Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2016) 25: 163-178

doi:10.3906/yer-1404-20

Nummulitic facies of the Crimean-Caucasian Region

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Received: 27.04.2015 • **Accepted/Published Online:** 26.10.2015 • **Final Version:** 08.02.2015

Abstract: The nummulitic limestones of Crimea and the southwestern Caucasus, often interpreted as "nummulite banks", formed carbonate platforms throughout most of the Ypresian–Lutetian. Such deposits were accumulated in shallow warm-water basins of Crimea and the Caucasus, which differed from each other by the structure of the basement and the hydrodynamic regime. The Crimean carbonate platform was relatively flat and was formed mainly within quiet hydrodynamic conditions below the fair-weather wave base (less than 50 m). The facies changes within it reflect variations in water depth. Facies distinguished there form the nummulite bank, its lee-side slope, the shelf plain in the rear of the bank (back-bank), and the relatively deep basin-ward slope with predominantly terrigenous sedimentation (fore-bank). Among larger benthic foraminifera (LBF), *Nummulites*, *Operculina*, and *Assilina* are the most typical. *Discocyclina* is less common; its increase in abundance is interpreted as deepening of the basin. Nummulitic limestones and marls reappear in the southwestern Caucasus within the shallow-marine deposits of the Georgian massif shelf basin. It was bordered with the Great Caucasus deep-water flysch basin in the north and the rift-related volcanic area of the Achara-Trialeti in the south. Nummulitic limestones of the Bzyp and Kodori river valleys and the Novy Afon district formed the "nummulite banks" upon the local basement uplifts within the Georgian massif shelf basin. The main components among the LBF are *Discocyclina*, *Nummulites*, and *Operculina*; *Assilina* is absent.

Key words: Crimea, southwestern Caucasus, Late Ypresian–Early Lutetian, nummulitic limestones, paleoenvironmental conditions

1. Introduction

Nummulitic limestones are widely distributed within the Northern Peri-Tethys from the Pyrenees to the Trans-Caspian region. Within the eastern Black Sea region they are dated as Late Ypresian–Early Lutetian. Throughout that interval vast carbonate platforms with "nummulite banks" were formed in the Crimean Mountains (Kopaevich et al., 2008; Lygina et al., 2010), in the territory of the Georgian Massif and Northern Turkey.

Nummulitic limestones can have high rates of porosity and permeability; they possess good to excellent reservoir properties in central and to a lesser extent southwestern Crimea (Kopaevich et al., 2008). The coeval nummulitic limestones of the Trans-Caucasus region do not possess such properties, as they are strongly condensed in the postdiagenetic alteration.

The main aim of this study was to establish the distribution of shallow-water nummulitic facies in the eastern Black Sea region and their prolongation into the offshore area of the Black Sea (Shatsky Rise). As the nummulitic limestones are known as good reservoirs in the Middle East, North Africa, and the Mediterranean region, the same is expected for this region. This work is based on the study of lithologic and sedimentological features of nummulitic facies and adjacent deposits of Crimea, the Sochi region (Russia), and Georgia (Figure 1). Data from microscopic study of thin sections, study of reservoir properties (porosity and permeability) of the rocks and well sections, and analysis of the published literature were used.

2. Materials and methods

During the fieldwork, detailed lithologic and sedimentological description of the Eocene deposits of 10 sections from Crimea and 4 outcrops of the southwestern Caucasus was done. The bulk of field data for the southwestern Caucasus region is affected by the worse exposure of the rocks and inaccessibility of the sections in the densely vegetated mountainous region. Thus, we were forced to use mostly published data. This also explains the difference in the number of studied thin sections.

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Figure 1. Sketch map of the investigated areas (hatched).

The samples were collected with an interval of 0.2–1 m or 1–3 m in monotonous sequences. More than 100 thin sections of Crimean and about 15 thin sections of Caucasian rocks were analyzed. Microscopic description focused on the ratio of micrite and biogenic components, composition, size, shape, degree of rounding and composition of skeletal remains, quantity and distribution of terrigenous component, authigenic mineralization and diagenetic changes. To define the texture of the carbonates the classification of Dunham, supplemented by Embry and Klovan (1971), was used.

To reconstruct paleoenvironmental conditions, the model of Wilson (1975), who recognized 24 standard microfacies assembled into nine standard facies belts, was used. Thus, at first various microfacies were singled out based on analysis of the macroscopic characters of deposits of Crimean and Caucasian outcrops (stratification, presence of unconformity surfaces of different types, etc.), as well as microscopic descriptions of thin sections (for detailed information about Crimean deposits see Lygina, 2010). The model of Arni (1965) for nummulitic accumulations was used for comparison. Nummulitid paleoecology and paleoenvironmental conditions of the studied nummulitic accumulations (paleodepth, sea bottom relief, hydrodynamics, etc.) were interpreted after Hottinger (1997), Nemkov (1962), Portnaya (1974), Zernetski (1980), and Zernetski and Lul'eva (1990).

Larger benthic foraminifera (LBF) generic abundance and its change in the sections and space were examined using published literature data. Analysis of the distribution of larger B-forms (microspheric generation) and smaller A-forms (megalospheric generation), allowing inference of whether a LBF assemblage is autochthonous or allochthonous (Aigner, 1985), was also done using published data.

Data on porosity and permeability of the nummulitic limestones of six Crimean sections and Caucasian outcrops were determined instrumentally with the kerosene impregnation technique. Sampling was carried out by drilling oriented cylinders of 4 cm in diameter with different lengths in the outcrops. The samples were taken from Inkerman (1 sample), Skalistoye (4 samples), Maryino (5 samples), Litvinenkovo (6 samples); in the sections of Ak-Kaya (4 samples) and Prolom (4 samples) the samples were drilled from blocks of limestones chaotically located at the bottom of the quarries. Laboratory preparation of the samples was conducted in accordance with GOST 26450.0-85 (Gosudarstvenniy Komitet po Standartam, 1985). The further drilling and trimming of the cylinders was carried out using a drilling machine (Coretest Systems, Inc.), universal cutting and grinding machine (Discoplan-TS), and grinding and polishing machine (Rotopol-35, Struers GmbH). Determination of porosity and permeability for gas (helium) was made on an STO 44235454-001-2006 with AR-608 installation (Coretest Systems).

Porosity percentage in the other Crimean outcrops was determined visually in the thin sections. Seventeen thin sections of the Crimean nummulitic limestones were made with epoxy impregnation for more accurate porosity determination.

Porosity and permeability of the Abkhazian nummulitic limestones were determined for a characteristic standard sample drilled from each outcrop.

3. Crimean Eocene

3.1. Stratigraphy

Eocene nummulitic facies of Crimea have been studied since the end of the 18th century. A review of these early studies up to the first half of the 20th century was provided by Voloshina and Nemkov (1969). Some historical background and modern ideas of stratigraphic zonation of studied deposits of Crimea are presented in Figure 1 from Lygina et al. (2010). The correlation scheme of studied sections of Crimea is shown in Figure 2. The correlation is based on the work of Bugrova (1988a, 1988b), Benyamovsky (2001), Bugrova et al. (2002), and Zakrevskaya (2005).

Biostratigraphic data for the Eocene of the Russian segment of the southern slope of the western Caucasus based on LBF were given by Zakrevskaya (2005), Zakrevskaya et al. (2009, 2011), and Koren' (2006). Stratigraphic references of the studied Abkhazian sections are based on Mrevlishvili (1978) and Salukvadze (1993).

3.2. Geologic setting of the Eocene Deposits of Crimea

The Upper Ypresian–Lower Lutetian nummulitic limestones belong to the Cretaceous to Cenozoic sedimentary cover of the Kimmerian (Pre-Cretaceous) folded region of the Crimean Highlands dipping slightly westward and northwestward. They form the westernmost

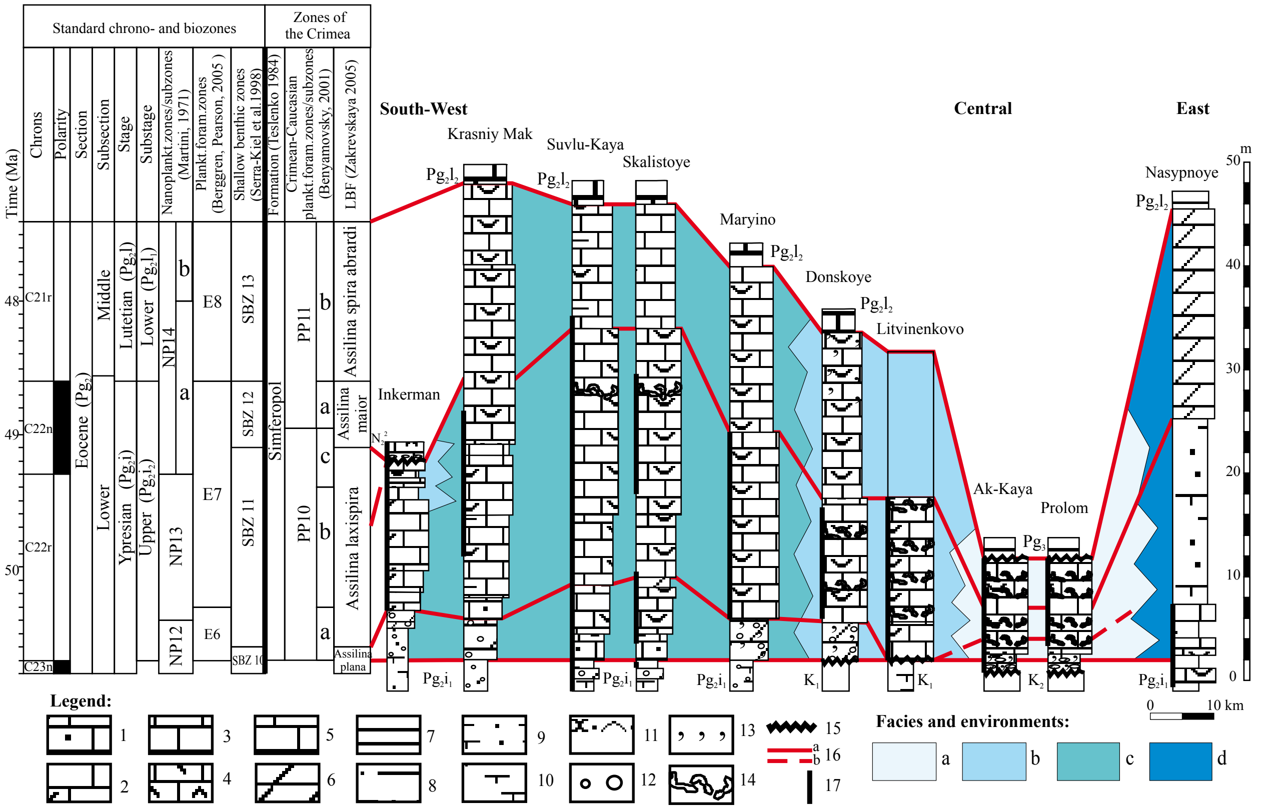

Figure 2. Correlation and facies scheme of studied sections of the Crimean Mountains (modified after Lygina et al., 2010). Correlation of standard chrono- and biozones is from Gradstein et al. (2004). Legend: 1 – silty nummulitic limestone; 2 – clayey nummulitic limestone; 3 – nummulitic limestone; 4 – detrital limestone without nummulitids; 5 – limestone; 6 – marl; 7 – clay; 8 – silty clay; 9 – calcareous silty clay; 10 – calcareous clay; 11 – calcareous sandstone with mollusk tests; 12 – rock with nummulitid tests of different sizes; 13 – glauconite; 14 – hardground surface with *Thalassinoides* burrows; 15 – unconformity surface; 16 – correlation line (a – certain, b – uncertain); 17 – sampled interval of section. Facies and environments according to the models of Arni (1965) and Aigner (1985): a – nummulite bank; b – nummulite bank, transitional to back-bank; c – back-bank; d – fore-bank.

chain of cuestas of the Second (Inner) Range of the Crimean Mountains. A band of nummulite limestone outcrops stretches northeastwards from the Sevastopol to Simferopol regions (southwestern and central Crimea) and then to the Stary Krym and Feodosia region in eastern Crimea (Figure 3). Sections of up to 60 m thick are well exposed in either building stone quarries or numerous natural scarps with characteristic tower- or statue-like weathering shapes (Figure 4). The studied sections are situated in southwestern Crimea (Inkerman, Krasniy Mak, Suvlu-Kaya, Skalistoye, and Maryino sections), in central Crimea east of Simferopol (Donskoye and Litvinenkovo), and near Belogorsk (Ak-Kaya and Prolom) and in eastern Crimea (Nasypnoye).

These rocks compose the Simferopol regional horizon and the formation of the same name. They concordantly overlap clayey and marly deposits of the Bakhchisaray Formation (lower to lowermost Upper Ypresian) in SW Crimea; a low-angular unconformity appears in Central Crimea, in the NE of Simferopol and in the Belogorsk district. The nummulite limestones overlie Paleocene and Upper and also Lower Cretaceous strata there, with total depth of erosion up to 400–500 m (Nikishin et al., 2006). Farther to the east, nummulitid-bearing beds' concordant relations with older beds reappear. The top of the Simferopol Formation in Central Crimea is erosional also, and Oligocene strata of the lower Maykop Superformation truncate the Upper Lutetian and Upper Eocene deposits there.

3.3. Description of the Crimean sections

Detailed macro- and microscopic descriptions of typical sequence units of each facies setting of the Crimean Mountains and their stratigraphic references based on published data were given by Lygina et al. (2010). Upper Ypresian to Lower Lutetian limestones concordantly overlie calcareous clays and marls of the lower and lowermost Upper Ypresian and have uniform structure in general. Wackestone texture dominates in the lower portions (5–10 m, SBZ10, Figure 2) of the Inkerman, Krasniy Mak,

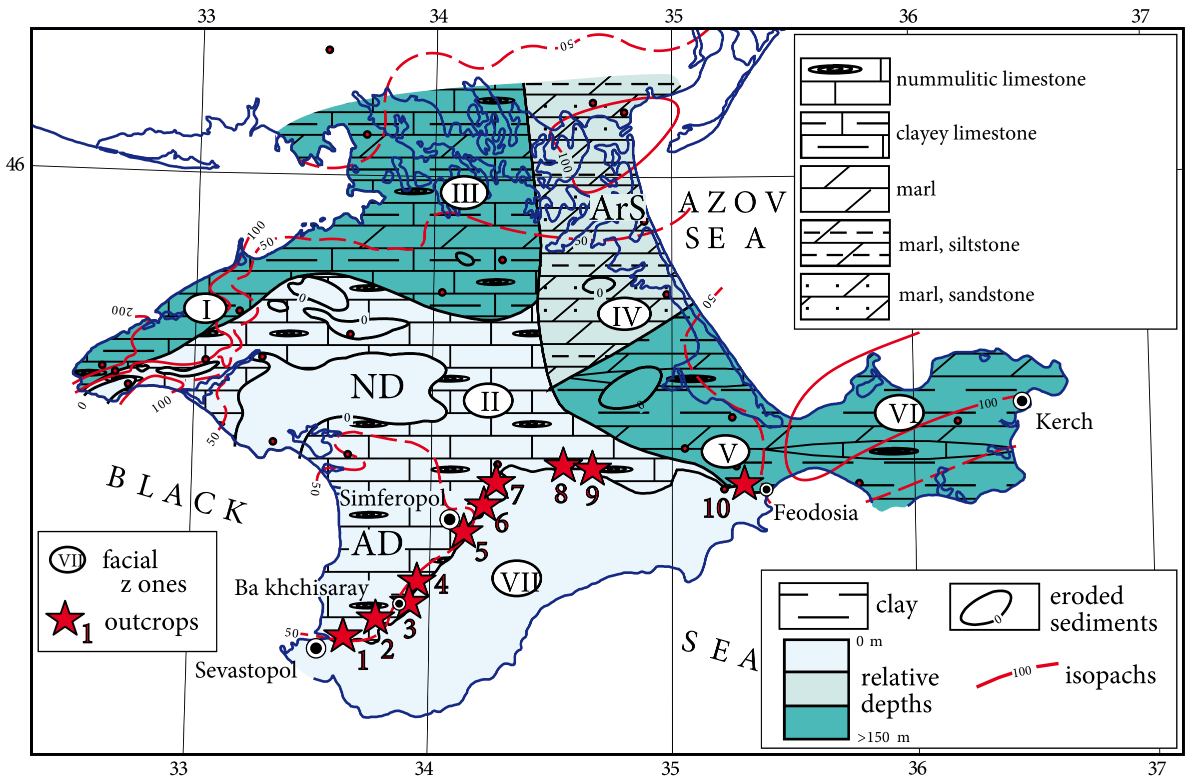

Figure 3. Early to Middle Eocene lithofacies map of the Crimea. Facies zones (Roman numerals in ovals): I – Tarkhankut; II – Central Crimea; III – Sivash; IV – North-eastern; V – Indol; VI – Kerch; VII – Crimean Mountains. Outcrops (red numbers): 1 – Inkerman; 2 – Krasniy Mak; 3 – Suvlu-Kaya; 4 – Skalistoye; 5 – Maryino; 6 - Donskoye; 7 - Litvinenkovo; 8 – Prolom; 9 – Ak-Kaya; 10 – Nasypnoye. Abbreviations: AD – Alma Depression, ArS – Arabat Spit, ND – Novosyolovka Dome.

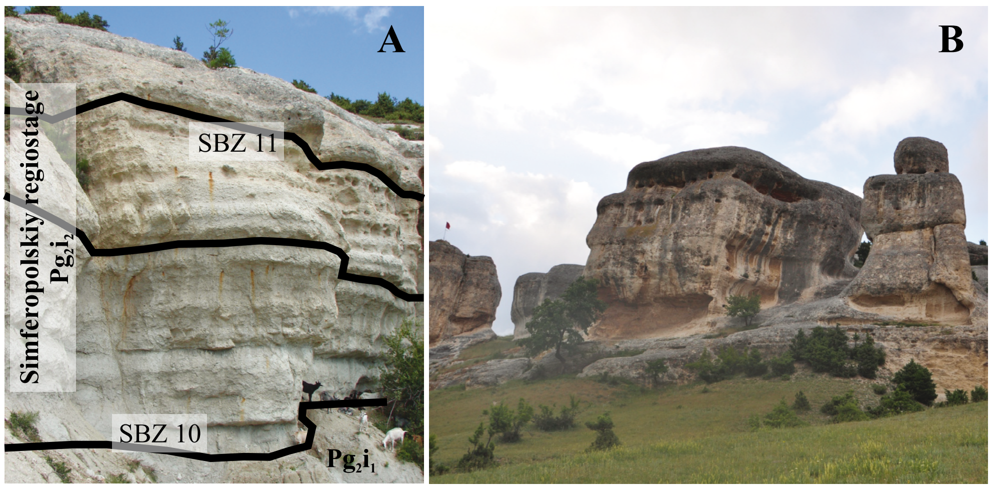

Figure 4. Nummulitic limestones of Suvlu-Kaya mountain near Bakhchisaray. A – part of the studied section with stratigraphic references seen in Figure 2. B – nummulitic limestone "statues" of Suvlu-Kaya.

Suvlu-Kaya, and Skalistoye (Figure 5A) sections; mud- and packstones are subordinate. Rudstone and floatstone interbeds occur in the Inkerman and Suvlu-Kaya sections. The micritic matrix contains carbonate skeletal debris. LBF tests (*Discocyclina* and small *Nummulites* mainly) are generally infrequent, and other bioclasts (echinoids, smaller benthic foraminifera, bivalves, and bryozoans) are rare. Dolomitization of the rocks is usually 1%–8%, with

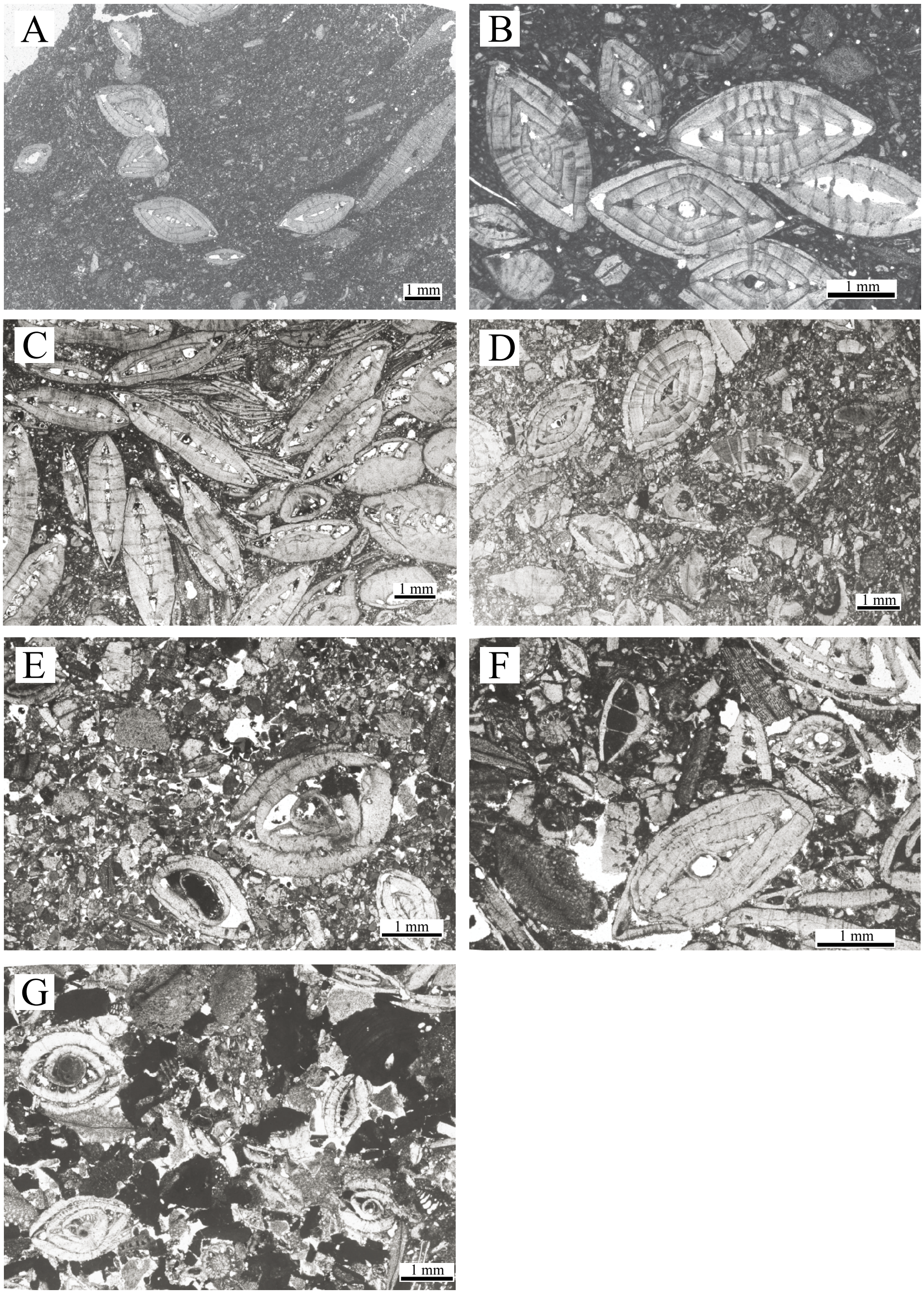

Figure 5. Thin sections of Crimean nummulitic limestones. Photomicrographs were done with parallel polars. A – Skalistoye section, the lower part. Nummulitic wackestone. *Nummulite* and *Discocyclina* tests encrust the walls of the bioturbation tunnel. B – Krasniy Mak section, the upper part. Nummulitic pack- and wackestone. Most of the *Nummulites* test chambers have no infill. C – Inkerman section, the upper part. Nummulitic rudstone with thin bioclastic matrix; *Assilina* tests are predominant and built of Mg-rich calcite. Most chambers of large tests have no infill. D – Suvlu-Kaya section, the upper part. Floatstone with dominant *Nummulites* tests with thin bioclastic matrix. The tests have traces of surficial bioerosion and borings. Glauconite fills some chambers of the tests. E – Ak-Kaya section, the lower part. Cement-poor grainstone composed of rounded nummulitid clasts mainly and resedimented glauconite grains. F – Litvinenkovo section. Nummulitic floatstone. Some pore walls are encrusted with thin drusy spar calcite rims. G – Nasypnoye section. Grainstone composed of *Nummulites* and red algae bioclasts with admixture of other LBF, echinoids, and sand-size quartz grains.

the highest values in the Inkerman section (up to 15%–20%).

The LBF assemblage consists of *Nummulites distans minor* d'Arch., *N. globulus* Leym., *N. rotularius* Desh., *N. atacicus* Leym., *N. murchisoni* Rütim., *N. irregularis* Desh., *N. distans* Desh. (the upper part of SBZ10, Figure 2), *Assilina placentula* (Desh.) (the lower part of SBZ10, Figure 2), *A. exponens* (Sow.), *Operculina gigantea* Mayer, *O. ammonea* Leym., *Discocyclina sella* (d'Arch.) (rock-forming species), *D. pratti* (Mich.), *D. archiaci* (Schlumb.), *D. dispansa* (Sow.), *D. discus* (Rüt), *D. strophiolata* (Gümb.), *D. fortisi* (d'Arch.), etc. (Nemkov and Barkhatova, 1961; Portnaya, 1974; Zakrevskaya, 1993).

Porosity varies significantly in accordance to pelitic and micritic content, and permeability is very low to low.

The main upper parts of those sections (up to 40 m, SBZ11-13, Figure 2) as well as the Maryino section consist of abundant Mg-rich calcite rudstones with subordinate float-, pack- grain-, and wackestones with low to moderate amounts of micrite and thin detrital component (Figures 5B and 5C). Bioclasts, among which are dominate large nummulitids (*Nummulites* and *Assilina*) and other biota remnants (bivalves, echinoids, bryozoans, rare red algae, ostracods, etc.), are commonly stacked parallel to lamination; in the uppermost parts of the sections the relative quantity of *Discocyclina* increases. Bioturbation ranges from intensive to very intensive; micritization of bioclasts is not typical. Bioeroded bioclasts are most typical in the Suvlu-Kaya section (Figure 5D). Silty to fine sand siliciclastic admixture is common, but very rare (less than 1%).

The LBF recorded here by Nemkov and Barkhatova (1961), Portnaya (1974), and Zakrevskaya (1993) are *Nummulites distans minor* d'Arch. (the lower part of SBZ11, Figure 2), *N. globulus* Leym., *N. rotularius* Desh., *N. atacicus* Leym., *N. irregularis* Desh., *N. distans* Desh., *N. murchisoni* Rütim., *N. nitidus* de la Harpe, *N. ficheuri* (Prever), *N. pratti* d'Archiac, *N. partschi* de la Harpe, *Assilina ? exponens* (Sow.), *A. laxispira* (de la Harpe) (the most abundant species), *A. reicheli* Schaub, *A. maior* (Heim) (topmost the upper part of SBZ11, Figure 2), *Operculina ammonea* Leym., *Discocyclina sella* (d'Arch.), *D. pratti* (Mich.), *D. archiaci* (Schlumb.), *D. dispansa* (Sow.), *D. aspera* Gümb., *D. andrusovi* Cizan., and *D. bartholomei* (Schlumb.). The LBF species composition of SBZ12-13 is similar to that of SBZ11, but the test diameter increases: *Nummulites* is up to 8.2 cm and *Discocyclina* is more than 10 cm.

High to very high porosity (18%–27%, up to 30%) of those rocks is isolated mainly due to the lack of mineral fill within the chambers of nummulitid tests. Permeability of the rocks varies from low to moderate.

In the subsurface nummulitic facies spread westwards into the Alma Depression and northwestwards into central and western Crimea (Figure 3). The limestones at the top of the Novosyolovka Dome and at the crests of the smaller anticlines were eroded during the post-Eocene break-ups (Nemkov and Barkhatova, 1961).

In the Belogorsk district, Eocene rocks unconformably overlap Paleocene and Upper Cretaceous carbonates with low-angular unconformity (Figure 6A). The Ak-Kaya (Figures 6A–6C) and Prolom (Figures 6D and 6E) sections are about 10 m thick; they are composed of sorted rudstone and medium to coarse grainstone (Figure 5E) with very uniform composition of carbonate grains: 60%–80% of bioclasts are LBF. Many hardground surfaces with subvertical burrows of crustaceans and sometimes with *Gastrochaeonolites* ichnofossils are present (Figure 6D). Low to very low micrite content (5%–7%, rarely 10%) and intensive fragmentation of bioclasts is typical for the rocks. The Donskoye and Litvinenkovo sections of the Simferopol district are similar to the former ones, but contain more numerous entire nummulitid tests and more micritic components. The LBF tests are concentrated in lenses and interbeds and randomly oriented. The drusy spar calcite incrustation of some pores in the Ak-Kaya and Litvinenkovo sections (Figure 5F) may have a vadose nature due to subaerial exposition. Visible porosity of the rocks varies from 10%–15% to 25% in thin sections.

Rare *Nummulites distans minor* d'Arch., *Assilina placentula* (Desh.), *Operculina gigantea* Mayer, numerous *Discocyclina sella* (d'Arch.), and also *D. discus* (Rüt), *D. andrusovi* Cizan., and *D. pratti* (Mich.) are present in the SBZ10 deposits (Figure 2). In SBZ11 *N. distans* Desh., *N. murchisoni*, rare *A. laxispira* (de la Harpe), *O. escheri* Hott., and *O. karreri* Penecke are present and in SBZ12-13 *D. pratti* (Mich.), *D. pseudoaugustae* Port., *A. maior*, and *A. spira abrardi* are present (Portnaya, 1974; Zakrevskaya, 1993).

The Nasypnoye section is composed of calcareous clays and marls (up to 75 m thick; Nemkov and Barkhatova, 1961) with small nummulitid tests and with thin lenses and interbeds (0.3–1 m) of bioclastic pack-, rud-, and grainstones (Figure 7). Those are composed of coarse to medium sorted and rounded fragments of nummulitids (2.4 mm on average; Lygina et al., 2010) and red algae with less common smaller benthic foraminifera, echinoids, and fish remnants (Figure 5G). Red algae sometimes encrust nummulitids.

Nemkov and Barkhatova (1961) recorded there *Nummulites planulatus* (Lam.), very rare *N. nitidus* de la Harpe, and *Discocyclina archiaci* (Schlumb.), *D. nummulitica* (Gümb.), *Asterocyclina taramellii* (Schlumb.), *A. stella* (Gümbel), and large *Operculina ammonea* Leym. of Early Ypresian age. *N. irregularis* Desh. and *N. murchisoni* Rut. found by Zakrevskaya (1993) determined the age of the deposits as Late Ypresian.

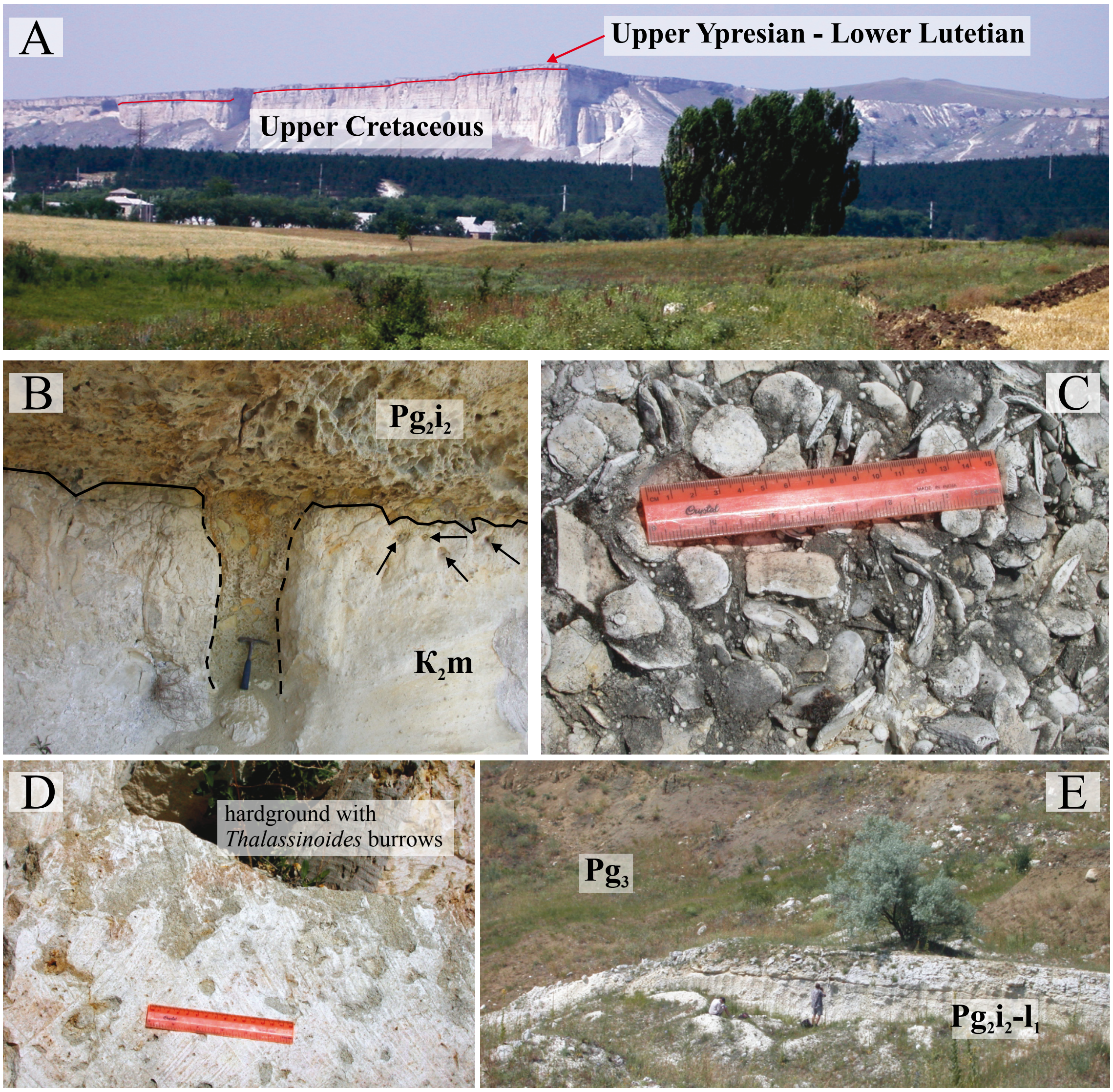

Figure 6. Bedded nummulitic limestones (Upper Ypresian-Lower Lutetian) of the Ak-Kaya mountain section (Belogorsk district) overlying Upper Cretaceous carbonates; the contact is shown by the red line (A). B – the contact surface (the solid line) between Maastrichtian (K_2m) and Upper Ypresian (Pg_2i_2) limestones is irregular with multiple burrows (arrows) and large cracks (dotted line) (the top of the mountain Ak-Kaya). C – accumulation of nummulitid tests in the block of limestone in the quarry on the top of the mountain Ak-Kaya. D – surface of hardground with *Thalassinoides* burrows in the block of limestone in the Prolom quarry (Belogorsk district). E – Oligocene clays (Pg3) overlying nummulitic limestones (Pg2i2-l1) in the Prolom quarry (Belogorsk district).

Those rocks grade eastwards (in the Indol and Kerch zones of eastern Crimea) into a sequence of calcareous claystones, marls, and limestones (40–300 m) with planktonic and smaller benthic foraminifera deposited within the deep (200 m and probably more) basin (Figure 3). The key wells to the north, in the Arabat Spit district, show a Middle Eocene sequence of glauconitic sandstones and limestones with small nummulitid tests (Portnaya, 1974). Those sections are reduced with the lack of E6-7 zones.

3.4. Distribution of large benthic foraminifera in Eocene deposits of Crimea

Basing on previous studies by Golev and Andreeva-Grigorovich (1982), Nemkov and Barkhatova (1961), Portnaya (1974), Zakrevskaya (1993, 2005), Zakrevskaya et al. (2011), Zernetski (1980), and Zernetski and Lul'eva (1990), the distribution of the LBF genera prevailing in the investigated sections from the Crimean Eocene was analyzed to reconstruct the paleoenvironmental conditions.

Figure 7. Graded nummulitic limestone bed in calcareous clays and marls of the Nasypnoye outcrop (A) with prevalence of sorted nummulitid tests (B).

Numerous small *Discocyclina* and *Nummulites* are common in the lower part of the southwestern and central Crimean sections, and the relative quantity and diversity of thick tests of nummulitids increases upwards. *Nummulites*, *Operculina*, and *Assilina* are the most typical in the upper part of those sections, while monotonous and large-sized *Discocyclina* is much less frequent. LBF tests are either lenticular or are flat having fine-sized granules and often located unoriented in the rock (Portnaya, 1974). Up-section (SBZ12-13) an increase in test size is observed, and maximum test diameters (8–10 cm) are reached in grainstone facies in central Crimea. Here *Nummulites polygyratus* Desh., *N. distans* Desh., *Assilina maior* (Heim), *A. spira abrardi* Schaub, and *Discocyclina pratti* (Mich.) have the biggest test size and mostly represent microspheric generation (Portnaya, 1974; Zakrevskaya, 1993). This LBF association represents a residual assemblage (Aigner, 1985). The reappearance of *Discocyclina* and other orthophragmines in the uppermost part of the sections is interpreted as a deepening of the basin.

Carbonate clays with small *Nummulites* and interlayered with nummulitic limestone dated to the Early-Late Ypresian transition have accumulated in eastern Crimea. Diversity and abundance of *Asterocyclina*, general low species diversity, and lack of microspheric B-forms of *Nummulites* are noted here (Bugrova et al., 2002). This suggests that tests were moved from their primary habitat and represent an allochthonous LBF assemblage (Aigner, 1985).

From western to eastern Crimea a number of *Nummulites* species with compressed or relatively compressed spiral (*N. distans*, *N. rotularius*, *N. globulus*) and granular forms (*N. burdigalensis*, *N. partschi* group) and *Discocyclina* and *Assilina* decrease, and a number of species with a high spiral (*N. nitidus*, *N irregularis*) and also the diversity of *Orbitoclypeus* (*O. schopeni*, *O. furcatus*, *O. bayani*, *O. douvillei*, *O. varians*) increase. The eastern Crimean assemblage is close to the North Caucasus (Zakrevskaya, 2011).

It is interesting also that *Assilina* is abundant in the Eocene of Tethyan basins, but absent in the Northern Peri-Tethys territories from eastern Crimea in the west to Central Asia in the east. This may be connected to the specific hydrology of periplatform seas distributed here and poorly connected to the open oceanic water (Zakrevskaya et al., 2011). A stable carbon and oxygen isotope study on Ypresian-Lutetian *Nummulites* and *Assilina* from the Bakhchisaray district (Suvlu-Kaya and Priyatnoye Svidaniye sections) by Vetoshkina and Zakrevskaya (2011) showed that *Assilina* could be more sensitive to decrease of salinity and is therefore absent in basins located farther from the ocean.

4. Eocene deposits of Georgia

4.1. Stratigraphy

Paleocene-Eocene deposits are widespread in Georgia (Figure 8). The area of mainly carbonate shallow-marine deposits of the Georgian Massif is bordered to the north by the remnants of deep troughs in the Greater Caucasus Southern Slope Zone. Within the Achara-Trialeti rifted zone to the south, thick terrigenous sequences with subordinate carbonates and volcaniclastics accumulated during the Paleocene-Early Eocene; sedimentation gave place to widespread basaltic-andesitic and alkaline volcanism in the Middle-Late Eocene. The main source area of clastics was located to the south of the Achara-Trialeti zone (Maysadze, 1998).

The Greater Caucasus Paleogene troughs received clastics mainly from the north (probably the territory of the recent Great Caucasus Ridge). However, some sectors within the shallow sea of the Georgian Massif (Racha-Vandam, Tkibooli-Sachkhere, Trialeti, and some other islands) at times emerged above sea level and supplied terrigenous material to the adjacent deep basin (Maysadze, 1998). During the Middle Eocene main transgression those islands were drowned and formed the substrate for isolated "nummulite banks".

We refer to the nummulitic facies of Abkhazia as "nummulite banks", although their exact facies interpretation remains conjectural, since data about adjacent deposits are scarce.

4.2. Description of the Caucasus sections

Lower and Middle Eocene strata including nummulitic limestones form a part of the Abkhazia tectonic zone (NW part of the Georgian Massif) sedimentary cover, partly detached and dislocated with large folds and disrupted with faults during the recent Great Caucasus orogeny. Due to the humid subtropical climate the mountains are densely vegetated, so natural outcrops are scarce; accessible quarries and road cuts are small and prevent the construction of thick stratigraphic sections. Stronger tectonics than in Crimea led to partial recrystallization of carbonates, commonly obliterating the primary structure. The thickness of the Lower-Middle Eocene limestones can be estimated at 50 to 100 m.

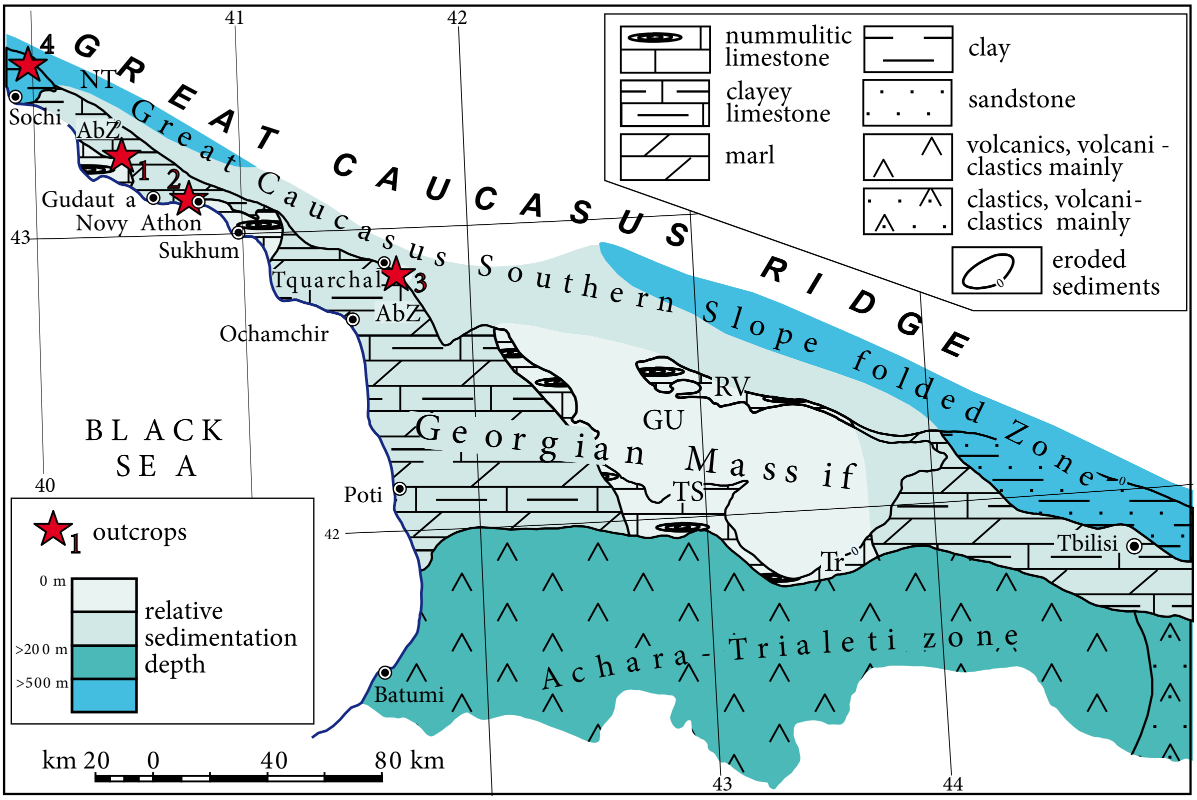

Figure 8. Middle Eocene lithofacies map of Georgia (after Maysadze, 1998, modified). Outcrops (red numbers): 1 – Bzyp; 2 – Novy Afon; 3 – Tquarchal; 4 – Kazachiy Brod. Abbreviations: GU – Georgian Uplift, NT – Novorossiysk Trough; "nummulite banks": RV – Racha-Vandam, Tr – Trialeti, TS – Tkibooli-Sachkhere.

Carbonates of Lower to Middle Eocene age are clayey and contain usually sparse LBF, but in a few localities (near Novy Afon, Sukhum, and Tquarchal) they become a significant component and form "nummulite banks". Locally, these sediments are cut off by the pre-Late Eocene unconformity. According to Salukvadze (1993), nummulitic limestones of Abkhazia are dated mostly as Upper Ypresian or Ypresian; the overlying Lower Lutetian deposits are represented by marls almost everywhere. The taxonomic diversity of nummulitids and orthophragmines of the southwestern Caucasus is close to but poorer than that of the northern Caucasus (Zakrevskaya, 2011).

The outcrops were studied near the Bzyp river canyon opposite the Bzyp Fortress and in the quarry near the Tskhuara hydrosulfuric springs in the area of Novy Afon. A small outcrop of nummulitic limestones with unclear relations (most likely tectonic) with Upper Cretaceous carbonates was discovered above the left flank of the Kodor river valley near Tquarchal (Figure 8).

Deeper marine clayey and marly Paleocene-Eocene deposits without nummulitids are known in the Sochi region in the northernmost part of the Abkhazia tectonic unit (Akhshtyr Formation, about 200 m thick). These soft rocks are easily eroded, affected by creep and slumping, and are rarely exposed in river banks and artificial outcrops.

The roadway in-cut outcrop near the Bzyp pass (Figure 9) is composed of partly recrystallized, bedded pack-, float-, and rudstones with unclearly distinctive bioclastic structure (Figure 10A). The strata dip steeply (ca. 60°) southwestwards. Two types of bioclasts prevail: broken red algae crusts, branches, and rhodolites, and *Discocyclina* tests. Subordinate bioclasts are smaller benthic foraminifera and strongly fragmented echinoids, bryozoans, and bivalve and brachiopod shells. The bioclasts are in part subrounded. The bioclastic wackestone matrix contains some admixture of small peloids; dolomitization is very weak. The rocks are very dense; the measured porosity is as low as 0.97%.

Figure 9. Outcrop of algal-nummulitic limestone near the Bzyp river pass. The outcrop height is about 3 m.

Probably a higher stratigraphic level (Gamkrelidze, 1964) crops out in the small quarry near Tskhuara (Novy Afon region; Figure 11). Thick bedded white and light gray detrital and bioclastic limestones contain fragmented macrofaunal fragments and larger foraminiferal tests. The beds are gently tilted (15°) to the southeast. Bioclastic pack-, rud-, and floatstones are rich in LBF, with prevalent *Discocyclina* tests, along with smaller benthic foraminifera, fragmented bryozoans, echinoids, and red algae crusts and rhodoliths (Figure 10B). Many bioclasts are rounded. The matrix is micritic mainly with an admixture of skeletal detritus. It contains very rare (less than 1%) dolomitic crystals. Total porosity of the rock is low (about 3%).

The Eocene nummulitic limestones in the small outcrop near Tquarchal are tectonically juxtaposed to Upper Cretaceous limestones. Bioclastic limestones (grain-packstone) are massive and unclearly laminated, partly bioturbated bedding dips steeply southwestwards. Entire or broken *Nummulites* and *Discocyclina* tests are abundant, and subordinate bioclasts are represented in the relative descending order by other larger and smaller benthic foraminifera, echinoderms, red algae, and scarce bryozoans and bivalves (Figure 10C). Broken bioclasts are rounded or subrounded. Bioturbation tubes (4–11 mm) are filled with wacke-packstone with smaller foraminifera. These rocks contain the smallest portion of micrite (about 16%).

In contrast to other outcrops, porosity (mainly intergranular) of the rocks rises to moderate values of 7.7%. The pores have thin rims of drusy spar calcite, precipitated probably within the vadose zone (Tucker, 1991).

The deeper shelf sediments of Early-Middle Eocene age between the "nummulite banks" are poorly exposed; they are represented by greenish clayey limestones with *Discocyclina* and marl interbeds with planktonic foraminifera (Gamkrelidze, 1964).

The Paleocene-Eocene Akhshtyr Formation was observed in the roadway in-cut near the Kazachiy Brod settlement (Sochi region, Russia, Figure 12). The grayish sequence of unevenly bedded soft marls and clayey limestones contains interbeds of greenish and purple wackestones (Figure 10D). Carbonate bioclasts are represented by planktonic foraminifera and very rare echinoid (crinoid?) remnants and sponge spicules. Scarce quartzose silt-size admixture is unevenly distributed within the rocks.

5. Discussion

5.1. Tectonic Position of the "nummulite banks"

Isolated shallow-marine carbonate platforms with nummulite banks were characteristic of the Northern

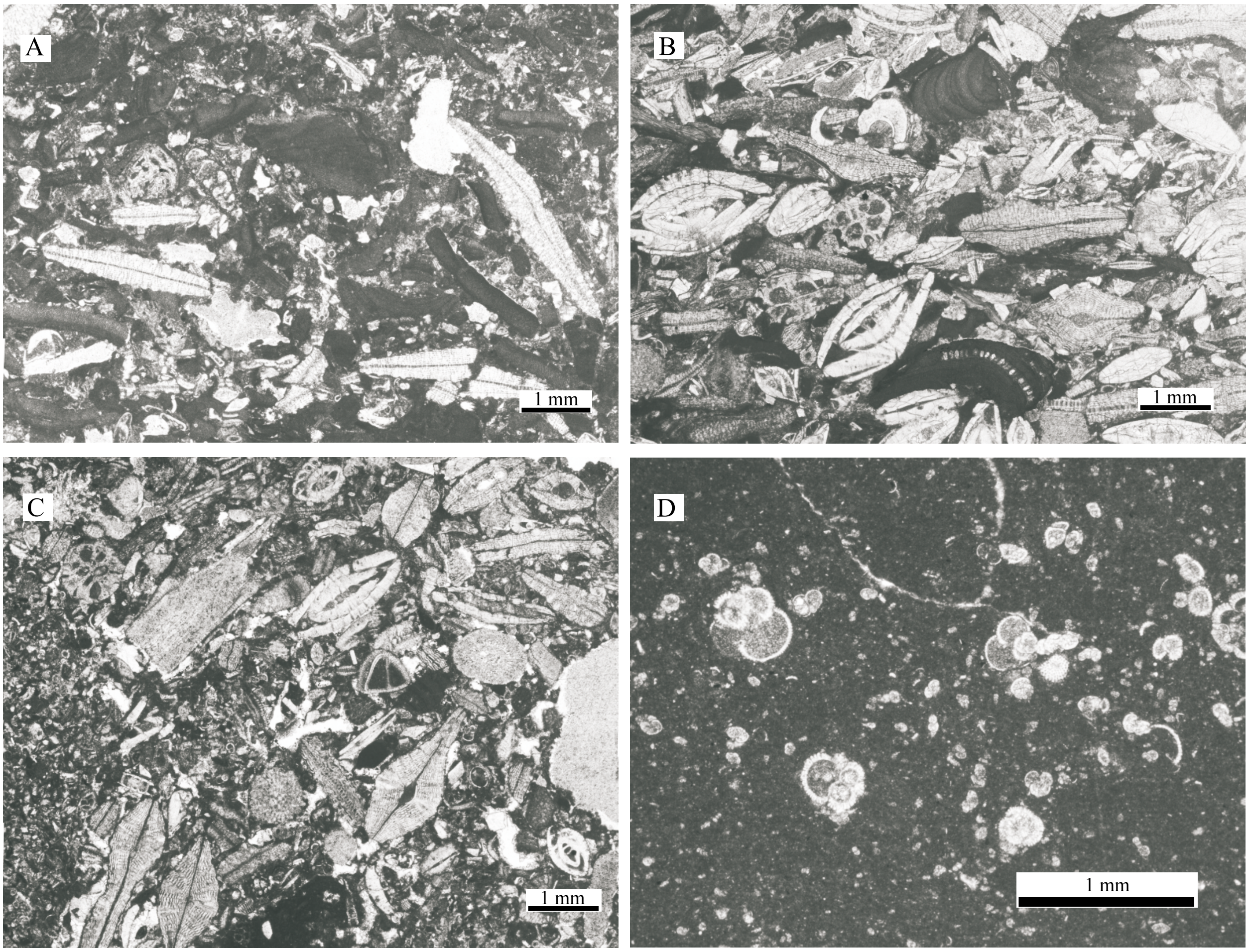

Figure 10. Thin sections of Abkhazian nummulitic limestones and Akhshtyr Formation (Sochi region, Russia) limestones. Photomicrographs were done with parallel polars. A – Bzyp pass entrance outcrop. Bioclastic grain-rudstone composed of red algae bioclasts and *Discocyclina* tests mainly. B – Tskhuara quarry. Polybioclastic pack-rudstone with multiple tests of *Discocyclina*, *Nummulites*, and red algae. C – Tquarchal district. Bioturbated polybioclastic rud-grainstone with multiple *Discocyclina* and *Nummulites* tests. D – Akhshtyr Formation, Kazachiy Brod outcrop. Planktonic foraminifera wackestone.

Peri-Tethys in the Eocene. The Crimean and Georgian platforms were situated upon uplifted blocks flanked by mobile basinal zones. The Crimean structure is placed on a basement of Late Hercynian and Kimmerian (pre-Cretaceous) consolidation, and the Georgian Massif has a heterogeneous basement of Baikalian (late-most Late Proterozoic) and Late Paleozoic folding.

The occurrence and position of "nummulite banks" appears to be linked to tectonics. Tectonic movements of the Paleocene-Eocene transition and Early Eocene known in Crimea (Nikishin et al., 2006) and Georgia (Maysadze, 1998) may be related to the main compressional event in the Pontides (Nikishin et al., 2011). Subsequent widespread rifting within the Pontides was accompanied with broad late Early-Middle Eocene transgression in adjacent regions and its deposits sealed the compressional tectonic structures. Within the Georgian Massif stress tectonics resulted in blocky movements, which created uplifts favorable for the origin of shallow-water nummulitic accumulations. The same paleo-uplift of Gudaut is distinctive in the offshore prolongation of the Georgian Massif, the Shatsky Swell structure (Nikishin et al., 2015), so we assume the presence of the "nummulite bank" on it too (Gudauta "bank" in Figure 13).

Disappearance of shallow-water carbonate sedimentation in Crimea and the western Caucasus at the Middle-Late Eocene transition may be related to the next peak of folding in the Pontides. Stress tectonics caused the appearance of local discontinuities and the former accelerated syncompressional subsidence of the Crimean and Georgian shelf basins and drastic increase of clastic influx to the second one (Maysadze, 1998).

Figure 11. The quarry near Tskhuara water springs. The thickness of the section is ca. 7 m.

Figure 12. Outcrop of the bedded marls and clayey limestones of Akhshtyr Formation near the Kazachiy Brod settlement (Sochi region, Russia), a general view of the about 7-m-thick studied section.

5.2. Paleoenvironmental interpretation of studied deposits

5.2.1. Crimea

The Crimean nummulite bank (Figure 14) was located upon the Early Eocene paleo-uplift, where the foot of bioclastic and detrital nummulitic limestones truncates Paleocene and Upper Cretaceous rocks.

The nummulite bank and its inner rim transitional to back-bank facies is exposed in the sections of the Belogorsk (Ak-Kaya and Prolom) and Simferopol (Donskoye and Litvinenkovo) districts accordingly (Figure 2). In the Ak-Kaya and Prolom sections the prevalence of LBF bioclasts (60%–80%), their intensive fragmentation in grainstone, and the presence of hardgrounds with subvertical crustacean burrows indicate small depth of accumulation (fair-weather wave activity zone, less than 20–30 m) of the nummulite bank. Hardgrounds with *Gastrochaeonolites* ichnofossils suggest a strong wave impact on the consolidated sediments. The Donskoye and Litvinenkovo sections contain more numerous entire nummulitid tests and micritic components formed behind the crest and at the leeward side of the nummulite bank (Figure 14). Sediments of the bank top with evidence of drainage (vadose low-Mg calcite drusy cement) are known in the areas of the Ak-Kaya and Litvinenkovo sections.

Accumulation of the lower part of the southwestern Crimean deposits (first 8–10 m of the Inkerman-Maryino sections, Figure 2) occurred in normal-salinity shallow waters of a restricted shelf, below the fair-weather wave base according to the model of Wilson (1975), but above the depth of occurrence of LBF (50–80 m) (Nemkov, 1962; Hottinger, 1997) that corresponds to the back-bank facies of Arni (1965). The main upper parts of those sections (up to 40 m thick) were deposited in the same conditions but in a zone of higher hydrodynamic activity, near the fair-weather wave base. The graded beds of nonoriented bioclasts were deposited with storm-induced gravity flows. Relative decrease of the depth is supposed in the Inkerman (because of the sharp abundance of *Nummulites* and *Assilina* and the higher primary dolomitization) and Suvlu-Kaya (the higher portion of bioclastic components of the rocks; noticeable bioerosion of bioclasts) districts. A local depression with relatively more numerous *Discocyclina* remnants separated those uplifts (Figure 15).

The inferred size of this bank (together with the back-bank facies) reaches 120–150 km and it may be assumed as a single isolated carbonate platform. The sea bottom was flat in general; it was in the photic zone, in relatively quiet hydrodynamic conditions, below and near the fair-weather wave base. The mean depth may be estimated as 20–50 m.

Calcareous clays with thin lenses and interbeds of nummulitic limestones of the Nasypnoye section correspond to the fore-bank facies of Arni (1965) and Aigner (1985). Nummulitic pack- and grainstones with sorted LBF and other remnants were deposited by storm-induced gravity currents (grain flows, turbidites, and calciturbidites) at the foot of the carbonate platform slope (Wilson, 1975). The presence of diverse *Asterocyclina*

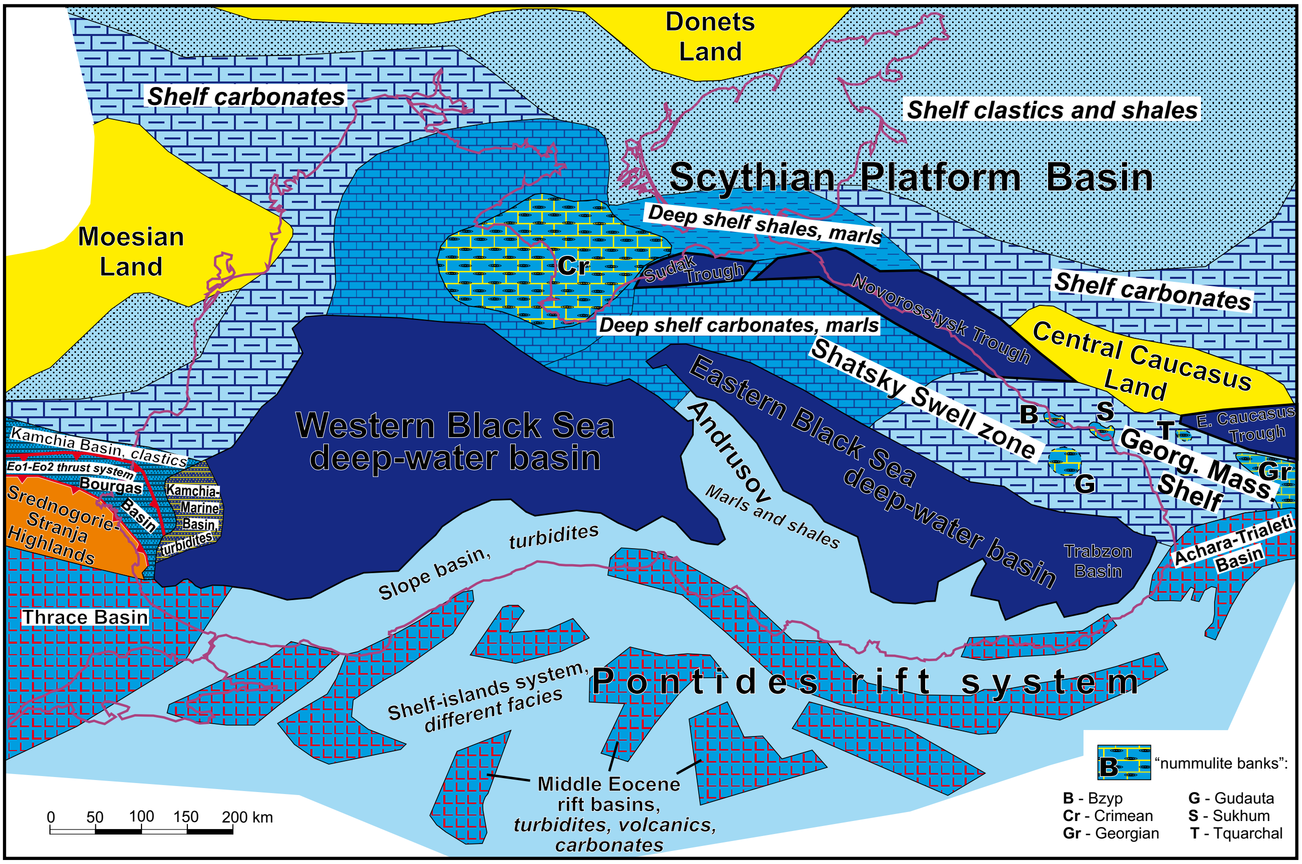

Figure 13. Middle Eocene paleotectonic-lithofacies map of the Black Sea region (adapted from Nikishin et al., 2015).

in clayey sediments indicates a probable depth of sedimentation of 80–120 m (Nemkov, 1962; Hottinger, 1997). *Lithotamnion* clasts resedimented here suggest the existence of a belt of red algae above, in the lower part of the photic zone (50–80 m). Indol and Kerch zones with LBF-free calcareous claystones, marls, and limestones belonged to the area of the deep shelf basin (150–200 m or more). The northern slope of that basin may be traced in the Arabat Spit zone with the increase of clastics and the reappearance of LBF tests (Portnaya, 1974).

5.2.2. Southwestern Caucasus

Within the Georgian Massif, the Racha-Vandam and Tkibooli-Sachkhere "nummulite banks" are in the neighborhood of the recent Georgian Uplift (Figure 8), with absent (probably eroded) Cenozoic strata, so the main Eocene crest of the massif coincides with its recent elevated part. The long northwestern slope of the massif (the Abkhazia zone) stretched out to the shelf break of the Novorossiysk Trough contained some minor "nummulite banks" upon the local basement uplifts (Figures 8 and 13). Marked segmentation of the ancient sea bottom, active terrigenous input from the south, and the complex tectonic situation in the region in the Eocene created unfavorable conditions for wide distribution of biogenic carbonate sedimentation there. The Sukhum-Novy Afon and Bzyp "banks" were about 25–30 km in diameter (Figure 8); the Tquarchal "bank" was of unknown size and its sediments were eroded almost completely during the pre-Late Eocene break and the recent Caucasian orogenic rising.

Relative prevalence of *Discocyclina* and appearance of red algae among the contributors may mean generally deeper conditions than of the Crimean bank. The deepest conditions may be inferred for the rocks of the Bzyp outcrop, because LBF are represented there with *Discocyclina* tests only. Relatively high micrite content, low diversity of bioclasts (mainly red algae and *Discocyclina*), and their subangular and subrounded shape suggest accumulation of the sediments in the lower part of the photic zone, below the fair-weather wave base but in the zone of high storm wave activity (Wilson, 1975; Tucker, 1991). Among the nummulitic limestones from the studied Abkhazian outcrops the rocks of the Bzyp area may belong to a lower stratigraphic level (Gamkrelidze, 1964) than others.

The deposits of the Tskhuara outcrop (Novy Afon region) with rounded bioclasts of *Nummulites* and *Discocyclina* and accessory biota remnants were accumulated in the shallow-marine moderately agitated

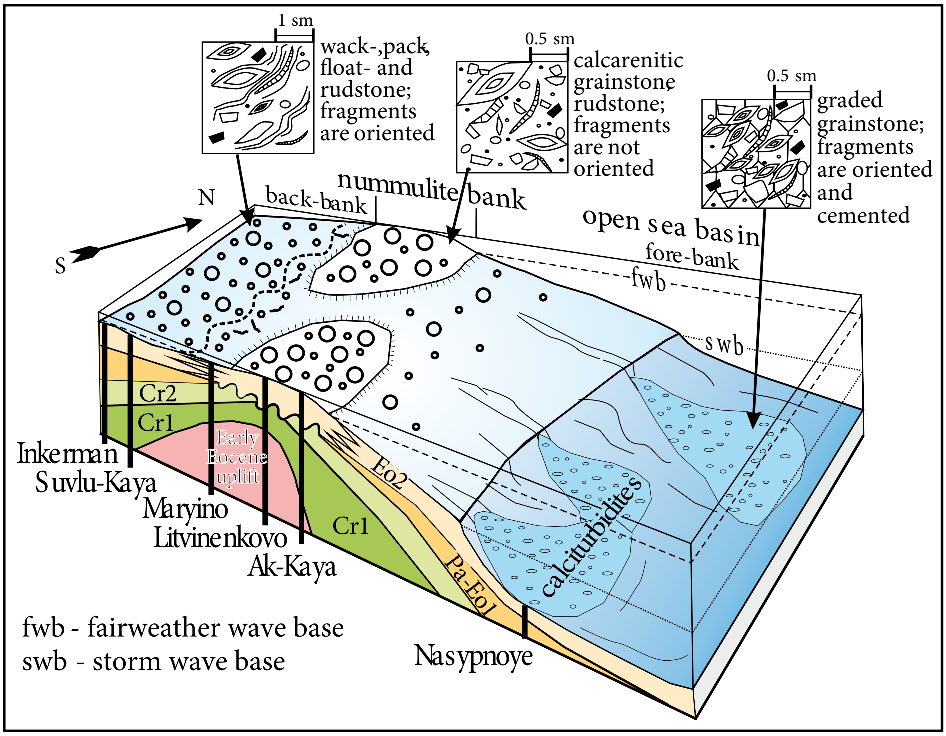

Figure 14. Simplified structure of the Crimean carbonate platform (after Lygina et al., 2010, with changes). Deposits: Cr1 – Lower Cretaceous, Cr2 – Upper Cretaceous, Pa-Eo1 – Paleocene-Lower Eocene, Eo2 – Middle Eocene.

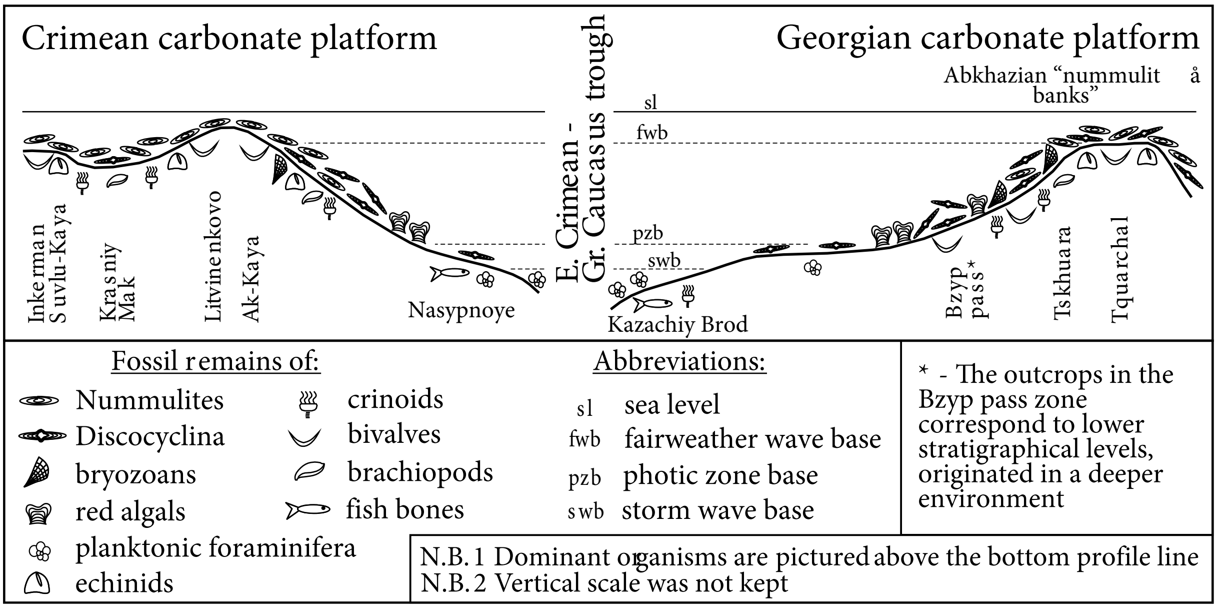

Figure 15. Distribution of the main organisms in the nummulite banks of Crimea and Abkhazia.

water within the fair-weather wave activity zone with episodes of quiet hydrodynamics (Wilson, 1975; Tucker, 1991). Those rocks contain the maximum quantity of bryozoan remnants (about 7%).

In the Tquarchal section, entire or broken tests of *Nummulites* and *Discocyclina* are abundant. Bioclasts within the rocks are broken and rounded or subrounded. Rocks contain the least portion of micrite. All of these characteristics indicate accumulation of the sediments in very shallow waters with inconstant, generally high fair-weather wave activity (Wilson, 1975; Tucker, 1991). Though the *Nummulites*/*Discocyclina* ratio for the studied Abkhazian outcrops is the highest for the Tquarchal outcrop deposits, it is lower than for central Crimea. However, the rocks show evidences of subaerial exposition: the presence of the vadose drusy spar low-Mg calcite in the pores (Tucker, 1991) may be related to drainage of the top of the "bank" during the Middle Eocene sea-level changes or the emergence of its territory at the Middle-Late Eocene transition.

The abundance of bioclastic limestones in the structure of the Abkhazian "nummulite banks" is a mark of higher hydrodynamic activity, presumably storm-induced. That is not surprising for the small size of banks and their position within the open sea close to the deep trough. Thus, the Georgian Massif acted as a carbonate platform in the Middle Eocene with local "nummulite banks" within it (Figure 13).

Micritic and clayey deposits with mainly planktonic foraminifers of the Paleocene-Eocene Akhshtyr Formation were sedimented within the distal deep shelf to the upper continental slope zone below the storm wave base (Wilson, 1975).

6. Conclusions

This work is one of the first attempts to investigate the conditions of nummulitic facies of the southwestern Caucasus for the last 20 years. The structure of the Crimean carbonate platform has been described in detail elsewhere (Kopaevich et al., 2008; Lygina, 2010; Lygina et al., 2010). Georgian nummulitic facies have not yet been studied sufficiently, neither in stratigraphic nor in sedimentological aspects. This investigation of Abkhazian rocks is still preliminary, and we plan to continue it.

Within the Crimean carbonate platform, clearly distinguished are the main facies of nummulite bank and its lee-side slope (central Crimea), back-bank shelf plain (southwestern Crimea) and fore-bank deep basin-ward slope with predominantly terrigenous sedimentation.

Abkhazian nummulitic facies were accumulated in the shallow marine photic conditions below or near the fair-weather wave base, in the zone of high storm wave activity.

Distribution of LBF and other characteristic forms is generally uniform in the structure of the banks. Most of the Crimean shallow-water nummulitic facies were inhabited with prevalent *Nummulites* and *Assilina*; the role of *Discocyclina* tests increases in the back-bank depression about 50–80 m deep.

The Abkhazian "nummulite banks" have a higher *Discocyclina*/*Nummulites* ratio, reflecting deeper waters than in Crimea. The distribution of the organisms is similar to that of the Crimean bank; a further difference is in the larger proportion of fragmented bryozoans that inhabited the level near the fair-weather wave base.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (15-05-03004-a and 15-05-04099-a) and sponsored by Rosneft and Total. We thank AS Alekseev and EYu Zakrevskaya for the critical remarks and valuable advices. We are grateful to all our friends, colleagues, and students who participated and supported our fieldwork.

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