Key problems of stratigraphy in the Eastern Crimea Peninsula: some insights from new dating and structural data

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Abstract: The tectonic evolution of the Eastern Black Sea Basin has previously been explained based on offshore and onshore data, some of the latter from the Crimean Mountains (CM). However, changes in the stratigraphy of the CM have recently been proposed: the Late Triassic–Early Jurassic Tauric Group was assigned as younger (Albian). To clarify the stratigraphy and the tectonic evolution of this area, we sampled the eastern CM for micropalaeontological datings (nannoplankton). The results demonstrate an Early Cretaceous age for the Tauric Group in the eastern CM. The samples contained substantial amounts of volcanic ash, indicating a period of magmatic activity along all the eastern CM. Our field observations allowed us to propose a new structural map and cross-sections, using which three main tectonic units were distinguished. We define a phase of extension during the Early Cretaceous and one of shortening during the Paleocene–Early Eocene, before the main Middle Eocene limestone unconformity. These two phases are related to: (1) the opening of the Eastern Black Sea Basin along NNW–SSE-trending normal faults and the associated magmatism; and (2) north–south shortening that could be comparable with the inversion in Dobrogea and/or with north–south shortening linked to the collision of continental blocks in the Pontides and Taurides domains.

Crimea is a geologically rich area that shows potential in natural resources (hydrocarbons) (Robinson *et al.* 1996; Robinson & Kerusov 1997; Khriachtchevskaia *et al.* 2009; Stovba *et al.* 2009) and has therefore been the target of numerous studies. The Crimean Mountains (CM) belong to the northern branch of the 'Alpine belt' and appear as an inverted part of the northwestern passive margin of the Eastern Black Sea Basin (e.g. Nikishin *et al.* 2001) (Fig. 1). In addition, this region has similarities with the Greater Caucasus and records extensional tectonic events related to the evolution of the Greater Caucasus basin as well as deformation connected to the Cenozoic shortening of the Eastern Black Sea and Greater Caucasus (Milanovskij 1991; Angelier *et al.* 1994; Nikishin *et al.* 1998, 2003; Ershov *et al.* 1999, 2003) (Fig. 2).

According to their geomorphological and geological setting, the Crimea corresponds to the north- to NW-dipping monocline and consist of two main areas represented by flat and mountainous domains, respectively. The flat part of the Crimea Peninsula and adjacent offshore shelf areas of the Black and Azov seas belong to the Scythian Platform, which joins in the north with the southern margin of the East European Platform (Fig. 2). A deep fault system separates the Scythian Platform from the southern CM, along which a transition to the deep-water Black Sea Basin occurs (e.g. Saintot *et al.* 2006; Yegorova & Gobarenko 2010; Starostenko *et al.* 2015; Gobarenko *et al.* 2015).

Despite the fact that the geology of the Crimea Peninsula has been studied for more than 100 years, there are key unsolved questions related to the stratigraphy and tectonics. Research has been carried out in the CM during the last few decades to constrain the stages of the tectonic evolution of the Black Sea Basin (Robinson *et al.* 1996; Robinson & Kerusov 1997; Saintot *et al.* 1999, 2007; Nikishin *et al.* 2003, 2012, 2015*a*, *b*; Afanasenkov *et al.* 2007; Stovba & Khriachtchevskaia 2009; Stovba *et al.* 2009; Yudin 2009; Khriachtchevskaia *et al.* 2010; Meijers *et al.* 2010; Stephenson & Schellart 2010; Popadyuk 2011; Yudin & Yurovskiy 2011; Okay *et al.* 2013; Popadyuk *et al.* 2013*a*, *b*; Stovba *et al.* 2013). Nevertheless, the tectonic structure of this area is still controversial because there are problems in the stratigraphy

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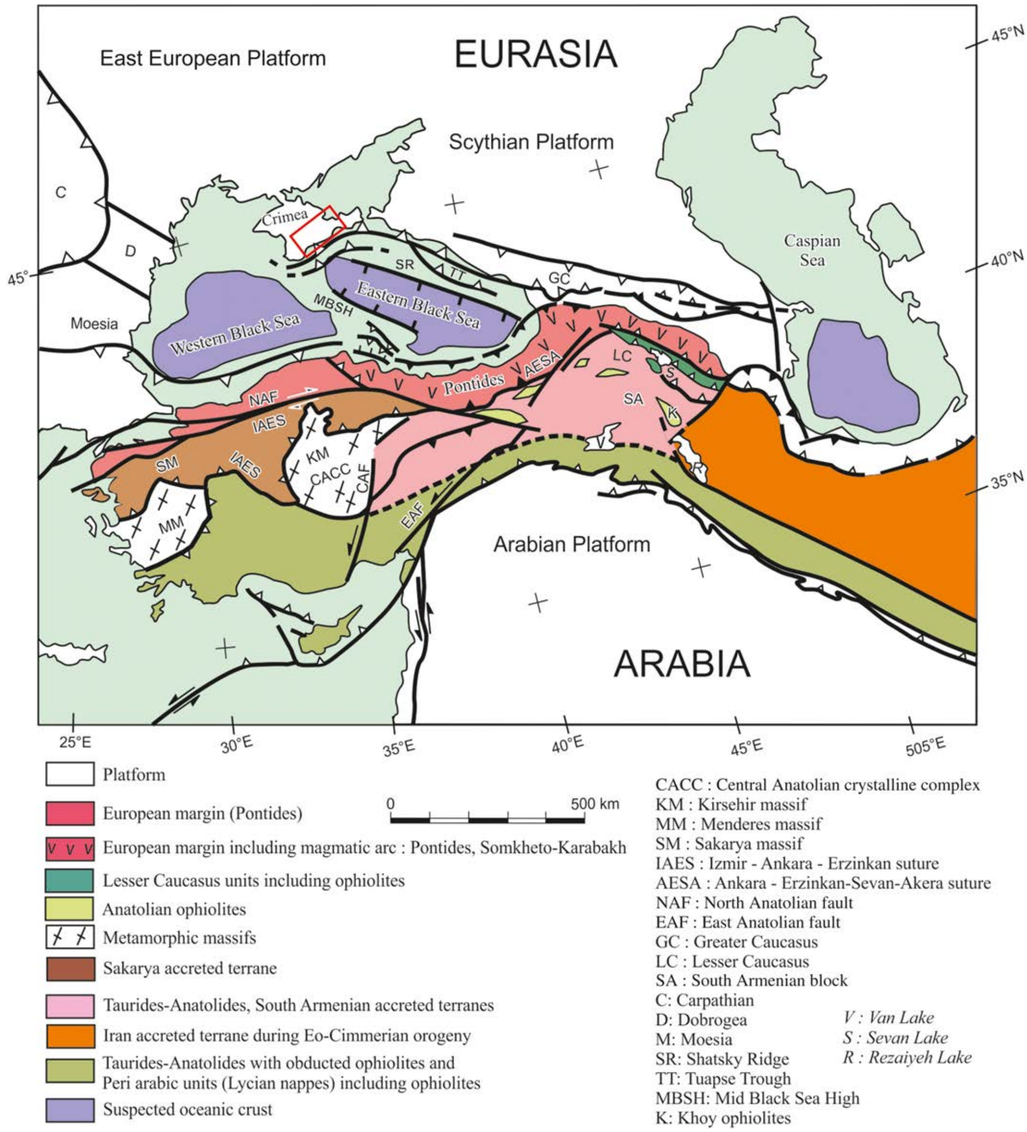

Fig. 1. Structural sketch map of the Alpine belt in the Middle East *sensu lato* Sosson *et al.* (2010). The location of the study area is shown as a red rectangle.

related to the question of the location of the Tauric flysch, questions about the age of the flysch-like rocks and, as a consequence, a lack of definition of their thickness. Also, all the flysch-like rocks are deformed mainly southwards and the lack of clarity in the age of the sediments does not help in establishing the timing of deformation.

Recent work has proposed a revision of the Triassic, Jurassic and, partly, Lower Cretaceous flysch-like rocks to an Albian age (Popadyuk *et al.* 2013*a*, *b*, 2014). This proposal was reflected in a new geological map of the Crimea, which has generated a great deal of controversy (e.g. Yudin *et al.* 2015).

Our study aimed to resolve several problems, namely: (1) the dating of formations still subject to debate (the Tauric flysch and Mesozoic olistostromal formations); (2) the structural analysis of deformation; and (3) identification of the stages of tectonic evolution.

The first part of the paper reviews the stratigraphy of Eastern Crimea and reveals the main

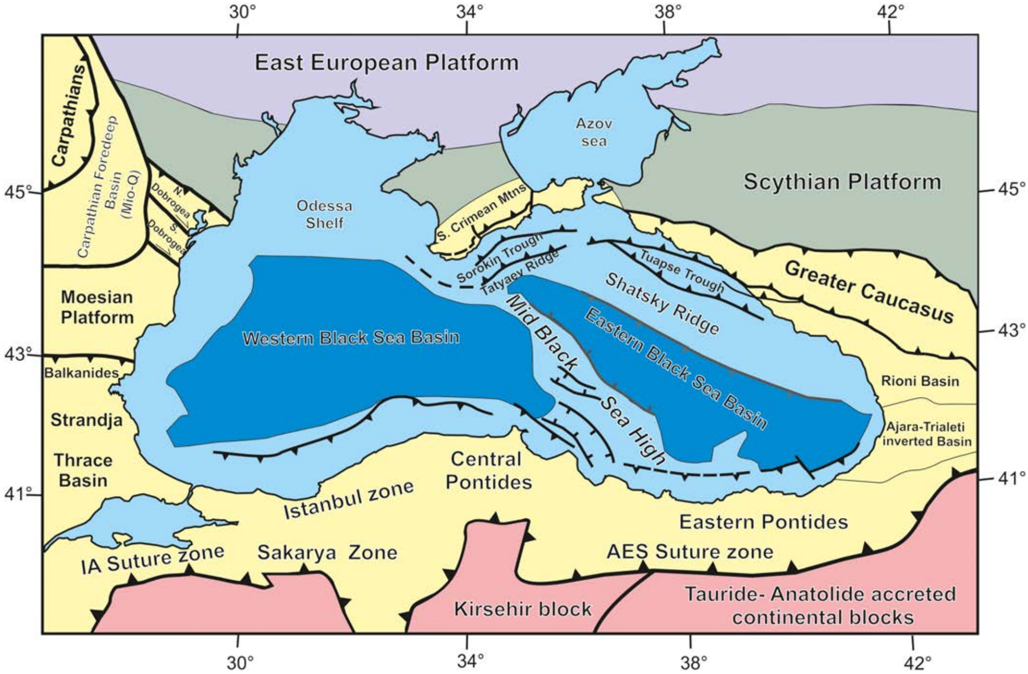

Fig. 2. General structural sketch map of the Black Sea domain, modified from Robinson *et al.* (1996), Okay *et al.* (1994) and Nikishin *et al.* (2015*c*).

problems and key facts that have not been taken into account or not well interpreted in recent studies. These omissions have, consequently, led to incorrect explanations of the tectonic evolution of the southern CM and the Eastern Black Sea Basin. The second part reports our new stratigraphic data and the new dating of sedimentary rocks, including the Tauric Group (TG). These new results, together with a description and analysis of the main structures recognized during fieldwork (the third part of the paper) allow us to propose a new structural map of the Eastern Crimea and to define the main stages of tectonic evolution.

Stratigraphy of Eastern Crimea: a critical review

The ‘classical’ stratigraphic log is presented in this volume by Nikishin *et al.* (2015*c*).

Basement of the Crimea Peninsula

According to borehole data (Muratov 1960; Letavin 1980; Kruglov & Tsypko 1988; Mazarovich & Mileev 1989; Milanovskij 1991; Gerasimov 1994; Afanasenkov *et al.* 2007), Crimea is underlain by Palaeozoic and/or older Eurasian crystalline basement, which could be a part of the Scythian Platform (the thinned margin of the East European Platform, the Ukrainian Crystalline Shield) (Khain 1984; Kruglov & Tsypko 1988; Kazantcev *et al.* 1989; Zonenshain *et al.* 1990; Gorbatchev & Bogdanova 1993; Stephenson *et al.* 2004; Saintot *et al.* 2006; Meijers *et al.* 2010), but the basement does not outcrop on the peninsula. Nevertheless, the oldest rocks were reached by drilling at depths from 500 to 2000 m (bottom). To the east from Simferopol, near the village of Mazanka, drilling has reached from 200 to 400 m depth (bottom) and to the north of Simferopol to a depth of 625 m (Albov 1964). This Precambrian and Palaeozoic basement consists of metamorphic rocks: quartzites, dark graphite–sericite schists and talc–chlorite shales, and marbles intruded by dykes (Muratov 1960; Sidorenko 1969). By drilling in the area of Zuya, an ultramafic complex (talc–chlorite schist) was revealed. These rocks are found as pebbles in the Cretaceous conglomerates on the outskirts of Belogorsk and Staryj Krym. Some Carboniferous and Permian limestone blocks outcrop in the TG around Belogorsk (the village of Velika Karasivka), Staryj Krym and Simferopol (the village of Maryino, south of Simferopol, and the village of Lozovoye) (Muratov 1960; Albov 1964; Dobrovolskaya 1964; Zaika-Novackij *et al.* 1976). Consequently, the Palaeozoic sedimentary rocks on top of the crystalline basement were outcropping during the deposition of the TG (Albov 1964).

Tauric Group

The Palaeozoic sedimentary rocks are unconformably overlain by a succession of thick, dark-coloured and deformed shales with intercalations of turbiditic material in the upper part, which contains blocks of limestones. These formations are called the TG, which is around 1500–2000 m in thickness (Muratov 1960; Astahova 1972, 1976). The TG is generally interpreted as an accretionary prism (Muratov 1960; Koronovskij & Mileev 1974; Khain 1984; Muratov *et al.* 1984; Afanasenkov *et al.* 2007; Meijers *et al.* 2010). The lithology is clearly characterized by detritic sequences (Muratov 1960; Shalimov 1960; Zaika-Novackij *et al.* 1976; Chernov 1981; Aspisov & Kostenko 1982; Panov *et al.* 2001; Bragin & Kuznetsova 2004; Ippolitov *et al.* 2008) (Fig. 3). The age of the TG is still unsolved. Evidence of Late Triassic and Early Jurassic age has been found: rare *Monotis decussata*: *Avicula decussata* (Dubois de Montpereaux 1837, 1843); *Pseudomonotis ochotica* Tell (Foht 1901, 1911); and *Pseudomonotis ochotica* (Keyserl) Tell (Milkevich 1902). The whole history of this Triassic–Early Jurassic palaeontological research has been described by Foht (1901), Moiseev (1932), Muratov (1960), Kazakova (1962), Astahova (1972, 1976 and references cited therein), Chernov (1981), Klikushyn (1988) and Okay *et al.* (2015).

According to some studies, the TG is younger, from Late Jurassic to Early Cretaceous, on the basis of the following observations:

(1) some blocks of volcanic rocks (presumably of Bajocian–Bathonian or Callovian age) were found in shales of a very dark colour (TG) in Lozovoye quarry (Zaika-Novackij 1981; Zaika-Novackij & Solov'ev 1988; Spiridonov *et al*. 1990*a*, *b*);
(2) in some places, the TG contains blocks of limestones of latest Triassic (Korchagin *et al.* 2003) and Early Jurassic (Kazantcev *et al.* 1989; Ippolitov *et al.* 2008) age;
(3) Triassic fauna selected from flysch are suggested to have been reworked (Spiridonov *et al*. 1990*a*, *b*; Popadyuk *et al.* 2013*a*);
(4) ammonites of Early Cretaceous age (Barremian–Aptian) were found in a limestone block inside the TG near Simferopol (Dehtyareva *et al.* 1978; Popadyuk & Smirnov 1991);
(5) Cenomanian foraminifers (*Guembelina cenomanica* Agal.) were found in the TG from depths of 94–200 m (Mender well) via drilling close to Prohladnoye and Bahchisaray (western Crimea) (Yanin 1976; Popadyuk *et al.* 2013*a*); and
(6) foraminifer assemblages of Albian age have been identified (Popadyuk *et al.* 2013*a*, *b*) in the siliciclastic sediments assumed to belong to the TG (Late Triassic–Early Jurassic age frame).

The age of deformation is also in doubt. Plahotnyj (1990) and Afanasenkov *et al.* (2007) assumed that 'some orogenic event was taken place between Triassic and Jurassic'. Yudin (2009) and Yudin & Yurovskiy (2011) suggest a period of compression at the end of the Early Jurassic after the deposition of clastic Tauric rocks.

Even if Triassic sediments are present in the Crimea, the outcrops of probable Triassic age seem very limited in space, except the region in the western CM with *Monotis* (Okay *et al.* 2015). There are several reasons why the TG was assumed to have more spatial frames:

(1) siliciclastic sediments contain rare fossils, which could be reworked (Lalomov 2001);
(2) the geological affixment is not always clearly ascribed in earlier studies, which creates difficulties in correlation between outcrops of flysch formations (Astahova 1972; Kazantcev *et al.* 1989; Mileev *et al.* 2004);
(3) the similarities in lithology (between the TG and younger flysch-like rocks) do not allow the distinct delineation of the locations at which the TG occurs (Favre 1877; Muratov 1960; Dovgal' & Zagorodnjuk 1985);
(4) approximately from the time of Muratov, there have been many studies that are not generalized – instead, different geological schools have worked with their own stratigraphic charts (Mikluho-Maklay & Porshnyakov 1954; Muratov 1960; Astahova 1972, 1976; Mileev *et al.* 2006; Stafeev *et al.* 2009; Yudin 2009; Yudin & Yurovskiy 2011), which has complicated synthesis with new research; and
(5) the TG is highly deformed by folding (very often of south vergence) and faulting, which complicate the characterization of the members, formations, groups and stratotypes of these rocks (Astahova 1972, 1976; Byzova 1980; Kazantcev *et al.* 1989; Saintot *et al.* 1999; Yudin & Yurovskiy 2011).

Middle Jurassic

The similarities between the TG and middle Jurassic detrital formations were mentioned by Favre (1877) and Muratov (1960). Muratov (1960) noticed that they could be distinguished only by colour. The middle Jurassic rocks are composed of siliciclastic

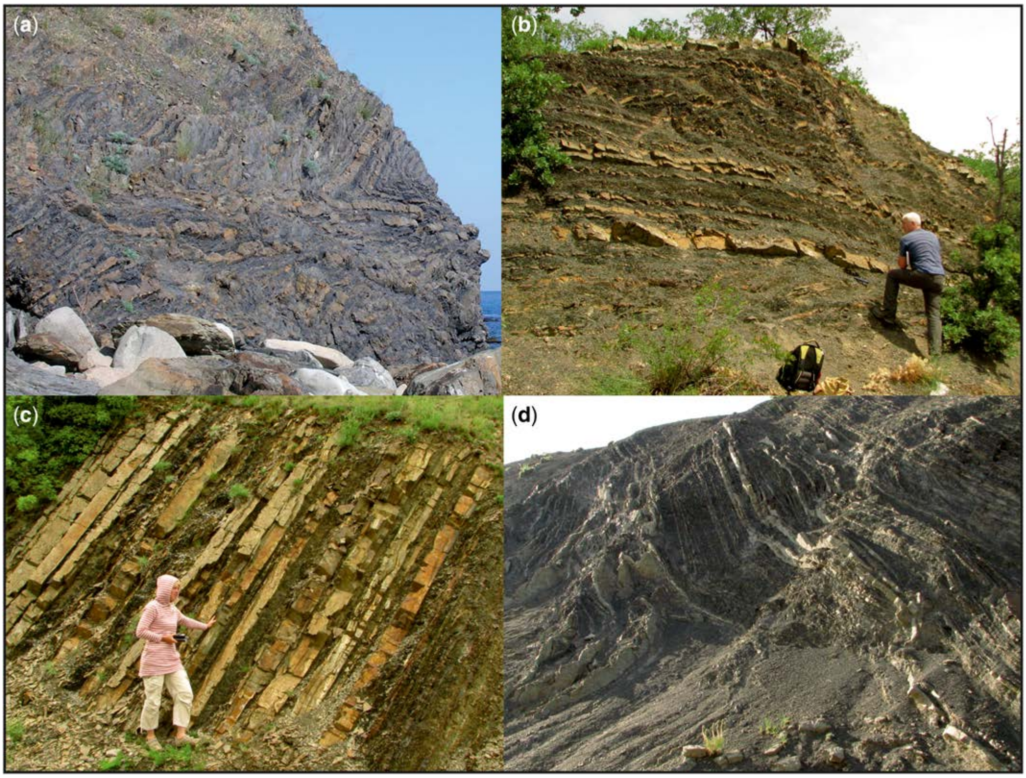

Fig. 3. Examples of the Tauric Group (TG). (**a**) Folding along the Crimean coast close to Cape Ayu-Dag, Arteck International Rest Camp, Gurzuf-Yalta (Western Crimea). (**b**) The TG close to the village of Izobilnoe, north of Alushta. (**c**) Beds of the TG to the north of the village of Privetnoye. (**d**) Shales of the TG along the road between the villages of Morskoye and Veseloye.

sediments (turbidites), dominated by sandstones in the upper part (Muratov *et al.* 1984; Lalomov 2007). They are characterized by rapid lateral changes (Muratov 1960; Dovgal' & Zagorodnjuk 1985; Slavin 1986, Afanasenkov *et al.* 2007). Nevertheless, the age of the sediments is uncertain, because:

(1) as suggested by Popadyuk & Smirnov (1991), the age was obtained on the basis of very few samples of ammonites, which may indicate the redeposition of these ammonites into the flysch, especially as it contains blocks of limestone of different ages;

(2) Byzova (1980) and Afanasenkov *et al.* (2007) provide a Middle Jurassic age (Aalenian–Early Bajocian) for the molasses of the Beshuy depression and Bitak basin (outcrop near the dam of Salgir water pool, south of Simferopol) (Fig. 4), but Yudin (2009) and Yudin & Yurovskiy (2011) proposed a Late Jurassic age for the Bitak and Demerji (Alushta region) formations;

(3) substantial quantities of crinoids of Late Jurassic and Early Cretaceous age have been gathered in some localities of Middle Jurassic outcrops (Arendt 1974) (eastern and northern CM) – also, Upper Cretaceous ferns were found in outcrops in the valley of the river Belbek (Teslenko 1991), although these observations were not convincing enough to revise the age of the rocks.

The Middle Jurassic was a period of magmatic activity in the CM (Dubois de Montpereaux 1843; Sludskij 1917; Muratov 1960; Lebedinskij & Shalimov 1967; Zolotarev 1968; Yamnychenko 1969; Nikitina *et al.* 1979; Zaika-Novackij 1981; Leshchuh *et al.* 1999; Afanasenkov *et al.* 2007). The most active phase of volcanic activity was the Middle Jurassic system, which includes the Early Bajocian Pervomaysko-Ayudag intrusive complex and the Late Bajocian Bodrak-Karadag volcanic unit and the Bodrak subvolcanic complex (Muratov 1960; Kazantcev *et al.* 1989; Spiridonov *et al.* 1990*a*, *b*; Teslenko & Yanovskaya 1990; Dovgal'

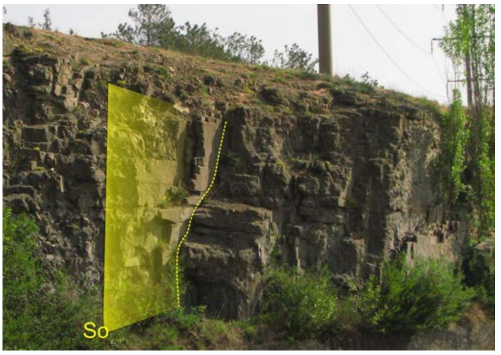

Fig. 4. Conglomerates of the Bitak Formation (near the dam of Salgir water pool, south of Simferopol). The age is under debate (Middle? or Upper? Jurassic).

et al. 1991; Leshchuh *et al.* 1999). Based on $^{40}Ar/^{39}Ar$ dating and the geochemical analysis of magmatic rocks in the central and eastern CM, Meijers *et al.* (2010) defined two age groups: an older (Middle–Late Jurassic age, *c.* 172–158 Ma in the Bodrak–Simferopol area) and a younger (latest Jurassic–Early Cretaceous age, *c.* 151–142 Ma in the Karadag massif). According to major and trace element analyses, these two groups could correspond to a magmatic arc setting related to northwards subduction below the Eurasian margin (Meijers *et al.* 2010).

As well as the TG, Middle Jurassic flysch-like rocks are folded and thickened by thrusts (Baraboshkin *et al.* 2004; Mileev *et al.* 2004; Yudin & Yurovskiy 2011). Plahotnyj (1990) and Afanasenkov *et al.* (2007) identified three Middle Jurassic phases of compressional deformation dated mainly by unconformities. However, Yudin & Yurovskiy (2011) interpreted these unconformities in Triassic–Jurassic flysch-like rocks as tectonic contacts in so-called mélanges. Consequently, it is clear that the stratigraphy of the region needs to be revised in the context of a structural analysis.

Late Jurassic

The Upper Jurassic series is characterized by quick lateral facies changes: conglomerates, sandstones, siltstones, large reef limestones (which form the chain of the highest peaks in the CM, the Main Ridge), limestone breccias and flysch-like rocks (Muratov 1960; Himshiashvili 1967; Tkachuk 1970; Lysenko & Janin 1979; Paryshev *et al.* 1979; Kazantcev *et al.* 1989; Arkad'ev & Rogov 2006; Afanasenkov *et al.* 2007) (Fig. 5). The thickness of the Upper Jurassic formations differs from area to area in the south of the CM: in the Sudak region it is assumed to reach 3–4 km, whereas in the northern part it is just a couple of hundred metres (Himshiashvili 1967; Lysenko & Janin 1979; Rogov 2004; Afanasenkov *et al.* 2007).

The Oxfordian mostly corresponds to a transgressive series capped by huge reefal limestones (Karlov 1963; Kazantcev *et al.* 1989; Robinson & Kerusov 1997; Mileev *et al.* 2004) (Fig. 5a). The reef limestones of the Main Ridge of the eastern CM were dated as Kimmeridgian–Tithonian by macrofauna (Muratov 1960; Sidorenko 1969; Lysenko & Janin 1979) (Fig. 5b). They are massive (up to 2500 m) platform limestones and carbonated breccia (Dolgorukovskaya Yayla, Chatyr-Dag, Demerji Yayla, Karabi Yayla, Agarmysh, Staryj Krym and Belogorsk) (Muratov 1960; Andruhovich & Turov 2002). Nevertheless, in the Karabi Yayla massif, according to palaeontological analyses, the lower part is of late Tithonian–early Berriasian age (Andruhovich & Turov 2002). The reef limestones are deformed: folded and thrust mostly in a southerly direction (Byzova 1980; Saintot *et al.* 1999; Yudin 2009; Yudin & Yurovskiy 2011).

According to most researchers, the conglomerates (100–800 m in thickness) within the flysch-like sediments between Feodosiya and Karabi Yayla range differently from Kimmeridgian to Berriasian in age (Tkachuk 1970; Andreev *et al.* 1993; Arkad'ev & Rogov 2006). This formation outcrops along a narrow zone of 75 km length (from Alushta to Cape Kiik-Atlama) (Arkad'ev & Rogov 2006; Yudin *et al.* 2015) and unconformably covers the Oxfordian and the TG (Muratov 1960; Arkad'ev 2007) (Fig. 5c). These conglomerates evolved vertically to rhythmic detrital layers alternating with carbonated breccia and siderites, sometimes with large lenses of limestones (blocks?); sometimes they change to clays containing lenses of white limestone (Muratov 1960; Arkad'ev 2007).

The Demerji conglomerates (>1000 m in thickness) unconformably overlie the siliciclastic formations present in the Alushta region and in the valley between Chatyr-Dag and Demerji Yaylas. These siliciclastic formations are reported by the majority of researchers to be part of the TG (Muratov 1960; Chernov 1963; Piskunov *et al.* 2012) (Figs 5d & 6). For others, this formation consists of Middle Jurassic flysch-like sediments (Andruhovich & Turov 2002). The precise age of the Demerji conglomerates is under debate. The age range is from late Middle Jurassic to latest Jurassic (Callovian) (Lalomov 2003), from Callovian to Tithonian (Andreev *et al.* 1993; Yudin & Yurovskiy 2011), Oxfordian (Chernov 1963; Geology of USSR 1969; Chernov 1971; Andruhovich & Turov 2002), Kimmeridgian–Tithonian (Lebedinskij & Dobrovolskaya 1965) and Kimmeridgian–Early Tithonian (Piskunov *et al.* 2012).

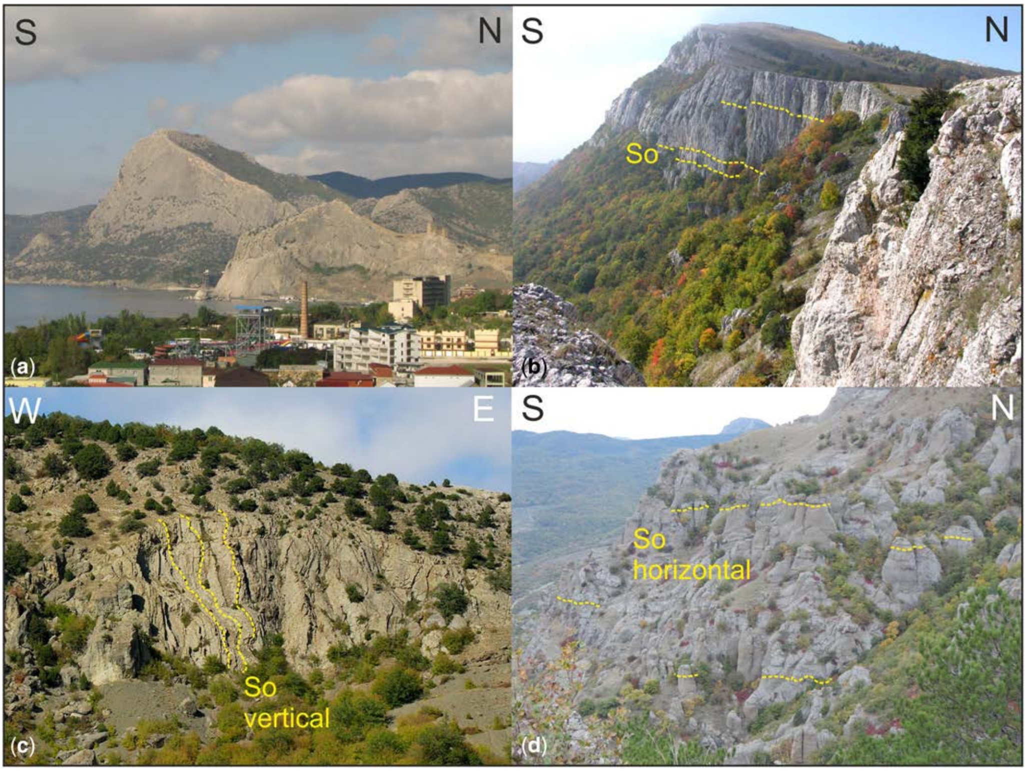

Fig. 5. Examples of Upper Jurassic rocks. (**a**) Huge reefal limestones of Oxfordian age in the outskirts of Sudak. (**b**) Massive platform limestones and carbonated breccia of Karabi Yayla (Tithonian–Berriasian). (**c**) Conglomerates with vertical bedding (age range from Kimmeridgian to Berriasian) (north of Vesele). (**d**) Upper Jurassic (according to the majority of researchers) conglomerates of South Demerji.

The conglomerates correspond to a huge alluvial fan produced by erosion of a southwestwards located region and/or delta deposition (Chernov 1963; Sidorenko 1969; Bragin & Aristov 2008; Piskunov *et al.* 2012). Some siliceous pebbles are Carboniferous (Tournaisian) in age (Bragin & Aristov 2008). The sediments of this age are widespread in the western and central Pontides (Turkey), which has been suggested as a sediment supply area (Bragin & Aristov 2008). Chernov (1963, 1971), in a detailed study of the composition of the conglomerates (granite, basalt, white quartz, sandstones of the TG and numerous limestone pebbles), noted that they differ from the other conglomerates of Late Jurassic age in Eastern Crimea. They may be evidence of basement erosion, probably of the Ukrainian Crystalline Shield (Lalomov 2003), and can be divided into two sedimentary units: a Lower Unit, with mostly granite pebbles, and an Upper Unit with Upper Jurassic rock pebbles and blocks (Chernov 1963, with reference to Lagorio 1894). Eastwards the conglomerate contains smaller clasts. Yudin & Yurovskiy (2011) described the Demerji conglomerates as molasse of the same age as the Bitak Formation (Upper Jurassic conglomerates in the Simferopol region). It follows that the Demerji conglomerates have to be taken into account in the description of the tectonic stages of the CM in this paper.

Early Cretaceous

According to Muratov (1960), Lysenko & Janin (1979), Gorbachik & Yanin (1998), Arkad'ev (2007) and Nikishin *et al.* (2013), the contact between Lower Cretaceous rocks and Tithonian limestones is clearly visible. It is difficult to identify this contact to the east from the Main Ridge of the CM as a result of the similarities of the flysch-like facies (in the region of Feodosiya, Grushevka and south of Belogorsk) in Upper Jurassic and Lower Cretaceous rocks.

Similar to the older formations, the Early Cretaceous is composed of facies that change from west to east (eastern CM) (Muratov 1960; Gorn 1974; Lysenko & Janin 1979; Arkad'ev 2007). In the

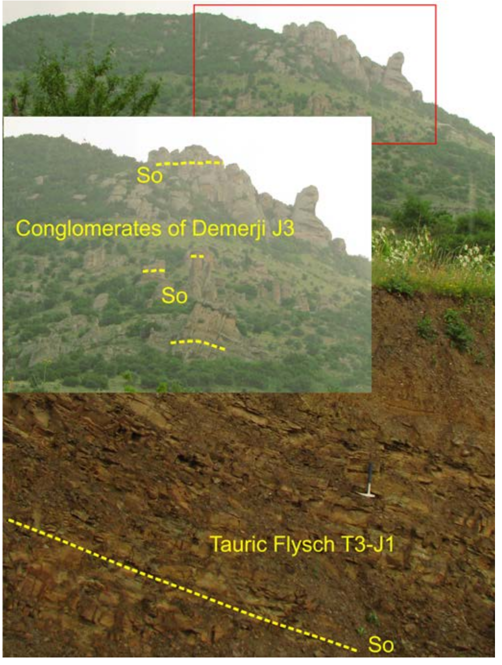

Fig. 6. The unconformity of Upper Jurassic conglomerates with flysch of the Tauric Group (South Demerji massif). S_0 (bedding surface) is horizontal in the conglomerates and dips in a southerly direction in the Tauric Group.

western region and in the area of the foothill ridge (north of the CM), the Lower Cretaceous formations are characterized by sediments of shallow marine depositional environments (limestones, limestone breccia and sandstones). To the east from the Main Ridge, sediments of deep marine facies are dominant: clays, turbidites and reworked material from older flysch formations (Muratov 1960; Himshiashvili 1967; Tkachuk 1970; Paryshev *et al.* 1979; Byzova 1980; Ivanik *et al.* 2013). Part of these turbidites consists of olistostromes with olistoliths of Upper Jurassic limestones, surrounded by conglomerates, in a Lower Cretaceous matrix (Byzova 1980; Kazantcev *et al.* 1989, and references cited therein; Dobrovolskaya & Salman 2008; Ivanik *et al.* 2013).

The Early Cretaceous sequence varies in thickness from 260 m in the western part (Lysenko & Janin 1979) to up to 1000 m in the east (Zaika-Novackij *et al.* 1976; Dobrovolskaya & Salman 2008; van Otterloo 2008).

As a result of rapid facies changes both in time and laterally (conglomerate, cross-bedded sandstones and reefal limestone), some researchers have assumed sea-level fluctuations (transgression–regression cycles) (Muratov 1960; Lysenko & Janin 1979; Gorbachik & Yanin 1998), while others (Lysenko & Janin 1979; Yudin 2013) suggested probable vertical motions before deposition of the Hauterivian, which is marked as an unconformity. The Hauterivian unconformably rests on the black shales of the presumed TG (in the Simferopol area) and on Middle Jurassic pillow lavas and massive flows (at Petropavlovskiy quarry) (Fig. 7).

The division of Early Cretaceous strata into formations is still poorly organized. Different researchers have defined formations as various ages, very often at the same place. The relationships between and the succession of formations are also interpreted differently (Arkad'ev 2007; Ivanik *et al.* 2013; Yudin *et al.* 2015). A good example of this is the conglomerate formation cropping out close to Staryj Krym (Fig. 8). On the analysis of pebbles and some structural reconstruction, the age of these conglomerates was Hauterivian for Muratov (1960), but Berriasian for Arkad'ev (2007). The second example is the flysch-like rocks in the Tonasu River. As described in earlier sources, this flysch is considered to be Tithonian (Muratov 1960; Himshiashvili 1967; Tkachuk 1970; Paryshev *et al.* 1979); more recent work (Arkad'ev 2007) refers to it as the thicker flysch unit of Berriasian age (Fig. 9). Dobrovolskaya & Salman (2008) described this formation, partly, as Valanginian–Hauterivian clay flysch containing a thick olistostrome with large olistoliths of Upper Jurassic limestones sliding down along a Berriasian slope and cemented within the Valanginian–Hauterivian clays.

Another example is the age of the Dvuyakornaya Formation (Feodosiya and its southern outskirts), which, for Arkad'ev *et al.* (2012) and Guzhykov *et al.* (2012), represents the full section, based on ammonites, of the stratigraphic boundary between upper Tithonian and lower Berriasian carbonate sediments. However, according to the analysis of forams and tintinnids (Ivanik *et al.* 2013), the age of mudstones around the limestones with ammonites is Late Cretaceous. Ivanik *et al.* (2013) explained the carbonated well-dated bodies (Tithonian–Berriasian) as olistoliths in olistostromes that began to form at the end of the Early Cretaceous. The same problem with the age of sediments occurs with flysch-like rocks close to Koktebel, which, on geological maps (Geology of USSR 1969; Pivovarov & Derenyuk 1984) are shown as Middle Jurassic flysch-like rocks, but are Albian according to Popadyuk & Smirnov (1991). In addition, an Albian age has been obtained on the basis of foraminifer assemblages in the formation attributed to the majority of flysch-like rocks of the CM (Popadyuk *et al.* 2013*a*, *b*). Consequently, there is an obvious problem in estimating the thickness of different formations and members of Early Cretaceous age, as well as the dating of other flysch-like rocks, that needs to be solved.

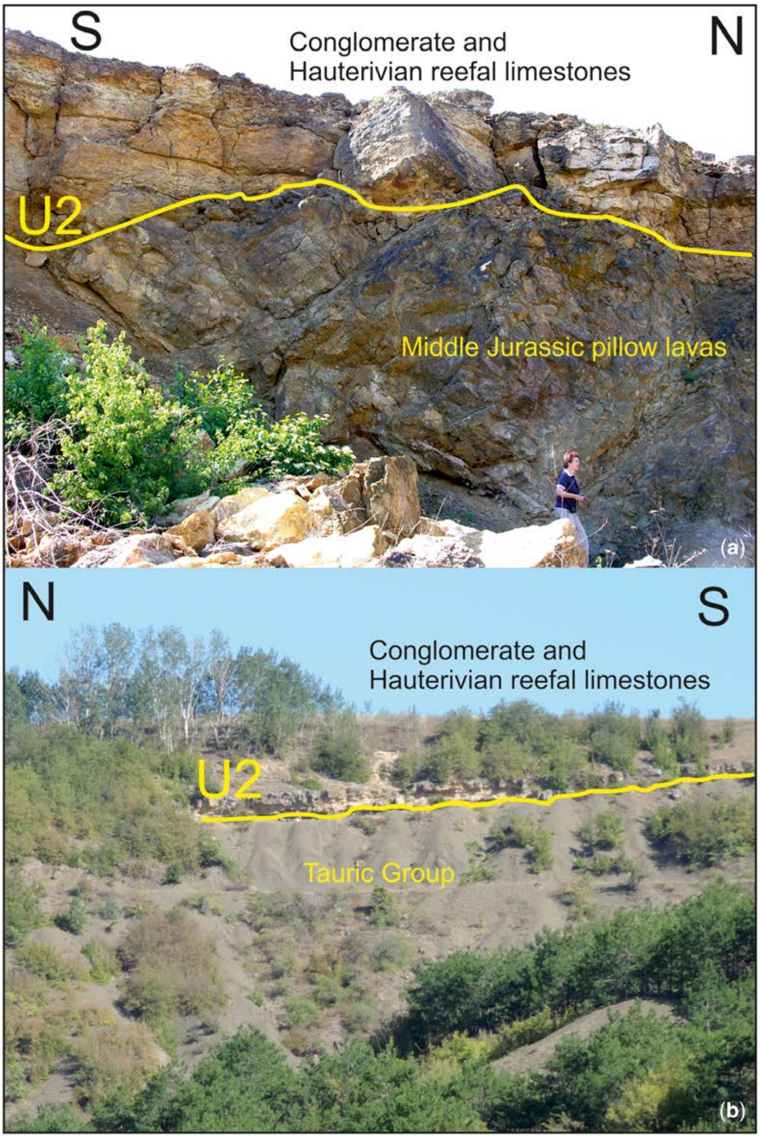

Fig. 7. The Hauterivian unconformity (labelled U2). (**a**) Hauterivian sandy limestones unconformably overlying Middle Jurassic pillow lavas and massive flows (Petropavlovskiy quarry, SW of Simferopol). (**b**) Hauterivian sandy limestones unconformably overlying black shales of the Tauric Group (village of Prohladnoye, western Crimea).

In the northern part of Eastern Crimea, clay deposits dominate in the Hauterivian through to the Barremian–middle Albian. Clays are observed from the Kacha to Big Salgir valleys (Gorn 1974). Barremian–Albian clays disconformably overlie the Hauterivian deposits (Gorn 1974; Lysenko & Janin 1979). The lithology of Barremian, Aptian and Albian clays is very homogeneous, but macrofauna are scarce (Fig. 10).

The Albian succession consists of conglomerate and coarse-grained sandstone beds at the base, thinning upwards to marl and finally black shales with siderite concretions towards the top. These strata have been interpreted to be deposited in a deepening marine basin (5.0 m–1.0 km), consisting of half-graben (Zaika-Novackij *et al.* 1976; van Otterloo 2008; Nikishin *et al.* 2013). The middle to upper Albian deposits do not form continuous layers and

Fig. 8. Conglomerates to the north of Staryi Krym (the age is under debate, see text for explanation).

unconformably overlie the Upper Jurassic rocks (Nikishin *et al.* 2013).

Volcanoclastic sediments of Late Albian age crop out in several areas in western Crimea (Nikishin *et al.* 2013). Evidence of volcanism of this age has been found in southern Crimea (Shnjukova *et al.* 1992; Nikishin *et al.* 2013).

There is also some debate about the age and style of deformation of the Lower Cretaceous rocks. For some researchers (Zaika-Novackij 1981; Afanasenkov *et al.* 2007), the Callovian–early Berriasian was a period of rifting climaxing in the Aptian–Albian or, according to Nikishin *et al.* (2015*a*, *b*, and references cited therein), during the Barremian–Albian; for Yudin & Yurovskiy (2011), a period of convergence started in latest Early Jurassic and continued throughout the Early Cretaceous.

Late Cretaceous

In the eastern CM, the Upper Cretaceous succession unconformably overlies those of the Lower Cretaceous (Muratov 1960; Zaika-Novackij *et al.* 1976; Alekseyev *et al.* 2005; Nikishin *et al.* 2013). It contains a rich fauna of belemnites, inocerams, nannoplankton, and planktonic and benthic foraminifers (Alekseyev *et al.* 2005). Upper Cretaceous sediments (thickness about 1850 m) spread to the north from the CM; they also cover the Crimean platform and are absent only in the area between Simferopol and Zuya (Muratov 1960). Cenomanian rocks (in the western CM) rest unconformably over upper Albian rocks (Muratov 1960).

The Late Cretaceous sequence of the Crimea is mostly characterized by chalky limestones (containing nodules of silex and marcasite), marls and sandy marls (Muratov 1960). Cenomanian–Campanian strata contain volcanic ashes, which could be evidence of rift-related volcanic activity starting during the Albian (Nikishin *et al.* 2013). Gaps in sedimentation occur in the early Turonian and the early Santonian (Zaika-Novackij *et al.* 1976). Late Santonian rocks disconformably overlie older sediments (Nikishin *et al.* 2015*a*, *b*).

Palaeogene

Palaeogene rocks cover all of the flat Crimea and Kerch peninsulas and form the foothill ridge and the outer ridge (Muratov 1960). In the eastern CM, Paleocene sandstones rest over an erosional surface of middle Maastrichtian marls. The lower Paleocene series is composed of sandy marls or carbonated sandstones (in the region of Belogorsk and Feodosiya), with lenses of limestone breccia with crinoids. The upper part of the Paleocene section is composed of glauconitic sandstones, which change to yellowish dense, coarse limestones or marls or carbonated marls with lenses of limestones (Muratov 1960; Bugrova *et al.* 2002). In the area of Mazanka, the Palaeogene sequence is composed of grey and black clays overlain by glauconitic clays (3 m of thickness) with small Eocene nummulites. The top of the section consists of nummulitic limestones of Middle Eocene age (Lysenko & Janin 1979).

There are two main unconformities in the Palaeogene: one at the base of the early Paleocene and the other at the base of the Middle Eocene. Middle Eocene massive nummulitic limestones unconformably cover older rocks (Naydin & Benyamovskiy 1994; Afanasenkov *et al.* 2007) (Fig. 11).

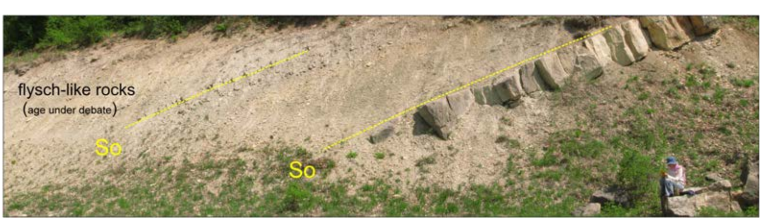

Fig. 9. The flysch-like strata in the Tonasu river basin. The age and origin of these beds is a matter of debate, as is the bedding surface.

Fig. 10. Albian clays, Kilovskiy quarry, Simferopol area.

Upper Oligocene and Lower Miocene strata consist of a thick formation of grey and chocolate-coloured to reddish clays with siderite concretions and gypsum, named the 'Maykopian' (Maykop Formation). These series unconformably overlie the Middle Eocene nummulitic limestones (Muratov 1960; Afanasenkov *et al.* 2007; van Otterloo 2008; Nikishin *et al.* 2015*a*, *b*). This is the third main unconformity in the Palaeogene section of the southern CM.

Neogene

Neogene strata occur mainly in flat Crimea and the Kerch Peninsula. They include the upper part of the Maykop Formation (Early Miocene) and Middle and Upper Miocene and Pliocene formations (Muratov 1960). They are composed of sands, sandstones and sandy limestones with freshwater gastropods (the areas of Zuya, Belogorsk and Simferopol) (Muratov 1960).

Some researchers considered that there was a disconformity (Chockrak Formation) between the Early and Middle Miocene (Nevesskaja *et al.* 2003). Barg (2008) suggested a gap in sedimentation here due to a Middle Miocene tectonic event. The Middle Miocene (the Chockrak Karaganskiy and Konskiy

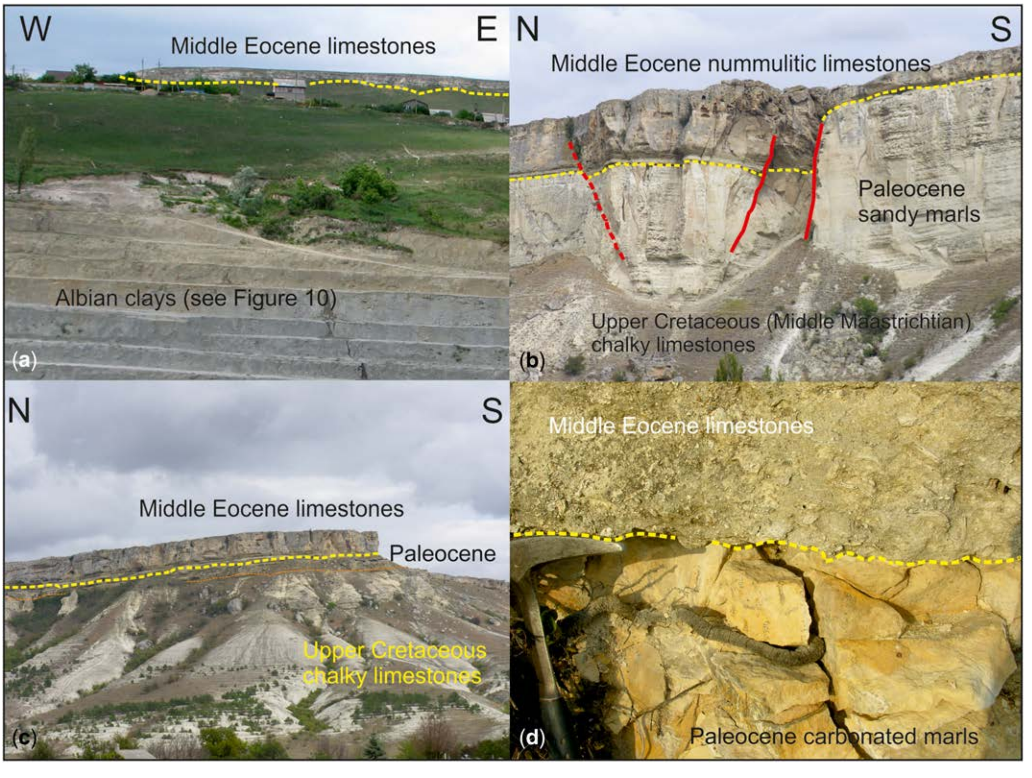

Fig. 11. The unconformity of the Middle Eocene nummulitic limestones (labelled U6, dashed yellow line on photographs) with (**a**) Albian clays (Kilovskiy quarry, Simferopol) and (**b, c**) Paleocene–Upper Cretaceous chalky limestones and marls (Belaya Skala Mountain, Belogorsk). (**d**) Middle Eocene nummulitic limestones on top of Paleocene terrigenous rocks (sandy marls, carbonated sandstones) to the east of Zuya.

formations) is widely represented in the southern CM (Muratov 1960); in western Crimea the Middle Miocene unconformably overlies older rocks (from the middle Jurassic to Oligocene).

There is an erosional surface between the Sarmatian and Maeotian (intra-Tortonian) (Muratov 1960). The lower Pliocene series (terrestrial loams, clays and gravels) completes the Neogene section in the eastern CM.

Main questions about the stratigraphy of Eastern Crimea

Based on these arguments, the best way to clarify the geological setting and to drive a new generation of detailed geological studies in the region is to solve the following stratigraphic problems.

(1) The first and the foremost question that needs attention is the age of the siliciclastic formation beneath the Upper Jurassic–Lower Cretaceous limestones forming the Main Ridge of the CM: are these Triassic–Late Jurassic or Early Cretaceous?

(2) If Early Cretaceous, then the second main question arises: what is the origin of the Upper Jurassic–Lower Cretaceous platform carbonates? Can they be explained as allochthonous and, consequently, in tectonic contact with the flysch formation below (Popadyuk 2011; Popadyuk *et al.* 2013*a*, *b*; 2014)? If so, then there is no evidence of the Cimmerian Orogeny in the eastern CM, as was assumed by Popadyuk *et al.* (2010).

(3) All of the flysch formations are characterized by strong localized deformations, well expressed as folds and faults of mostly south vergence (Byzova 1980; Saintot *et al.* 1999). In order to date the age of deformation and to investigate the origin of the flysch (did deformation occur during Cenozoic shortening or before, during the Late Cretaceous, and are the flyschs related to a back-arc basin or linked to an accretionary prism?), the age of deposition needs to be determined more precisely as it is a key to the reconstruction of the tectonic evolution of the Crimea region.

New palaeontological and stratigraphic results

The eastern CM were sampled during 2012–2014 (352 samples in different stratigraphic levels) (Fig. 12). These samples were analysed for nannoplankton assemblages. Only 82 samples allowed a determination of age, with Early Cretaceous being found for 60 sites (Fig. 12). Many of these ages were from the mapped TG (Late Triassic–Early Jurassic) and from flysch-type sediments previously assigned to the Late and Middle Jurassic (Sheremet *et al.* 2014). The detailed results of the nannoplankton analyses are shown in Tables 1–6 and on the upgraded structural map of this area (Fig. 13), which was compiled according to these new stratigraphic age determinations.

Samples UK01.2012, UK02.2012, UK.20.2012, UA9gm2012 and UA12gm2012 reaffirmed ages assigned by earlier studies, especially those of Late Cretaceous (Table 2) and Cenozoic (Table 1) age in the northern part of the study area. This means that the present results are in accordance with the results obtained from previous palaeontological dating (using macrofauna). Locally, they are also consistent with those obtained by Popadyuk *et al.* (2013*a*, *b*; 2014) (from foraminifer assemblages). According to these researchers, the age of the flysch-like deposits is Albian (Figs 12 & 13). Our new dating indicates a much wider age range for the flysch-type sediments: Berriasian to Barremian ages (Tables 3–6) are common to the flysch-like sediments in the eastern part (Sudak, Novyj Svet, Veseloye, Mezhdurechye, Zelenogorye and Gromovka; see locations on Figs 12 & 13). These formations are characterized by turbidites, conglomerates and olistostromes containing large blocks of Upper Jurassic reefal limestones. Along the coast (between Morskoye and Zelenogorye; samples 22 and 23) and along the Simferopol–Alushta road (to the south of Perevalnoye, Figs 12 & 13, samples 24, 25 and 26), we obtained an Aptian–Albian age for the turbidites (Table 3). The area of Alushta-Rybache, according to published sources cited earlier in this paper, is characterized by Upper Triassic–Middle Jurassic flysch intruded by Bajocian–Bathonian magmatic rocks. Because the flysch samples are barren of nannoplankton, it was decided to interpret the data as shown on the map (Fig. 13). The explanation of how this interpretation was made is given later in this paper.

The nannofossils in barren samples were probably dissolved as a result of a poor environment for preservation. Most of the samples were abundant in volcanic ash partly altered to clay. The volcanoclastic lithology in this unit indicates deposition during a period of intense volcanic activity in the eastern CM during the Early Cretaceous, which is supported by the radiometric dating of Meijers *et al.* (2010) and in the work devoted to Albian–Late Cretaceous rifting in western Crimea by Nikishin *et al.* (2013).

Some nannofossil ages obtained from the eastern part of Karabi Yayla were unexpected. According to previously published stratigraphic descriptions

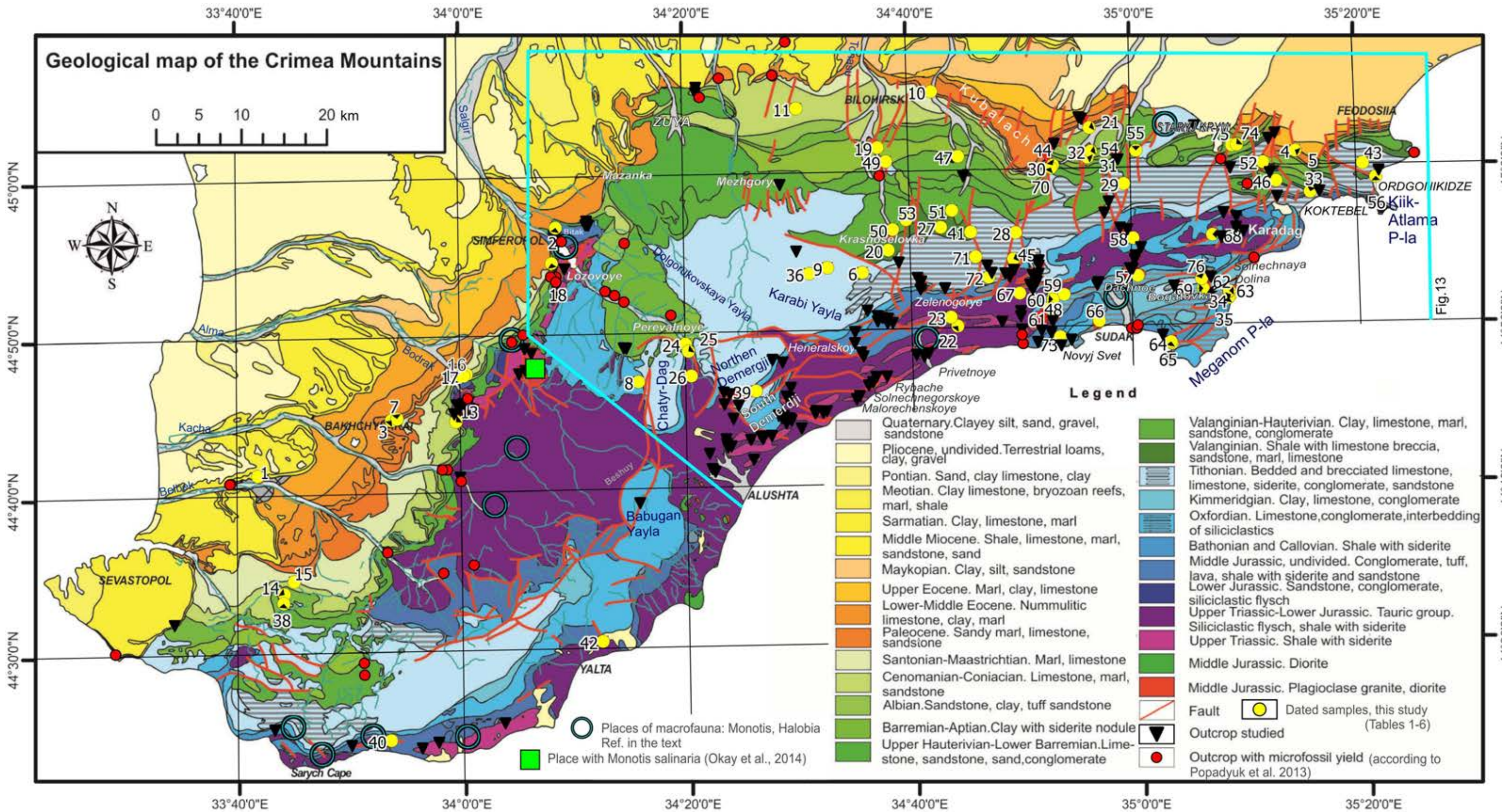

Fig. 12. Geological map of the Crimean Mountains, modified from Muratov (1960) and Popadyuk *et al.* (2013*a*), with locations of new dating of rocks shown with yellow circles (this study; numbers correspond to sample number in Tables 1–6). The red circles indicate locations of Upper Triassic–Jurassic rocks redated by Popadyuk *et al.* (2013*a*, *b*; 2014) as Albian based on foram analysis.

Table 1. *Eocene–Paleocene nannoplankton dating with (WGS84) GPS locations*

Sample number on map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation (m)	Age	Lithology	Nannofossil assemblages
1	Verhnyesadovoye	UK 172012	44° 41.448	33° 41.867	111	Late Eocene NP 19	Mudstones, argillites, sandstones	*Ericsonia subdisticha*, *Reticulofenestra umbilica*, *Dictyococcites dictyadus*, *Coccolithus pelagicus*, *Coccolithus eopelagicus*, *Cyclococcolithus formosus*, *Helicosphaera seminula*, *Isthmolitus recurvus*, *Discoaster taninodifer*, *Discoastesaipanensis*, *Cribrocentrum reticulatum*, *Sphenolithus moriformis*
2	Simferopol	UK 001gm2012	44° 56.752	34° 08.679	316	Early Eocene	Mudstones argillites	*Coccolithus pelagicus*, *Sphenolithus moriformis*, *Cyclococcolithus formosus*, *Sphenolihus radians Toweius tovae, Chiasmolihus solitus*
3	Bakhchysarai	Cr 38 2014	44° 44.817	33° 53.790	579	Late Paleocene NP6	Sandy limestones	*Heliolithus kleinpellii*, *Ericsonia subpertusa Coccolithus pelagicus*, *Cruciplacolithus tenuis*
4	Nanikovo	Cr 22 2014	45° 00.933	35° 14.295	244	Early Paleocene NP2	Sandy limestones	*Coccolithus pelagicus*, *Sphenolithus moriformis Ericsonia subpertusa*, *Cruciplacolithus tenuis*
		Cr 23 2014	45° 00.933	35° 14.295	244	Early Paleocene NP3	Sandy limestones	*Coccolithus pelagicus*, *Chiasmolithus danicus Ericsonia subpertusa*, *Cruciplacolithus tenuis*

Table 2. *Upper Cretaceous Nannoplankton dating with (WGS84) GPS locations*

Sample number on the map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation m	Age	Lithology	Nannofossil assemblages
5	Bakhchysarai	Cr 32 2014 Cr 32a2014	44° 47.529	34° 0.282	347	Early Maastrichtian	White chalky limestones and marls	*Watznaueria barnesae*, *Zygodiscus diplogrammus*, *Parhabdolithus embergi*, *Reinhardtites anthophorus*
6	Karabi yayla	Cr 27 2014	44° 53.655	34° 35.783	882		Sandy grey marls and yellowish sandstones	*Micula staurophora*, *Quadrum gothicum*, *Quadrum trifidum*, *Watznaueria barnesae*, *Ellipsolithus communis*
7	Bakhchysarai	UK 16 2012	44° 44.910	33° 54.304	281		White chalky limestones	*Micula staurophora*, *Gartnerago obliquum*, *Prediscosphaera cretacea*, *Arkhangelskiella cymbiformis*, *Quadrum gothicum*, *Eiffelithus turriseiffeli*
8	Northern Chatyr-Dag	Cr 4b 2014	44° 47.0	34° 15.757	906	Early Maastrichtian–Late Campanian	Sandy reddish argillites	*Quadrum gothicum*
9	Karabi yayla	Cr 26 2014	44° 53.989	34° 32.701	902		Light grey oolithic limestones	*Coccolithus pelagicus*, *Quadrum gothicum*
10	Michurinskoye	UA206gm2012	45° 4.956	34° 42.162	206	Late Campanian	Argillites and sandstones, conglomerates	*Micula staurophora*, *Watznaueria barnesae*, *Broinsonia parca*, *Quadrum gothicum*
11	Belogorsk	Cr 29 2014	45° 04.019	34° 30.192	349		White chalky limestones and marls	*Watznaueria barnesae*, *Quadrum gothicum*, *Ellipsolithus communis*, *Quadrum trifidum*, *Eiffellithus eximius*
12	Trudolyubovka	Cr 30 2014	44° 47.627	34° 00.520	397		Light yellow limestones and marls	*Watznaueria barnesae*, *Quadrum gothicum*, *Ellipsolithus communis*, *Quadrum trifidum*, *Eiffellithus eximius*
13	Prohladnoye	Cr 36 2014	44° 44.691	33° 59.514	496		White limestones and marls	*Watznaueria barnesae*, *Quadrum gothicum*, *Ellipsolithus communis*, *Quadrum trifidum*, *Eiffellithus eximius*
14	Ternovka	Cr 40 2014	44° 34 47.2	33° 44 53.3	189		White marls and limestones	*Eiffellithus eximius*, *Broinsonia parca*, *Watznaueria barnesae*, *Micula staurophora*
15	Kuybishevo	UK 13 2012	44° 34.787	33° 44.888	147	Campanian	White chalky limestones and marls	*Watznaueria barnesae*, *Eiffellithus eximius*, *Micula Staurophora*, *Quadrum sathicum*
16	Trudolyubovka	UK 15 2012	44° 47.629	34° 0.522	370		White chalky limestones and marls	*Coccolithus pelagicus*, *Dictyococcites dictyadus*, *Reticulofenestra umbilica*
17	Trudolyubovka	Cr 31a 2014	44° 47.529	34° 0.282	347	Santonian	Dark yellow sandstones and sandy argillites	*Watznaueria barnesae*, *Marthasterites furcatus*

Table 3. *Late Aptian–Early Barremian nannoplankton dating with (WGS84) GPS locations*

Sample number on the map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation (m)	Age	Lithology	Nannofossil assemblages
18	Simferopol, Kilovskiy quarry	UK_01_2012, UK_02_2012	44° 54.522	34° 8.268	310	Late Aptian–Albian	Grey mudstones	*Watznaueria barnesae*, *Eprolithus floralis*, *Lithraphidites carniolensis* *Nannoconus truitti rectangularis*, *Nannoconus elongates*, *Nannoconus quadrangulus quadrangulus*, *Patlabdolithus angustus*, *Patlabdolithus asper*, *Patlabdolithus infinitus*, *Crucillipsis chiastria*
19	Belogorsk	UK 20 2012	45° 1.480	34° 37.323	223		Shales	*Cyclicargolithus margerellii*, *Watznaueria barnesae*, *Rucinolithus irrerularis*, *Eprolithus floralis*, *Parhabdolithus asper*, *Parhabdolithus embergeri*
20	Krasnosiolovka	UK 21 2012, UK 22 2012 UK 23 2012	44° 55.032	34° 38.103	445		Sandstones, mudstones	*Nannoconus bolerus curtus*, *Nannoconus calpidomorphus*, *Nannoconus regularis*, *Nannoconus quadrangulus quadrangulus*, *Rucinolithus irrerularis*
21	Kurskoye	UA 84.13	45° 02.547	34° 56.131	215	Late Aptian	Grey argillites and marls	*Watznaueria barnesae*, *Elipsolithus communis*, *Manivitella pemmatides*, *Eprolithus flrdanus*, *Parhabdolithus asper*, *Parhabdolithus embergeri*, *Chiastozygus litterarius*, *Rucinolithum irregularis*
22 23	Zelenogorye	UA 36.13 UA 35.13	44° 50.194 44° 50.762	34° 44.138 34° 43.562	114 244		Light brown mudstones and yellowish sandstones	*Eprolithus flralis* *Watznaueria barnesae*, *Corrolithion achylosum*, *Parhabdolithus angustus*
24	Alushta Simferopol	UA 6.13	44° 49.331	34° 19.969	486		Dark grey siltstones and marls	*Chiastozygus litterarius*, *Eproliyhus floralis, Watznaueria barnesae*, *Ellipsolithus communis*, *Corolithion achylosum*, *Cruciellipsis chiastia*, *Parhabdolithus embergeri*, *Parhabdolithus asper*
25	Alushta–Simferopol	UA 5.2013	44° 48.868	34° 20.233	495		Dark grey siltstones and marls	*Watznaueria barnesae*, *Cruciellipsis chiastia*, *Eprolithus floralis*, *Corrolithion achylosum, Parhabdolithus embergeri*, *Parhabdolithus asper*, *Parhabdolithus angustus*, *Rucinolit*, *Ellipsolithus communis*, *laffitei*
26	Angar pass	UA 3.13	44° 47.322	34° 20.449			Dark grey siltstones and marls	*Watznaueria barnesae*, *Eprolithus floralis*
27	Povorotnoye	UA12gm2012	44° 56.429	34° 42.794	481	Barremian	Dark grey mudstones, and thin layers of sandstones	*Watznaueria barnesae*, *Nannoconus colomii*, *Cyclicargolithus margerellii*, *Watznaueria britannica*
28	North of Voron	UA 133.13	44° 56.021	34° 49.421	330	Early Barremian	Marls, argillites, sandstones	*Watznaueria barnesae*, *Ellipsolithus communis*, *Cyglagelosphaera margerellii*, *Nannoconus colomnii*, *Nannoconus kamptnerii*, *Micrantholithus obtusus*, *Calcicalathna oblongata*

and maps (see earlier discussion), the youngest rocks forming the top of the Main Ridge are Late Jurassic–Berriassian in age (e.g. Kuznetcova & Gorbatchik 1985; Andruhovich & Turov 2002). Nevertheless, we observed in this region sandy limestone layers, siltstones and yellowish sandy marls overlying the Upper Jurassic–Berriasian limestones. The ages obtained from this detrital unit are late Campanian and early Maastrichtian (samples Cr.26.14 and Cr.27.14; location 6 and 9, respectively; Table 2, Fig. 13). In the northern CM (Simferopol–Belogorsk–Feodosiya), the Late Cretaceous is characterized by a white chalky limestone with black siliceous concretions. Consequently, these results provide evidence of different facies environments during the Late Cretaceous.

In summary, the ages from the newly dated samples lead to the following assertions about the geological setting.

(1) The Lower Cretaceous sediments have a much wider spatial setting than was previously suggested.
(2) The updated age of the flysch-like rocks to the east from Karabi Yayla to Feodosyia is in agreement with the interpretation of some researchers (e.g. Sokolov, Veber and Moiseev; references cited in Karlov 1963; Popadyuk & Smirnov 1991; Dobrovolskaya & Salman 2008; Popadyuk 2011; Popadyuk *et al.* 2013*a*, *b*; 2014) about a large mass sliding of the Upper Jurassic platform limestones along the slope on the surface of flysch. Thus, as it is possible to see in outcrop, the limestone massifs in the eastern CM (Krasnoselovka, Shebetovka, Povorotnoye, Alekseyevka, Sudak and Veseloye) (Fig. 13) may be olistoliths within the Lower Cretaceous flysch.
(3) The age of conglomerates overlying the flysch in the eastern part of the study area (Upper Jurassic) lies within Lower Cretaceous succession.
(4) The Early Cretaceous age of magmatic rocks intruding the flysch-like series, obtained by Meijers *et al.* (2010) for the Simferopol area (Middle Jurassic) and Karadag massif, is in agreement with our sampling and field data.

Structures and ages of deformation

The timings of deformation in the CM from the Middle Miocene to Recent have been discussed by many researchers: Muratov (1960), Scherba (1978), Byzova (1980), Kazantcev *et al.* (1989), Milanovskij (1991), Mileev *et al.* (1997, 2006), Nikishin *et al.* (1998, 2003, 2015*a*, *b*), Gintov (2005), Afanasenkov *et al.* (2007), Yudin (2009), Yudin & Yurovskiy (2011); Stovba *et al.* (2013), Popadyuk *et al.* (2014).

By summarizing previous research (the stratigraphic review in this paper and cartographic sources) and our newly gathered data (structural sketch map, Fig. 13; stratigraphic logs, Fig. 14; cross-sections, Fig. 15; and structural analysis with stereodiagrams, Fig. 16), three main tectonic units (Upper, Middle and Lower; Fig. 17) and several angular unconformities and disconformities beneath the Maykop Formation (Late Oligocene–early Middle Miocene) can be distinguished in the northern part of Eastern Crimea.

The unconformities and disconformities are in the order listed below (from top to bottom) (Fig. 14):

U6: Middle Eocene angular unconformity within the Upper Unit, clearly seen on top of the Lower Cretaceous, Upper Cretaceous and Paleocene formations (Muratov 1960; Lysenko & Janin 1979; Naydin & Benyamovskiy 1994; Afanasenkov *et al.* 2007);

U5: Early Paleocene angular unconformity on top of Upper Cretaceous carbonates and Lower Cretaceous detrital (north of Koktebel area) and carbonate formations in the northern region (Naydin & Benyamovskiy 1994; Bugrova *et al.* 2002; Afanasenkov *et al.* 2007);

U4: Late Cretaceous disconformity on top of the Albian formations in the northern region (Upper Unit);

U3: Albian disconformity on the lowest Cretaceous limestones and sandstones in the western part of the northern region;

U2: Early Cretaceous disconformity with Upper Jurassic limestones (Upper Unit) (Pivovarov & Derenyuk 1984; Yudin 2009; Yudin & Yurovskiy 2011) and with Middle Jurassic volcanites;

U1?: Upper Jurassic unconformity with the TG (Muratov 1960; Yudin 2009;Yudin & Yurovskiy 2011).

Based on the unconformities, we focused on two main tectonic phases from the Early Cretaceous to Middle Eocene to determine the precise timing of tectonic deformation. The compressional stages occurring after the Middle Eocene have previously been described as only one stage, connected to the main compressional tectonic stage of the Greater Caucasus (e.g. Milanovskij 1991; Nikishin *et al.* 1998, 2003, 2015*a*, *b*; Ershov *et al.* 1999, 2003).

Paleocene–Early Eocene: a compressional tectonic event

As shown on the structural map (Fig. 13) and the schematic stratigraphy logs (Fig. 14), the southern region is mostly composed of siliciclastic sediments and corresponds to a structural unit (Lower Unit) that is overthrust by the older formations of the Upper Unit (Fig. 15, cross-sections B, C and D; Fig. 17).

Table 4. *Barremian–Hauterivian nannoplankton dating with (WGS84) GPS locations*

Sample number on the map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation (m)	Age	Lithology	Nannofossil assemblages
29	Perevalovka	UA23gm2012	44° 59.004	34° 59.084	356	Early Cretaceous, not younger than Barremian	Sandstones and argillites	*Nannoconus colomii*, *Watznaueria barnesae*, *Cyclicargolithus margerellii*, *Conusphaera mexicana*
30	Kubalach	UA 89.13	45° 00.051	34° 52.654	321		Sandy argillites and mudstones	*Watznaueria barnesae*, *Watznaueria britannica*, *Nannoconus colomii*, *Ellipsolithus communis*, *Cyglagellosphaera margerellii*, *Parhabdolithus embergeri*
31	Kurskoye	UK019gm2012	45° 00.675	34° 55.906	246		Black slates, argillites, sandstones	*Watznaueria barnesae*, *Ellipsosphaera communis*, *Nannoconus colomii*, *Watznaueria britannica*
32	Kurskoye	UK021gm2012	45° 01.054	34° 56.210	253		Sandstones, argillites	*Watznaueria barnesae*, *Ellipsosphaera communis*, *Nannoconus colomii*, *Watznaueria britannica*
33	Koktebel	UK029gm2012	44° 57.990	35° 15.872	31		Reddish sandstones and argillites	*Watznaueria barnesae*, *Ellipsosphaera communis*, *Nannoconus colomii*, *Watznaueria britannica*
34	Pribrezhnoye	UK73gm2012	44° 51.914	35° 08.357	47		Sandstones, argillites and mudstones	*Cyglagelosphaera margerellii*, *Watznaueria barnesae*, *Ellipsosphaera communis*
35	Pribrezhnoye	UK76gm2012	44° 51.744	35° 08.172	20		Sandstones, sandy argillites	*Ellipsolithus communis*, *Watznaueria barnesae*, *Cyglagelosphaera margerellii*, *Nannoconus colomii*
36	Karabi yayla	Cr 25 2014	44° 53.640	34° 31.050	872		Light grey limestone	*Nannoconus colomii*, *Watznaueria barnesae*
37	Nanikovo	Cr 18 a 2014	45° 00.235	35° 11.422	81		Grey clay and mudstones, thin layers of sandy marls	*Watznaueria barnesae*, *Cyclicargolithus margerellii*, *Ellipsolithus communis*, *Nannoconus colomii*, *Micrantholithus obtusus*

38	Rodnoye	Cr 41 2014	44° 33.432	33° 43.920	205		Sandstones and argillites	*Cyglagellosphaera margerellii*, *Watznaueria barnesae*, *Nannoconus colomii*
39	Demerji yayla	CR 01 2014	44° 46.320	34° 26.151	1093		Mudstones and sandstones	*Ellipsolithus communis*, *Watznaueria barnesae*, *Nannoconus colomii*
40	Beregovoye (Kastropol)	Cr 50a 2014	44° 24.539	33° 53.066	166	Hauterivian–Early Barremian	Dark grey shales, sandstones, marls	*Ellipsolithus communis*, *Lithraphidites bollii*
41	Povorotnoye	UA205gm2012	44° 56.091	34° 45.433	534		Silstones	*Nannoconus colomii*, *Conusphaera mexicana*, *Watznaueria barnesae*, *Watznaueria britannica*, *Cyclicargolithus margirellii*, *Lithraphidites bollii*, *Lithraphidites carniolensis*
42	Yalta	Cr 51a 2014	44° 30.757	34° 12.126		Late Valanginian–Early Barremian	Tuff, siltstones	*Ellipsolithus communis*, *Watznaueria barnesae*, *Calcicalathina oblongata*
43	Ordgonikidze	UA28gm2012	45° 0.095	35° 20.277	146	Hauterivian	Argillites, marls, sandstones	*Nannoconus colomii*, *Watznaueria barnesae*, *Cyclicargolithus margerellii*, *Cyclicargolithus deflandrei*, *Lithraphidites bollii*
44	Kubalach	UA 90.13	45° 00.226	34° 52.826	283		Argillites, sandstones	*Watznauera barnesae*, *Ellipsoithus communis*, *Parhabdolithus asper*, *Parhabdolithus embergeri*, *Lithraphidites carniolensis*, *Manivitella pemmatoides*, *Cruciellipsis cuvillierii*, *Cyglagellosphaera margerilii*, *Stephanolithion laffittei*
45	North of Voron	UA 132.13	44° 54.359	34° 49.202	330		Black shales, argillites, sandstones, marls	*Watznaueria arnesae*, *Cyglagelosphaera margerellii*, *Ellipsolithus communis*
46	Nanikove	Cr 21 2014	44° 59.062	35° 12.576	77		White sandy limestones	*Cyglagellosphaera deflandrei*, *Lithraphidites bollii*, *Watznaueria barnesae*, *Nannoconus colomii*, *Ellipsolithus communis*, *Watznaueria britannica*

Table 5. *Valanginian nannoplankton dating with (WGS84) GPS locations*

Sample number on the map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation (m)	Age	Lithology	Nannofossil assemblages
47	Cheremisovka	UA14gm2012	45° 0.855	34° 44.434	346	Late Valanginian	Sandstones, siltstones	*Watznaueria barnesae*, *Bipodorhabdus colligatus*, *Parhabdolithus infinitus*, *Cyclicargolithus deflandrei*, *Tubodiscus verenae*, *Lithraphidites camiolensis*
48	Veseloye	UA 66.13	44° 51.961	34° 52.672	201		Marls	*Cyglagellsphera deflandrei*, *Cyglagellsphera margereli*, *Watznaueria barnesae*, *Watznaueria britannica*, *Ellipsolithus communis*, *Rucinolithum weiseii*, *Hayesites radiatus*
49	Ulyanovka village	UA6gm2012	45° 0.605	34° 38.040	318	Valanginian	Mudstones	*Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*
50	Krasnoselovka	UA9gm2012	44° 56.325	34° 38.532	440		Sandstones, mudstones	*Watznaueria barnesae*, *Nannoconus colomii*, *Cyclicargolithus margerellii*, *Cyclicargolithus deflandrei*, *Nannoconus steinmanii*, *Tubodiscus verenae*
51	Povorotnoye	UA18gm2012	44° 57.472	34° 43.814	508		Sandstones, mudstones	*Watznaueria barnesae*, *Nannoconus colomii*, *Cyclicargolithus margerellii*, *Cyclicargolithus deflandrei*, *Tubodiscus verenae*
52	Nanikove	Cr 18 b 2014	45° 00.235	35° 11.422	81		Grey shales	*Watznaueria barnesae*, *Cyglagellosphaera deflandrei*, *Parhabdolithus embergeri*, *Micrantholithus obtusus*, *Nannoconus colomii*, *Tubodiscus verenae*
53	Alekseevka	UA8gm2012	44° 56.917	34° 39.755	408	Early Cretaceous, not younger than Valanginian	Shales sandstones	*Nannoconus colomii*, *Watznaueria barnesae*, *Cruciellipsis cuvillieri*, *Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*
54	Grushevka	UA21gm2012	45° 1.054	34° 56.210	268		Dark brown shales, sandstones	Very poor *Cyclicargolithus deflandrei*; *Nannoconus colomnii*, *Watznaueria barnesae*, *Cyglagellosphaera margerellii*, *Cyglagellosphaera deflandrei*, *Conusphaera mexicana*, *Rucinolithum weiseii*
55	Grushevka	UA 50.13	45° 01.069	35° 00.227	404		Light grey sandstones, shales	
56	Dvuyakornaya bay	UA26gm2012	44° 59.213	35° 21.406	2		Mudstones, marls	*Cyclicargolithus margerellii*, *Cyclicargolithus deflandrei*, *Watznaueria barnesae* (very poor)
57	Dachnoye	UA37gm2012	44° 53.206	35° 0.184	213		Sandstones, Mudstones	*Nannoconus colomii* *Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*
58	Dachnoye	UA39gm2012	44° 55.574	34° 59.804	200		Dark grey shales and sandstones	*Nannoconus colomii* *Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei* *Nannoconus colomii*

Table 6. *Valanginian–Latest Jurassic nannoplankton dating with (WGS84) GPS locations*

Sample number on the map	Location	Sample number	Latitude (N)	Longitude (E)	Elevation (m)	Age	Lithology	Nannofossil assemblages
59	Veseloye	UA43gm2012	44° 52.087	34° 53.592	209	Early Cretaceous, not younger than Valanginian	Marls, shales, siltstones	*Cyclicargolithus margerellii*, *Cyclicargolithus deflandrei*, *Watznaueria barnesae* (very poor)
60		UA 68 13	44 51.776	34 52.598	190		Sandstones, siltstones	*Rucinolithum weiseii*, *Watznaueria barnesae*, *Watznaueria britannica*, *Ellipsolithus communis*, *Cyglagellosphaera margerellii*, *Cyglagellosphaera defandrei*
61		UA 43 13	44° 51.243	34° 52.297	208		Sandy clays and marls	*Watznaueria barnesae*, *Cyglagellosphaera deflandrei*, *Cyglagellosphaera margerellii*, *Ellipsolithus communis*, *Rucinolithus weiseii*
62	Pribrezhnoye	UA74gm2012	44° 52.132	35° 8.214	30		Marls, siltstones	*Nannoconus colomii*, *Watznaueria britannica*
63		UA75gm2012	44° 52.156	35° 8.247	10		Marls, siltstones	*Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*
64	Meganom	UA81gm2012	44° 48.937	35° 3.073	21		Shales, argillites, marls, siltstones	*Nannoconus colomii*, *Watznaueria britannica*
65		UA 46 13	44° 49.020	35° 3.000	1		Argillites and siltstones	*Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei* *Cyglagellosphaera deflandrei*, *Cyglagellosphaera margerellii*, *Watznauerya britannica*, *Watznauerya barnesae*, *Ellipsolithus communis*
66	Novyj Svet	UA89gm2012	44° 50.409	34° 56.689	286		Argillites, siltstones	*Cyclicargolithus deflandrei* (very poor)
67		UA90gm2012	44° 52.214	34° 49.671	42		Sandy limestones, siltstones, argillites	*Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*, *Watznaueria barnesae*
68	Krasnokamyanka	UK35gm2012	44° 55.725	35° 06.861	135		Sandy limestones, marls, argillites	*Cyglagelosphaera deflandrei*, *Cyglagelosphaera margerellii*, *Watznaueria barnesae*, *Ellipsosphaera communis*
69	Kurortnoye-Solnechnaya Dolina	UA 44 13	44° 52.336	35° 05.933	91		Shales, mudstones, marls, siltstones	*Watznaueria barnesae*, *Watznaueria britannica*, *Cyglagelosphaera defandre*, *Cyglagelosphaera margerellii*, *Ellipsolithus communis*
70	Kubalach	UA 88 13	45° 00.051	34° 52.654	321		Sandstones, argillites	*Cyglagellosphaera deflandrei*, *Cyglagelosphaera margerellii*, *Watznaera barnesae*
71	Shelen pass	UA94gm2012	44° 54.540	34° 45.843	698		Sandstones, siltstones, sandy clays	*Cyclicargolithus margirellii*, *Cyclicargolithus deflandrei*, *Nannoconus colomii*
72	Gromovka	UA93gm2012	44° 53.238	34° 46.957	216		Sandstones, siltstones, argillites	*Watznaueria barnesae*, *Cyclicargolithus deflandrei*, *Watznaueria britannica*
73	Veseloye	UA 64 13	44° 49.434	34° 53.186	151	Berriasian	Mudstones, marls, siltstones	*Polycostella beckmannii*, *Ellipsolithus communis*, *Watznaueria baresae*, *Watznaueria britannica*
74	Nanikove	Cr 15 a 2014	45° 01.324	35° 08.706	217	Tithonian	Argillites, marls, siltstones	*Watznaueria barnesae*, *Watznaueria britannica*, *Polycostella beckmannii*
75		Cr 15 b 2014						
76	Solnechnaya Dolina	UA71gm2012	44° 52.963	35° 5.809	185	Latest Jurassic	Argillites, marls, siltstones	*Watznaueria barnesae*, *Polycostella beckmanii*, *Cyclicargolithus margirellii*

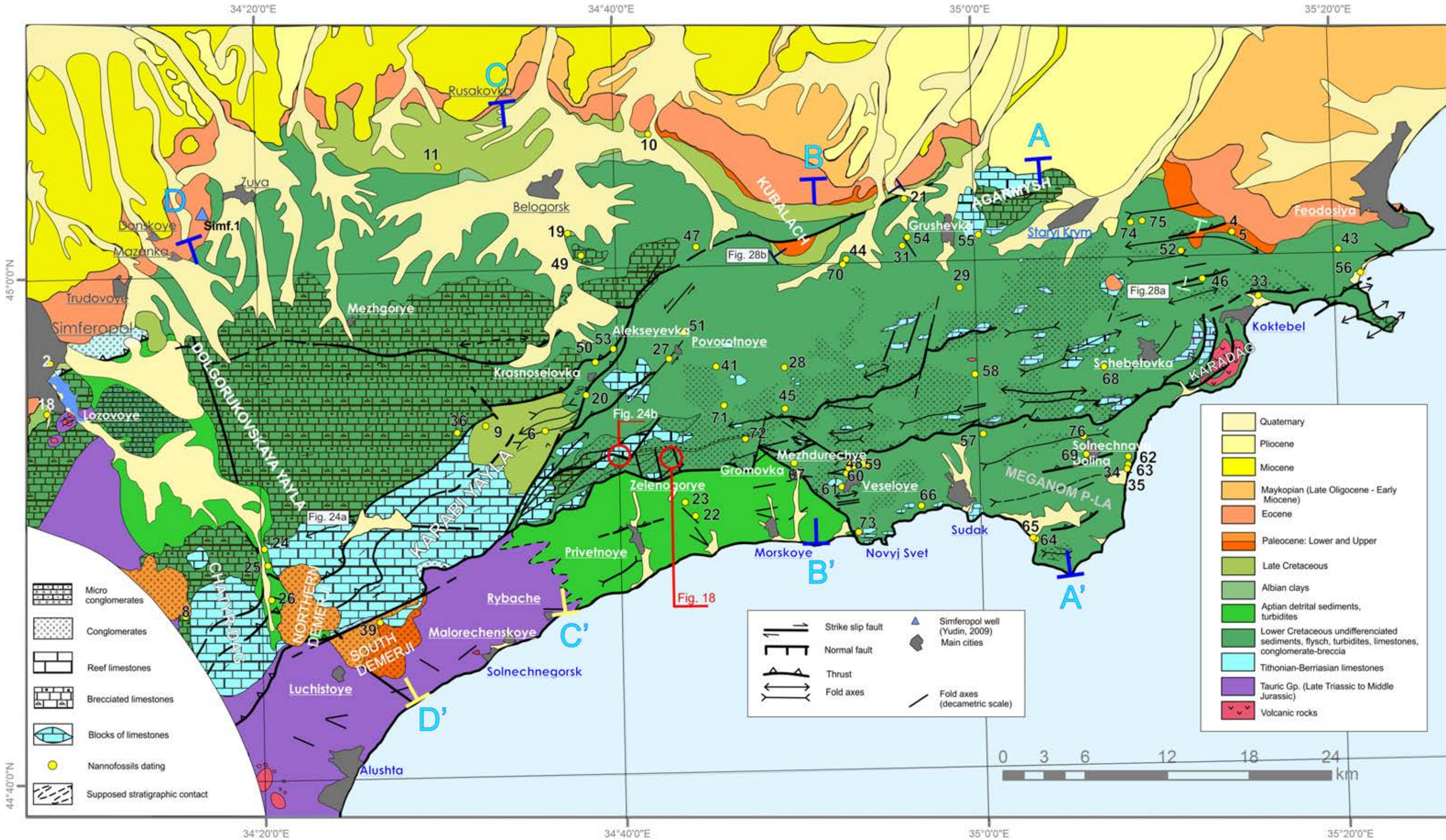

Fig. 13. New structural map of the eastern Crimean Mountains built using the new dating results and new structural field data. The cross-sections (A–A′, B–B′, C–C′ and D–D′) are shown in Figure 15; cross-sections *a* and *b* are shown in Figure 28.

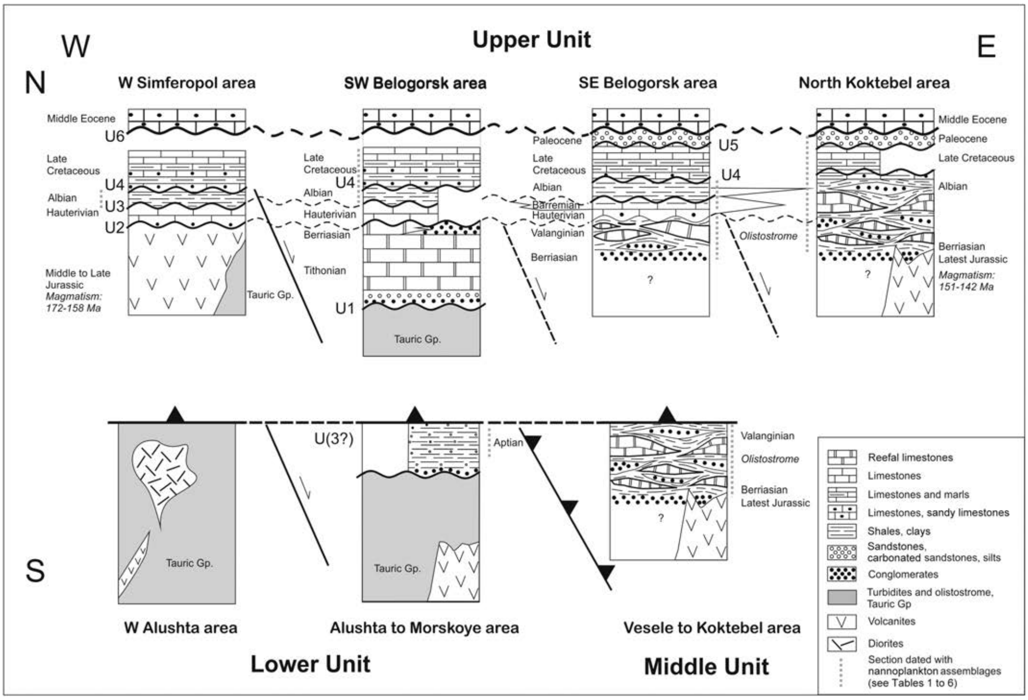

Fig. 14. Schematic stratigraphic logs built for the eastern Crimean Mountains. The synthetic logs of the hanging wall of the main thrust are shown in the upper part of the figure. These logs summarize the stratigraphy of the northern part of the eastern Crimean Mountains, see also Figure 17 illustrating the location of these three tectonic units.

The following observations allowed us to conclude that the age of compressional deformation is post-Late Cretaceous and before the Middle Eocene: (1) the Middle Eocene unconformity (U6) of nummulitic limestones on the top of the hanging wall; (2) the Late Aptian age obtained from nannoplankton analysis for some levels in the Lower Unit (Figs 13 & 15); and (3) the folded Upper Cretaceous rocks.

Main zone of deformation. A major thrust zone stands out in relief all along the Main Ridge in the eastern CM. Figure 18 shows this relief to the north of the village of Zelenogorye, where Lower Cretaceous sandy grainstone rocks dip with a low angle (20–25° to the north). Southwards, the dip angle gradually increases. It reaches 50–60° to the north in the conglomerates, which finally thrust over the Aptian series (Fig. 13 & 15, cross-section C–C′). The steep dip of the thrusted flysch-like rocks is shown on Figure 18a & c. This thrust zone (Zelenogorye) has been described by Kazantcev *et al.* (1989). Although we do not agree with the structural interpretation of Kazantcev *et al.* (1989), these researchers reported Upper Jurassic forams (Uspenskaya 1969) in the strata located at the base of the hanging wall. This observation fits well with our structural analysis, which shows this hanging wall thrusting over younger rocks (the upper Aptian turbidites dated by nannofossil assemblages; see sample numbers UA.35.13 and UA 36.13, locations 22 and 23 on Fig. 13; Zelenogorye location on Table 3, and Fig. 15, cross-section C–C′).

All along its strike, this thrust is well expressed by ductile (Fig. 19) and brittle zones of deformation in conglomerates, limestones and sandstones, all of which are common in the southwestern part of the study area (regions of Demerji, Karabi Yayla, Privetnoye, Zelenogorye and Mezhdureche; Fig. 13). Eastwards, the thrust becomes a blind thrust, forming high-amplitude folds in the flysch-like rocks with ductile behaviour and containing large limestone blocks (Veseloye, Sudak, Shebetovka and Koktebel).

Westwards from northern Demerji this thrust zone can be traced in the direction of the Angar pass (the valley between Chatyr-Dag and Demerji) (Fig. 13), then it goes to the south of northern Chatyr-Dag and turns in the direction of Babugan Yayla (Fig. 12). Here, in this segment of thrust, we agree with the map interpretation shown by Muratov (Geology of USSR 1969). This zone of south

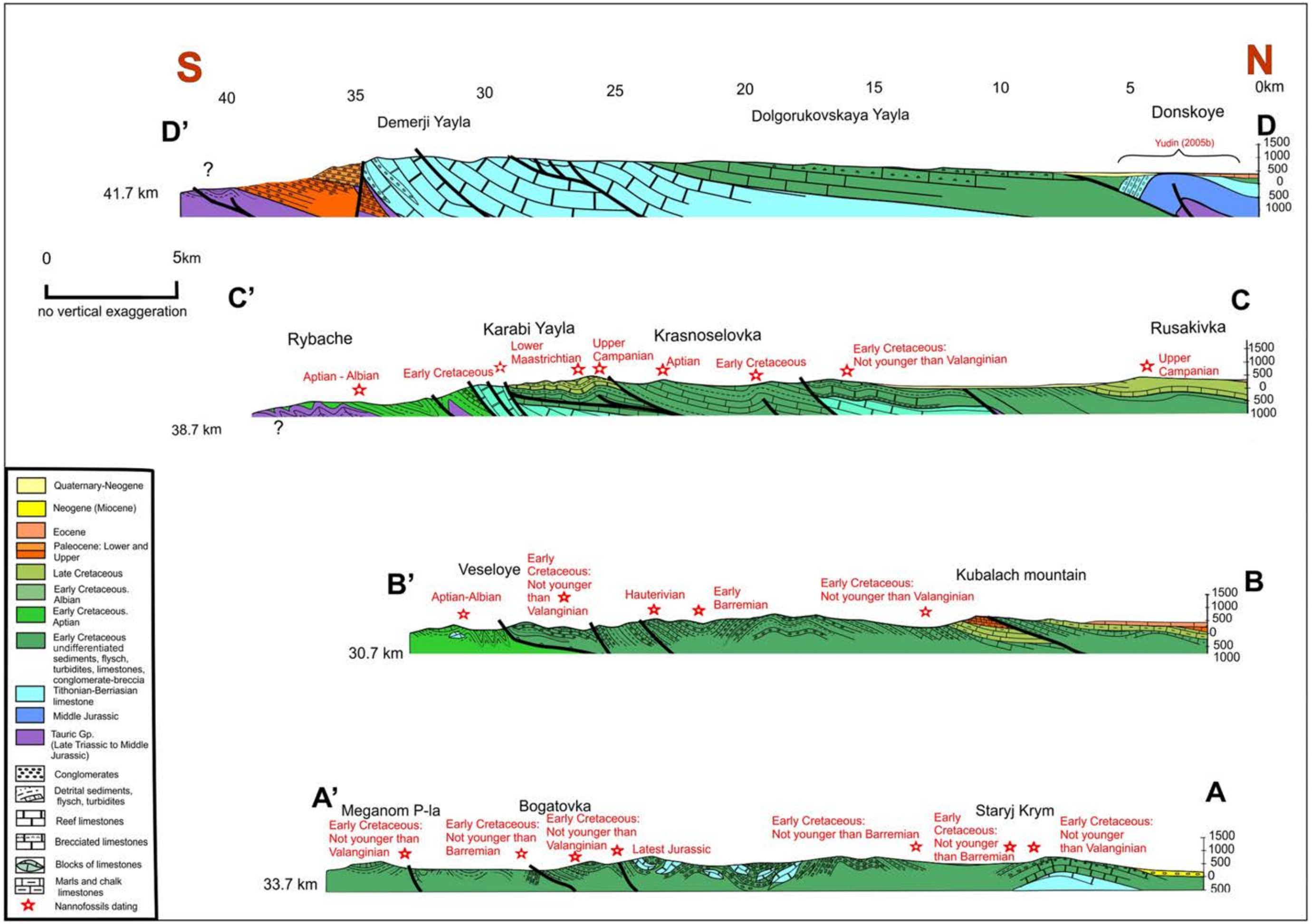

Fig. 15. Geological cross-sections constructed using new ages and structural data and showing the main shortening structures. The locations of the sections are shown on Figure 13.

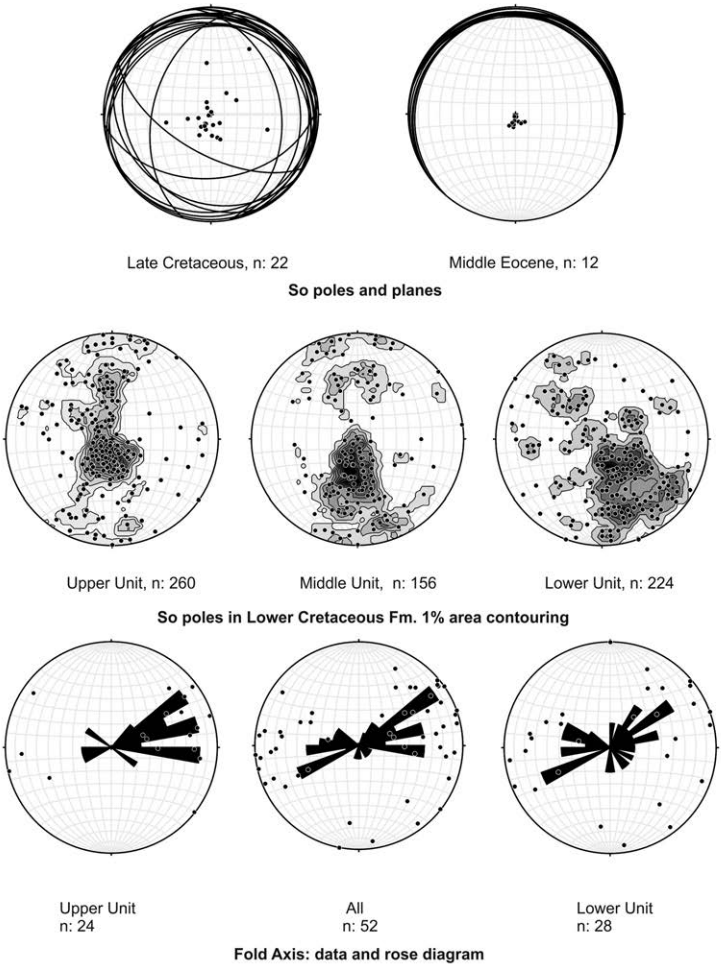

Fig. 16. Stereogram analysis of the fold axes and dip azimuth in different structural units and rocks of different age (Schmidt diagram; lower hemisphere). The Middle Eocene clearly shows an absence of folding in the northern part of the eastern Crimean Mountains. See text for detailed explanation.

vergence is observed in the hanging wall by steeply dipping Upper Jurassic–Berriasian limestones (Fig. 20). Various researchers have noted the complex geological relationships between 'blocks' in this area (South Demerji, North Demerji and Tyrke Yayla). Yudin (2001, 2005*a*, 2009), for example, described a thrust between North and South Demerji with very steeply dipping (70–80°) limestones and conglomerates in the footwall and isoclinal folding of south vergence further to the west. Baraboshkin & Piskunov (2010) and Piskunov (2013) also mentioned thrusts with dip directions to the NW.

Structures related to this thrust were also observed in the siliciclastic sediments in an exposure created during road construction between Simferopol and Alushta (Fig. 13, valley between Chatyr-Dag and Demerji, location 26 with dating; Fig. 21). The siliciclastic sediments are unconformably covered by 'Upper Jurassic(?)' conglomerates (Fig. 12). These siliciclastic sediments, probably because of similarities in lithology with TG and an absence of *Monotis* and *Halobia* macrofauna (see circles, Fig. 12) were assumed to be TG or Middle Jurassic (Upper Jurassic; see literature review). As they are deformed, the age of deformation was assumed to be Cimmerian. We obtained a Late Aptian age (Table 3) from samples in the silisiclastic sediments in this valley and, in this case, the age of the conglomerates requires further explanation.

The conglomerates can easily be divided into two different lithological units (Chernov 1963). A Lower Unit is made up of dark reddish brown

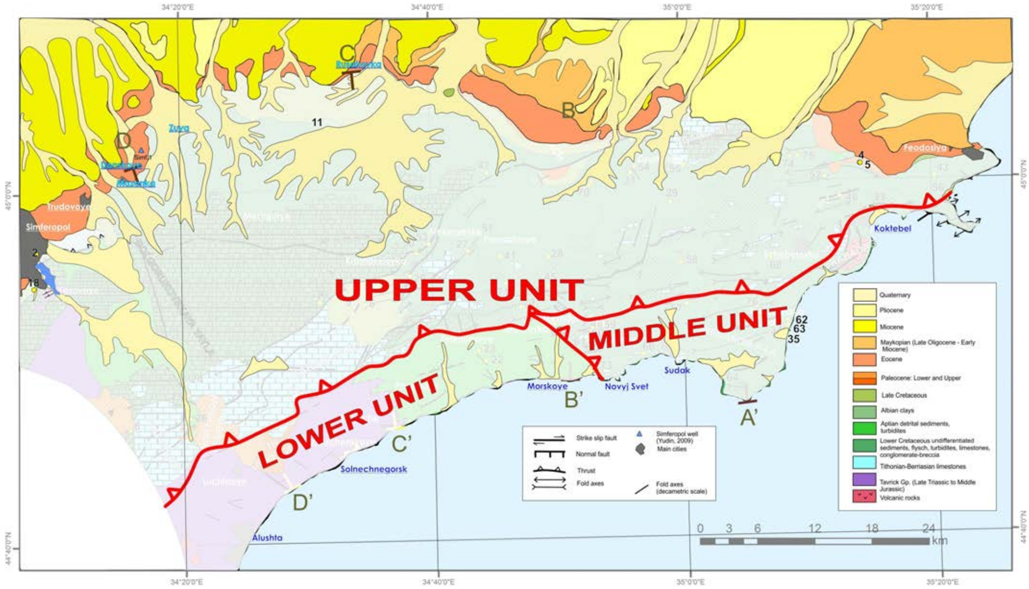

Fig. 17. Main structural units separated by thrust faults. The age of the Upper Unit is limited by the unconformity of the Middle Eocene nummulitic limestones (U6). See the legend on Figure 13.

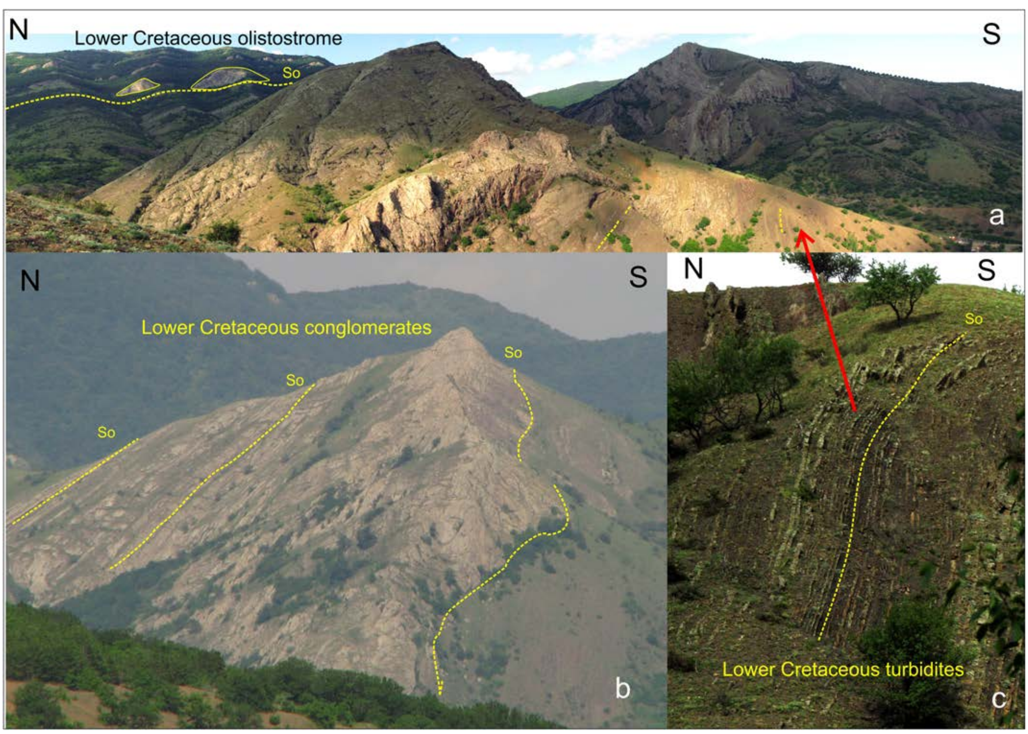

Fig. 18. The main thrust zone near the village of Zelenogorye. (**a**) View to the main thrust zone, north of the village of Zelenogorye; (**b**) gradual change of the dip angle in the rocks involved in the thrust; and (**c**) steep beds of the siliciclastic sediments that thrust over the Aptian–Albian flysch of the Lower Unit.

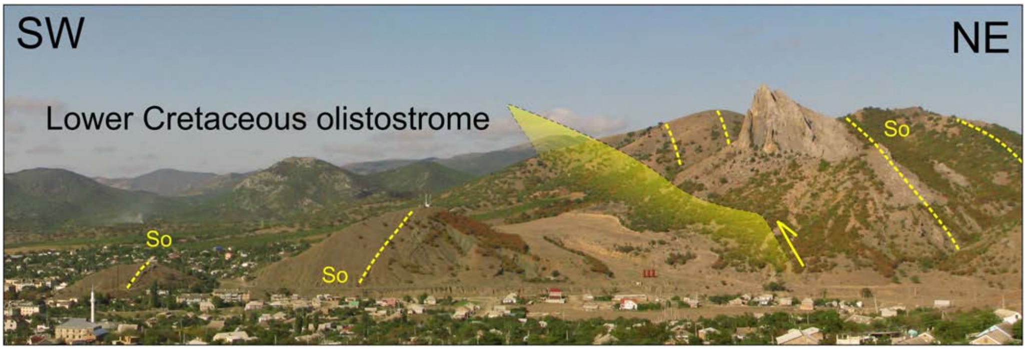

Fig. 19. View of the thrust zone to the east of Karabi Yayla, Sudak-Dachnoye area: a high-amplitude fold in a Lower Cretaceous olistostome is cut by a south-vergent thrust

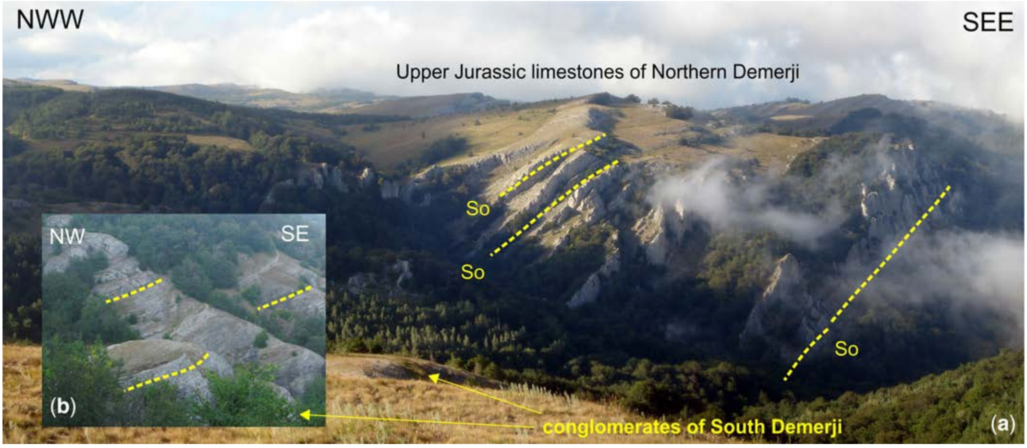

Fig. 20. Structural settings of Demerji Yayla. (**a**) Steep-dipping Upper Jurassic limestones; and (**b**) shallow-dipping Upper Jurassic conglomerates.

Fig. 21. Example of shortening structures in the siliciclastic sediments in the outcrop along the Simferopol–Alushta road (south of the village of Perevalnoye).

conglomerates with large pebbles of reworked flysch material (sandstones and argillites) (Fig. 22a). This unit forms the base of the conglomerates of Demerji and can be observed between the villages of Luchistoye and Heneralskoye (Fig. 12). The Upper Unit is characterized in its upper part by light grey carbonated conglomerates with limestone pebbles, white quartz, sandstones and argillites and, sometimes, blocks of reworked conglomerates (Fig. 22b). The previously reported unconformity between these two units does not exist, although, based on Figure 23, it could be outlined. The Upper Jurassic limestones are deformed southwards (Fig. 24; Fig. 20a folding and Fig. 17a), as are the siliciclastic sediments in the valley between Chatyr-Dag and Demerji (Fig. 20a, b). However, these deformations are not present in the so-called 'Upper Jurassic' conglomerates (Figs 5d, 6 and 20b). Figure 25 illustrates

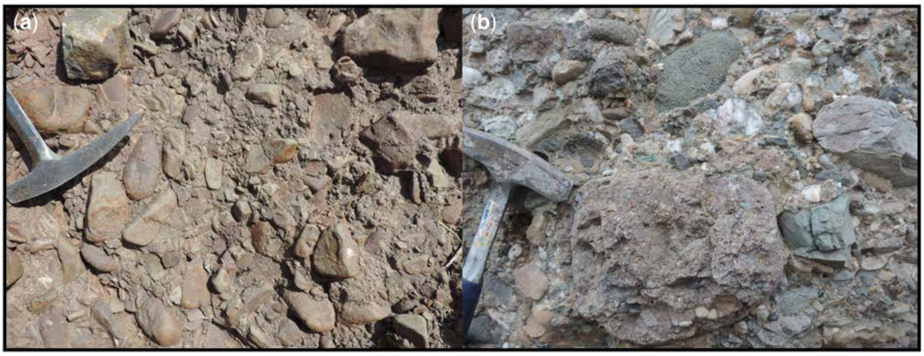

Fig. 22. Conglomerates of South Demerji. (**a**) Dark reddish brown conglomerates with large pebbles of reworked flysch material (sandstones and argillites) of the Lower Unit. (**b**) Light grey carbonated conglomerates with limestones pebbles, white quartz, sandstones and argillites and sometimes blocks of reworked conglomerates of the Upper Unit.

Fig. 23. View of conglomerates of South Demerji Mountain. The visual difference in dip angle between conglomerates of the Upper and Lower units implies an angular unconformity between them.

Fig. 24. Folds in TithonianBerriasian limestones. (**a**) Folding in the limestones of the Dolgorukovskaya Yayla and (**b**) east of Karabi Yayla.

Fig. 25. Demerji conglomerates. (**a**) Growth strata due to deformation southwards. (**b**) Progressive change in dip angle of these conglomerates from their base to their upper part.

the progressive change in dip angle of these conglomerates from its base (south foothill of South Demerji 35° NW) to its northern prolongation in the valley (5–0°); this can be explained as growth strata due to deformation (uplifting and/or folding) southwards with onlap/offlap geometries depending

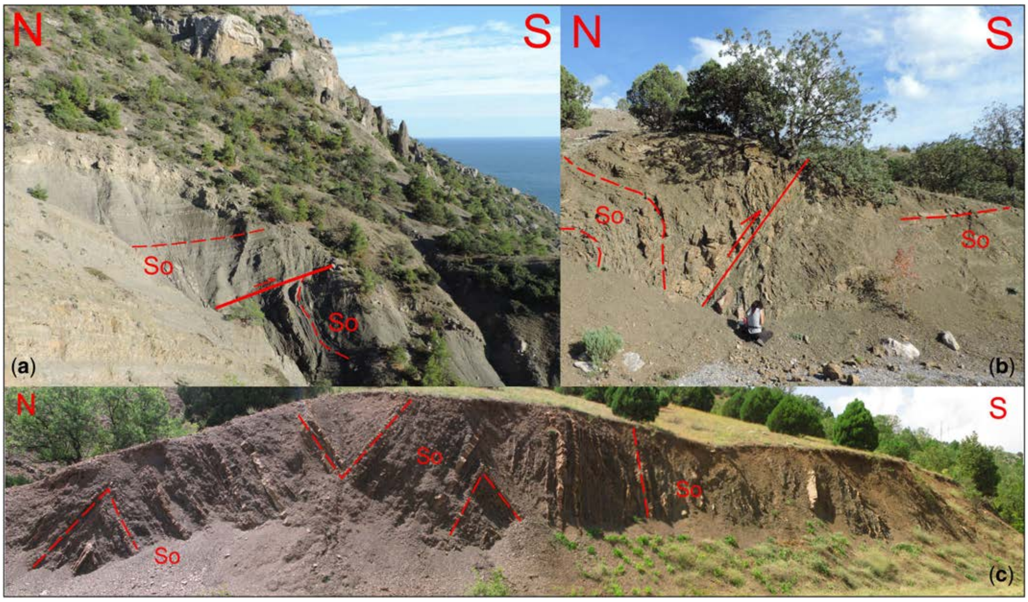

Fig. 26. Near the village of Veseloye: (**a**) thrust; (**b**) shear zone associated with the thrust; and (**c**) chevron fold.

on the rate of uplift and/or deformation and the rate of deposition. Thus these conglomerates are related to a phase of deformation which is at least post-Aptian. The red conglomerates (Lower Unit) to the SW of Heneralskoye cannot be observed because of the overthrusting of Upper Jurassic limestones (Fig. 13). The age obtained from sample CR 01 2014 (Table 4, location 38 on Fig. 13) can be explained in the context of our reconstruction by reworked nannoplankton from Lower Cretaceous flysch-like rocks during the deposition of the conglomerates.

Another zone of shortening is well expressed south of the village of Veseloye near the sea (Fig. 26a). It is the basal tectonic contact of the Middle Unit (Fig. 17). A décollement level of SW vergence appears in the Lower Cretaceous shaley flysch-like rocks. A few metres beneath this contact, the faulted and folded exposed strata also indicate a SW vergence. This 100 m thick tectonic contact can be observed to the NW (Fig. 13). All this area is characterized by the ductile behaviour of the material (shales, silts, thin layers of sandstone), interpreted as representing a shear zone. For example, chevron folds are produced by the disharmonic component of the deformation within the shale and sandstone beds (Fig. 26).

Deformations showing compressional structures can also be found in the Lower Cretaceous turbidites around Privetnoye, Zelenogorye, Rybachye, the outskirts of Alushta and along the Simferopol–Alushta road (Fig. 27).

As shown on the structural map (Fig. 13), the fold axes trends of decametric scale are mainly in accordance with the main trend of the thrust (see diagram of fold axes; Fig. 16). Those that are not parallel to the trend of the thrust could involve the reactivation of previous structural anisotropies as NW–SE to NE–SW Early Cretaceous normal faults (Fig. 13). These will be discussed as brittle extensional structures in the second part of this section. Moreover, such reactivations during compression could be the cause of the strike-slip component observed on some vertical faults. However, some of these folds could also be due to slumping along an ESE-dipping slope.

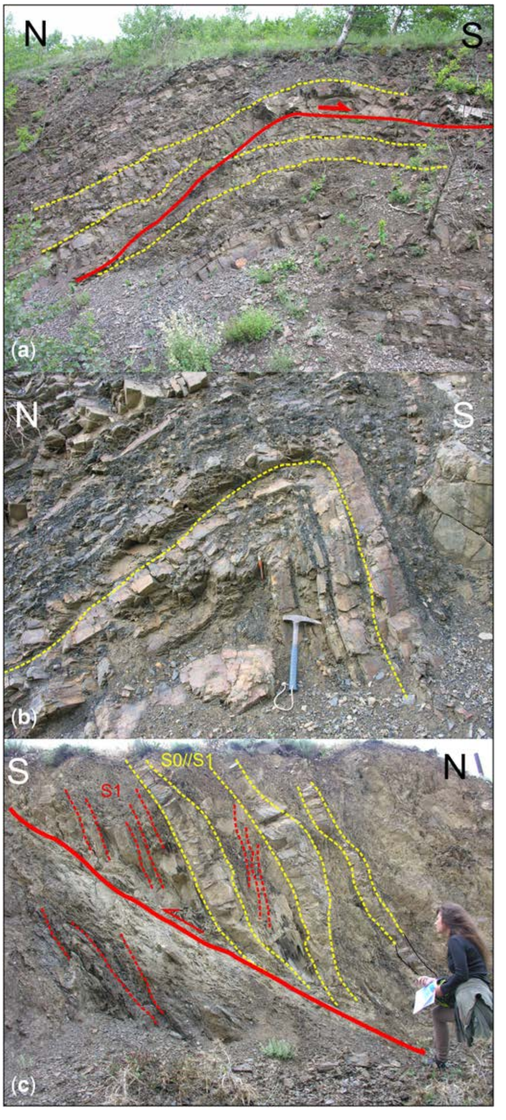

Fig. 27. Shortening structures near the village of Privetnoye: (**a**) ramp-and-flat type deformation; (**b**) folds; and (**c**) ductile shear zone.

Age of the compressional event. The age of the compressional deformation can be estimated on the basis of the newly reported ages. As shown on cross-section C (Fig. 15), the Upper Cretaceous limestones and detrital rocks are involved in the folding close to the main thrust zone (section C–C′, Fig. 15). The Middle Eocene limestones are not involved in the same type of deformation (Fig. 16). They dip northwards as a monocline with a low angle ($\leq 10^{\circ}$) (Fig. 11). To the NE of Koktebelt, the Lower Paleocene sandy limestones overlie, with an angular unconformity, the Lower Cretaceous flysch-like formation (Figs 15 and 28a, cross-section). Cross-section a on Figure 28 shows that even if the Paleocene strata could be involved in the folding due to overthrusting by Lower Cretaceous units, the rocks beneath the Paleocene are deformed. Accordingly, the deformation of Lower Cretaceous turbidites commenced at least no later than the Late Paleocene to Early Eocene (Nikishin *et al.* 2003) because the Lower Cretaceous rocks do not thrust over the Middle Eocene limestones (see section b on Fig. 28). Figure 28, section a also shows the thrusting of Lower Cretaceous strata onto Paleocene rocks, indicating post-Paleocene shortening, which is most likely an early phase of Oligo-Miocene shortening, well-documented on the Kerch Peninsula (east of the Crimea Peninsula) (Muratov 1960; Nikishin *et al.* 2003; Yudin & Yurovskiy 2011). Taking into account the structural data and the prevalence of the terrigenous component in the Paleocene strata, we conclude that the first stage of compressional tectonics in the eastern CM commenced sometime between the Paleocene and Middle Eocene.

Extensional deformation during the Early Cretaceous

Because of the subsequent compressional phase of deformation, evidence of extension in the eastern CM is difficult to define. One indication of vertical motion in the eastern CM during the Early Cretaceous is the appearance of blocks (olistoliths) of Upper Jurassic limestones within the Lower Cretaceous olistostrome (siliciclastic sediments, turbidites, shales or rhythmic flysch-like sequence) (Dobrovolskaya & Salman 2008), which can be observed eastwards from Karabi Yayla (Fig. 13; Fig. 29a). The age of blocks varies from Oxfordian to Tithonian–Berriasian and the size of blocks varies from 10 to 100 m (Karlov 1963; Kazantcev *et al.* 1989, with references cited therein; Andruhovich & Turov 2002; Dobrovolskaya & Salman 2008; Yudin & Yurovskiy 2011) (Fig. 29).

According to the stratigraphic description of the Lower Cretaceous facies and olistostromes, and in view of the new dating, we suggest that the Late Jurassic carbonate platform was destroyed by vertical motion linked to the deepening of the basin to the east. Consequently, the platform was the source of sliding blocks, mass wasting and slumping to the east along a slope into siliciclastic sediments and conglomerates.

The subsidence is evidenced by changes in the composition of the matrix from carbonaceous and shallow marine deposition eastwards (Karabi Yayla, sample Cr.25.14, see Table 4 and Fig. 13) to deeper marine facies of clay and turbidites (Muratov 1960; Himshiashvili 1967; Tkachuk 1970; Paryshev *et al.* 1979) during Berriasian–Late Aptian–Albian times (Muratov 1960; Lysenko & Janin 1979; Arkad'ev 2007).

West of Simferopol, Hauterivian strata unconformably overlie Middle Jurassic magmatic rocks (Fig. 7a), but to the east of Simferopol they rest with disconformity on Upper Jurassic–Berriasian limestones (Fig. 14). Consequently, there is a normal fault that separated these two areas before the deposition of Hauterivian sediments. Another normal fault, which could be related to extension, is inferred in the area of Rybache because: (1) there are intrusions that may correspond to a weakening zone; and (2) the Karabi carbonate platform rapidly decreases in thickness to the east and is covered by Upper Cretaceous deposits (Fig. 13; section C–C′ Fig. 15).

In summary, we suggest that the inferred vertical displacements were controlled by NW–SE- to NE–SW-trending normal faults (Fig. 30), as was proposed in western Crimea by Hippolyte *et al.* (2014). Several NW–SE-trending normal faults were described by Saintot *et al.* (1999) in the area of Dolgorukovskaya and Babugan Yaylas in Upper Jurassic–Berriasian limestones. Some vertical faults, observed in the field and shown on the structural map (Fig. 13), were probably reactivated as strike-slip faults during the compressional stage (Kazantcev *et al.* 1989). These faults could be evidence of normal faults developed during the Early Cretaceous extensional event.

There is also evidence of magmatism during the Early Cretaceous. The Karadag massif was active during Tithonian–Berriasian times (*c.* 151–142 Ma) according to the results of $^{40}Ar/^{39}Ar$ dating (Meijers *et al.* 2010). This Early Cretaceous event could also have promoted the destruction of the platform, leading to the appearance of blocks of a different age in the basin. Although there is no known volcanic body of this age in the eastern CM, all samples selected for nannofossil dating contain a substantial component of volcanic ash, partly altered to clay. Thus magmatic activity is inferred to have taken place during the Early Cretaceous. Such a conclusion is in accordance with the work of Nikishin *et al.* (2013) on a rifting phase during Barremian–Aptian times in western Crimea.

Discussion and conclusion

The results of the field and analytical work discussed here allowed us to assign a new age to the majority of the flysch-like strata of the eastern CM. Exposures in several regions, as seen on the structural map (Fig. 13), have not been included in this reassignment for the following reasons.

(1) Middle Jurassic magmatic bodies in the Simferopol (Meijers *et al.* 2010) and Alushta–Rybache regions cannot have intruded Lower Cretaceous flysch.

(2) According to Popadyuk *et al.* (2013*a*, *b*; 2014) the age of the oldest flysch-like rocks in the CM is Albian. However, the Hauterivian unconformity with the Middle Jurassic volcanic units (Simferopol area) and the Hauterivian unconformity with the TG (western

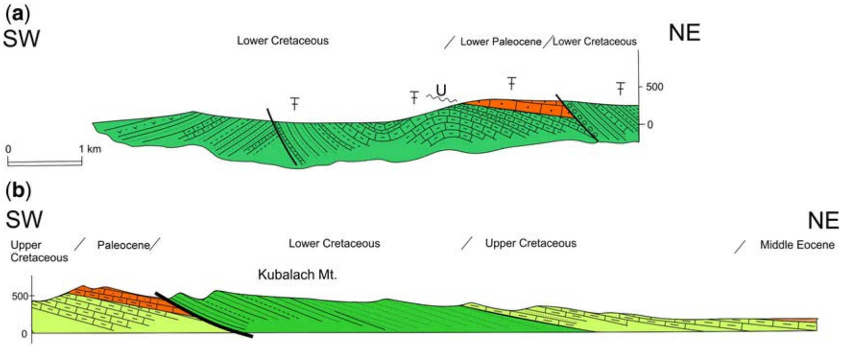

Fig. 28. Geological cross-sections: (**a**) to the west from the village of Nannikovo; and (**b**) Kubalach Mountain. The location of the sections is shown on the structural geological map (Fig. 13).

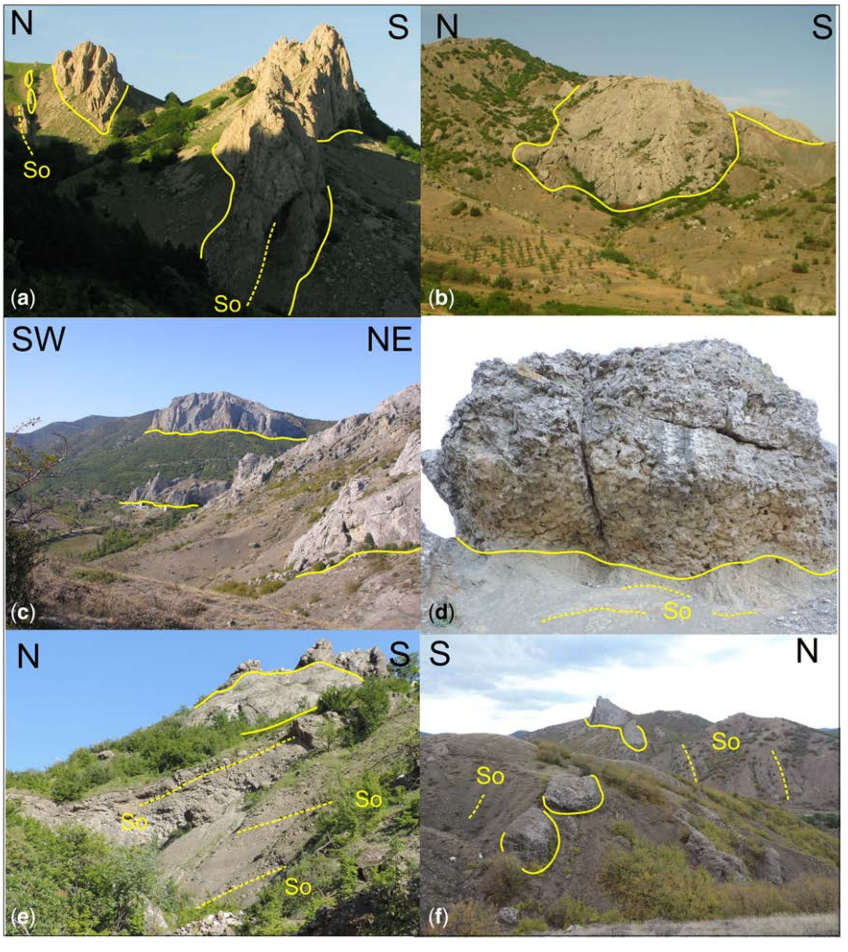

Fig. 29. Lower Cretaceous olistostrome. (**a**) Blocks of Upper Jurassic limestones in the Lower Cretaceous flysch-like rocks (eastern part of Karabi Yayla); (**b**, **c**) Upper Jurassic olistoliths near the village of Solnechnaya Dolina; (**d**) block of conglomerates in Lower Cretaceous olistostrome; (**e**) block of reefal limestone in Lower Cretaceous olistostrome (to the north of the village of Gromovka); and (**f**) blocks of conglomerates in Lower Cretaceous turbidites.

Fig. 30. Normal faults east of Karabi Yayla, north of the village of Privetnoye.

Crimea, Fig. 7) preclude the presence of Albian flysch beneath the Hauterivian.

(3) The absence of nannofossil assemblages in some samples selected from this region does not allow such a reassignment when it differs from those of previous researchers (Figs 12 & 13).

A plausible conclusion is that there are two flysch units of different ages in the southern CM (Afanasenkov *et al.* 2007; Okay *et al.* 2013, 2015): the oldest unit is of Late Triassic–Middle Jurassic age and the other is of Early Cretaceous age.

The oldest flysch complex has a Late Triassic–Middle Jurassic age and is mostly located in the western CM. It contains blocks of Palaeozoic limestones (Carboniferous and Permian) and its areal distribution is fixed by the Middle Jurassic magmatic rocks that intrude it (west of Alushta). The faunal finds of *Monotis* (villages of Prohladnoye and Partizanskoye) are also evidence of this. Detrital zircon fission track dating of Mesozoic clastic complexes in the western CM and the Alushta region (Solov'ev & Rogov 2010) has supported such an age for the oldest flysch complex.

The approximate boundary between the older flysch complex and the younger complex can be inferred along the Simferopol–Alushta road. When describing the extensional deformation, we mentioned normal faulting prior to the deposition of the Hauterivian. The abrupt cutting of red conglomerates (Lower Unit of the Demerji conglomerates) from the west (as shown on the map) can be explained by activation of this fault zone. This zone is called the Salgir–Oktyabrskaya Fault Zone, has a NW–SE strike, and passes via this valley (Khain 1984; Saintot *et al.* 1999). It is considered to be one the major, deep structures of Crimea, running from Alushta to Simferopol (Sollogub 1977; Morgunov *et al.* 1979; Byzova 1980; Khain 1984; Koronovskij 1984; Saintot *et al.* 1999). Some researchers (Saintot *et al.* 1999; Gintov 2005; Gonchar 2005; Volfman 2015) used this fault in their stress field reconstructions, whereas others (Yudin & Yurovskiy 2004) have doubted its existence. This fault zone would have been active twice:

(1) as a normal fault, separating the region with old flysch complex (western CM) from the region with young flysch (eastern CM) and could explain the reworked character of Triassic–Jurassic age macrofauna in Lower Cretaceous rocks (eastern CM); and
(2) as a strike-slip fault zone during the Cenozoic.

We assumed the presence of NW–SE- and NE–SW-trending normal faults during the Early Cretaceous. The flysch rocks of the TG would have been eroded along these faults, providing a source for detrital rocks and most likely the redeposition of Triassic–Jurassic fauna into the forming Cretaceous basin. It is sometimes impossible to distinguish the age of the flysch-like rocks by their lithology alone. Such similarity could be due to the erosion and redeposition of TG rocks in the Early Cretaceous in a comparable turbiditic depositional environment.

Some researchers (Yanin 1976; pers. comm. A.Yu. Guzhykov 2014 about Sheremet *et al.* 2014; Yudin *et al.* 2015) have previously explained the appearance of nanno- and microfossils of Early Cretaceous age by their inclusion and re-cementation in fractures in the TG. Such an explanation is only plausible locally and cannot be applied to all our results (Tables 1–6, Fig. 12). Moreover, we only took samples from the interbedded levels of the siliciclastic rocks, not from the fractures (see Table 1 for the exact GPS coordinates of our samples).

Many of the structures within the TG and Upper Jurassic–Berriasian strata (flysch-like rocks and limestones) discussed in this paper have been described in earlier studies: Muratov (1960), Scherba (1978), Byzova (1980), Kazantcev (1982), Kazantcev *et al.* (1989), Milanovskij (1991), Popadyuk & Smirnov (1991), Galkin *et al.* (1994), Smirnov & Popadyuk (1997), Mileev *et al.* (1997, 2006), Nikishin *et al.* (1998, 2003, 2015*a*, *b*), Saintot *et al.* (1999), Lalomov (2001), Yudin (2001, 2009), Gintov (2005), Afanasenkov *et al.* (2007), Yudin & Yurovskiy (2011), Stovba *et al.* (2013) and Popadyuk *et al.* (2014). These were almost always ascribed to the earlier Cimmerian phase of deformation. With our revised age of the flysch in the eastern CM, the age of deformation must be understood as younger. The revisions do not negate the work of several generations of geologists, but help to explain previous attempts to justify thrusts of Upper Jurassic–Berriasian limestones onto what is now seen as Lower Cretaceous flysch.

Our structural analysis has documented a thrust zone and related compressional structures. Thrust zones have been identified in several places in the study area (Fig. 13), with folds of south vergence on different scales. East of Rybache the Upper Jurassic limestones thrust over Aptian–Albian strata. West of Rybache, the thrust zone possibly cuts the TG strata. Given that there are no new nannofossil ages from this area and for the reasons described earlier in this paper, we do not consider it possible to carry out the same interpolation as that of Popadyuk *et al.* (2013*a*, *b*; 2014). We prefer to understand this segment of compressional deformation as a reverse fault. Perhaps this fault formed as the result of older structural anisotropies as, for example, west–east-trending normal faults during the opening of the Triassic basin. In the Alushta region and the transition area between the TG and the Lower Cretaceous flysch-like rocks (Aptian–Albian; Fig. 13; Fig. 15, section C–C′), we draw a dotted line between these two formations, indicating that both flysch units are folded. Yudin (2009) and Yudin & Yurovskiy (2011) resolved this problem by proposing a complex of compressional tectonic mélanges, which could reach several tens to hundreds of kilometres. In our opinion, this question can be answered by more and better dating. However, even if the age of the flysch in the area of Alushta is confirmed as Early Cretaceous in the future, it will not require a major revision of the structures in this region.

The age of compressional deformation is most probably connected to the formation of the Greater Caucasus Orogen, which took place during the Late Eocene, as reported by Saintot *et al.* (2006), Afanasenkov *et al.* (2007), Yudin (2009), Yudin & Yurovskiy (2011), Gonchar (2013) and Nikishin *et al.* (2015*a*, *b*). However, we consider that the first stage of shortening could have appeared during the Paleocene. This early compressional event could be related to that described in Dobrogea (see Fig. 2 for location) by Hippolyte (2002) from the Late Cretaceous to Paleocene and/or with north–south shortening due to the onset of continental collision in the Pontides and Taurides (Nikishin *et al.* 2003), with the probable transfer of deformation to the north in the Crimea Peninsula.

Our data do not document a compressional event during latest Jurassic–Early Cretaceous times as suggested by Yudin & Yurovskiy (2011). The early stages of the compressional event were probably not very intense and did not last for a long time because there is a significant unconformity the Middle Eocene nummulitic limestones everywhere in the CM.

On the basis of our structural analysis of the Early Cretaceous phase of extension, we suggest that the subsidence of the Early Cretaceous basin was accompanied by destruction of the pre-existing carbonate platform with a series of NNE-SSW- and NNW-SSE-trending normal faults (Saintot *et al.* 1999), volcanic activity (Spiridonov *et al*. 1990*a*, *b*; Dovgal’ *et al.* 1991; Meijers *et al.* 2010) and gravitational sliding of Upper Jurassic limestones blocks along the slope (Popadyuk *et al.* 2014) eastwards from Karabi Yayla into the basin.

The Early Cretaceous extensional stage was obtained by Gonchar (2013) as a result of palaeostress field reconstruction in the eastern CM. This extension could be related to back-arc rifting (Gonchar 2013).

The extensional structures that we have described are probably related to opening of the Eastern Black Sea Basin during the Early Cretaceous (Khriachtchevskaia *et al.* 2009; Stephenson & Schellart 2010), Late Barremian–Albian (Nikishin *et al.* 2015*a*, *b*; Popadyuk *et al.* 2013*a*, *b*), but we did not find any evidence documenting the beginning of this stage to Callovian time (Zaika-Novackij 1981; Afanasenkov *et al.* 2007), the Late

Cretaceous–Paleocene (Okay *et al.* 1994) or the Cenozoic (Paleocene–Eocene) (Adamia *et al.* 1981; Robinson *et al.* 1996; Spadini *et al.* 1996; Vincent *et al.* 2005).

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