ISSN 0145-8752, Moscow University Geology Bulletin, 2018, Vol. 73, No. 4, pp. 346–360. © Allerton Press, Inc., 2018.
Original Russian Text © R.R. Gabdullin, N.V. Badulina, E.A. Bakai, E.V. Rubtsova, A.Yu. Yurchenko, E.V. Karpova, A.V. Ivanov, M.A. Varzanova, A.V. Sergienko, T.A. Konovalova, M.V. Parakhina, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, 2018, No. 3, pp. 25–40.

The Structure and Formation Conditions of the Callovian–Oxfordian Deposits of Sudak Bay (Crimea)

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Received August 25, 2017

Abstract—The composition and origin of the Callovian–Oxfordian deposits of the Sudak Bay were characterized on the basis of the generalization and analysis of our own results, as well as published and unpublished data. The botanical future was first implemented for the geological mapping of the Oxfordian deposits.

Keywords: Mesozoic, Callovian stage, Oxfordian stage, stratigraphy, Crimea

DOI: 10.3103/S0145875218040063

INTRODUCTION

In spite of long-term geological study (since the 18th century) and the large number of published works dedicated to the vicinity of Sudak, radically different models of the geological structure for this area exist (Fikolina et al., 2008; Yudin, 2009). In the course of our recent field observations and the following laboratory and office works, we collected a great amount of factual material and assumed a new, third, model of the geological structure of the vicinity of Sudak.

During the field works in 2015, we described terrigenous and carbonate deposits of the lower and upper parts of the Verkhnesudakskaya subformation of the Sudak Formation at 15 observation points.

MATERIALS AND METHODS

The methods involved: (1) collection, analysis, and systematization of unpublished, archive, and published materials; (2) field observations; (3) laboratory studies; (4) office works.

To collect, analyze, and systematize the unpublished materials we reviewed the works of our previous workers.

In the field works, the Callovian–Oxfordian Deposits of the upper part of the Sudak suite ($J_{2-3}sd_2$) were described at 15 observation points in the area of the Sudak Bay (Fig. 1a) and at two observation points in the area of the Dachnoye settlement (Fig. 1b); the elements of rock bedding were measured and rocks were sampled. The field observation included the description of reference sections and the special lithofacies studies in the natural outcrops and mine openings (Fig. 1b).

The laboratory works included the petrographic study of ten thin sections, the determination of the concentration of an insoluble residue and composition of rock-forming minerals of carbonate rocks (the gas-volumetric method and the insoluble residue method) for ten samples, the analysis of the isotope composition of the carbon and oxygen of carbonates, and paleothermometric tests for eight samples (six samples from Sudak Bay and two samples from Dachnoye).

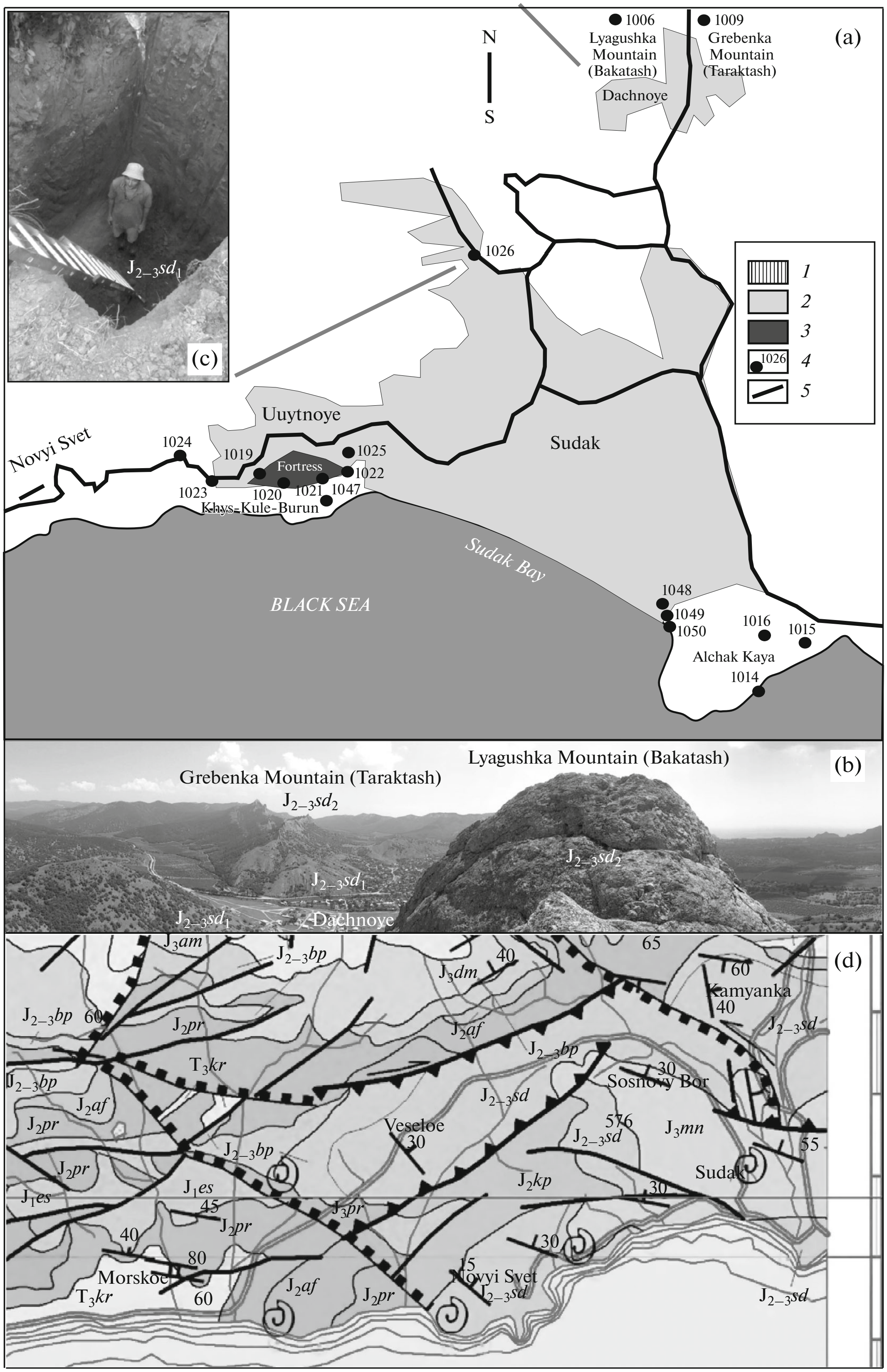

Fig. 1. The geological structure of the vicinity of Sudak: (a) the scheme of the location of the studied sections of the Sudak Bay: (*1*) Black Sea; (*2*) the urban complex; (*3*) Sudak Fortress; (*4*) an observation point and its number; (*5*) motor roads; (b) the panorama of the area of the Dachnoye settlement from Lyagushka Mountain (Bakatash); (c) the mine opening in the area of the Sudak bus terminal; (d) a fragment of the The 1 : 200000 State Geological Map of Ukraine (Fikolina et al., 2008).

The thin sections were produced and described at the Department of Geology of Moscow State University. The petrographic studies of the rocks in thin sections were carried out according to the standard technique by E.V. Karpova and M.A. Varzanova (MSU). To define the concentration of the insoluble residue, carbonate rocks were dissolved in acetic acid according to the standard technique (*Analysis*..., 1969) at the Department of Geology of Moscow State University (analyst M.A. Varzanova, MSU).

The gas volumetric analysis was carried out on the Karbonatometr KM-04 instrument (analyst E.A. Bakai, MSU); the technique is described in (Gabdullin et al., 2017).

The isotope analysis was carried out on the Delta V Advantage integrated equipment for the analysis of stable isotopes of light elements (analyst A.Yu. Yurchenko, MSU). The technique has been described in several works (Gabdullin et al., 2016; Faure, 1986; Hoefs, 1980; Kaplin and Yanina, 2010; Verzilin, 1979).

At the stage of the office works, the collections of rocks that were sampled in the area (map sheets L-36-XXIX, L-36-XXX, L-36-XXXIV, L-37-XXXV) were studied and the data of the analytical study were interpreted.

The lithological and stratigraphic characteristics of the Callovian–Oxfordian deposits of the Sudak Bay. In the vicinity of Sudak, in the time interval from the second part of the Callovian up to the Lower Oxfordian including, the deposits are associated with the Sudak Formation (Fig. 1d). The lower part of the Sudak Formation (lower subformation, $J_{2-3}sd_1$) is composed of clays with interbeds of sandstones, limestones, and lenses of conglomerates. The upper part of the formation (upper subformation $J_{2-3}sd_2$) is composed of clays with siderite concretions and bioherm limestones. The formation rests on the eroded deposits of the Kapsel Formation; the upper conformable boundary is designated along the bottom of the Mandzhil Formation (Fikolina et al., 2008); here, the deposits are exposed as a band with a wide ranging from several hundred meters to several kilometers. The lower subformation is 20–180 m thick, while the upper subformation is 600–800 m thick. The stratotype of the Formation was described by M.V. Muratov in 1949 (Anfimova, 2015) in the vicinity of Sudak, near the eastern frame of sheet L-36-XXIX. On the recently published state geological map (sheet L-36-XXIX) (Uspenskaya, 1969), the mapping stratons are associated with stages; on the geological map of Ukraine (Fikolina et al., 2008) the distribution of the Sudak Formation is shown in the area of the Sudak Bay.

The typical sections of the formation are traced in the outcrops of the Karaul-Oba and Sokol mountains and the Kapchik, Koba-Kaya, Alchak-Kaya, and Perchem capes. On the northeastern slope of the Karaul-Oba Mountain, the lower part of the section is composed of thin-bedded sandstones with siderite concretions. The sandstones are overlain by sandy limestones and replaced by massive reef limestones to the southwest and up to the section. The thickness of limestones on the northwestern slopes of the Karaul-Oba Mountain is up to 215 m, increasing up to 400 m to the southwest. On the northern slope, the lower part of the bioherm massif is composed of recrystallized, indistinctly-bedded, coral–algal limestones; the upper part, near the top, is composed of bedded ogranogenic detrital limestones (Fikolina et al., 2008).

The corals *Isastraca pronihgua* Thurm., I., *explanata* Goldf. and others were identified here in sandy limestones.

To the northeast, organogenic detrital and bioherm limestones are laterally replaced by calciferous varieties of sandstones enriched by gravel. Similar rocks strengthen the amphitheater of the Novyi Svet Bay; here, the upper part of the section is composed of clays and siltstones, among which a large bioherm massif, that is, Sokol Mountain, is located. The maximum thickness of the reef limestones is up to 500 m. The thickness of the Sudak Formation generally ranges from 400 to 800 m (Fikolina et al., 2008).

The main litho-petrographic types of the Sudak Formation are composed of clays, sandstones, and limestones. The clays are dark gray, with an aleuropelitic texture. The clayey fraction consists of hydromicas (60%) and chlorite (35%); the silty fraction consists of quartz, feldspar, calcite, and mica. The sandstones are dark gray, with psammitic texture; there are debris of quartz, feldspar, and pyroxene; cement (up to 20%) is characterized by clayey–carbonate composition. The limestones are gray, organogenic-detrital, and recrystallized; they are composed of fauna remains (up to 70%) cemented by cryptocrystalline calcite (Fikolina et al., 2008). Data from an aerospace survey (MAKS) show that the Kapsel Formation is characterized by gray or dark color in photographs, while the Sudak suite is characterized by white or light color.

The limestones of the Sudak Formation are excavated at small-scale deposits.

The map of magnetic-field anomalies shows that the distribution of the formation corresponds to low values ranging from –0.25 to 0.5 nT $\times$ 10^{-2}; on the map of gravity anomalies the distribution of the formation corresponds to high values (approximately 2.5–4.0 mGal).

No signs of metamorphism and metasomatic changes of the rocks were observed in the course of our study or in the data of previous workers. There are no the data of the radiological dating of the rocks in the works of previous researchers.

The Sudak Formation is unevenly described in terms of the faunal content. There are abundant fossils in the lower part of the section; these are attributed to the zones of Sigalloceras encodatum and Quenstedtoceras lamberti of the Middle and Late Callovian. The upper part is rather impoverished in terms of faunal remains; it contains the faunistic assemblage of the zone Cardioceras cordatum of the Early Oxfordian. Generally, the age of the Sudak Formation corresponds to the second half of the Middle Callovian–Early Oxfordian (Fikolina et al., 2008). The Callovian–Oxfordian boundary lies inside the deposits of the upper subformation; at this, the terrigenous deposits are dated as the Callovian and carbonate deposits as the Oxfordian. The Callovian deposits of the Verkhnesudakskaya subformation were studied in five sections in the vicinity of Sudak and to the north of this area, near the Dachnoye settlement (on Bakatash and Taraktash mountains, where the Nizhnesudakskaya subformation is also exposed). No sections in the Dachnoye area are described in this work.

Section 1 (observation point 1014). The area of Alchak-Kaya Mountain, the coastline near the base of the southeastern part of the mountain top. A beach that is 5–6 m wide occurs at the observation point; it is composed of limestone pebbles of the Verkhnesudakskaya subformation. Pebbles have various degrees of roundness and different sizes. The ratio varies from gravel to large boulders for rounded fragments and from gruss to small blocks for unrounded fragments of the rocks. The thickness of the beach deposits mostly depends on the size of boulders and blocks; however, usually, it is several tens of centimeters. In the beach zone, the bedrocks consist of mudstones with siderite concretions of the Verkhnesudakskaya subformation; the outcrops of the Oxfordian limestones rest above them. On the slope of Alchak Mountain adjacent to the beach the rocks are well exposed. The degree of the plant cover is approximately 20%; generally it is grass.

Here, the Callovian deposits consist of the cyclic interbedding of two elements. Element A is composed of carbonate mudstones with cleavage that is typical for marlstone with a strong response to acetic acid in some spots. Muscovite and quartz veins occur in the rock. The rocks have a gray color on fresh cleavages; in some spots, they are intensively gray and gray brown without a visible bedding on the weathered surface. When weathered, the rocks form prismatic multifaceted rubble with a thin platy structure in some places. Element B is mudstone, carbonate, massive, solid, tough, slightly sandy, with muscovite. The mudstone forms visible benches in the slope. The rock is ferruginate locally due to diagenesis, and is sometimes transformed into siderite concretions or strongly ferruginate manifesting typical rusty, red brown, and orange red colors on the weathered surface. The rock is gray on fresh cleavage; massive; no bedding was fixed; there are spots where the rock looks like highly clayey and sandy-ferruginate marlstone. For the Callovian flysch formation, a dip azimuth is 283°, the angle of inclination (∠) is 47°. A 54.5-m-thick section is stratigraphically described upsection in moving along the coastline and a dip of the beds. Table 1 shows the brief description of the section layer by layer.

The following pattern was established: the thickness of the carbonate mudstones increases up the section (not less than by two times in comparison with the lower part of the section). The thickness of ferruginate interbeds of mudstones also increases significantly; for example, the interbeds of siderite concretions correspond to these interbeds in the middle part of the section.

Section 2 (observation point 1023). The motorway from Sudak to Novyi Svet, 20 m above the Sudak–Novyi Svet motorway, 1 km west of the western closure of Sudak Bay. Here, on the slope and down to the bottom of the near-top cliff there is the strata that is composed of repeatedly interbedding siltstones and interbeds of siderite concretions or levels of siderite concretions. The siltstones are gray brown at the weathered surface and light brown at the surface of fresh cleavages; they include muscovite; when weathered, they form isometric angular rubble (Fig. 2a). The siltstones have a moderate response to acetic acid. At the observation point, the degree of the plant cover is approximately 35%, vegetation is dominated by grass and coniferous trees. The composition, structure, and age of the formation are similar to the deposits of Alchak-Kaya Mountain. The formation is composed of cyclic interbedding of reddish-brown siderite concretions (A) and gray black siltstones (B). The thickness is 701 cm.

Table 2 gives a brief description of the section layer by layer. Microscopically, (Fig. 2a), sample 1023/1 is silty fine-grained sandstone with elements of crossbedding. It is composed of poorly rounded mesomictic quartz grains (60%), plagioclase and potassic feldspars (15–20%), lithoclasts of magmatic and metamorphic rocks (15–20%), rarely mica (5%) with film-like hydromica and locally chlorite cement, secondary calciferous; the dip azimuth is 141°, ∠19°.

Separate outcrops of thick interbeds of siderite concretions (0.3–0.4 m thick) alternating with siltstones are observed up the slope for a distance of 9–11 m (Fig. 2a). No elements of bedding are changed.

Section 3 (observation point 1024) is located 300 m to the west of the western outskirts of Uyutnoye settlement, on the Sudak–Novyi Svet motor road. Bedrock outcrops of the terminal part of the formation are observed; they contain interbedding of siltstones and beds of siderite concretions of Callovian age (Fig. 2b). The apparent thickness of the outcrop is more than 1 m. The Oxfordian sandy limestones with thin lenses and interbeds of brownish-gray siltstones rest above the outcrop without a distinct stratigraphic hiatus. The elements of bedding of the Callovian and Oxfordian rocks are similar and equal to the values in the preceding point of observation. There are no tectonic dislocations here.

Section 4 (observation point 1025) is situated at the northeastern periphery of the wall of the Genoese Fortress, in the middle of the distance between ul. Genuezskaya Krepost and ul. Rybachiya, on the path

Table 1. The distribution of the thicknesses of the alternating elements in the member of the cyclic interbedding of the mudstones and siderite concretions of the Verkhnesudakskaya subformation ($J_{2-3}sd_2^1$) in Section 1 (observation point 1014) on the coastline near the foot of the southeastern part of the top of Alchak-Kaya Mountain

Bed No.	Element of cycle	Thick-ness, cm	Note	Bed No.	Element of cycle	Thick-ness, cm	Note
1	A	40		42	B	12	
2	B	7		43	A	74	Sample 1014/50
3	A	142		44	B	10	Sample 1014/51
4	B	8		45	A	105	
5	A	114		46	B	10	
6	B	20		47	A	115	
7	A	100		48	B	15	
8	B	13		49	A	140	
9	A	60	Sample 1014/15	50	B	10	
10	B	10	Sample 1014/16	51	A	12	Sample 1014/58
11	A	5		52	B	24	Sample 1014/59
12	B	9		53	A	116	
13	A	10		54	B	20	
14	B	8		55	A	44	
15	A	60		56	B	13	
16	B	10		57	A	44	
17	A	70		58	B	10	
18	B	10		59	A	127	
19	A	10		60	B	34	
20	B	10		61	A	220	Sample 1014/68
21	A	116	Sample 1014/27	62	B	20	Sample 1014/69
22	B	10	Sample 1014/28	63	A	60	
23	A	88		64	B	6	
24	B	14		65	A	163	
25	A	79	Sample 1014/31	66	B	24	
26	B	12	Sample 1014/32	67	A	101	
27	A	153		68	B	20	
28	B	10		69	A	82	
29	A	112		70	B	7	
30	B	14		71	A	23	Sample 1014/78
31	A	12		72	B	45	Sample 1014/79
32	B	3	An ammonite core was found (approximately half of a spiral turn of a coiled shell); the turn height is 5 cm; the length is 13 cm; the preservation is satisfactory	73	A	52	
				74	B	16	
				75	A	106	The scar of a satisfactorily preserved ammonite and bivalve were found. Sample 1014/83a (ammonite), sample 1014/83b (bivalve)
33	A	180	Sample 1014/39				
34	B	10	A flexure is clearly observed, the amplitude of the bends is 116 cm	76	B	33	
				77	A	226	
35	A	151	Sample1014/41a, siderite. A scar of an ammonite was observed in one of the siderite concretions found in the rockslide; sample 1014/41b, macrofauna (ammonite)	78	B	5	
				79	A	323	Sample 1014/87
				80	B	4	Sample 1014/88
				81	A	396	
36	B	270		82	B	8	Sample 1014/7F (corals from rockslide)
37	A	13					
38	B	12	Sample 1014/45	83	A	120	
39	A	74		84	B	12	
40	B	10		85	A	80	Sample 1014/93
41	A	175		86	B	10	Sample 1014/94

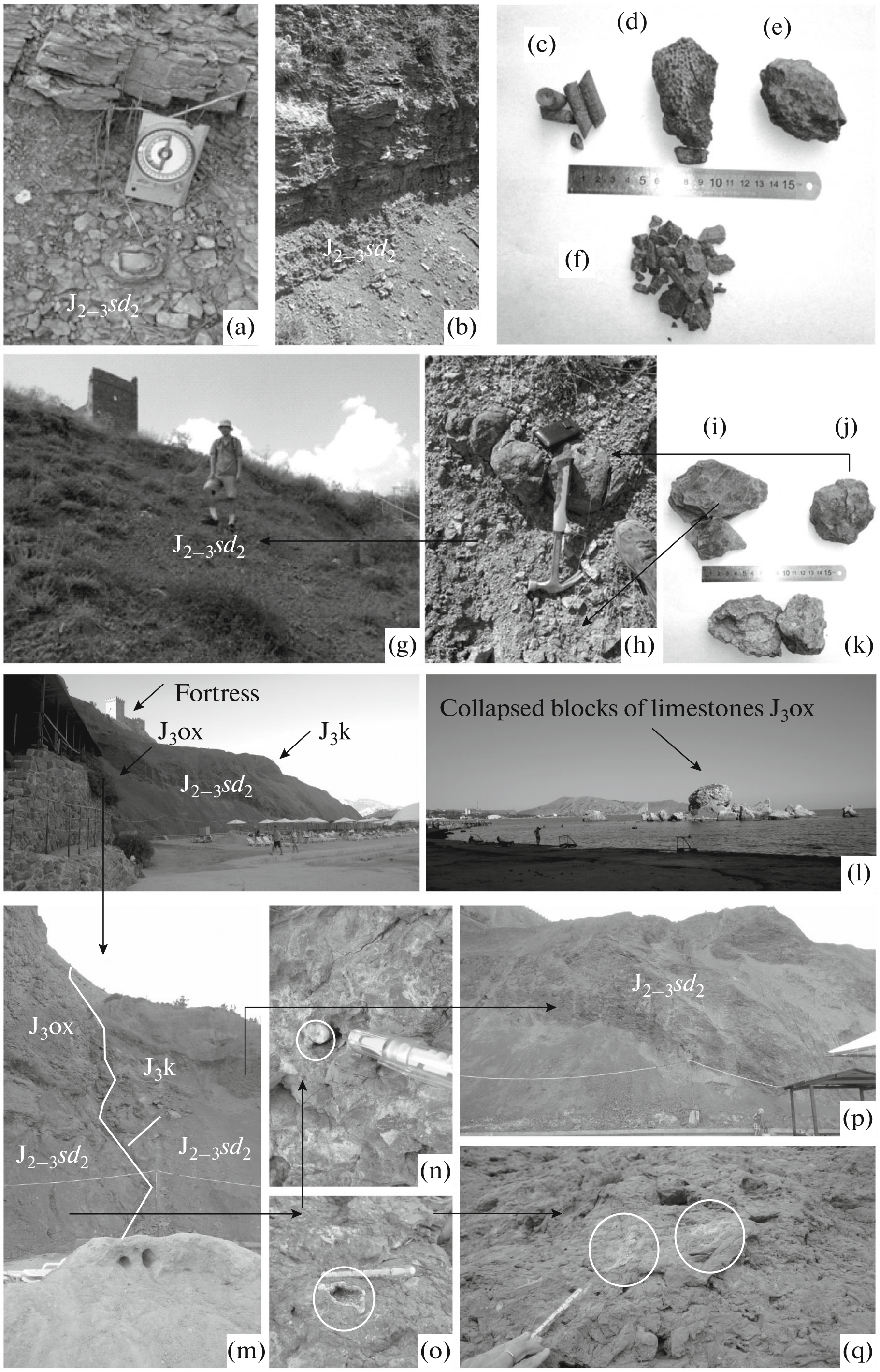

Fig 2. Photos of the outcrops: (a) the formation of the cyclic interbedding of siltstones and interbeds of siderite concretions (point 1023); (b) the bedrock exposures of the terminal part of the Callovian deposits (point 1024); (c) crinoid columns in the Callovian deposits (point 1025); (d) fragments of sponge goblets in the Callovian deposits (point 1025); (e) ferruginate siltstone (point 1025); (f) sandy siltstone (point 1025); (g) the Callovian terrigenous deposits underlie the Oxfordian limestones (point 1025); (h) the formation of the cyclic interbedding of siltstones and interbeds of siderite concretions (point 1025); (i) siltstone (point 1025); (j) siderite (point 1025); (k) limestone of the Oxfordian stage (point 1025); (l) the panorama of the western closure of the Sudak Bay, blocks of the Oxfordian limestones are observed on the shallows; (m) on the beach. the Callovian ($J_{2-3}sd_2$) and Oxfordian ($J_{2-3}sd_2$) deposits are at the same hypsometric level (a white line is a dividing boundary); (n) crinoid columns in the marmorized limestones; (o) rudists replaced by calcite; (p) the formation of the cyclic interbedding of siltstones and interbeds of siderite concretions of the Verkhnesudakskaya subsuite ($J_{2-3}sd_2$); (q) clusters of rudists.

leading from the fortress to the beach. The outcrops of the formation, which is represented by interbedding siltstones and beds of siderite concretions of the Callovian age with fauna, are observed on the slope (Figs. 2c–2f). Organic remains of macrofauna, crinoid columns, and fragments of sponge goblets, were found in the siltstones. The occurrence of the crinoid columns coincides with the bedding. Macrofauna was sampled from poorly sandy carbonate siltstone and ferruginate siltstone (which could be transformed into a siderite concretion during diagenesis).

Therefore, the deposits of the Callovian stage consist of carbonate mudstones, massive carbonate mudstones, interbeds of siltstones and siderite concretions, and siderites.

Section 5 (observation point 1026), the northern outskirts of Sudak, ul. Chekhova 18 (Fig. 1c). A test pit 2.83 m in depth was excavated. Monotonous sections of the Quaternary deposits with horizontal bedding were revealed on all four walls of the pit. On the northwestern wall of the pit the section (stratigraphically from up to down) is composed of the following beds: bed 1, topsoil (p-d IV) 35-cm thick; bed 2, silty clay, brown, pale brown on the weathered surface, with limestone rubble, gruss, and gravel (p-d IV), 49-cm thick; bed 3, the horizon of limestone rubble with the silty clay brown filling, (p-d IV), 5-cm thick; bed 4 is similar to bed 2 (p-d IV), 9-cm thick; bed 5 is similar to bed 3; however, the size of debris is approximately two times smaller, basically contains gruss (p-d IV), 9-cm thick; bed 6, silty clay, reddish brown, on the weathered surface light reddish brown with single inclusions of sandstone rubble and limestones (p-d IV), 130-cm thick; bed 7, bed rocks of the Callovian age, limey mudstones from the formation of interbedding mudstones and beds of siderite concretions. The visible thickness is more than 30 cm (sample 1036/7). The total thickness of the described Quaternary deposits at the northwestern wall is 2.37 m.

The boundary between the Callovian and Oxfordian deposits was studied at the western and eastern margins of the Sudak Bay in sections 2, 4, 6, and 7.

Section 2 (observation point 1023). The formation of interbedding siltstones and limestones of the Oxfordian age is observed above the member of the interbedding siltstones and siderite concretions of the Callovian age.

The top rock (cliff), which was formed by Oxfordian limestones, is observed higher up the slope (Fig. 2c). The limestones are gray reddish-brown on the weathered surface and light gray on the surface of fresh cleavages with remains of bivalves and echinoderms. The limestones form a top cliff 25-m in height (Fig. 3, samples 1023/2 and 1023/3). Microscopically, sample 1023/2 is coral framestone (60%) with float-wackestone filling (5–10%), with admixtures of silty fine-grained material, and siderite (10%), which consists of secondary incrusted trough skeletal crystal forms and

Table 2. The distribution of the thicknesses of the alternate elements in the member of the cyclic interbedding of mudstones and siderite concretions of the Verkhnesudakskaya subformation ($J_{2-3}sd_2^1$) in Section 2 (observation point 1023) on the Sudak–Novyi Svet motor road

Bed no.	Element of cycle	Thickness, cm	Note
1	A	20	Sample 1023/1 (sandstone), sample 1023/2 (siltstone)
2	B	82	
3	A	19	
4	B	123	
5	A	8	
6	B	112	
7	A	21	Sample 1023/7
8	B	23	Sample 1023/8
9	A	15	
10	B	72	
11	A	9	
12	B	42	
13	A	19	
14	B	111	
15	A	25	

silty–clayey matter. Clayey material was deposited and siderite with intraclasts was formed under conditions of diagenesis (Figs. 3b and 3c). In a thin section, sample 1023/3 appears to be a coral structure (88%) with a rare cyanobacteria–algal replacement. Other marine fauna is absent (Figs. 3d and 3e).

The elements of bedding of the Oxfordian limestones are similar to those for the Callovian siltstones. This points to the lack of an angular unconformity and indicates the conformable bedding of terrigenous (Callovian) and carbonate (Oxfordian) formations. The boundary between the Callovian and Oxfordian is not exposed directly at this observation point; however, the leveled area, above which the interbedding of the Oxfordian limestones occurs, is attributed to this boundary. The sod covering this part of the section is attributed to the Callovian–Oxfordian boundary. The thickness of the Oxfordian section is 6.5 m.

Section 4 (observation point 1025). The Oxfordian limestones are underlain by the formation of interbedding siltstones and siderite concretions around the Genoese Fortress area (Figs. 2g–2j). Bedding is characterized by a dip azimuth of 6°, ∠47°. There are drainage ditches and water collectors near the observation point. This indicates that atmospheric precipitation infiltrates through the cleavaged massif of limestones and seeps at the boundary between the Callovian and Oxfordian. The Callovian rocks are an aquiclude. Siltstones of the formation of the interbed-

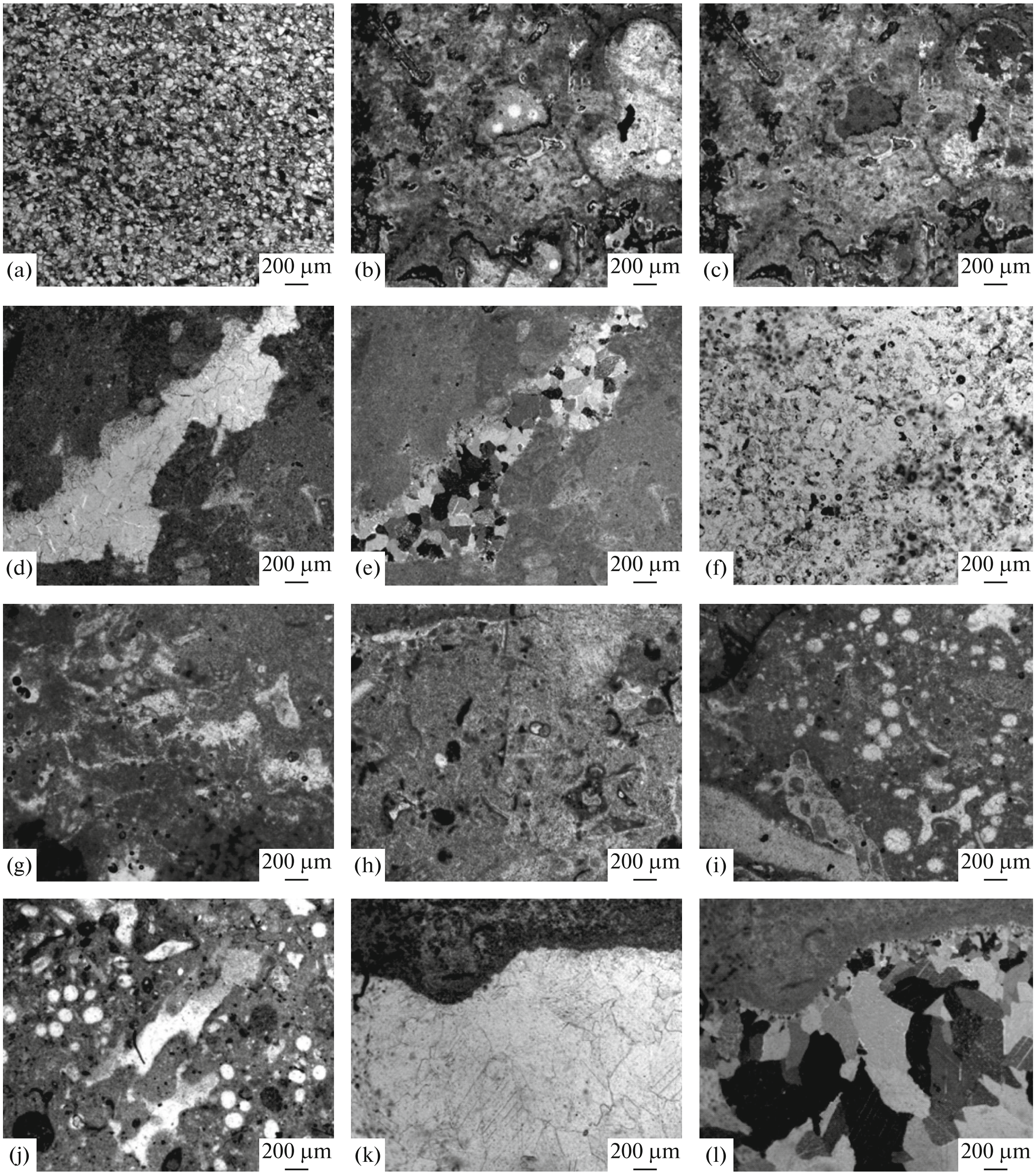

Fig. 3. Microphotographs of thin sections: (a) sample 1023/1 (the analyzer was turned off), sandstone fine grained silty; (b) sample 1023/2, coral framestone with float-wackestone filling (the analyzer was turned off); (c) the same (the analyzer was turned on); (d) sample 1023/3, a coral structure with rare cyanobacteria—algal replacement (the analyzer was turned off); (e) the same (the analyzer was turned on); (f) sample 1047/1, siltstone with admixture of fine grained material, well sorted, non-bedded (the analyzer was turned off); (g) sample 1016, polybioclastic limestone, floatstone; (h) sample 1019, fragmental limestone, floatstone (the analyzer was turned off); (i) sample 1020, limestone with lithoclasts of cyanobacteria—algal limestones, sphere limestones, immersed into cyanobacterial algal matrix (the analyzer was turned off); (j) sample 1021, coral structure, limestone with a fine-grained secondary skeletal frame and micritic cyanobacteria—algal filling of the inter-skeletal space (the analyzer was turned off); (k) sample 1022, limestone from wackestone to floatstone with spots of framestone, a fragment of corallites with cyanobacteria—algal filling of cavities and micritic matrix with admixture of fine sandy silty material (the analyzer was turned off); (l) the same (the analyzer was turned on).

ding siltstones and siderite concretions have clayey admixtures; mudstone beds are scattered. The Oxfordian limestones are found in the rockslide.

Section 6 (observation point 1047). The western margin of the Sudak Bay below the Genoese Fortress (Figs. 2l–2q). The rocks are well exposed; there is practically no vegetation at this outcrop. The Callovian and Oxfordian deposits are observed at the same hypsometric level on the beach (Fig. 2m). The siltstones with the Callovian interbeds of siderite concretions and the block of the Oxfordian limestones, on which the Genoese Fortress is situated, are exposed. The limestones have a strong response to acetic acid; on a fresh cleavage they are black, while on a weathered surface they are gray. The limestones are marmorized; they contain crinoid columns up to 1 cm in diameter (Fig. 2n), clusters of rudists replaced by calcite (Figs. 2o–2q). The surface of the limestone bears marks of dissolution of marine salt; it is covered by scattered black-orange lichens *Rhizocarpon geographicum* (L.) and fruticose gray white lichens *Parmelia sulcata* Taylor. The dip azimuth is 320°, ∠33°. Samples 1047/1 (mudstone) and 1047/2 (limestone) were taken here. Microscopically, sample 1047/1 is siltstone with scattered chlorite, limey, with an admixture of fine-grained material (20%), well-sorted, nonbedded. The siltstone is composed of unrounded quartz grains (75–89%), mica (5%), feldspar and plagioclase (10–15%), and sporadic lithoclasts of metamorphic and magmatic rocks with porefilling hydromica cement (Fig. 3f). Microscopically, sample 1047/2 is dolomitic limestone (82%), microclearly-grained with silt admixtures (<5%) with spots of secondary siderite, nonbedded.

The blanketlike rockfall and landslide deposits of the Holocene age (dr-ds IV) occur in the upper part of the outcrop; they are composed of carbonate silty clays with blocks and breccia of limestones 10–15-m thick. Blocks of the Oxfordian limestones lie in the shallows at a distance of several tens of meters from the coastline. The visible part of the blocks is 15 m and higher above the waterline (Fig. 3l). Usually, this type of a geological structure is classified either as a clastolit of limestones (Oxfordian) in a mudstone matrix (Callovian) or as a result of tectonic dislocations (stripping in layers or in sublayers), including a tectonic mélange (Yudin, 2009, 2011). In our opinion, the area of the stripping in layers or in sublayers and the zone of mélange in the vicinity of Sudak actually appears to be part of the landslide–rockfall. In this part, the Callovian terrigenous deposits are completely disintegrated and the limestones that are lying near the zones of the block slipping bear the traces of mechanical treatment. The rock has a crumbly structure, a dull lustre with a leather coat of mudstones.

Section 7 (observation point 1015). At the foot of the top cliff of the Alchak-Kaya Mountain, on the eastern slope. A smooth transition of the Callovian formation of the interbedding mudstones and concretion interbeds of siderite to the Oxfordian terrigenous rocks is observed. The rocks are well exposed. At the observation point, the degree of plant cover is approximately 15%; vegetation is dominated by grass and dwarf trees. No tectonic contacts were observed. Table 3 shows the description of the reference section of the Callovian–Oxfordian deposits up to the section. Eight types of elements of interbedding cyclites were distinguished in the section. Element A is composed of calcareous mudstone. Element B is similar to bed 21 in the observation point 1014. Element C is the unit of high-sandy and less sandy mudstones (with lenses and lens-shaped interbeds of limestones at the top) several centimeters thick. The mudstones contain abundant corals (isolated) and remains of crustaceans, bivalves, and numerous burrows of fossil animals (ichnofossiles) in the form of silicified nonferruginate sandstones. Mudstones and siltstones are highly calcareous with a good response to acetic acid. Biogenic limestones have a strong response to acetic acid. The remains of echinoderms (cidaroida sea urchins) were also found.

Element D is composed of calcareous black mudstone; it is gray on the weathered cleavages. The mudstone forms isometric, sharply angular rubble. Element E is composed of silt, indistinctly-bedded, gray on the fresh cleavage and gray brown, reddish red on the weathered surface, with a weak response to acetic acid. Element F is silt, dry, weakly calcareous, with a weak response to acetic acid, massive. Element G is limestone, massive, indistinctly-bedded, with quartz veins, gray on the fresh cleavage, gray–brown on the weathered surface; 50% of the surface is covered by black-orange lichens *Rhizocarpon geographicum* (L.) and gray white fruticose lichens *Parmelia sulcata* Taylor without visible macrofauna. Element H is composed of sandy limestone, less solid than the underlying bed; it develops holes in the profile of weathering. The element is characterized by the occurrence of small interbeds that form a step-like slope. These beds emphasize the linear distribution of grass and woody vegetation. The total thickness of this interval of the section is 103 m. Up the section, the step pattern of the slope disappears being followed by a top cliff consisting of a limestone formation 54-m thick. While ascending to the top, no significant changes were observed in the character of the formation; there are no finds of macrofauna. Calcite veins 15–20-cm thick, several meters in length, with subvertical bedding, and a strike azimuth of 60° were found on the top (observation point 1016). Microscopically, sample 1016 is polybioclastogene limestone, floatstone; it consists of debris of corals (5%), moss animals (2%), crinoids (3%), brachiopods (1%), shellfish (2%), gastropods (3%), and thalomes of green algae with an abundant cyanobacteria–alga filling, totally micritic in some spots, with secondary giga-crystalline grains of calcite (80%) in cavities (Fig. 3g). The thickness of the reference section is 157 m.

Table 3. The distribution of the thicknesses of the alternating elements in the member of the cyclic interbedding of the terrigenous–carbonate deposits of the Verkhnesudakskaya subformation ($J_{2-3}sd_2^2$) in Section 7 (observation point 1015) at the base of the top cliff of Alchak-Kaya Mountain, on the eastern slope

Bed no.	Element of cycle	Thickness, cm	Note
1	A	>50	Sample 1015/1
2	B	22	Element B is similar to bed 21 at point 1014. Sample 1015/2, siderite concretions
3	A	40	Gradual transition into the overlying Oxfordian bed (no. 4) without an apparent gap was observed in the bed top
4	C	135	Samples: 1015/4a (oolitic limestone with quartz veins, gray on a fresh cleavage, gray brown on a weathered cleavage); 1015/b, (macrofauna, corals); 1015/4c (macrofauna, bivalves); 1015/4e (macrofaunal, ichnofossils); 1015/4f (macrofauna and echinoderms).
5	D	22	
6	C	135	Here, the thickness of the limestone interbeds is much larger; it is approximately 25 cm
7	E	30–50	
8	F	13	Sample 1015/8
9	E	10	
10	F	7	
11	E	17	
12	C	58	
13	E	100	
14	G	115	
15	H	2	Sample 1015/15
16	G	170	
17	H	5	
18	G	85	
19	H	4	
20	G	9266	

The Oxfordian deposits were studied in sections 8–14 on the western and eastern closures of the Sudak Bay.

Section 8 (observation point 1048) in the mouth of the Suuk-Su River, the eastern margin of the Sudak Bay, the western slope of Alchak-Kaya Mountain (a cape), near the "Natural reserve Alchak Kaya" sign. The rocks are well exposed in the observation point; the degree of the plant cover is no more than 35%, (grass and trees). The flow rate at the location where the river flows into the Black Sea is 0.4 m/s. A large amount of household waste (tIV) is in the estuary. Alluvial deposits (aIV) are observed in the riverbed; they are composed of pebble and small debris of Oxfordian limestones, presented by limey sandstones and the interbedding of limestones and sandstones in the lower part. Shallow-marine fauna of bivalves (pectenids, sample 1048/1) is found. The rocks are similar to those that occur in the basal part of the section of Alchak-Kaya Mountain, on the opposite eastern slope, at the observation point 1015, and on Khys-Kule-Burun Mountain (observation point 1047), where the Sudak Fortress is situated. Therefore, the boundary between the Callovian formation of calcareous mudstones with interbeds of siderite concretions and the Oxfordian limestones (under a rock massif with the "Caution! Rockfall" sign) passes under the riverbed alluvium. Holocene blanketlike rockfall-colluvial deposits descend along the slopes of the limestone massif. The deposits are composed of silty clays with debris of rubble and calcareous breccia with a strong response to acetic acid; there are rubble and blocks with a wide range of sizes; the thickness of the deposits is 4–6 m in the lower part. The collapsed blocks of Oxfordian limestones 10–15 m in diameter are sporadically distributed near the coastline or in the shallows. These blocks are similar to those that were described in the opposite part of the Sudak Bay at observation point 1047. Marine abrasion, on the one hand, and gravitational processes in combination with weathering, on the other hand, led to the rockfalls. Traces of limestone desalination, small karst forms (caverns and sinkholes), and large forms (grottoes) are observed in this point. A tourist path leading from the western part of the Alchak-Kaya Cape to its eastern and top parts begins from this point.

Sections 9 and 10 (observation points 1049 and 1050) are located 70 m to the south of point 1048 (observation point 1049) and 82 m to the south of point 1049 (observation point 1050) on the tourist path. The rocks are well exposed; the degree of the plant cover is no more than 27% (grass and trees). The tourist path (similar to the Golitsyn path in the Novyi Svet settlement) goes along the massif of the Oxfordian limestones, which consist of the younger intervals of the limey formation, generally, by the interbedding of limestones and sandstones without macrofauna, but with calcite veins (up to 0.5 m thick and several meters length, sample 1049/1, calcite) and sandstones similar to those in the section on the opposite slope, at observation point 1015. In the area of the path, the caved blocks of the Oxfordian limestones 12–15 m in diameter are observed near the coastline and in the shallows (similar to the described blocks in the opposite part of the Sudak Bay, at observation points 1047 and 1048).

Marine abrasion and gravitational processes in combination with weathering caused the caving. Traces of leaching of limestone, small karst forms (caverns and sinkholes), and large forms (rockshelters) are observed in this point.

Section 11 (observation point 1019) is on Khys-Kule-Burun Mountain (a cape) at the southwestern corner of the Sudak Fortress (Uyutnoye settlement). The limestones are covered by black-orange lichens *Rhizocarpon geographicum* (L.), fruticose gray–white lichens *Parmelia sulcata* Taylor, and scattered conifers and herbaceous plants, which generally grow in the fractures of weathering and indicate the indistinctive bedding of limestones in the massif. The bedding is characterized by a dip azimuth of 115°, ∠36°. Fragments of macrofauna skeletons, mostly shellfish and echinoderms, are found in the massif; they indicate the biogenic origin of this formation. The rocks are well exposed; the degree of the plant cover is approximately 5% (Fig. 4a). The limestones have a gray and, sometimes, a light-brown color on the weathered surface; on the fresh cleavages they are intensively gray; they are recrystallized in some spots; mostly, with massive structure (Figs. 4b and 4c). Microscopically, sample 1019 is fragmental limestone, floatstone; it is composed of lithoclasts of cyanobacterial algal limestones (52%), stromatolithic limestones (40%), sometimes, with the finest detritus. The bioclastic part consists of brachiopods (3%), foraminifers (2%), thallome algae (3%), crinoids (2%), and moderately-sorted clusters and clumps of cyanobacterial algal calcite. The limestone is moderately sorted with various degrees of roundness, with pore-filling, basal, microdistinctly-crystalline cement (Fig. 3h). The visible thickness is approximately 16 m. The rocks form an almost sheer cliff (Figs. 4a and 4d). Indistinctive bedding is indicated by parallel hollows in the profile of weathering. These hollows are attributed to varieties of sandy limestones, which are less resistant to weathering (Fig. 4e). On the way from observation point 1019 to point 1020, a cyclic formation of the interbedding of two varieties of limestone occurs; sample 1019/20 was taken from the massive limestone approximately in the middle of the distance (Fig. 4f).

Section 12 (observation point 1020) at the southern edge of the fortress wall, below the triangulation mark on the top of the Khys-Kule-Burun Cape. Closer to the top, the bedding becomes indistinctive, fractures along the bedding planes change the elements of the bedding (the dip azimuth is 234°, ∠37°). At the point of observation, the limestones become lumpy, brecciated, knotted, with indistinct bedding or without bedding, with of calcite and quartz veins, with recrystallized remains of macrofauna (mostly from a prismatic layer of mollusk shells). Sample 1020 is microscopically similar to sample 1016; it is limestone with lithoclasts of cyanobacterial algal limestones (48%) and sphere limestones (36%) immersed in the cyanobacterial algal matrix (Fig. 3i). The carbonate massif is segmented by numerous fractures, along which grass and coniferous trees grow. Descending filtration of atmospheric precipitation occurs through the fractures. In some places, the rocks are slightly wet; many pill bugs occur here.

Following the description from point 1019 to point 1020, the approximate thickness of the Oxfordian deposits is approximately 70 m.

Section 13 (observation point 1021). The southeastern corner of the fortress wall, near the donjon (the main tower of the fortress, Fig. 4g). The top castle of the Genoese Fortress is situated at the top of the massif of the Oxfordian limestones. The view over Sudak Bay is revealed from a small sightseeing site on the leveled surface of the limestone roof. Large collapsed blocks of limestones are observed in the bay. Moving from point 1020 to point 1021, the structure, composition, and properties of limestones are similar to those that were described at point 1020, and microscopically, appear to be a coral structure (sample 1021). This is limestone (80%) with a fine-grained secondary skeletal frame and micritic cyanobacterial algal filling of the inter-skeletal space (Fig. 3j).

Section 14 (observation point 1022) is attributed to the eastern corner of the fortress wall. Here, cyanobacterial algal limestones, usually, massive, indistinctly-bedded, and nodular are found (Figs. 4h and 4i). Microscopically, sample 1022 is a fragment of corallite with a cyanobacterial algal filling and a micritic matrix with admixtures of silty material (8%). The rock varies from wackestone to floatstone with spots of framestone (Figs. 4k and 4l). The reef-constructing organisms were corals, cyanobacterias, algae, and rudists. Herbaceous plants and scattered trees occur at this observation point. It was noted that in all studied points where the Oxfordian limestones are exposed their surface is covered by lichens, as described at observation point 1019.

RESULTS AND DISCUSSION

The results obtained during the field work in 2015 allow us to divide the structure of the Sudak subformation into two parts, a lower part (mostly terrigenous) and an upper part (mostly carbonate). The lithotypes of the main rocks of the subformation, which we distinguished under field and laboratory conditions, generally coincide with the results of the preceding studies (Fikolina et al., 2008).

In the vicinity of the town of Sudak, the boundary between the Callovian and Oxfordian is disconformable in the most studied sections, where the elements of the bedding are not changeable in the parts of the formation divided by a disconformity. The boundary is inside the Verkhnesudakskaya subformation. It was noted that the lower terrigenous and the upper carbonate parts of the Verkhnesudakskaya subformation occur at the same elevation level only in the western closure of the Sudak Bay under the Genoese Fortress (Khys-Kule-Burun Cape). This fact was previously considered (Yudin, 2009, 2011) as a result of tectonic

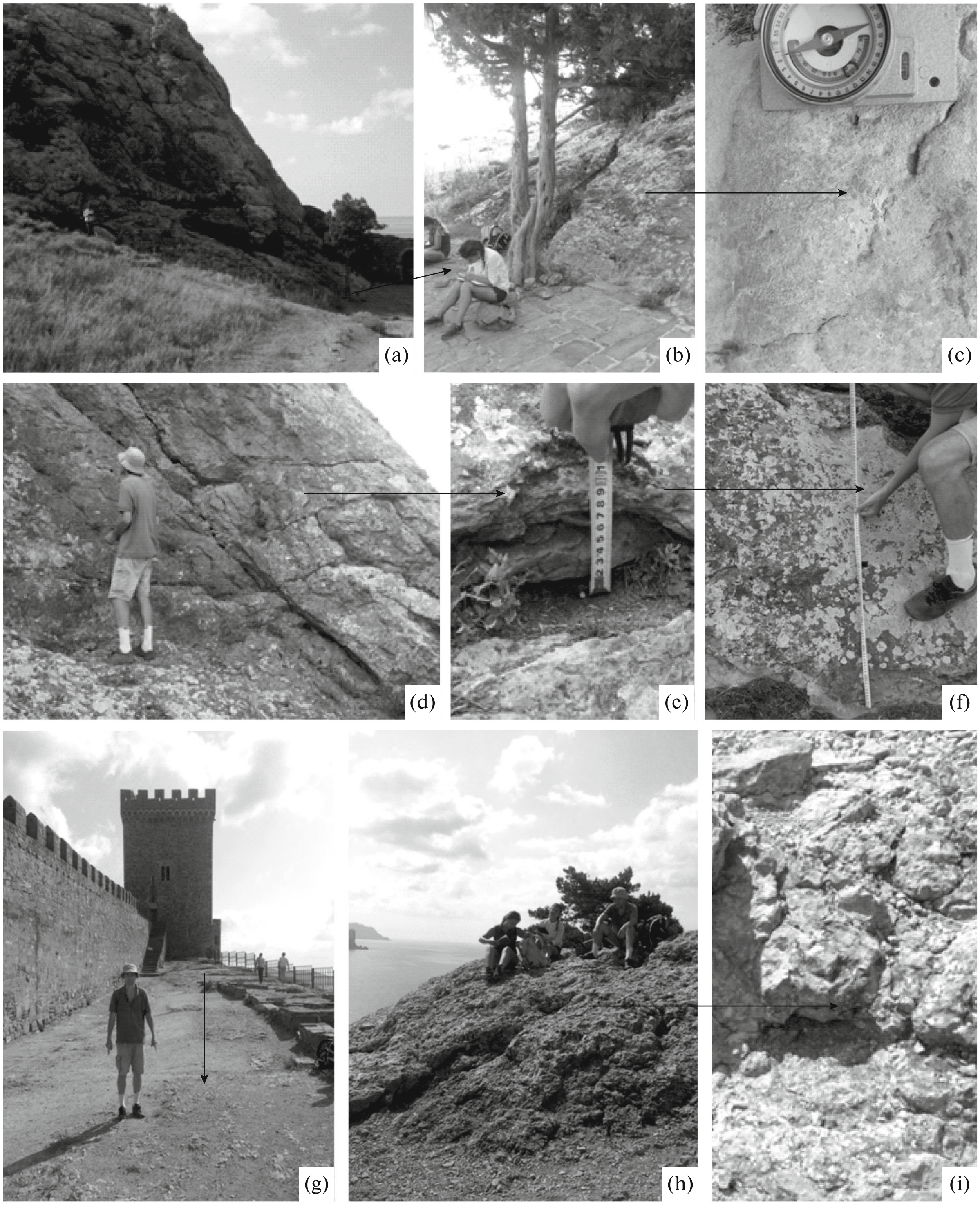

Fig. 4. Photos of the outcrops: (a) the Oxfordian limestones developing the almost vertical cliff (point 1019); (b) the same, but of larger scale, the alternating massive and loose varieties of limestones are visible (point 1019); (c) massive limestones (point 1019); (d) on the rock massif the banding that was formed due to the interbedding of limestones with different densities is visible (point 1019); (e) sandy limestones, which are less resistant to destruction that the massive limestones develop the hollows in the profile of weathering (point 1019); (f) massive limestone developing overhangs in the profile of weathering; (g) the sightseeing site of the upper castle of the Genoese Fortress, attributed to the leveled surface of the roof of the Oxfordian limestones (point 1021); (h) limestones, massive, nodular, indistinctly-bedded (point 1022); (i) the same, but at a larger scale (point 1022).

Table 4. The mineral composition of the rocks of the Verkhnesudakskaya subformation

Sample no.	Insoluble-residue method		Gas-volumetric method			Petrographic method (rock name and carbonate content (calcite%)
	carbonate content (calcite%)	insoluble residue, %	calcite, %	dolomite,%	insoluble residue, %	
1015	0	0	0	0	100	Mudstone, 0
1016	27.3	72.7	90.2	0.0	9.8	Polybioclastic limestone, 80
1019	7	93	88.6	0.0	11.4	Limestone, 60
1021	22.5	77.5	83.9	0.0	16.1	Coral limestone, 52
1022	7.9	92.1	82.5	0.0	17.5	Fragment of corallites, 50
1023/1	0	0	0	0	100	Sandstone
1023/2	15.5	84.5	67.7	0.0	32.3	Coral limestone, 60
1023/3	33.8	66.2	88.7	0.7	10.6	Coral limestone, 88
1047/1	8.5	91.5	8.1	0.0	91.9	Siltstone, 8
1047/2	20.7	79.3	82.3	2	15.6	Dolomite limestone, 82

dislocations (stripping in layers or in sublayers), in particular, as a tectonic melange (here and in the Alchak-Kaya Mountain area). In our opinion, the areas of stripping in layers or in sublayers and the zone of "melange" in the vicinity of Sudak actually appear to be part of a landslide–rockfall, where the Callovian terrigenous deposits are completely disintegrated; the limestones that lie near the zones of the block slipping have signs of mechanical treatment. The rocks are lumpy, with a dull lustre and mudstone leather coats.

The model of the large landslide–rockfalls in the southern coast of Crimea was first proposed by O.V. Zerkal and E.N. Samarin[1] (MSU) in 2017. We agree with their ideas.

The data on the mineral composition of the rocks were obtained as a result of laboratory testing (the insoluble residue method, the gas volumetric method, and petrographic study of rocks in thin sections) (Tables 4, 5). The almost complete absence of dolomite in the samples was found. The mean content of calcite (carbonate content) was determined according to the data obtained by three methods (Table 6). According to our own field observations, laboratory studies, and the data of our previous researchers , it is possible to assume that corals, cyanobacterias, algae, and rudists were the reef-constructing organisms in the Oxfordian time, during the time when the sediments of the upper part of the Verkhnesudakskaya Formation were accumulated. Echinoderms and shellfish were also in the composition of the paleocoenosis. The presence of corals in the studied rocks shows that in the Oxfordian time the water temperature was higher than 20°C on average. In addition, the presence of cyanobacteria and algae among the reef-constructing organisms indicates temperature variations.

The determination of the paleotemperatures showed that the mean temperature at the northern margin of the Tethys Ocean on the sections of the Sudak Bay was 23.6°C (the obtained temperature of 46°C was not considered in further calculations), whereas temperatures of 25°C and higher are typical for the southern margin of the Tethys Ocean. Over the period of the time from the Callovian to the Oxfordian and during the Oxfordian stage, the climate became warmer (Matthias et al., 2017; Wierzbowski, 2015).

The Sudak Formation is associated with the Late Jurassic transgression, which began in the Late Callovian and extended from the areas of stable downwarping, the western part of the Southwestern Crimea trough, the eastern part of the Eastern Crimea trough, and the Sudak trough. The suite was accumulated under conditions of normally-marine oceanic waters, climate warming (change of terrigenous facies by carbonate facies), and frequent eustatic variations (diversity of sediments, facies).

The studied stratigraphic interval of the section is attributed to the Callovian–Oxfordian complex of syn-rift sediments of the Callovian–Berriasian megasequence (Nikishin et al., 2015; Okay and Nikishin, 2015). The sediments of the lower subformation and the lower part of the upper subformation of the Sudak Formation were formed in the Sudak deep-sea trough. They are composed of a flysch complex presented by clays with sandstone interbeds, limestones, and lenses of conglomerates (the lower subformation ($J_{2-3}sd_1^1$)), and calcareous mudstones (clays) with concretions of

[1] This model was first mentioned in the oral report of O.V. Zerkal, E.N. Samarin "Role of the large-scale slope processes in the formation of the Quaternary deposits of the southern coast of the Crimea Peninsula (for the Alushta–Sudak area) on the 10th All-Russian conference on the study of the Quaternary Period "Fundamental problems of the Quaternary Period: results of the study and the main directions for further research" (Moscow, September 25–29, 2017).

Table 5. The total carbonate content of the rocks of the Verkhnesudakskaya subformation

Sample no.	Insoluble residue method	Geochemical method (dolomite + calcite), %	Petrographic method, %	The average carbonate content, %
1016	27.3	90.2	80	65.8
1019	7	88.6	60	51.8
1021	22.5	83.9	52	52.8
1022	7.9	82.5	50	46.8
1023/2	15.5	67.7	60	47.7
1023/3	33.8	88.7	88	70.2
1047/1	8.5	8.1	5	7.2
1047/2	20.7	82.3	82	61.6

siderites (the lower part of the upper subformation ($J_{2-3}sd_2^1$)). The depth of the basin gradually decreased over geological time. This is illustrated by the fact that the deep-sea forms, ammonites, crinoids, and sponges appeared at the end of the Callovian ($J_{2-3}sd_2^1$), and the shallower forms, including reef-constructing corals, appeared later, from the beginning of the Oxfordian in the formation of terrigenous–carbonate sediments ($J_{2-3}sd_2^2$). In the Early Oxfordian time, the depth of the basin was several tens of meters (on the basis of corals) or even less (on the basis of cyanobacterial structures).

The botanical indirect features were used for the geological mapping of the studied deposits. The surface of the limestones of the upper part of the Verkhnesudakskaya subformation shows the traces of marine salt dissolution; the surface is frequently covered by black-orange lichens *Rhizocarpon geographicum* (L.) and gray-white fruticose lichens *Parmelia sulcata* Taylor, making it impossible to study the primary structure and texture of the rock (excluding the area of the Golitsyn path in Novyi Svet).

Table 6. Comparison of the contents of $\delta^{13}C$, $\delta^{18}O$ (‰VPDB), and T(°C) with $\delta^{18}O$ water of 0‰ for the rocks of the upper part of the Verkhnesudakskaya subformation

Sample no.	$\delta^{13}C$, ‰VPDB	$\delta^{18}O$, ‰VPDB	T, °C with $\delta^{18}O$ water of 0‰
*1015**	*–0.125*	*–6.28*	*46*
1022	3.795	–1.69	22
1021	4.265	–0.73	17
1023/3	3.205	–1.2	19
1016	2.435	–4.11	34
1019	4.095	–0.51	16
1006/1	1.105	–4.64	37
1009/1	3.155	–1.36	20

* Italics. values omitted in the calculation

Biohermal carbonate massifs are destroyed due to weathering. As a result, blocks and boulders collapsed in or slipped down the slopes of the First Mountain Range and soil development occurred.

In the Sudak area, soils are generally brown, mountainous, and rubbly. The area of the soil distribution is very limited on the Crimean Peninsula. The soils are formed on the Southern Coast of Crimea under the influence of the climatic barrier, the Main Mountain Range with a height of 1200–1500 m, on the products of the weathered limestones, marls, shales, sandstones, and magmatic rocks. The formation of the soils depends directly on the specific hydrothermal regime that is formed in humid and warm winters. Humus is conserved in the soils because mineralization becomes slower under dry climatic conditions. The brown mountainous rubbly soils on eluvium and deluvium of the bedrocks are characterized by a high content of carbonates along the entire profile; they contain a large amount of humus (7–10%). These soils are formed in xerophyte (plants adapted to an environment with very little water) forests and bushes. The climate of the area is arid and hot with mild winters (Sub-Mediterranean southern coast of the Crimea Peninsula).

CONCLUSIONS

The Upper Callovian and Lower Oxfordian deposits of the Sudak Formation were characterized on the basis of 14 sections in the vicinity of the Sudak Bay. The botanical indirect mapping future was used for the first time; the surface of the limestones of the Verkhnesudakskaya subformation bears marks of marine salt dissolution and are frequently covered by black-orange lichens *Rhizocarpon geographicum* (L.) and fruticose gray white lichens *Parmelia sulcata* Taylor.

In Oxfordian time, the main reef-constructing organisms were corals, cyanobacterias, algae, and rudists. Echinoderms and shellfish were also in the composition of paleocoenosis. The presence of corals in the studied rocks indicates that in the Oxfordian time the water temperature was higher than 20°C on average; this is confirmed by the mean values of the paleotemperature of 23.6°C, which we obtained. The presence of cyanobacteria and algae among the reef-constructing organisms indicates temperature variations.

We proposed a new model of the large landslides–rockfalls, which explains the presence of local areas of "dislocated" bedding of the different parts of the same suite, which were formerly interpreted as "melange zones."

ACKNOWLEDGMENTS

The authors are grateful to A.M. Nikishin (Moscow State University) for consultations during the field observations and interpretation of the obtained data.

This work has been supported by the Ministry of Education and Science of Russian Federation (grant no. 5.5177.2017/8.9).

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Translated by V. Krutikova