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Lithogeochemical Characterization of Depositional Environments in the Crimean-Caucasian Trough during the Early Jurassic–Aalenian (Kacha Uplift and Kranaya Polyana)

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Abstract—This study presents the first results of the comparison of depositional environments in the Crimean and Caucasian regions of the Crimea–Caucasus trough during the Early Jurassic and Aalenian using lithological and geochemical methods. In this study we proposed new models for variations of temperature, salinity, and bathymetry in the Early Jurassic and Aalenian.

Keywords: Jurassic, turbidites, geochemistry, paleogeography, bathymetry, salinity, temperature, Crimea, Caucasus

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INTRODUCTION

The Lower–Middle Jurassic terrigenous flysch unit of the Crimea–Caucasus trough is composed of rocks of complex deformation that visually appear cyclic and uniform in lithology and contain very scarce macrofauna and a few microfauna and microflora, which hampers their subdivision and correlation. Therefore, their investigation is of great importance. The construction of the 2014 Olympic sites created temporary outcrops in the Mzymta River valley and caused a number of specific difficulties faced by researchers in their attempt to establish the subdivision and correlation of outcrop and well sections. In addition, the presence of slumps that overlap in places made correlation and age determination difficult. The large number of sections required a rapid age-determination technique, e.g, micropaleontological analysis. At the same time, some of the ages obtained from nannoplankton were inconsistent with the generally accepted ages of formations, which still, however, remain debated (Panov, 2003).

An example of the above would be an outcrop that existed prior to the installation of sound walls and reconstruction of the roadway at Esto–Sadok on the right bank of the Mzymta River (site 457 in Gabdullin, Ivanov (2013)) (Fig. 1). Here, the bedrocks are exposed in a sandstone cliff near an old Adler–Alpika-Servis road. The section was found to contain no identifiable conodonts (A.S. Alekseev, Moscow State University). On geologic maps that were published in the past, this section is assigned either to a Triassic or Lower Jurassic age, although the bituminous mudstone from the opposite site 458 on the left bank of the Mzymta River contains a Sinemurian–Pliensbachian nannoplankon assemblage consisting of *Mitrolithus elegans* and *Crepidolithus granulates*, which was identified by E.A. Shcherbinina (Geological Institute, Russian Academy of Sciences) in (Gabdullin, Ivanov, 2013). In addition, most sections of the Northwestern Caucasus contain evidence of the Late Aalenian mass extinction of molluscan and foraminiferal species associated with paleogeographic changes and the appearance of the oxygen-deficient marine basins in Early Aalenian times (Ruban, Tyszka, 2005; Ruban, 2012) during marine regression (Fig. 2).

In view of the above, the results from the first geochemical study of these sediments in the sections of Crimea and Caucasus were used for correlation and paleogeographic reconstruction.

The results of this study will be of interest for field-geological training of students of Moscow State University, as well as for conducting additional geological survey and exploration (GDP-200) at sites of Crimea.

METHODS

In the Caucasus (Fig. 1), studies were conducted in the region of Krasnaya Polyana in the Mzymta River valley, near the Esto–Sadok and Krasnaya Polyana train stations. Site 458 is located east of the Esto–Sadok hub, at the northern portal of road tunnel 4. In the vicinity of ski lifts in the lower base area of Rosa Khutor, we examined sections on the left (site 460) and right (site 461) banks of the Mzymta River. Sites 462–464 are located on a motor road to Snow Park.

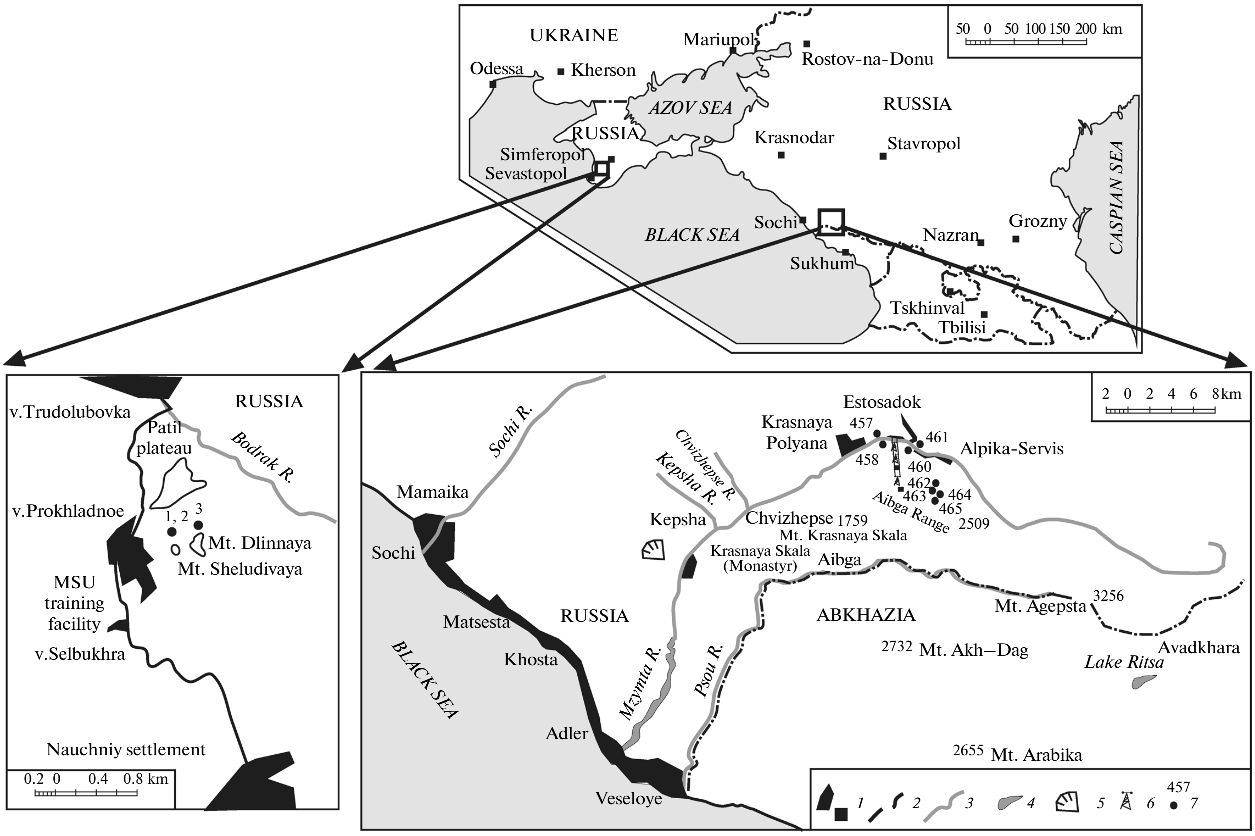

Fig. 1. A schematic map that shows the locations of observation sites: (*1*) boundaries of settlements, (*2*) state boundaries, (*3*) rivers, (*4*) lakes, (*5*) quarry, (*6*) Gornaya Karusel aerial railway, (*7*) observation sites and their numbers.

Site 465 is located in the road undercutting near a creek above tunnel 6. In Crimea (Fig. 1), we studied several sections on the Kacha uplift in the vicinity of a stationary training facility of the Moscow State University in the village of Prokhladnoye (Bakhchisarai region). Sites 1 and 2 are located in Mangush gully near its junction with Yaman gully; site 3 is situated in the watershed between Mounts Sheludivaya and Dlinnaya.

This study is focused on terrigenous flysch deposits of the Crimea–Caucasus deep-water trough. Because of the great thickness of intensely dislocated formation sediments, the sections were not subdivided and the samples were tied to local stratigraphic units. Only fragments (intervals) ranging from a few meters to a few tens of meters were described. The rhythmic flysch sequences were analyzed by constructing of rhythmograms, which are useful for detailed stratigraphic positioning of a certain fragment (interval) within the entire sedimentary section. A macroscopic description of rocks was supplemented by microscopic examination (65 thin sections analyzed are not included in this study) and geochemical analysis.

The geochemical analysis of 30 terrigenous sediment samples was performed using a MARC.GV (NPO Spektron, St. Petersburg) X-ray fluorescence spectrometer at the Faculty of Geotechnical Engineering, Moscow State University (analyst E.N. Samarin). The analysis was conducted on 14 samples that were collected from seven Lower–Middle Jurassic sections in the Krasnaya Polyana region of the Greater Caucasus and 16 samples from three sedimentary sections of the Upper Taurian Series on the Kacha uplift (Mountainous Crimea).

To refine the previous paleoenvironmental reconstructions we calculated some significant element ratios and abundances, which can be used as indicators of changes in the depositional environment (water depth, hydrodynamic and climate conditions, etc.).

CHARACTERIZATION OF LOWER JURASSIC–AALENIAN SECTIONS OF THE CRIMEA–CAUCASUS TROUGH

The section consists of terrigenous, mostly sandy-argillaceous flysch rhythms. Their lithological and paleontological characterization, stratigraphic position, tectonic setting and historical background have been discussed in a number of previous studies (Afanasenkov et al., 2007; Baraboshkin, Degtyarev, 1988; Geologiya SSSR, 1968, 1969; Gustomesov, 1967; Korolev, 1983; Logvinenko et al., 1961; Mileev et al., 1989; Muratov, 1959; Nikishin et al., 1997, 2006; Panov, 1997, 2006, 2009; Panov et al., 2001; Panov,

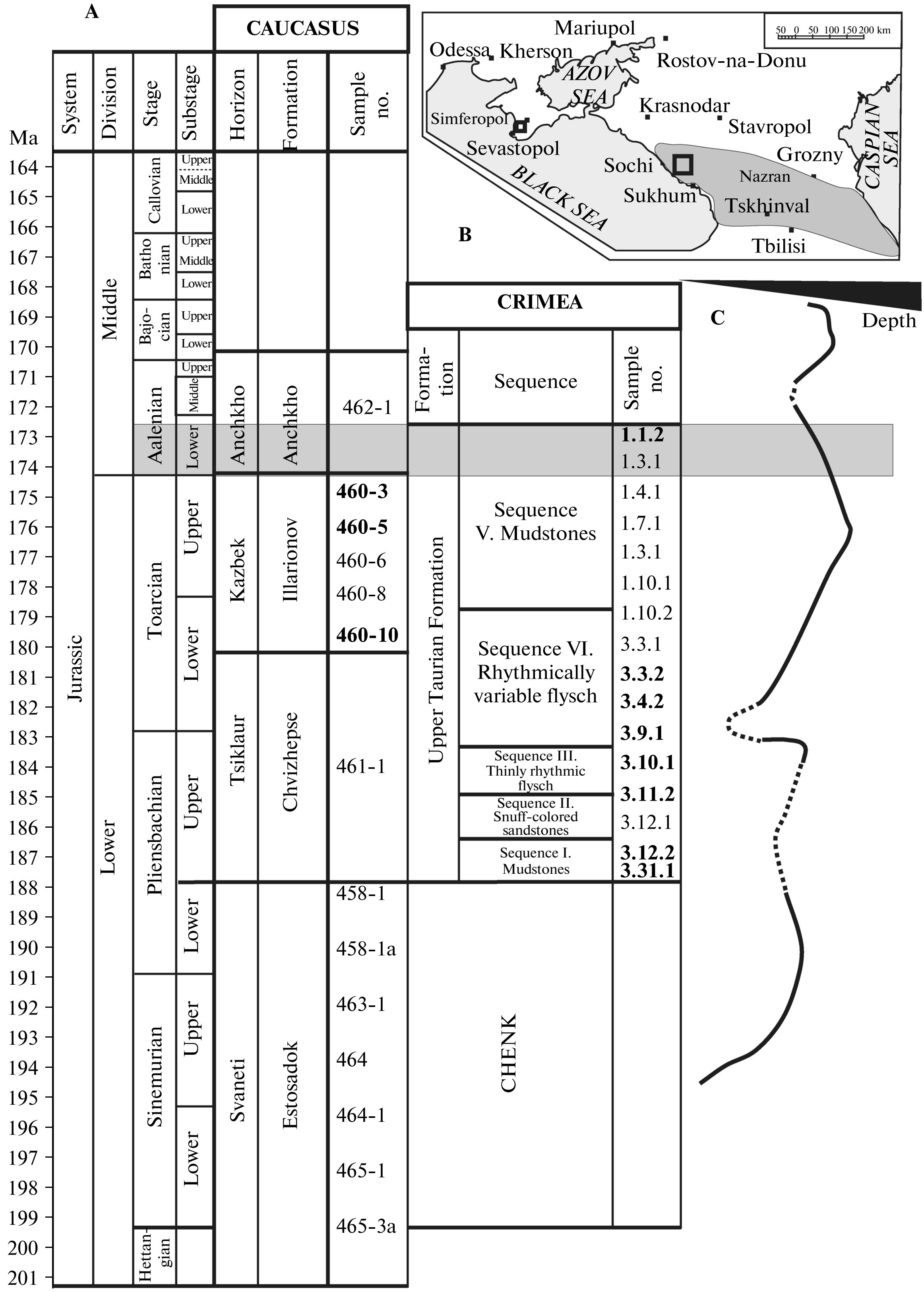

Fig. 2. Geologic history of the Crimean–Caucasian region: (a) chronostratigraphic correlation of formations in the Caucasian and Crimean regions of the trough and location of sampling sites; sandstone samples are shown in semibold, the remaining are mudstones; oxygen deficient waters during the Early Aalenian are shown in grey color, after (Ruban, 2012); (b) schematic map showing the location of study area; oxygen deficient waters during the Early Aalenian are shown in grey color, after (Ruban, 2012) (for explanation see in Fig. 1); (c) regional paleobathymetry curve for the Northwestern Caucasus, after (Ruban, Tyszka, 2005).

Prutskii, 1983; Slavin, 1958; Tseysler et al., 1999). The correlation of the stratigraphic schemes of Crimea and the Greater Caucasus for the studied interval and location of sampling sites were shown in Fig. 2.

CHARACTERIZATION OF LOWER JURASSIC–AALENIAN SECTIONS OF THE KRASNAYA POLYANA REGION OF WESTERN CAUCASUS

This stratigraphic interval is subdivided into the Anchkho, Illarionov, Chvezhipse, and Esto–Sadok of the Krasnaya Polyana series (Fig. 2).

The Esto–Sadok Formation (J_1*es*, J_1*s*–p_1) is of the same age as the Svaneti horizon on the Southern Slope of the Greater Caucasus and was first described in the Mzymta River valley, near the village of Esto–Sadok. It is composed of banded mudstone with sandstone and gravelstone interbeds, limestone lenses, and basal conglomerate. The Sinemurian–Early Pliensbachian age of the formation is constrained by its stratigraphic position and the ammonite *Arietites* (*Coroniceras*) cf. *bucklandi* Sow. (Panov, Prutskii, 1983). The thickness of the formation is 550 m.

A unit of black thinly laminated weak mudstones crops out east of the Esto–Sadok transfer hub, near the northern portal of tunnel 4 (site 458). The layers are boundinaged and deformed. Under the microscope (thin section no. 458/1) the rock is seen to be a fine-grained, polymictic, mostly hydromicaceous mudstone, containing minor amounts (15–20%) of angular and subrounded fine- to very fine-grained quartz and biotite, which are horizontally laminated due to the presence of microscopic-scale lenses of organic matter (30%), and sideritized (5%). The clay content varies between 50 and 45%. Secondary alteration is indicated by the presence of iron oxides and pyrite.

Farther south, the Esto–Sadok Formation is observed in a series of exposures near K-95 and K-125 jumping hills on the left bank of the Mzymta River just opposite the Esto–Sadok transfer hub. The formation represents a sequence of irregularly but rhythmically interbedded fine-grained micaceous (muscovite), quartz, red-brown (when fresh) to brown (when weathered) sandstones (30–50 cm thick) and black (when fresh) to brown (when weathered), boudinaged mudstones (30–50 cm to a few centimeters thick). Occasional layers of brown siltstone are also present. The layers have the dip direction of 190° and dip angle of 20° (hieroglyphs indicate inverted bedding).

The outcrop of graphitic (grey-black) bituminous mudstones, weak and thinly laminated exhibiting disrupted bedding (slumps) is observed at site 463 (J_1s–p_1, Estosadok Formation), near a sharp bend in a motor road below the Snow Park, on the right bank of an unnamed creek mudflow.

The outcrop at site 464 (J_1s-p_1, Esto–Sadok Formation) consists of bedrock that is bituminous, grey-black, thin-scaly, very weak, friable in hand and falling due to vibrations from heavy traffic on a nearby road and is located near a sharp bend in a motor road below the Snow Park, on the left bank of the unnamed creek mudflow. The beds are contorted into a small antiform fold (slump, inverted bedding, dip direction 260°, dip angle 26°).

The out crop consisting of black bedrock bituminous, thin-scaly and weak mudstones is observed at site 465 (J_1s–p_1, Esto–Sadok Formation), in the road undercutting above tunnel 6, near the unnamed creek. The apparent thickness of the formation is > 10 m.

The Chvezhipse Formation (J_1*čv*, J_1p_2–J_1t_1) is recognized within the Tsiklaur horizon on the Southern Slope of the Greater Caucasus and consists of non-laminated, conchoidal mudstones, micaceous siltstones, with marl and limestone lenses and abundant charred plant debris.

The age of the formation is constrained by its stratigraphic position and the occurrence of the ammonite *Amaltheus margaritatus* Montf. and belemnites *Rhabdobelus exilis* Orb., *Coeloteuthis* sp. (Panov, Prutskii, 1983). The thickness of the formation is 700 m.

South of the northern portal of tunnel 4, near the K-95 and K-125 jumping hills, the outcrops of the Chvezhipse Formation are represented by dark grey to black mudstones, non-laminated, often micaceous. They are weak and contain abundant charred plant debris. A distinctive feature of these mudstones is their spotty texture caused by the presence of black sub-parallel segregations forming irregularly shaped lenses. The dip direction of bedding is 240° and dip angle is 30–40°.

The Illarionov Formation (J_1*il*, J_1t_2) represents a sequence of alternating packets of sandy–argillaceous and silty–argillaceous rocks. The age of the formation is inferred from its stratigraphic position (Panov, Prutskii, 1983). The thickness of the formation is about 1600 m.

In the vicinity of the ski lifts in the lower base area of Rosa Khutor, on the left bank of the Mzymta River (site 460), we examined deluvial–proluvial fan deposits and outcrops of Jurassic bedrocks. The rocks are boudinaged and deformed. The dip direction of bedding is 200° and dip angle is 65° (hieroglyphs indicate inverted bedding). The section of the Illarionov Formation (J_1t_2) comprises the following layers (from the top downward):

Layer 1: ginger-brown fine-grained sandstones, tight silts, >3 m thick;

Layer 2: grey-green fine-grained sandstones, 2–2.5 m thick;

Layer 3: green-grey fine-grained iron-rich sandstones (brown when weathered), 2.5 m thick;

Layer 4: black, fine-scaly, bituminous mudstones, ferruginous when weathered, weak, with intercalations of grey-green to black, weak mudstones, 6 m thick;

Layer 5: grey–green fine-scaly, fine-grained sandstones, weak, containing organic matter, 2.5 m thick;

Layer 6: black, boudinaged and deformed, weak mudstones, 0.6 m thick;

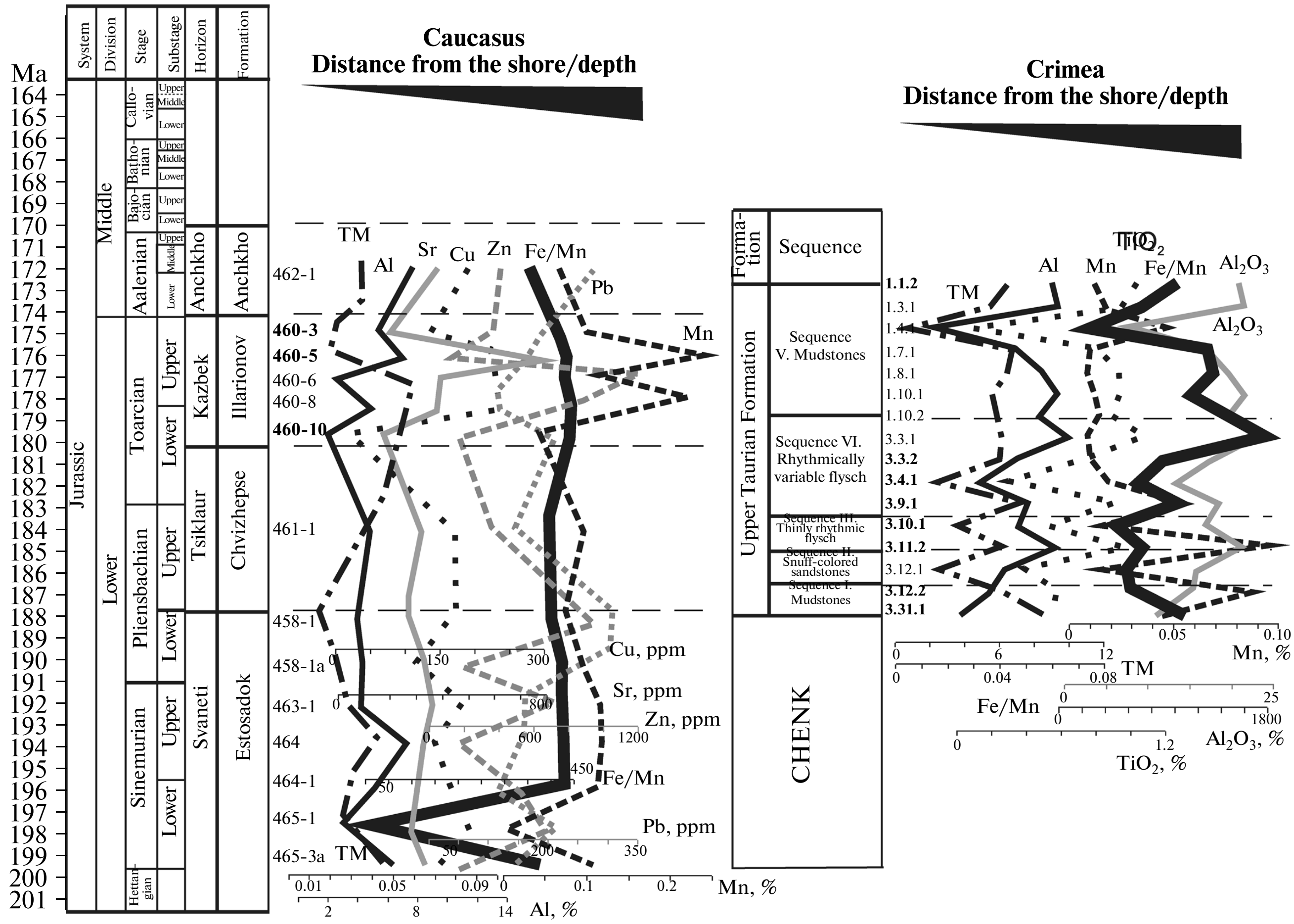

Fig. 3. Geochemical characterization of variations in water depths of the Crimea–Caucasus trough.

Layer 7: interbedding of black, weak, boudinaged and deformed mudstones and grey–brown fine-grained, laminated, weak sandstones, 4.5–5 m thick.

These are followed by an unexposed interval located 30 m upstream the river;

Layer 8: black, boudinaged and deformed mudstones, moderately tight, with cross-cutting bedding-parallel calcite veins; the thickness is unknown. The layer is followed by a fault;

Layer 9: similar to layer 8; the thickness is unknown. It is seemingly followed by a fault and a boundary with the other sequence;

Layer 10. grey fine-grained sandstones of unknown thickness.

In the vicinity of ski lifts in the lower base area of Rosa Khutor, on the right bank of the Mzymta River (site 461), the outcrop is composed of black boudinaged mudstones similar to those observed at Site 460. The dip direction of bedding is 355° and dip angle is 25°.

The Anchkho Formation (J_2an, J_2a) consisting of boundinaged mudstones with rare and thin pyroclastic layers is identified in the vicinity of the Anchkho pass in mountainous Abkhazia and can be traced well into the Sochi River basin. The formation was assigned an Aalenian age based on the occurrence of *Leioceras bifidatum* Buckm. and *Ludwigia* sp. The thickness of the formation is 500–700 m at Anchkho pass and 1000 m in the Chvezhipse River basin (Panov, Prutskii, 1983).

The outcrop of black weak bituminous mudstones of the Anchkho Formation is found near the road bend at site 462 (dip direction 120°, dip angle 55°).

CHARACTERIZATION OF UPPER PLIENSBACHIAN–AALENIAN SECTIONS OF THE KACHA UPLIFT

The "Taurian series" is defined as a thick sequence of terrigenous flysch and flyschoid deposits of late Triassic and early Jurassic age, which locally comprise volcanic units, horizons of limestone blocks, and members of gravelstones and comglomerates.

The Taurian series on the Kacha uplift comprises the following formations (Figs. 1, 2): Lower Taurian (T_3tv_1, T_3k–n), Chenk ($J_1\check{c}n$, J_1s–p), and Upper Taurian ($J_{1-2}tv_2$, J_1p_2–J_2a), with the latter being subdivided into five sequences. We examined all five sequences of the Upper Taurian Formation, which have conformable stratigraphic boundaries. The first

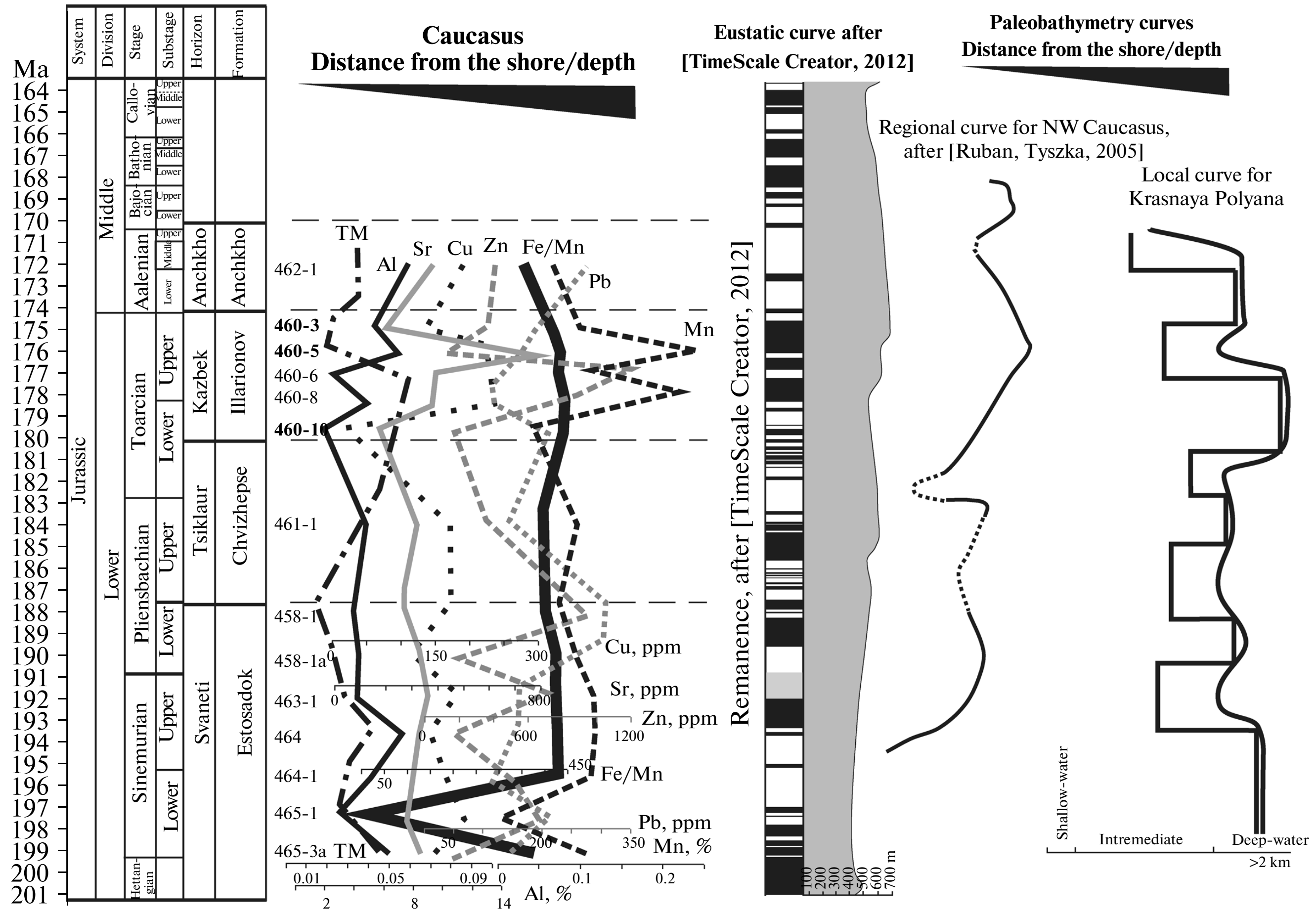

Fig. 4. Geochemical characterization of variations in water depths in the Crimean region of the trough.

three sequences are late Pliensbachian, the fourth 1 sequence is Late Pliensbachian—Early Toarcian, and 1 the fifth sequence is Late Toarcian—Aalenian. The age of the lower three sequences (I, II, and III) of the Upper Taurian Formation is inferred from their stratigraphic position.

Sequence I, mudstones $(J_{1-2}tv_2^{I})$ is composed of black homogeneous comminuted mudstones, containing abundant large siderite nodules. Occasional interlayers of tight siltstones are present. The mudstone sequence locally contains occasional units composed of mudstone—silt and sometimes normal (fine-grained sandstone—siltstone—mudstone) finely rhythmic flysch, but with a sharp predominance of mudstones. The sequence conformably overlies the Chenk Formation and reaches 500 m in thickness.

The clay minerals (%) are represented by hydromica (44—53) and mixed-layer minerals (8—18); chlorite is completely absent, while kaolinite is usually present (up to 29).

Sequence II, snuff-colored sandstones $(J_{1-2}tv_2^{II})$ is homogeneous in lithology throughout the study area and consists of sandy flysch deposits. The sequence is made up of large (up to a few meters thick) rhythms with a thick (up to 1.5—2.0 m) first element composed of greenish grey snuff-colored sandstones. Flysch hieroglyphs, mostly scour markings, are developed at the base of sandstone layers. Small fragments of undetermined pelecypod shells and crinoid skeletons are common.

Sequence II has a relatively uniform thickness of 220—300 m.

Sequence III, thinly rhythmic flysch $(J^{1-2}tv_2^{III})$ consists of stacked, 7—25-cm-thick rhythms, with the first element composed only of tight, finely laminated siltstones, and the second element is largely mudstones with occasional siderite nodules. The thickness of the rhythms is 5—20 cm. The lower surface of the first element may contain flysch hieroglyphs, mostly bioglyphs.

Sequence III is estimated to be 300 m thick.

Sequence IV, rhythmically variable flysch $(J_{1-2}tv_2^{IV})$ comprises normal three-component (sandstone—siltstone—mudstone) flysch with variable rhythm thickness. In the yaman gully, between Mounts Sheludivaya

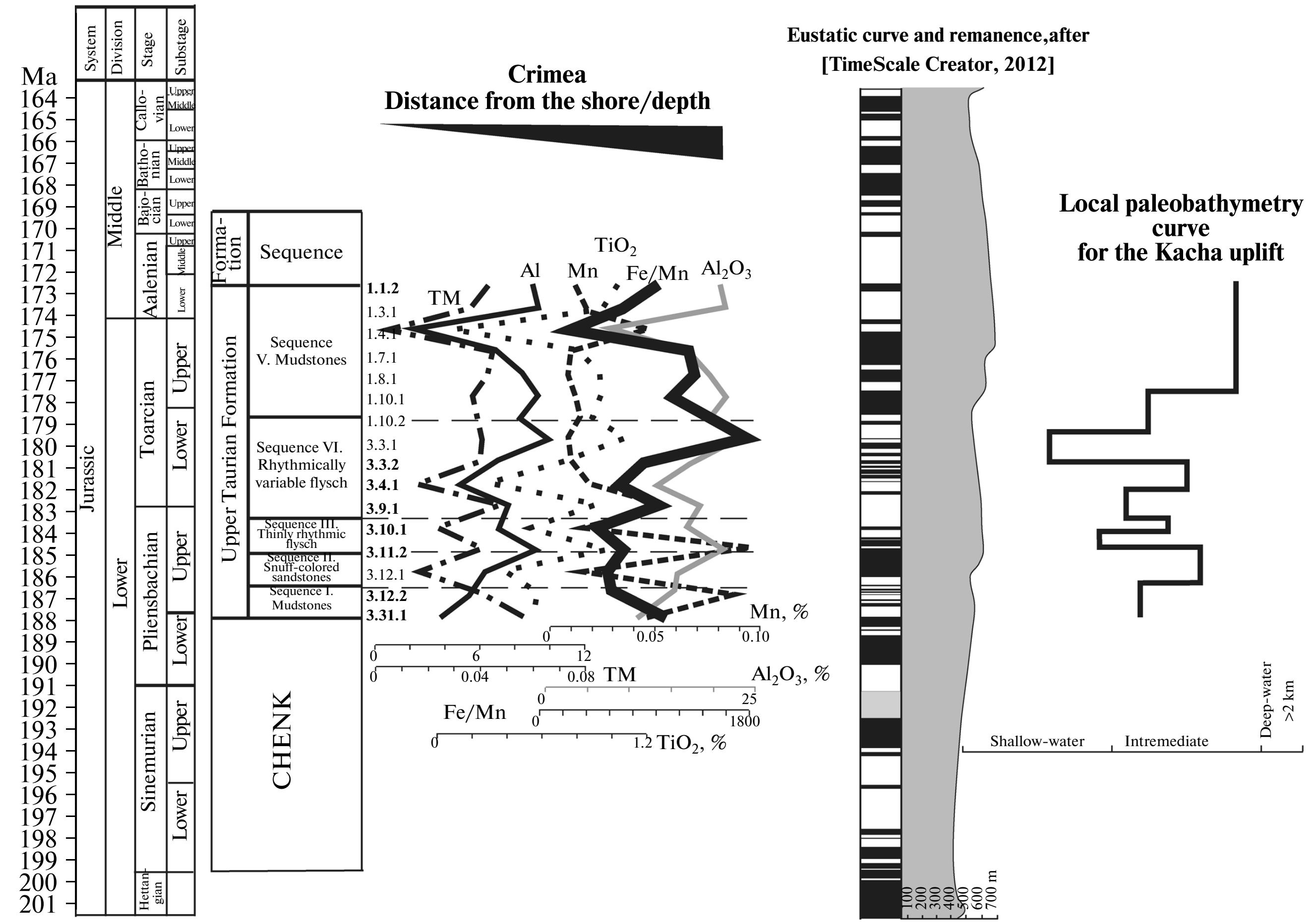

Fig. 5. Geochemical characterization of variations in water depths in the Caucasian region of the trough.

and Dlinnaya, the sequence is composed of 10–12 and 30–40-cm-thick rhythms, with the thicker ones being predominant.

Sequence IV is inferred to be upper Upper Pliens-
1 bachian–Lower Toarcian in age based on the molluscan fauna, which includes the Pliensbachian ammonites *Aegoceras* sp. and *Liparoceras* sp., Pliensbachian belemnites *Nannobelus pavloviensis* Men. et Erl.
1 (probably), Early Toarcian ammonites *Dactylioceras* sp. and belemnites *Dactyloteuthis* cf. *attenuata* Ernst. The thickness of Sequence IV is ~750 m.

Sequence V, mudstone subflysch ($J_{1-2}tv_2^V$) consists of the alternation of mudstone (4–10 m thick) and flysch (3.5–11.5 m) members. The mudstone members are uniform and contain only layers of siderite nodules (or isolated nodules). Most rhythms in the flysch members are dominated by mudstones, which may reach in thickness 40–50 cm.

The basal rhythms of the flysch members often contain brown iron-rich, calcareous gravelstones with traces of leached shell debris. The mudstones from the upper part of the rhythms contain layers of nodular limestone. The mudstone members and extremely thick (up to 2 m) rhythms of the flysch members contain numerous lenses of unsorted argillaceous siltstones with abundant small clasts of mudstones, sandstones, and concretions.

The age of this sequence is thought to be Late Toar- 1
cian–Early Aalenian, as indicated by the presence of the Late Toarcian belemnites *Mesoteuthis quenstedti* Opp. 1

The apparent thickness of Sequence V in the core of the Prokhladnaya syncline is 250 m.

Samples for geochemical analysis were collected from all five sequences of the Upper Taurian Formation and include two sandstone samples from Sequence I, one mudstone sample from Sequence II, two sandstone samples from Sequence III, three sandstone samples and one mudstone sample from Sequence IV, seven mudstone samples and one sandstone sample from Sequence V.

The geochemical data for Lower–Middle Jurassic interval of the section, which included the concentrations (%) of 29 elements and major oxides and values of six geochemical modules, were used to reconstruct depositional environments and determine the genesis of cyclicity (Figs. 3–8). A total of 16 samples from sections in the Mountainous Crimea and 14 samples from section in the Greater Caucasus were used for analysis.

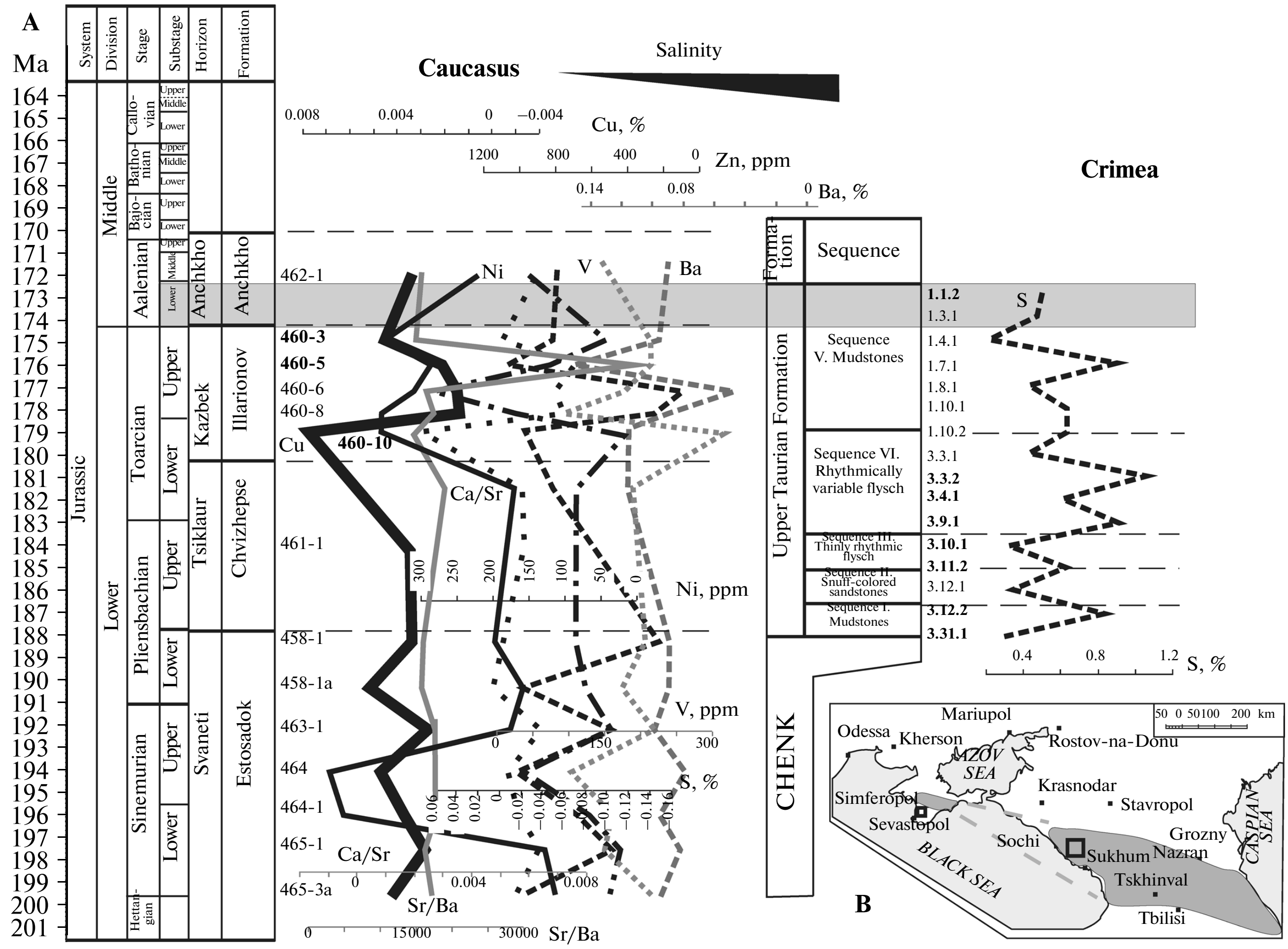

Fig. 6. Geochemical characterization of salinity variations in the Crimea–Caucasus trough (a) and map showing the inferred extension of oxygen-deficient zones during the Early Aalenian (b), modified after (Ruban, 2012).

The method used in the study was described in a number of previous publications (Engalychev, Panova, 2011; *Klimat*..., 2004; Sklyarov, 2001). Some of the results were ambiguous for our paleogeographic interpretation and require further investigation, which will be the focus of an upcoming paper.

A brief characterization of concentrations of elements, major oxides and geochemical modules is given below.

Variations in water depths can be reconstructed using the following paleoenvironmental proxies: Fe/Mn, TM, and concentrations of Zn, Pb, Al, Mn, Cu, Sr, and Ba, which are indicative of facies changes (Figs. 3–5).

Fe/Mn ratio. This decreases with increasing water depth and indicates a transition from a shelf to a pelagic facies. The decreasing trend in Fe/Mn with increasing water depth is explained by the uptake of Mn from the water column by sediments, which tends to increase in a deeper water environment. Based on their Fe/Mn ratios, the sedimentary rocks can be divided into deep-water (<40), shallow-water (~80) and shallow-water–marginal marine with a dominant terrigenous provenance (>160). The Fe/Mn ratio is useful in the case of clayey or clay-rich sediments and less useful in the case of carbonates (Sklyarov, 2001).

The Fe/Mn ratio varies from 38 to 70 (averaged 40, with anomalous values of up to 110), suggesting a deep-water environment.

In addition, the deep-water facies can be supported by another proxy, e.g, the concentration of Sr increases with distance from the source of terrigenous sediment. This proxy has average values of 230–270 ppm and anomalous values of 320–340 ppm.

Titanium module, TM, is the ratio between TiO_2 and Al_2O_3, reflecting both the facies dynamics and the titanium content of rock. Therefore, given a constant value of the facies factor, TM can serve as a useful indicator for basic and felsic rock compositions. Different TM values reflect different climatic conditions. For example, the TM is higher in humid than arid sand–silty rocks. A similar trend is typical of argillaceous rocks. The application of the TM proxy to paleoclimatic reconstructions might be limited to special cases

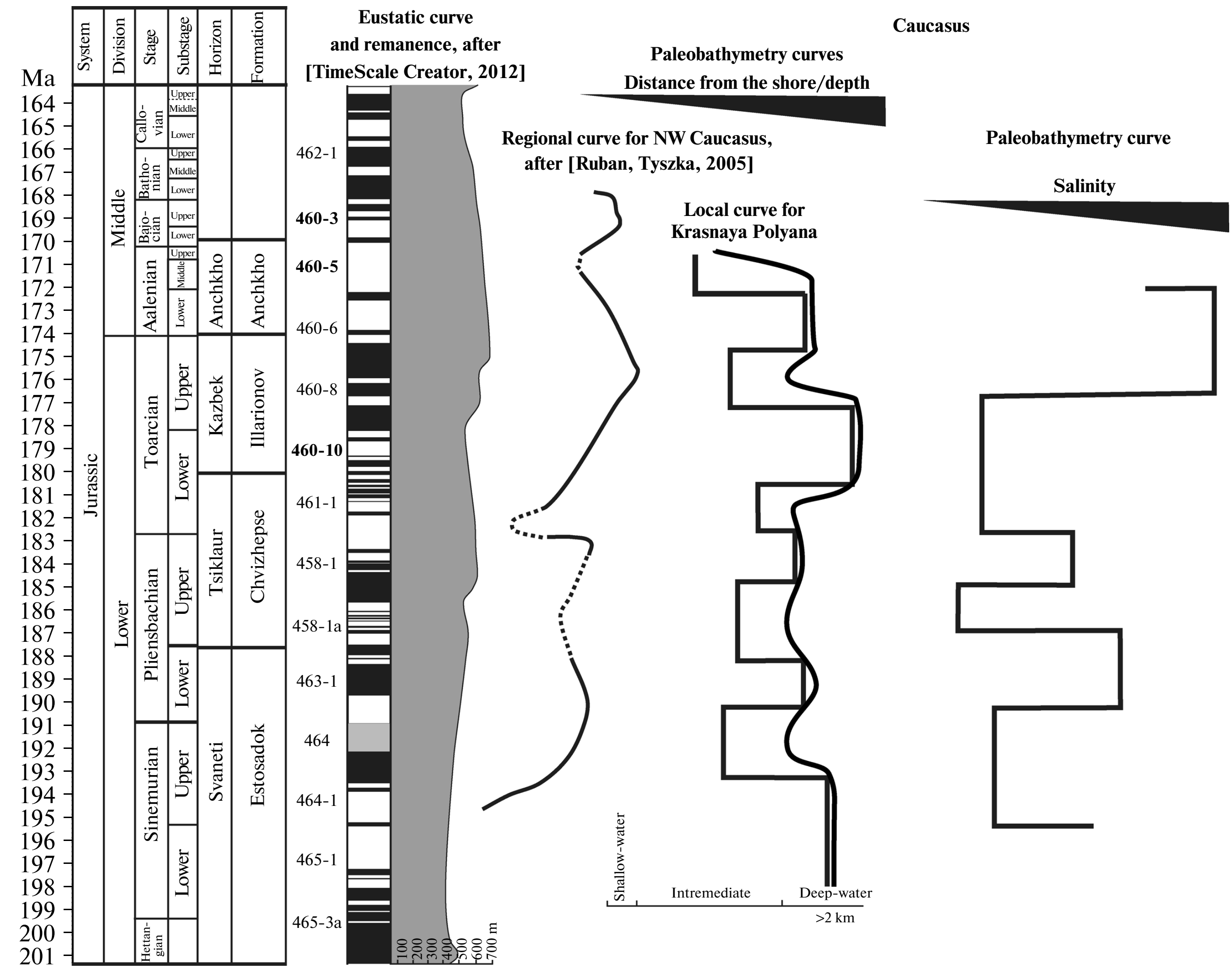

Fig. 7. The correlation between depth and salinity variations for the Caucasian region of the trough based on geochemical data.

of permanent terrigenous sources. In most cases, TM values might be more affected by the dynamic sorting of the sediment and rock composition than by the climate factor. To summarize, it can be noted that the TM values increase during transition from arid to humid climate conditions; in humid conditions this proxy increases from a deep-water toward a marginal marine and continental environment (Engalychev, Panova, 2011).

Sr and Ba concentrations. The concentration of Sr increases with distance from terrigenous sources, opposed to Ba concentrations, which increase in proximity to terrigenous sources. The concentrations of dissolved Ba increase with water depth, but Ba concentrations may reach maximum values at a depth of 4–5 km due to precipitation reactions.

Pb and Zn concentrations. The concentrations of Pb and Zn increase in proximity to terrigenous sources or with the increase in water salinity.

The early Toarcian sediments are characterized by a decrease in Fe/Mn, Sr, Ba, Al, and Mn proxies, suggesting shallow depths of the trough basin. However, theses proxies increase in the late early Toarcian–early Late Toarcian, indicating the deepening of the basin.

The decrease in the rate of subsidence and depth may reflect the onset of basin extension and a gradual increase in the maturity of clastic sediment input, which can explain the cyclic structure of the Upper Taurian Formation (Panov, 1997). The tectonic factor played a dominant role in the eustatic changes within the trough.

The results of our study were used to construct paleobathymetric curves for the Caucasian and Crimean regions, which reflect the eustatic changes of sea-level in the Early Jurassic–Aalenian deep-water trough basin (Figs. 3–5). The global eustatic curve and paleomagnetic curve were taken from the charts produced with the TimeScale Creator-2012 program.

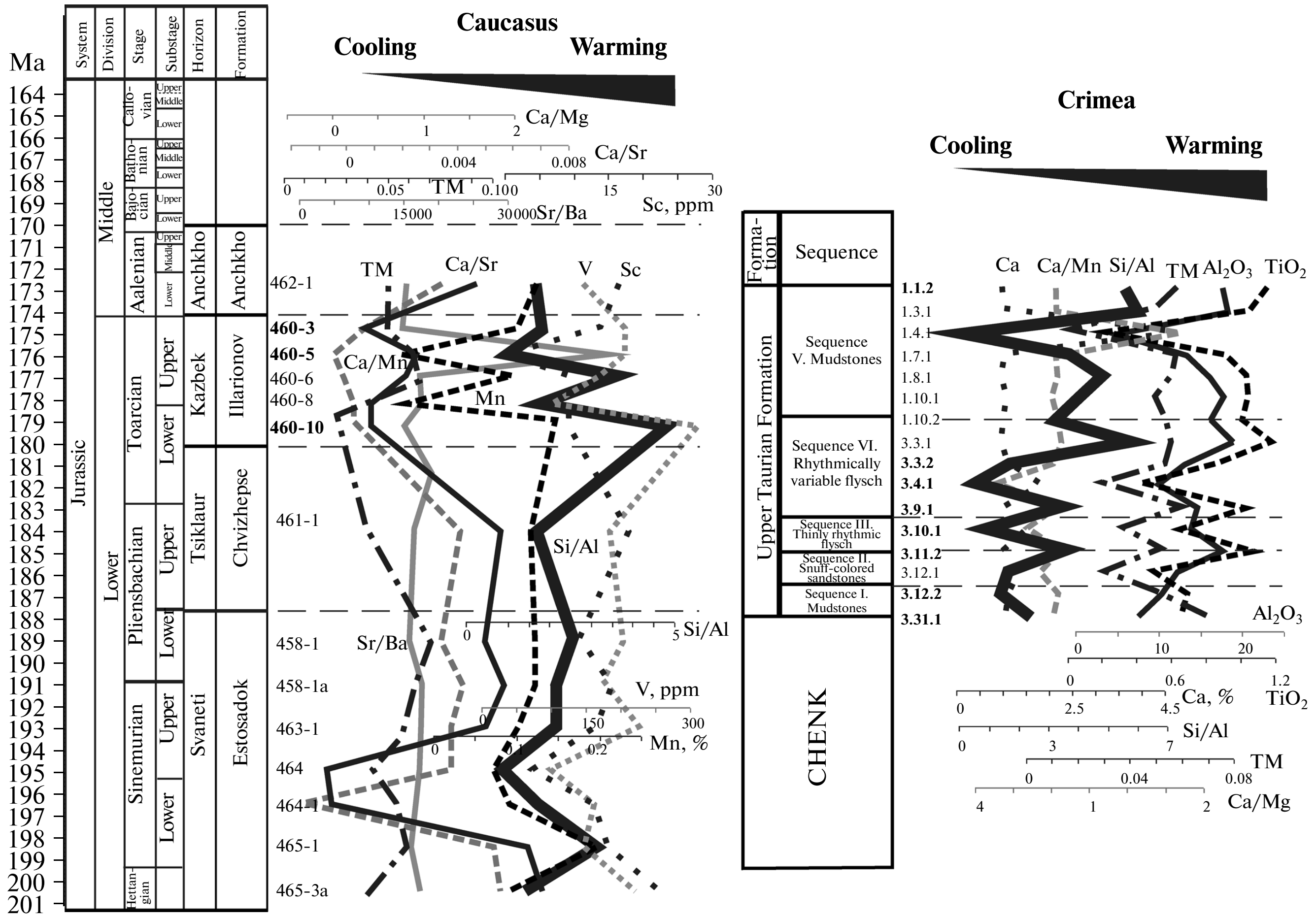

Fig. 8. The correlation between temperature variations in the Caucasian and Crimean regions of the trough based on geochemical data.

A comparison of our results with previous data shows that local paleobathymetric curves for Krasnaya Polyana are generally consistent with that for the Northwestern Caucasus (Ruban, Tyszka, 2005). The results also confirmed the trend of increasing salinity with decreasing depth of the trough basin.

For analysis of *salinity variations*, we used Sr/Ba and Ca/Sr ratios. The disruption of the physicochemical equilibrium in a saline solution during burial can cause dissolution of some minerals (calcite) and precipitation of the others (dolomite), which leads to a deep transformation of the brine composition. At the same time, the solution may selectively dissolve and precipitate elements of interest, such as Ca, Sr, and Ba. This is typical of hypersaline solutions in which Ca concentrations approach zero, because with increased salinity Ca is replaced by Mg contained in the sediment. Therefore, an increase in Sr/Ba and Ca/Sr ratios is indicative of increased salinity of the solution.

The concentrations of Â, S, Cr, Cu, Ga, Ni, and V in marine sediments are higher than in freshwater sediments. The concentrations of Zn and Cu are also useful salinity indicators as the mobility of these elements is a function of the salinity. Since the concentration of Cu in riverine waters tends to remain constant, its concentrations in sediments decrease due to the decreased rate of Cu precipitation during mixing of riverine water with more saline seawater. The mobility of Zn also decreases with increased salinity.

Therefore, the results of the analysis were used to construct paleosalinity curves for Caucasus, which reflect fluctuations in salinity of seawater in the deep-water trough basin during Early Jurassic–Aalenian time (Figs. 6, 7). Thus salinity variations in the trough basin during the Toarcian can be an indirect indicator 1
of variations in basin depth. The paleosalinity curve demonstrates that seawater freshening occurred during the Early Toarcian, which can be correlated with 1
deepening of the basin, whereas an increase in salinity in the Late Toarcian reflects shallowing environments. 1
Due to lack of data, salinity variations in the Crimean region of the trough were not analyzed.

As seen in Fig. 6 A, all sections of Crimea and Caucasus show an increase in the sulfur content by Early Aalenian time, probably reflecting an episode of widespread oxygen deficiency. Therefore, we proposed to

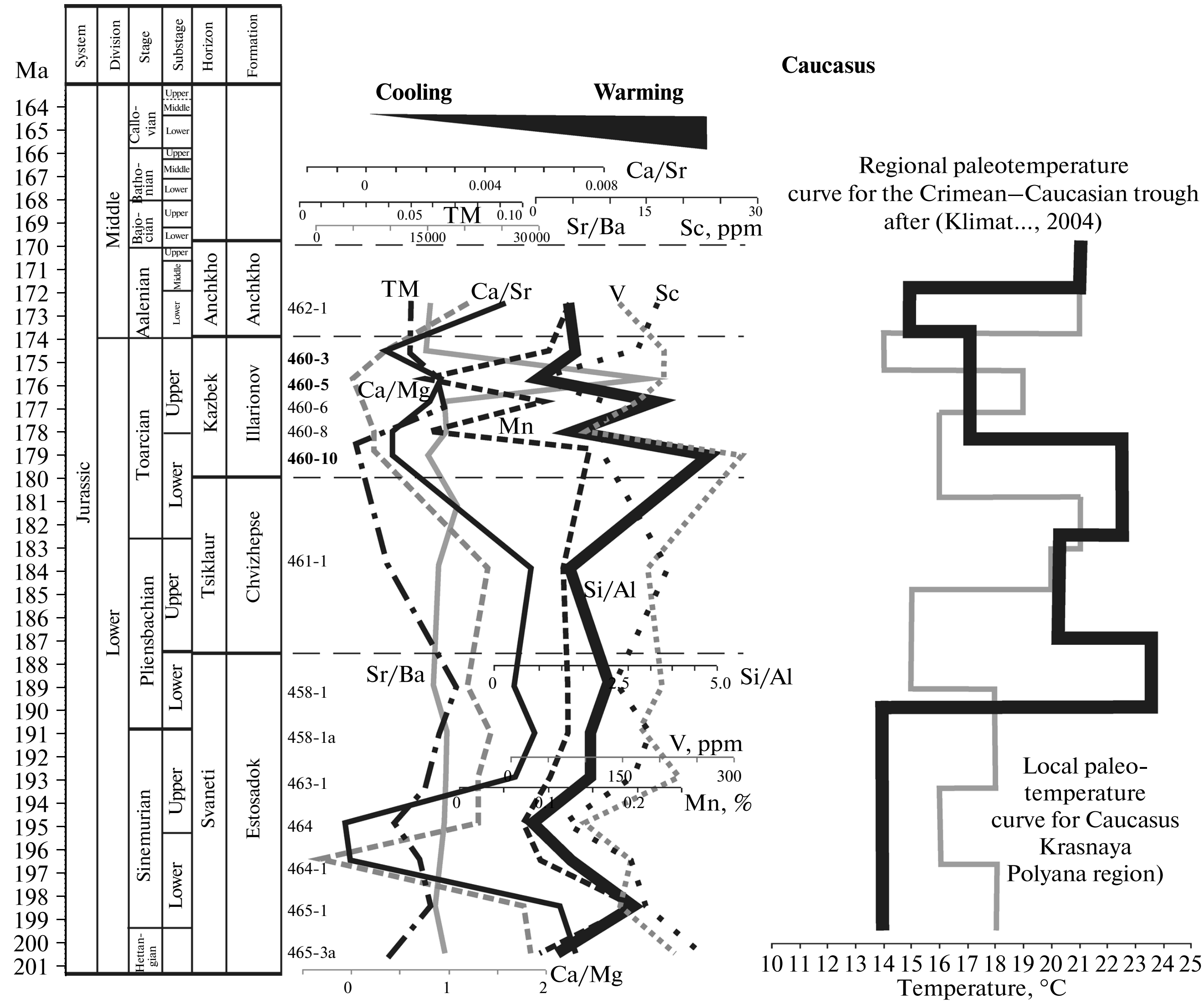

Fig. 9. Seawater temperature variations in the Caucasian region of the trough based on geochemical data.

extend the boundaries of this area to the NW into Crimea (Fig. 6 B).

The concentrations and ratios of the following elements have been widely used as paleotemperature proxies V, Ca/Sr, TM, Mn, and Si/Al. Variations in temperature can also be estimated using the following ratios: Ca/Mg, Sr/Ba, Zn/Nb, and (Ce, Nd, La, Ba)/Yb (Y, Zr). All estimates were taken from previous studies (*Klimat*..., 2004). For example, seawater temperature in the basins of Crimea, Carpathians, Caucasus, and
1 Pamir was 20–22°C in the Early Toarcian and 15–
1 17°C in the Late Toarcian. The Toracian paleobasins of Europe are characterized by warmer water temperatures (27–28°C). An overall temperature rise in
1 European paleobasins from Pliensbachian to Toarcian
1 was culminated in the Toarcian Climatic Optimum when the mean annual temperatures reached 28.4–32.9°C in Northern Europe. The cooling in the Caucasian region in the Early Aalenian (14–14.5°C) is documented by the absence of planktonic foraminifera in the Aalenian section, except for the only occurrence of Protoglobigerinids from transitional
Toarcian and Aalenian beds in Turkey (*Klimat*..., 1
2004). This fact can be interpreted as representing regression and widespread oxygen deficiency during the Early Aalenian. In the Late Aalenian, the seawater temperature in the trough basin was similar to that of West European paleobasins, reaching 20–22°C (*Klimat*..., 2004). A comparison of data from the literature and paleotemperature estimates obtained in this study for the Early Jurassic (Figs. 8–10) reveals that the average temperature of the trough basin range from 14 to 22°C in the Greater Caucasus region (Fig. 9) and 14.0 to 21.5°C in the Crimean region (Fig. 10). The paleotemperature curves derived in this study (thin line) show a general similarity (with a minor temporal

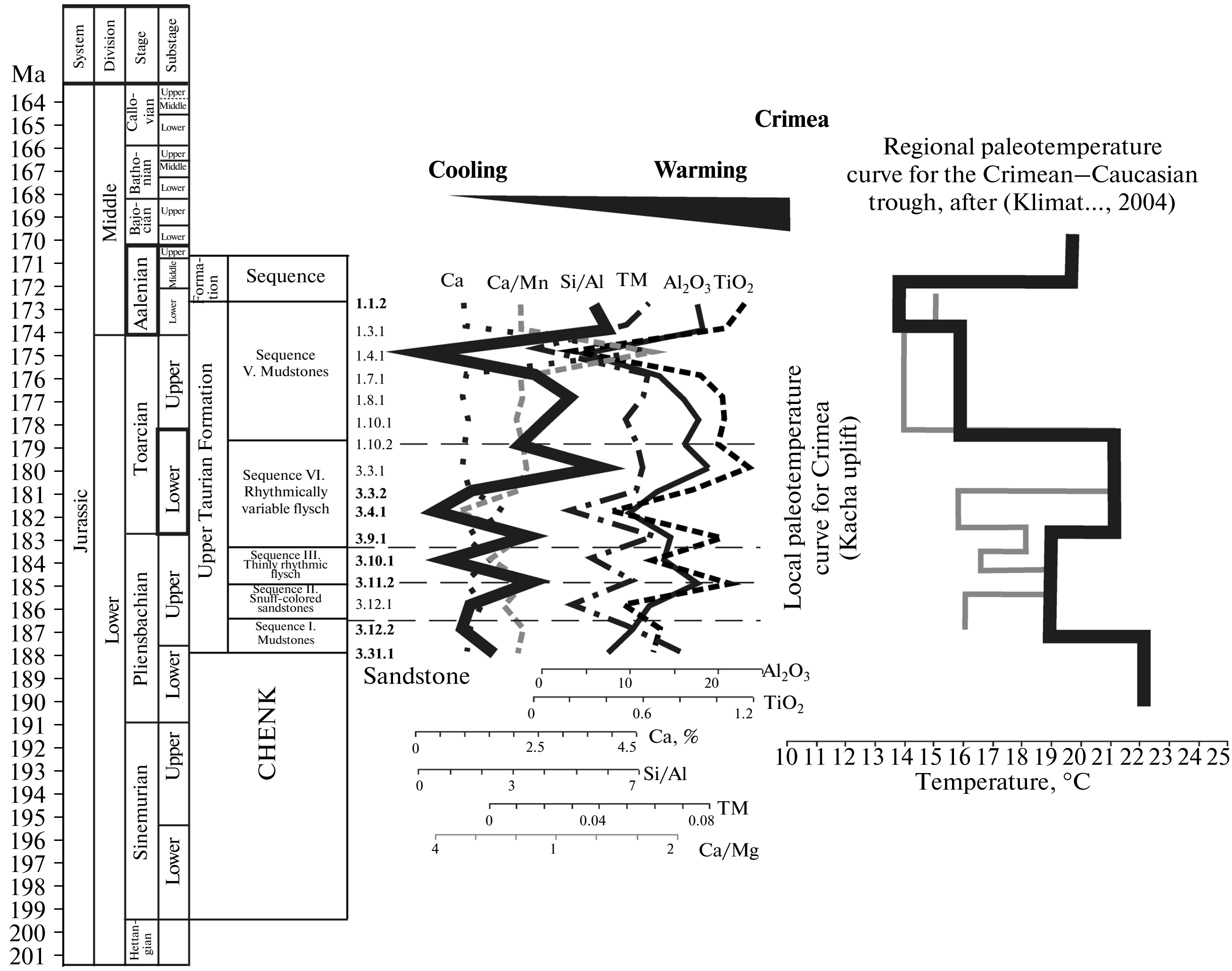

Fig. 10. Variations of seawater temperature in the Crimean region of the trough based on geochemical data.

shift) to those reported in the previous literature (*Klimat*..., 2004).

The increase in the values of marine temperature proxies (V, Ca/Sr, TM, Mn, and Si/Al) in the Early
1 Toarcian is consistent with an overall temperature rise,
1 whereas the decrease in these values in the Late Toarcian
is interpreted as the temperature drop (Figs. 6–8). A similar trend for this period is seen on the previously reported paleotemperature curve (*Klimat*..., 2004). In addition, the higher temperatures result in faster rates of chemical weathering, which can indirectly affect the rates of sedimentation in the trough basin. Paleotemperature variations are indirectly associated with variations in seawater salinity, since salinity increases with increasing temperature.

The increased concentrations of Ca, Sr, and Mg may indicate an arid climate, whereas increased concentrations of Sc, Ni, Zn, Y, W, U, Cu, V, and REE suggest humid depositional environments.

Climatic warming (*Klimat*..., 2004) and reductions
in discharge (aridization) during the Early Toarcian in 1
the Caucasian region of the trough basin are documented by increased concentrations of Cu, Sc, and V (Figs. 3 and 8). A decrease in the concentrations of
these elements in the Late Toarcian during cooling is 1
interpreted to reflect decreased input of terrigenous material from the nearby land (discharge).

RESULTS OF GEOCHEMICAL STUDIES AND DISCUSSION

Climate changes directly affect the weathering rates. The deposition of sandstones and clays is largely controlled by climate. Unfortunately, almost all samples collected in the Greater Caucasus are clayey rocks (with minor sandstone varieties) and thus do not provide a complete record of climate change. Among samples collected in Mountainous Crimea, sandy and clayey rocks are represented in equal proportions. The paleotemperature curve (Figs. 9 and 10) shows that a decrease in temperature during the Late Toarcian–Early Aalenian reflects deposition of mudstones and siltstones. This may indicate a more humid climate at that time. The J_1p_2–J_2t_1 interval records an increase in paleotemperatures reflecting the onset of sandstone deposition (Figs. 9, 10).

Salinity was used as an additional indicator for depositional environments. Variations in salinity are commonly interpreted to reflect freshening of seawater due to increased riverine discharge. The substantial freshening of seawaters in the Late Toarcian was accompanied by a shallowing of the trough basin and a decrease in water temperature, which can be related to an increase in fluvial discharge under humid climatic conditions and reflects the onset of clay deposition.

Climate is an important factor that controls the sediment warmth and humidity (*Klimat*..., 2004); the average temperature variation in the trough basin was 5–7°C.

CONCLUSIONS

1. This study presents data from the first geochemical analysis of Lower Jurassic–Aalenian deposits of the Crimea–Caucasus trough.

2. The geochemical data were used to refine Early Jurassic–Aalenian paleogeographic reconstructions.

3. The study reveals a general trend in tectonically-controlled paleobathymetry variations and fluctuations in seawater salinity and temperature in the trough basin.

4. The following stages of variations in the basin depth can be distinguished: the Sinemurian was marked by a gradual deepening of the trough basin with maximum water depths at the Sinemurian–Pliensbachian boundary and a marine regression at J_1p_1 followed by transgression at J_1p_2; an abrupt fall of eustatic sea-level occurred in the Early Toarcian, general subsidence and deepening of the trough basin occurred by the end of the Toarcian, which was followed by a regression from the late Toarcian through Aalenian.

Freshening of seawater in the Late Toarcian took place almost synchronously with a phase of shallowing of water depths and a decrease in temperature. The Early Aalenian marine regression disrupted water circulation in the basin and caused widespread oxygen deficiency. Climate-driven fluctuations in water temperatures in the trough basin were estimated to be 5–7°C, and the water temperature was warmer in the Crimean region of the trough.

5. Analysis of rhythmograms and the deposition character of flysch sequences showed that the J_1s–J_2a interval provides evidence for the existence of a deep-water trough basin with several sources of terrigenous material.

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