tertiary in terms of major tectonic events. This review incorporates data which have become available from the region over the last ten years. The geological data are shown through outcrop distribution maps of the Black Sea region for the critical periods. There is a large body of geological literature on the Black Sea region in Russian and Turkish; however, for ease of access, the references here are restricted to those in English. Other reviews of the geology of the region (e.g. Nikishin et al. 1996, 2001, 2012; Okay and Şahintürk 1997; Adamia et al. 2011; Somin 2011) have citations to references in these languages.

The Pontides were adjacent to Laurasia before the Late Cretaceous opening of the Black Sea, and constituted its southern continental margin during much of the Phanerozoic. They consist of several continental and oceanic blocks, which were accreted to Laurasia over the last 500 million years. A significant feature of the Pontides is the presence of extensive outcrops with a wide range of ages and rock types, which contrasts with the almost complete lack of pre-Tertiary outcrops north of the Black Sea (Figure 1). The geological evolution of the Black Sea region is, therefore, based to a very large extent on data from Crimea, Caucasus, Pontides, Balkans, and Dobruja, which were exhumed during the late Tertiary (e.g. Vincent et al. 2011; Albino et al. 2014). Especially, the Pontides and the Caucasus with their widely exposed and varied Precambrian to Mesozoic sequences are critical for deciphering the geological history of the southern margin of Laurasia.

The interaction of two megacontinents, Gondwana and Laurasia, and the intervening oceans, forms the dominant motif in the geological evolution of the Black Sea region. The general pattern is the separation of continental slivers from Gondwana and their accretion to Laurasia (e.g. Şengör 1984; Stampfli and Borel 2002). One additional process, which is emphasized here, is the growth of Laurasia by addition of oceanic subduction complexes during the Mesozoic.

The collision of Gondwana and Laurussia in the late Carboniferous led to the Variscan orogeny in southern Europe, southeastern North America, and northwest Africa and resulted in the creation of the supercontinent Pangea (e.g. Ziegler 1989). In contrast, most of Asia escaped the collision and continued to face a Palaeo-Tethyan ocean in the south (e.g. Dercourt et al. 2000;
The Black Sea region is located in this transitional region between Carboniferous continental collision in the west and continuing oceanic subduction in the east. Laurasia, Laurussia, and Baltica are the names used for the same continent north of the Black Sea over geological time (cf. Cocks and Torsvik 2006). However, as there has been no change in the configuration of the stable shield north of the Black Sea since the Neoproterozoic (e.g. Gorbatev and Bogdanova 1993), the northern continent is referred to here as Laurasia. The East European Platform refers to the Archaean–Palaeoproterozoic basement and its Proterozoic and younger sedimentary cover.

Geological setting

A major distinction in the Black Sea region is between the East European Platform with its Archaean and Palaeoproterozoic basement, and the Gondwana-derived blocks in the south (Figure 1). The Black Sea is a Late Cretaceous back-arc basin with oceanic crust (e.g. Okay et al. 1994; Robinson et al. 1996; Nikishin et al. 2015a),
and prior to its opening, the Pontides were located directly south of the East European Platform between Moesia and the Greater Caucasus (Figure 2). The Pontides consist of three terranes, which were amalgamated before the Tertiary. From west to east, these are the Strandja Massif and Istanbul and Sakarya zones (Figure 1). The Lesser Caucasus forms the eastward extension of the Sakarya Zone, separated only by the national border between Turkey and Georgia (e.g. Yılmaz et al. 2000). The Greater Caucasus is a predominantly Variscan orogen and was the site of a Jurassic–Cretaceous basin, which was inverted in the Miocene due to the Arabia–Eurasia collision (e.g. Vincent et al. 2011; Adamia et al. 2011).

The Kırşehir Massif is a Cretaceous ensialic magmatic arc accreted to Laurasia in the early Tertiary (e.g. Whitney and Hamilton 2004; Lefebvre et al. 2013).

The Anatolide–Tauride Block forms the latest Gondwana-derived block accreted to the Laurasia margin during the Palaeocene–Eocene. Early palaeogeographic reconstructions show the Pontides and the Anatolide–Tauride Block as a single continental unit prior to early Mesozoic rifting (e.g. Şengör and Yılmaz 1981). However, data obtained subsequently showed that although both were located on the margins of Gondwana during the Neoproterozoic, they did not form conjugate margins (Figure 3; e.g. Dean et al. 2000; Okay et al. 2006a). The

Figure 2. A possible configuration of the Laurasia margin during the Middle Jurassic before the opening of the Black Sea basin. The location of the Tornquist suture is highly uncertain.
The location of the Anatolide–Tauride Block is relatively well constrained on the northeast margin of Africa—north of Egypt, Syria, and Iraq (cf. Figure 3; e.g. Schattner and Ben-Avraham 2007). In the classical view, the Pontides were rifted from the northern margin of the Anatolide–Tauride Block during the Triassic or Early Jurassic (e.g. Şengör and Yılmaz 1981). However, the Pontide terranes and the Anatolide–Tauride Block have very different pre-Jurassic geological histories. For example, Variscan and Cimmeride deformation and metamorphism, prominent in the Pontides, are not observed in the Anatolide–Tauride Block, which has a thick, well-developed Palaeozoic sedimentary succession, similar to that of the Arabian Plate. Furthermore, recent discovery of Carboniferous and Permain pelagic sedimentary deposits in the ophiolitic melanges in the Taurides (Moix et al. 2011) suggests that the Anatolide–Tauride Block was facing a Palaeozoic Tethyan ocean in the north, in other words, it was part of the passive margin of Gondwana during the Palaeozoic (Figure 3). The Triassic rift deposits in the Anatolide–Tauride Block are related to its separation from the Africa–Arabia, to its southern rather than to its northern margin. The Istanbul and Sakarya zones of the Pontides were part of Avalonia and Armorica, respectively, and were located on the northwestern margin of Africa in the early Palaeozoic (Figure 3). The Palaeozoic–Mesozoic history of the Anatolide–Tauride Block is hence unrelated to that of the Laurasia and will not be considered here.

East European platform

Archaean and Palaeoproterozoic gneisses and granites locally overlain by a thin veneer of sedimentary rocks constitute the basement of the East European Platform north of the Black Sea; they form two vast masses—the Ukranian shield and the Voronezh Massif (Figure 1; Claesson et al. 2006; Bogdanova et al. 2008). The Archaean and Palaeoproterozoic basement is a characteristic feature of the East European Platform and distinguishes it from the Gondwana-derived terranes farther south. Gondwana margins were shaped by the late...
Neoproterozoic Pan–African orogeny, characterized by the dominance of granitoids of 590–560 Ma ages (e.g. Stern 1994). The distinctive basement ages, Archaean–Palaeoproterozoic versus late Neoproterozoic, allow recognition of Gondwana-derived fragments in the Alpine–Himalayan chain (e.g. Neubauer 2002).

The Ukrainian Shield and the Voronezh Massif are separated by a large Upper Devonian–Carboniferous intra-cratonic rift, the Dniepr–Donets basin (Figure 1) with up to 22 km-thick upper Palaeozoic–Mesozoic sedimentary rocks (Stovba and Stephenson 1999). The basin was inverted during the latest Cretaceous–early Tertiary forming the Donbass Foldbelt. Stovba and Stephenson (1999) also describe a strong Late Triassic folding in the eastern part of the Donbass Foldbelt. The Tornquist–Teisseyre Line forms the western edge of the East European Platform. It is a major tectonic lineament separating the East European Platform from Gondwana-derived blocks in central Europe, which were deformed during the Palaeozoic (e.g. Guterch et al. 1999).

The Ukrainian Shield is bordered in the south by a wide belt known as the Scythian Platform. Information on the stratigraphy and structure of the Scythian Platform is very limited as it is covered by Tertiary sedimentary rocks (Figure 1). It is generally considered as a Variscan belt (e.g. Zonenshain et al. 1990); however, its locations north of the Variscan core of the Greater Caucasus with Carboniferous eclogites and serpentinites, and stratigraphic data from the Pontides suggest that at least part of the Scythian Platform could have been accreted to the East European Platform during the early Palaeozoic and part of it could represent an even older continental margin (Figure 2; Stephenson et al. 2004; Saintot et al. 2006).

**Gondwana-derived blocks**

Gondwana-derived blocks in the Black Sea region can be broadly divided into two types: the Avalonia and Armorica. The first were accreted to the East European Platform during the early Palaeozoic, whereas the accretion of the Armorica-type blocks to the East European Platform occurred during the Carboniferous (Figure 2).

**Avalonia-type blocks**

The Avalonia-type blocks include Moesia, Dobruga, Istanbul Zone, and probably part of the Scythian Platform. They are characterized by a late Neoproterozoic granitic basement (590–560 Ma, Seghedi 2001, 2011; Chen et al. 2002; Ustaömer et al. 2005; Okay et al. 2008) overlain by a Palaeozoic sedimentary sequence of Ordovician to Carboniferous age (Göör et al. 1997; Tari et al. 1997; Dean et al. 2000; Kalvoda and Bábek 2010; Özkul 2012; Sayar and Cocks 2013). The sedimentary sequence has a transgressive character and ranges from Ordovician red continental clastics to Upper Devonian–lower Carboniferous deep marine sedimentary rocks with marked lateral facies differences, and ends with lower Carboniferous turbidites or upper Carboniferous coal measures (Figure 4).

**Armorica-type blocks**

The Armorica-type blocks include the Greater and Lesser Caucasus, Strandja Massif and the Sakarya Zone. The lower Palaeozoic sequences in these blocks are metamorphosed or not present. Another distinguishing feature of these blocks is the extensive Carboniferous plutonism and high-temperature metamorphism.

**Early Ordovician: separation of the Avalonian Moesia–Istanbul Block from Gondwana**

Early in the Ordovician, the Istanbul Zone and Moesia and probably part of the Scythian Platform were separated from the margins of Gondwana and drifted north, opening the Rheic Ocean in their wake. These blocks were part of a much larger microplate, termed Avalonia, a major component of the early Palaeozoic palaeogeography in Europe (e.g. Cocks and Torsvik 2002).

Palaeozoic rocks are now buried under the Tertiary sediments of the Scythian Platform; therefore, most of the information on the Palaeozoic history of the region comes from the Pontides. The crystalline basement of the Istanbul Zone with widespread late Neoproterozoic granitoids (Figure 1) attests to its location on the northern margin of Gondwana at this period. The basement is overlain by a Lower–Middle Ordovician red sandstone and conglomerate, over 3000 m thick (Figure 4). This continental sequence probably marks the rifting of the Istanbul Zone from the northern Gondwana margin.

The thick and well-developed Palaeozoic succession of the Istanbul Zone indicates that it was not an isolated continental sliver but was part of a much larger lithospheric plate. Its early Palaeozoic history and trilobite and brachiopod faunas are similar to Avalonia in northwest Europe (e.g. Dean et al. 2000), and the Istanbul Zone has been considered as the eastward extension of Avalonia (Stampflí and Borel 2002; Stampflí et al. 2002; Winchester 2002; Kalvoda et al. 2003; Okay et al. 2006a, 2008; Bozkurt et al. 2008; Sunal et al. 2008; Franke 2014). This is also supported by the detrital zircons from the Ordovician and Silurian sandstones (Ustaömer et al. 2011), which show an absence of 2400–2050 Ma detrital zircons, a characteristic Avalonian feature (Samson et al. 2005). In northwest Europe, Avalonia was separated from Gondwana during the Early–Middle Ordovician with the opening of Rheic Ocean to its south and was accreted to the southwestern margin of Baltica during latest
Before the Late Cretaceous opening of the western Black Sea, the Istanbul Zone was adjacent to Moesia (Figure 2; Okay et al. 1994). Although Moesia is largely covered by Cretaceous and younger sedimentary rocks, well data indicate that it has a Palaeozoic stratigraphy similar to that of the Istanbul Zone, including Carboniferous coal measures in southeast Moesia, which correlate with those in the Zonguldak region of the Istanbul Zone (Tari et al. 1997; Kalvoda and Bábek 2010). The eastward extension of the Avalonian Moesia-Istanbul (MOIS) terrane is difficult to trace since the region between the Ukranian Shield and mountainous Crimea-Caucasus is covered by Neogene deposits. The presence of Carboniferous eclogites on the northern
margin of the Caucasus (Philippot et al. 2001) indicates that the Avalonia-type terranes, if present, must lie north of the Crimea and Greater Caucasus (Figure 2).

Late Ordovician–early Silurian: amalgamation of Moesia–Istanbul Block with Laurasia

Data from northwest Europe suggest that during the latest Ordovician (Ashgill) Avalonia collided with Laurasia (e.g. Cocks and Torsvik 2002, 2006). The accretion of the Istanbul and Moesian blocks to Laurasia, on the other hand, is poorly constrained. Palaeomagnetic studies suggest that after the middle Silurian the Istanbul Zone was located on the southern margin of Laurasia and constituted part of the northern passive margin of the Rheic Ocean (Evans et al. 1991). The Devonian and Carboniferous foraminiferal assemblages in the Istanbul Zone are also typically Laurasian (Kalvoda et al. 2003). The northern margin of the Istanbul terrane, where there might be stratigraphic evidence for collision, lies under the Black Sea or is covered by Tertiary sediments (Figure 1). The Upper Ordovician interbedded sandstone–siltstone–shale sequence, interpreted by Sayar and Cocks (2013) as turbidites, may have been deposited during the accretion of the Istanbul terrane to Laurasia. The collision of the MOIS Block to Laurasia must have been soft, which is also the case for the Avalonia–Laurasia collision in northwest Europe. The thick and well-developed Ordovician–Silurian sequence of the Istanbul Zone, Moesia and Dobrugea are devoid of volcanic rocks (Tari et al. 1997; Seghedi 2011; Özgül 2012), which implies that the subduction was dipping under Laurasia, unlike the case for the western parts of Avalonia (Figures 2 and 3).

From Silurian onwards, the Istanbul Zone and Moesia formed part of the passive margin of Laurasia characterized by a deepening upward sedimentary sequence (Figure 4) facing the Rheic Ocean in the south (Stampfl 2002). The eastern part of the Istanbul Zone was in a shallower and more proximal position closer to the continent.

Carboniferous: Variscan orogeny – collision of a continental magmatic arc with Laurasia

During the Carboniferous, a continental magmatic arc collided with the southern margin of Laurasia. In the Black Sea region, this arc is represented by a zone of Permo-Carboniferous metamorphism and magmatism south of the Avalonian blocks (Figure 5); they include the Rhodope and Strandja massifs in the Balkans, the Sakarya Zone in the Pontides and the Caucasus, which can be correlated with the Armorican terranes in central Europe. Their location south of the Avalonian blocks and local presence of late Neoproterozoic granitoids indicate that they were also derived from Gondwana. However, data on the age of separation of the Black Sea Armorican terranes from Gondwana are virtually non-existent since their lower Palaeozoic sequences are either metamorphosed or are not present. Stampfl and Borel (2002) favour a late Silurian (Ludlow) age of rifting for the Armorican terranes.

The best evidence for a suture between the Avalonia and Armorican-type terranes in the Black Sea region comes from the northern margin of the Caucasus, where Perchuk and Philippot (1997) and Philippot et al. (2001) describe a tectonic belt of ultramafic rocks and kyanite-eclogites (Figure 5) with late Carboniferous (316–300 Ma) Sm–Nd, Lu–Hf garnet, and Ar–Ar phengite ages. Carboniferous granitoids with 330–300 Ma ages and with subduction geochemical signatures are widespread in the Greater Caucasus and in the Eastern Pontides–Lesser Caucasus region (Figure 5). In both regions, they are associated with granulite to high amphibolite facies metamorphic rocks and migmatites. The peak of the high-temperature metamorphism is estimated to have taken place at 330 Ma both in the Eastern Pontides and in the Lesser Caucasus (Topuz et al. 2004a; Mayringer et al. 2011). The plutonism and high-temperature metamorphism most likely occurred in the core of a magmatic arc.

As both the Istanbul Zone and Moesia are free of Devonian or Carboniferous magmatism and have characteristics of a passive continental margin, the Rheic Ocean must have been consumed by southward subduction. The collision occurred between a magmatic arc, represented by the Armorican-type terranes, and the passive margin of Laurasia. The latest Carboniferous (Kasimovian and Gzelian) molasse-type shallow marine to continental sedimentary rocks in the Eastern Pontides and Caucasus (Okay and Leven 1996; Çapkanoğlu 2003; Somin 2011) provide an upper age limit for the collision, which probably occurred at 320–310 Ma (Bashkirian–Moscovian) in the east in the Caucasus–Eastern Pontide region. In the west in the Istanbul Zone and in the Balkans, the collision was probably earlier. In the western part of the Istanbul Zone, siliciclastic turbidites, over 2000 m thick, were deposited during the early Carboniferous (Figure 4). The source of the turbidites was in the south from an approaching Armorican arc-terrane, as indicated by detrital zircon and rutile ages from the turbiditic sandstones, which are dominated by Late Devonian–early Carboniferous ages and do not comprise zircons of 700–1700 Ma age interval (Okay et al. 2011b). These are typical features of the Armorican terranes. The detrital zircon-rutile data and the abrupt termination of lower Carboniferous turbidite sedimentation followed by folding and thrusting with a NE vergence suggest that the collision of the Armorican terrane, possibly the Sakarya Zone, with Istanbul segment of the Laurasia margin started in the early Carboniferous (Visean, 340–330 Ma) in the west.
Permo-Triassic: restoration after the Variscan orogeny

The Carboniferous collision between Laurasia and Gondwana created the megacontinent Pangea, which during the Permian was predominantly a region of erosion or continental sedimentation (e.g. Ziegler 1989). Most of the Black Sea region was also undergoing uplift in the Permian, and Permian deposits are either not present or are represented by continental red beds, except for some shallow marine deposits in the Caucasus (e.g. Gaetani et al. 2005). Permian continental red beds are difficult to distinguish from those of the Lower Triassic; however, palynology and vertebrate palaeontology from the eastern part of the Istanbul Zone indicate that some of the red beds are truly Permian (Gand et al. 2011; Stolle 2015). Late Permian granitoids occur widely in the Strandja Massif and are also found in the Istanbul Zone and in Dobrugea (Figure 5). There is little evidence for subduction in the Permian in the Black Sea region, except for a small accretionary complex in the Eastern Pontides with MORB-type metabasalts with late Permian (~260 Ma) Rb–Sr and Ar–Ar ages (Figure 7; Topuz et al. 2004b). On the other hand, late Permian granitoids in the western part of the Black Sea region are probably related to rifting, which started over a wide area during the latest Permian to Early Triassic (e.g. Nikishin et al. 2002) with the deposition of uppermost Permian to Lower Triassic fluvialite red sandstones and conglomerates intercalated with basaltic lavas, best observed in the western part of the Istanbul Zone and in Dobrugea (Figure 6). The continental red beds pass up into an increasingly deeper marine sedimentary sequence, characterized by the deposition of pelagic nodular limestones in the Middle Triassic.

Latest Triassic: Cimmeride Orogeny – oceanic accretion

The Late Triassic in the Black Sea region is characterized by the deposition of siliciclastic turbidites followed by uplift and deformation, and emplacement of oceanic accretionary complexes (Figure 6; Nikishin et al. 2012).
Deformation is even recorded in Moesia (Tari et al. 1997) and within the East European Platform in the Donbass fold belt (Stovba and Stephenson 1999). The cause of this Cimmeride orogeny is enigmatic. It has been related to the collision of a Cimmerian continent with the Laurasian margin (e.g. Şengör 1984); however, it has not been possible to define a coherent Cimmerian continent in the Pontides or anywhere else in the Black Sea region (e.g. Okay 2000; Topuz et al. 2013a). On the other hand, evidence for subduction and accretion during the Late Triassic is provided by large volumes of accreted oceanic complexes, including eclogites and blueschists, in the Pontides, which are commonly tectonically juxtaposed with the Late Cretaceous accretionary complexes (Figure 7; Bozkurt et al. 1997; Okay et al. 2002; Yılmaz and Yılmaz 2004). The Cimmeride deformation and metamorphism have a short duration and are largely restricted to the latest Triassic (Rhaetian) to the earliest Jurassic. The absence of a colliding continent, short time span of deformation, and great thicknesses of accreted oceanic crustal sequences suggest that the Cimmeride orogeny was caused by a collision and partial accretion of an oceanic plateau (Figure 8), thus it was an accretionary orogeny similar to those in the North American Cordillera (Okay 2000).

The accreted Permo-Triassic oceanic unit in the Sakarya Zone is represented by the Karakaya Complex (e.g. Okay and Gönçüoğlu 2004; Robertson and Ustaömer 2012). A major component of the Karakaya Complex is a tectonically thickened pile of metabasite with minor marble and phyllite of Triassic age, called the Lower Karakaya Complex, which extends throughout the Sakarya Zone. The Lower Karakaya Complex is metamorphosed mainly in high-pressure greenschist facies but also includes Upper Triassic eclogites and blueschists (Okay et al. 2002). The geochemistry of the metabasites indicates predominantly an intra-plate setting (Pickett and Robertson 2004; Sayit et al. 2010; Catlos et al. 2013). With these features the Lower Karakaya Complex is interpreted as a Triassic oceanic plateau, which collided with
and partially accreted to the Laurasian margin during the latest Triassic (Okay 2000; Genç 2004).

The Lower Karakaya Complex is overlain by strongly deformed and locally metamorphosed Permo-Triassic clastic and volcanic rocks, representing trench and fore-arc deposits and accreted oceanic crustal rocks, over several thousand metres in structural thickness (Figure 8). This Upper Karakaya Complex includes olistostromes with Carboniferous and Permian shallow marine limestone blocks both in Turkey and in Crimea (Leven and Okay 1996) and smaller blocks of radiolarian cherts of Devonian, Carboniferous, Permian, and Triassic ages and tectonic slices of pre-Jurassic serpentinites (Kozur and Kaya 1994; Okay et al. 2011a, 2015; Sayit et al. 2011), suggesting subduction-accretion of a Devonian to Late Triassic oceanic crust, the Palaeo-Tethys. The Dizi series on the southern flank of the Greater Caucasus (Figure 7) shows similar features to the Upper Karakaya Complex including upper Palaeozoic limestone blocks, Late Triassic deformation and Lower Jurassic unconformity (Adamia et al. 2011; Somin 2011).

Although there is ample evidence for subduction in the Black Sea region during the Late Triassic, there are no outcrops of Triassic granitoids. Nevertheless, their presence is indicated by the Triassic zircons, which form the dominant population among clastic zircons in the Upper Triassic turbiditic sandstones in Turkey (Karslıoğlu et al. 2012; Ustaömer et al. 2014) and in Crimea (Nikishin and Khudoley, unpublished data). Further support for Triassic acidic to intermediate volcanic rocks is provided by well data, which shows a large belt of Triassic volcanic rocks in the Scythian Platform buried under the Tertiary cover (Figures 7 and 8; Alexandre et al. 2004; Tikhomirov et al. 2004) extending from the northern Crimea in the west (Nikishin et al. 2012) to Central Asia in the east (Natal’ in and Şengör 2005).

Figure 7. Outcrops of Triassic subduction-accretion complexes (Karakaya Complex), and the marine Triassic sequence in the Istanbul and Dobrugea regions. Also shown is the subsurface Triassic magmatic arc. The subsurface distribution of the Triassic subduction-accretion complex is much more continuous and larger than shown here. The isotopic ages and the outcrops of Triassic eclogites and blueschists are from Okay and Monié (1997), Okay et al. (2002), Catlos et al. (2013), and Topuz et al. (2014). The map is based on Anonymous (1972), MTA (2002), and Adamia (2010).
Published palaeogeographic reconstructions for the Triassic show a back-arc basin behind the northward subducting Palaeo-Tethys Ocean in the Black Sea region (e.g. Stampfl and Borel 2002; Barrier and Vrielynck 2008). This is based on the presence of Upper Triassic flysch in the Küre region (Figure 7), which is situated north of a magmatic arc and subduction-accretion complex, which were presumed to be of Triassic age (Ustaömer and...
Robertson 1993, 1994). However, the magmatic arc is recently dated as Middle Jurassic (Figure 9; Okay et al. 2014) and the subduction-accretion complex as Early Cretaceous (Figure 10; Okay et al. 2006b, 2013); the actual Triassic magmatic arc lies north of the Upper Triassic flysch (Figure 7). Hence, the Upper Triassic flysch in the Central Pontides has a similar tectonic setting with the rest of the Upper Karakaya Complex and represents a deformed fore-arc basin sequence (Okay et al. 2015).

**Jurassic: subduction and formation of a continental magmatic arc**

By the Early Jurassic (Sinemurian), deformation related to the Cimmeride orogeny was largely over; the region underwent uplift and erosion followed by a major transgression, which is especially marked in the Sakarya Zone and in the Caucasus (e.g. Robinson et al. 1995; Okay and Tüysüz 1999; Gaetani et al. 2005; Ruban 2007; Adamia et al. 2011; Somin 2011). The Permo-Triassic subduction-accretion complex and the Variscan granitic and metamorphic basement are overlain with a pronounced unconformity by Lower Jurassic fluviatile to shallow marine conglomerates and sandstones, locally with coal seams, except in Crimea and the Central Pontides, where Cimmeride deformation lasted into the Early Jurassic.

During the Jurassic, there was differentiation between the eastern and western parts of the Black Sea region. In the east, a major extensional magmatic arc developed during the Middle–Late Jurassic (174–158 Ma, Toracian–Oxfordian) along the southern margin of Laurasia. Jurassic volcanic and plutonic rocks with subduction signatures extend from the Central Pontides through Eastern Pontides and Caucasus to Makran forming a linear belt, 2800 km long (Figure 9; McCann et al. 2010; Meijers et al. 2010a; Chiu et al. 2013; Okay et al. 2014). The magmatic arc is marked by a thick sequence of volcaniclastic and volcanic rocks, and minor acidic to intermediate intrusive rocks, which have subduction-related geochemical signatures (Yılmaz and Boztuğ 1986; Mengel et al. 1987; Şen 2007; Genç and Tüysüz 2010; Meijers et al. 2010a; Okay et al. 2014). In the Central
Pontides, high-temperature low-pressure metamorphic rocks, representing mid-crustal levels of a Middle Jurassic continental magmatic arc, are also exposed (Okay et al. 2014). The Jurassic arc granitoids intrude Triassic subduction-accretion complexes in the Pontides, indicating that the subduction zone jumped south of the accreted oceanic complexes. South of the Jurassic arc, there is a wide belt of ophiolite, ophiolitic mélangé and related metamorphic rocks in the Central and Eastern Pontides (Figure 9), which were considered to be Cretaceous in age. However, recent isotopic data have shown that at least some of the ophiolites and related metamorphic rocks are Middle Jurassic in age (Figure 9; Dilek and Thy 2006; Celik et al. 2011; Göncüoğlu et al. 2012; Okay et al. 2013, 2014; Topuz et al. 2013a, 2013b), providing further support for subduction during the Jurassic.

In the west, the Lower–Middle Jurassic sequences are either missing, as in the Istanbul Zone, or are represented by shallow marine sedimentary rocks with no trace of volcanism, as in the Strandja Massif (Figure 9).

**Late Jurassic–Early Cretaceous (Kimmeridgian–Valanginian): continental collision in the west and carbonate deposition in the east**

The differentiation between the western and eastern parts of the Black Sea region continued in the Late Jurassic and Early Cretaceous. In this period (Kimmeridgian to Valanginian), an extensive carbonate platform was established in the east in the Sakarya Zone, in Crimea, and in the Caucasus (Figure 10; Altiner et al. 1991; Kuznetsov 1993; Robinson et al. 1995; Ruban 2007; Krajewski and Olszewska 2007; Guo et al. 2011; Nikishin et al. 2015b). The shallow marine carbonates, locally with basal continental clastic rocks, unconformably cover the Lower–Middle Jurassic volcanic or granitoidic rocks (Okay et al. 2014). In the southern margins of the Eastern Pontides and Caucasus, they pass into pelagic limestones and calciturbidites, which suggest that the carbonate platform was facing an ocean in the south (Figure 10; Okay and Şahintürk 1997). There is no evidence for subduction during the Late Jurassic and early part of the Early

Figure 10. Outcrops of the Upper Jurassic–Lower Cretaceous (Kimmeridgian–Valanginian) carbonates, and Lower Cretaceous (Aptian–Albian) subduction-accretion complexes in the Black Sea region. The isotopic ages are from Okay et al. (2006b, 2013). The map is based on Anonymous (1972), MTA (2002), Adamia (2010), and Okay et al. (2013).
Cretaceous possibly because there was little convergence between Laurasia and Gondwana in this period, the plate motion being left-lateral transform (Smith 2006).

In contrast to the quiet carbonate deposition in the east, regional metamorphism associated with N-vergent contractional deformation took place in the west in the Strandja Massif and possibly in the Circum–Rhodope Belt during the Late Jurassic (Oxfordian, 160–150 Ma, Okay et al. 2001; Elmas et al. 2011; Sunal et al. 2011). The geological history of the Strandja Massif is linked to that of the Rhodope Massif in the west, which has a complicated poorly understood tectonic and metamorphic evolution (e.g. Burg 2012). Prior to the Late Jurassic deformation and metamorphism, the Strandja Massif was located on the continental shelf of Europe (Okay et al. 2001). The thick-skinned deformation of the continental shelf and its regional metamorphism, the scarcity of oceanic crustal rocks and the duration of the orogeny (160–140 Ma) suggest a continental collision, possibly between Rhodope and the Strandja massifs. The deformation in the Strandja Massif was over by the Cenomanian (ca. 99 Ma) when shallow marine sandstones and limestones were deposited on the metamorphic rocks (Okay et al. 2001).

Early Cretaceous (Hauterivian–Albian): subduction erosion

Subduction under Laurasia in the second half of the Early Cretaceous, in the Aptian–Albian, is evidenced by the eclogites and blueschists of this age in the Central Pontides (Figure 10; Okay et al. 2006b, 2013). They form part of a large oceanic subduction complex accreted to the southern margin of Laurasia during the Aptian–Albian. The Aptian–Albian subduction-accretion complexes, which crop out farther west between Istanbul and Sakarya zones (Figure 10; Akbayram et al. 2013), are either induced later by strike-slip faulting (e.g. Elmas and Yiğitbaş 2001) or indicate the existence of a Mesozoic ocean between these blocks.

Although there is clear evidence for subduction, a contemporary magmatic arc is not exposed. Based on subsurface data, Nikishin et al. (2012, 2015b) show magmatism north of Crimea (Figure 10); this is also supported by the abundance of Albian zircons in the Cretaceous–Eocene sediments of southern Crimea (Nikishin and Khudoley, unpublished data). The Aptian–Albian subduction was preceded by a widespread uplift in the middle of the Early Cretaceous (Hauterivian–Barremian), which terminated the carbonate deposition in the Sakarya, Crimea, and the Caucasus. Most of the region stayed above sea level until the Late Cretaceous.

An exception to the general absence of late Lower Cretaceous sedimentary rocks is the Central Pontides where a large submarine turbidite fan fed partially from the East European Platform extended from the shelf down to the ocean (Figure 10; Okay et al. 2013). The distal parts of the turbidite fan were subducted and metamorphosed during the Aptian–Albian. The source to basin relation between the East European Platform and the Pontides indicates that the Black Sea, as a large basin, was not in existence in the Early Cretaceous.

Subduction erosion is common along the present-day convergent margins and is expected to have occurred widely in the past (e.g. Scholl and Von Huene 2010). It is characterized by the erosion of the upper plate, which is marked by landward migration of the magmatic arc. The magmatic arcs form at 100–125 km above the subducting slab and generally 200 km inland of the trench (e.g. Hamilton 1995; Stern 2002; Heuret et al. 2011). The Middle Jurassic magmatic-arc front in the Pontides is located south of the Cretaceous one and very close the İzmir–Ankara suture (Figure 11), indicating that a large crustal section south of the magmatic arc is missing, most likely through subduction erosion (Topuz et al. 2013b). The subduction erosion is constrained between the Late Jurassic (Oxfordian) and Early Cretaceous (Albian), and most probably occurred in the Early Cretaceous (Hautevian–Barremian), when there was widespread uplift through the Black Sea region.

Late Cretaceous: subduction in extensional mode, development of a major magmatic arc and opening of the Black Sea

The arc magmatism in the Black Sea region started in the early Late Cretaceous (Turonian) and continued for at least 20 million years, until the end of the Campanian (Okay and Şahintürk 1997). It formed a continuous Upper Cretaceous volcanic belt extending from the Lesser Caucasus to the Balkans (Figure 12). South of the volcanic belt there was a fore-arc basin, with several thousand metre thick siliciclastic turbidites. Shallow marine sedimentation prevailed in northern part of the Black Sea, except in the Greater Caucasus, where there was a basin with turbidite deposition (Nikishin et al. 2008). The magmatism waned in the Maastrichtian, when white marly limestones ( chalk) were deposited over large areas.

The Late Cretaceous volcanism was all submarine; this feature and the large accumulated thickness of volcanoclastic and volcanic rocks, locally over 2000 m, indicate an extensional magmatic arc. The volcanic centres are probably now located offshore in the Black Sea (Nikishin et al. 2015a, 2015b). The opening of the Western and Eastern Black Sea basins occurred during the arc magmatism, predominantly in the Coniacian–Santonian (Tüysüz 1999; Okay et al. 2013). Late Cretaceous magmatic rocks in the Eastern Pontides are predominantly extrusive; the volumetrically minor
plutonic rocks are restricted to the west, mainly to the Balkans (Figure 12).

In the early part of the Late Cretaceous (Cenomanian–Turonian), just prior to the inception of arc magmatism, there was northward emplacement of ophiolitic mélange in the Eastern Pontides and Lesser Caucasus (Okay and Şahintürk 1997), possibly related to the steepening and back-thrusting of the oceanic accretionary complex.

A different Late Cretaceous magmatic arc crops out in the Kırşehir Massif south of the İzmir-Ankara suture. It consists predominantly of granitoidic rocks of Cenomanian–Campanian ages (95–75 Ma) intruding Late Cretaceous metamorphic rocks of continental crustal origin and the overlying ophiolites (Figure 12; Whitney and Hamilton 2004; Lefebvre et al. 2011, 2013). This Central Anatolian magmatic arc is unrelated to the Pontide arc and probably constituted an isolated island arc within the Neo-Tethyan Ocean (Figure 13), which collided with the Pontides in the Palaeocene (e.g. Lefebvre et al. 2013).

Ophiolite and ophiolitic mélange crop out over large areas in western Turkey south of the İzmir-Ankara suture (Figure 12). The ophiolites have formed during the early Late Cretaceous (Turonian–Cenomanian), which is based on the age of the sub-ophiolite metamorphic rocks (95–90 Ma), whereas the ophiolitic mélange includes radiolarian cherts of Triassic to Cretaceous ages (Tekin et al. 2002), indicating subduction of a Mesozoic oceanic crust (Okay and Whitney 2010; Plunder et al. 2013). Their emplacement is related to the subduction of the continental margin of the Anatolide–Tauride Block in an intra-oceanic subduction zone during the Campanian (Figure 13). Pontides were on a different lithospheric plate during the Late Cretaceous and were not affected by this major phase of high-pressure metamorphism and deformation.

Palaeocene–early Eocene: collision and amalgamation of the Anatolide–Tauride Block

In the Palaeocene and early Eocene, the Anatolide–Tauride Block and the Kırşehir Massif collided with the Laurasia margin and thereby closed the northern Neo-Tethys (Şengör and Yılmaz 1981; Okay and Şahintürk 1997; Kaymakçı et al. 2009; Sosson et al. 2010). The collision produced Palaeocene fore-land basins in the Eastern Pontides, and northward imbrication of the Eastern Pontides and the Lesser Caucasus. The arc-shaped
geometry of the Central Pontides was also formed during the collision in the latest Cretaceous and Palaeocene (Meijers et al. 2010b). The final major event in the long history of the Gondwana–Laurasia convergence was the Miocene collision between Arabia and Laurasia (Okay et al. 2010).

Subduction episodes along the southern Laurasia margin

Oceanic subduction can be accretionary or erosive (e.g. Scholl and Von Huene 2010). Erosive subduction is characterized by landward migration of the trench and leaves little in the rock record. In contrast, accretionary subduction is marked through arc magmatism and by the growth of accretionary complexes, which may include rocks metamorphosed at high pressures. The duration of subduction is difficult to establish from a study of accretionary complexes since differentiation of the age of the matrix from the age of the blocks or tectonic slices in an accretionary complex is ambiguous. High-pressure metamorphic rocks provide primary evidence for subduction since no other tectonic environment on Earth can produce similar P-T conditions. However, their metamorphic ages provide an imprecise signature for the timing of subduction for two reasons. First, Ar–Ar phengite dating, the predominant dating method in high-pressure metamorphic rocks, gives inaccurate and imprecise results in eclogites and blueschists due to problems with excess argon or argon loss (e.g. Sherlock et al. 1999). Second, high-pressure metamorphism occurs at several tens of kilometres depth and not all blueschists and eclogites are necessarily returned to the surface. The best record for accretionary subduction is provided by arc magmatism, which is produced once the subducting slab reaches a depth of about 100–125 km (e.g. Stern 2002), which with average subduction rates can occur within two million years. Table 1 shows the palaeontological and isotopic ages for arc magmatism, that of subduction- and arc-related metamorphism, along with the primary data sources, for the five major accretionary subduction episodes in the Laurasian margin. The duration of accretionary subduction episodes ranges between 7 and 30 million years and they are interspersed with periods when the subduction was erosional, such as

---

**Figure 12.** Outcrops of Upper Cretaceous magmatic rocks, fore-arc turbidites and ophiolites in the Black Sea region. The isotopic ages are from Moore et al. (1980) and Şahin et al. (2012). The map is based on Anonymous (1972), MTA (2002), and Adamia (2010).
during the Early Cretaceous (Hauterivian–Barremian), or when the margin was transform, such as during the latest Jurassic–earliest Cretaceous (Kimmeridgian–Valanginian).

Conclusions
The geological evolution of the southern margin of Laurasia can be viewed as the growth of the Archaean–Palaeoproterozoic core by addition of Gondwana-derived continental blocks and oceanic subduction complexes. The major geological events along the southern margin of Laurasia are summarized in Figure 14 and Table 1 and are listed below.

1. The Laurasian margin was generally a passive margin during the Palaeozoic and an active margin during most of the Mesozoic and Tertiary.

2. The first collision occurred in the early Palaeozoic, probably at around the Ordovician–Silurian boundary, when the Gondwana-derived Istanbul Block collided with the Laurasia margin. Data for this collision are very weak since the zone of collision is buried under younger sedimentary cover.

3. During the Carboniferous, a magmatic arc collided with the Laurasian margin resulting in the Variscan orogeny. The magmatic arc is represented by the Strandja Massif and the Sakarya Zone of the Pontides and by the Caucasus, which are characterized by Carboniferous plutonism and high-temperature metamorphism. The suture zone is marked by late Carboniferous eclogites and serpentinites on the northern margin of the Greater Caucasus.

4. There is little evidence for subduction during the Permian. However, in the Late Triassic, northward subduction under Laurasia is evidenced by eclogites and
Table 1. Palaeontological and isotopic data on arc magmatism and subduction-related metamorphism on the Laurasia margin.

<table>
<thead>
<tr>
<th>Subduction episodes</th>
<th>Magmatism—palaeontological and isotopic ages</th>
<th>Facies and age of metamorphism in the subduction zone</th>
<th>Facies and age of metamorphism under the arc</th>
<th>Age of the subduction-accretion complex</th>
<th>Time and duration of documented subduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Cretaceous</td>
<td>Turonian to Campanian1,2,3 93–74 Ma4,5,6,7,8,9</td>
<td>Eclogite to blueschist 90–80 Ma10,11</td>
<td>Not known</td>
<td>Late Cretaceous20,30</td>
<td>Turonian–Campanian 94–72 Ma 22 million years</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Albian12 age poorly constrained</td>
<td>Eclogite to blueschist 112–104 Ma2,13</td>
<td>Not known</td>
<td>Poorly constrained Albian</td>
<td>Albian 112–104 Ma 8 million years</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Toarcian to Oxfordian14–17 172–158 Ma18,19</td>
<td>HP greenschist to amphibolite13,20,21</td>
<td>HT amphibolite19</td>
<td>Poorly constrained Toarcian–Oxfordian</td>
<td>174–158 Ma 16 million years</td>
</tr>
<tr>
<td>Late Triassic</td>
<td>Triassic22,23 age poorly constrained</td>
<td>Eclogite to blueschist 24,25</td>
<td>Not known</td>
<td>Late Triassic27,28</td>
<td>NAV–Rhaetian 210–203 7 million years</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>330–295 Ma31–36</td>
<td>Eclogite17,38</td>
<td>HT amphibolite to granulite15,39</td>
<td>Not known</td>
<td>Late Carboniferous 330–300 Ma 30 million years</td>
</tr>
</tbody>
</table>

blueschists in the Pontides and by a buried magmatic arc north of the Caucasus (Figure 7). At around the Triassic–Jurassic boundary, there was widespread deformation throughout the Black Sea region, possibly caused by the collision and accretion of an oceanic plateau.

5. In the Middle Jurassic, northward subduction was established and resulted in the formation of an extensional magmatic arc, which can be traced for 2800 km from the Central Pontides to Makran (Figure 9).

6. Subduction was interrupted during the latest Jurassic–Early Cretaceous (Kimmeridgian–Berriasian) because of slowing down of the plate convergence, and a carbonate platform was established in the eastern part of the Black Sea region (Figure 10).

7. In the western part of the Black Sea region, in the Balkans, there was continent–continent collision during the latest Jurassic–Early Cretaceous (Kimmeridgian–Berriasian), possibly caused by the closing of an ocean between the Strandja and Rhodope massifs.

8. There was subduction erosion during the Early Cretaceous (Hauterivian–Barremian), when the crust south of the Middle Jurassic magmatic arc was
tectonically removed. The present Middle Jurassic arc-front lies south of the Cretaceous magmatic arc and very close to the Izmir–Ankara suture (Figure 11).

9. Subduction became accretory in the second half of the Early Cretaceous (Aptian–Albian), as shown by blueschists and eclogites of oceanic crustal origin in the Central Pontides. There was arc volcanism north of Crimea and possibly in the Caucasus, as revealed by well and elastic zircon data (Figure 10).

10. The subduction was extensional in the Late Cretaceous and lead to the formation of a well-developed magmatic arc, predominantly of Turonian to Campanian age, which can be traced from the Lesser Caucasus through the Pontides to Iran (Figure 12).

11. The subduction was terminated in the Palaeocene–early Eocene by the collision of the Anatolide–Tauride Block, which closed the northern branch of the Neo-Tethys. The last ocean between Gondwana and Laurasia closed through the collision of Arabian Plate in the Miocene.

12. The major unknown in the history of subduction in the Black Sea region is the extent of strike-slip faulting. Orogen parallel transport along major strike-slip faults is common in active margins, where such faults take up the oblique motion of convergence. Strike-slip faulting was most likely important during the Mesozoic along the southern margin of Laurasia but is difficult to document since it was subparallel to the structural grain and left no palaeomagnetic record in the generally E–W-trending Tethyan subduction zones. One possible example is the Tornquist–Teissseyre line, which might have allowed eastward translation of the Istanbul Zone after the Carboniferous (Okay et al. 2011a), another is the possible strike-slip emplacement of Cretaceous ophiolite mélanges between Istanbul and Sakarya zones (Elmas and Yiğitbaş 2001). It is also tempting to speculate large-scale sinistral strike-slip faulting between the Greater and Lesser Caucasus, based on the unusually wide Middle Jurassic magmatic belt (Figure 9), and the location of the Dizi series (Figure 7).

Acknowledgements

We thank Shota Adamia for geological field trips to the Lesser Caucasus, Gültekin Topuz for discussions and an internal review, and Douwe van Hinsbergen for a detailed review, which improved the text.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Geological research in the Pontides over many years for Aral Okay was supported by MTA, TPAO; TÜBA and TÜBİTAK [grant number 109Y049], [grant number 101Y032]. Work of Anatoly Nikishin was supported by the Russian Foundation for Basic Research (RFBR grant 15-05-03004) and Darius project.

References

Adamia, S., 2010, Geological map of Caucasus 2010, 1/1 000 000 scale: M. Nodia Institute of Geophysics, Tbilisi State University, Georgia.


Anonymous, 1972, Internationalen Geologischen Karte von Europa und der Mittelmeerlander, 1/5 000 000 scale: Bundesanstalt für Bodenforschung, Hannover.


Genç, Ş.C., and Türüsüz, O. 2010, Tectonic setting of the Jurassic bimodal magmatism in the Sakarya Zone (Central and Western Pontides), Northern Turkey: A geochemical and isotopic approach: Lithos, v. 118, p. 95–111. doi:10.1016/j.lithos.2010.03.017


Special Publication 81.


Kalvoda, J., Leichmann, J., Babek, O., and Melichar, R., 2003, Brunovistulian Terrane (Central Europe) and Istanbul Zone (NW Turkey): Late Proterozoic and Paleozoic tectonostratigraphic development and paleogeography: Geologia Carpathica, v. 54, p. 139–152.


MTA., 2002, Geological map series of Turkey, 1: 500 000 scale, 18 sheets: Maden Teknik ve Arama Genel Müdurlüğü, Ankara.


Sayar, C., and Cocks, L.R.M., 2013, A new Late Ordovician Hirnantia brachiopod fauna from NW Turkey, its biostatigraphical relationships and palaeogeographical setting: Geological Magazine, v. 150, p. 479–496. doi:10.1017/S0016766312000520


Sayit, K., Tekin, U.K., and Gönçüoğlu, M.C., 2011, Early-middle Carnian radiolarian cherts within the Eymir Unit, Central


Stolle, E., 2015, Çakrak Formation, Çamdağ area, NW Turkey: Early/mid-Permian age, Rotliegend (Germany) and Southern Alps (Italy) equivalent—A stratigraphic re-assessment via palynological long-distance correlation: Geological Journal. doi:10.1002/gj.2620.


