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GEOLOGY

New Data on the Geological Structure of the Southwestern Mendeleev Rise, Arctic Ocean

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Abstract—This communication considers the ideas about the geological structure of the southwestern Mendeleev Rise belonging to the East Arctic rises of the Arctic Ocean. These ideas have resulted from analyzing the data obtained from bathymetric surveys, visual observations, and bottom coring using the technical tools of a research submarine. We distinguished the lower sequence of quartzite sandstones and dolomites, which has a visible thickness of about 230 m and occurs in the lowermost visible section, at depths between 1500 and 1270 m. This sequence is superimposed with stratigraphic and angular unconformity by the upper sequence of limestones and sandstones having a visible thickness of 40 m. The lower sequence is pierced by subvolcanic rocks of basaltic to andesitic composition, and in the lowermost part of the slope, a tuffaceous sequence having a visible thickness of 50 m adjoins it.

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The largest structures in the Amerasian part of the Arctic Ocean (AO) are the East Arctic rises, which include, in particular, Mendeleev Rise. Investigation of their geology is a difficult problem because of the presence of ice cover for most of the year in the AO water above them. In this respect, new data on the structure of the ocean floor in this poorly studied region are of great scientific interest.

A great amount of information about the composition of rocks and the structure of the Mendeleev Rise was obtained during the Arktika-2012 expedition in 2012 [2–4]. Rock samples were collected by dredging and submarine drilling and with the use of a research submarine (RS). However, specialists in geology of the AO have certain doubts regarding the nature of the dredged samples, which make up the majority of rock material, because rock material can be transported from land into water with ice and icebergs [1], whereas there are no clear criteria of distinguishing between rock material that drifted into an area and rock formed in situ. Dredged material also does not allow us to determine the position of rocks having different compositions and ages in a geological section.

Given these problems, bathymetric survey, video recording, and sampling of bedrock outcrops were performed in 2014 on the ocean bottom in the southwestern part of Mendeleev Rise using technical tools of a RS to characterize reliably the geological section of this submarine rise. The study area was limited to the coordinates 78°09′–78°15′ N and 178°58′–179°20′ W (Fig. 1). Based on analysis of the seismic profiling data, the locations of bedrock outcrops not covered by Cenozoic syn-oceanic deposits were preliminarily determined.

Bathymetric survey in the study area was made by using a multi-beam echo sounder. The survey was implemented at speed of 3.4 to 6.4 knots and emitted a signal power of 220 dB with 25-dB amplification and a pulse length of 8 ms, enabling us to obtain depth values with an accuracy of 50 cm. At the beginning of and after the survey, the RS locations were determined by the GLONASS navigational system. During the survey, RS was coordinated by an inertial navigational system (INS). The deviation between the real RS location and the INS-determined location was 180 m. Five sounding lines of 45.3 km total length were passed. The distance between sounding lines ensured that the entire bottom was covered by the survey.

According to the bathymetric map made on the basis of the survey results (Fig. 2), the slope of the Mendeleev Rise begins from 1500 m depth. Below is a depression with a gently sloped bottom. The slope is subdivided into two segments in terms of the character of landforms. The central segment is bounded on troughs of 400–500 m prograded 1.0–1.5 km southward (hereinafter, they are referred to as the Western and Eastern capes). The bottom profile in the central segment is subdivided into four parts. On the lower part of the slope, the gentle Lowermost terrace, confined by a scarp inclined at 15°–20° to the depression, is located: its width is 100–500 m and up to 50 m high.

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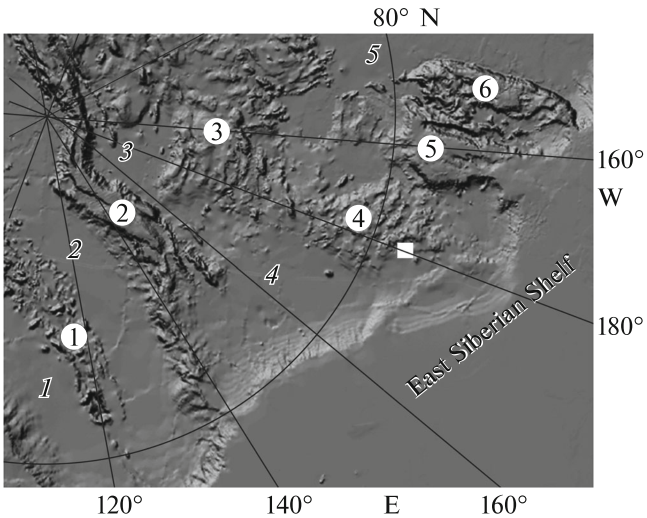

Fig. 1. Scheme showing bottom topography of the East Arctic region and location of the study area (light-colored rectangle), constructed on the basis of the shaded bottom relief map, IBCAO grid (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/). Basins (white numerals): *1*, Nansen; *2*, Amundsen; *3*, Makarov; *4*, Podvodnikov; *5*, Canada; rises and ridges (black numerals): *1*, Gakkel Ridge; *2*, Lomonosov Ridge; *3*, Alpha Ridge; *4*, Mendeleev Rise; *5*, Chukchi Plateau; *6*, Northwind Ridge.

Up there, in the depth interval of 1450–1380 m, the middle slope extends at angle of about 30°, and above it there is the Vertical escarpment of up to 100 m high. At depths of 1275–1290 m, this escarpment changes to the uppermost gently inclined (about 7°) part of the slope. In the Western segment and in the area of the Eastern Cape, the Vertical escarpment is cut by narrow (10–40 m) terraces into a series of escarpments with heights ranging from 5 to 20 m.

There were continuous video observations of the bottom ground in the study area. Video documenting accompanied the finding of objects of geological value and during collection of samples. The sensitivity of RS onboard video cameras allowed the video recording to be performed at an average distance of 15–20 m from the bottom. Video records were stored on a DVD-recorder. For the purpose of video documentation and sample collection, 19 near-bottom measuring lines were passed by the RS (total length is 20 km). The submarine measuring lines were planned by using a bathymetric map (Fig. 2); coordination during these works was carried out by using a special INS of the RS. The accuracy of the RS location definition was no more than 500 m.

The samples were collected by using RS mechanical arms after grounding. At 18 points (Fig. 2), 29 samples were collected (Table 1); the points are uniformly distributed over the study area and represent all landforms. Samples were collected by the following methods: (a) breaking off of pieces from thin (about 5 cm) layers and from layers composed of weakly cemented rocks; (b) pulling of fragments from the layers preserving their consistency but partitioned by fractures into blocks; and (c) picking from boulder streams and screes. The collection method is indicated in Table 1. The collected material includes dolomites (ten samples), quartzite sandstones (five samples), volcanic rocks (seven samples) ranging from basalts to andesites, sandstones, limestones, and tuffs (two samples each), and one sample of diorite.

Video observations showed the following. The depression is completely filled with silt, while the

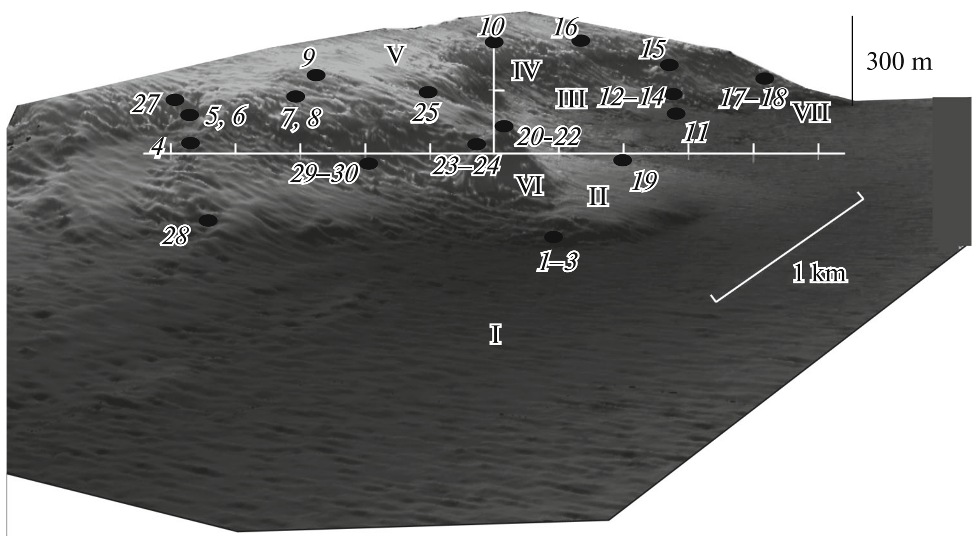

Fig. 2. 3-D model of bottom relief in the study area. Ovals mark the sampling points with the indicated numbers of samples. Roman numerals denote the following: I, depression; II, Lowermost terrace, III, middle slope; IV, Vertical escarpment; V, upper slope; VI, Western Cape; and VII, Eastern Cape.

Table 1. Coordinates, depth, and characteristics of samples

Samp. nos.	Latitude, N	Longitude, W	Depth, m	Rock	Size, cm	Sampling method
14-01	78°10.2′	179°07.5′	1493	Dolomite	9 × 6 × 3	4
14-02	78°10.2′	179°07.5′	1493	Andesite	28 × 14 × 7	2
14-03	78°10.2′	179°07.5′	1493	Dolomite	25 × 15 × 10	4
14-04	78°10.6′	179°09.0′	1409	Quartzite sandstone	20 × 18 × 3	2
14-05	78°10.6′	179°08.8′	1353	Andesite	35 × 22 × 14	2
14-06	78°10.6′	179°08.8′	1353	Andesite	17 × 12 × 10	2
14-07	78°10.7′	179°08.5′	1278	Dolomite	23 × 11 × 11	3
14-08	78°10.7′	179°08.5′	1278	Dolomite	16 × 14 × 13	3
14-09	78°10.7′	179°07.0′	1230	Sandstone	16 × 16 × 7	2
14-10	78°10.7′	179°08.5′	1282	Limestone	20 × 20 × 5	1
14-11	78°10.6′	179°01.5′	1510	Andesite	45 × 30 × 20	4
14-12	78°10.7′	179°02.0′	1400	Diorite	8 × 5 × 4	4
14-13	78°10.7′	179°02.0′	1400	Quartzite sandstone	9 × 5 × 5	4
14-14	78°10.7′	179°02.0′	1400	Dolomite	20 × 12 × 2	2
14-15	78°10.75′	179°00.7′	1304	Dolomite	14 × 12 × 8	2
14-16	78°10.8′	179°00.7′	1267	Dolomite	17 × 11 × 5	4
14-17	78°10.6′	178°59.8′	1310	Andesite basalt	15 × 5 × 5	4
14-18	78°10.6′	178°59.8′	1310	Basalt	13 × 9 × 6	4
14-19	78°10.5′	179°06.0′	1455	Tuff	14 × 15 × 7	1
14-20	78°10.5′	179°07.2′	1340	Dolomite	15 × 8 × 2	3
14-21	78°10.5′	179°07.2′	1340	Dolomite	10 × 6 × 6	3
14-22	78°10.5′	179°07.2′	1340	Basalt	10 × 8 × 5	3
14-23	78°10.6′	179°07.7′	1287	Quartzite sandstone	8 × 6 × 3	3
14-24	78°10.6′	179°07.7′	1287	Sandstone	12 × 11 × 9	3
14-25	78°10.5′	179°07.3′	1287	Quartzite sandstone	20 ×14 × 13	3
14-27	78°11.0′	179°09.7′	1318	Limestone	20 × 20 × 5	1
14-28	78°10.6′	179°09.7′	1488	Tuff	8 × 6 × 3	1
14-29	78°10.5′	179°08.1′	1379	Dolomite	19 × 17 × 12	2
14-30	78°10.5′	179°08.1′	1379	Quartzite sandstone	35 × 28 × 14	4

Sampling methods: 1, breaking off of pieces from exposed bedrock; 2, pulling of fragments from the layers partitioned by fractures into blocks; 3, picking out of a boulder stream; 4, picking out of a scree. Numbers of samples in table correspond to those in Fig. 2 in a way like “14-01” corresponds to “1.”

Lowermost terrace and the middle slope are considerably covered by silt. In erosional windows of the Lowermost terrace, there are bedrock outcrops in the form of cascade escarpments at the bottom of 1–5 m high, represented by tuffs (samples 19, 28). Tuffs are weakly cemented and can be broken by a mechanical arm; they compose layers of 10–20 cm thick, dipping northeast at about 20° (Fig. 3a). In the middle slope, there are screes consisting of fragments of 10–20 cm in cross-size; the screes are partially covered by silts and combined with bedrock outcrops (outliers of up to 50 cm high). The samples from screes are diorite (sample 12) and quartzite sandstone (sample 13), and also dolomite pulled from one of the escarpments (sample 14). There also are escarpments of up to 15 m high at the bottom: they extend along the slope and the rocks in them are fractured into individual blocks. Two of these blocks were sources of dolomite (sample 15) and quartzite sandstone (sample 4). Beneath the escarpments, we observed screes consisting of fragments of 10 to 30 cm in cross size.

The Vertical escarpment is composed of massive and laminated rocks (Fig. 3b). In the latter case, layers dip at 30°–40° either westwards or southeastwards. At the continuation of the Vertical escarpment in the western segment, we collected volcanic rocks (samples 5, 6) and dolomite (sample 29) from escarpments of 1–15 m high, and a sample of quartzite sandstone

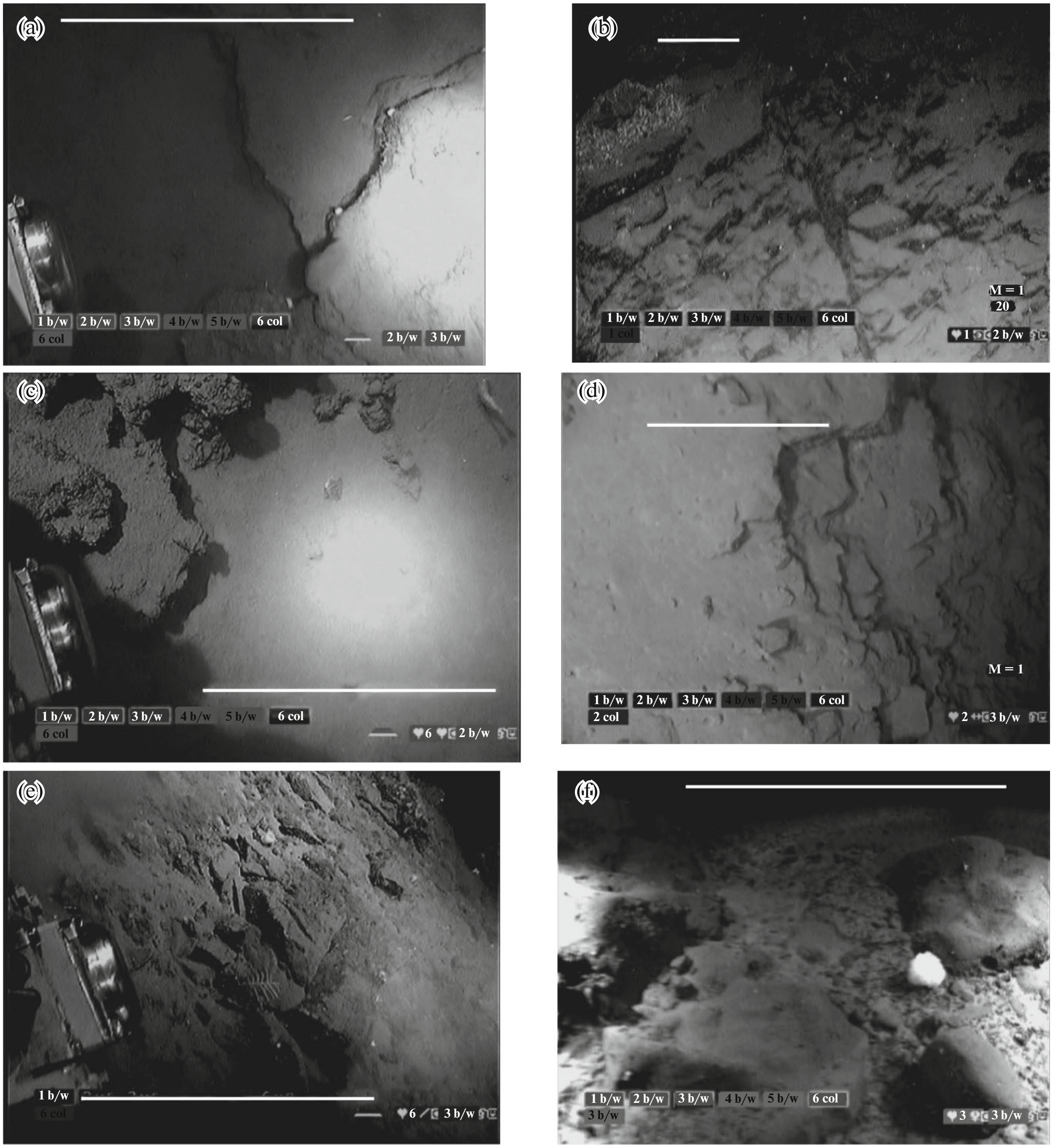

Fig. 3. Images of characteristic sites on the slope of the Mendeleev Rise in the study area: (a) tuff layers; (b) laminated rocks of the Vertical escarpment, with layers dipping eastwards at about 30°; (c) escarpment composed of laminated cavernous limestones at the bottom; (d) cascaded escarpment composed of laminated sandstones; (e) minor ridge of volcanic rocks extending along the slope; (f) pipelike protrusions at the bottom in the summit part of the Western Cape. Horizontal straight lines in images are 1-m long scale references.

was also collected from the accompanying boulder streams (sample 30). At the same level within the limits of the Eastern Cape, we collected volcanic rocks (samples 17, 18) from the scree surrounding small bedrock outcrops of up to 50 cm high.

The uppermost gently inclined part of the slope is generally covered by silt. Above the ledge of the Vertical escarpment, we observed outcrops of breccia-like rocks in the form of cascaded escarpments of 2–3 m high (Fig. 3c). Their sampling has shown that these are highly cavernous limestones (sample 10); limestones form layers of 5–10 cm dipping southwestwards at 15°–20°. Similar outcrops of limestones (sample 27) in the western part of the study area are located at greater depths (1315 m). Above limestone outcrops and among the covering silts, an outcrop of sandstones (sample 9) in the form of a cascaded escarpment was found (Fig. 3d). Sandstone layers of about 10 cm thick are of the same dip as the limestone layers.

The Western Cape, beneath which the Lowermost terrace is absent, is of an unusual structure. Here the scree composed of large blocks and fragments extends from the depression to the Vertical escarpment (hereinafter referred to as the Big scree). Obviously, the Big scree was produced by a partial collapse of this escarpment; we collected dolomites (samples 1, 3) from it. In the lower part of the scree, from a minor ridge of about 1 m wide (Fig. 3e) extending along the slope, a volcanic rock (sample 2) was pulled. In the summit part of the Western Cape, we can observe either escarpments accompanied by a boulder stream, from which we collected quartzite sandstone (sample 25), or outliers of 0.5–3.0 m high at the bottom, between which boulder stream deposits represented by quartzite sandstone (sample 23) and sandstone (sample 24) are located. At the bottom we also found pipelike projections of up to 30 cm high and 0.75 m, on average, in diameter, which looked like prepared volcanic conduits (Fig. 3f). Out of the boulder stream occurring between "pipes," we collected dolomites (samples 20, 21) and volcanic rock (sample 22).

Before we proceed to the reconstruction of the geological section, let us show that the collected rock material formed in situ instead of having been transported by drifting ice. First, there are many bedrock outcrops in the forms of ledges, projections, and escarpments on the studied slope. Limestones and tuffs were broken off from them, while part of the dolomites, one volcanic rock sample, and one quartzite sandstone sample were pulled by a mechanical arm from cracked ledges. Second, the material of boulder streams developed on the summits of the Western Cape and the edge of the Vertical escarpment is also represented by bottom bedrocks, because fragments in boulder streams could have formed in the case of physical weathering of the underlying rocks. Dolomites are predominant among the material composing boulder streams; however, sandstones, quartzite sandstones, and volcanic rocks were also found. Third, screes occurring beneath ledges, in particular, the one below the Vertical escarpment, were produced by weathering and collapse of these ledges and escarpments, as was visually traced in the case of the Big scree. This is also indicated by the common composition of stone material from screes, ledges, and boulder streams. Seemingly, only diorite, which sharply differs from other igneous rocks, could have been transported by drifting ice.

We distinguished three associations of rocks composing various elements of the studied slope: (1) tuffs occurring within the limits of the Lowermost terrace; (2) dolomites, quartzite sandstones, and volcanic rocks found within the limits of the steepest part of the slope, from the depression to the edge of the Vertical escarpment; and (3) limestones and sandstones from the upper gentle part of the slope. On the basis of this subdivision, in the visible geological section of this slope of Mendeleev Rise, we can distinguish three sequences (Fig. 4): tuffaceous, lower, and upper. Judging by the morphology of the Lowermost terrace (Fig. 2) and taking into account that rocks of the lower sequence reach the level of the depression in the area of the Western Cape, it is obvious that the tuff sequence adjoins the rocks of the lower sequence (Fig. 4), with the layers of the latter having dip directions and angles different from those of tuff layers. These relationships between the mentioned sequences could be the result of (1) washing and redeposition of tuff deposits composing horizons in the uppermost part of the slope, or (2) accumulation of tuff material, which was deposited on steep slopes of the rise after eruption, in the bending zone, or (3) sinking of the upper parts of the section down along the slope. Determination of tuff ages can help in determining their position within the section. The visible thickness of the tuff sequence is about 50 m (Fig. 4).

We distinguished volcanic rocks extracted from the lower sequence as an independent subvolcanic complex: their bedrock outcrops are morphologically close to either sills (Fig. 3e) or conduits (Fig. 3f); additionally, they contain xenoliths (of up to 2 mm in size) of dolomites and quartzite sandstones. Thus, the lower sequence is composed of quartzite sandstone dolomites, which, probably, layer with each other; its visible thickness is at least 230 m. In the upper sequence (the visible thickness is about 40 m), sandstones and limestones, judging by the character of their occurrence and hypsometric position, also interlayer with each other. The contact between the upper and lower sequences is rough and runs at different hypsometric levels: at about 1280 m in the area of the Vertical escarpment, and at 1315 m in the western segment; however, above the Eastern Cape it can be expected at a level higher than 1267 m, because we collected dolomite (sample 16) from the scree at this level. This character of the contact is caused by a stratigraphic hiatus between sequences, which is indicated by the presence of dolomite and quartzite sandstone detrital grains in limestones. There is also an angular unconformity between the lower and upper sequences; this leads to the fact that either dolomites or quartzite sandstones become exposed at the same level in different places of contact.

The rocks collected during our works are, as has been shown above, of local origin; moreover, they are more similar to the samples dredged on Mendeleev Rise during the Arktika-2012 expedition [1–4], indicating that a considerable part of dredged rocks also formed in situ. In this case, the comparison between the results obtained and the results of the Arktika-2012 expedition [3] gives us grounds to suppose that dolo-

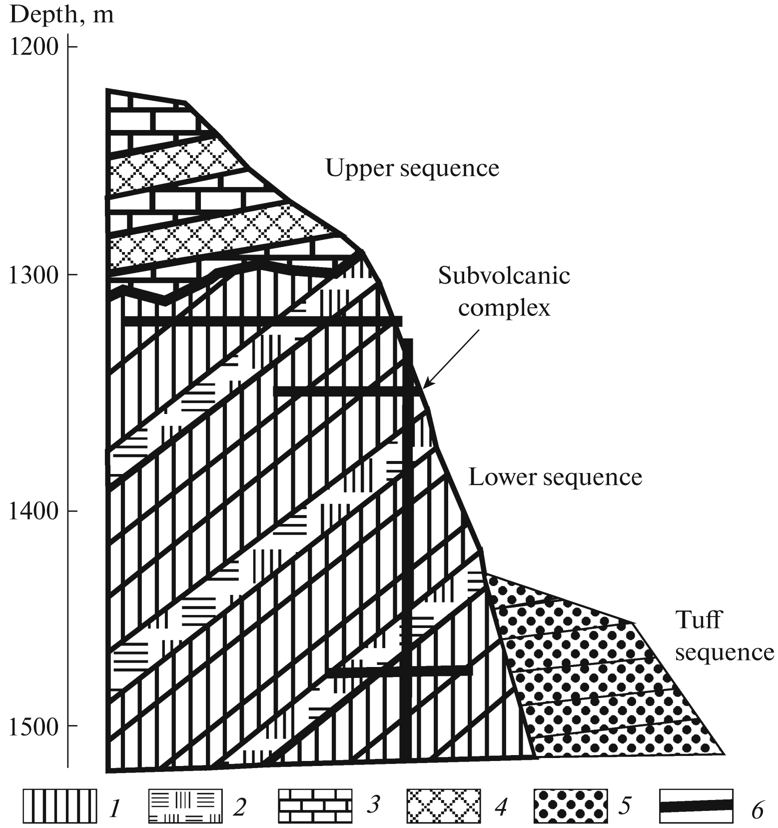

Fig. 4. Conceptual geological cross section of Medeleev Rise in the study area. Arbitrary notes: (*1*) dolomites, (*2*) quartzite sandstones, (*3*) limestones, (*4*) sandstones, (*5*) tuffs, (*6*) volcanic rocks.

mites and limestones collected in 2014 are of Paleozoic age.

In summary, we should emphasize that the main result is understanding the main features in the geological section of one of the southern terminations of Mendeleev Rise. Here, in the lowermost part of the visible section, at depths between 1500 and 1270 m, the lower sequence composed of quartzite sandstones and dolomites occurs with stratigraphic unconformity beneath the upper sequence composed of limestones and sandstones and having a visible thickness of 40 m. The lower sequence is pierced by a subvolcanic complex of basalts and andesites, and a tuff sequence having a visible thickness of 50 m adjoins it in the lowermost part of the slope.

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