Geological evolution of the Central Pontides

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Abstract: Before the Late Cretaceous opening of the Black Sea, the Central Pontides constituted part of the southern margin of Laurasia. Two features that distinguish the Central Pontides from the neighbouring Pontide regions are the presence of an extensive Lower Cretaceous submarine turbidite fan (the Çağlayan Formation) in the north, and a huge area of Jurassic–Cretaceous subduction–accretion complexes in the south.

The Central Pontides comprise two terranes, the Istanbul Zone in the west and the Sakarya Zone in the east, which were amalgamated before the Late Jurassic (Kimmeridgian), most probably during the Triassic. The basement in the western Central Pontides (the Istanbul Zone) is made up of a Palaeozoic sedimentary sequence, which ends with Carboniferous coal measures and Permo-Triassic red beds. In the eastern Central Pontides, the basement consists of Permo-Carboniferous granites and an Upper Triassic forearc sequence of siliciclastic turbidites with tectonic slivers of pre-Jurassic ophiolite (the Küre Complex). The Küre Complex is intruded by Middle Jurassic granites and porphyries, which constitute the western termination of a major magmatic arc.

Upper Jurassic–Lower Cretaceous shallow-marine limestones (the İnaltı Formation) lie unconformably over both the Istanbul and Sakarya sequences in the Central Pontides. Two new measured stratigraphic sections from the İnaltı Formation constrain the age of the İnaltı Formation as Kimmeridgian–Berriasian. After a period of uplift and erosion during the Valanginian and Hauterivian, the İnaltı Formation is unconformably overlain by an over 2 km-thick sequence of Barremian–Aptian turbidites. Palaeocurrent measurements and detrital zircons indicate that the major part of the turbidites was derived from the East European Platform, implying that the Black Sea was not open before the Aptian. The Çağlayan turbidites pass northwards to a coeval carbonate–clastic shelf exposed along the present Black Sea coast. In the southern part of the Central Pontides, the Lower Cretaceous turbidites were deformed and metamorphosed in the Albian. Albian times also witnessed accretion of Tethyan oceanic crustal and mantle sequences to the southern margin of Laurasia, represented by Albian eclogites and blueschists in the Central Pontides.

A new depositional cycle started in the Late Cretaceous with Coniacian–Santonian red pelagic limestones, which lie unconformably over the older units. The limestones pass up into thick sequences of Santonian–Campanian arc volcanic rocks. The volcanism ceased in the middle Campanian, and the interval between late Campanian and middle Eocene is represented by a thick sequence of siliciclastic and calciclastic turbidites in the northern part of the Central Pontides. Coeval sequences in the south are shallow marine and are separated by unconformities. The marine deposition in the Central Pontides ended in the Middle Eocene as a consequence of collision of the Pontides with the Kırşehir Massif.

Supplementary material: The palaeontological data (foraminifera, nannofossil and pollen) are available at: https://doi.org/10.6084/m9.figshare.c.3842359

The Pontides and the Anatolide–Tauride Block are two major tectonic units of Anatolia, representing the former active and passive margins of the Tethyan Ocean, respectively. The Pontides consists of three terranes, which were amalgamated during the Mesozoic; these are the Strandja Massif in the west, and the Istanbul and the Sakarya zones in the east (Fig. 1) (Okay & Tüysüz 1999). The Central Pontides constitute the northwards arched central segment of the Pontides, and includes parts of the

From: Simmons, M. D., Tari, G. C. & Okay, A. I. (eds) 2018. *Petroleum Geology of the Black Sea*. Geological Society, London, Special Publications, **464**, 33–67.
First published online September 15, 2017, https://doi.org/10.1144/SP464.3

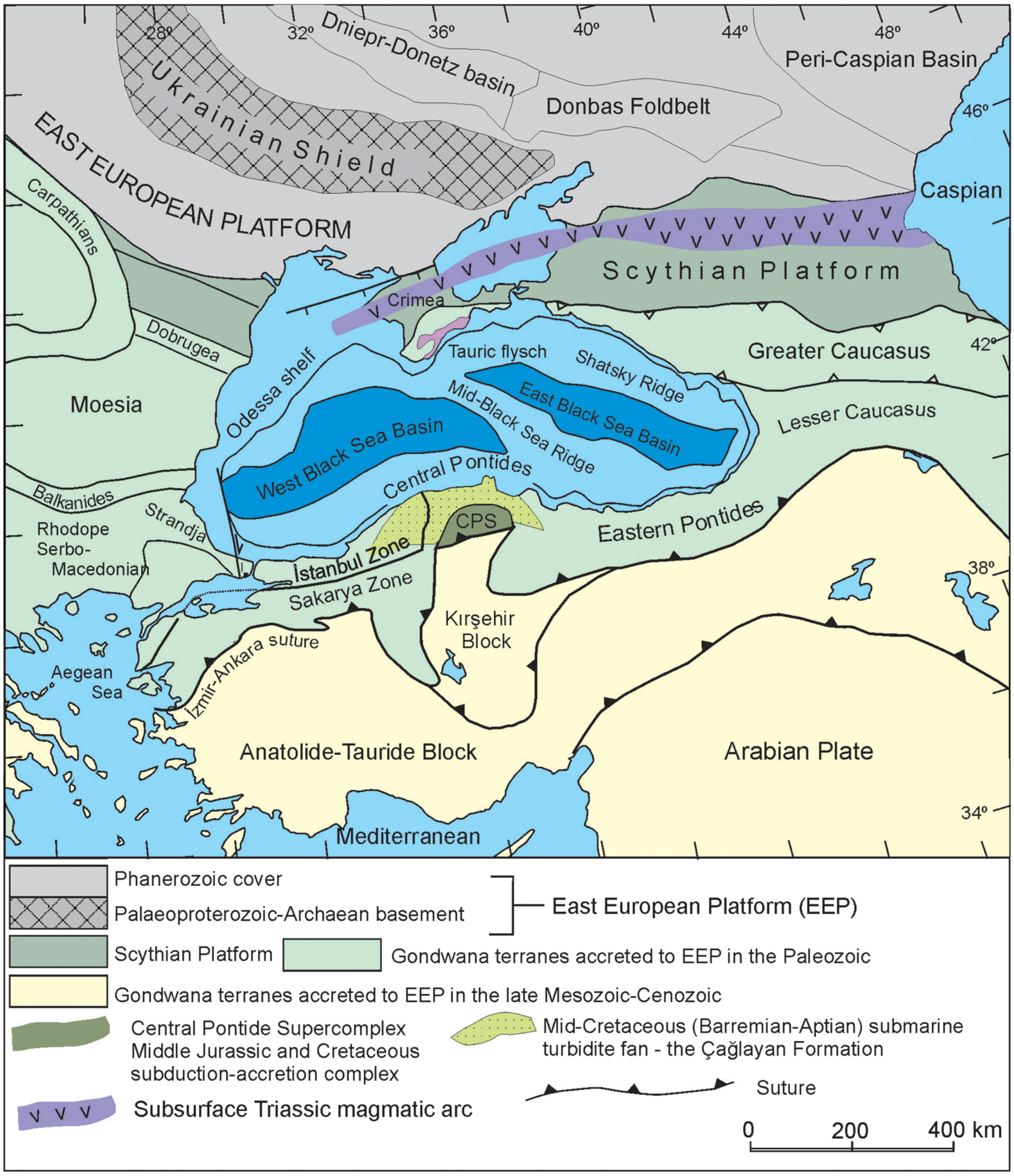

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Fig. 1. Tectonic map of the circum-Black Sea region (modified from Okay & Nikishin 2015) showing the distribution of the mid-Cretaceous turbidites and Jurassic–Cretaceous subduction–accretion complexes in the Central Pontides. CPS, Central Pontide Supercomplex.

Istanbul and Sakarya zones. It is distinguished from the Western and Eastern Pontides by the presence of a very large mid-Cretaceous turbidite fan, which is bordered to the south by an extensive Jurassic and Cretaceous subduction–accretion complex, the Central Pontide Supercomplex (Fig. 1).

The Central Pontides and their offshore extension have been a target for petroleum exploration for many years with dry wells drilled both onshore and offshore (Robinson *et al.* 1996; Görür & Tüysüz 1997; Şen 2013). The accepted geological framework and understanding of the Central Pontides during this phase of exploration changed drastically as a result of new data. The large metamorphic and ophiolitic area in the southern Central Pontides, which was long considered as pre-Jurassic basement, was shown to be made up of Jurassic and Lower Cretaceous subduction–accretion complexes and accreted oceanic island arcs (Fig. 1) (Okay *et al.* 2006, 2013; Marroni *et al.* 2014; Aygül *et al.* 2015*a*, *b*, 2016; Çelik *et al.* 2016). New studies have also shown the presence of Permo-Carboniferous granitic magmatism, and Jurassic high-temperature–low-pressure (HT–LP) metamorphism and associated magmatism in the Central Pontides (Nzegge *et al.* 2006; Okay *et al.* 2015; Gücer *et al.* 2016). New precise palaeontological data have led to the establishment of a more robust biostratigraphy (Hippolyte *et al.* 2010, 2015, 2016; Gand *et al.* 2011; Okay *et al.* 2015; Stolle 2016; Tüysüz *et al.* 2016). Detrital zircon U–Pb dates provided a new perspective to the Mesozoic palaeogeography (Karslıoğlu *et al.* 2012; Okay *et al.* 2013; Akdoğan *et al.* 2017). The present paper synthesizes these recent data into an internally consistent Late Palaeozoic–Cenozoic evolution of the Central Pontides. We also provide new biostratigraphic data on the Mesozoic and Cenozoic sequences of the Central Pontides, including several measured stratigraphic sections with the biostratigraphy controlled by the palaeontological study of over 300 thin sections.

Stratigraphic framework

The Central Pontides can be divided into crescent-shaped northern and southern sectors. The northern sector consists of sequences deposited on continental crust, whereas most of the southern Central Pontides are made up of Mesozoic oceanic subduction–accretion complexes, collectively called as the Central Pontide Supercomplex (Fig. 1).

The northern Central Pontides comprises two types of pre-Jurassic basement; in the western part of the Central Pontides (Istanbul Zone), the basement consists of late Neoproterozoic crystalline rocks and an overlying Palaeozoic sedimentary succession (Fig. 2). Permian and Triassic sequences are represented by fluviatile red beds and lacustrine deposits with acidic magmatic rocks, reminiscent of the Rotliegende and Keuper series of Central Europe (e.g. Stolle 2016). In the eastern Central Pontides, which is part of the Sakarya Zone, the pre-Jurassic basement consists of low-grade metamorphic rocks intruded by Upper Carboniferous and Lower Permian granites (Okay *et al.* 2015). The bulk of the Triassic is represented by a thick sequence of distal forearc turbidites (the Akgöl Formation), which were deposited partly on oceanic crust and partly on Lower–Middle Triassic pelagic carbonates (Fig. 2). During the Middle Jurassic, the eastern Central Pontides were part of a magmatic arc; several shallow-level intrusions were emplaced into the Triassic turbidites. Heat flow associated with the arc resulted in high-temperature metamorphism of the middle crust, which crops out in two large massifs (Fig. 3) (Okay *et al.* 2014; Gücer *et al.* 2016).

The Upper Jurassic–Lower Cretaceous shallow-marine carbonates (the İnaltı Formation) are the first major unit in the Central Pontides, and were deposited over both the Istanbul and Sakarya zones; they provide a time constraint for the amalgamation of these two tectonic terranes (Figs 2 & 3). The carbonates are unconformably overlain by a thick sequence of Lower Cretaceous (upper Barremian–Aptian) siliciclastic turbidites (the Çağlayan Formation). Turbidite deposition was followed by a major phase of shortening, uplift and erosion in the Albian, especially evident in the south. This event is linked to accretion of subduction complexes to the southern margin of Laurasia, represented by Albian eclogites and blueschists in the Central Pontide Supercomplex.

A new depositional cycle started with the Upper Cretaceous (Turonian–Santonian) deep-marine red limestones (the Kapanboğazı Formation); these generally lie unconformably above the Lower Cretaceous turbidites, as well as on the older formations. The Turonian–Santonian transgression also marks the inception of Late Cretaceous arc magmatism; the volcanic rocks are intercalated and interfinger with Santonian–Campanian pelagic limestones. The arc volcanism waned in the Late Campanian–Maastrichtian, and was succeeded in the northern parts of the Central Pontides by the deposition of Maastrichtian–Paleocene turbidites (the Gürsökü, Akveren and Atbaşı formations). The coeval sequences in the southern parts of the Central Pontides are shallow-marine sandstones and limestones. The marine deposition in the Central Pontides ended with a thick sequence of Lower–Middle Eocene turbidites in the north, and coeval carbonates in the south.

The southern part of the Central Pontides consists mainly of metamorphic and ophiolitic rocks representing Jurassic and Cretaceous oceanic subduction–accretion complexes (Fig. 1) (Okay *et al.* 2006, 2013; Marroni *et al.* 2014; Aygül *et al.* 2015*a*, *b*, 2016; Çelik *et al.* 2016). The metamorphism is in eclogite, blueschist and greenschist facies, with two age peaks in the Middle–early Late Jurassic and Early Cretaceous.

The pre-Late Jurassic stratigraphy of the western Central Pontides: the Istanbul Zone

Neoproterozoic crystalline basement and the Palaeozoic sequence

In the western Central Pontides, the crystalline basement is composed of late Neoproterozoic granites

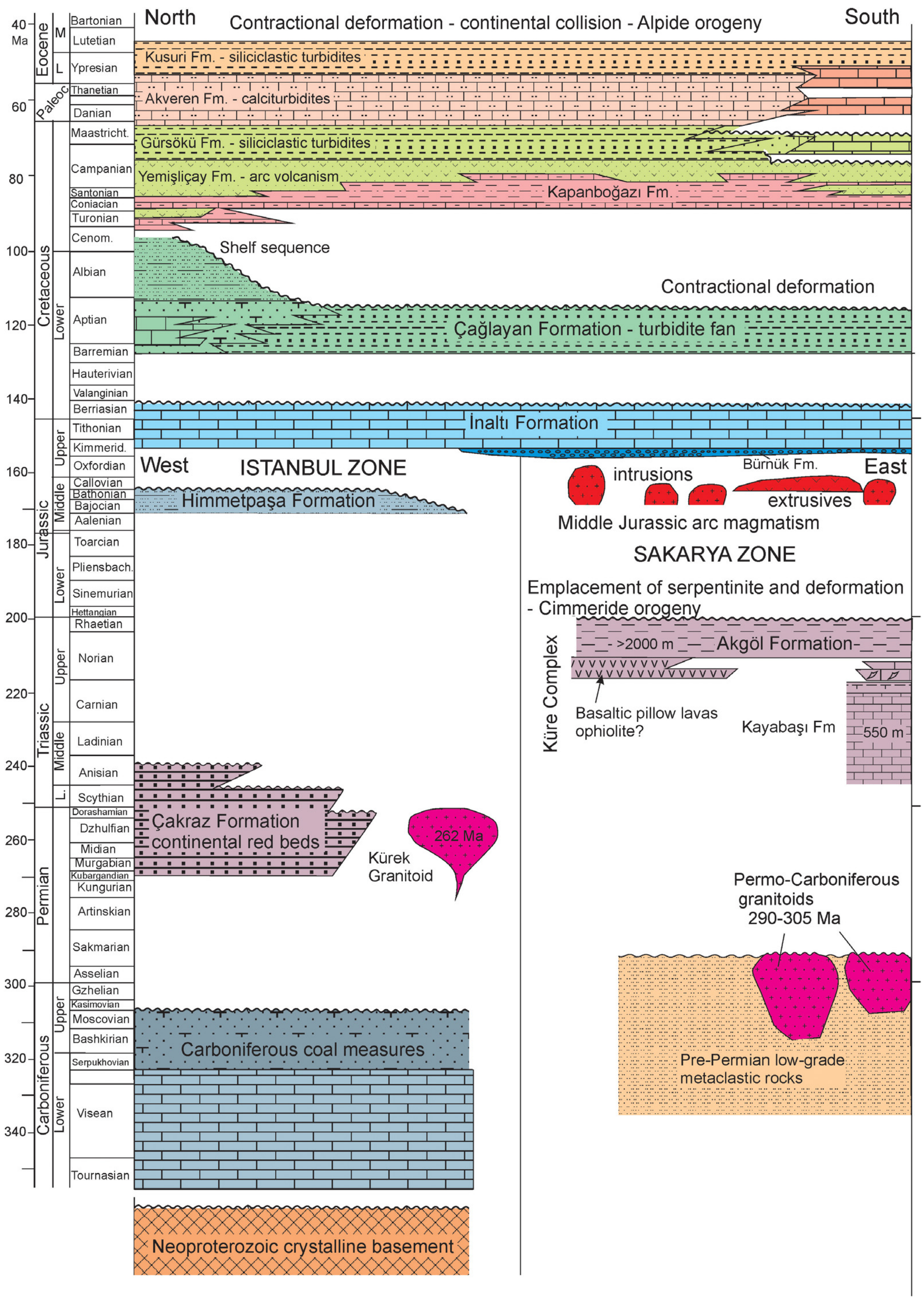

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Fig. 2. Generalized stratigraphic section of the Central Pontides. The timescale is from Cohen *et al.* (2013).

and gneisses, which crop out in a small area in the Karadere region north of Araç (Fig. 3) (Chen *et al.* 2002). The granites have yielded latest Neoproterozoic zircon U–Pb (590–560 Ma) and Rb–Sr biotite ages (548–545 Ma), the latter indicate that the sequence has not been reheated since the Neoproterozoic. Larger outcrops of the late Neoproterozoic Pan-African basement exists in the Bolu Massif further west (Fig. 3) (Ustaömer *et al.* 2005).

The late Neoproterozoic metagranites are stratigraphically overlain by a Palaeozoic sedimentary sequence ranging in age from Ordovician to Carboniferous (Fig. 4). The lower part of the sequence, which is Ordovician–Silurian in age, is well exposed in the Karadere region, and consists mainly of dark shale and siltstone with graptolite faunas (Boztuğ 1992; Dean *et al.* 2000). The upper part of the Palaeozoic sequence, Devonian–Late Carboniferous in age, crops out mostly along the Black Sea coast in the Zonguldak and Amasra regions (Fig. 3). It consists mostly of shallow-marine Devonian–Lower Carboniferous limestones (Dil 1976; Dil *et al.* 1976), similar to those of NW Europe. The transition from carbonate to clastic deposition occurs at the end of the Visean, and the Namurian–Westphalian (middle Serpukhovian–Moscovian) is represented by coal series several kilometres in thickness (Fig. 4) (Kerey 1985), which crop out along the Black Sea coastal area.

Permo-Triassic red beds and Middle Jurassic shallow-marine clastic rocks

The Palaeozoic sedimentary rocks are unconformably overlain by a thick Permo-Triassic continental sequence called the Çakraz Formation (Figs 2 & 3). The lower parts of the Çakraz Formation consist of fluviatile red sandstone, siltstone and conglomerate with middle Permian vertebrate imprints and spores (Gand *et al.* 2011; Stolle 2016). The upper part is made up of lacustrine siltstone and marl possibly of Triassic age (Alişan & Derman 1995). The Permian red beds (New Red Sandstone) are widespread in the Balkans and in Central Europe, and represent continental deposition following the Variscan Orogeny. In the western part of the Istanbul Zone, close to the city of Istanbul, the Palaeozoic sedimentary sequence is intruded by Upper Permian (*c.* 254 Ma) granite (Yılmaz 1975). A granite of similar age (*c.* 262 Ma), albeit in an allochthonous position, crops out in the southern part of the western Central Pontides (Fig. 3) (Okay *et al.* 2013). There are also possibly Permian rhyolitic domes within the Permian red beds SW of Cide (Akyol *et al.* 1974).

The Permo-Triassic red beds of the Çakraz Formation are unconformably overlain by continental to shallow-marine sandstone, siltstone, shale and conglomerate, about 375 m in thickness. This Himmetpaşa Formation contains ammonites and palynomorphs of Middle Jurassic age (Akyol *et al.* 1974; Derman *et al.* 1995).

The pre-Late Jurassic stratigraphy of the eastern Central Pontides: the Sakarya Zone

Palaeozoic subduction–accretion complex and Permo-Carboniferous granites

The oldest sequence, which crops out in the eastern part of the Central Pontides, is a pre-Permian succession of black to brown slate and phyllite interbedded with metasiltstone and fine-grained meta-sandstone, which crops out close to the Black Sea coast (Fig. 3) (Boztuğ & Yılmaz 1983; Okay *et al.* 2015). There are also tectonic lenses of serpentinite within this low-grade metasedimentary sequence. The metasedimentary rocks and the serpentinite lens are intruded by Upper Carboniferous granitoids, providing an upper age for the deposition, deformation and metamorphism (Okay *et al.* 2015). The metasedimentary sequence with serpentinite lenses probably represents a Palaeozoic subduction–accretion complex.

Two Permo-Carboniferous granites with U–Pb zircon ages of 303–291 Ma crop out close to the Black Sea coast (Fig. 3) (Nzegge *et al.* 2006; Nzegge 2008; Okay *et al.* 2015). They range from hornblende–biotite granodiorite to two-mica granite, and are peraluminous, calc-alkaline and high-K in composition (Nzegge *et al.* 2006). Their $\varepsilon Nd_{(t)}$, $\delta^{18}O$ values and $Sr_{(i)}$ ratios suggest derivation by dehydration melting of metapelitic and mafic crust (Nzegge *et al.* 2006), which is in accordance with the presence of primary muscovite and enclaves of high-temperature metamorphic rocks in one of the granites. On the tectonic discrimination diagrams, most samples plot in the field of volcanic arc granitoids (Nzegge *et al.* 2006). Their peraluminous nature, high K and Sr contents, high Rb/Sr values, and initial Sr ratios point to crustal melting and suggest an episode of crustal thickening.

Permo-Carboniferous granites also crop out in other parts of the Sakarya Zone (Topuz *et al.* 2010; Ustaömer *et al.* 2012; Ustaömer *et al.* 2013) and in the Greater Caucasus (Hanel *et al.* 1992; Somin 2011). Carboniferous and Permian detrital zircons are generally the dominant population in the upper Palaeozoic and Mesozoic sedimentary rocks of the Pontides and of the Crimea (Okay *et al.* 2013; Nikishin *et al.* 2015*c*; Akdoğan *et al.* 2017), suggesting that Permo-Carboniferous granites are widely present under the Mesozoic cover in the Central Pontides and possibly in the Scythian Platform, and extend westwards into the Balkans; their generation

(a)

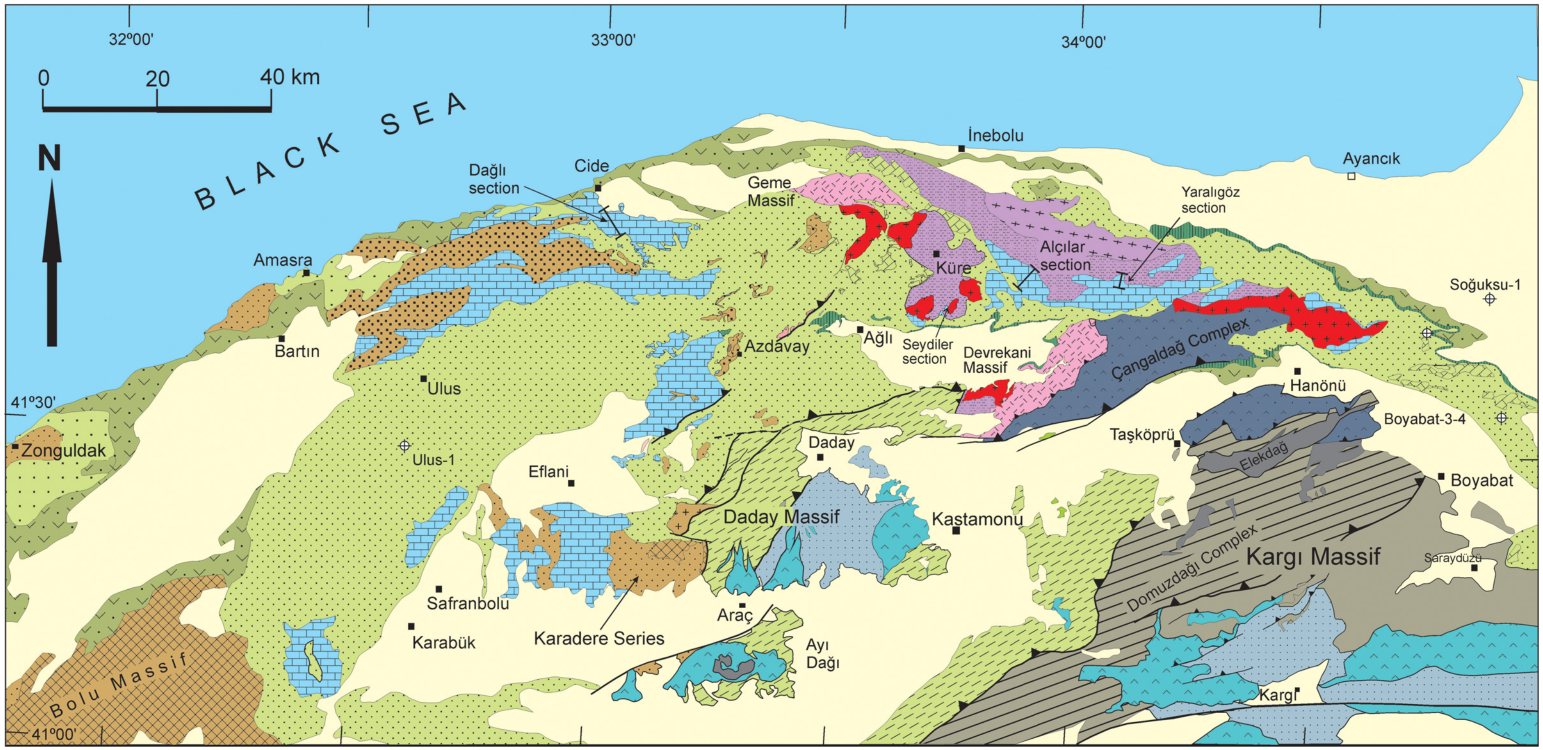

Fig. 3. Geological map of the Central Pontides (modified from Okay *et al.* 2013).

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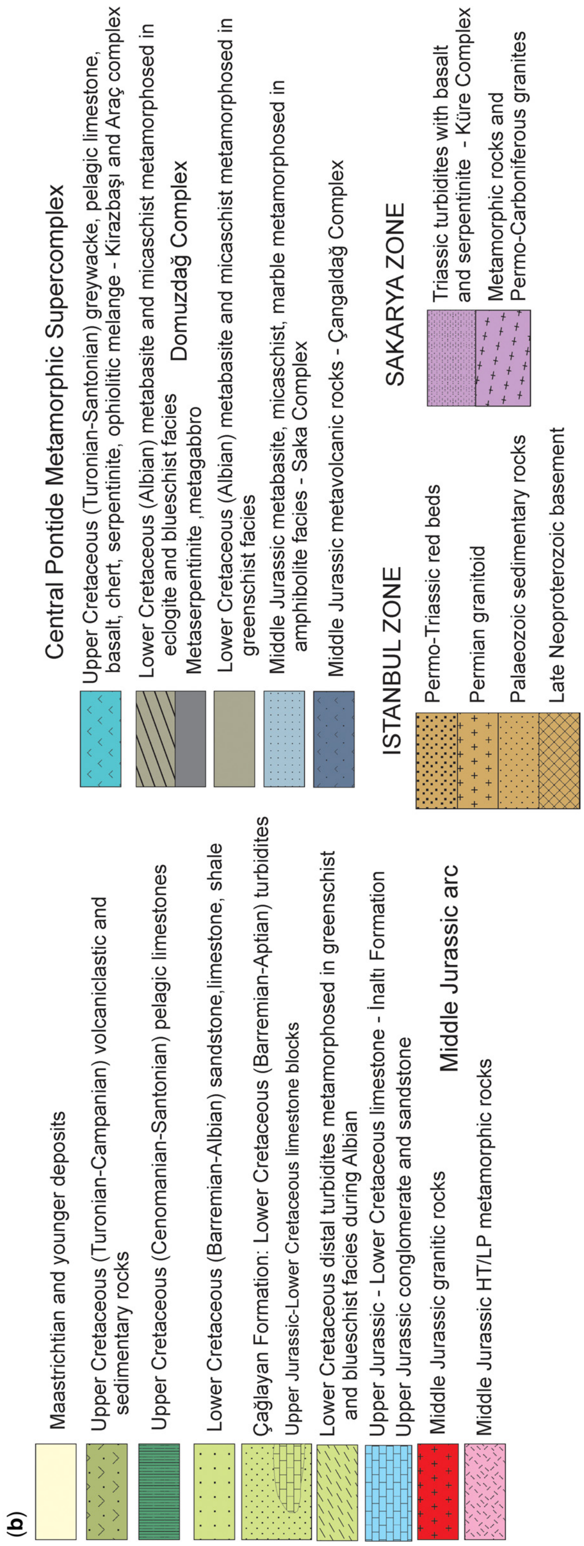

Fig. 3. *Continued.*

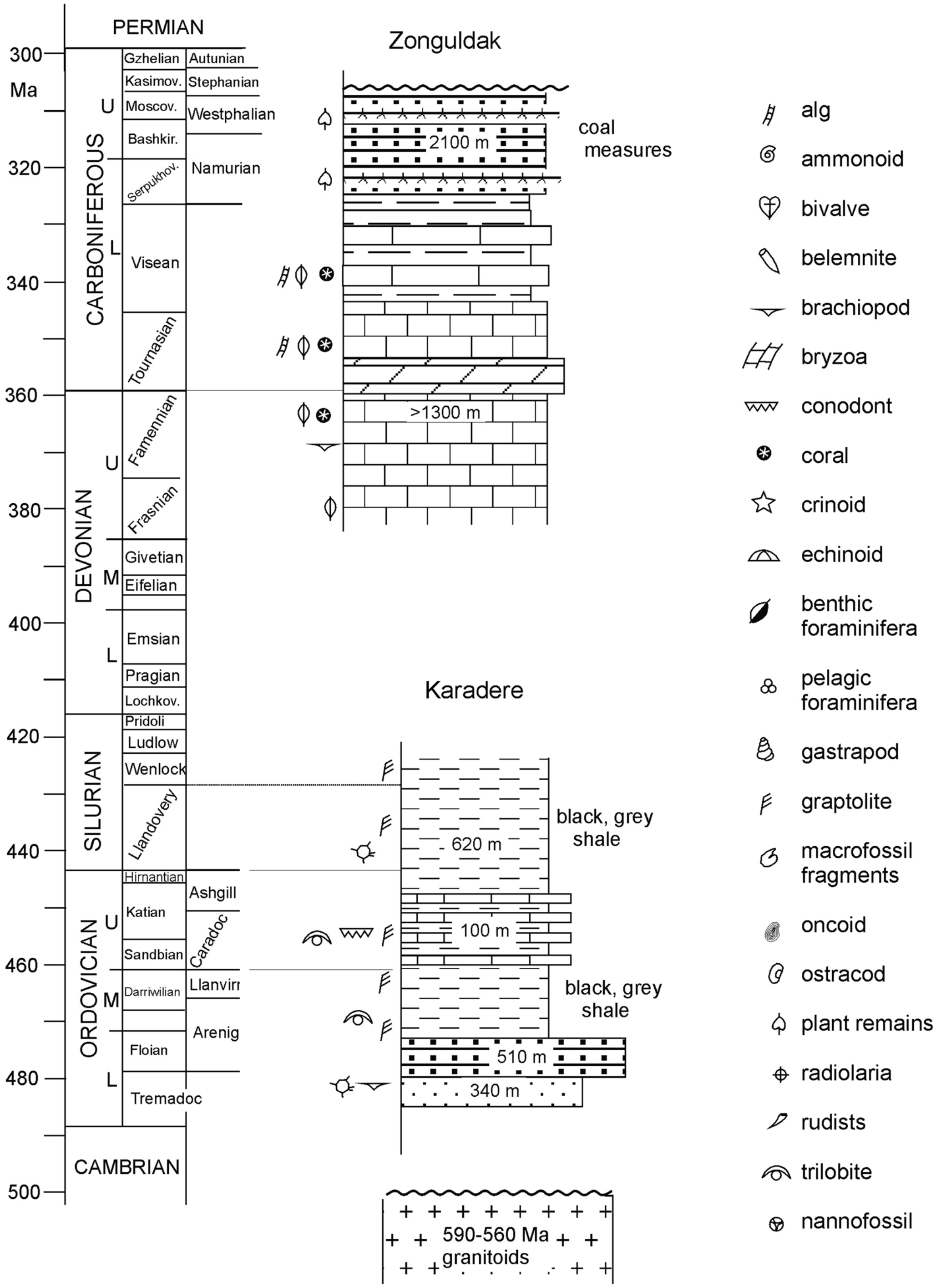

Fig. 4. Generalized Palaeozoic stratigraphic section of the western Central Pontides (eastern Istanbul Zone). The stratigraphic and palaeontological data are from Dil *et al.* (1976) and Dean *et al.* (2000).

is related to the Variscan Orogeny (e.g. Okay & Topuz 2017).

Triassic: Cimmeride Orogeny

The latest Triassic Cimmeride Orogeny in the Pontides, specifically in the Sakarya Zone, was a short-lived accretionary rather than collisional event (Okay 2000; Robertson & Ustaömer 2011; Topuz *et al.* 2013). It was caused by the accretion of a major oceanic plateau or a number of oceanic islands along with trench deposits to the southern active margin of Laurasia (Fig. 5b). In NW Turkey, the Triassic subduction–accretion units are known as the Karakaya Complex, and include Triassic eclogites and blueschists (Fig. 1) (Okay & Göncüoğlu 2004). Similar sequences crop out in the northern part of the Central Pontides, where there are known as the Küre Complex (Fig. 3) (Ustaömer & Robertson 1994). The bulk of the Küre Complex consists of dark siliciclastic distal turbidites of Late Triassic (Norian) age, more than 2000 m in thickness (Kozur *et al.* 2000; Okay *et al.* 2015). The geochemistry of the shale and sandstone suggests deposition in an active continental margin (Ustaömer & Robertson 1994). This Akgöl Formation has a composite stratigraphic basement (Fig. 2); in some regions, the distal turbidites are stratigraphically underlain by a pelagic Middle–Upper Triassic (Anisian–Carnian) limestone sequence with conodonts and ammonites, yet in some other areas they are underlain by pillow basalts (Okay *et al.* 2015). The basalts are tholeiitic and mostly mid-ocean ridge (MORB) type (Ustaömer & Robertson 1994). Economic chalcopyrite and pyrite mineralization, exploited in the ancient Küre mine, has developed along the contact between basalt and black shale. There are also several kilometres of large tectonic serpentinite slivers within the turbidites. The serpentinite and the Upper Triassic turbidites are intruded by a Middle Jurassic (162 ± 4 Ma) granite indicating a pre-Jurassic, most probably Triassic, age for the ultramafic rocks and associated gabbro and diabase (Okay *et al.* 2015). Serpentinite, gabbro and basalt constitute a dismembered ophiolite on which the Upper Triassic turbidites of the Akgöl Formation were deposited (Ustaömer & Robertson 1994). The Küre Complex was deformed by folding and thrusting during the latest Triassic–?earliest Jurassic before the intrusion of the Middle Jurassic granites and deposition of the Upper Jurassic conglomerates and limestones.

Detrital zircon ages from the turbiditic sandstones of the Akgöl Formation are predominantly Triassic (Karslıoğlu *et al.* 2012). A similar dominance of Triassic detrital zircons is recorded in the Upper Triassic Tauric flysch of the Crimea (Nikishin *et al.* 2015*c*; Nikishin pers. comm.), which shares a similar lithology and stratigraphic position with the Akgöl Formation. Ustaömer *et al.* (2016) reported an extensive zircon dataset from the sandstones of the Karakaya Complex; the ages are also predominantly Triassic. The abundance of Triassic detrital zircons and the presence of Triassic subduction–accretion complexes in the Pontides suggest that a now-hidden Triassic magmatic arc is present in the Scythian Platform north of the Black Sea (Fig. 5b), as implied by some well data (Tikhomirov *et al.* 2004). The arc is now buried beneath Cenozoic sediments. The Triassic arc extends from the northern Crimea to Central Asia (Fig. 1) (Natal'in & Şengör 2005; Nikishin *et al.* 2012). The Akgöl Formation and its lateral equivalent, the Tauric flysch in the Crimea, were deposited in a forearc between the subduction–accretion units of the Karakaya Complex and the Triassic magmatic arc (Fig. 5b).

Middle Jurassic arc magmatism

During the Middle Jurassic, a major Andean type magmatic arc was established along the southern margin of Laurasia; the arc extended for 2800 km from Makran in Iran to the Pontides in Turkey (Fig. 5c) (Şengör *et al.* 1991; Şen 2007; Dokuz *et al.* 2010; Genç & Tüysüz 2010; McCann *et al.* 2010; Adamia *et al.* 2011). Jurassic arc magmatism is observed in the eastern Central Pontides and in Crimea, where they are represented by shallow-level intrusions, dacite and andesite porphyries, with lesser amounts of volcanic rocks and granites (Fig. 3) (Yılmaz & Boztuğ 1986; Meijers *et al.* 2010*b*; Okay *et al.* 2014). The geochemistry of the Jurassic porphyries and volcanic rocks has a distinct arc signature with a crustal melt component (Boztuğ *et al.* 1984, 1995; Okay *et al.* 2014). A crustal melt component is also suggested by cordierite and garnet in the magmatic assemblage and the abundance of inherited zircons in the porphyries. The age of magmatism, based on zircon U–Pb data, is predominantly Middle–early Late Jurassic (175–155 Ma: Okay *et al.* 2014). Radiolaria in the mudstones intercalated with basaltic flows also give Callovian–Oxfordian ages (Bragin *et al.* 2002). The magmatic arc developed largely on the continental crust; the possible exception is the Çangaldağ Complex, a thick pile of basic and intermediate volcanic rocks of Middle Jurassic age, which is considered as a magmatic arc built on oceanic crust (Fig. 3) (Ustaömer & Robertson 1999; Okay *et al.* 2014). In contrast to the other Jurassic magmatic rocks, the Çangaldağ Complex underwent a low-grade greenschist- to blueschist-facies regional metamorphism in the Early Cretaceous (Okay *et al.* 2013; Çimen *et al.* 2016).

The high heat flow, which produced the arc magmatism, also led to the metamorphism of the

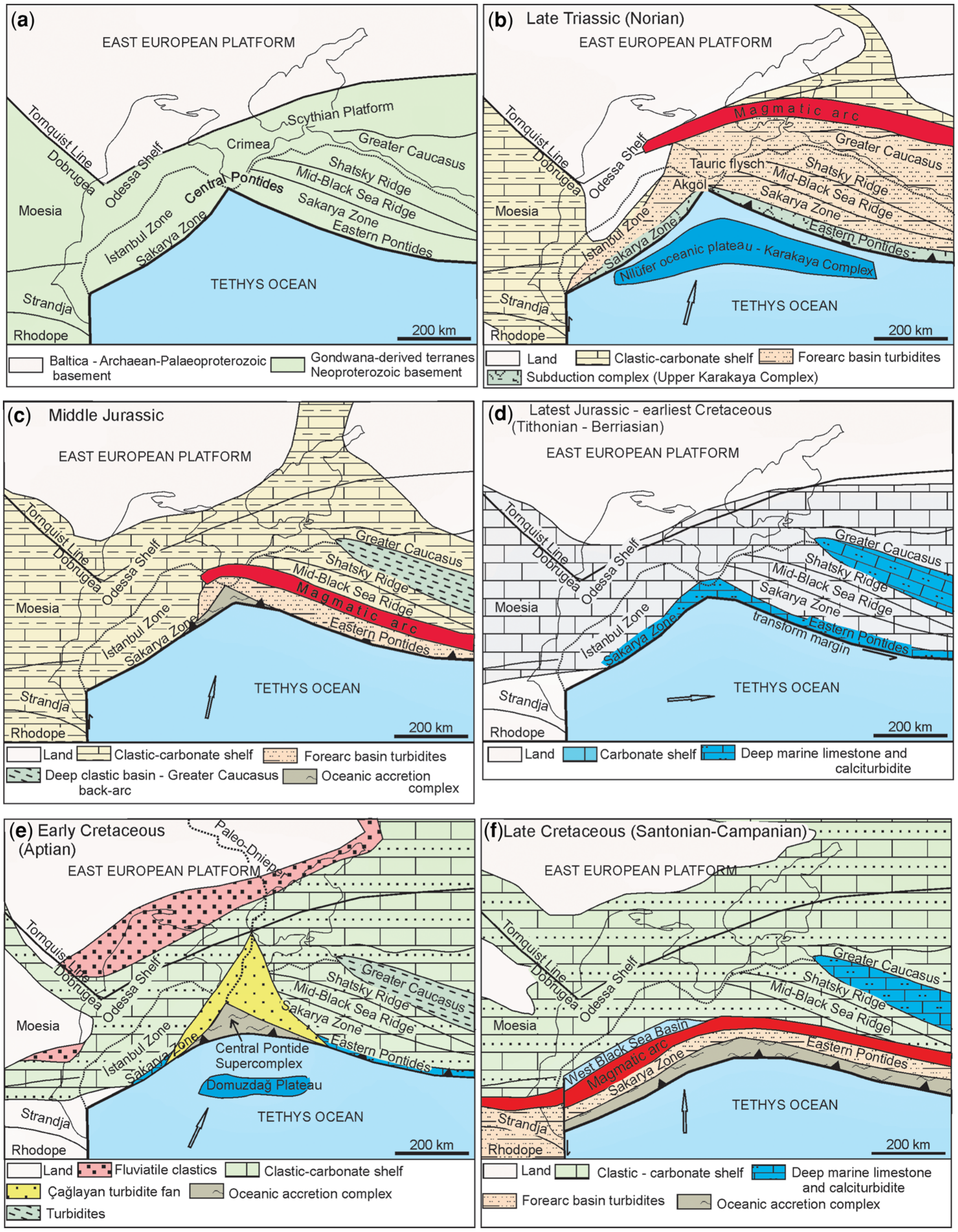

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Fig. 5. Palaeogeographical maps for the Central Pontides and the surrounding regions for the Mesozoic. (**a**) A probable configuration of the Black Sea terranes in the early Mesozoic. (**b**) Late Triassic. The major event is the collision of the Nilüfer oceanic plateau with the Laurasian margin deforming the active margin and causing the Cimmeride Orogeny. (**c**) Middle Jurassic. Subduction, arc magmatism and accretion continue but do not extend to the western part of the Black Sea region. (**d**) Latest Jurassic–earliest Cretaceous. This interval is characterized by the cessation of subduction and widespread carbonate deposition in the Black Sea region. (**e**) Early Cretaceous. Shallow subduction leads to the uplift of the East European Platform, which is eroded into the Çağlayan turbidite fan, at the same time there is a major oceanic accretion in the south. (**f**) Late Cretaceous. Subduction, arc magmatism and extension led to the opening of the western Black Sea as a back-arc basin. The palaeogeographical maps are based on Barrier & Vrielynck (2008), Okay *et al.* (2013) and Nikishin *et al.* (2015*b*).

basement. In the Central Pontides, there are two large outcrops of Middle Jurassic (*c.* 172 Ma) HT–LP (4 kbar and 720°C) metamorphic rocks in the Geme and Devrekani complexes (Fig. 3) (Okay *et al.* 2014; Gücer *et al.* 2016). They consist predominantly of gneiss and migmatite with cordierite and sillimanite. The metamorphic rocks are intruded by the Middle Jurassic granitic veins, stocks and larger magmatic bodies. The detrital zircons in the gneisses indicate that the metamorphic rocks represent Hercynian basement, which was remobilized under the Middle Jurassic magmatic arc.

Middle Jurassic subduction–accretion: high-pressure amphibolite-facies metamorphism

Part of the Central Pontide Supercomplex is made up of micaschists and amphibolites with Middle–early Late Jurassic (170–159 Ma) Ar/Ar mica ages (Okay *et al.* 2013; Marroni *et al.* 2014; Aygül *et al.* 2016; Çelik *et al.* 2016). The metamorphism is in high-pressure amphibolite facies (10 kbar and 620°C), and the metamorphic rocks are tectonically intercalated with Cretaceous subduction–accretion complexes and lie tectonically beneath the metamorphosed flysch of the Lower Cretaceous Çağlayan Formation (Fig. 3). This Saka Complex has formed during the Middle Jurassic subduction, which also gave rise to the arc magmatism. Similar Jurassic subduction–accretion complexes are also described from other parts of the Pontides (Çelik *et al.* 2011; Topuz *et al.* 2013).

Upper Jurassic–Lower Cretaceous platform limestones

Pre-Jurassic sequences in the northern Central Pontides are unconformably overlain by Upper Jurassic–Lower Cretaceous limestones, the İnaltı Formation (Fig. 2). The İnaltı Formation is the first lithostratigraphic unit that indisputably extends both over the Istanbul and Sakarya zones, and thereby provides an upper age (Kimmeridgian) for the juxtaposition of these two terranes in the Central Pontides. Upper Jurassic–Lower Cretaceous limestones are ubiquitous in the Balkans and in the Pontides, and also extend eastwards into the Caucasus (Fig. 5d) (Altıner *et al.* 1991; Taslı 1993; Tari *et al.* 1997; Rojay & Altıner 1998; Koch *et al.* 2008; Guo *et al.* 2011; Kaya & Altıner 2015; Nikishin *et al.* 2015*c*). The Late Jurassic–earliest Cretaceous (Kimmeridgian–Berriasian) was a tectonically quite period in the northern Tethys, with little tectonic activity fostering carbonate accumulation.

In the western Central Pontides, Upper Jurassic–Lower Cretaceous limestones lie unconformably above the Permo-Triassic red beds of the Çakraz Formation or above the Himmetpaşa Formation, whereas in the eastern Central Pontides they lie unconformably, through a basal continental clastic unit, above the Upper Triassic Akgöl Formation (Fig. 2). The basal clastic unit (Bürnük Formation) is made up of fluviatile red sandstone, siltstone and conglomerate, with a thickness varying from a few metres up to 500 m; the clasts in the conglomerate are predominantly subvolcanic rocks derived from the Middle Jurassic intrusives.

The İnaltı Formation in the Central Pontides is reported to be Late Jurassic (Aydın *et al.* 1995), or Late Jurassic–Early Cretaceous (Oxfordian–Berriasian/Valanginian) in age (Derman & Sayılı 1995; Tüysüz 1999). There are no published detailed measured stratigraphic sections from the İnaltı Formation. To determine the age of the İnaltı Formation in the Central Pontides, four stratigraphic sections were measured (Fig. 3): one in the western part and three in the eastern part. Two of these sections are described below:

- The Alçılar section – The Alçılar section is located east of Küre in the eastern Central Pontides (Figs 3 & 6a). Here, limestones of the İnaltı Formation overlie the fluviatile conglomerates and sandstones of the Bürnük Formation, and are overlain unconformably by the conglomerates and breccias of the Çağlayan Formation (Fig. 7). The Bürnük Formation itself lies unconformably above the Upper Triassic turbidites of the Akgöl Formation. The İnaltı Formation in the Alçılar section is 600 m thick and is made up of Kimmeridgian–lower Berriasian shallow-marine limestones (Fig. 7). Altogether, 107 limestone samples from the Alçılar section were examined petrographically and palaeontologically. The basal part of the section is made up of slightly nodular, thin- to medium-bedded micritic limestones (Fig. 6a) of Kimmeridgian age with gastropods and other macrofossil fragments. The bulk of the section consists of medium-bedded, grey Tithonian limestone with macrofossil fragments, oncoids and locally corals. Limestones in the top part of the section are massive and rich in oncoids (Fig. 6a); this part of the section is middle Tithonian–early Berriasian in age. The limestones are rich in benthic foraminifera and partly in algae, including *Freixialina planispiralis*, *Charentia* spp., *Pseudocyclammina sphaeroidalis*, *P. lituus*, *Rectocyclammina* sp., *Everticyclammina virguliana*, *E. praekelleri*, *Alveosepta* sp., *Anchispirocyclammina lusitanica*, *Kastamonina abanica*, *Coscinoconus alpinus*, *C. elongatus*, *C. delphinesis*, *C.* spp., *Frentzenella* ? *odukpaniensis*,

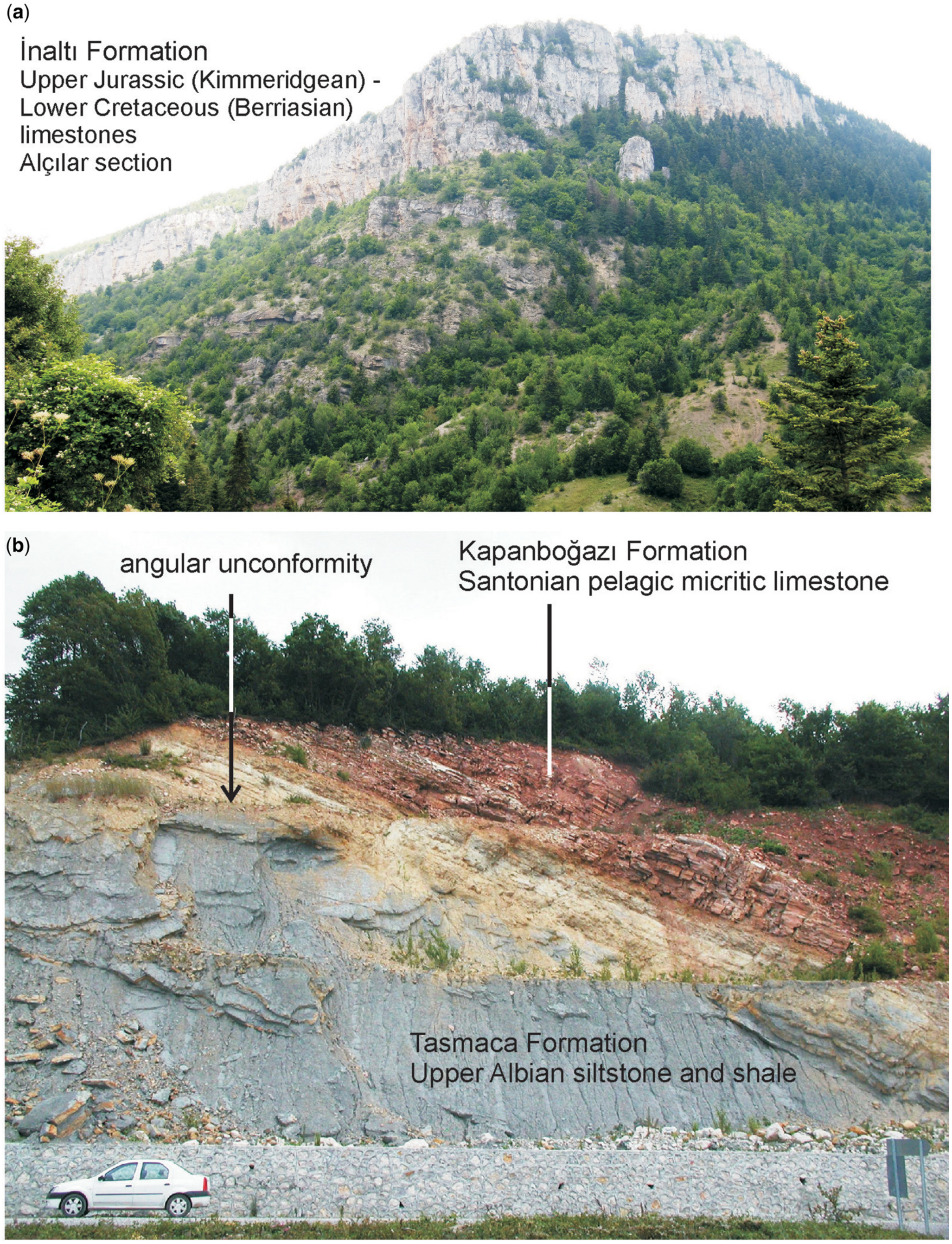

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Fig. 6. Field photographs illustrating sequences and unconformities in the northern Central Pontides. (**a**) Upper Jurassic–Lower Cretaceous limestones of the Inaltı Formation north of Kastamonu; the Alçılar section (Figs 3a & 7) was measured on this cliff face. (**b**) Upper Albian siltstone and shales (the Tasmaca Formation) overlain with an angular unconformity by the Santonian red pelagic limestones (the Kapanboğazı Formation), Amasra. Note the yellowish basal sandstones below the red limestones. Two shale samples from this locality (AM5 and AM9: see the Supplementary material) have yielded late Albian nannofossils, younger than the Aptian ages reported by Hippolyte *et al.* (2010) from this locality.

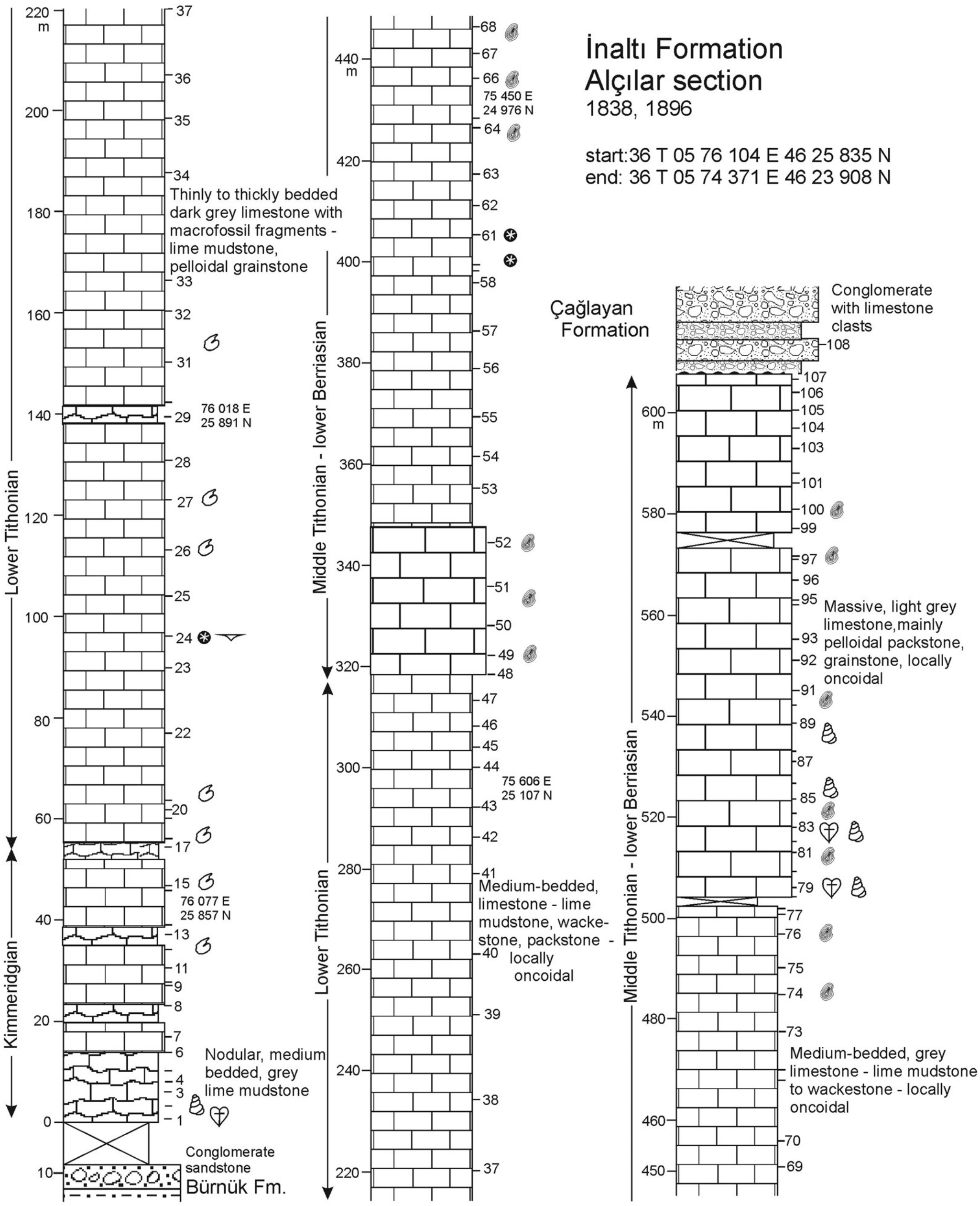

Fig. 7. The Alçılar measured stratigraphic section in the Upper Jurassic–Lower Cretaceous İnaltı Formation. For the location, see Figure 3; for the symbols, see Figure 4.

Mohlerina basiliensis, *Protopeneroplis ultragranulata*, *'Quinqueloculina' robusta*, *Crescentiella morronensis*, *Campbelliella striata* and *Salpingoporella annulata*, which allowed the section to be divided into three zones (Figs 8 & 9). The lower zone of Kimmeridgian age is characterized by the coexistence of the benthic foraminifera *Freixialina planispiralis* and *Kastamonina abanica*, and the absence of *Campbelliella striata* (samples 1–16). The second zone is of early Tithonian age (samples 17–48), and is distinguished by *Campbelliella striata* and *Kastamonina abanica*.

Fig. 8. Foraminifera, calpionellids and dascylad algae from the İnaltı Formation from the Alçılar and Dağlı measured sections. (**1**) & (**2**) *Protopeneroplis ultragranulata* (Gorbachik): (1) sample AA 107, A3 Zone, middle Tithonian–lower Berriasian; and (2) sample AA 96, A3-a Subzone, middle Tithonian–lowermost Berriasian. (**3**) & (**4**) *Freixialina planispiralis* Ramalho: (3) sample AA 9/2, A1 Zone, Kimmeridgian; and (4) sample AA 38, A2 Zone,

The third and highest zone is middle Tithonian–early Berriasian in age (samples 59–107) and is characterized by *Protopeneroplis ultragranulata*. The top of the third zone is calibrated by the B or C zone of calpionellids. A subzone within zone 3 is distinguished by the presence of *Anchispirocyclina lusitanica* and *Protopeneroplis ultragranulata* (middle Tithonian–lowermost Berriasian, samples 49–97). The presence of *Calpionella alpina* in the topmost part of the section indicates deepening of the platform in the Berriasian.

- The Dağlı section – The Dağlı section is located in the western Central Pontides in the Istanbul Zone along the main Cide–Azdavay highway (Fig. 3). The base of the section is a thrust fault: however, in nearby localities, limestones of the İnaltı Formation lie on the Triassic continental red beds (the Çakraz Formation: Fig. 3). The Dağlı section is 1400 m thick, and consists of shallow-marine limestones and dolomites (Fig. 10). The basal part of the section consists of medium-bedded micritic limestones, which are overlain by 500 -m-thick massive dolomites; the dolomites are in turn overlain by thickly bedded to massive limestone, 800 m thick. The limestones are mainly peloidal grainstones intercalated with subordinate lime mudstone beds. In the Dağlı section, the İnaltı Formation is overlain by the Lower Cretaceous Çağlayan Formation along a fault contact. Seventy-one samples from the Dağlı section were petrographically and palaeontologically examined. The foraminifera fauna and algal flora include *Belorussiella* sp., *Charentia* spp., *Redmondoides lugeoni*, *Pseudocyclammina lituus*, *Rectocyclammina* sp., *Alveosepta jaccardi*, *Kastamonina abanica*, *Coscinoconus alpinus*, *C. elongatus*, *C. cherchiae*, *C. delphinensis*, *C.* spp., *Mohlerina basieliensis*, *Protopeneroplis ultragranulata*, *'Quinqueloculina' robusta*, *Hectina praeantiqua*, *Clypeina sulcata*, *Campbelliella striata* and *Salpingoporella annulata*, and indicate a late Kimmeridgian–early Berriasian age (Fig. 8). Based on the foraminifera, it is possible to differentiate three zones (Fig. 9). The basal zone is of late Kimmeridgian age, and is characterized by *Alveosepta jaccardi* and *Clypeina sulcata* (samples 1–16); the second zone of early Tithonian age is distinguished by the coexistence of *Campbelliella striata* and *Clypeina sulcata*, and the absence of *Protopeneroplis ultragranulata* (samples 17–25). The third zone (middle Tithonian–lower Berriasian) is characterized by *Protopeneroplis ultragranulata* (samples 26–71); it is subdivided into two subzones: subzone D3-a is characterized by *Campbelliella striata* and *Protopeneroplis ultragranulata* (middle–upper Tithonian, samples 26–67), and subzone D3-b by *Clypeina sulcata* and *Protopeneroplis ultragranulata* (lower Berriasian, samples DG 67–71).

Fig. 8. (*Continued*) lower Tithonian. (**5**) *Mayncina* ? sp. Sample DG 38, D3-a Subzone, middle–upper Tithonian. (**6**) & (**7**) *Charentia* sp.: (6) sample AA 4, A1 Zone, Kimmeridgian; and (7) sample AA 8, A1 Zone, Kimmeridgian. (**8**) & (**9**) *Charentia* sp.: (8) sample AA 74, A3-a Subzone, middle Tithonian–lowermost Berriasian; and (9) sample AA 95, A3-a Subzone, middle Tithonian–lowermost Berriasian. (**10**) *Charentia* sp. Sample DG 43, D3-a Subzone, middle–upper Tithonian. (**11**)–(**13**) *Pseudocyclammina sphaeroidalis* Hottinger: (11) sample AA 20/3, A2 Zone, lower Tithonian; (12) sample AA 10, A1 Zone, Kimmeridgian; and (13) AA 37, A2 Zone, lower Tithonian. (**14**)–(**16**) *Pseudocyclammina lituus* (Yokohama): (14) sample AA 73, A3-a Subzone, middle Tithonian–lowermost Berriasian; (15) sample AA 38, A2 Zone, lower Tithonian; and (16) sample AA 42, A2 Zone, lower Tithonian. (**17**) *Everticyclammina virguliana* (Koechlin). Sample AA 93, A3-a Subzone, middle Tithonian–lowermost Berriasian. (**18**) & (**19**) *Everticyclammina praekelleri* Banner and Highton. Sample AA 33, A3-a Subzone, lower Tithonian. (**20**) *Bramkampella* or *Pseudocyclammina* sp. Sample AA 34, A2 Zone, lower Tithonian. (**21**) *Pseudocyclammina* sp. Sample AA 42, A2 Zone, lower Tithonian. (**22**)–(**24**) *Alveosepta jaccardi* (Schrodt): (22) sample DG 2/A, D1 Zone, upper Kimmeridgian; (23) sample DG 2/B, D1 Zone, upper Kimmeridgian; and (24) sample DG 1/B, D1 Zone, upper Kimmeridgian. (**25**)–(**27**) *Anchispirocyclina lusitanica* (Egger): (25) sample AA 90, A3-a Subzone, middle Tithonian–lowermost Berrriasian; (26) sample 96, A3-a Subzone, middle Tithonian–lowermost Berrriasian; and (27) sample 25, A3-a Subzone, middle Tithonian–lowermost Berrriasian. (**28**) & (**29**) *Kastamonina abanica* Sirel. 28: sample AA 33, A2 Zone, lower Tithonian; and (29) sample AA 9/2, A1 Zone, Kimmeridgian. (**30**) *Redmondoides lugeoni* (Septfontaine). Sample DG 64, D3-a Subzone, middle–upper Tithonian. (**31**) *Coscinoconus alpinus* Leupold. Sample AA 38, A2 Zone, lower Tithonian. (**32**) *Coscinoconus elongatus* Leupold. Sample DG 66, D3-a Subzone, middle–upper Tithonian. (**33**) *Frentzenella* ? *odukpaniensis* (Dessauvagie). Sample AA 97, A3-a Subzone, middle Tithonian–lowermost Berriasian. (**34**) *Coscinoconus campanellus* (Arnaud-Vanneau, Boisseau and Darsac). Sample DG 58, D3-a Subzone, middle–upper Tithonian. (**35**) *Coscinoconus cherchiae* (Arnaud-Vanneau, Boisseau and Darsac). Sample DG 71, D3-b Subzone, lower Berriasian. (**36**) *Coscinoconus sagittarius* (Arnaud-Vanneau, Boisseau and Darsac) ? Sample DG 71, D3-b Subzone, lower Berriasian. (**37**) *Coscinoconus delphinensis* (Arnaud-Vanneau, Boisseau and Darsac). Sample DG 54, D3-a Subzone, middle–upper Tithonian. (**38**) *Clypeina sulcata* (Alth). Sample DG 26, D3-a Subzone, middle–upper Tithonian. (**39**) *Campbelliella striata* (Carozzi). Sample DG 27, D3-a Subzone, middle–upper Tithonian. (**40**) *Troglotella incrustans* Wernli and Fookes. Sample AA 77, A3-a Subzone, middle Tithonian–lowermost Berriasian. (**41**) *Calpionella alpina* Lorenz. Sample AA 105, uppermost part of the A3 Zone, lower Berriasian. (**42**) *Tintinopsella* ? sp. Sample 108, reworked calpionellid in a pebble derived from the İnaltı Formation, probably Berriasian. The scale bar is 100 µm for (1)–(10), (31)–(37) and (40)–(42); and 250 µm for (11–30), (38) and (39).

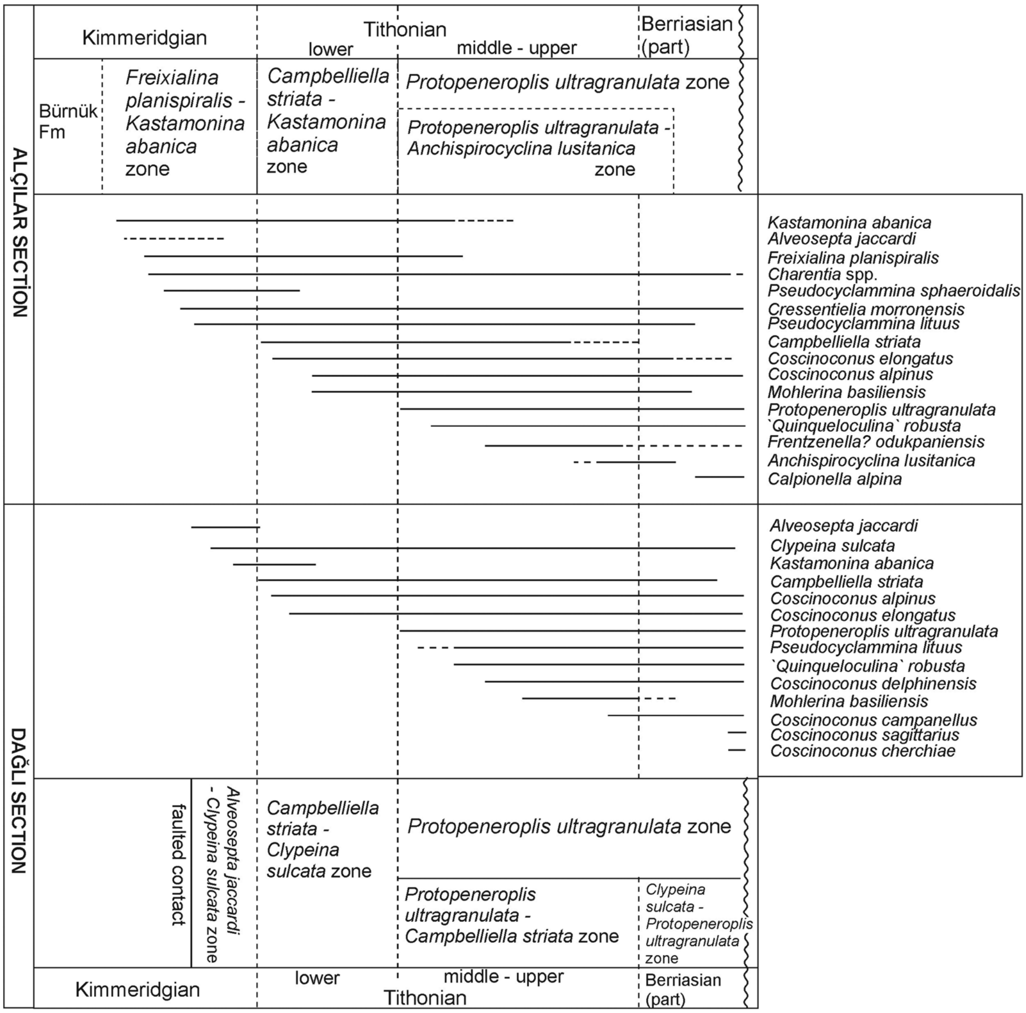

Fig. 9. Stratigraphic distribution of some diagnostic foraminifera in the Alçılar and Dağlı sections.

In the other measured sections (Yaralıgöz and Seydiler) the age of the İnaltı Formation is also Kimmeridgian–Berriasian, which is compatible with the Middle Jurassic age of the underlying magmatic rocks. The Upper Jurassic–Lower Cretaceous carbonates on both sides of the Black Sea, in the Central Pontides and in Crimea, are shallow marine and have a similar Kimmeridgian–Berriasian age range (Krajewski & Olszewska 2007). There is no evidence for the existence of a deep-marine Late Jurassic–Early Cretaceous sea between the Central Pontides and Crimea in the present position of the Black Sea, as suggested by some models (e.g. Barrier & Vrielynck 2008; Nikishin *et al.* 2012). In the Pontides, the Upper Jurassic–Lower Cretaceous shallow-marine carbonates must have passed southwards to a continental margin. Such a margin is missing in the Central Pontides but exists in the north-vergent thrust sheets in the Eastern Pontides (Okay & Şahintürk 1997).

Early Cretaceous evolution of the Central Pontides: development of a submarine fan and subduction–accretion complexes

After the Jurassic, the Central Pontides became a single tectonic unit, and the differentiation of the Istanbul and Sakarya zones ceased to exist. The deposition of the Upper Jurassic–lowermost Cretaceous shallow-marine carbonates (the İnaltı Formation) was followed by uplift and erosion. Valanginian

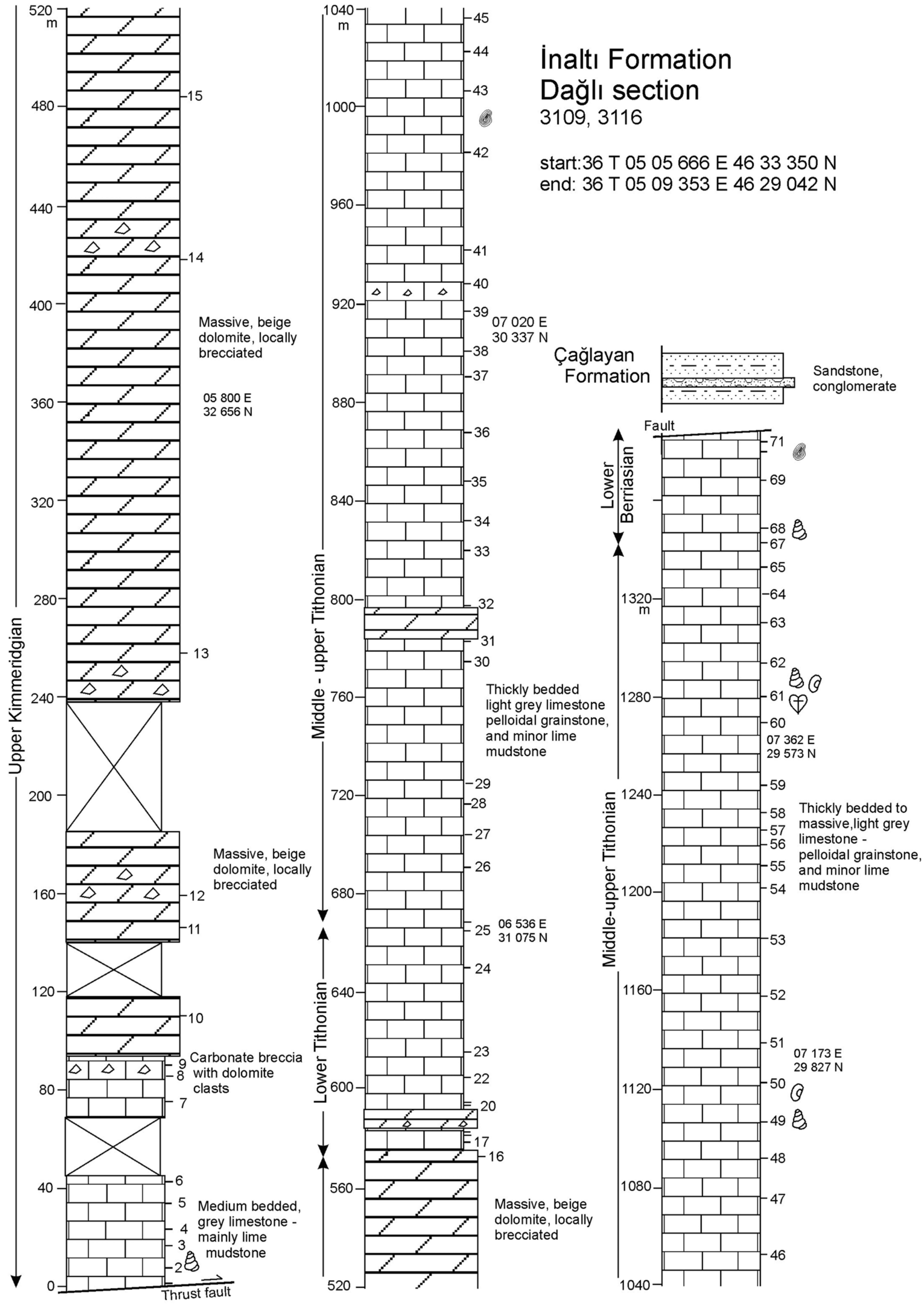

Fig. 10. The Dağlı measured stratigraphic section in the Upper Jurassic–Lower Cretaceous İnaltı Formation. For the location, see Figure 3; for the symbols, see Figure 4.

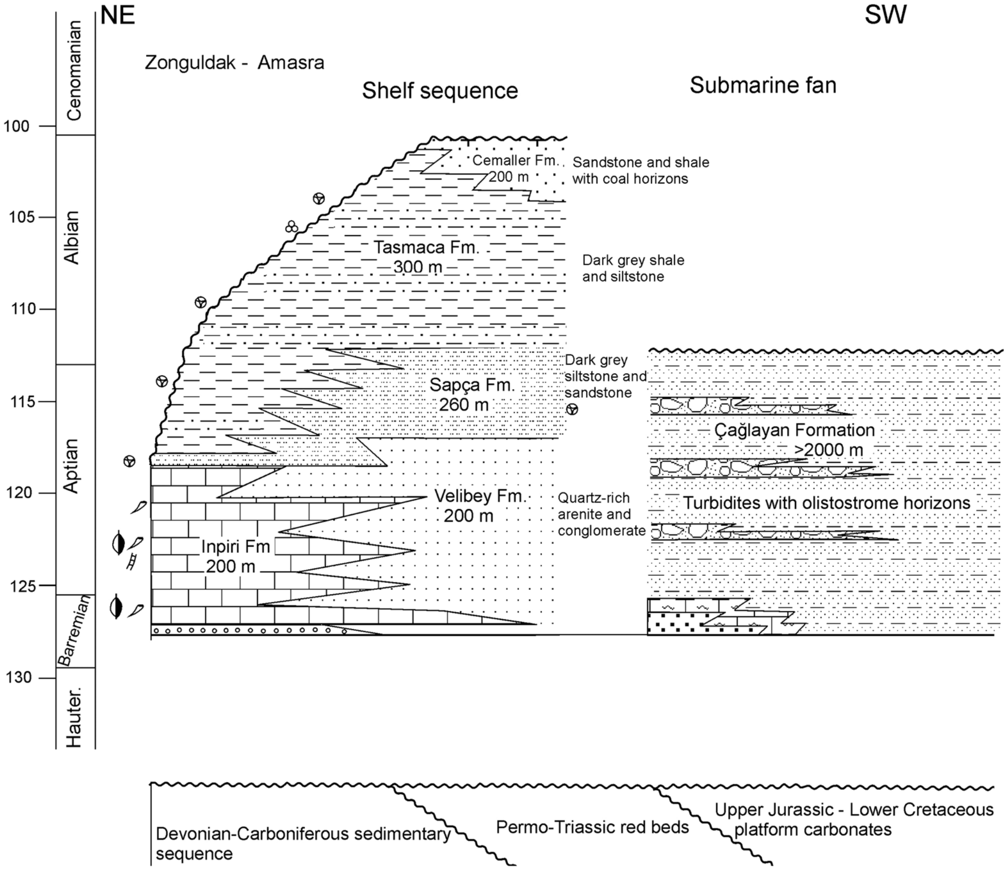

Fig. 11. Generalized stratigraphic section of the Lower Cretaceous shelf and slope sequences of the Central Pontides. For the symbols, see Figure 4.

and Hauterivian rocks have not been recognized in the Pontides. The uplift and erosion was followed by a major phase of clastic deposition during the Early Cretaceous (Barremian–Aptian), when there was a differentiation into a clastic–carbonate shelf in the north along the present Black Sea coast and a major turbidite fan in the south extending to the Tethyan Ocean (Fig. 5e) (Okay *et al.* 2013).

Early Cretaceous shelf

The Lower Cretaceous shelf sequence crops out along the Black Sea coast between Zonguldak and Amasra (Fig. 3). It lies unconformably above the Upper Jurassic–Lower Cretaceous shallow-marine carbonates or above the Palaeozoic and Permo-Triassic sedimentary series of the Istanbul Zone. The sequence starts with quartz-arenites and conglomerates, which interfinger with upper Barremian–Aptian shallow-marine carbonates (Fig. 11) (Yılmaz & Altıner 2007; Masse *et al.* 2009). Detrital zircons from the quartz-arenites indicate a source in Permo-Carboniferous and late Neoproterozoic granitoids (Akdoğan *et al.* 2017). The quartz-arenites and shallow-marine carbonates pass up into glauconite-bearing dark siltstone and sandstone of Aptian age, which are in turn overlain by dark shale and siltstones of the Tasmaca Formation (Fig. 6b). Several shale samples from this Tasmaca Formation collected from Zonguldak and Amasra regions have yielded late Albian nannofossils and foraminifera (for more detail, see the Supplementary material). The Early Cretaceous transgression is followed by a regression during the topmost Albian–Cenomanian, when shallow-marine to continental sandstone and shale with coal horizons were laid down (Fig. 11).

Early Cretaceous submarine turbidite fan: the Çağlayan Formation

The Lower Cretaceous shelf sequence of the Central Pontides passed southwards to a Barremian–Aptian submarine turbidite fan succession; the fan extended from the Laurasian margin southwards to the Tethyan Ocean (Fig. 5e). The turbidite fan sequence, the Çağlayan Formation, has a thickness of more than 2 km and its outcrops stretch out over an area of 400 × 60 km (Fig. 3) (Gedik & Korkmaz 1984; Tüysüz 1999; Hippolyte *et al.* 2010; Okay *et al.* 2013; Akdoğan *et al.* 2017). The western part of the turbidite fan is ascribed to the Ulus Formation (e.g. Tüysüz 1999): however, it has the same age range and facies as the Çağlayan Formation and there is no palaeo-high separating the two; here they are considered as part of the same basin.

The Çağlayan Formation consists predominantly of sandstone and shale but also includes significant amounts of debris flows and olistostromes. The blocks in these mass flows are mainly Upper Jurassic–Lower Cretaceous limestones but there are also large clasts of Permo-Triassic red sandstone, Carboniferous sandstone, Middle Jurassic dacite-porphyry and metamorphic rock (Okay *et al.* 2013). The age of the Çağlayan Formation, based on nannofossils, is Barremian–late Aptian (Hippolyte *et al.* 2010). Two shale samples collected during this study from north of Boyabat (Fig. 3) yielded uppermost Barremian and middle Aptian nannofossils and pollen (see the Supplementary material), confirming these ages.

The large metamorphic area south of the Lower Cretaceous turbidites in the Central Pontides, the Central Pontide Supercomplex, was regarded as a pre-Jurassic basement, and hence a potential source area. However, recent isotopic dating has shown that the Central Pontide Supercomplex consists predominantly of Early Cretaceous subduction–accretion complexes (Okay *et al.* 2006, 2013; Aygül *et al.* 2016). Palaeocurrent measurements in the turbiditic sandstones of the Çağlayan Formation indicate that the material was coming predominantly from the north to NW (Akdoğan *et al.* 2017). Detrital zircons from the turbiditic sandstones also indicate a major source area from the Palaeoproterozoic–Archaean granitoids of the Ukrainian Shield north of the Black Sea (Okay *et al.* 2013; Akdoğan *et al.* 2017). This shows that the Black Sea did not exist, or at least did not form a barrier between the Pontides and the Ukrainian Shield during the Early Cretaceous. During this time, a large river was flowing from the Ukrainian Shield south into the Tethys Ocean (Fig. 5e). Most of the sediment brought down by the river was trapped on the continental slope but some reached the trench and was subducted, resulting in an Albian accretionary complex made up of metamorphosed distal turbidites (see below).

The uplift preceding the deposition of the Çağlayan Formation is commonly ascribed to rifting leading to the opening of the Black Sea (e.g. Görür 1997). However, a period of contractional deformation and metamorphism followed the deposition of the Çağlayan Formation during the Albian (see below); thus, the extension related to the deposition of the Çağlayan Formation and the later opening of the Black Sea as a back arc-basin are two separate events (Okay *et al.* 2013).

Albian: subduction and HP–LT metamorphism

A major phase of subduction and accretion took place during the Albian in the southern part of the Central Pontides (Fig. 5e); Albian subduction–accretion complexes make up the bulk of the Central Pontide Supercomplex. Most of the accreted rocks consist of oceanic crustal sequences metamorphosed in eclogite, blueschist and greenschist facies (Okay *et al.* 2006, 2013; Aygül *et al.* 2015*a*, *b*, 2016). Metabasites are the dominant lithology, followed by micaschist and meta-ultramafic rocks with minor amounts of metachert and metagabbro. The distal parts of the mid-Cretaceous turbidite fan, the Çağlayan Formation, were also entrained in the trench, and were metamorphosed in blueschist and greenschist facies (Okay *et al.* 2013; Aygül *et al.* 2015*b*, 2016). They consist of phyllite, slate, marble, meta-sandstone and serpentinite lenses; detrital zircons from the meta-sandstones are as young as Middle Jurassic (171 Ma: Okay *et al.* 2013). The Ar/Ar phengite ages from the metamorphic rocks are mainly Albian (113–102 Ma: Okay *et al.* 2006, 2013; Aygül *et al.* 2016). The metamorphic rocks are unconformably overlain by lower Turonian pelagic limestones (Fig. 12) (Okay *et al.* 2006).

Albian metamorphism is not observed north of the Central Pontide Supercomplex: however, the intense deformation of the Çağlayan Formation most probably also took place in the Albian. Albian depositional ages are only recorded close to the Black Sea coast in the Lower Cretaceous shelf sequences (Figs 6b & 12); further south, Albian was a time of uplift and erosion.

Although there is clear indication of Albian subduction in the Central Pontides, in terms of oceanic eclogites and blueschists, there is no evidence for an Albian magmatic arc. The Çağlayan Formation, deposited in a basin above the subduction zone, does not contain any Early Cretaceous zircons (Okay *et al.* 2013; Akdoğan *et al.* 2017). The absence of an Albian magmatic arc may be related to flat subduction, which also induced uplift and exhumation of the East European Platform north of the present Black Sea, thus supplying detritus to the Çağlayan Basin (Akdoğan *et al.* 2017). Most of the East European Platform was an erosional area in the Hauterivian–Albian interval (Baraboshkin *et al.* 2003; Nikishin *et al.* 2012).

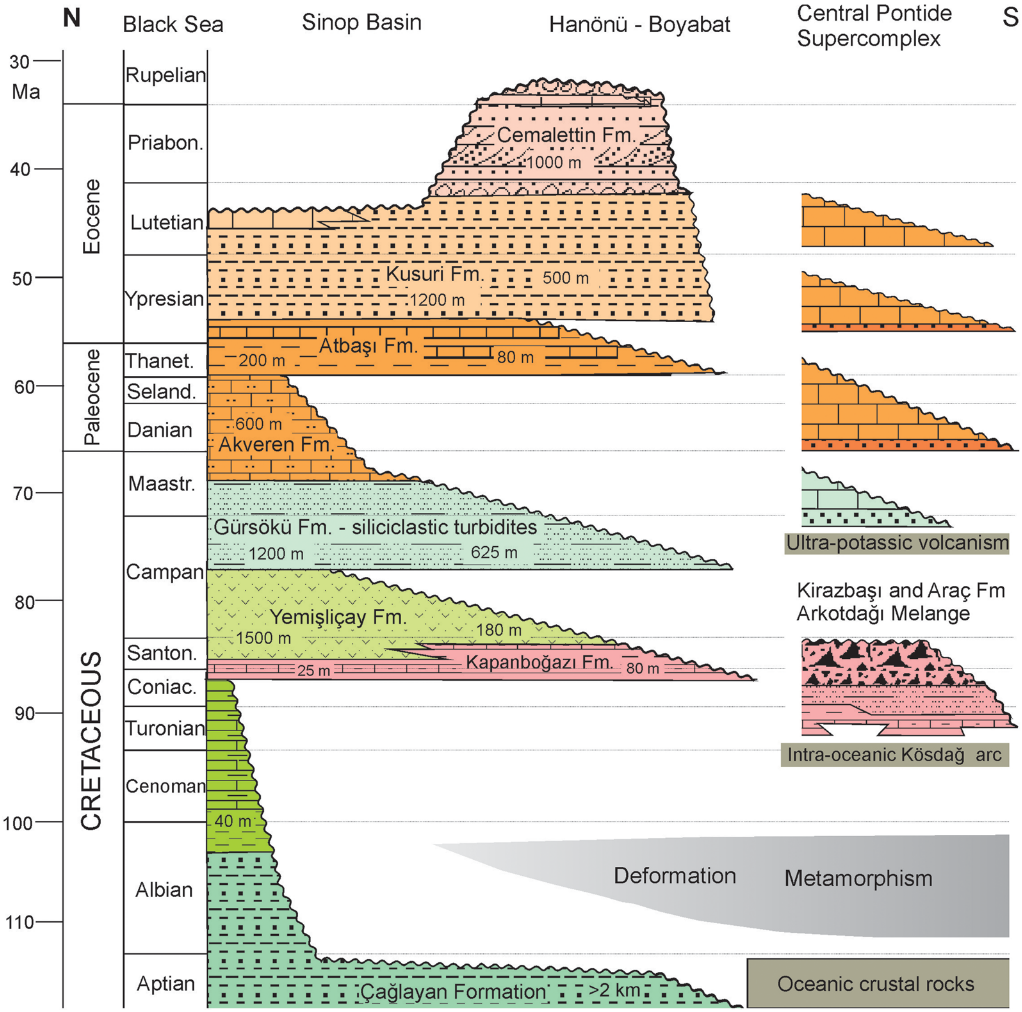

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Fig. 12. Generalized stratigraphic section of the Upper Cretaceous–Cenozoic sequences of the Central Pontides. For the symbols, see Figure 4.

Late Cretaceous – a new depositional cycle: sedimentation, arc volcanism and the opening of the Black Sea

In the Central Pontides, a new sedimentary–volcanic cycle started in the Late Cretaceous, which was characterized by thicker and more continuous sequences in the north, reflecting the presence of the Western Black Sea Basin (Figs 5e & 12) (Hippolyte *et al.* 2016). In the early part of the Late Cretaceous, in the Turonian–early Campanian, carbonate deposition and arc volcanism were dominant, which switched to turbidite sedimentation from the late Campanian onwards, reflecting the uplift of the Central Pontide Supercomplex. In the Central Pontides, magmatism started in the Santonian; the volcanic rocks form part of the magmatic arc that can be followed for more than 2000 km from the Lesser Caucasus in Georgia to the Balkans in Romania (e.g. Okay & Şahintürk 1997; Adamia *et al.* 2011; Gallhofer *et al.* 2015).

In the northern parts of the Central Pontides, Upper Cretaceous–Eocene sequences are more continuous and show increasingly deeper marine conditions towards the Black Sea, attesting to its influence (Fig. 12). The coeval sequences in the south are shallower marine and are marked by unconformities. A marine volcanosedimentary sequence containing ultrapotassic lavas and dykes was deposited in the Late Cretaceous on the accretionary complex in the south (Gülmez *et al.* 2016).

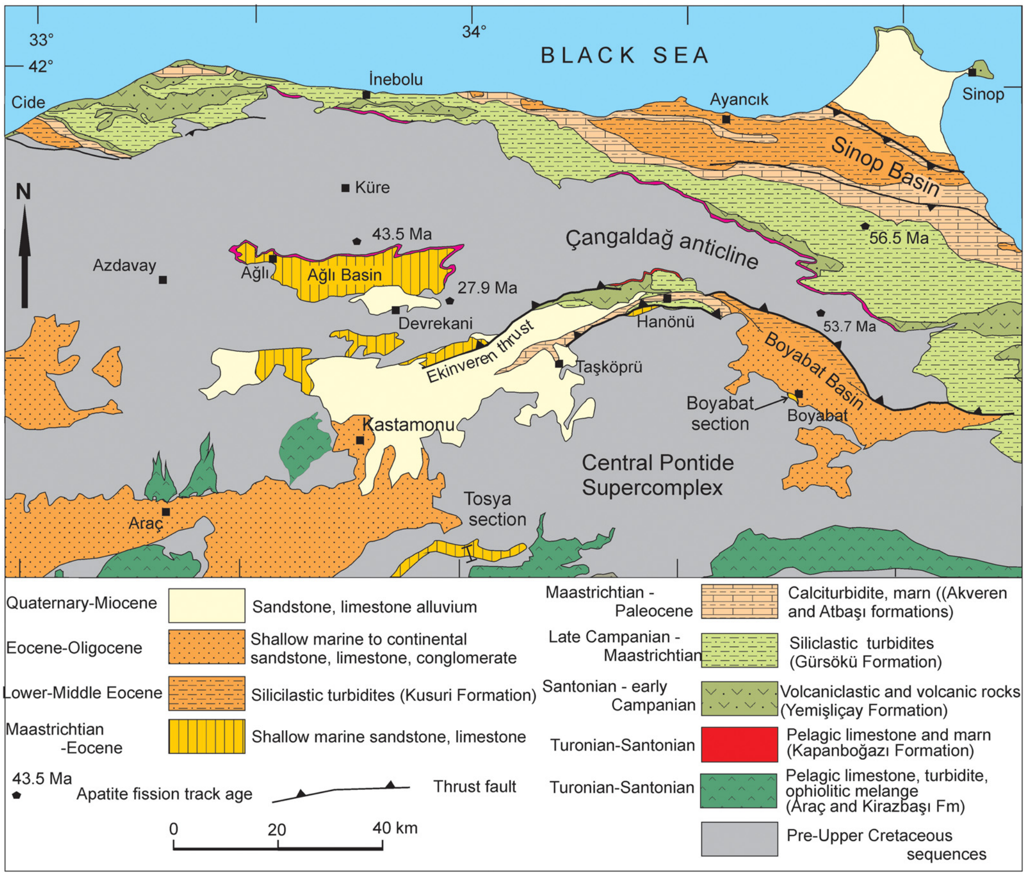

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Fig. 13. Geological map of the Central Pontides showing the distribution of the Upper Cretaceous and younger sequences (based on Uğuz *et al.* 2002; Okay *et al.* 2013). The apatite fission-track ages are from Cavazza *et al.* (2012) and Espurt *et al.* (2014).

The post-Eocene uplift and erosion in the Central Pontides have isolated the Upper Cretaceous–Eocene sequences into several domains (Fig. 13). The Sinop Basin along the Black Sea coast shows the most complete record, other domains in the south (the Hanönü, Ağlı and Boyabat regions) provide examples of Upper Cretaceous–Eocene sedimentation along the southern margin of the continental Central Pontides.

Turonian–Campanian: carbonate deposition and arc volcanism

The Turonian–Santonian sequences along the Black Sea coastal area consist mainly of pelagic limestone, marl and shale, which are overlain or intercalated with volcaniclastic rocks. Locally, the transition from Lower to Upper Cretaceous sequences is conformable (Tüysüz *et al.* 2016), whereas in most areas, such as on the Boyabat–Sinop road, Amasra or Hanönü regions (Fig. 13), Cenomanian–Turonian sequences are missing and Coniacian–Santonian red pelagic limestones lie unconformably above the deformed Çağlayan Formation (Figs 6b & 12) (Okay *et al.* 2006, 2013; Hippolyte *et al.* 2010). The pink Coniacian–Santonian pelagic limestones, typically a few tens of metres thick, are overlain and interfinger with volcaniclastic and volcanic rocks. Within the Cenomanian–Santonian sequence, Tüysüz *et al.* (2012, 2016) differentiated two distinct pelagic limestone horizons, of Cenomanian–Turonian and Santonian ages, respectively, separated by a Turonian–Santonian volcanic interval: however, interfingering of deep-marine carbonates, volcaniclastic and volcanic rocks is more likely.

The earliest precisely dated Upper Cretaceous volcanic rocks in the Central Pontides are Santonian in age; Middle Turonian basalts intercalated with deep-marine limestones are described from the Eastern Pontides (Taner & Zaninetti 1978). The bulk of the volcanism in the Pontides extends from the Santonian to the early Campanian (Hippolyte *et al.* 2016). In the Central Pontides, the arc volcanism consists predominantly of submarine pyroclastic rocks of andesitic and basaltic origin; lava flows are rare. The thickness of the volcanic sequence ranges from less than 100 m in the south to more than 1000 m along the Black Sea coast. Seismic reflection profiles in the Black Sea show that the volcanic centres are located offshore (Nikishin *et al.* 2015*a*), which suggests the opening of the Western Black Sea Basin through the splitting of the magmatic arc.

Turonian–Santonian debris flows and mélanges in the Central Pontide Supercomplex

During the early part of the Late Cretaceous, the Central Pontide Supercomplex formed a wide submarine accretionary complex on the northern margin of the Tethys Ocean. The accretionary complex consisted of oceanic crustal rocks and of intra-oceanic arcs, such as the Cenomanian–Turonian Kösdağ arc (Fig. 12) (Aygül *et al.* 2015*a*). Olistostrome-bearing, deep-marine Turonian–Santonian sequences were deposited on this accretionary complex. These sequences, known as the Kirazbaşı or Araç formations or Arkotdağı Mélange (Okay *et al.* 2006, 2013; Göncüoğlu *et al.* 2014), occur as tectonized slices between metamorphic thrust sheets (Fig. 13). They are often described as ophiolitic mélange (Göncüoğlu *et al.* 2014): however, at several localities they lie stratigraphically above the Albian metabasites and phyllites (Yiğitbaş *et al.* 1990; Okay *et al.* 2006). The sequence starts with Turonian pelagic limestones, less than 10 m thick, which are overlain by greywacke and shale followed by debris flows with blocks of radiolarian chert and Albian pelagic limestone (Fig. 12). The debris flows are overlain by ophiolitic mélange of basalt, radiolarian chert, serpentinite and limestone. The chert blocks yielded Middle Jurassic–Early Cretaceous radiolaria ages (Tüysüz & Tekin 2007; Göncüoğlu *et al.* 2012).

Maastrichtian–Eocene: turbidite deposition

Thick sequences of turbidites were deposited in the northern parts of the Central Pontides during the Maastrichtian–Eocene interval, probably sourced from the Central Pontide Supercomplex. These are best preserved in the Sinop Basin (Gedik & Korkmaz 1984; Hippolyte *et al.* 2010), which was separated from the West Black Sea Basin by the Sinop horst, where Santonian volcanic rocks crop out (Fig. 13) (Leren *et al.* 2007; Espurt *et al.* 2014). The Sinop horst formed during the Late Cretaceous opening of the Black Sea by footwall uplift, and generated the Sinop Basin on its lee side. More discontinuous and shallower marine sequences were formed in the southern parts of the Central Pontides and on parts of the Central Pontide Supercomplex, which are best preserved in the Hanönü region.

The Sinop Basin. In the Sinop Basin, the Coniacian–middle Campanian volcaniclastic rocks are succeeded by middle Campanian–lower (?) Maastrichtian siliciclastic turbidites, the Gürsökü Formation, 700–1200 m in thickness (Gedik & Korkmaz 1984; Hippolyte *et al.* 2010). The bulk of the Gürsökü Formation in the Sinop Basin consists of sheet-like, Bouma-type turbidites (Leren *et al.* 2007). The sandstones are litharenites with volcanic and minor calcareous clasts; the amount of limestone clasts increases upwards in the section. The palaeocurrents indicate predominantly eastwards axial flow (Leren *et al.* 2007). A mudstone sample from the Gürsökü Formation collected during this study from the north of Boyabat contains abundant nannofossils of early–middle Campanian age (Zone UC15, for more details, see the Supplementary material).

The Gürsökü Formation passes upwards with a gradual increase in the carbonate clasts into the calcareous turbidites of the Maastrichtian–Paleocene Akveren Formation (Fig. 12). The Akveren Formation consists of calcarenite beds alternating with marl and calcareous mudstone (Leren *et al.* 2007). A mudstone sample from the Akveren Formation north of Boyabat contains Danian (NP2) nannofossils. The calciturbidites of the Akveren Formation also show eastwards palaeocurrents, and are overlain by Upper Paleocene (Thanetian) reefal limestones. A renewed transgression in the Early Eocene leads to the deposition of pink calcareous mudstones and subordinate thin calc-arenite beds of the Atbaşı Formation.

The pink mudstones of the Atbaşı Formation gradually pass upwards into Eocene siliciclastic turbidites and associated mudstones of the Kusuri Formation (Gedik & Korkmaz 1984; Görür & Tüysüz 1997). The sequence, which is 1200 m thick, is Early and early Middle Eocene (Ypresian–Lutetian) in age (Janbu *et al.* 2007). The age is confirmed from a shale sample close to Ayancık, which contains Middle Eocene (NP15) nannofossils. The Kusuri Formation starts with mudstones intercalated with thin carbonate-rich turbidite sandstone beds. These are overlain by sandstone-rich turbidites showing west- to NW-directed palaeocurrents (Janbu *et al.* 2007). The sequence becomes calcareous towards the top, and ends with shallow-marine Lutetian limestones, which crop out on the Black Sea coastal area. The Eocene turbidite sequence shows evidence for syndepositional contractional deformation (for more details, see the Supplementary material).

Hanönü and Boyabat regions. The Hanönü region on the southern limb of the Çangaldağ anticline preserves a record of Late Cretaceous–Eocene sedimentation on the southern margin of the continental Central Pontides and on the Central Pontide Supercomplex (Figs 13 & 14) (Okay *et al.* 2006). The region lies within the Eocene fold and thrust belt, and shows a comparable Upper Cretaceous–Eocene stratigraphy with the Sinop Basin but marked by several unconformities (Fig. 12).

The Çağlayan Formation with very large blocks of metamorphic rocks is unconformably overlain by red pelagic limestone, shale and debris flows (the Kapanboğazı Formation). Two measured stratigraphic sections in the Kapanboğazı Formation in the Hanönü area (Vakıf and Kaşharman) indicate a Santonian age; Cenomanian–Coniacian stages are missing (Fig. 15). The Kapanboğazı Formation is overlain by volcaniclastic and volcanic rocks (the Yemişliçay Formation) with lenses of Santonian pelagic limestone. Lying unconformably above the volcaniclastic sequence are Maastrichtian proximal turbidites of the Gürsökü Formation. The base of the Gürsökü Formation steps down to the Çağlayan Formation, indicating a period of uplift and erosion in the Campanian (Fig. 14). The turbidites consist of thick-bedded coarse sandstone and conglomerate with minor shale, and contain transported large benthic foraminifera. A sample from the basal parts of the Gürsökü Formation contains benthic foraminifera such as *Siderolites* cf. *calcitrapoides*, *Cideina* cf. *soezerii* and *Lepiorbitoides* sp., indicating a Maastrichtian age (Fig. 15, Ballıkaya section) (see also Özkan-Altıner & Özcan 1999).

The Gürsökü Formation is unconformably overlain by the Upper Paleocene–Lower Eocene white marl and pelagic limestone with calciturbidite beds, the equivalent of the Akveren Formation of the Sinop Basin (Fig. 12). Measured stratigraphic sections of the Akveren Formation in the Hanönü area indicate a Thanetian–Early Eocene age (Figs 14 & 15). The base of the Akveren Formation in the Hanönü area is a major angular unconformity and steps down to the Santonian volcaniclastic rocks, indicating tilting, uplift and erosion in the Early Paleocene (Fig. 16a).

Lower–Middle Eocene (Lutetian) turbidites (the Kusuri Formation) crop out in the Boyabat Basin east of the Hanönü region (Fig. 13). The turbidites pass up into a thick fluviatile to deltaic sequence of sandstone, conglomerate and mudstone of Oligocene age (the Cemalettin Formation). Within this continental sequence, Sanders *et al.* (2014) described a shallow-marine mudstone horizon of latest Eocene–earliest Oligocene age, which if confirmed would constitute the youngest marine bed in the southern Central Pontides.

The Upper Cretaceous–Eocene sequence in the Hanönü region is bounded in the south by the Gökırmak Fault, a major Late Cretaceous–Paleocene normal fault reactivated as an Eocene thrust (Figs 13 & 14). South of the Gökırmak Fault, the Çangaldağ Complex, consisting of Middle Jurassic metabasite, meta-andesites, phyllite and marble, is unconformably overlain by shallow-marine Maastrichtian, Paleocene and Eocene sandstone–limestone sequences (Fig. 12). The Maastrichtian–Eocene sequence is not continuous but different parts lie isolated on the metamorphic basement (Figs 13 & 17), indicating periodic uplift and erosion, as also deduced by Aydemir & Demirer (2013). Özcan *et al.* (2007) described two Eocene shallow-marine limestone sequences, of Ypresian and Lutetian ages, respectively, lying unconformably above the metamorphic rocks in the Kastamonu region. Similar shallow-marine Paleocene sandstone–limestone sequences, a few hundred metres thick, crop out south of Boyabat and south of Kastamonu lying unconformably on the metamorphic rocks of the Central Pontide Supercomplex (Figs 16b & 17; Özgen-Erdem *et al.* 2005). Such Maastrichtian and Paleocene carbonate built-ups must have been the source of the calciturbidites of the Akveren Formation.

Collision, uplift and erosion

Marine sedimentation in the Pontides largely ended at the end of the Middle Eocene (Lutetian) as a result of collision of the Central Pontides with the Kırşehir Block. Continent–continent collision is a prolonged process, as exemplified by the India–Asia collision, which started in the Eocene and is still continuing (e.g. Najman *et al.* 2010). It starts when the distal parts of the passive continental margin enter the subduction zone, which leads to the uplift of the active margin. This process leads to the development of retro forearc basins filled with turbidites. A critical stage in the collision is reached when the whole of orogen is lifted above sea level, this corresponds to the end of the Lutetian (Middle Eocene) in the Central Pontides.

The first signs of impending collision in the Central Pontides are the deposition of the Upper Campanian–Maastrichtian turbidites in retro fore-arc basins. The turbidites were probably sourced from the Central Pontide Supercomplex, which was undergoing uplift due to underthrusting by the Kırşehir Block. Palaeomagnetic studies have also shown that the northwards concave shape of the Central Pontides started to form in the Maastrichtian as a result of collision with the Kırşehir Block (Channel *et al.* 1996; Meijers *et al.* 2010*a*). The

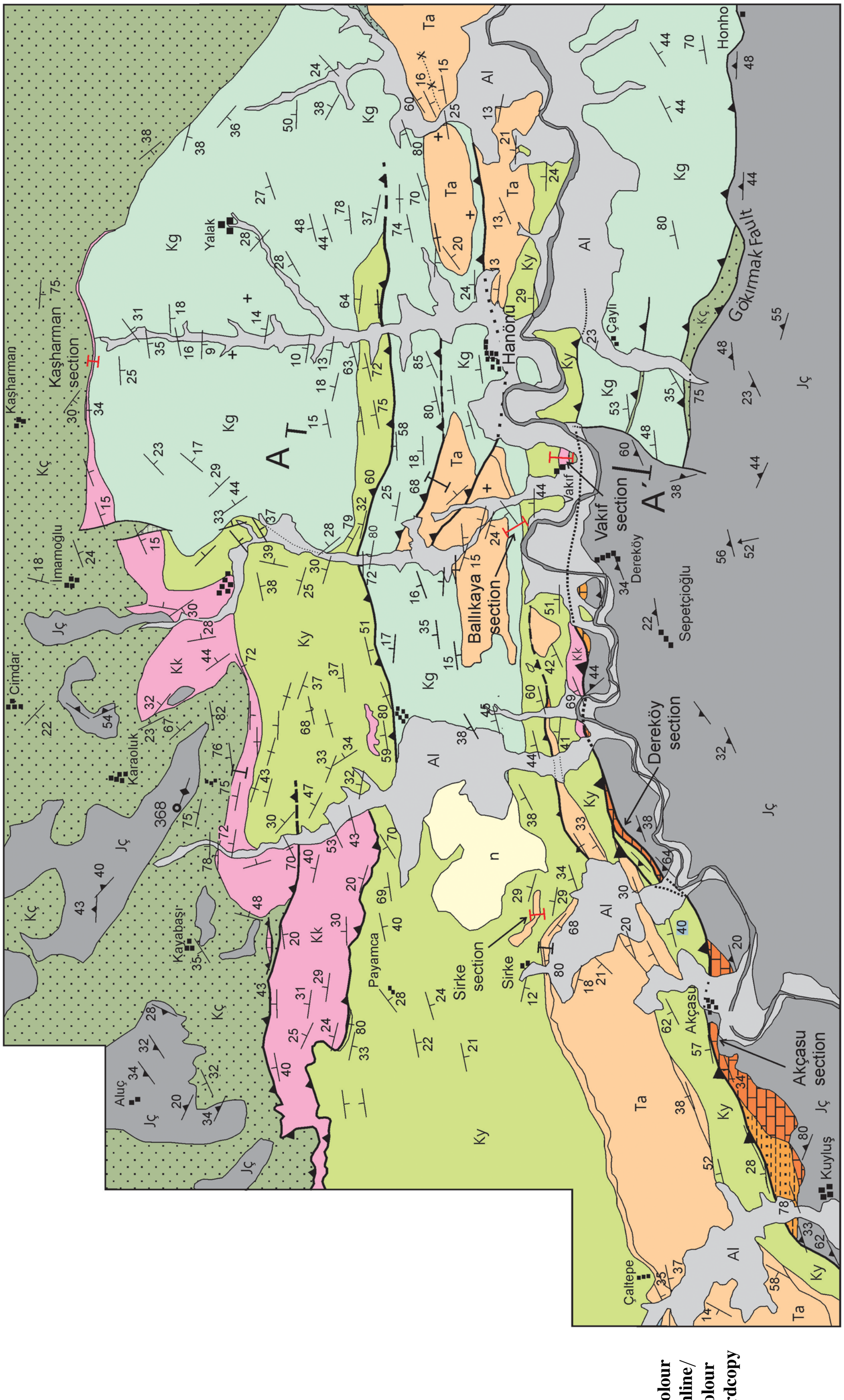

Fig. 14. *Continued.*

Colour online/colour hardcopy

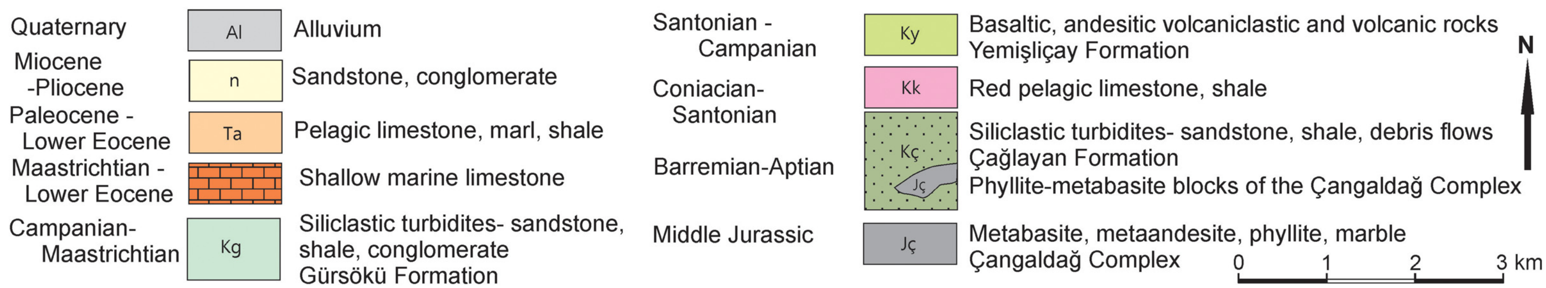

Fig. 14. Geological map of the Hanönü region in the southern Central Pontides. For the location, see Figure 13. Modified from Okay *et al.* (2006).

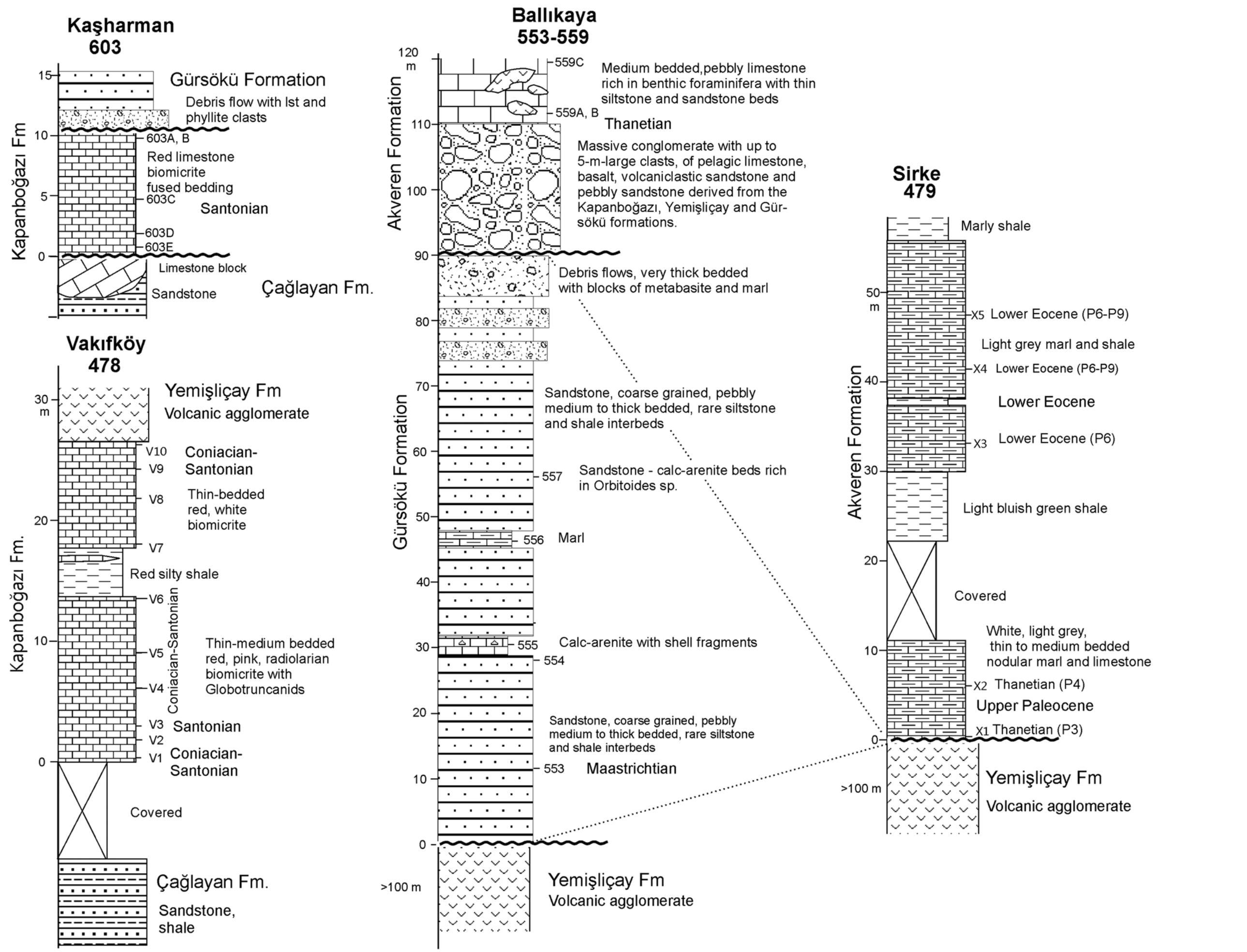

Fig. 15. Measured Cretaceous–Paleocene stratigraphic sections in the Hanönü area of the southern Central Pontides. For the location, see Figure 13; for a list of fossils, see the Supplementary material.

Colour online/ colour hardcopy

Fig. 16. Field photographs illustrating sequences and unconformities in the southern Central Pontides. (**a**) Upper Paleocene–Lower Eocene marl and shale lying with an angular unconformity over the tilted Santonian volcaniclastic rocks of the Yemişliçay Formation, Sirke, Hanönü. This section is logged in Figure 15. (**b**) Lower–Middle Paleocene shallow-marine sandstones and limestones lying unconformably over the metabasites of the Domuzdağ Complex, Pervanekaya Hill, Boyabat. This section is logged in Figure 17.

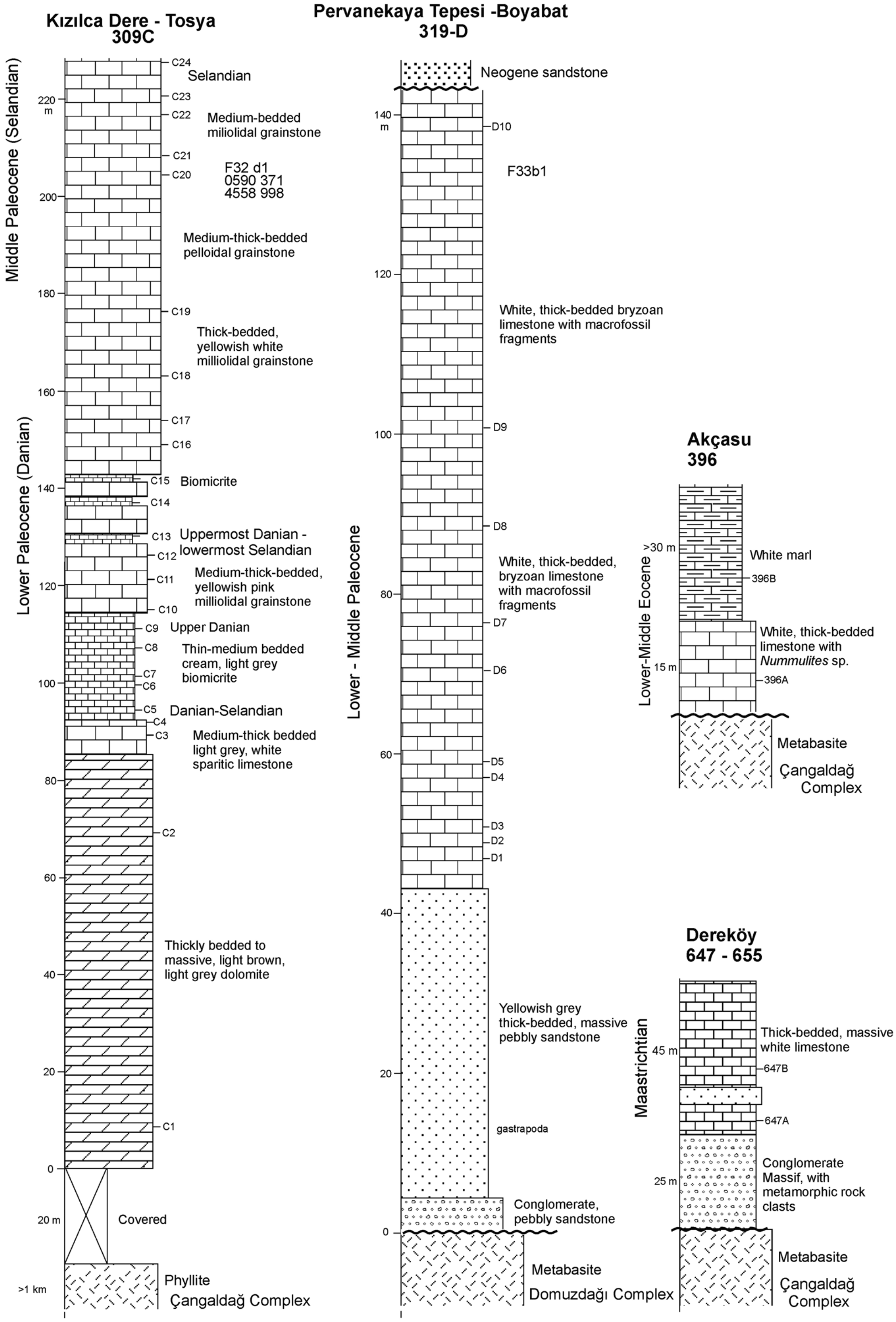

Fig. 17. Measured stratigraphic sections of the Upper Cretaceous–Eocene sequences lying on the metamorphic rocks of the Central Pontide Supercomplex. For the locations of the Tosya and Boyabat sections, see Figure 3; for the others, see Figure 13. For a list of fossils, see the Supplementary material.

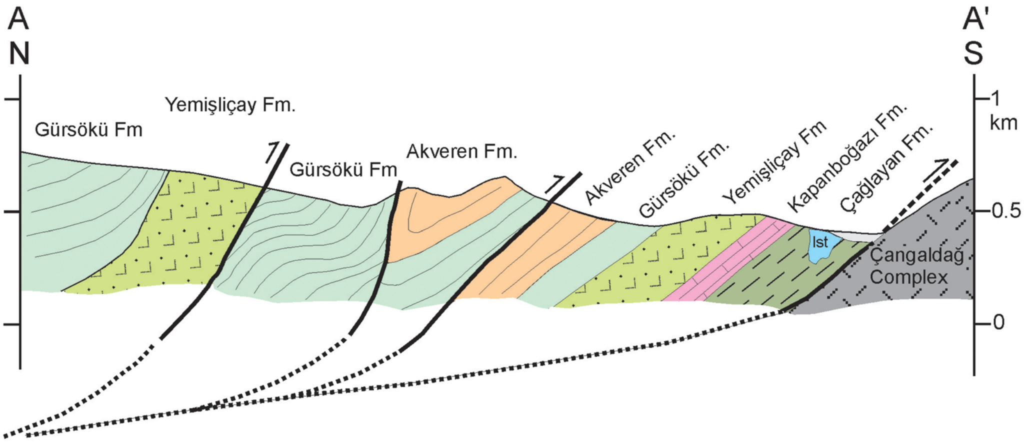

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Fig. 18. Geological cross-section from the Hanönü region in the southern Central Pontides showing the south-vergent Eocene fold and thrust belt. For the location of the section, see Figure 13.

convergence rate between the Pontides and the Anatolide–Tauride and Kırşehir blocks probably decreased in the Paleocene, when there was deposition of carbonates and shales. An acceleration of convergence rate during the Early–Middle Eocene led to the deposition of widespread siliciclastic turbidites due to renewed uplift in the source region.

Thrust faulting in the Central Pontides started in the Late Eocene and continued episodically since then, propagating northwards to the Black Sea and southwards to the Çankırı Basin (Kaymakçı *et al.* 2009; Espurt *et al.* 2014; Hippolyte *et al.* 2016). The M 6.6 Bartın earthquake on 3 September 1968, with the epicentre located offshore in the Black Sea 10 km north of Amasra, occurred on a north-vergent thrust fault (Alptekin *et al.* 1986; Yıldırım *et al.* 2011), indicating active ongoing shortening. The shortening direction (σ_1) in the Central Pontides shows a change from NW–SE to NNE–SSW, going from clockwise apparently with little variation since the Late Eocene (Sunal & Tüysüz 2002; Hippolyte *et al.* 2016).

In the southern Central Pontides, the thrusting was south-vergent. A major structure was the Ekinveren Thrust, which can be followed for more than 100 km along strike (Fig. 13) (Yıldırım *et al.* 2011), and overthrust sequences as young as Miocene in the Kastamonu Basin. Another major structure is the Gökırmak Fault, located along the northern boundary of the Central Pontide Supercomplex (Figs 12 & 13). It was a major normal fault, controlling the sedimentation during the Cretaceous and Paleocene, which was reactivated as a thrust fault in the Eocene. In the Hanönü region, the Gökırmak Fault consists of several splays, which form an imbricate thrust stack (Fig. 18). The Oligocene fluvio-deltaic clastic rocks of the Boyabat Basin are folded and thrust-faulted, indicating continuing shortening in the Oligocene (e.g. Espurt *et al.* 2014). In the northern Central Pontides, the Eocene and younger thrusting was north-vergent and led to the uplift of the Sinop Basin (Fig. 13) (Sunal & Tüysüz 2002). The present structure of the Central Pontides is a doubly-vergent orogen, which formed from the Eocene onwards (Aydın *et al.* 1995; Şengör 1995; Espurt *et al.* 2014). Based on seismic reflection sections and surface geology, Espurt *et al.* (2014) estimated the north–south crustal shortening in the Central Pontides as 33%. The few apatite fission-track ages from the Central Pontides are Late Paleocene–Oligocene, with a general younging towards the north (Fig. 13) (Cavazza *et al.* 2012; Espurt *et al.* 2014).

Conclusions

- Before the Late Cretaceous opening of the Black Sea, the Central Pontides constituted part of the southern margin of Laurasia. During most of the Mesozoic, the margin was active due to Tethyan Ocean subducting northwards below the Laurasia. In the Central Pontides, there were pronounced phases of oceanic subduction–accretion during the Late Triassic, Middle–early Late Jurassic, Early Cretaceous (Albian) and Late Cretaceous (Santonian–Campanian). The evidence includes subduction–accretion complexes, magmatic arcs and forearc sequences of these ages. The Late Jurassic–earliest Cretaceous (Tithonian–Berriasian) was a tectonically quiescent period.
- The Central Pontides comprises two tectonic terranes: the Istanbul Zone in the west and the Sakarya Zone in the east. They were amalgamated

before the Late Jurassic (Kimmeridgian), most probably during the Triassic. The Istanbul Zone has a thick well-developed Palaeozoic sedimentary basement, whereas the basement of the Sakarya Zone includes Permo-Carboniferous granites and Triassic and older subduction–accretion complexes.

- Two features that distinguish the Central Pontides from the western and eastern Pontides are: the presence of a vast region of Jurassic–Cretaceous subduction–accretion complexes in the south; and a large mid-Cretaceous submarine turbidite fan, the Çağlayan Formation, in the north. These unique features are probably related to its location at a cusp between the subduction segments (Okay *et al.* 2013; Nikishin *et al.* 2015*b*)
- The first stratigraphic unit that clearly extends both over the İstanbul and Sakarya zones in the Central Pontides is the İnaltı Formation, comprising Upper Jurassic–lowermost Cretaceous shallow-marine limestones,. Two new detailed measured stratigraphic sections (Figs 7 & 10) indicate a Kimmeridgian–Berriasian age range for the Inaltı Formation showing that the Istanbul and Sakarya zones were amalgamated before the Kimmeridgian.
- Carbonate deposition during the earliest Cretaceous (Berriasian) was followed by widespread uplift and erosion during the Valanginian and Hauterivian.
- In the Central Pontides, clastic deposition took place during the Lower Cretaceous (Barremian–Aptian), when the region was differentiated into a clastic–carbonate shelf in the north and a large submarine turbidite fan in the south (the Çağlayan Formation). Turbidites of the Çağlayan Formation crop out over an area of 400 × 60 km. Detrital zircons from the sandstone turbidites indicate a dominant source area in the north in the East European Platform, which implies that the Black Sea was not yet open in the Aptian.
- Large segments of subducted oceanic crust and mantle were accreted to the southern margin of the Central Pontides in the Albian, represented by eclogites and blueschist with oceanic protoliths with metamorphic ages of 114–105 Ma. Distal parts of the Çağlayan turbidite fan were entrapped in the Albian subduction zone and were metamorphosed. During the Albian subduction–accretion event, the Central Pontides was uplifted; the southern parts close to the subduction zone were deformed.
- A new sedimentary cycle, controlled by the opening of the Western Black Sea Basin, started in the Late Cretaceous with the deposition of Turonian–Santonian pelagic limestones, which interfinger and are overlain by arc volcanic rocks. In the middle–late Campanian, volcanism was replaced by the deposition of siliciclastic turbidites in response to uplift of the Central Pontide Supercomplex. In the northern parts of the Central Pontides, sedimentation was continuous from the Campanian to the Middle Eocene, whereas it was marked by several angular unconformities in the south reflecting the growth of the orogen.
- In the Central Pontides, the marine sedimentation ended in the Middle Eocene (Lutetian) as a result of the collision with the Kırşehir Massif and/or the Anatolide–Tauride Block. The Eocene and younger contraction created a doubly vergent orogen.

The work in the Central Pontides has been supported over the last 15 years by the TÜBİTAK projects 101Y032 and 109Y049 and partly by TÜBA. We thank E. Sirel and Mike Bidgood for additional foraminifera determinations, B. Riding for the characterization of the palynomorphs, and Paul Bown and Steve Starkie for nannofossil determinations. Michael Wagreich and Anatoly Nikishin provided constructive reviews.

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