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Paleogene extension in the Northern Aegean: Colluvial/debris flow deposits of the early–middle Eocene in the NW Thrace Basin, Turkey

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Abstract: The Thrace Basin consists of Paleogene–Neogene deposits that lie in the lowland south of the Strandja highlands in NW Turkey, where metagranitic and metasedimentary rocks occur. The Akalan Formation consisting of colluvial fan/debris flow deposits represents the base of the sequence in the northern Thrace basin where it is bounded by a right lateral strike-slip oblique fault called "The Western Strandja Fault Zone". This formation exhibits a coarse-grained, angular and grain-supported character close to the fault zone which has releasing-bends. Fine-grained, rounded, and matrix-supported sediments occur away from the contact. During this study, the Akalan Formation is described for the first time as having larger benthic foraminifera (LBF) of *Coskinolina* sp of Ypresian–Lutetian, *Nummulites obesus* of early Lutetian, *Dictyoconus egyptiensis* of Lutetian, *Orbitolites* sp. of Ypresian–Bartonian, *Miliola* sp of early–middle Eocene, *Idalina grelaudae* of early Lutetian–Priabonian, *Ammobaculites agglutinans*, *Amphimorphina crassa*, *Dentalina* sp., *Nodosaria* sp., *Operculina* sp., *Lenticulina* sp., *Quinqueloculina* sp. and *Amphistegina* sp. of Eocene. This unit passes upward with a conformity into reefal limestones of the middle/late Eocene–early Oligocene Soğucak Formation. At times, the limestone overlies the conformity, there is an indication of a prograding sedimentary sequence. The new stratigraphic, paleontological, sedimentological and structural findings related to the NW Thrace Basin suggest a strong transtensional/extensional tectonic control for the initial Paleogene sedimentary deposition during the Ypresian–Lutetian period as shown by fossil content of the Akalan Formation. Right lateral-slip extensional tectonics appears to have had activity during the middle–late Eocene transgressive deposition of the Soğucak Formation when the basin became deepened and enlarged.

Keywords: Strandja Massif, basin deposits, large benthic foraminifera (LBF), early–middle Eocene, Western Strandja Fault, tectonics.

Introduction

Bound by Bulgaria to the north and Greece to the west, the Thrace Basin is a triangle-shaped sedimentary basin in NW Turkey (Fig. 1). The hydrocarbon potential of the basin has been of interest in the region and it has been studied by many researchers beginning in the 1960s. The Thrace Basin consists of a sedimentary sequence with its sedimentation beginning in the Eocene and reaching a depth of about 9 km (e.g., Kopp et al. 1969; Doust & Arıkan 1974; Keskin 1974; Perinçek 1991; Görür & Okay 1996; Turgut & Eseller 2000; Siyako & Huvaz 2007). The basement of this sedimentary succession is underlain by the metamorphic rocks of the Rhodope–Strandja Massif in the north and the Istanbul Paleozoic rocks in the east (e.g., Yaltırak 1996; Yazman 1997; Şen et al. 1998; Elmas 2012a,b).

Previous work suggests that shallow-marine limestones (namely the Soğucak Formation or the Kırklareli Limestone) are the earliest sediments of the northern Thrace Basin and commonly overlie the Strandja Massif (Turgut et al. 1983; Türkecan & Yurtsever 2002; Siyako 2006; Varol et al. 2009; Okay et al. 2010; Less et al. 2011). Besides, uniformly sorted terrigenous sediments, namely the Koyunbaba Formation (Keskin 1974; Kasar et. al. 1983), the Islambeyli Formation (Çağlayan & Yurtsever 1998), or the Akalan Formation (Elmas 2012a) are reported stratigraphically below the limestones and unconformably over the metamorphics in drill holes and some limited localities.

This study was carried out in the NW portion of the Thrace Basin with the aim of investigating the lithological, stratigraphic, depositional and structural properties of the initial Thrace Basin sediments and the relationships between these sediments and the underlying metamorphic basement units, as the studies carried out in the region with these specific aims are rare and rather contentious (c.f., Görür & Okay 1996; Koral 1998; Okay et al. 2010, 2019; Elmas 2012a; Yücel et al. 2019; Özcan et al. 2019). In the context of this paper, new structural, stratigraphic and paleontological data obtained in the NW margin of the Thrace Basin will be presented and discussed.

Methods

For investigating the tectonic setting of the NW Thracian Basin, we have implemented an integrated approach. Initially, outcrops which show the relationship between the sedimentary and the basement units were sought. Then, geological

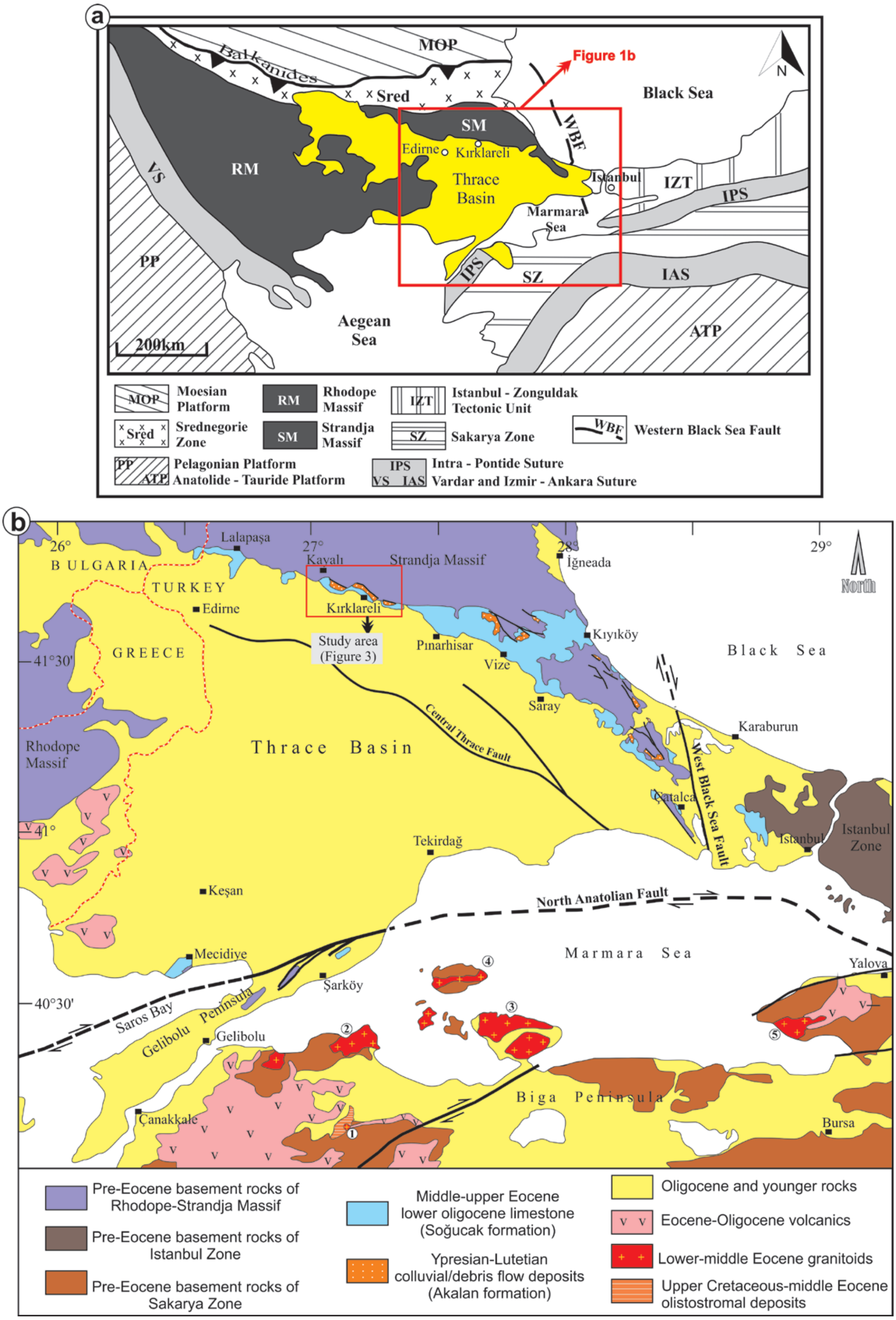

Fig. 1. a — Map showing the principal tectonic features and the sutures in the Thrace Basin and adjacent terrains (after Burchfiel 1980; Ricou et al. 1998; Okay et al. 2001). **b** — Generalized geological map of the Thrace and Rhodope–Istranca Region (modified from Türkecan & Yurtsever 2002; Okay et al. 2010, 2019; Elmas 2012a; and this study) and distribution of early to middle Eocene plutons: 1. Asartepe Pluton (47 Ma; Akgündüz et al. 2012), 2. Karabiga Pluton (45 Ma; Delaloye & Bingöl 2000), 3. Kapıdağ Pluton (42 Ma; Delaloye & Bingöl 2000), 4. İlyasdağ Pluton (47.6 Ma; Ustaömer et al. 2009), 5. Fıstıklı Pluton (48.2 Ma; Delaloye & Bingöl 2000).

investigations of these outcrops were carried out by geological mapping, stratigraphical, sedimentological, and structural investigations of both the sedimentary and basement units. Field mapping included transposition of the boundaries of rock units initially onto 1/25,000 scale topographical maps, determinations of the general stratigraphical, sedimentary and metamorphic features of the exposed rock units and the character of their boundary. Where the boundary between sedimentary and metamorphic units is represented by a fault, planar properties and kinematic indicators were recorded. Structural data were later evaluated by the Fault Kin program (V.7.7.4, 2017, by Rick Allmendiger), and with data collected properties of the principal faults, the fault mechanisms and principal stress axes were determined.

For the depositional setting and timing (age) of the sedimentary unit on the basement, rock and grain samples were collected from silicified pebblestone, sandstone and carbonate cemented pebbly sandstone horizons. They were then studied paleontologically to identify the associated fauna and flora in rock thin sections and grain samples. Grain samples were first crushed in a porcelain mortar, followed by washing in a sieve with mesh size of 63 µ to remove its clay and mud. The samples were then treated with 10 % HCl in porcelain vessels for 24 hours. This was followed by washing of the samples with pressurized water and then drying, in an oven set to 200 °C. The dried samples were then sieved and size fraction below 500 µm were examined under a binocular microscope. Fossils were handpicked, determined, and photographed in the Paleontology Laboratory of Geological Engineering Department at Istanbul University-Cerrahpaşa.

Geological setting

Stratigraphy of the NW Thrace Basin

The metamorphic rock units of the Strandja Massif and the sedimentary cover rock units of the Thrace Basin are exposed in NW Turkey (Fig. 1). The metamorphic rocks in the region are divided into two groups as the Paleozoic high-grade metamorphic basement and the overlying Mesozoic meta-sedimentary deposits. The Paleozoic basement of the Strandja Massif is composed of predominantly granitic and felsic gneissic rocks, and to a lesser extent of migmatite, amphibolite and mica schists along with some granitic bodies which cut these rocks (Okay et al. 2001b; Elmas et al. 2011; Bonev et al. 2019). The Triassic–Middle Jurassic meta-sedimentary sequence of the Strandja Massif on the Paleozoic basement starts with metaconglomerates and metasandstones and continues upward into phyllite-calc-schist-marble alternation (Aydın 1974, 1982; Chatalov 1988; Çağlayan & Yurtsever 1998; Okay et al. 2001b; Hagdorn & Göncüoğlu 2007; Akgündüz 2017). The metamorphic rocks of the Strandja Massif are juxtaposed by unmetamorphosed sedimentary rock units of the Thrace Basin to the south (Fig. 2).

The sedimentary sequence exposed in the NW Thrace Basin, and examined in this study, grades laterally into matrix-supported and grain-supported, mostly sharply edged conglomerate and coarse sandstones. This has similarities to olistostromal/blocky unit previously called the Akalan Formation in SE extension of the Strandja Massif, which has been interpreted as colluvial/alluvial fan deposits containing clasts of the underlying metamorphic units (c.f., Elmas 2012a).

Along the NW-oriented margin of the Thrace Basin in the western Strandja, the Akalan Formation mostly has a linear trend in many places with the underlying metamorphic rocks of the Strandja Massif (Figs. 3 and 4). It continues upward with reefal carbonates of the Soğucak Formation which has previously been considered to have middle/late Eocene to early Oligocene age (Keskin 1974; Sirel & Gündüz 1976; Siyako & Kasar 1985; Batı et al. 1993, 2002; İslamoğlu & Taner 1995; Özcan et al. 2019). In some areas, the Soğucak Formation lies directly on the metamorphic base with limited or scarce exposures of the Akalan Formation (Fig. 3). A Neogene unit, consisting of partially consolidated gravel, sand and chalk overlies unconformably all the units in the study area (Figs. 2 and 3).

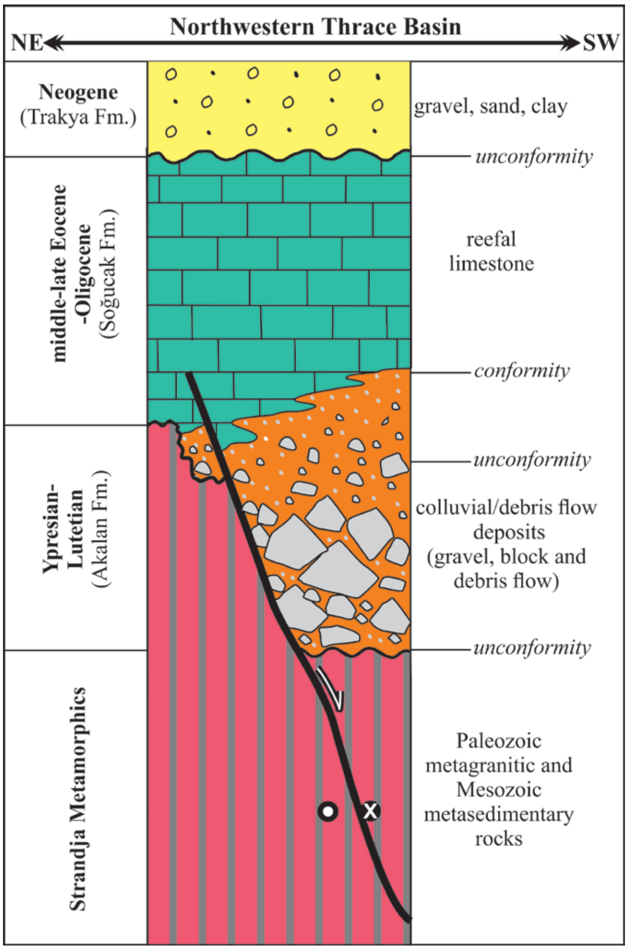

Fig. 2. Generalized stratigraphic section of the NW Thrace Basin and Strandja Massif.

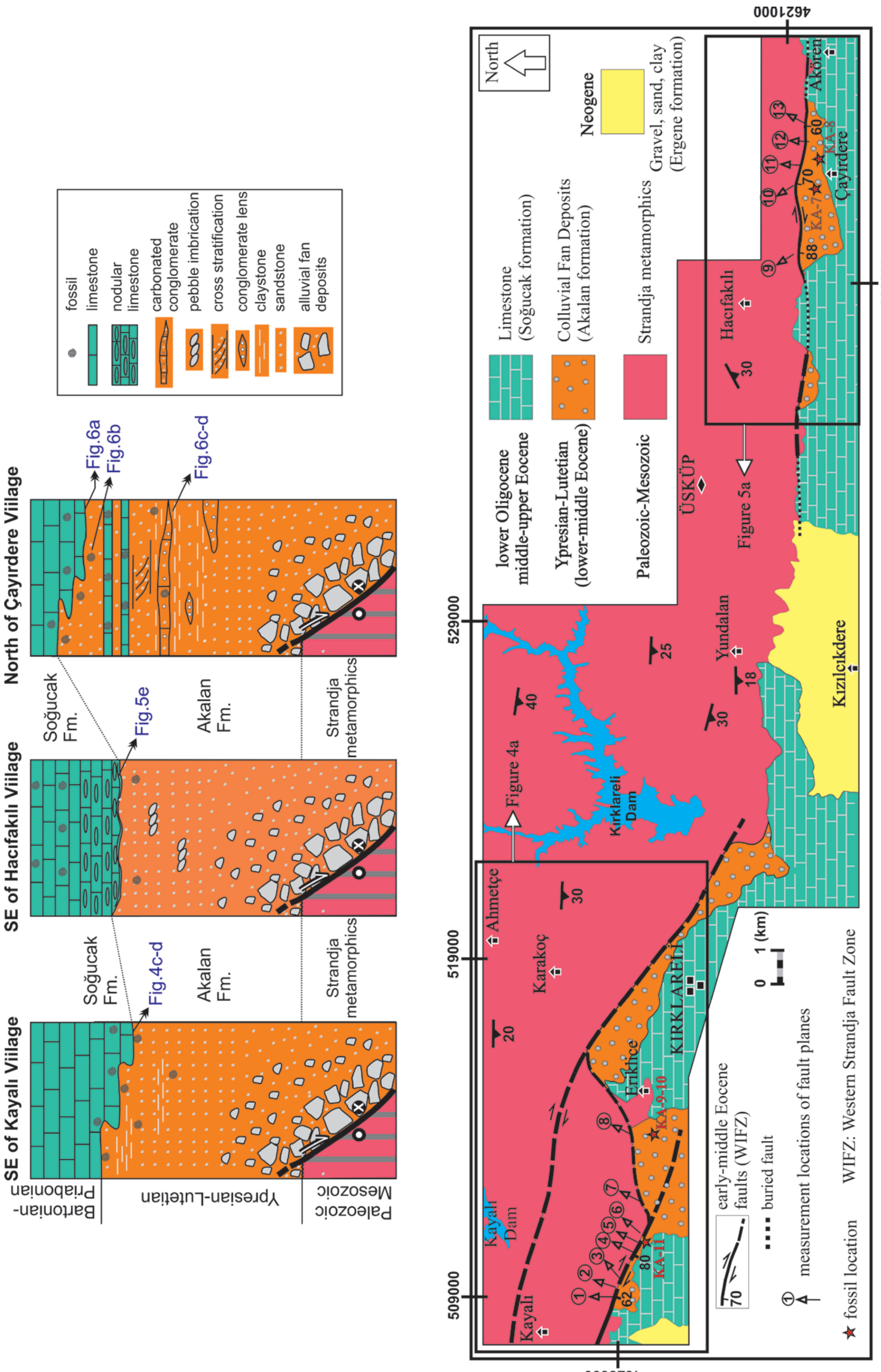

Fig. 3. Geological map and vertical stratigraphic sections of the NW Thrace region.

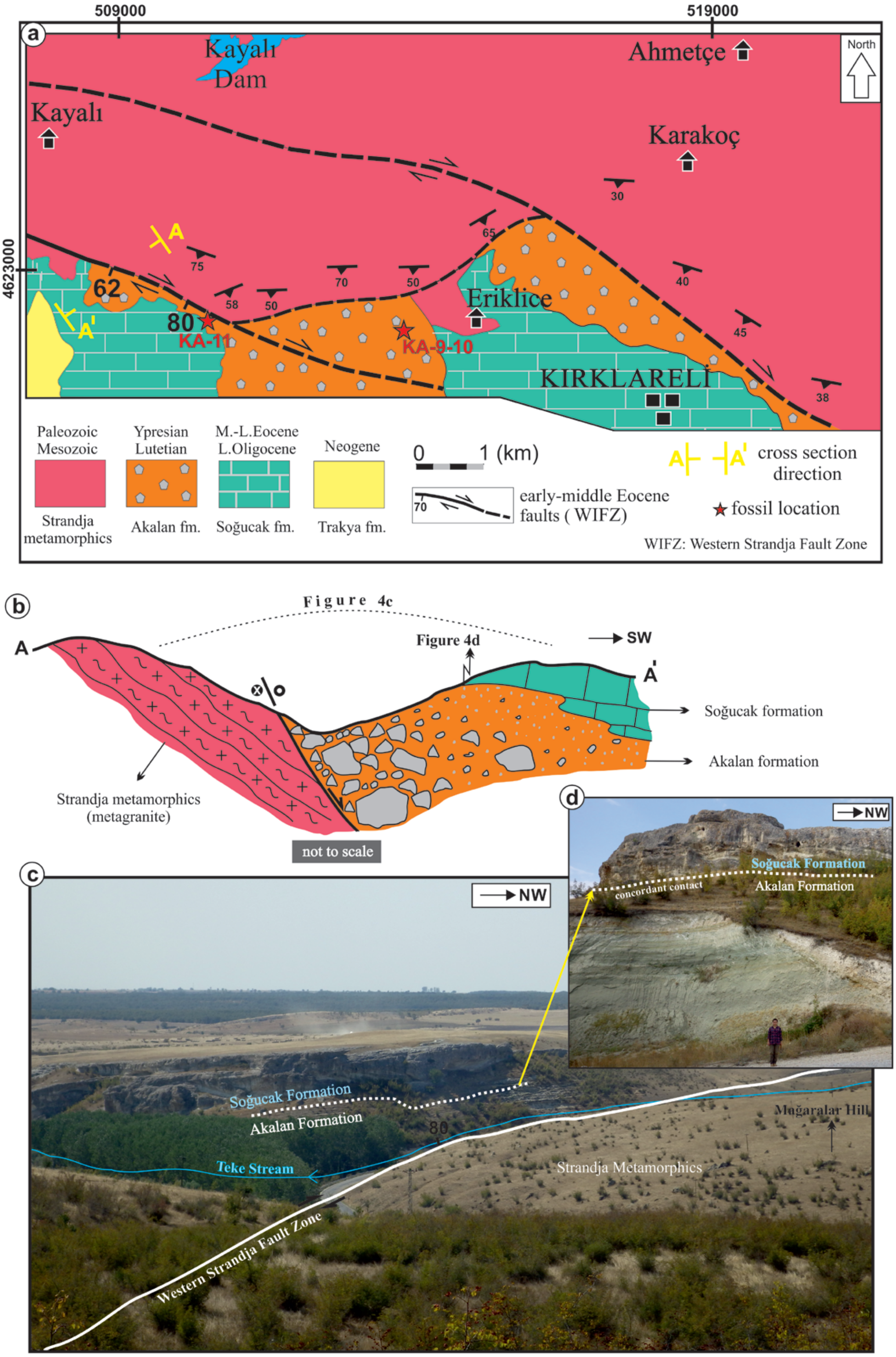

Fig. 4. a — Geological map of the area west and north-west of Kırklareli City. **b** — Geological cross section through Western Istranca Fault Zone. **c** — Extent of Western Strandja Fault Zone and stratigraphic relations of between Kırklareli Metagranite, Akalan and Soğucak Formation in NW of Kırklareli City. **d** — Concordant contact between the Akalan and Soğucak Formations.

Colluvial fan-debris flow deposits of the NW Thrace Basin (Akalan Formation)

Colluvial fan/debris flow sediments of the NW Thrace basin are generally white, greenish grey and beige in colour and begin with an olistostromal and debris flow character. At its base, it contains blocks and angular cobbles and pebbles of the underlying metamorphic rocks, varying in size from 1 cm up to 4 metres (Fig. 5c, d). They are surrounded by a fine-grained matrix composed of metamorphic basement rock fragments. This chaotic/colluvial unit has a grain-supported character, but occasionally it becomes a matrix-supported unit and the grain sizes of gravel/blocks diminish (Figs. 4–6). These sediments are indicative of a rapid sedimentation process in terms of their lithological and textural properties and are interpreted as colluvial/alluvial debris-flow deposits. Above, the sequence passes into sandy-clayey layers comprising rock fragments of units below (Figs. 4d, 5e and 6). Besides, this unit exhibits a rich fossil content at the levels, which include limestone bands and pebblestone-pebbly sandstone horizons with carbonate cement. The fauna comprises larger benthic foraminifera (LBF), pelecypods and gastropods (Fig 6). Such a sedimentary unit defined as the Akalan Formation in the NE Thrace Basin (Elmas 2012a) has been documented for the first time in the NW Thrace Basin and studied in this work for its fossil content besides its sedimentological character.

In the study area, the Akalan Formation is exposed along a NNW–SSE oriented strip, tracking the southern slopes of the Strandja highland towards the NW of Eriklice village and Kırklareli city, and to the N of Çayırdere village (Fig. 1b). It is also exposed near Sergen and Vize Districts of Kırklareli Province. This unit is laterally transitional to and is overlain by the middle-late Eocene–early Oligocene aged reefal carbonates of the Soğucak Formation (also Oktay et al. 1992; Baykal et al. 2009) or as it is called the Kırklareli Limestone in some publications (Keskin 1966). The Soğucak (or Kırklareli Limestone) Formation is previously considered to have middle/late Eocene to early Oligocene age (Keskin 1974; Sirel & Gündüz 1976; Siyako & Kasar 1985; Batı et al. 1993, 2002; İslamoğlu & Taner 1995; Özcan et. al 2019). Along some areas of the metamorphic basement–sedimentary cover boundary in the study area, the Soğucak Formation rests directly on the metamorphic base without a notable thickness of the Akalan Formation (Fig. 3). They are unconformably overlain by a Neogene unit, consisting of partially consolidated gravel, sand and chalk in the study area (Figs. 2 and 3).

Results

Paleontological findings

In previous studies, no paleontological data have been published concerning the Akalan Formation (Elmas 2012a). However, early Priabonian ages were derived from the palynomorph, pelecypod and gastropod assemblages in the Koyunbaba and/or İslambeyli Formations, which also lie below the Soğucak Formation. They may be used in comparison with the possible age of this unit (Keskin 1974; Umut et al. 1983; İslamoğlu & Taner 1995).

For the first time during this study, larger benthic foraminifera (LBF) *Coskinolina* (Coskinon) sp. of the Coskinolinoidea super family representing Ypresian–Lutetian (early to middle Eocene) age, *Orbitolites* sp, of the Soritoidea super family characterizing Ypresian–Bartonian (early to middle Eocene), and *Discocylina* sp from the Nummulitoidea superfamily indicating Eocene age are determined in KA-11 sample to the south of the Kayalı village (Fig. 7; GPS coordinates: 41°44.982’N, 27°7.652’E). *Orbitolites* sp. of Ypresian–Bartonian (early–middle Eocene), *Nummulites obesus* d’Archiac, 1852 of early Lutetian, *Dictyoconus egyptiensis* (Chapman, 1900) of Lutetian age and *Ammobaculites agglutinans* (d’Orbigny, 1846), *Amphimorphina crassa* Cushman & Bermudez, 1936, *Dentalina* sp., *Nodosaria* sp., *Quinqueloculina* sp., *Amphistegina* sp. and *Discocyclina* sp. of Eocene age were determined to the SW of Eriklice village in KA-09 and KA-10 samples (Fig. 8; GPS coordinates: 41°45.228’N, 27°10.572’E). Besides, some LBF from the Miliolidea superfamily such as *Idalina grelaudae* Gallardo-Garcia & Serra-Kiel, 2016 of early Lutetian–Priabonian age, *Miliola* sp. of early–middle Eocene age, *Lenticulina* sp. and *Operculina* sp. of Paleocene–Miocene age have been determined in samples KA-07 (GPS coordinates: 41°42.187’N, 27°30.779’E) and KA-08 (GPS coordinates: 41°42.140’N, 27°30.983’E) taken to the N-NE of Çayırdere village (Figs. 7–8). Fossils such as *Coskinolina* sp., *Orbitolites* sp., *Idalina grelaudae* Gallardo-Garcia & Serra-Kiel, 2016, *Nummulites obesus* d’Archiac, 1852, *Dictyoconus egyptiensis* (Chapman, 1900) and *Miliola* sp. together indicate the Ypresian–Lutetian age interval. Based on the stratigraphic relationships and the paleontological findings, the age of the Akalan Formation is considered to have latest Ypresian–late Lutetian biostratigraphic age.

Western Strandja Fault Zone

Field evidence, map pattern of the Akalan Formation in NW Thrace Basin and kinematic data on fault outcrops indicates the presence of a strike-slip fault system along the southern margin of the Strandja Mountains, where the metamorphic rocks of the Strandja Massif are juxtaposed against the sedimentary units of the Thrace Basin (Figs. 3–5). This fault comprising both dextral strike and normal slip dominant fault segments in the western part of the Strandja Massif are collectively called the “Western Strandja Fault Zone” in this study. This fault lies in the eastern continuation of the Maritsa Fault described north of the Rhodope block, which is intruded by granitoids (e.g., Meyer 1968; Soldatos & Christofides 1986; Del Moro et al. 1988; Dinter et al. 1995; Peytcheva et al. 1998; Pe-Piper & Piper 2002) and is covered by Late Cretaceous, late Eocene–Oligocene to Neogene sedimentary and volcanic sequences (e.g., Ivanov & Kopp 1969; Innocenti et al. 1984;

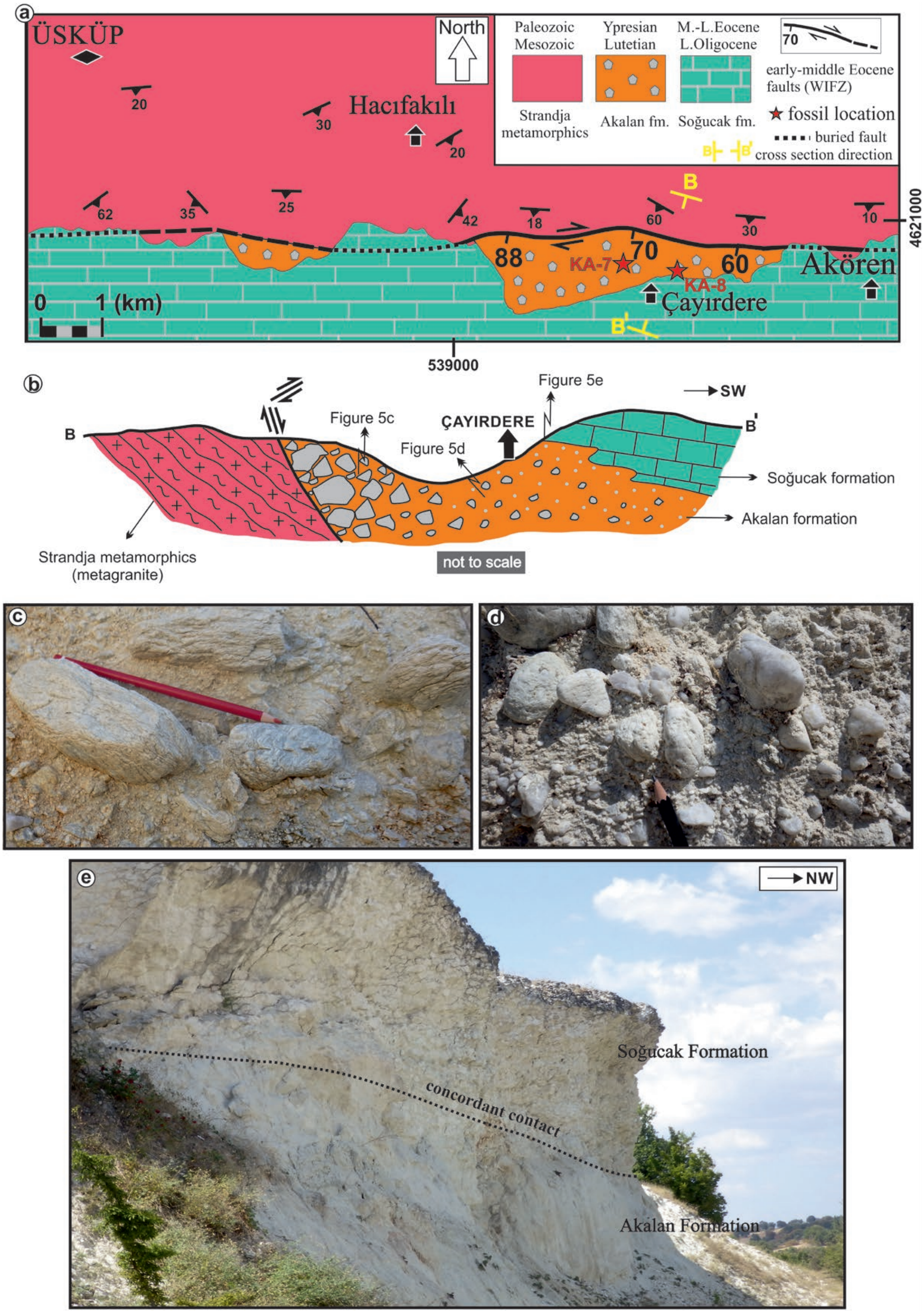

Fig. 5. a — Geological map and cross section of the Çayırdere–Hacıfakılı area. **b** — Blocky and grain-supported section of the Akalan Formation. Fragments are of the underlying metamorphics. **c** — Gravel rich coarse-grained and matrix supported level of the Akalan Formation. **d** — Conformable and grading relationship between the Akalan and Soğucak Formations. Photographs are taken from the vicinity of Çayırdere Village.

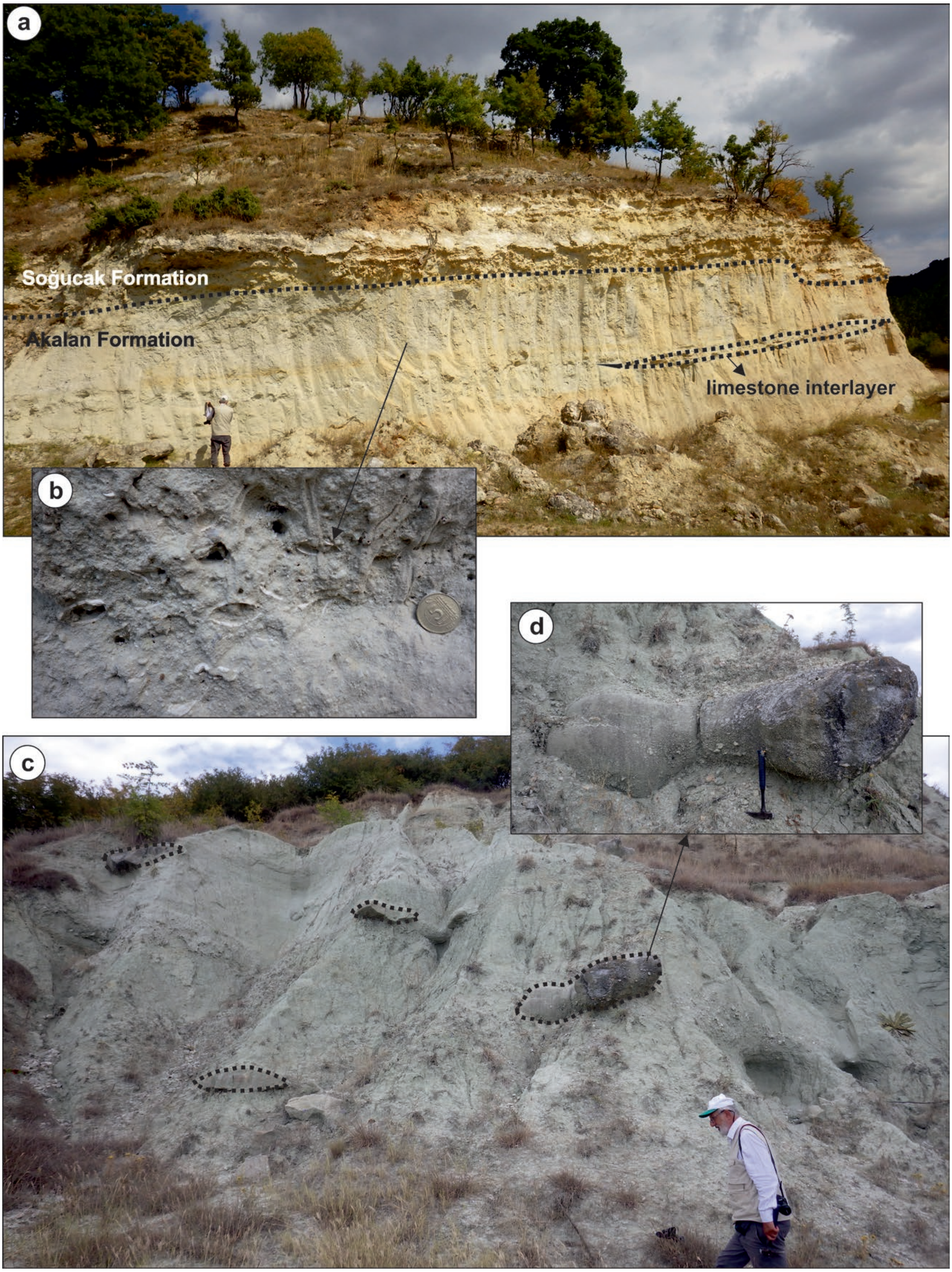

Fig. 6. a — Graded transitional relationship of the Akalan Formation with the Soğucak Formation and the occurrence of limestone interlayers within this zone. **b** — Fossiliferous horizons in the Akalan Formation. **c, d** — Silty-sandy level of the Akalan Formation and pebble-sand lenses in this zone.

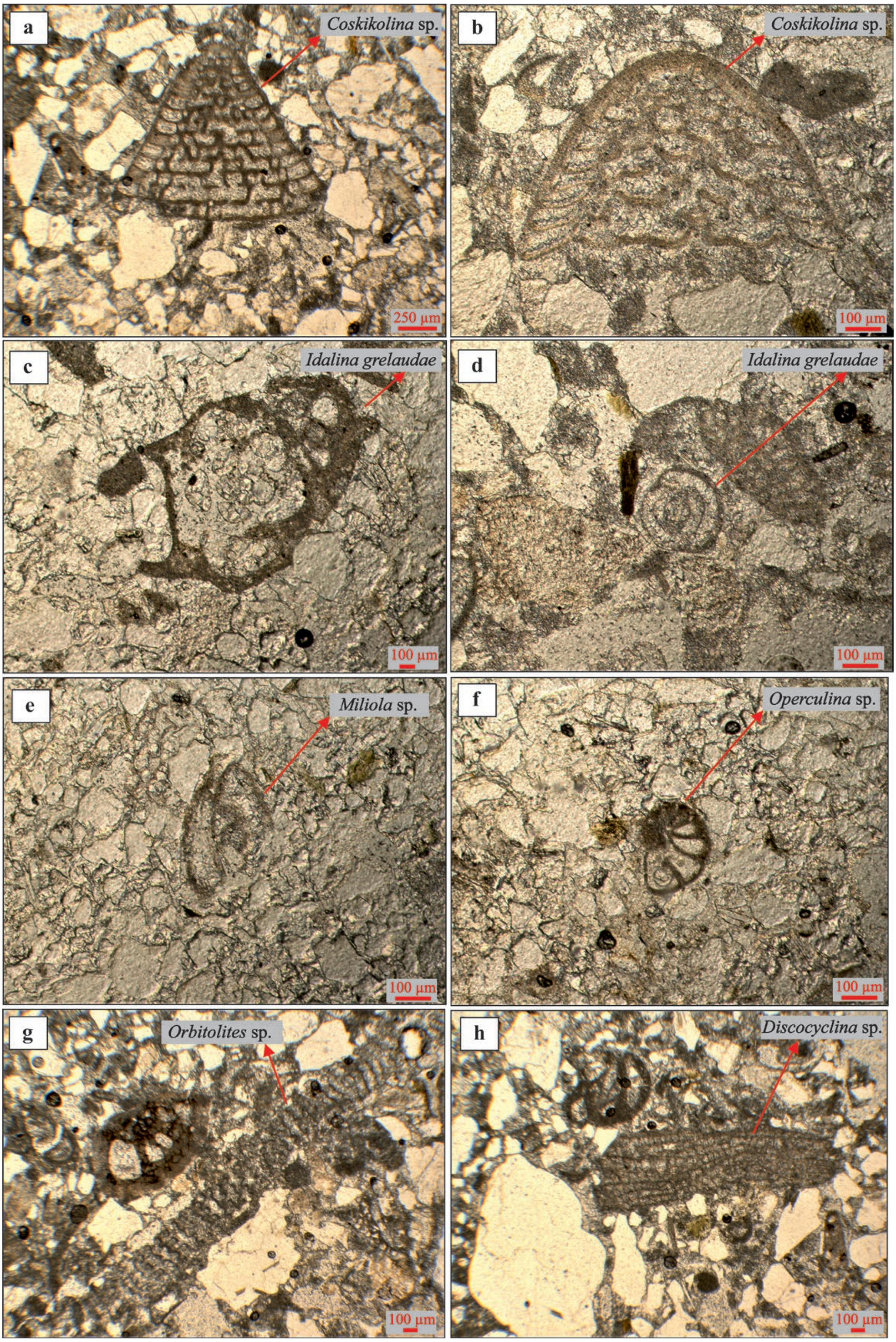

Fig. 7. Fossil photos from Akalan Formation: **a, b** — *Coskinolina* sp., Ypresian–Lutetian (sample KA-11); **c, d** — *Idalina grelaudae*, Lutetian (sample KA-07); **e** — *Miliola* sp., early–middle Eocene (sample KA-07); **f** — *Operculina* sp., Eocene (sample KA-08); **g** — *Orbitolites* sp., Ypresian–Bartonian (sample KA-11); **h** — *Discocylina* sp., Eocene (sample KA-11).

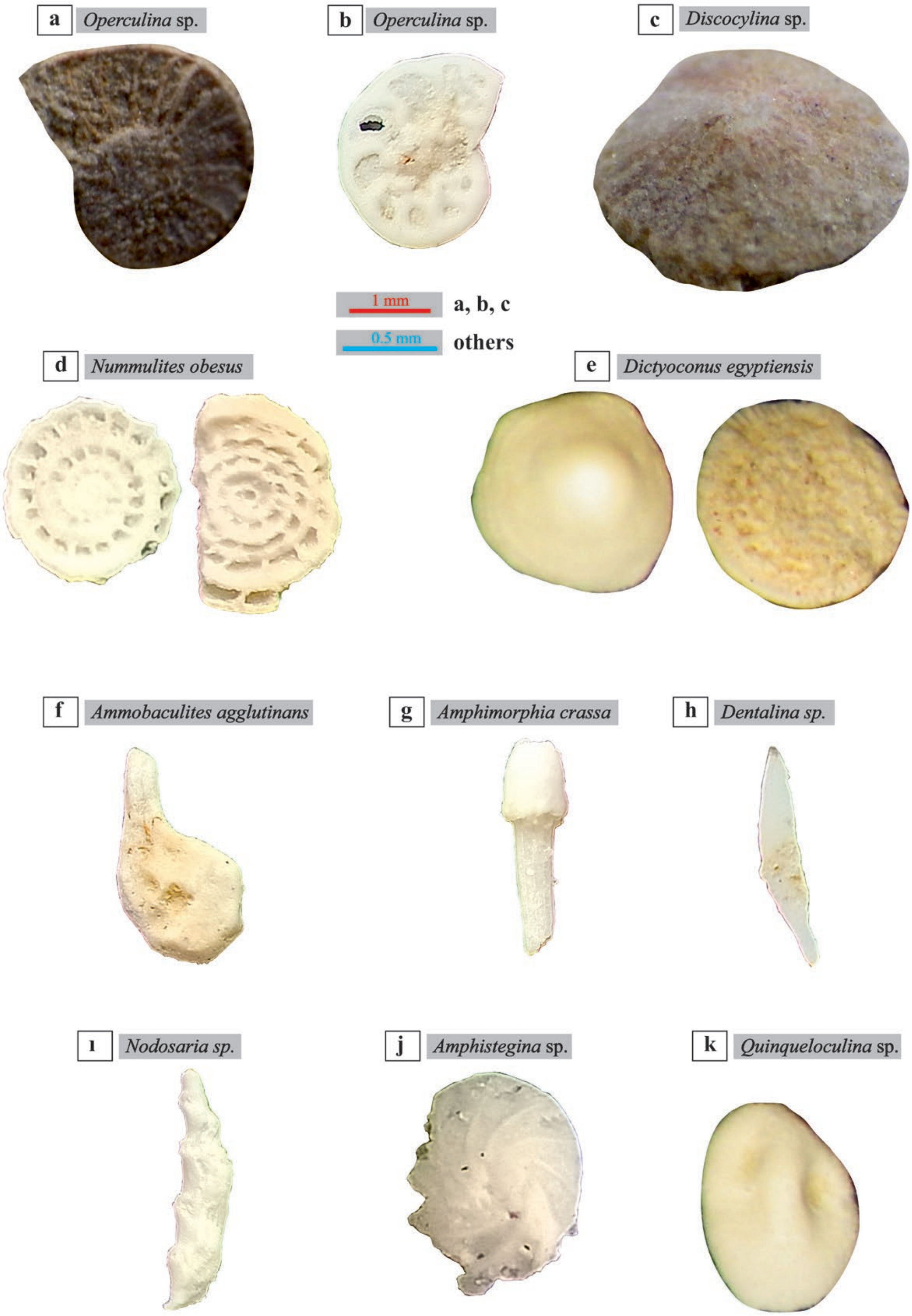

Fig. 8. Fossil photos from Akalan Formation: **a, b** — *Operculina* sp., Eocene (a: sample KA-09, b: sample KA-10); **c** — Discocylina sp., Eocene (sample KA-09); **d** — *Nummulites obesus*, early Lutetian (sample KA-09); **e** — *Dictyoconus egyptiensis*, Lutetian (sample KA-09); **f** — A*mmobaculites agglutinans*, Eocene (sample KA-09); **g** — *Amphimorphina crassa*, Eocene (sample KA-09); **h** —*Dentalina* sp., Eocene (sample KA-09); **i** — *Nodosaria* sp., Eocene (sample KA-09); **j** — *Amphistegina* sp., Eocene (sample KA-10); **k** — *Quinqueloculina* sp., Eocene (sample KA-10).

Harkovska et al. 1989; Yanev & Bardintzeff 1997; Boyanov & Goranov 2001). The Late Alpine Maritza dextral strike-slip fault delimits the Late Cretaceous volcanic arc of the Sredna Gora Zone against the Rhodope Massif in the north (Bonev & Bacceletto 2007; Kaymakçı et al. 2007).

The WSFZ in the Thrace Basin comprises two segments and the first of those concerns dip-slip faults with a variable strike-slip component. They separate blocky horizons of the Akalan Formation from the metamorphic units and have NW–SE'ly orientations (Fig. 5c,d). In places, they exhibit slickensided fault planes and slickenside lineation. The second concerns dextral slip faults with a varying dip-slip component. They largely form a boundary between the clastics of the Akalan Formation (Fig. 4c) and the adjacent metamorphic rocks, but sometimes are overlain by the neritic limestones of the Soğucak Formation. They also extend within the metamorphics and carbonates and have WNW–ESW'ly orientations (Figs. 3–5). Along the observed faults, greenschist facies metagranitic basement rocks and metasedimentary rocks show foliation lying sub-parallel to the faults, and they are partially cataclastically deformed.

In the study area, the Western Strandja Fault Zone exposures begin to the south of Kayalı village striking east-west, then continue to the north of Kırklareli province and extend to the east towards the Çayırdere-Akören villages (Fig. 3). Fault planes are frequently observed in SE of Kayalı village, S of Hacıfakılı village and NE of Çayırdere village. The characteristics of the faults are determined by kinematic markers such as slickenlines, notches, chatter marks and steps on the fault planes. The dip direction and dip angles of the fault planes with the trend and plunge of the fault lines were measured and these data are given in Table 1. Both strike- and dip-slip components are observed, suggesting varying degrees of oblique-slip on the faults (Figs. 9, 10). Kinematic analyses generally indicate an overall WNW–ESE trending master fault with a NW–SE oriented principal maximum stress axis (Fig. 9).

Geological evolution and discussion

The Strandja and Rhodope metamorphic complexes were similarly considered as a stack of crustal-scale ductile nappes during the Late Cretaceous–early Tertiary subduction and closure of the Vardar Ocean (Şengör & Yılmaz 1981; Şengör et al. 1982; Okay 1989; Koukouvelas & Doutsos 1990; Burg et al. 1996; Görür & Okay 1996; Yılmaz et al. 1997; Okay et al. 2001a, 2010; Elmas 2012a). In the Strandja Massif, there are some differences in the geological history for the different parts of the massif. In general, the units are considered to have been metamorphosed during the late Jurassic–early Cretaceous interval and have developed penetrative foliation via N-verging thrust tectonics (Gočev 1976, 1979; Aydın 1982; Şengör et al. 1984; Okay et al. 2001b; Sunal et al. 2011; Bedi et al. 2012; Natal'in et al. 2012, 2016; Bonev et al. 2020). Also, for the massif and adjacent areas, extension has been documented for different periods. Following the late Jurassic–early Cretaceous orogenesis, Cenomanian shallow marine deposits overlie transgressively the exposed metamorphics and rocks in the northern margin of the Strandja Massif. Granodiorite plutons and dikes, andesitic volcanics, tuffs and volcanoclastics point to magmatic arc and intra-arc formation associated with the Vardar–Intra Pontide Ocean subduction during early Senonian (Boccaletti et al. 1974; Okay et al. 2001a). A late extension is proposed for the early Paleogene period (e.g., Elmas et al. 2011; Akgündüz 2017).

In the Rhodope, the nappes were assembled by southward syn-metamorphic thrusting in the hanging wall of the north-dipping subduction of the Vardar slab, rooted in the present-day Vardar suture zone (Koukouvelas & Doutsos 1990; Ricou et al. 1998). Regional NNE–SSW-trending stretching lineations, associated with top-to-the-SSW ductile shearing coeval with amphibolite-facies metamorphism, were considered as the transport direction during syn-metamorphic nappe stacking (Burg et al. 1996). Opposite directions of tectonic transport (i.e. towards ENE and NNE), documented as well in some

Table 1: Kinematic data obtained from measurements on the fault plane.

Fault Zone	Study Area	Location No. (Figure 3)	Fault planes dip direction-dip	Fault lines trend-plunge	Fault type
Western Strandja Fault Zone	SE of Kayalı Village	1	180/62	202/50	Normal with dextral component
	SE of Kayalı Village	2	201/50	192/46	Normal with dextral component
	SE of Kayalı Village	3	198/48	190/42	Normal with dextral component
	SE of Kayalı Village	4	180/80		
	SE of Kayalı Village	5	198/40	227/30	Normal with dextral component
	SE of Kayalı Village	6	212/42	230/38	Normal with dextral component
	SE of Kayalı Village	7	200/40		
	SE of Kayalı Village	8	200/55		
	South of Hacıfakılı Village	9	190/88		
	North of Çayırdere Village	10	190/70		
	NE of Çayırdere Village	11	192/70		
	NE of Çayırdere Village	12	180/70	238/20	Normal with dextral component
	NE of Çayırdere Village	13	230/60		

thrust sheets and they were related to coeval or subsequent extensional deformation (Burg et al. 1996; Kilias et al. 1999; Bonev et al. 2006). Krohe & Mposkos (2002) later suggested, mainly on petrological grounds, that the predominantly SSW-directed shearing and kinematic patterns do not reflect progressive thrusting, but were probably associated with extensional deformations.

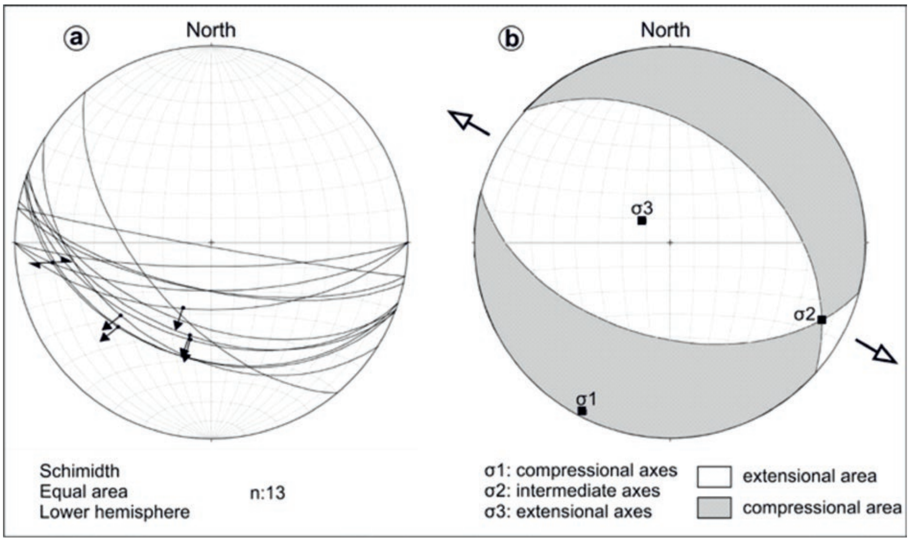

Fig. 9. a — Stereographic (equal area, lower hemisphere) projections of the fault–slip data on the fault zones; **b** — Calculated principal stress axes (σ1, σ2, σ3) using the FaultKin (V.7.7.4, 2017) program by Rick Allmendiger (for the science behind the algorithms in FaultKin, see Marrett & Allmendiger 1990; Allmendiger et al. 2012). The focal mechanism of the fault zone indicating extension and shortening directions. The data used to construct the projection are from Table 1.

The Thrace Basin is a triangle-shaped Cenozoic depression in NW Turkey adjacent to the Strandja Massif and has a sedimentary sequence of 9 km in thickness from the Eocene to Pliocene (Kopp et al. 1969; Doust & Arikan 1974; Keskin 1974; Turgut et al. 1983, 1991; Siyako & Huvaz 2007). This basin is divided by finger-shaped uplift areas namely the Istranca, central Thrace, Şarköy-Bolayır uplifts (Bayrak et al. 2004, 2006).

The middle–upper Eocene age carbonate rock units of the Thrace Basin exposed along the south margin of the Strandja Massif are suggested to overlie nonconformably on the metamorphic rocks and conformably on the Eocene terrestrial detrital sedimentary units along their NNW–SSE'ly trend (Koyunbaba and Islambeyli Formations) (e.g., Siyako 2006; Siyako & Huvaz 2007; Less et al. 2011; Özcan et al. 2019). However, in the eastern part of the massif, the metamorphic rocks of the Strandja Massif have been suggested to be in contact with the alluvial fan sediments called the Akalan Formation along the NW–SE trending lateral strike-slip faults (Elmas 2012a), while no such unit had been reported in the western part of the Strandja Massif.

This study suggests that the sedimentary unit of olistostromal debris-flow/colluvial fan deposits exposed on the western portion of the Strandja Massif can be considered the spatial equivalent of the Akalan Formation and represents the beginning of a sedimentary sequence in this area. With the fossil content of *Coskinolina* sp of Ypresian–Lutetian, *Nummulites obesus* d'Archiac, 1852 of early Lutetian, *Dictyoconus egyptiensis* (Chapman, 1900) of Lutetian, *Orbitolites* sp. of Ypresian–Bartonian, *Miliola* sp of early–middle Eocene, *Idalina grelaudae* Gallardo-Garcia & Serra-Kiel, 2016 of early Lutetian–Priabonian, *Ammobaculites agglutinans* (d'Orbigny, 1846), *Amphimorphina crassa* Cushman & Bermudez, 1936, *Dentalina* sp., *Nodosaria* sp., *Operculina* sp., *Lenticulina* sp., *Quinqueloculina* sp. and *Amphistegina* sp. of Eocene, the Akalan Formation has latest Ypresian–late Lutetian (early–middle Eocene) age and therefore are indicative of sedimentation at that time in the region. Coskinolina and Dictyoconus fossil groups indicate shallow and tropical settings of the Tethys Ocean during the early–middle Eocene (BouDagher-Fadel 2018). The accompanying LBF are likewise found in shallow benthic zones of the Tethys in the Eocene (Serra-Kiel et al. 1998).

Data compiled from the sediments and fossil content during this study in the NW Thrace basin indicate that a change from the initial terrestrial to a marine sedimentation in the Thrace Basin occurred in the early–middle Eocene period. This is consistent with a previous finding that Eocene sedimentation began in the early–middle Eocene in the NW Thrace basin in Greece (Chatalov et al. 2015). It is also in agreement with late Lutetian sedimentation in the northern and north-eastern parts of the basin, early–middle Eocene deposition in the middle parts, and early Eocene sedimentation in the SW of the basin in Turkey (Elmas 2012a). They altogether suggest the deposition existed in different parts of the basin.

Besides, the Akalan Formation juxtaposed with the metamorphic rocks of the Strandja Massif suggests an interrelationship with exposures of NNW–SSE'ly right lateral strike-slip and oblique faults called "Westward Strandja Fault Zone", which could be considered as the eastern extension of the dextral Maritsa Fault. The Akalan Formation exhibiting coarse grained, grain supported, poorly sorted lithology in the areas close to this fault system, but fine grained, matrix supported, well-sorted character at a distance to the fault, together with the conformable middle–upper Eocene/lower Oligocene aged reefal limestones (Soğucak Formation) supports a tectonically-controlled mechanism for the initiation and progression of the sedimentation in the Western Pontides. These field observations and geological (stratigraphic, paleontological and structural) data indicate that oblique-slip tectonic

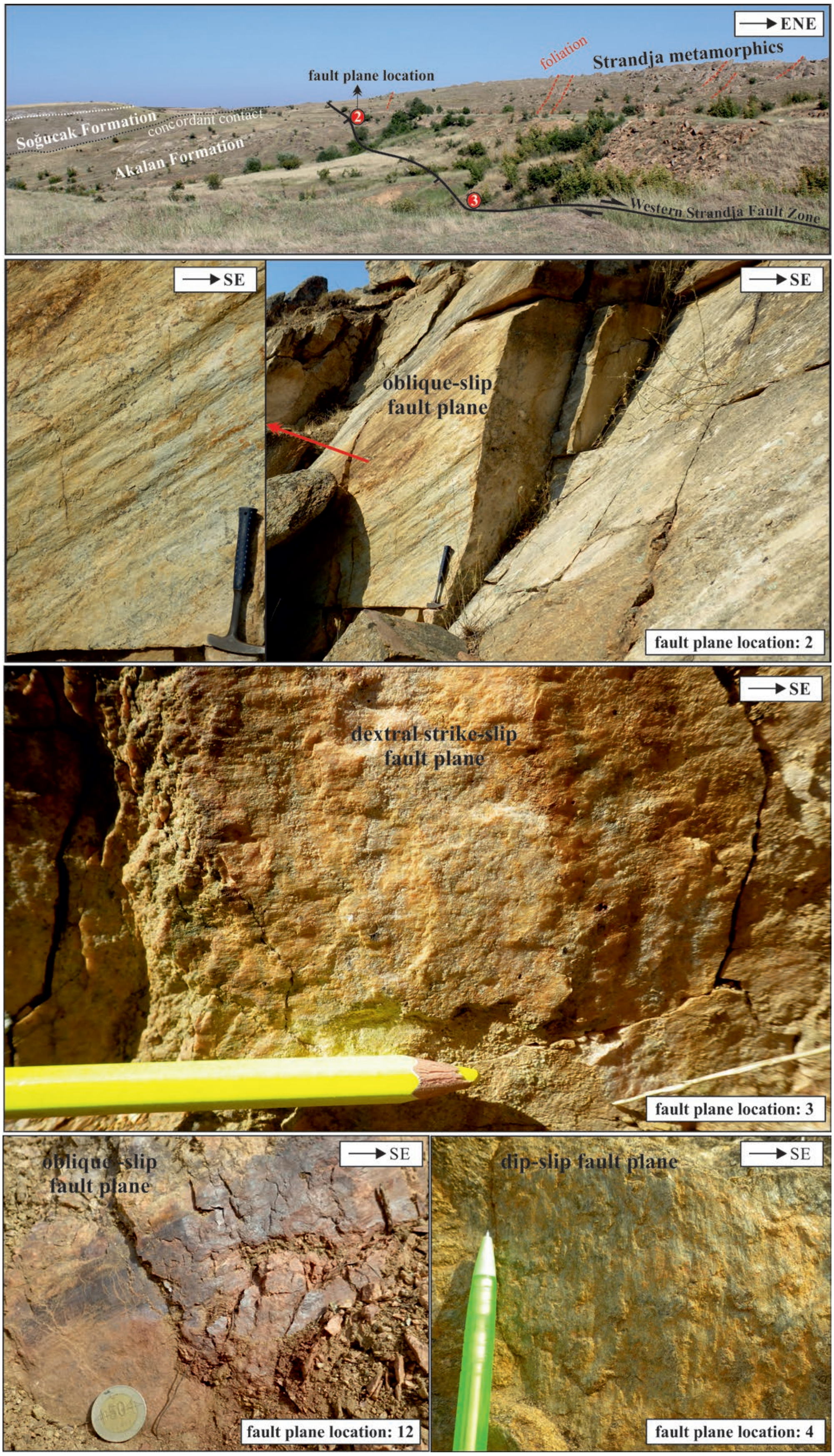

Fig. 10. Fault plane photos of Western Strandja Fault Zone. For fault plane locations, see Figure 3.

setting on the WSFZ along the southern skirts of the Istranca Massif was effective during the Ypresian–Lutetian (early–middle Eocene) times (Figs. 11a, 12a, 13a). This mode of tectonics controlled the deposition of the Akalan Formation as the basal sediments of the Thrace Basin. This unit may be considered temporally transitional with the previously defined middle–upper Eocene age Koyunbaba and İslambeyli Formations (Keskin 1974; İslamoğlu & Taner 1995) exposed in the northern Thrace Basin where depositional setting is relatively stable.

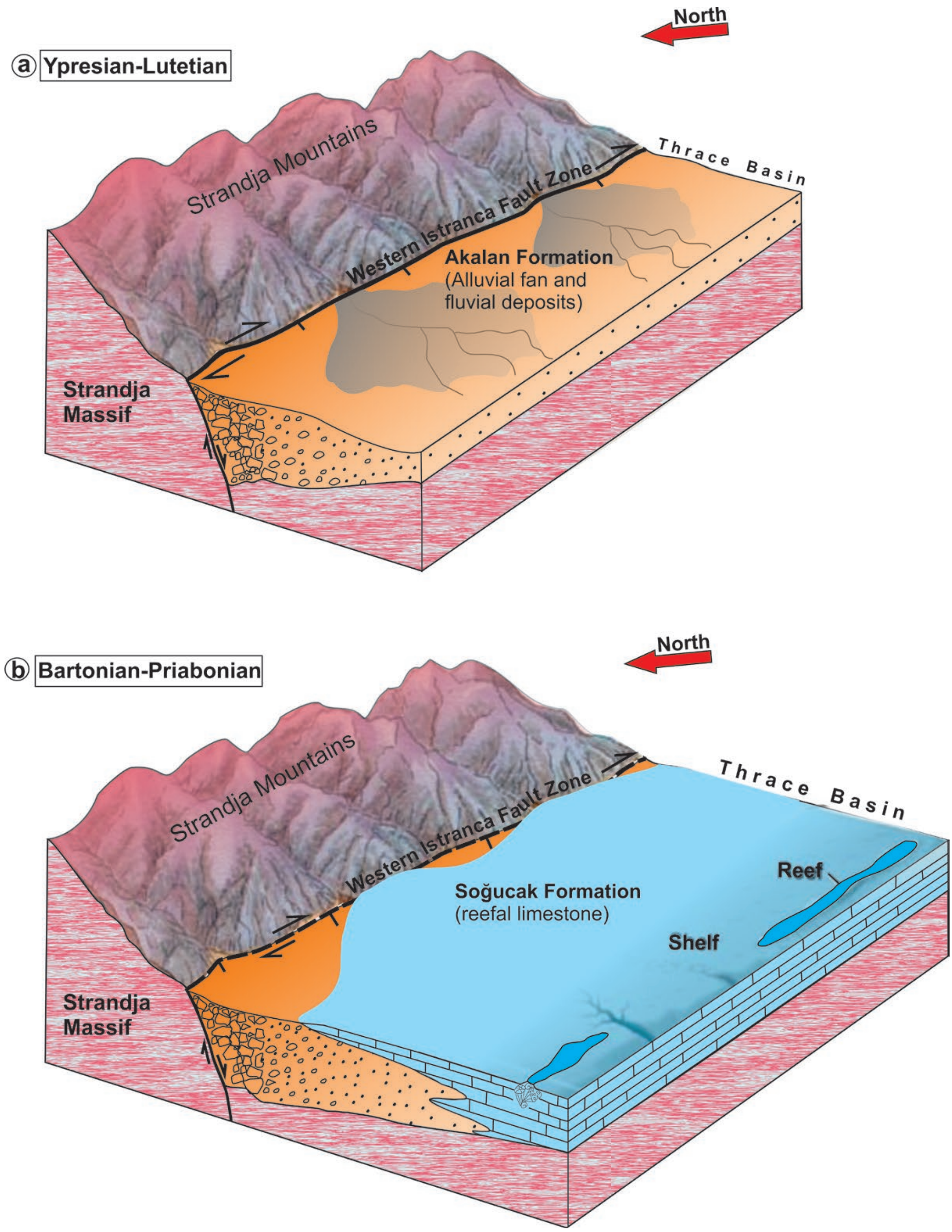

Fig. 11. a — Block diagram showing the geological characteristics of Ypresian–Lutetian time in the NW of the Thrace Basin. **b** — Block diagram showing the geological characteristics of Bartonian–Priabonian time in the NW of Thrace Basin.

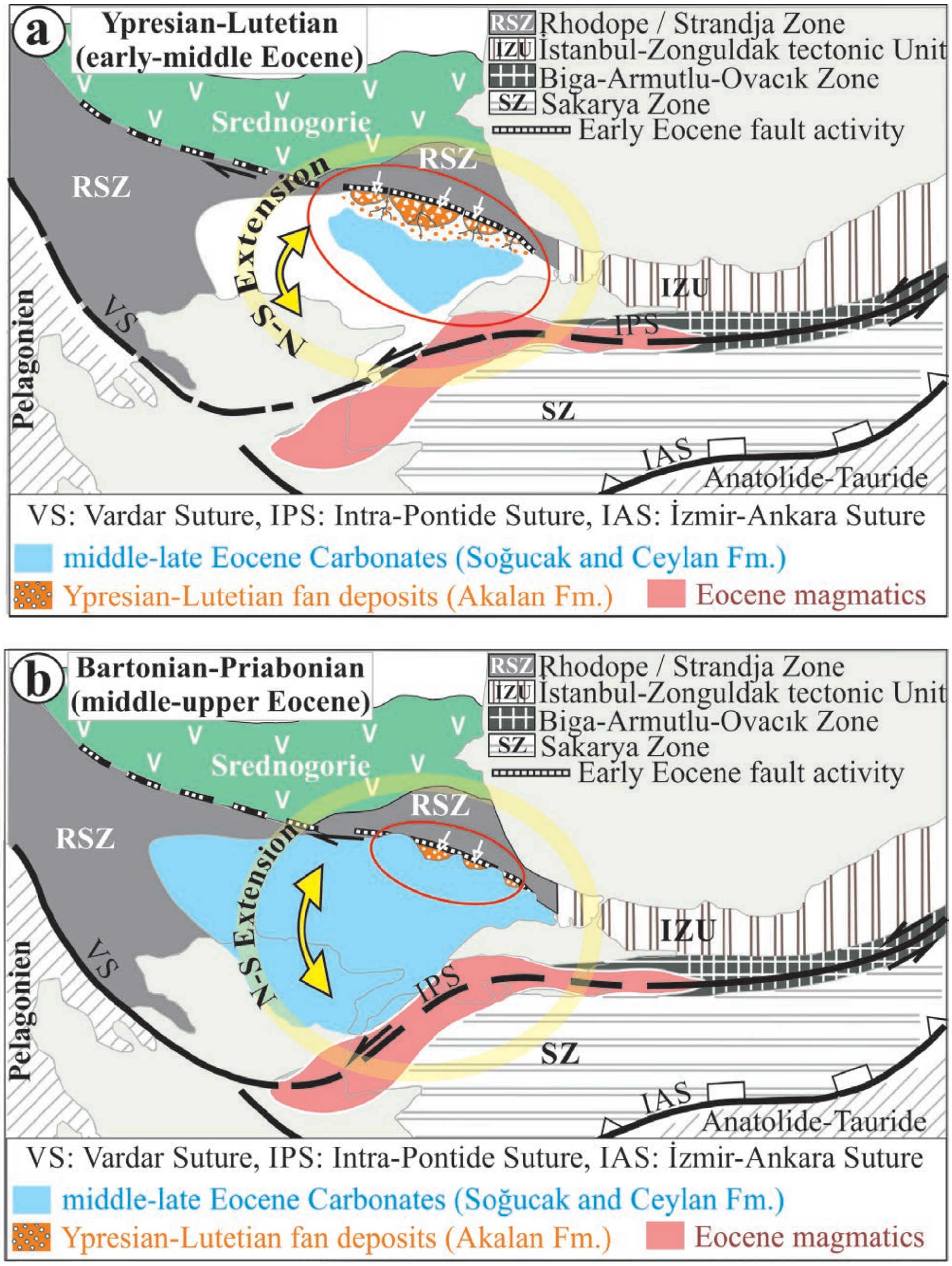

Fig. 12. a, b — Paleogeographic maps of the northern Aegean, northwestern Anatolia, and the Balkans during the early–late Eocene and illustrating the evolution of the northern Thrace Basin (modified from Elmas 2012a).

Following the deposition of colluvial fan deposits of the Akalan Formation the progressive transgression continued with the deposition of reefal carbonates of the Soğucak Formation during the late Eocene (Priabonian)–early Oligocene in this study area and elsewere (Figs. 11b, 12b, 13b). Deposition of the overlying Ceylan Formation and turbiditic Keşan Formation, which overlie with conformity the Soğucak Formation, indicates the marine environment dominated the region until the early Oligocene, and may imply that activity of the Western Strandja Fault in the Thrace basin continued longer.

The geometry of the Western Strandja Fault, which controlled the depositional environments of the Akalan Formation and the overlying Soğucak Formation, suggests a larger extensional tectonic setting. While the Cretaceous–Paleocene period primarily represents the collisional process in the western Pontides due to the northward movement of the Sakarya and Rhodope blocks via the subduction to the north of the Vardar Oceanic plate (Şengör & Yılmaz 1981; Şengör et al. 1982; Okay 1989; Koukouvelas & Doutsos 1990; Görür & Okay 1996; Yılmaz et al. 1997; Okay et al. 2001a, 2010; Burg et al. 1996; Elmas 2012a), an extensional setting seems

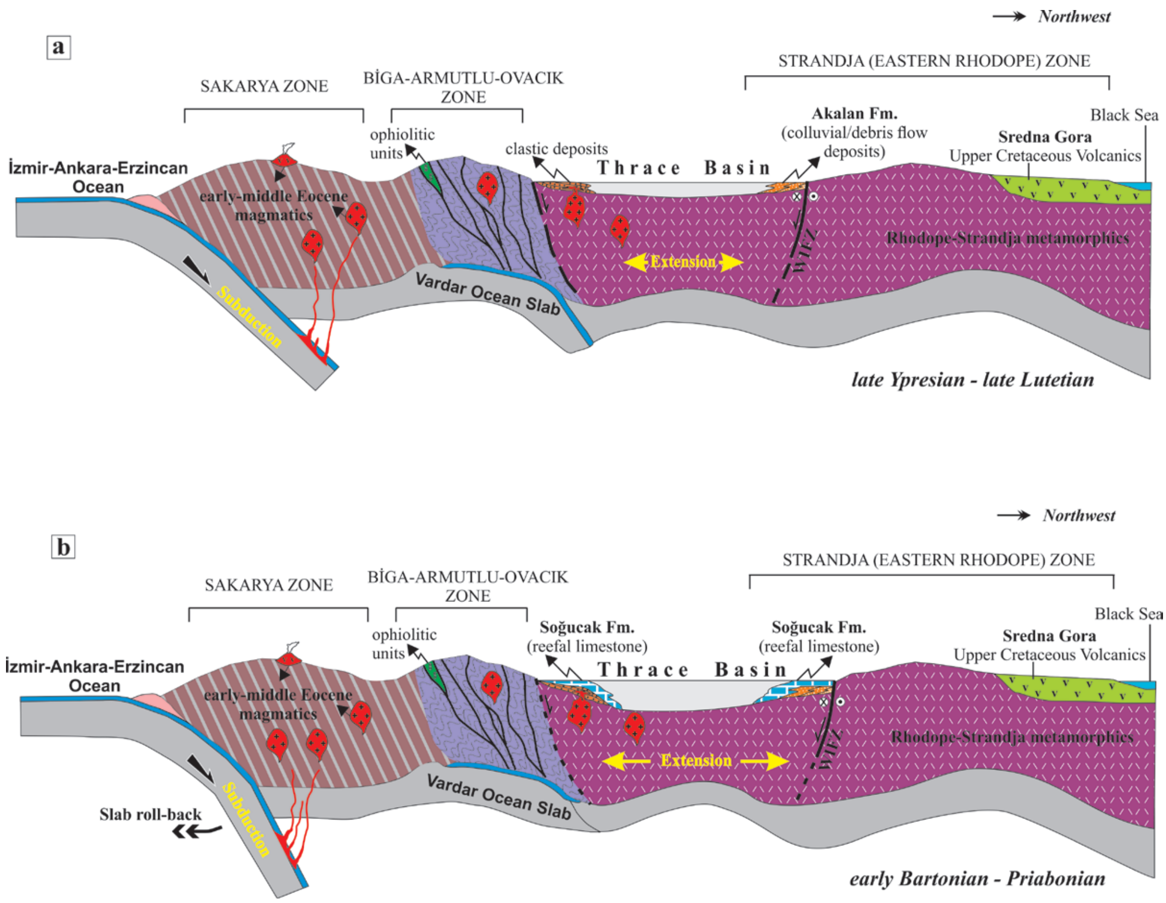

Fig. 13. Sketches illustrating the evolution of the northern Thrace Basin. **a** — A mode of extensional tectonics in association with an oblique fault at the southern margin of the Rhodope–Strandzha Massif and initial colluvial and debris deposits of the late Ypresian–late Lutetian. **b** — Enlargement of the Thrace basin under the influence of the extensional tectonics that continued during early Bartonian–Priabonian times and led to the deposition of reefal limestones (Soğucak Formation).

contradictory. This could be explained by a reversal from the contractional tectonic setting for which several models have been proposed (Burg et al. 1996; Kilias et al. 1999, Krohe & Mposkos 2002; Elmas 2012a; Akgündüz 2017). The extensional Eocene magmatism documented in the western Pontides (Figs. 1 and 12; Okay & Satır 2006; Siyako & Huvaz 2007; Elmas 2012b) is consistent and coincides with the age and tectonostratigraphic findings on the Akalan Formation, which documents the early sedimentation of this extensional period during the early–middle Eocene in the NW Thrace Basin.

The Akalan Formation, significant in terms of initiation of sedimentation in an extensional tectonic setting in the northern Thrace Basin during the Ypresian–Lutetian times, is further evidence for the varying conditions that prevailed in the basin and may indicate asymmetry of the basin. This asymmetry can be observed in the variation of the synchronous units documented in the basin: for instance besides the colluvial Akalan, the shallow marine Koyunbaba or İslambeyli Formations occur in the Northern Thrace basin; retrogressive sequence of the Karaağaç and Fıçıtepe Formations in the SW Thrace Basin (i.e., Gökçeada and SW Gelibolu) (Siyako & Huvaz 2007; Elmas 2012a; Özcan et al. 2019), transgressive shallow-marine to basinal sequence of the Dişbudak Serie in the SE (SE Gelibolu; Okay et al. 2010; Özcan et al. 2019); deep marine sediments of the Balıkkaya Formation (Akgündüz & Özkar Öngen 2021), submarine fan deposits of the Hamitabat Formation in the central part of the Basin (Turgut et al. 1983; Siyako & Huvaz 2007), each unit representing a different depositional setting than the other. Such a variety in the sedimentary facies in different parts of the Thrace basin is consistent with a tectonically active nature of a northern basin margin during the early–middle Eocene times.

Conclusions

The Akalan Formation represents the base of the sequence in the northern Thrace basin. It consists of colluvial fan/debris flow deposits and is described for the first time as having several larger benthic foraminifera of Ypresian–Lutetian of the Eocene. This formation passes upward with a conformity into reefal limestones of the middle/late Eocene–early Oligocene Soğucak Formation. Therefore, the Akalan Formation where it bounds the Strandja Metamorphics by a right lateral strike-slip oblique fault called "The Western Strandja Fault Zone" signifies the initiation of sedimentation in a transtensional/extensional tectonic setting in the northern Thrace Basin during the Ypresian–Lutetian times. The Akalan Formation and the overlying Soğucak Formation suggest an extending tectonic setting. It is further evidence for the varying conditions that prevailed in the Thracian Basin during the Eocene period.

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