Provenance of a large Lower Cretaceous turbidite submarine fan complex on the active Laurasian margin: Central Pontides, northern Turkey

Remziye Akdoğan\textsuperscript{a, b, d,*}, Aral I. Okay\textsuperscript{a, b}, Gürsel Sunal\textsuperscript{a}, Gabor Tari\textsuperscript{c}, Guido Meinhold\textsuperscript{d}, Andrew R.C. Kylander-Clark\textsuperscript{e}

\textsuperscript{a}Istanbul Technical University, Faculty of Mines, Department of Geology, Maslak 34469, Turkey

\textsuperscript{b}Istanbul Technical University, Eurasia Institute of Earth Sciences, Maslak 34469, Turkey

\textsuperscript{c}OMV Exploration and Production, Trabrennstraße 6-8, Vienna 1020, Austria

\textsuperscript{d}Geowissenschaftliches Zentrum der Universität Göttingen, Abteilung Sedimentologie/Umweltgeologie, Goldschmidtstraße 3, D-37077 Göttingen, Germany

\textsuperscript{e}University of California Santa Barbara, Department of Earth Sciences, Santa Barbara, CA 93106 USA, 18058934688

*Corresponding author at: Istanbul Technical University, Faculty of Mines, Department of Geology and Eurasia Institute of Earth Sciences, Maslak 34469, Turkey

E-mail address: rakdogan@itu.edu.tr (R. Akdoğan).
Abstract

The Pontides formed the southern active margin of Laurasia during the Mesozoic. They became separated from mainland Laurasia during the Late Cretaceous, with the opening of the Black Sea as an oceanic back-arc basin. During the Early Cretaceous, a large submarine turbidite fan complex developed in the Central Pontides. The turbidites cover an area of 400 km by 90 km with a thickness of more than 2 km. We have investigated the provenance of these turbidites—the Çağlayan Formation—using paleocurrent measurements, U-Pb detrital zircon ages, REE abundances of dated zircons and geochemistry of detrital rutile grains. 1924 paleocurrent measurements from 96 outcrop stations indicate flow direction from northwest to southeast in the eastern part of the Çağlayan Basin and from north-northeast to west-southwest in the western part. 1194 detrital zircon ages from 13 Lower Cretaceous sandstone samples show different patterns in the eastern, central and western parts of the basin. The majority of the U-Pb detrital zircon ages in the eastern part of the basin are Archean and Paleoproterozoic (61% of all zircon ages, 337 grains); rocks of these ages are absent in the Pontides and present in the Ukrainian Shield, which indicates a source north of the Black Sea. In the western part of the basin the majority of the zircons are Carboniferous and Neoproterozoic (68%, 246 grains) implying more local sources within the Pontides. The detrital zircons from the central part show an age spectrum as mixture of zircons from western and eastern parts. Significantly, Jurassic and Early Cretaceous zircons make up less than 2% of the total zircon population, which implies lack of a coeval magmatic arc in the region. This is compatible with the absence of the Lower Cretaceous granites in the Pontides. Thus, although the Çağlayan Basin occupied a fore-arc position above the subduction zone, the arc was missing, probably due to flat subduction, and the basin was
largely fed from the Ukrainian Shield in the north. This also indicates that the Black Sea opened after the Early Cretaceous following the deposition of the Çağlayan Formation.

**Keywords:** Black Sea, Central Pontides, Early Cretaceous, paleocurrent, provenance, detrital zircon.

1. Introduction

During the Mesozoic, the Pontides formed the active margin of Laurasia, with the Tethys ocean dipping north under the Pontides along the present İzmir-Ankara-Erzincan Suture (e.g., Şengör and Yılmaz, 1981; Okay and Nikishin, 2015). The subduction resulted in the formation of Middle-Late Jurassic and Late Cretaceous magmatic arcs in the Pontides. Between these magmatic events, a large submarine turbidite basin formed in the Central Pontides during the Early Cretaceous. Northward subduction of the Tethyan ocean during the deposition of the turbidites is shown by the presence of subduction-accretion complexes in the southern part of the Central Pontides (called the Central Pontide Supercomplex) with Early Cretaceous (136-102 Ma) greenschist, blueschist and eclogite facies metamorphism (Okay et al., 2006a, 2013; Aygül et al., 2015, 2016). However, there is no evidence for a contemporaneous magmatic arc development in the Central Pontides or to the north. The basinal sediments, called the Çağlayan Formation, occupy an area of 400 km by 90 km and with a thickness of over two kilometers (this study and Okay et al., 2013). We provide data on the provenance of these turbidites from paleocurrent measurements, U-Pb detrital zircon ages and detrital rutile geochemistry from the sandstones, and discuss the source of the turbidites and their relation to the opening of the Black Sea Basin. The Black Sea is a back-
arc basin with oceanic crust, which opened during the Late Cretaceous and separated the Pontides from the mainland Laurasia (Nikishin et al., 2015a).

Large turbidite fans are commonly deposited on passive continental margins at shelf edges and are fed by a point source (often a submarine canyon) (e.g., Rupke, 1978; Reading and Richards, 1994). The Çağlayan turbidite fan complex, that formed on an active continental margin above a subduction zone (Okay et al., 2013) and was fed by multiple sources, differs with its size (400 km by 90 km) from the known fans that formed on active margins (e.g., Shanmugam and Moiola, 1988; Mattern, 2005). It occupied the position of a fore-arc, such as the Great Valley Basin in California (e.g. Ingersoll, 1979), yet unlike typical fore-arc basin strata, the Lower Cretaceous Çağlayan Formation has very minor amounts of syn-depositional detrital zircons and is devoid of volcanic rock fragments. This is compatible with the absence of an Early Cretaceous arc in the Black Sea region. The amount of syn-depositional detrital zircons is higher than 80% in the fore-arc basinal strata in the western US (e.g., Sharman et al. 2015). Thus, the Çağlayan Basin provides an unusual example of a basin at an active continental margin, which has features of a submarine fan complex deposited at a passive continental margin.

2. Geology of the tectonic units of the Central Pontides

The Pontides form an E–W trending mountain range between the Black Sea to the north and the İzmir-Ankara Suture to the south (Fig. 1). They consist of three distinct terranes, called the Sakarya, Istanbul and Strandja Zones (Okay and Tüysüz, 1999). The Lower Cretaceous shelf and turbidite sequence occupy a large area in the Central Pontides, covering both Istanbul and Sakarya Zones. The main features of these terranes are described below as a basis for the discussion of the detrital zircon data.
2.1. The Istanbul Zone

The Istanbul Zone is characterized by a continuous, well-developed, transgressive Paleozoic sedimentary succession ranging from Ordovician to Carboniferous (Görür et al., 1997; Dean et al., 2000; Özgül, 2012), which lies over a late Neoproterozoic granitic and metamorphic basement (Chen et al., 2002) (Figs. 2 and 3). The late Neoproterozoic crystalline basement consists of gneiss, amphibolite, metaophiolite, metavolcanic and metasedimentary rocks and many granitic plutons dated 560–590 Ma (Yiğitbaş et al., 1999, 2004; Ustaömer P. and Rogers, 1999; Chen et al., 2002; Ustaömer P. et al., 2005; Okay et al., 2008). The Paleozoic rocks of the Istanbul Zone were deformed during the Carboniferous Variscan Orogeny and were intruded by the latest Permia (255–261 Ma) granites (Yılmaz-Şahin et al., 2009; Ustaömer P. et al., 2005; Okay et al., 2013) (Figs. 2 and 3). The Paleozoic sequence of the Istanbul Zone is unconformably overlain by the Permo–Triassic sedimentary rocks. In the eastern part of the Istanbul Zone in the Central Pontides Upper Jurassic–Lower Cretaceous shallow marine platform carbonates lie unconformably over the Permo–Triassic series; the same limestones extend east to the Sakarya Zone providing an upper age limit for the juxtaposition of these two terrains. The Upper Jurassic–Lower Cretaceous limestones are unconformably overlain by the Lower Cretaceous shelf clastic and carbonate sequences and by the siliciclastic turbidites of the Çağlayan Formation, which also extend both over the Istanbul and Sakarya Zones (Figs. 1, 2 and 3).

2.2. The Sakarya Zone

The Sakarya Zone has a pre-Jurassic basement consisting of two main components. The continental part of the basement is made up of metamorphic rocks intruded by the
Devonian, Carboniferous and Permian granites (Okay, 1996; Okay et al., 1996; 2006a, b; Ustaömer P. et al., 2012; Ustaömer et al., 2012; Aysal et al., 2012; Sunal, 2013; Nzegge et al., 2006; Topuz et al., 2004, 2007, 2010; Dokuz, 2011; Kaygusuz et al., 2012) (Fig. 2). The other part of the basement consists of the Permo–Triassic accretionary complexes, called the Karakaya Complex (Okay and Göncüoğlu, 2004). The Karakaya Complex is subdivided into a lower part made up of metabasites with Late Triassic eclogite and blueschist tectonic slices (Okay and Monié 1997; Okay et al., 2002), and an upper part of chaotically deformed greywackes and basalts with exotic Permo–Carboniferous limestone blocks. The Triassic Küre Complex in the Central Pontides, consisting of the Upper Triassic flysch with serpentine, pillow lava and dolerites (Ustaömer and Robertson, 1994) can be correlated with the Upper Karakaya Complex. The basement rocks of the Sakarya Zone are overlain by Lower Jurassic sandstone and conglomerate, which pass up into a thick series of volcanioclastic and volcanic rocks of Lower–Middle Jurassic age (Kandemir and Yılmaz, 2009; Genç and Tüysüz, 2010). High-level, acidic to intermediate intrusions of Middle Jurassic age crop out widely in the Central Pontides (Yılmaz and Boztuğ, 1986; Okay et al., 2013, 2014). The Middle Jurassic magmatic rocks in the Central Pontides are unconformably overlain by Upper Jurassic–Lower Cretaceous carbonates and by the Lower Cretaceous turbidites of the Çağlayan Formation, which extend west to the İstanbul Zone (Tüysüz, 1999; Hippolyte, et al., 2010) (Fig. 3).

3. Lower Cretaceous clastic sequence of the Central Pontides

The Lower Cretaceous turbidites are bounded in the north by the Black Sea Basin and in the south by a large area of Jurassic–Cretaceous accretionary complex, the Central Pontide Supercomplex, which is associated with the İzmir-Ankara Suture (Okay et al., 2013). The Lower Cretaceous clastic sequence (the Çağlayan Formation) of the Central Pontides can be...
divided into a shelf sequence exposed along the western Black Sea margin and a deep marine turbidite system that crops out over a wide area in the Central Pontides (Fig. 1).

3.1. Lower Cretaceous shelf deposits

The Lower Cretaceous (Barremian-Albian) shelf sediments are exposed along the southern coast of the Black Sea in the Central Pontides (Figs. 1 and 2), where they lie unconformably over the Upper Paleozoic and Triassic sedimentary rocks (Figs. 1 and 3). The sequence begins with white clean quartz arenites (Velibey Formation) which pass laterally and upwards into rudist-bearing shallow marine limestones of Barremian–Aptian age (Varol and Akman, 1988; Tüysüz et al., 2004; Yilmaz and Altiner, 2007; Masse et al., 2009; Hippolyte et al., 2010) (Fig. 4a and b). The limestones are conformably overlain by glauconite-bearing dark sandstones and siltstones, which pass into the black Aptian–Albian shales (Görür et al., 1993; Hippolyte et al., 2010). The sequence ends with Albian shallow marine to continental sandstone and shale with coal horizons (Hippolyte et al., 2010).

3.2. Lower Cretaceous turbidites

The Lower Cretaceous (Barremian-Late Aptian) turbidites, called the Çağlayan Formation, crop out over an area of 400 km by 90 km in the Central Pontides and have a thickness of over 2000 meters (Tüysüz, 1999; Derman, 2002; Hippolyte et al., 2010; Okay et al., 2013) (Figs. 3 and 4c). They consist mainly of an intercalation of medium grained sandstone and shale (Fig. 4c and d). The basin itself shows deepening character to south having finer grain size and thinner beds well as increasing shale/sandstone ratio. The sandstones display typical turbidite features including graded bedding, cross bedding, abundant slumps, debris flows, and sole marks (Fig. 4e). The sandstone–shale sequence commonly includes mass
flow horizons ranging from debris flows to olistostromes (Fig. 4f). The debris flows are more common in the western part of the basin. The clasts in the debris flows and olistostromes are mainly Upper Jurassic–Lower Cretaceous limestones with lesser blocks of Paleozoic and Triassic sedimentary rocks, and Jurassic dacite. The limestone blocks may reach up to a few kilometers across. Distal parts of the Çağlayan Formation is strongly deformed by folding and thrusting, and in the south it shows low-grade metamorphism dated using laserprobe technique on muscovites as Early Cretaceous (112–102 Ma, Okay et al., 2013). The Çağlayan Formation rests unconformably over various units, including the Paleozoic and Triassic sedimentary rocks and the Upper Jurassic–Lower Cretaceous shallow marine limestones, and is unconformably overlain by the Upper Cretaceous (Santonian) pelagic limestones (Okay et al., 2013) (Fig. 3). The depositional age of the Çağlayan Formation is constrained to Barremian–Late Aptian based on nannoplanktonsp (Hippolyte et al., 2010). The same interval is represented by hemipelagic limestone deposition in the western Sakarya Zone and by a stratigraphic gap in the Eastern Pontides (Okay and Şahintürk, 1997; Altiner et al., 1991).

4. The provenance of the Lower Cretaceous turbidites

The metamorphic area in the Central Pontides south of the Çağlayan Formation in the Central Pontides was previously considered as a pre-Jurassic basement, and thus could have constituted a potential source area for the Lower Cretaceous turbidites. However, recent studies have shown that this region (the Central Pontide Supercomplex) consists of subduction-accretion complexes mainly of Early Cretaceous age (Okay et al., 2013), and thus an unlikely source for the Çağlayan Formation. They were accreted before or during the deposition of the Çağlayan Formation. We investigated the provenance of the Lower
Cretaceous turbidites through the paleo-current analysis, U-Pb detrital zircon dating and detrital rutile geochemistry.

4.1. The paleocurrent analysis

The paleocurrent analysis is based on 1924 measurements in 96 outcrop stations over an area of 400 km by 90 km (Fig. 5). Measurements include mainly unidirectional indicators from flute casts (1308) and cross beddings (34), and bidirectional (linear) indicators from groove casts (582). All measurements are corrected for tectonic tilting. There is no cleavage development in the bulk of the Çağlayan Formation and no other evidence for ductile deformation; the folding was cylindrical and involved buckling, which allows restoration of the paleocurrents to their original position. We avoided measuring paleocurrent directions in outcrops where the strata were strongly deformed and folded, especially in the southern parts of the basin. Fig. 5 shows the paleocurrents from the Lower Cretaceous turbidites.

The 96 outcrop stations are reduced to 30 by combining the nearby stations with an average separation of 3 km and which have similar paleocurrent directions. Data from each station, as well as information on the location and sedimentological features of each outcrop, are given in Appendix A and the methods are given in Appendix B.1. The paleocurrent data from the Çağlayan Formation can be divided into three gradational areas in the Central Pontides. In the east, almost all of the measured paleocurrents are from the northwest to the southeast (Fig. 5); in the central part, the paleocurrents are more varied with both southward and northward directed paleocurrents. In the west, the paleocurrents are generally to the south, although some indicate northward flow.

The Central Pontides form a broad arc, which was produced through oroclinal bending during the Late Cretaceous to Eocene as a result of continental collision with the Kırşehir
Massif (Meijers et al., 2010b). Paleomagnetic data indicate anticlockwise and clockwise rotations of up to 30° in the eastern and western parts of the Central Pontides and no rotation in the central part of the Central Pontides. Fig. 6 shows the paleocurrents that are restored to their pre-Late Cretaceous positions. In their pre-Cretaceous positions, the paleocurrents are more axial with east-southeasterly flow in the eastern part of the basin and predominantly southwestward flow in the west. The picture is that of a large submarine fan feeding from the north (Fig. 2).

4.2. U–Pb ages of detrital zircons from the Lower Cretaceous sandstones

Detrital zircon ages are widely used for provenance analysis to constrain paleogeography, tectonic reconstructions, and crustal evolution (e.g., Gehrels et al., 1995; Fedo et al., 2003; Okay N. et al., 2010; Jacobson et al., 2011; Meinhold et al., 2013). In this study we have used detrital zircon ages from 13 sandstone samples from the Lower Cretaceous sequence of the Central Pontides. These include newly determined zircon ages from nine sandstone samples, as well as zircons from four samples published by Okay et al. (2013). Two of 13 samples are shelf quartz arenites of the Velibey Formation (samples 1A and T23) and the remaining are turbiditic sandstones. The samples from turbiditic part of the basin were collected over an east-west distance of 400 km (Fig. 5), two are from the west (samples 13 and 22A), four from the center (samples 2221, 2640, 2721 and 2239) and five from the east (samples T2, T3, T9, T11 and 38). The petrography of the samples is described in Appendix C and their UTM coordinates are given in Table 1. The relative stratigraphic locations of the samples are not clear because of strong folding and faulting in the Çağlayan Formation, the large area of sampling and the considerable sedimentary thickness.
1348 detrital zircon ages have been obtained from 13 sandstone samples of which 1194 (89% of all zircons) are concordant at 90–110%. Among these 80 concordant detrital zircon ages obtained from sample 1A, 168 ages from sample T23, 74 ages from sample 13 and 43 ages from sample 22A representing the western part of the basin. 63 concordant detrital zircon ages from sample 2221, 89 ages from sample 2239, 51 ages from sample 2640 and 74 ages from sample 2721 represent the central part of the basin. We have 158 concordant detrital zircon ages from sample T2, 165 ages from sample T3, 77 ages from sample T9, 85 ages from sample T11 and 67 ages from sample 38 representing the eastern part of the basin.

The analytical methods are given in Appendix B.3 and the U–Pb data in Appendix D. Fig. 7 shows the age distribution of 1194 zircons. There are three main and four minor peaks. The main peaks are at Carboniferous–Permian (252–356 Ma; 26%, 308 grains), Paleoproterozoic (1700–2200 Ma; 17%; 208 grains) and Archean (2750–3000 Ma; 15%; 185 grains). The subsidiary peaks are late Neoproterozoic–Cambrian (525–650 Ma; 9%; 104 grains), Triassic (6%, 76 grains), late Mesoproterozoic–early Neoproterozoic (875–1100 Ma; 4%; 48 grains) and Silurian (2%; 22 grains). Zircon ages from the western, central and eastern parts of the Çağlayan Formation show different patterns and will be discussed separately below (Fig. 8).

Four samples from the western part of the Çağlayan Formation yielded 365 concordant detrital zircon ages (Fig. 9). Two samples (1A and 23) are quartz arenites from the Velibey Formation from the shelf sequence, the other two (13 and 22A) are from turbiditic sandstones (Figs. 5 and 8, Table 1). Carboniferous (43% of the detrital zircons, 156 grains) and Neoproterozoic (25%, 90 grains) zircons dominate the zircon population from the western part of the Çağlayan Formation (Fig. 10). The Neoproterozoic zircons are predominantly late Neoproterozoic passing into early Cambrian (665–510 Ma; 27%, 97
zircons). There are few Paleoproterozoic (7%, 26 grains), Devonian (6%, 26 grains), Mesoproterozoic (4%, 13 grains) and Archean zircons (2%, 7 grains), no zircons of Jurassic age, and only two Triassic and Silurian zircon grains (Figs. 10 and 11).

From the central part of the Çağlayan Formation, 227 concordant detrital zircon ages were obtained from three turbiditic sandstone samples (2221, 2640 and 2721) and from one metasandstone (2239) sample. The metasandstone sample is from distal part of the Çağlayan Formation metamorphosed under low grade conditions (Okay et al., 2013) (Figs. 5 and 8, Table 1). The major zircon populations are Paleoproterozoic (2090–1730 Ma; 22%, 62 grains), Neoproterozoic (760–1070 Ma; 14%, 40 grains) and Triassic (15%, 41 grains) (Figs. 9 and 10).

From the eastern part of the Çağlayan Formation, 552 concordant detrital zircon ages were obtained from five turbiditic sandstone samples (T2, T3, T9, T11 and 38; Figs. 5 and 8, Table 1). Archean (38%, 209 grains), and Paleoproterozoic (23%, 128 grains) zircons are dominant followed by Permian (15%, 82 grains) and Triassic (6%, 34 grains) zircons. Rest of the ages show scattered distribution without significant clustering.

4.3. The Th/U ratios and REE contents of the detrital zircons

The Th/U ratio is the first order discriminant between igneous and metamorphic zircons (Hoskin and Ireland, 2000; Belousova et al., 2002; Rubatto, 2002). The metamorphic zircons have the Th/U ratios generally less than 0.1, whereas this value in igneous zircons is above 0.2 (Hoskin and Schaltegger, 2003; Rubatto, 2002; Vavra et al., 1999). The Th/U ratios of the analyzed zircons are predominantly above 0.1, which suggests a mainly magmatic origin (Fig. 12) with only a few number of metamorphic zircons. Most of the metamorphic zircons are from the central and eastern part, and are generally older than 1800 Ma (Fig. 12).
Rare earth elements (REE) are indicators of crystallization environments; they are considered incompatible for rock forming minerals during the crystallization of felsic magma and are accumulated in many accessory minerals such as zircon (Rollinson, 1993). REE abundances of detrital zircons from seven samples (1A, 13, 2221, 2721, 2640, 2239 and 38) are determined simultaneously along with their U–Pb ages using a laser ablation split stream petrochronology at UC Santa Barbara (following the procedure described by Kylander-Clark et al. (2013); for analytic methods and data sets see Appendix B.3. and E). Fig. 13 shows the REE patterns of detrital zircon from seven sandstone samples normalized to chondrite values of McDonough and Sun (1995). REE patterns of all samples show steeply rising slopes from LREE to HREE with more or less pronounced positive Ce and negative Eu anomalies suggesting an igneous origin (Fig. 13-a1-g1) (Rubatto, 2002; Hoskin and Schaltegger, 2003).

Zircon grains with Th/U ratios in the range of 0.02–0.1 and with low total REE concentrations (<1000 ppm) are regarded as of metamorphic origin and are shown separately in Fig. 13. Some of metamorphic zircons show depleted MREE and HREE, which are typical for the zircons produced by sub-solidus growth with garnet; samples with these zircons (2239 and 2721) come from the central part (Fig. 13-a2-g2) (Rubatto, 2002). Zircons from mafic rocks are generally characterized by low total REE (<450 ppm) values, high Th/U ratios (>0.1) and depletion of HREE and MREE (Belousova et al., 1998, 2002); such zircons (%3 of all zircon ages, 44 grains), shown in blue in Fig. 13, are concentrated in the central and eastern parts of the Çağlayan Formation, which may have originated from mafic rocks.

4.4. Detrital rutile geochemistry and thermometry

Rutile is mainly formed during medium-to high-grade metamorphism and is not usually abundant in igneous rocks (e.g., Force, 1980; Meinhold, 2010). It is chemically and physically
stable and is not affected by weathering, transport and diagenesis (e.g., Morton and Hallsworth, 1999), and therefore can provide important information about the source area of sedimentary rocks (e.g., Zack et al., 2004; Meinhold et al., 2008; Meinhold, 2010; Okay N. et al., 2010; Triebold et al., 2007; 2012). 269 detrital rutile grains from four samples across the basin (Fig. 5, 1A, 13, 2721 and 38) were analyzed with an electron microprobe (EMP) to constrain the metamorphic sources of the Lower Cretaceous deposits (see Appendix B.4 for analytical details). Detrital rutiles are mostly light brown, reddish brown and dark brown, subrounded to rounded. Compositions with unusually high or low oxide totals (9 grains with wt % of 99< or >101) and the brookite–anatase polymorphs (17 grains, following the discrimination procedure outlined in Triebold et al., 2011) were excluded from the analysis. In total 242 detrital rutile compositions were used for interpretation; 75 are from sample 1A, 69 from sample 13, 40 from sample 2721 and 58 from sample 38. Rutile growth temperatures, calculated using the calibration of Tomkins et al. (2007), range between 525–917 °C (Fig. 14, Appendix F). The lithology and metamorphic facies of the rutile-bearing host rocks were estimated using the Nb and Cr contents of the rutiles as outlined in Triebold et al. (2012). Most rutile grains have originated from metapelitic rocks of amphibolite facies (Fig. 14). Rutiles from granulite-facies rocks occur mainly in the central and western parts, where they make up 15 and 12% of the rutiles, respectively.

5. Discussion

Below we discuss the source of the Çağlayan Formation based on the paleocurrent measurements and detrital zircon and rutile data. Zircons are predominantly found in felsic plutonic rocks, as also reflected in the high Th/U values of the analyzed zircons (Fig. 12). Therefore, the detrital zircon ages do not provide a true reflection of the lithologies in the
source area but rather that of the felsic igneous rocks in the source. However, the quartz-rich nature of the Çağlayan Formation sandstones suggests that felsic plutonic rocks were a major component in the source region. A second complication in the interpretation of the detrital zircon ages is that some of the zircons could be recycled from older clastic sequences. We checked this possibility by comparing the detrital zircon spectra from the Çağlayan Formation sandstones with those from other clastic units in the circum-Black Sea region (Karslioğlu et al., 2012; Okay N. et al. 2010; Nikishin et al., 2015b; Ustaömer P. et al., 2011; Ustaömer et al., 2016).

Overall, the detrital zircon ages from the Çağlayan sandstones show four major peaks in Archean, Paleoproterozoic, late Neoproterozoic and Carboniferous–Permian (Fig. 7). The distribution of these peaks is, however, different between western, central and eastern parts of the Çağlayan Basin (Figs. 8 and 9). These peak ages as well as their possible source areas are discussed below.

5.1. Archean and Paleoproterozoic zircons

Archean and Paleoproterozoic zircons, make up 19% (229 grains) and 20% (235 grains) of the total detrital zircon population of the Çağlayan Formation, respectively (Fig. 7) but they are heavily concentrated in the eastern and central parts of the basin, where they constitute 61% (337 grains) and 34% (94 grains), respectively, of the total zircon population (Figs. 9 and 10). Archean and Paleoproterozoic rocks are unknown from the Pontides, whereas such rocks crop out widely in the Ukrainian Shield (e.g., Shchipansky and Bogdanova, 1996; Claesson et al., 2006; Bogdanova et al., 2008, 2010; Bibikova et al., 2015) (Figs. 1 and 2).

Present day sands from the large rivers draining the East European Platform, contain dominant populations of Archean and Paleoproterozoic zircons (Safonova et al., 2010; Wang
et al., 2011). The absence of Archean–Paleoproterozoic rocks in the Pontides and their presence north of the Black Sea coupled with the southeasterly paleocurrents measured in the eastern and central parts of the Çağlayan Basin indicate that these parts of the basin were sourced from north of the Black Sea. The REE patterns of pre-1800 Ma zircons from mafic rocks and metamorphic rocks, and geochemistry of detrital rutiles indicate that the most probable source for the eastern and central parts of the Çağlayan Basin is the East European Platform, where intense granulite to amphibolite facies metamorphic events that predate 1800 Ma were reported (e.g., Shchipansky and Bogdanova, 1996; Claesson et al., 2006; Bogdanova et al., 2008; Bibikova et al., 2015 and references there in). This conclusion is independently supported by the paleogeographic maps showing the East European Platform as an erosional area during the early Cretaceous (Baraboshkin et al., 2003).

5.2. Late Neoproterozoic zircons

Late Neoproterozoic (700–541 Ma) zircons are significant in the western part but less so in the central and eastern part of the basin (Figs. 9 and 10). Late Neoproterozoic–Cambrian granites make up a major part of the basement of northern Gondwana and Gondwana-derived terranes, which include the Istanbul Zone, Strandja Massif and Moesia (590–560 Ma; Neubauer, 2002; Chen et al., 2002; Ustaömer P. et al., 2005; Yılmaz-Şahin et al., 2014; Okay and Nikishin, 2015). The closest outcrop of the Neoproterozoic basement is in the Bolu Massif of the Istanbul Zone (Fig. 2), where granites have ages of 576 to 565 Ma (Ustaömer P. et al., 2005). This, together with the variable paleocurrent directions in the western part of the basin and debris flows with large blocks from the basement rocks of the Istanbul Zone indicates local sources for this part of the basin.
5.3. Carboniferous–Permian zircons

Carboniferous (17%) and Permian (9%) zircons make up 26% of the total detrital zircon population (Fig. 7). Their distribution is uneven; in the western part of the basin the Carboniferous zircons make up 43% of the total zircon population; this decreases to 8 and 4% in the central and eastern parts, respectively (Fig. 10). In contrast, the Permian zircons increase from 1% to 7% and to 15% from west to east. However, it should be pointed out that 56% (60 of 107 grains) of Permian ages come from a single sample T3 (Fig. 11).

The closest outcrop of Carboniferous–Permian granites is in the northern part of the Central Pontides, where zircons from two granitic bodies yield zircon U–Pb ages straddling the Carboniferous–Permian boundary (303–291 Ma, Nzegge, 2008; Nzegge et al., 2006) (Fig. 2). Such granites could be the source of the Permian detrital zircons from the Çağlayan Formation, whose ages generally cluster at 270–298 Ma (Fig. 11). Detrital zircons from the Middle Jurassic–Neogene sandstones from Crimea also show Permian age peaks of 280 Ma and 247 Ma (Nikishin et al., 2015b).

Carboniferous and Permian granites crop out in the Strandja Massif, in the Sakarya Zone and in the Caucasus (Fig. 2). In the Sakarya Zone and in the Lesser Caucasus their ages range from 330 to 317 Ma (Topuz et al., 2007; 2010; Nzegge et al., 2006; Mayringer et al., 2011; Ustaömer P. et al., 2012; Ustaömer et al., 2012) while in the Strandja Massif and in the Balkanides they are younger, with an age range of 315–250 Ma (Sunal et al., 2006, 2008; Carrigan et al., 2005). 68% and 82% of all Carboniferous detrital zircons from central and eastern part of the basin, respectively, yielded ages mostly in the 300–330 Ma range. In contrast, 88% of all Carboniferous zircons from the western part of the basin are mostly in range of 330–357 Ma. Early Carboniferous granites of these ages are not known in the Pontides or in the Black Sea region. Detrital zircons of this age range are common in the
Carboniferous turbidites of the Istanbul Zone (Okay N. et al. 2010) and could have possibly been recycled into the Lower Cretaceous sandstones.

5.4. Other zircon ages

Triassic detrital zircons constitute 6% of the total detrital zircon population of the Çağlayan Formation (Fig. 7). They are mostly concentrated on the central and eastern parts of the basin (Fig. 10). Triassic detrital zircons are also common in the Triassic subduction accretion complexes (Karakaya Complex) of the Sakarya Zone (Ustaömer et al., 2016) and in the Triassic Akgöl flysch of Küre Complex of the Central Pontides (Karslıoğlu et al., 2012) and Tauric flysch of Crimea (Nikishin personal communication 2015). In the Jurassic and younger sediments of Crimea, the Lower Triassic zircons with a peak age of 247 Ma constitute an important population (Nikishin et al., 2015b). Despite the wide presence of Triassic zircons in the circum-Black Sea sandstones, Triassic granitic rocks are not known from outcrop in the Pontides, Caucasus or from the Balkans. A Triassic magmatic arc, however, most likely exist in the subsurface beneath the Tertiary sediments in north of the Black Sea (Okay et al., 2013; Ustaömer et al., 2016) (Fig. 2). The Triassic detrital zircons in the Çağlayan Formation have most probably derived from this Triassic arc, although part of the Triassic zircons could also have been recycled from the Triassic Akgöl and Tauric flysch.

The amount of Ordovician, Silurian and Devonian detrital zircons in the Çağlayan Formation does not exceed a few percent (Fig. 7). Jurassic detrital zircons make up only 2% of the total zircon population, despite widespread outcrops of Middle Jurassic granites and porphyries in the Central Pontides (Yılmaz and Boztuğ, 1986; Nzegge, 2008; Okay et al., 2014). This shows that these intrusives were not exposed in the Early Cretaceous. The Lower Cretaceous detrital zircons are virtually absent, which argues against the presence of an Early
Cretaceous magmatic arc north of the Black Sea contrary to the suggestion of Nikishin et al. (2015a, b).

In summary, the paleocurrent and detrital zircon data show that the eastern and central parts of the Çağlayan Basin were fed from the East European Platform from the north, whereas more local sources, dominated by Carboniferous granites, were important for the western part of the basin. The importance of the local sources in the western part of the basin is also shown by the abundance of, debris flows with blocks of Upper Jurassic limestones, Triassic and Paleozoic sandstones in this part of the basin. The debris flow conglomerates and sandstones of the western part also have metamorphic rock fragments, and detrital epidote and garnet which are not observed in the eastern part (Fig. 4f and Appendix C). Poorly sorted semi-angular shaped clasts of the conglomerates (Fig. 4f) and the large size of the olistoliths, locally reaching up to one kilometer or more, indicate short transport distance. They must have been derived from locally uplifted parts of the basement. Differences in the source between different parts of the Çağlayan Basin may suggest more than one river system flowing north to south to the Çağlayan Basin forming a fan complex, consisting of several coalescing fan systems (Fig. 15a). A lesser possibility is a large submarine system fan fed by a single river with local sources from fault blocks in the western part of the basin (Fig. 15b).

The Central Pontide Supercomplex south of the Çağlayan Formation predominantly consists of Early Cretaceous subduction-accretion complexes with eclogites and blueschists with 136-102 Ma metamorphic ages (\(^{40}\text{Ar}/^{39}\text{Ar}\) mica ages; Okay et al., 2006a, 2013; Aygül et al., 2015, 2016) (Figs. 1 and 15). Thus, Tethys Ocean was subducting northward during the deposition of the Çağlayan Formation. The southern distal parts of the Çağlayan turbidites were also subducted and metamorphosed; the white mica \(^{40}\text{Ar}/^{39}\text{Ar}\) ages from the phyllites and slates
from this part of the Lower Cretaceous turbidites are 106–112 Ma (Okay et al., 2013).

Sample 2239 is a metasandstone yielding post Jurassic detrital zircon ages similar to other samples, represents the metamorphosed distal parts of the Çağlayan Formation (Okay et al., 2013; Fig. 5, 8 and 11). This shows that the Çağlayan Basin was in a convergent margin setting similar to fore-arc basins. However, Early Cretaceous zircons are very rare in the Çağlayan Formation (less than 1%) and no Lower Cretaceous granites are known in the Central Pontides or from the northern margin of the Black Sea. This indicates that a magmatic arc did not develop during the Early Cretaceous, possibly because of flat-subduction (Fig. 16). The subduction-accretion of the Çangaldağ and Domuzdağ oceanic plateaus may have resulted in the flat subduction (Okay et al., 2013). Flat subduction of young oceanic crust with aseismic ridges, oceanic plateaus or seamount chains typically coincides spatially and temporally with the absence of arc volcanism, intense normal faulting of the fore-arc block and local block uplifts in the hinterland (e.g., Dickinson and Snyder, 1978; McGeary et al., 1985; Cloos, 1993; van Hunen et al., 2002), which is compatible with the Early Cretaceous tectonic setting of the Black Sea region. Although flat-slab subduction occurs at about 10% of the modern convergent margins (Gutscher et al., 2000), its effects on the sedimentation in the convergent margins are rare (e.g., Kortyna et al., 2014; Finzel et al., 2015). The Lower Cretaceous fan complex is a good example showing the effects of volcanic gap due to flat subduction processes on sedimentation; having no volcanic rock fragments in the sandstones, almost no coeval detrital zircons with sedimentation and no dykes cross cutting the strata.

In the Central Pontides and in Crimea there are no known outcrops of the Lower Cretaceous granitic or volcanic rocks (e.g., Nikishin et al., 2015b). Nikishin et al. (2015a) show Albian volcanic centers in the Black Sea offshore but these are not reflected in the sedimentary
record of the Early Cretaceous turbidites and need to be confirmed. The magmatic arc in the Pontides developed only in the beginning of the Late Cretaceous in the Turonian.

In the last ten years, Black Sea has been a target for hydrocarbon exploration (Şen, 2013). The main problem encountered along the Turkish sector of the Black Sea has been the poor porosity and permeability of the sandstone reservoirs. A northward source from the granitoids and gneisses of the East European Platform for the Lower Cretaceous sediments imply possible good reservoir sandstones within the Black Sea.

6. Conclusions

The Lower Cretaceous turbidites, called as the Çağlayan Formation, and associated shelf deposits crop out over an area of 400 km by 90 km and have a thickness of over two kilometers in the Central Pontides in northern Turkey. Here, we report detrital zircon ages from 1348 grains from 13 sandstone samples and REE abundances of detrital zircons of the Lower Cretaceous turbidites, the geochemistry of 242 detrital rutile grains from 4 sandstone samples and 1924 paleocurrent measurements from 96 stations.

1. Th/U ratios and REE values in the detrital zircons indicate that they were predominantly derived from magmatic protoliths either directly or indirectly through recycling.

2. Turbidites of the Lower Cretaceous Çağlayan Formation are bordered in the south by the Lower Cretaceous subduction-accretion units including eclogites and blueschists (Okay et al., 2006a, 2013; Aygül et al., 2015). The southern distal parts of the turbidites were also subducted and metamorphosed during the Early Cretaceous. Thus, The Çağlayan Formation occupies a fore-arc position immediately north of the Tethyan subduction zone.
3. The paleocurrent measurements, restored to their pre-rotational, pre-Late Cretaceous stage, indicate paleoflow direction towards ESE in the eastern part of the basin and predominantly paleoflow direction towards WSW in the western part of the basin (Fig. 6).

4. Detrital zircon ages show significant differences between the western, central and eastern part of the Çağlayan Basin (Figs. 9 and 10). In the eastern part the dominant zircon population is Archean and Paleoproterozoic. Rocks of these ages are unknown in the Pontides but crop out in the Ukrainian Shield north of the Black Sea. This together with ESE paleocurrents indicate that the eastern part of the basin was fed from the Ukrainian Shield (East European Platform). In the western part of the basin late Neoproterozoic and Carboniferous detrital zircons are predominant (Figs. 9 and 10), probably sourced from local sources in the Pontides. Zircon ages from the central part of the basin show a mixture of zircon age patterns of western and eastern parts of the Lower Cretaceous Basin.

5. Although the Çağlayan Formation occupied a fore-arc position during the Early Cretaceous, Lower Cretaceous detrital zircons are very rare in the sandstones (less than 1% of the total detrital zircon population). This, together with the absence of Lower Cretaceous intrusives in the Pontides, indicates that no magmatic arc developed during the Early Cretaceous, possibly due to flat subduction.

6. We envisage one or more rivers (Figs. 15a, b and 16) draining the East European Platform south to the Tethyan ocean and feeding the Çağlayan Basin during the Early Cretaceous. Local sources from uplifted fault blocks were important in the western part of the basin.

7. The close connection between the East European Platform and the Central Pontides, as shown by the detrital zircon and paleocurrent data, indicate that the Black Sea did not exist as a deep oceanic basin during the Early Cretaceous. It opened during the Late Cretaceous (Turonian-Santonian) along with the start of the arc volcanism.
8. Our data show that a major part of the Çağlayan Basin is fed from the Archean–Paleoproterozoic granitic rocks of the Ukrainian Shield suggesting suitable sandstone reservoirs may exist in the Çağlayan Formation offshore.

Acknowledgements

This study was supported by TÜBİTAK grant 109Y049, TÜBİTAK grant 113R007, TÜBİTAK 2214-A research abroad fellowship program and by TÜBA. The field expenses were funded by ITU Division of Scientific Research Projects for PhD students (project no. 37264). Constructive reviews by Alastair Robertson and Inga Sevastjanova improved the manuscript. We also thank Evren Çubukçu for help with the cathodoluminescence images of zircons, Cansu Demirel and Muhammed Ali Kuru for company during field and Nurullah Kızılay for help during the mineral separation.

Supplementary material

Supplementary data associated with this article can be found, in the online version, at xxxx

Appendix A. Paleocurrent measurement data sets and locality descriptions of the Lower Cretaceous Basin.

Appendix B. Paleocurrent measurement and sample preparation methods, and analytical techniques for U–Pb detrital zircon dating and rutile geochemistry.

Appendix C. Petrographic descriptions of the samples dated by U–Pb method and used for rutile geochemistry.

Appendix D. U–Pb isotopic ages of 13 samples from the detrital zircons of the Lower Cretaceous sandstones.
Appendix E. REE concentrations of the detrital zircons from the Lower Cretaceous sandstones.

Appendix F. Detrital rutile geochemistry of the Lower Cretaceous sandstones obtained by EMP.

References


Genc, S.C., Tuyusuz, 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 118, 95–111.


Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform.


Ustaömer, P.A., Mundil, R., Renne, P.R., 2005. U/Pb and Pb/Pb zircon ages for arc-related intrusions of the Bolu Massif (W Pontides NW Turkey): evidence for Late Precambrian (Cademian) age. Terra Nova 17, 215–223.


**Fig. Captions**

Fig. 1. The main tectonic units of Black Sea region and depositional area of the Lower Cretaceous sediments. Abbreviations: CPS, Central Pontide Metamorphic Complex; EEC, East European Craton; E, Erzincan; Ç, Çankırı; WBS Fault, Western Black Sea Fault (modified from Okay et al., 2013).

Fig. 2. Outcrops of magmatic rocks with U–Pb zircon ages (modified from Okay and Nikishin, 2015). Isotopic ages of Jurassic magmatism are from Dokuz et al. (2010), Meijers et al. (2010a), Nzegge (2008), Okay et al. (2013, 2014); Carboniferous–Permian are from Dokuz (2011), Kaygusuz et al. (2012), Mayringer et al. (2011), Nzegge et al. (2006), Okay et al. (2001, 2006b, 2013, 2014), Somin (2011), Sunal et al. (2006), Topuz et al. (2004, 2010), Ustaömer et al. (2012), Ustaömer P. et al. (2012), Yilmaz-Şahin et al. (2009); Devonian
plutons are from Aysal et al. (2012), Okay et al. (1996, 2006b), Sunal (2013); Late Neoproterozoic–Ordovician plutons are from Akbayram et al. (2012), Chen et al. (2002), Mayringer et al. (2011), Okay et al. (2008), Ustaömer et al. (2012), Yılmaz-Şahin et al. (2009, 2014).

Fig. 3. Generalized stratigraphic section of the Central Pontides. For intrusion ages see Fig. 2.

Fig. 4. Field photographs of the Lower Cretaceous shelf and turbidite sequence of the Central Pontides. (a) Thickly bedded shelf carbonates interbedded with sandstone layers in the western part of the basin (Çengellidere). (b) The quartz arenites of shelf sediments near Zonguldak, (Kozlu). (c) Sandstone-shale alternations from turbidites (Boyabat-Gerze road). (d) General view of strongly folded distal parts of turbidites consisting mainly dark shales (~70%), in the southwestern part of the basin near Yenice, Karabük. (e) Flute casts indicating the paleocurrent direction to the southeast. (f) Mass flows in proximal parts of the turbidites in the western part, near Bartın. The clasts are mainly Late Jurassic–Early Cretaceous limestones.

Fig. 5. Paleocurrent directions in the Lower Cretaceous sediments in the Central Pontides. All measurements are corrected for tectonic tilting (for full data sets and methods see, Appendix A and B.1). Locations of samples for detrital zircon geochronology are also shown.

Fig. 6. Paleocurrents restored to their original directions after correction for oroclinal bending using the values in Meijers at al. (2010). The rotation angles for each locations are given in Appendix B.1.

Fig. 7. Histogram and pie chart showing the zircon age distribution of 13 samples from the Lower Cretaceous clastic rocks.
Fig. 8. Histogram with probability density curves and pie charts of 13 samples from the western, central and eastern parts of the basin. The violet probability density curve shows 90–110% concordant ages and the grey curve shows others.

Fig. 9. Combined histogram and probability density curves of the detrital zircon ages from western, central and eastern part of the Lower Cretaceous clastic rocks.

Fig. 10. Pie charts of the detrital zircon ages from the western, central and eastern parts of the Çağlayan Formation.

Fig. 11. Histogram showing the Phanerozoic and late Neoproterozoic zircon ages from all samples. The violet probability density curve shows 90–110% concordant ages and the grey curve shows others.

Fig. 12. Th/U ratio versus U–Pb ages of the detrital zircons from 13 samples. Discrimination lines are from Linnemann et al. (2011) and Rubatto (2002).

Fig. 13. Chondrite normalized REE patterns of detrital zircons from seven sandstone samples representing the western, central and eastern parts of the basin. Figures a1-g1 show detrital zircons are igneous in origin with steeply increasing LREE towards to HREE and with positive Ce and negative Eu anomaly (Hoskin and Schaltegger, 2003; Rubatto, 2002). Figures a2-g2 show metamorphic zircons (lines in red, zircons with Th/U ratio <0.08, some of them show subsolidus growth with garnet with flat or depleted HREE pattern) and zircons from mafic rocks (blue lines) with depletion in HREE and Th/U ratios > 0.1. Chondrite values are from McDonough and Sun, (1995).

Fig. 14. Combined histogram and pie charts showing detrital rutile source lithology and crystallization temperatures of four sandstone samples representing western, central and eastern parts of the Lower Cretaceous Basin. Source lithology discriminations of detrital
rutiles based on Nb and Cr contents according to Triebold et al. (2011, 2012). Zr in rutile thermometry of Tomkins et al. (2007) is used for temperature calculations.

Fig. 15. Paleographic maps of the southern active margin of Eurasia for Barremian–Aptian interval; a) more than one river feeding the basin, b) one major river feeding the basin an alternative model.

Fig. 16. Block diagram showing the tectonic setting of the Çağlayan Basin during the Early Cretaceous.

Table 1. Sample locations for U-Pb detrital zircon geochronology and detrital rutile geochemistry.

Biographies of the Authors

Remziye Akdoğan
Remziye Akdoğan holds a BSc and a MSc degree in geology from the Karadeniz Technical University, Turkey. Currently she is doing her Ph.D. in geology at Istanbul Technical University, Turkey. Her main research topics are provenance analysis and paleotectonic evolution of the Mesozoic basins of Turkey.

Aral I. Okay
Aral I. Okay holds a BSc degree in geology from the University College London and a Ph.D from the University of Cambridge. Between 1980-1983 he worked as a field geologist at the Geological Survey of Turkey (MTA), and since then he has been doing research and teaching in the Istanbul Technical University. His main research interest are regional geology,
tectonics and metamorphic geology. For more information see his web page at

http://web.itu.edu.tr/~okay/.

Gürsel Sunal
Gürsel Sunal is an Associate Professor in the Department of Geology at İstanbul Technical University, İstanbul, Turkey, since 2014. Sunal received his BSc (1993) and MSc (1997) from Istanbul Technical University, Turkey, and PhD (2008) from the University of Tübingen, Germany. His main research interests include geochronology of metamorphic and magmatic rocks and exhumation history of tectonically active belts. He has published a number of research papers on these topics.

Gabor Tari
Dr. Gabor Tari holds an MSc degree in Geophysics from Eötvös University of Budapest, Hungary, and a Ph.D. in Geology and Geophysics from Rice University, Houston, Texas. After starting with Amoco on Romanian exploration projects in 1994, he transferred to the Angola Team in 1996. Gabor continued to work BP Amoco until 1999 when he joined Vanco Energy Company. At Vanco, as Chief Geophysicist, then as Vice President of Geosciences, he worked mostly on projects around Africa. Since 2007, Gabor is with OMV in Vienna, Austria, working as the Group Chief Geologist on various Mediterranean, Middle Eastern and African basins.

Guido Meinhold
Dr. Guido Meinhold holds a Diplom in Geology from the University of Jena, Germany, and a Ph.D. in Geology from the University of Mainz, Germany. From 2008 until 2010, he worked
as Research Geologist at CASP in Cambridge, United Kingdom. Currently, he holds a position as Akademischer Rat (comparable to Assistant Professor) at the Geoscience Center of the University of Göttingen, Germany. Research projects focus, amongst others, on the Paleozoic evolution of northern Gondwana, the Paleozoic to Cenozoic evolution of the Eastern Mediterranean and Middle East, and the Late Neoproterozoic and Paleozoic evolution of Baltoscandia.

Andrew R.C. Kylander-Clark

Dr. Andrew R.C. Kylander-Clark holds a MSc degree in geology from University of North Carolina, Chapel Hill and a Ph.D from University of California, Santa Barbara, U.S.A. He studied as a postdoctoral researcher at the same university after his Ph.D in geochronology and tectonics. Between 1998-2000 he worked as an optical network engineer at the Lucent Technologies. Since 2008 he is working as a lecturer and senior development engineer at University of California, Santa Barbara. For more information see his web page at http://www.geol.ucsb.edu/people/andrew-kylander-clark
Western part

1A-T23-13-22A  n=365
min. age=109 Ma  max. age=2785 Ma

Central part

2221-2640-2721-2239  n=277
min. age=169 Ma  max. age=3066 Ma

Eastern part

T9-T11-38-T2-T3  n=552
min. age=141 Ma  max. age=3469 Ma
Figure 16

Diagram showing tectonic features including:
- Moesian Platform
- East European Platform
- Coastal Plain
- Çaglayan turbidites
- Flat-slab subduction
- Accreted Çangaldağ Complex

Legend:
- Shelf Clastics
- Istanbul Zone
Table 1. Sample locations for U-Pb detrital zircon geochronology and detrital rutile geochemistry.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Description</th>
<th>Analysis</th>
<th>Concordant Analysis (90-110 %)</th>
<th>Concordant ages %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1A**</td>
<td>Sapça (Zonguldak)</td>
<td>41° 25' 45.90&quot;</td>
<td>31° 51' 57.52&quot;</td>
<td>Quartz arenite</td>
<td>103</td>
<td>80</td>
<td>78</td>
</tr>
<tr>
<td>2 T23</td>
<td>Kozlu (Zonguldak)</td>
<td>41° 22' 43.22&quot;</td>
<td>31° 40' 43.51&quot;</td>
<td>Quartz arenite</td>
<td>173</td>
<td>168</td>
<td>97</td>
</tr>
<tr>
<td>3 13**</td>
<td>Ulus (Bartın)</td>
<td>41° 31' 28.21&quot;</td>
<td>32° 30' 31.91&quot;</td>
<td>Sandstone</td>
<td>87</td>
<td>74</td>
<td>85</td>
</tr>
<tr>
<td>4 22A</td>
<td>Pınarbaşı (Kastamonu)</td>
<td>41° 39' 41.03&quot;</td>
<td>32° 57' 13.04&quot;</td>
<td>Sandstone</td>
<td>58</td>
<td>43</td>
<td>74</td>
</tr>
<tr>
<td>5 2221*</td>
<td>Azdavay (Kastamonu)</td>
<td>41° 31' 20.73&quot;</td>
<td>33° 18' 32.87&quot;</td>
<td>Sandstone</td>
<td>72</td>
<td>63</td>
<td>88</td>
</tr>
<tr>
<td>6 2640*</td>
<td>Azdavay (Kastamonu)</td>
<td>41° 36' 38.09&quot;</td>
<td>33° 25' 01.99&quot;</td>
<td>Sandstone</td>
<td>58</td>
<td>51</td>
<td>88</td>
</tr>
<tr>
<td>7 2721**</td>
<td>Ağılı (Kastamonu)</td>
<td>41° 26' 57.54&quot;</td>
<td>33° 34' 28.17&quot;</td>
<td>Sandstone</td>
<td>82</td>
<td>74</td>
<td>90</td>
</tr>
<tr>
<td>8 2239*</td>
<td>Daday (Kastamonu)</td>
<td>41° 26' 58.57&quot;</td>
<td>33° 19' 27.78&quot;</td>
<td>Metasandstone</td>
<td>98</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>9 T11</td>
<td>Hanönü (Kastamonu)</td>
<td>41° 37' 01.69&quot;</td>
<td>34° 26' 50.49&quot;</td>
<td>Sandstone</td>
<td>86</td>
<td>85</td>
<td>99</td>
</tr>
<tr>
<td>10 38**</td>
<td>Hanönü (Kastamonu)</td>
<td>41° 40' 38.76&quot;</td>
<td>34° 38' 11.37&quot;</td>
<td>Sandstone</td>
<td>101</td>
<td>67</td>
<td>66</td>
</tr>
<tr>
<td>11 T09</td>
<td>Çanaldağ (Kastamonu)</td>
<td>41° 43' 14.22&quot;</td>
<td>34° 38' 27.05&quot;</td>
<td>Sandstone</td>
<td>82</td>
<td>77</td>
<td>94</td>
</tr>
<tr>
<td>12 T02</td>
<td>Boyabat-Gerze (Sinop) road</td>
<td>41° 35' 02.12&quot;</td>
<td>34° 51' 02.40&quot;</td>
<td>Sandstone</td>
<td>168</td>
<td>158</td>
<td>94</td>
</tr>
<tr>
<td>13 T03</td>
<td>Boyabat-Gerze (Sinop) road</td>
<td>41° 37' 34.51&quot;</td>
<td>34° 51'</td>
<td>Sandstone</td>
<td>180</td>
<td>165</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>21.78&quot;</td>
<td>06.71&quot;</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1348</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1194</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Samples used for rutile geochemistry.

*Samples with REE abundances of detrital zircons additional to U-Pb ages.
Highlights

1. A 400x90 km large Cretaceous submarine turbidite fan complex on the southern Laurasia margin.

2. Turbidite fan complex in the Pontides developed on the active Laurasia margin.

3. No coeval magmatic detritus in the turbidite sandstones.

4. The eastern part of the fan was fed from the Archean-Paleoproterozoic Ukrainian Shield.

5. The Black Sea opened after deposition of Lower Cretaceous (Barremian-Aptian) clastics.