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A Characterization and the Formation Conditions of the Callovian–Upper Jurassic Deposits in the Akhtsu Zone (Krasnodar Krai)

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Abstract—Deposits in the Akhtsu zone have been characterized, with the Mzymta River valley as an example. A lithological–paleontological and geochemical characterization of Callovian–Tithonian deposits has been given. A paleogeographic model has been proposed for the Akhtsu reef, and a chronostratigraphic profile has been established for the Callovian–Albian sedimentary basin in the Easter Black Sea region.

Keywords: reefs, Mzymta, Northwestern Caucasus, Callovian, Late Jurassic

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INTRODUCTION

Reef massifs are good traps for oil and the Callovian–Upper Jurassic biogenic calcareous deposits in the Mediterranean zone (Tethys Ocean), e.g., Caucasus, are not an exception. Information acquired from the studies of biogenic deposits, including reef deposits, in the Caucasian region is of great importance for oil prospecting in the Black Sea–Caspian basin and interpretation of seismic data. Callovian–Tithonian deposits within the Mzymta River valley of the Akhtsu zone (Krasnodar Krai, Russia) were studied with the purpose of updating the reported data. Five sites were not mentioned earlier, and we were first to study them.

Some outcrops appeared in the past years because of exploration and the following construction of the Olympiad-2014 objects; the study of these outcrops adds greatly to the existing concepts.

MATERIALS AND METHODS

Data were acquired during the expedition to the Mzymta River valley near the settlement of Monastyr' (Krasnaya Skala) on the Akhtsu reef (sites 1–5, Mzymta River right bank) and at the town of Aibga in the region of Krasnaya Polyana and Estosadok (sites 6–7, Mzymta River left bank, Fig. 1) in September of 2012. Sites 1 and 1a were described earlier (Dublyanskii et al., 1985; Guo et al., 2011); the profile at site 4 in the quarry above the village of Monastyr' has been repeatedly studied by researchers from Moscow State University. Site 1 is located at the advertising tower "Sochi park. Kepsha forestry" of an old motor road to the Krasnaya Polyana, at a distance of 100 m from the settlement of Monastyr'. Site 1a is located to the northeast of site 1, at the southwestern mouth of a road tunnel. Site 2 is above the village of Monastyr', at the foot of a scarp above the quarry, at pole 10 of the Monastyr'–Chvezhipse power line; site 3 is located at pole 10 of the same line near a capping spring that is out of operation; site 5 is located at the crossing of a clearing for gas pipeline and power line with an earth road; site 6 is at the upper station of the Gornaya Karusel aerial railway, and site 7 is located in the region of its lower station.

Observations were performed at 8 sites, where outcrops were described, fossils were collected and described, and 20 samples were taken. The samples were ground, their petrography was studied, and structures were classified (Folk, 1959; Danham, 1962). In addition, E.N. Samarin (Moscow State University) analyzed their chemical composition on a MARC.GV X-ray-fluorescent spectroscope (NPO Spektron, St. Petersburg). The acquired corals and stromatolites were identified by I.L. Soroka (Vernadsky State Geological Museum).

Note that the Akhtsu massif, as well as Mt. Aibga, form krantzes of up to 100–200 m in height, which makes their detailed study impossible without special alpine equipment; therefore, quarries, foots of scarps, and large blocks translocated by recent gravity processes can be considered as the main points for studying Upper Jurassic limestones, as was noted earlier (Dublyanskii et al., 1985; Guo et al., 2011). Thus, these are only observation sites rather than full-scale geological profiles.

CHARACTERIZATION OF CALLOVIAN–UPPER JURASSIC DEPOSITS IN THE AKHTSU ZONE

The Akhtsu massif, which is predominantly composed of Upper Jurassic limestones, is located at about 20 km to the northeast of the Black Sea coast, between the Sochi and Psou river valleys (Fig. 1). The Callov-

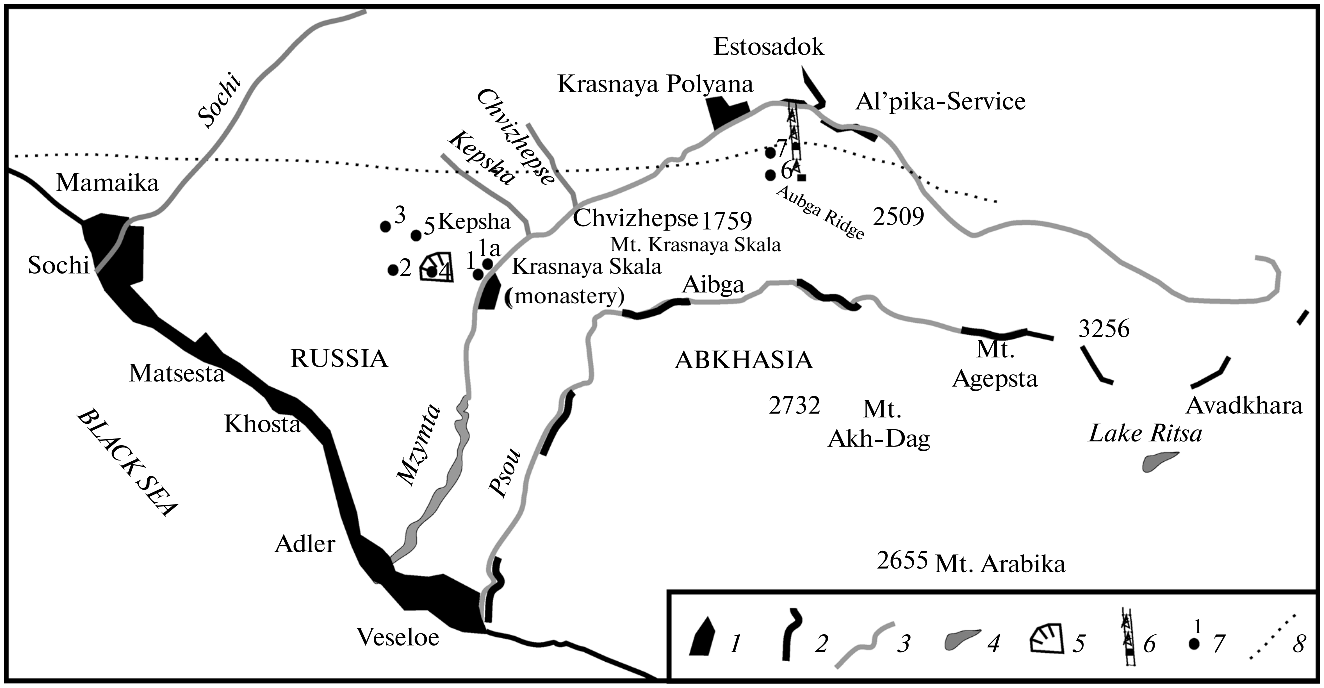


Fig. 1. A schematic map of the observation sites: (*1*) boundaries of settlements; (*2*) Russia–Abkhazia frontier; (*3*) rivers; (*4*) lakes; (*5*) quarry; (*6*) Gornaya Karusel aerial railway; (*7*) observation sites and their numbers; (*8*) Akhtsu zone northern boundary.

ian–Upper Jurassic deposits within the Akhtsu massif occur transgressively, with an abrupt angular displacement, on the Bajocian volcanogenic–sedimentary stratum (Fig. 2a).

In spite of numerous publications devoted to the stratification of this region of Western Caucasus, integrated descriptions of barrier reefs in the trough of this Great Caucasus zone are given in a few papers. Only Bendukidze (1960) thoroughly described the Akhtsu reef and reported its paleontological characterization and, to a lesser extent, paleogeographic interpretation.

The Callovian–Upper Jurassic stratum of the profile is characterized by two formations, viz., the Aibga and Katsirkha ones.

Aibga formation (Callovian–Lower Oxfordian) was first described by V.I. Kurochkin in 1941. According to the primary description, this was a terrigenous stratum underlain by conglomerates (Kurochkin, 1941); the author erroneously dated its lower part to the Bathonian age. Later, its Callovian age was confirmed by index ammonite fossils that were found on the southern slope of Mt. Akh-Ag (Fig. 1). The Aibga formation is distributed in the upper Psou and Gega river basins; it is involved in the structures of Ritsa, Psou, and Kozyrka anticlines and Ozertso and Akh-Ag synclines. In lithological terms, it consists of alternating sandy siltstones, greywacke sandstones, and gravelstones with rare and thin interlayers of sandy limestones. In the lower part of the formation, a band of conglomerates alternating with greywacke sandstones and gravelstones is distinguished. The thickness of the conglomerate band varies from 30 to 150 m. The lower part of the band can belong to the Bathonian regressive stratum. The thickness of the supra-conglomerate terrigenous formation of the Callovian–Lower Oxfordian deposits varies in the range of 120–200 m (Adamiya et al., 1972). The upper boundary of the formation is somewhere clearly traced at the bottom of the Upper Oxfordian limestone–conglomerate breccias. A gradual transformation of the terrigenous formation into the overlying calcareous deposits is sometimes observed (Adamiya et al., 1972).

Deposits at the base of the Aibga formation composed of small-grained greywacke sandstones with lime cement were found at site 1a (at the southwestern mouth of the road tunnel on the Mzymta River right bank near Krasnaya Skala, Fig. 2B).

The stratotype of the **Katsirkha formation**, which corresponds to the upper part of the middle Oxfordian (Tithonian), occurs in the Psou River canyon near the village of Aibga. The rocks of this age play a leading role among the terrigenous-calcareous formations in the northwestern Abkhazia. In later publications (Rostovtsev, 1992), facial zonality was noted in the deposits; it included a zone of subplatform facies, a zone of transitional facies, and a zone of subflysch facies.

The zone of subplatform facies is located in the middle Psou and Gega basins; it covers the southern wing of the large Akh-Ag syncline and the area located

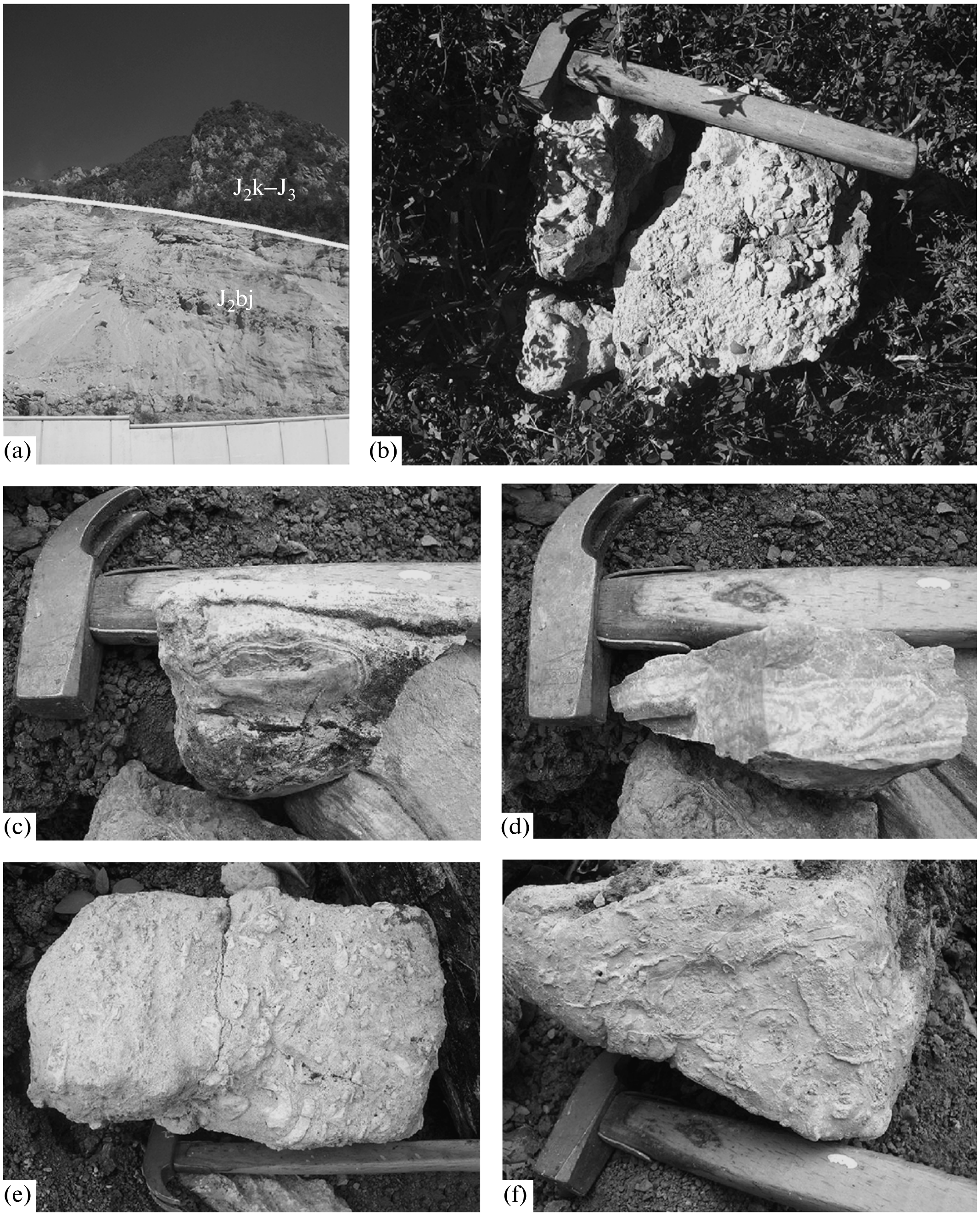


Fig. 2. Macroscopic lithological–paleontological characterization of Callovian–Tithonian deposits in the Akhtsu zone: (a) it is seen behind the village of Monastyr' (near site 1) that Callovian–Upper Jurassic terrigenic calcareous deposits occur on Bajocian volcanites; (b) Callovian conglomerate–breccias at site 1 (northeastern edge of the village of Monastyr'); (c) algal bindstone on weathered shear surface; (d) algal bindstone on fresh shear surface; (e) sorted algal–scaleworm rudstone (reef talus) at site 5 (gas pipeline trench); (f) unsaturated coral biomicrite (or packstone) at site 5.

to the south of it. In this zone, deposits consist of epicontinental calcareous marine rocks: thick, most frequently reef limestones.

This zone was observed at sites 1–5. Callovian deposits were found at sites 1, 1a, 6, and 7, and Lower Oxfordian deposits were found at sites 2–4; debris of Tithonian limestones were identified at site 5 in the gas pipeline trench. The stratigraphic positions of the deposits were determined after the comparison of their lithological–paleontological description with the reported description of the Akhtsu profile (Bendukidze, 1959).

The thickness of the Upper Oxfordian–Tithonian deposits gradually decreases from south to north. This can be related to the fact that the active settling of the bottom of a relatively deep basin section was not balanced by the accumulation of the corresponding sediment layer, while the slow warping of the bottom in the shallow subplatform zone was accompanied by the development of a powerful barrier reef and internal reef massifs (Adamiya et al., 1972).

REEF-BUILDING ORGANISMS IN THE AKHTSU ZONE

Field studies allowed us to elaborate and supplement the current concepts. We found macrofauna at sites 1 (solitary oyster shells), 3 (numerous gastropods), and 5 (the richest macrofauna complex). No macrofauna was found in stony debris at sites 6 and 7 on the Aibga Range.

According to the literature data (Guo et al., 2011), corals and sponges were the main reef builders in the Akhtsu zone with the following species composition: *Calamophylliopsis*, *Cyathophora*, *Dermoseris*, *Isastraea*, *Montlivaltia* (*Montlivaltiidae*), *Stylina* (*Stylinidae*), *Stylosmilia*, *Thammasteria*, *Thecosmilia*, and laminar *Microsolenidae*.

Corals are associated with the small portion of another macrofauna: pearlworts, sponges, brachiopods, and bivalves, which equally contribute to reef formation. Coral structures have variable morphologies and different sizes; they usually make up 20–50% of the total rock volume; laminar corals are relatively frequent.

In lithological terms, rewashed reef carbonates are distinguished: rudstones in the lower part of the profile and grainstones in its middle part. The upper part of the profile in the southern region of the Akhtsu zone in the Mzymta valley is formed by tidal bioclastic limestones, grainstones–packstones, and algal packstones. Breccias and red-colored sediments are also found (Guo et al., 2011).

Along with the above forms, reef species were also identified in our field observations; the main rock-forming role was played by algae (Figs. 2c, 2d); corals made a smaller contribution, and sponges, worms, and echinoderms played a subordinated role (Figs. 2e, 2f). Such reef constructions have not been reported earlier.

In particular, massive bioclastic, dense, solid limestones containing an abundant complex of fossil invertebrates that compose up to 30% of the rock volume were found in cliff debris at site 5 (at the gas pipeline trench). Algal tufts several centimeters high and several decimeters in area (stromatolites) and spherical tufts to 5 cm in diameters (oncolites) were identified among invertebrates, as well as corals (solitary corals with goblets to 10 cm high and to 4–5 cm in diameter and colonial ones), probably pearlworts, scaleworms, gastropods, and echinoderms (sea urchin spines and crinoid columnals). Algae are predominant (50%); corals (colonial, 15%; solitary, 10%) and scaleworms (10%) are frequent; gastropods to 5 cm in size are slightly less frequent (7%); echinoderms, pelecypods (small scallops), and probably pearlworts (8%) are also found.

We distinguish the following limestone lithotypes (according to Folk, 1959, and Danham, 1962):

(1) rudstones: (1.1) sorted algal–scaleworm; (1.2) unsorted coral–gastropod–algal–scaleworm–echinoid; (1.3) unsorted coral (colonial and solitary corals); (1.4) unsorted algal–scaleworm–crinoid; (1.5) unsorted gastropod–algal;

(2) bindstones: (2.1) algal; (2.2) coral–algal; (2.3) coral ((2.3.1) solitary corals; (2.3.2) colonial corals; (2.3.3) mixed solitary and colonial corals));

(3) packstones (Danham, 1962) or biomicrites (saturated or unsaturated with the predominance of the latter): (3.1) coral; (3.2) scaleworm; (3.3) echinoid–crinoid–gastropod, probably with pearlworts; (3.4) pelecypod–echinoid–crinoid–coral–scaleworm–gastropod; (3.5) oncolite.

The classification of laminar biogenic reef carbonates is debatable. Guo et al. (2011) consider them as laminar corals; however, in our opinion, these structures are more similar to stromatolites (Figs. 2c, 2d), so much more that stromatolites themselves are frequently associated with corals (Fig. 3a), as was noted in earlier works.

Let us enlarge upon the coral diversity of this reef structure. Bendukidze (1959) was the first to describe reef corals (in Georgian). He also proposed the first stratigraphic differentiation of the reef fauna. His list of reef fauna species was more complete than the lists reported later. *Microsolenidae* and *Stylina* are typical for all European reefs of the Late Jurassic; *Thecosmila* and *Dermoseris* are mainly typical for the reefs of Caucasus and Switzerland (Bendukidze, 1982). The other forms presented in Table 1 are not widely distributed in Europe. Table 1 also includes the comparative characterization of coral diversity in the Akhtsu reef according to our results and literature data. It can be seen that our studies confirmed the earlier results.

Such colonies are primarily composed by massive forms (to 75% of the total mass), and phaceloids make up only 25%. The colony described by Guo et al. (2011) is not an exception; e.g., we found no more than 20% phaceloids (predominantly *Stylosmila*) in the selected samples. The bulk of the corals consist of massive subplacoid colonies composed by the *Stylina* and *Isastreae* genera; solitary subplacoid colonies of *Montlivaltia* are also found. According to these authors, corals usually form the major component of the coral skeleton and a factor of vertical reef growth. They are associated with microorganisms (mainly microproblematica) such as *Bacinella–Lithocodium*, *Iberopora*, *Koskinobullina*, *Prismenproblematikum*, *Tubiphytes*, and *Polychaeta*. Residues of rinoids, brachypods, and other benthic organisms in the form of bioclasts are typical for bioclast wackestones and packstones (Guo et al., 2011). Pearlworts and sponges

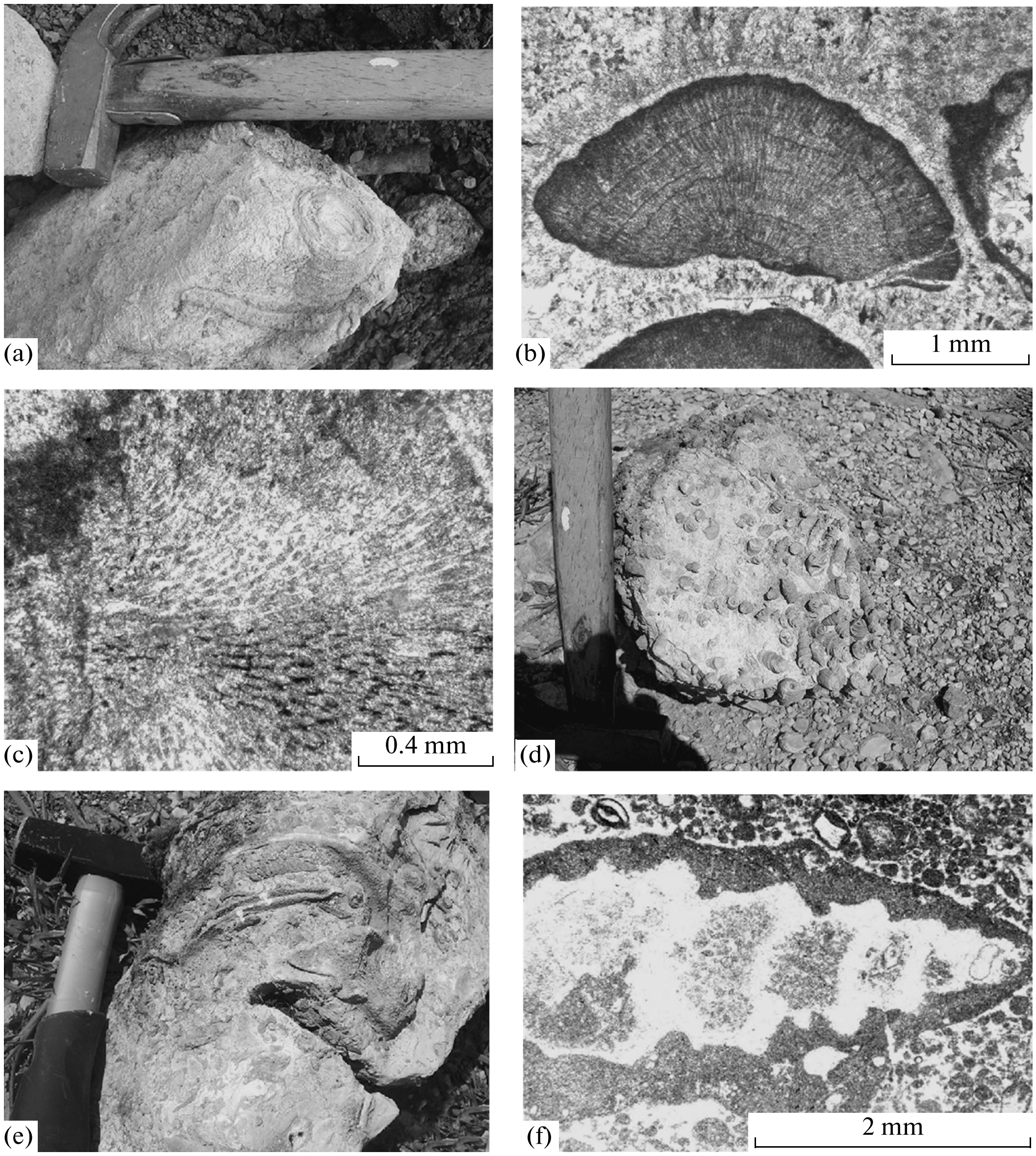


Fig. 3. Macro- and microscopic lithological–paleontological characterization of Oxfordian–Tithonian deposits in the Akhtsu zone: (a) coral–algal bindstone (solitary coral) at site 5; (b, c) debris of cyanobacterial colony in thin section 5.7a (site 5, without analyzer); (d) gastropod rudstone at site 3; (e) fragment of large Nerinea body whorl at site 3; (f) gastropod shell in thin section 3/2 (site 3, without analyzer).

are also found in the studied rocks; they were noted by previous authors, but we failed to identify them.

Persisting rounded fragments of cyanobacterial structures were found in thin rock sections (Figs. 3b, 3c). They were presumably identified as *Rivularia* sp. (?) typical for back-reef and shelf-edge facies (Manchinelli, Ferrandes, 2001).

The presence of gastropods, including *Nerinea*, is noteworthy. They make up to 30% of rock in the upper part of the reef (Figs. 3d–3f). Kozlov indicated that a layer of Upper Jurassic limestones more than 900 m thick is observed along the Mzymta River in the Akhtsu canyon. The upper part of this layer almost completely consists of *Nerinea* shells. Along with them, *Aptyxis terscundensis* Pchel., *Prygmatis carpatica* Zeusch., *Diptyxis* cf. *plessensis* Peters, *Phaneroptyxis staszycii* Zeusch, and *Diceras* sp. are also found, which indicates the Tithonian age of the layer (Kozlov, 1937b). Due to these findings, it was established that the *Nerinea* facies occurs stratigraphically above the "classical" Akhtsu profile described by Bendukidze (1959).

Microscopic descriptions of rock in thin section 3/2 (site 3) are given as an example in Fig. 3f. The rock is polybioclastic peloid limestone of pale gray color, with a peloid grainstone structure, nonlaminar texture, and the following composition: peloids of 0.2–0.7 mm, 50%; bioclasts, 27%; accumulations of calcite crystals 0.7–2 mm, 8%; microsparite cement, 10%; and sparite cement, 5%. Among the bioclasts, rounded residues of gastropods (to 4 mm in size) in micrite envelope and foraminifers (0.3 mm) are found, as well as segments of cyanobacteria (0.6 mm). Bioturbation signs (to 0.4 mm) are also detected.

Nerinea is a group of gastropods that are closely associated with coral–algal communities, which explains the confinement of their shells to calcareous reefogenic facies (Pchelintsev, 1948). The diversity of reef facies directly correlates with explosions in the evolution of coral polyps.

According to reported data (Leinfelder et al., 2002), *red algal–coral reefs* to 1000 m thick with high species diversity prevailed in the Western Caucasus area during the Callovian–Late Jurassic period. Another, less abundant reef type consists of *coral–pearlwort–microbial reefs with zonally distributed cyanobacterial bindstones* overlain by coral structures with lower species diversity. *Thin silicon-sponge and microbial structures to 50 km in length* are mainly typical for deep-water communities. Such complexes are present in almost all Upper Jurassic shelf peripheries of the Tethys Ocean.

The reef structure of the Akhtsu zone can be classified among the latter type (as a coral–pearlwort–microbial reef with zonally distributed cyanobacterial bindstones overlain by low-diversity coral structures). However, pearlworts are rare and cyanobionts are abundant in the Akhtsu reef.

Reef structures in this zone were studied and described by Guo et al. (2011). The predominant coral–microbial reefs with different types of colonies (from branching to massive ones), which we revealed, are also typical for other numerous Late Oxfordian–Early Kimmeridgian reef structures at the edges of the Tethys Ocean, e.g., in western France, Burgundy, and Friuli (Italy) (Insalaco et al., 1997).

Guo et al. (2011) classified the Akhtsu reef structure into type VII according to Insalaco et al. (1997): a microbial–coral reef characterized by the predominance of massive and faceloid colonies with abundant solid intra-shelf microbialites and local biointrasparites. However, the structure under consideration is larger by several times (Figs. 4a, 4b). The reef facies that we described in the field studies belong to type IX. This agrees well with the data of Insalaco et al. (1997), who noted that type VII presented by massive colonies developed in the intrashelf area frequently border from the top with the beach facies of conglomerates composed by rounded segments of reef-builders.

Stages of reef formation. A close correlation was found between the stages of reef formation and the explosions in the evolution of corals in the Jurassic (Krasnov, 1973). In particular, Krasnov distinguished the following five stages:

Table 1. Comparative characterization of biodiversity in the Akhtsu zone on the basis of literature data and our observations

Taxon	(Bendukidze, 1959)	(Guo et al., 2011)
Amphiastraea cf. gracili Koby	+	
Amphiastraea sp.	+	
Rhypidogyra cf. elegans Koby	+	
Aplosmilia cf. semisulcata Michelin	+	
Schizosmilia rollieri Koby	+	
Stylina parvipora Ogilvie	+	+
Hlicoenia costulata Koby	+	
Cladophyllia aff. chofatti Koby	+	
Cryptocoenia castellum Michelin	+	
****Montlivaltia truncate*** Edw. et Haime	+	+
Calamophyllia flabellum Blainv.	+	+ {*Calamophyllia* sp.)
Calamophyllia etalloni Koby	+	
Calamoph. (?) tubiparaeformis Felix	+	
Tbamnoseris cf. strambergensis Ogilvie	+	+
Comoseris cf. brevivllis Ogilvie	+	
Dermoseris sp.		+
Thecosmilia sp.		+

Forms identified during field observations are typed in bold italics
* The identification was confirmed by I.L. Soroka (Vernadsky State Geological Museum).

—Stage 1, *Bathonian–Callovian*. The beginning of a large explosion in the development of hermatypic corals: an increase in the number of genera in all groups and the expansion of ranges of the known genera;

—Stage 2, *Oxfordian–Early Kimmeridgian*. The development of many families of fungiids, stylinids, and amphiastreids. The maximum propagation of reef forms in Eurasia, Africa, and America;

—Stage 3, *Late Kimmeridgian*. An abrupt decrease in the numbers and ranges of reef-forming scleractinians related to the manifestations of the Andian folding stage in many regions of the Tethys Ocean;

—Stage 4, *Early and Middle Tithonian*. A new explosion in the development of reef *Thecosmiliidae*, *Donacosmiliidae*, and *Dennosmiliidae* in Eurasia;

—Stage 5, *Late Tithonian*. The death of most Early- and Middle-Tithonian reef-building corals. The development of coral "meadows" (*Latomeandriidae*, *Cyathopltoriidae*, *Axosmiliidae*, *Montlivaltiidae*, etc.).

At the studied sites, terrigenous deposits (breccias and sandstones) and sandy limestones characterize the Callovian formation (Figs. 5a–5b); calcareous deposits composed of various limestone varieties are typical for the Oxfordian (Figs. 5d–5f) and Tithonian (Figs. 5g–5h) formations.

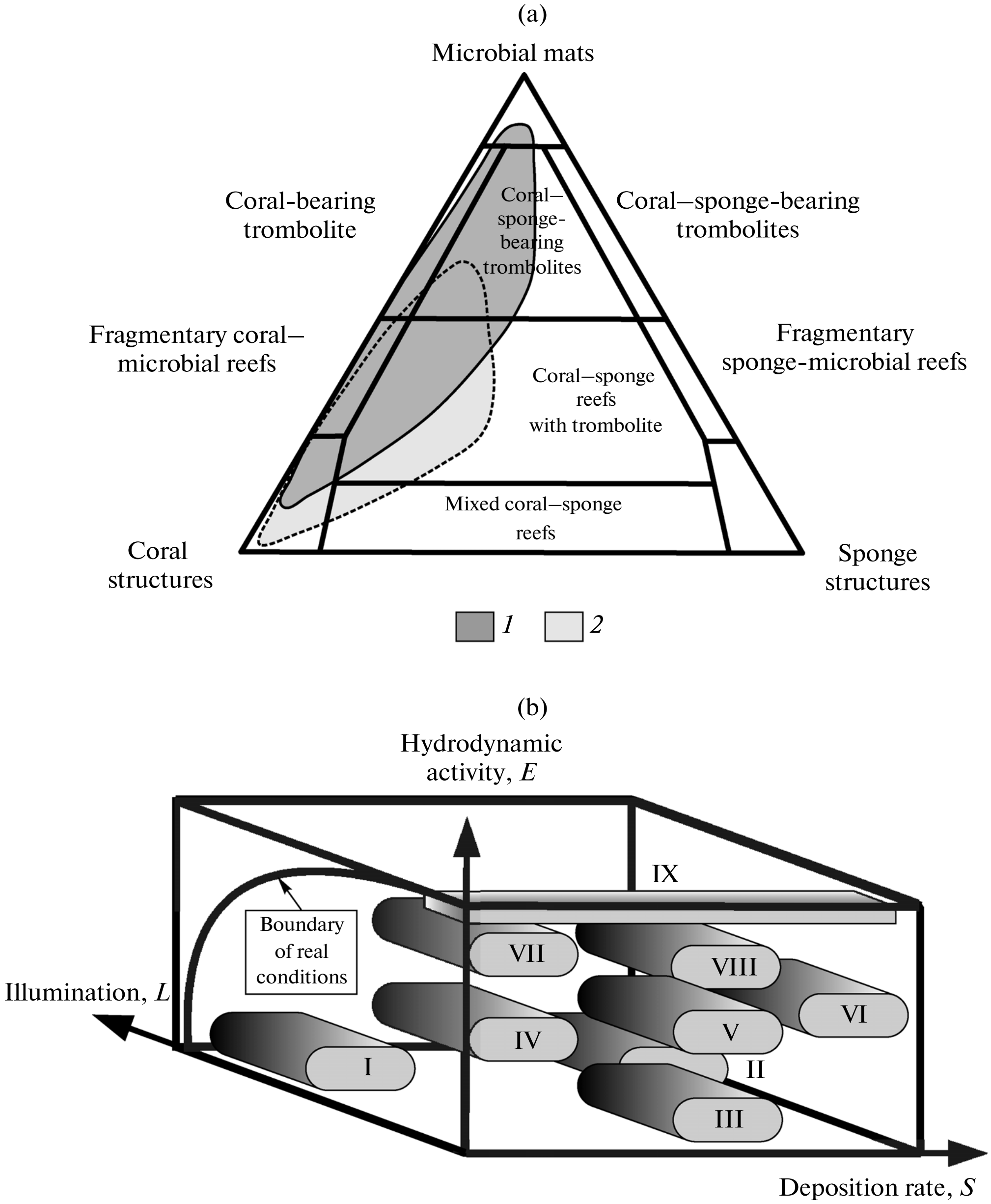
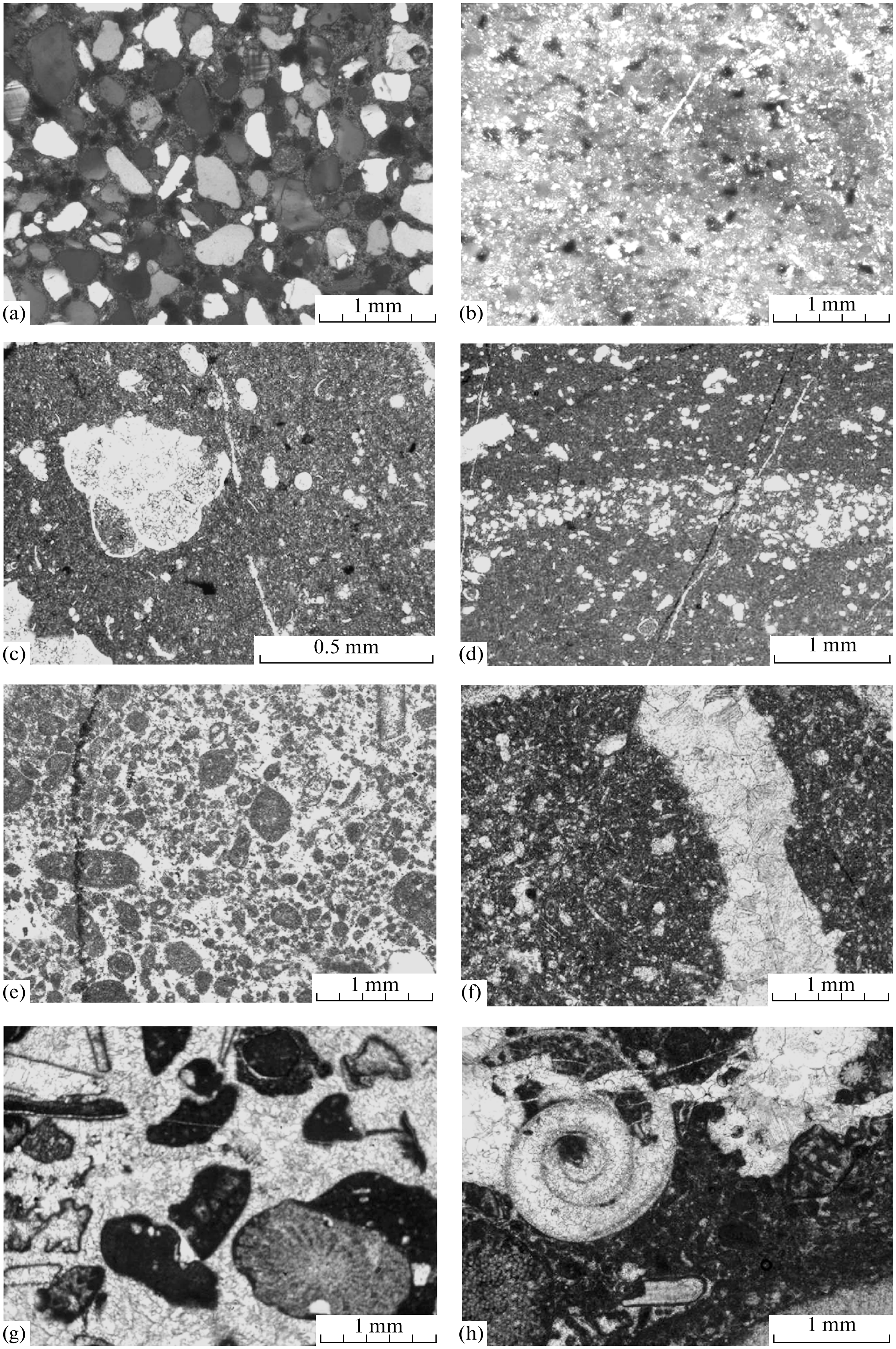


Fig. 4. Characterization of reef-forming organisms in the Akhtsu zone according to Insalaco et al. (1977): (A) proportions of reef-forming organisms in the Akhtsu zone (*1*) from our data; (*3*) according to Guo et al. (2011); (B) colony types as functions of hydrological conditions.

To analyze the distribution of reef facies and the stages of biogenic carbonate accumulation in the Black Sea region, Gabdullin constructed a chronostratigraphic profile for the Callovian–Albian deposits in Crimea, Abkhazia, and Georgia on the basis of field and literature data (Fig. 6). In particular, the reef facies of the region agree well with stages 2–5 of reef formation and the corresponding explosions of coral

Fig. 5. Petrographic examination of rock thin sections: (a) Callovian deposit, section 1/2 (site 1), quartz sandstone with glauconite grains (with analyzer); (b) Callovian deposit, section 6 (site 6), sandstone with lime cement (with analyzer); (c) section 1/1 (site 1), foraminifera in organogenic detrital micrite limestone; (d) Lower Oxfordian deposit, section 2/1 (site 2), interlayer with high concentration of foraminifera shells in organogenic detrital micrite limestone (without analyzer); (e) Lower Oxfordian deposit, section 3/1 (site 3), peloid material in peloid–polybioclastic limestone (without analyzer); (f) section 4 (site 4), limestone (packstone) with calcispheres and crinoids (without analyzer); (g) Tithonian deposit, section 5/1, organogenic fragmentary sparite limestone (biosparite) (without analyzer); (h) Tithonian deposit, section 5/2 (site 5), biomicrite limestone, partially peloid with various bioclasts (without analyzer).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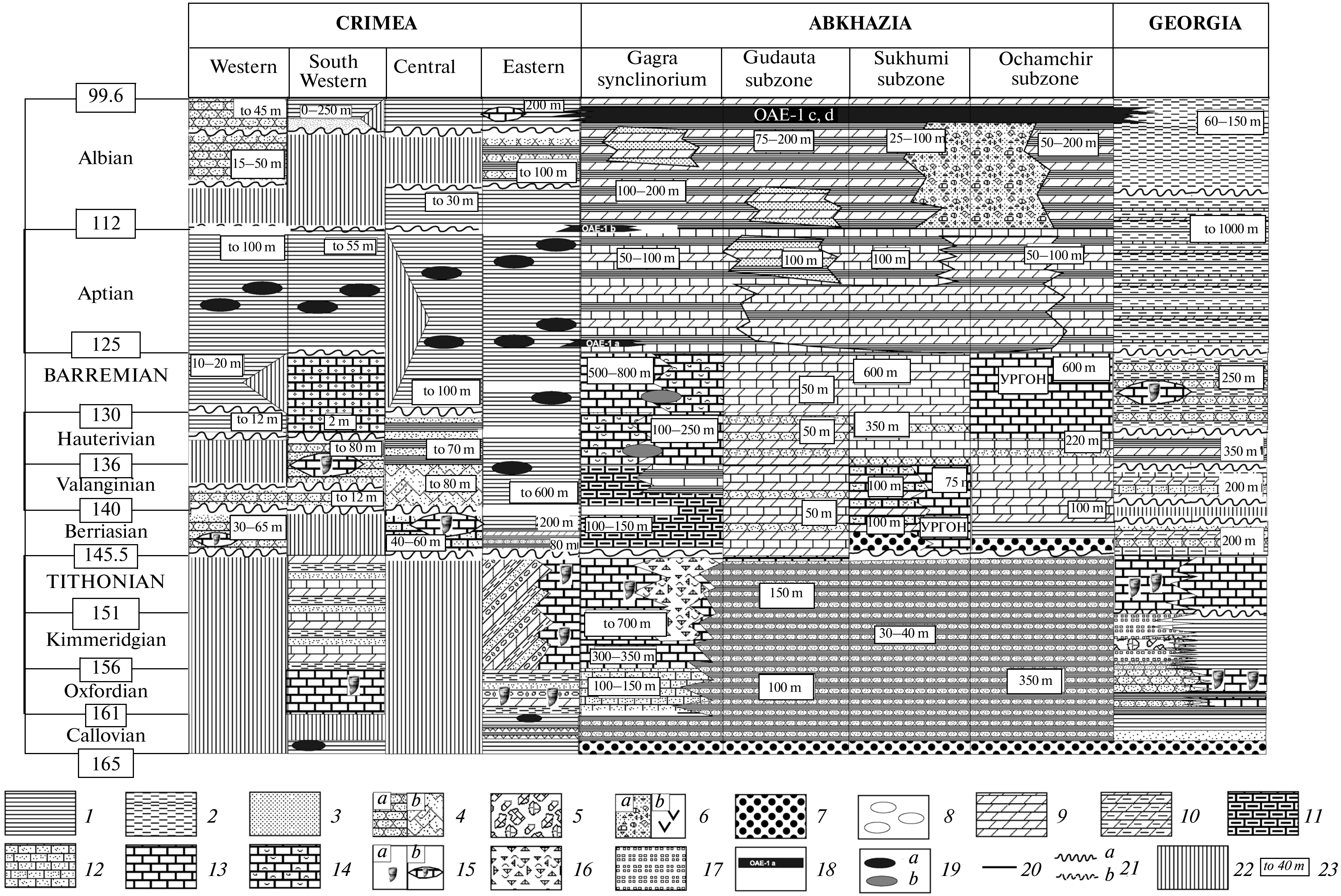

Fig. 6. Chronostratigraphic profile of the Black Sea region for the Callovian–Albian time: (*1*) clays; (*2*) argillites; (*3*) sands and loose sandstones; (*4*): (a) sandstones; (b) sandstones with wavy stratification; (*5*) calcareous breccias; (*6*): (a) tuff breccias and tuffs; (b) tuffs; (*7*) basal conglomerates; (*8*) conglomerates; (*9*) marls; (*10*) loamy marl; (*11*) marlstones; (*12*) sandy limestones; (*13*) limestones; (*14*) shell limestones; (*15*): (a) corals; (b) coralrag lenses; (*16*) limestones and reef talus breccias; (*17*) evaporites (salts, solomites); (*18*) bituminous interlayers (marls, shales) and OAE number; (*19*) concretions ((a) siderite and ancerite; (b) flints); geological boundaries: (*20*) concordant; (*21*) disconcordant ((a) proved; (b) inferred)); (*22*) hiatuses; (*23*) thickness of geological units (composed by R.R. Gabdullin).

Table 2. A comparison of the geochemical analysis results with the literature data

Component	Mean value for site 5	J_3km-ox, (Dublyanskii et al., 1985)	J_3t, (Dublyanskii et al., 1985)
CaO	47.1	44.2	54.2
MgO	–	9.0	0.8
SiO_2	4.5	<4.8	<4.8
Al_2O_3	5.7	<2.9	<2.9

evolution according to Krasnov (1992). However, the Caucasus area includes not only the reef zones that are analogous to the Akhtsu–Katsirkha reefs (these are the Racha, Iori–Tsiteli-Tskaro, and Vandam zones (Rostovtsev, 1992)), but also separate levels of appearance of rudists and corals and local development of reef structure in the later Cretaceous time, which were thoroughly described by Sikharulidze (1970).

For example, some levels of appearance of corals in the region of the Dzirula Ridge include coral–rudist banks of the Barremian age about 80 m thick near the village of Ali. An analogous structure up to 120 m thick is located near the village of Mukhuri. Near the Tskhradzhvari sanitarium to the northwest of the village of Mukhuri, Barremian deposits are composed of two benches: dolomitized limestones with colonies of *Actinostrea* and *Stylicosmilia* and overlaying massive limestones with rudists. The next coral–chaetetid reef structure of the Hauterivian–Barremian age to 200 m thick is located near the village of Shkmeri, between the Georgian Rock and the Great Caucasus trough. In the region of the Tsnakhari syncline (at the village of Tsnakhari), two Upper Aptian–Lower Albian coral–chaetetid lenses 1.5 and 3.5 m thick with massive and branched corals, respectively, are located. These are separated by crags to 40 m thick. Large reef structures several hundreds of meters in thickness are associated with transgressions, and small lens structures are associated with regressions (Sikharulidze, 1970).

ANALYSIS OF THE GEOCHEMICAL DATA

The obtained concentration of CaO is typical for any pure limestone. In samples from site 1, the content of CaO is analogous to that in the Oxfordian deposits that were determined earlier (Dublyanskii et al., 1985), which can indirectly confirm the Oxfordian age of these deposits. The authors believe that the normal content of insoluble components (SiO_2 and Al_2O_3) is 1.5%, although, in sandy interlayers, the concentration of SiO_2 increases to 4.8% and that of Al_2O_3 to 2.9%. According to our data, the average content of aluminum oxide is almost double the reported value, although this can be related to a SpectroScan error.

An analogous situation is observed for MnO: a zero content of this component was found in all studied samples of calcareous rocks (except sandstones), which does not agree with the earlier results. According to Dublyanskii et al. (1985), limestones are dolomitized and contain to 9% MgO. In some samples dolomitization was observed even by the unaided eye.

The elevated content of P_2O_5 (0.3–0.5%) compared to the background level can indicate either the erosion of phosphate-bearing sedimentary rocks or the volcanogenic alkaline-basalt mineralogy (Yudovich and Ketris, 2011). In all studied samples, the content of phosphorus oxide does not exceed 0.22%, which corresponds to the typical clarke level and attests to its natural occurrence in the sea basin.

From the determined concentrations of oxides, some oxide or element ratios can be calculated.

The Ti/Mn ratio is an indicator of deposition shallowness: it decreases with the distance from the source area and increases at the approach to the land (Tables 2, 3). Under continental conditions, the ratio is 110–150. Titanium minerals are resistant to chemical weathering; therefore, they are accumulated under alluvial and coastal-maritime conditions. In the normal saline sea basin, the content of Ti is decreased because of the absence of its true solutions (Yudovich and Ketris, 2011).

At site 5, an interesting regularity in deposit composition was observed: the plot of the increasing Ti/Mn ratio is a consistent succession of pelsparite grainstones to biosparite rudstones (Fig. 7). This suggests that pelsparite grainstones were accumulated near the source area and rudstones were accumulated at the periphery, but geochemical data indicate an opposite effect: rudstones occur near the source area

Table 3. Titanium modules and Ti/Mn ratios from geochemical analysis for samples from site 5

Sample, number, and description [Folk, 1959; Danham, 1962]	Titanium module	Ti/Mn
Ax 5-9, unsorted coral–gastropod–algal–serpulid–echinoid rudstone	0.0161	8.81
Ax 5-8, unsorted coral (colonial and solitary) rudstone	0.0126	8.81
Ax 5-7b, unsorted gastropod–algal rudstone	0.0136	12.69
Ax 5-7a, unsorted gastropod–serpulid–crinoid rudstone	0.022	30.05
Ax 5-4, algal bindstone	0.0162	8.12
Ax-5-3, unsaturated echinoid–crinoid–gastropod biomicrite (packstone)	0.0184	15.04
Ax 5-2, unsaturated serpulid biomicrite (packstone)	0.0201	15.61
Ax5-1, saturated coral biomicrite (packstone)	0.0196	17.21

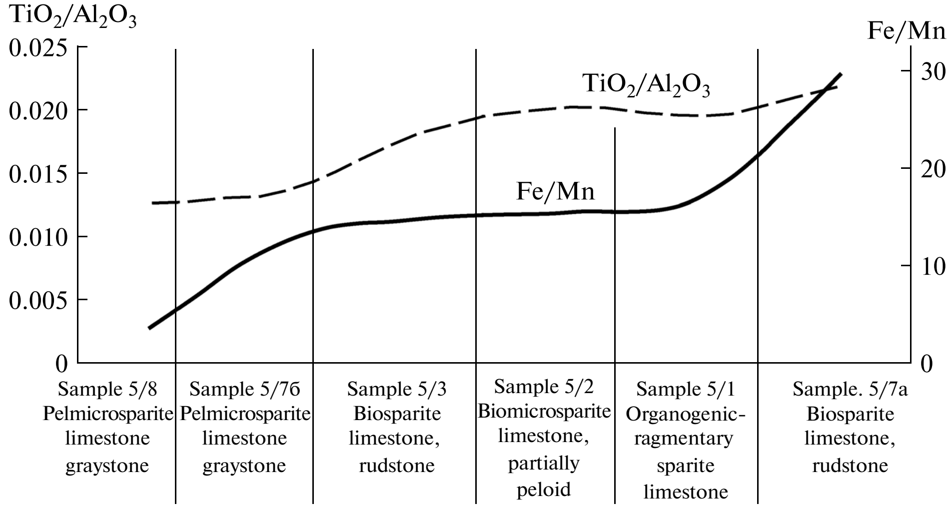

Fig. 7. Titanium modules (TMs) and Ti/Mn ratios for samples taken from site 5 (Tithonian deposits).

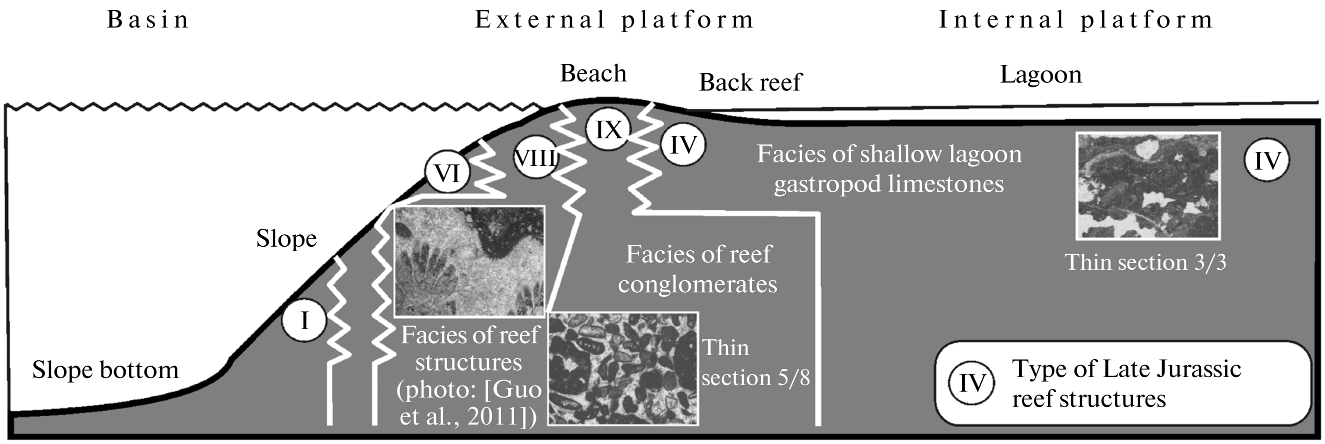

Fig. 8. Paleogeographic model proposed for the Akhtsu zone.

and grainstones occur at some distance. However, this is unlikely from the paleogeographic point of view; therefore, we suppose that this phenomenon is mainly due the different degrees of diagenesis and contents of sparite cement. The porosity of the Oxfordian–Kimmeridgian and Tithonian limestones is 0.6% (Dublyanskii et al., 1985).

THE PALEOGEOGRAPHIC CONDITIONS OF THE AKHTSU ZONE

In the Jurassic period, reef structures were most typical for the northern regions of the Tethys Ocean. They were most distributed in the Oxfordian age; their number decreased later and they almost disappeared by the Early Cretaceous time (Leinfelder, 2002). The reef structures of Western Caucasus are not an exception.

General ideas on the development and paleogeography of the Akhtsu zone and adjacent areas were presented by Adamiya at el. (1972): the Akhtsu–Katsirkha Island (cordillera) was apparently formed in the western part of the basin since the Bathonian; it was separated from the southern land by a small bay. The island provided only debris of the Bajocian porphyritic series, and the southern land also provided materials of acidic volcanic and crystalline rocks. In the Late Bathonian–Callovian, the size of the land increased, which resulted in coarsening of Callovian deposits: coarse-grained sandstones, gravelites, and conglomerates appeared (sites 1, 1a, 6). In the Early Oxfordian, the land area increased and transgression created favorable conditions for the development of reefs (sites 2–4, 7). At the beginning of the Late Oxfordian, the area of the Akhtsu–Katsirkha land slightly increased, and a local erosion of Lower Oxfordian deposits took place, which was immediately followed by subsidence and transgression dominating until the Late Tithonian (site 3) (Adamiya et al. 1972).

Reef massifs in the development zone of subplatform facies form two narrow sublatitudinal outcrops.

The northern outcrop coincides with the Akhtsu–Katsirkha cordillera (in the recent structure, Akhtsu–Katsirkha anticline and the Akhshtyr anticline to the south), and the southern outcrop coincides with the Bzyb anticline. During the Late Oxfordian, Kimmeridgian, and Tithonian, these structures were submarine ridges (Fig. 8) favorable for the formation of reef structures (Adamiya et al., 1972).

CONCLUSIONS

The results of field and laboratory studies agree well with the earlier data (Adamiya et al., 1972; Guo et al., 2011; Bendukidze, 1959). In addition, we determined the amount of algae and cyanobacteria that participate in the construction of the reef.

All processed data are mutually consistent. At each observation site, rocks were exactly dated and they largely correspond to stratotypic rocks of the studied formation. The facial distribution of coeval rocks also agrees well with the paleogeographic structure of the region.

The integrated studies allowed determining the type of the reef: this was a coral–pearlwort–microbial reef with zonally distributed cyanobacterial bindstones in its basis overlain by low-diversity coral structures. The reef occurred in the shallow intrashelf area with high hydrodynamic activity. It is associated with beach facies of a shallow lagoon, whose deposits consist of gastropod limestones.

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