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The K–Ar System, Lithomineralogical, and Geostructural Characteristics of the Jurassic Terrigenous Complex in the Northeastern Caucasus

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Abstract—The paper discusses changes in both mineral composition and structural-textural characteristics of the Jurassic terrigenous complex along the Avar Koisu River (Dagestan) profile that intersects rocks with significantly various types of deformation. The profile extends from the monoclinal zone to the intense deformation and cleavage development zone. The alterations are manifested in the change of clay mineral assemblages, polytype modifications of micaceous minerals and their crystallinity index, rock density, reflectance of vitrinite, and other properties. Growth of the degree of secondary alterations (primarily, cleavage intensity) is accompanied by an appreciable decrease in K–Ar age of rocks and simultaneous increase of their stratigraphic age.

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In the course of postsedimentary development, the Lower and Middle Jurassic sedimentary complex of the Greater Caucasus underwent various transformations through diagenesis and burial to appreciable depths under the influence of intense lateral loads (stress) and the formation of cleavage. These transformations were accompanied by intense mineralogical and geochemical alterations of rocks. As demonstrated in our previous works (Gavrilov, 2005; Gavrilov and Tsipursky, 1987; Gavrilov et al., 2000, 2001; Bujakaite et al., 2003; Kushcheva et al., 2007; and others), alterations of clayey rocks are primarily manifested in the change of minerals assemblages, crystallinity index of minerals, their polytypism, and other properties. The development of cleavage was accompanied with both dissolution of some primary terrigenous minerals and formation of new ones. These processes caused redistribution of elements or their compounds resulting in change in proportions of the parental (initial) and daughter (secondary) isotopes. Rearrangement of the isotope systems "reset radiological clock," allowing one to date the postdiagenetic alterations of rocks with a certain precision. Earlier we examined changes in isotope systems of clayey rocks within a large terrigenous complex of the Lower and Middle Jurassic rocks in the central Greater Caucasus. Investigations were carried out along the geological profile across the entire area where the Lower–Middle Jurassic rocks occur in the Terek River valley of the Central Caucasus (Bujakaite et al., 2003; Gavrilov, 2005). It was established that the measured radiological age suggests a significant "rejuvenation" of rocks, relative to their real stratigraphic age. In different parts of the Greater Caucasus, for example, in its western area roughout the profile across the Belaya River (Adygeya) (Kushcheva et al., 2007), such alterations of sedimentary sequences differ in intensity. Since our task was to elucidate the character and dynamics of secondary transformations of the Jurassic terrigenous complex throughout the entire area of its occurrence, it required to carry out the corresponding investigations in Dagestan in the eastern Greater Caucasus (Fig. 1).

OBJECTS AND METHODS

Investigations in the Eastern Caucasus were carried out along the Avar Koisu River valley and its sources along the profile across a major portion of the Lower–Middle Jurassic rock terrane (Figs. 2, 3). Data on stratigraphy of this region are presented in (Gushchin and Panov, 1983). As compared to other profiles studied previously (Bujakaite et al., 2003; Kushcheva et al., 2007), the Dagestan profile is characterized by the presence of distinct zones with similar deformations—monocline zone, flexure and box fold zone, acute upright and inclined fold zone, and Bezhita depression zone with irregular deformations. Rocks of the profile show intense development of cleavage in some areas and its absence in other areas. These areas are separated by transitional zones. We recorded the deformation mode of textures and structures in different parts of the profile. In order to study the lithological, mineralogical, and geochemical composition of rocks along the profile, we took about 100 samples from rock sequences ranging from the upper Pliensba-

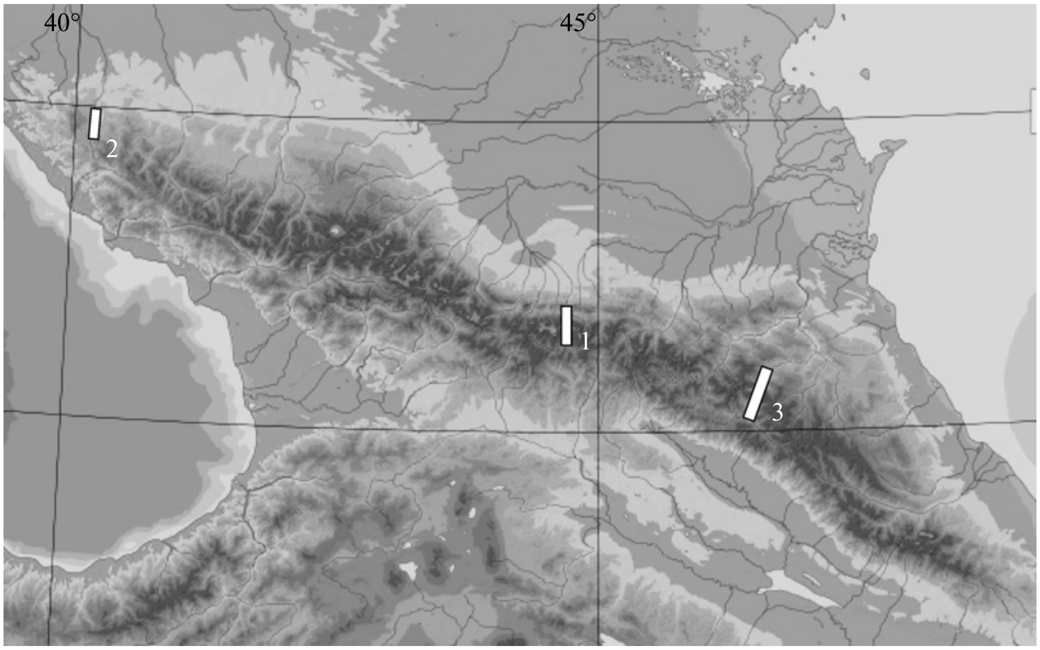


Fig. 1. Schematic map of the Greater Caucasus and sections therein (geological profile) provided with the K–Ar age determinations of rocks. Profiles along rivers: (1) Terek, (2) Belaya, (3) Avar Koisu.

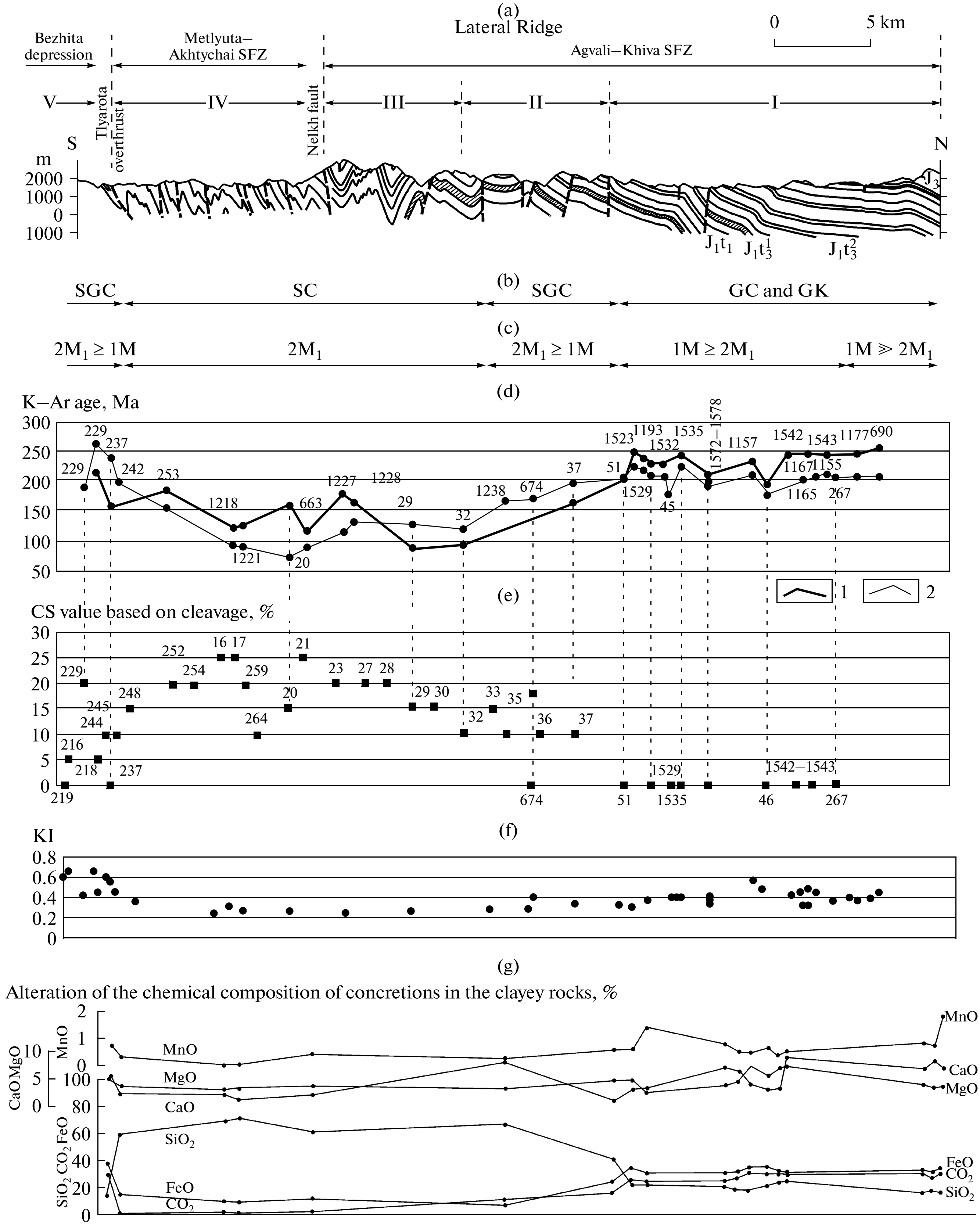
chian to the Bathonian. The samples were examined with various methods.

The X-ray study of samples was carried out to characterize clay minerals from different parts of the profile (Gavrilov and Tsipursky, 1987; Gavrilov, 2005). Study of the oriented preparations and their powder samples were analyzed with a DRON-2 diffractometer (CuK_{α}) to determine the phase composition of the clayey rock fraction <0.001 mm. The results revealed that the samples contain different proportions of micaceous minerals, kaolinite, and chlorite. Diffractograms of the natural oriented preparations show integral or nearly integral series of basal reflections 00*l* (*d*(001) ~ 10 Å) that are typical of the micaceous minerals. After the saturation of preparations with glycerin, diffractograms of some samples demonstrate a slight high-angle shift of the first basal reflection 001, suggesting the presence of expandable (2 : 1) layers in the minerals (Drits and Sakharov, 1976). Following the classification of micaceous minerals with different contents of expandable layers (Omel'yanenko et al., 1982), we subdivided the studied micas into two groups: sericites (expandable layers <5%) and hydromicas (expandable layers 5–10%, up to 15% in some samples).

Some samples were examined by the oblique-texture electron diffraction (OTED) method to unravel the possible differences in the polytype modifications of micas and to determine parameters of their unit cells. The chlorite-bearing samples were subjected to preliminary treatment to remove the admixture. The study was carried out with an ER-100 electron diffractometer at 100 kV. Deciphering of the OTED results unraveled the presence of various combinations of the micaceous minerals of polytype modifications 1M and $2M_1$ in the samples. Their contents vary in different parts of the profile: modification 1M prevails in some parts; proportions of micas 1M and $2M_1$ are approximately equal in other parts; and virtually pure micas $2M_1$ prevail in some parts (Gavrilov and Tsipursky, 1987; Gavrilov, 2005).

Analysis of diffractograms of the clayey rocks shows that crystallinity degree of the layer silicates is variable in different parts of the profile. Different types of crystallinity index are used to assess the variation. Although this method has several shortcomings (Frey, 1970; Eberl and Velde, 1989; Drits et al., 1997; and others), sufficiently great number of determinations of this parameter (in our case, Kübler index KI) makes it possible to obtain a statistically reliable pattern that

Fig. 2. Geological profile across the Avar Koisu River (Dagestan). Textural-structural, mineralogical, and geochemical parameters of Jurassic terrigenous rocks. (a) Geological profile and zones with different degrees of rock deformation: (I) monoclinal zone; (II) flexure and box fold zone, (III) upright arc fold zone, (IV) acute and inclined fold zone, (V) Bezhita depression with irregularly dislocated rocks; (b) assemblages of clay minerals: (h) hydromica, (k) kaolinite, (chl) chlorite, (ser) sericite; (c) proportion of polytype modifications of micaceous minerals 1M and $2M_1$; (d) calculated K–Ar age of rocks based on the measurements in (1) rock and (2) fraction <0.001 mm; (e) cleavage compression (%); (f) KI value of micaceous minerals; (g) diagram of alteration of the chemical composition of concretions, %.


(a)
Lateral Ridge
0 5 km
Bezhita depression
Metlyuta–Akhtychai SFZ
Agvali–Khiva SFZ
V
IV
III
II
I
Tlyarota overthrust
Nelkh fault
S
N
m
2000
1000
0
1000
J_3
J_1t_1
$J_1t_3^1$
$J_1t_3^2$
(b)
SGC
SC
SGC
GC and GK
(c)
$2M_1 \geq 1M$
$2M_1$
$2M_1 \geq 1M$
$1M \geq 2M_1$
$1M \gg 2M_1$
(d)
K–Ar age, Ma
1
2
(e)
CS value based on cleavage, %
(f)
KI
(g)
Alteration of the chemical composition of concretions in the clayey rocks, %
MnO
MgO
CaO
SiO_2
FeO
CO_2
CaO MgO
SiO_2 CO_2 FeO

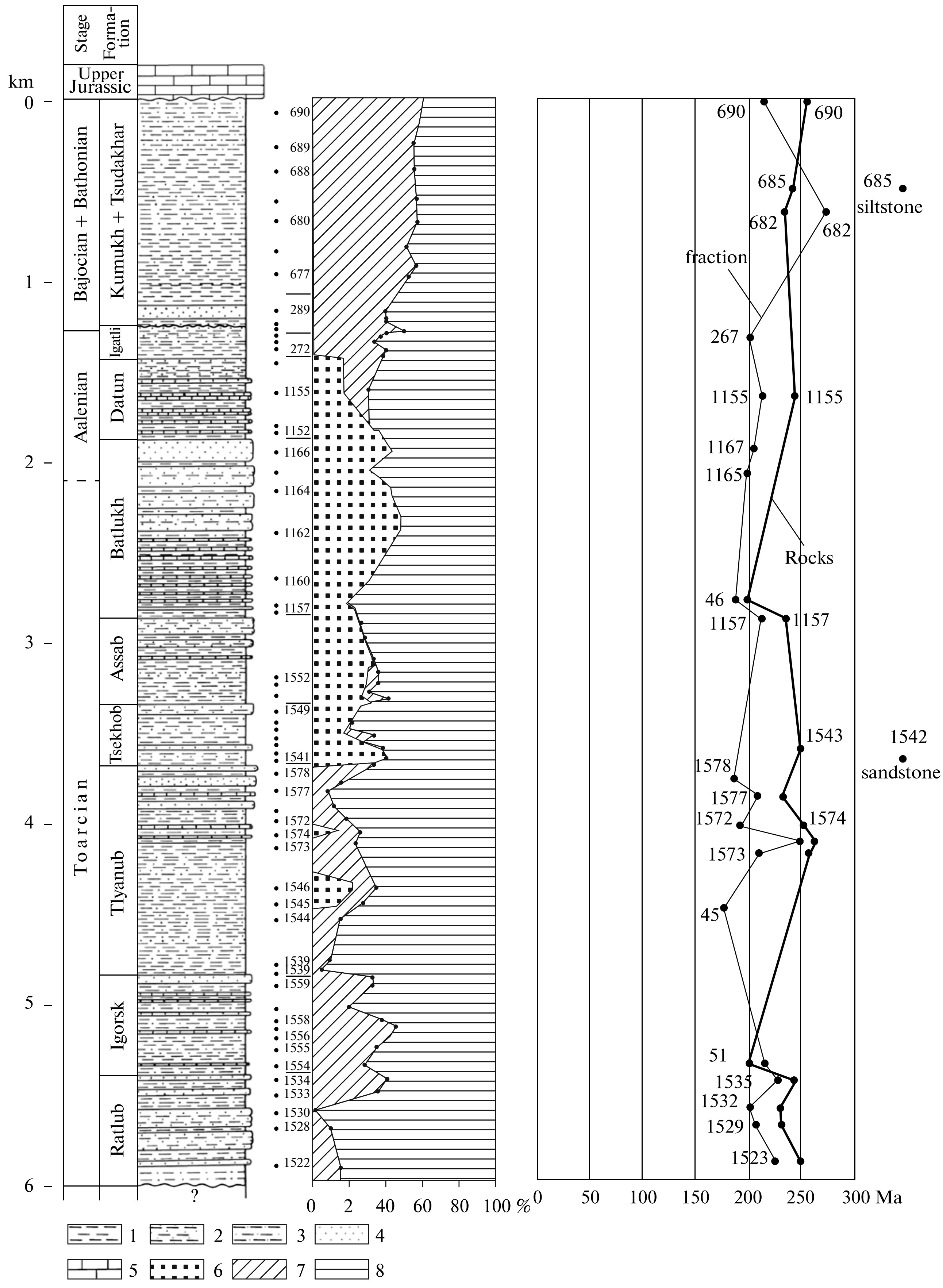

Stage
Formation
Upper Jurassic
km
Bajocian + Bathonian
Kumukh + Tsudakhar
Igatli
Aalenian
Datun
Batlukh
Toarcian
Assab
Tsekhob
Tlyanub
Igorsk
Ratlub
?
0 20 40 60 80 100 %
0 50 100 150 200 250 300 Ma
fraction
Rocks
685 siltstone
1542 sandstone
1 2 3 4
5 6 7 8

Fig. 3. Lithostratigraphic column of the Toarcian–Bathonian rocks in the monoclinal zone and the K–Ar age data on rocks. (1) Clayey rocks (mudstones); (2) alternation of mudstone and sandstone interlayers; (3) siltstones; (4) sandstones; (5) Upper Jurassic limestones; (6) kaolinite; (7) chlorite; (8) hydromica.

adequately reflects variations in the layer silicates. Therefore, parameter KI of micas and other minerals is applied widely by geologists to assess the intensity of postsedimentary alterations of rocks (Arkai and Lelkes-Felvari, 1993; Bastida et al., 1999; Battaglia et al, 2004; Biševac et al., 2010; Bozkaya and Yelçin, 2004; Brime et al, 2008; Frey, 1987, 1988; Garcia-Lopes et al., 1997; Gutierrez-Alonso, Nieto, 1996; Offler and Brime, 1994; Potel, 2007; Verdel et al., 2011; and others). We determined the KI value for micas based on the method described in (Köbler, 1964; Kisch, 1991a, 1991b) by measuring the half-height width of 10 Å reflex (°Δ 2θ) of the micaceous mineral. The results of KI measurements are presented in Fig. 2f.

We determined the reflectance of vitrinite in the organic matter (OM) remains in mudstones and cleaved shales. We also measured the density of rocks along the profile.

Since the profile shows an irregular development of cleavage, its evaluation was based on quantitative parameters (Talitskii, 1989; Gavrilov et al., 1999). The first (microscopic) signs of cleaving are observed as separate cleavage development zones at a compressive strain (CS) of 5–7%. At CS = 10–15%, cleavage is distinct and developed throughout the rocks. Cleavage is perfect at CS = 20–25%. In the present paper, we used this scale for an approximate assessment of the value of rock deformation in mineral grains (Fig. 2e).

We revealed significant changes in the composition of diagenetic concretions (mainly siderite nodules) in the clayey rocks confined to the intense secondary alteration and cleaving zone. They are replaced by the siliceous–chlorite mass, with the development of abundant sulfide (mainly pyrite) dissemination (Gavrilov, 1982, 2005). We examined such transformations of concretions in order to examine changes in the host clayey rocks.

Changes in both mineralogical composition and textural-structural features of rock sequences due to intense secondary alterations affect the isotope systems in the mineral mass of rocks. The radiological age of sedimentary rocks determined with the K–Ar and other methods of isotope dating is widely used in geological investigations for timing the responsible tectonic and magmatic events (Bujakaite et al., 2003; Gavrilov, 2005; Kushcheva et al., 2007; Belmar et al., 2004; Biševac et al., 2010; Crouzet et al., 2007; Doublier et al., 2006; Fergusson and Phillips, 2001; Hunziker et al., 1986; Kligfield et al., 1986; Kover et al, 2009; Muller, 2003; Muller et al., 2000; Reuter and Dallmeyer, 1989; Sherlock et al., 2003; Wemmer et al., 2011; and others).

In order to unravel the main evolution trends of isotope systems in the Jurassic terrigenous sequences of Dagestan, we studied clayey rocks with the K–Ar method, which appeared most informative for resolving the above problem because of several reasons. We analyzed both samples of the clay (<0.001 mm) fraction extracted from rocks and samples of original rocks.

Contents of the radiogenic Ar were measured in charges of 60–90 mg with a MI 1201IG mass spectrometer complex by the isotope dilution technique under the following conditions: sample fusion at 1600–1800°C; purity of tracer monoisotope ^{38}Ar 97.5%; and uncertainty of the radiogenic Ar measurement not more than ±1%. The share of atmospheric Ar was 5–10%. The K concentration was measured with an AAS-3 atomic absorber in the Chemical-Analytical Laboratory of the Geological Institute (Russian Academy of Sciences) with uncertainty less than 1%. Error of the calculated age (2–2.5%) was checked on the basis of repeatability of duplicate measurements in samples and reproducibility of analyses of standard samples. Calculation of age was based on the following constants: $\lambda_e = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; ^{40}K/K = 1.167×10^{-4} (Steiger and Jäger, 1977).

STRUCTURAL-FACIES ZONATION, MODE OF OCCURRENCE, AND DEGREE OF THE LOWER–MIDDLE JURASSIC ROCK DISLOCATION

As indicated by many researchers, the Early–Middle Jurassic trench in the Greater Caucasus was characterized by a distinct longitudinal structural-facies zonation, which made it very different from the adjacent areas – the Scythian plate in the north and the Transcaucasian median massif in the south (Leonov, 1966; Panov, 1988; Panov and Lomize, 2007; *Yura Kavkaza*, 1992; and others). In the Liassic–Aalenian, zones corresponded to different parts of the trough, namely to axial trough and its framing (northern and southern slopes); in the Bajocian and Bathonian, to trough systems on the northern and southern slopes and the central geoanticlinal uplifts between the troughs (Panov, 1988). The structural-facies zones (SFZ) are characterized by specific type sections. The term "type section" implies stratigraphic volume, completeness, succession of rocks therein, their lithology and thickness, and so on. Zones identified on this basis correspond to certain paleotectonic elements.

The profile studied along the Avar Koisu River intersects the following structural-facies zones (from north to south, Fig. 2): Agvali–Khiva (northern slope of the trough) and Metlyuta–Akhtychai (northern slope of the trough). According to (Panov and Lomize,

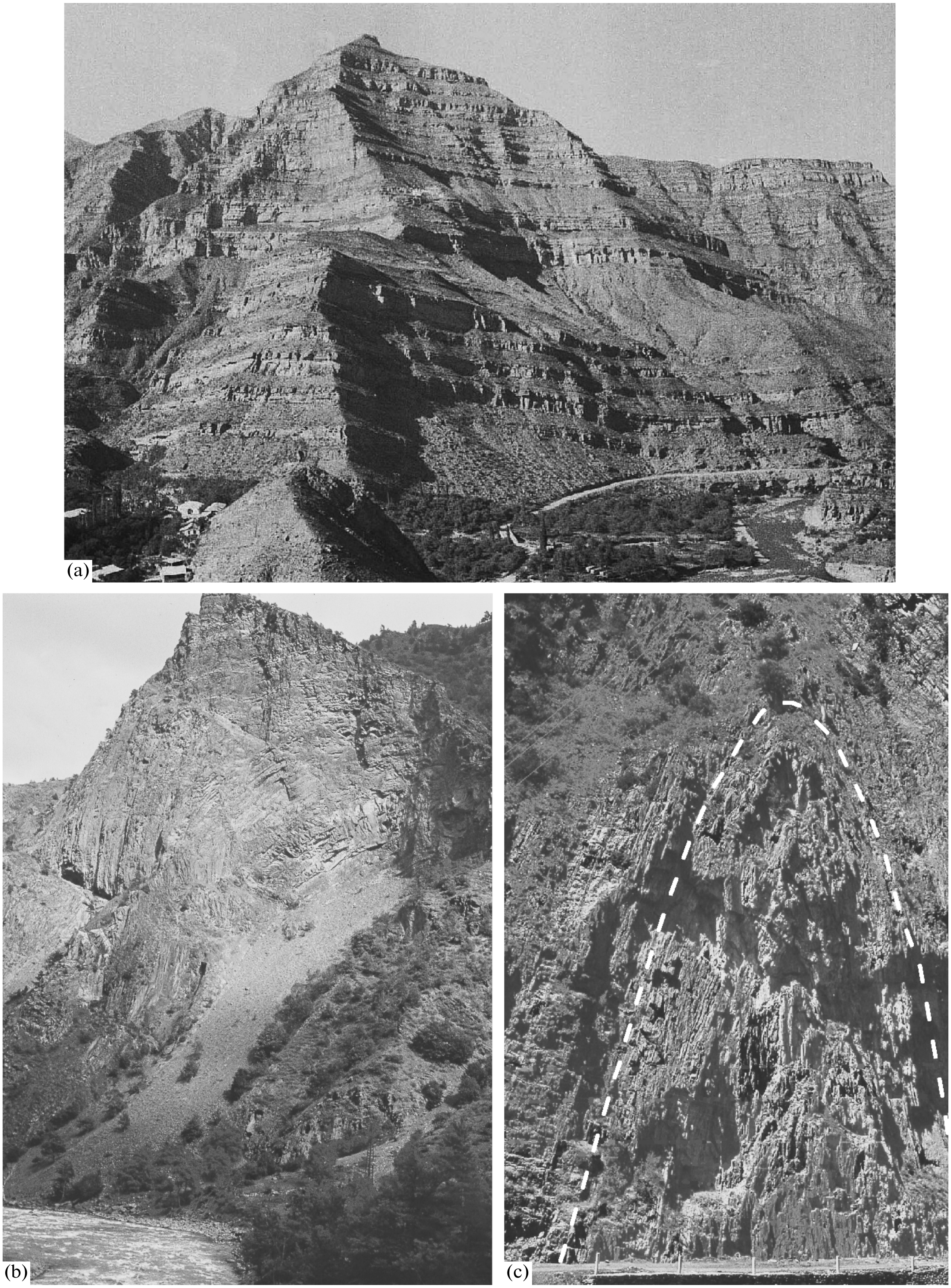

(a)
(b)
(c)

Fig. 4. Occurrence mode of Jurassic rock layers in different parts of the Avar Koisu River profile. (a) Monoclinal zone; (b) flexure and box fold zone; (c) complete fold (acute and inclined fold) zone; (d) relationship between cleavage and bedding in the anticlinal fold core (the arrow shows a hammer 0.7 m long).

2007), the southern area located to the south of the Tlyarota overthrust fault accommodates several tectonic plates of the Main Caucasian Range. Among them, the northernmost member is represented by the Bezhita plate of Toarcian rocks that can be assigned to a paleotrough in the Greater Caucasus.

As is evident from the profile (Fig. 2) drawn along the left bank of the Avar Koisu and Dzhurmut rivers, the degree of layer dislocation is variable in its different parts. The northern part of the profile (south of the exposure of Upper Jurassic carbonate rocks) includes a sufficiently wide band of gently northward dipping layers (monocline zone, Fig. 2a, I; Fig. 4a). The monocline is complicated by numerous small flexures and fractures. The structure is composed of the upper Toarcian and Middle Jurassic rocks.

In the southern areas, the degree of rock dislocation increases toward the Bokovoi (Lateral) Ridge axis: areas located near the axis show steep flexures and box folds crosscut by fractures, with the morphology emphasized by thick sandstones of the Ratlub Formation (box fold and steep flexure zones are shown in Fig. 2a, II; Fig. 4b). As mentioned in (Sholpo, 1964, 1978), deeper beds are most intensely folded at hinges of the anticlinal folds, and small folds with low-angle hinges appear near the fractures. In some places of this zone, the clayey rocks are crosscut by a unidirectional fracture system of the general Caucasian orientation, testifying to the origination of cleavage.

The southern area includes folds (mainly, upright arc-shaped) with relatively rounded hinges. As compared to the box folds, the size of the arc-shaped folds decreases from a few hundreds to several tens of meters (upright arc-shaped fold zone). This zone is complicated by numerous fissures of variable amplitude, but the dominant dislocation reaches a few tens of meters. Cleavage is sufficiently distinct in this zone. Such deformations are traced up to the Nelkh (Tlimkapuslin) fault passing between the Toarcian and middle Liassic rock terranes (Fig. 2a, III).

The middle Liassic shales are most dislocated. Here, one can see small (up to a few tens of meters) folds mainly with the low-angle keel-shaped hinges. Some places include inclined and rare overturned folds. The rock sequence is crosscut by numerous fractures of different amplitudes. The shales are marked by intense perfect cleavage with a steep (often nearly vertical) plane (Fig. 2a, IV; Fig. 4). The quartz-filled Alpian-type veins often occur in the folded and cleaved rocks.

The southern area located beyond the Tlyarota overthrust fault with the northward-inclined plane accommodates sandy–clayey rocks of the upper Toarcian Bezhita Formation. They are less dislocated than the middle Liassic rocks. The folding is irregular over the area. In some places, the beds are strongly folded and the cleavage is prominent, whereas they are undisturbed in other places (Fig. 2a, V; Figs. 5a, 5b).

When passing from the weakly dislocated zone to the intensely folded zone, the clayey rocks are subjected to significant alterations. The clayey rocks are represented by mudstones in the monoclinal area. Their color varies form the pale to dark gray with a brownish tint depending on the OM admixture. Mudstones are split into lumpy or flattened (along bedding) rubble due to weathering, but they preserve sedimentary textures and structures in some places. The authigenic minerals are represented by diagenetic products, such as globular pyrite, siderite concretions, and rare Fe-chlorite oolites.

The zone subjected to folding and intense cleaving (particularly, the middle Liassic sector) accommodates dark gray, often almost black, shales (brown tints are absent here). The shales are hard and clearly split into flat chips along the cleavage planes. Sedimentary

(d)

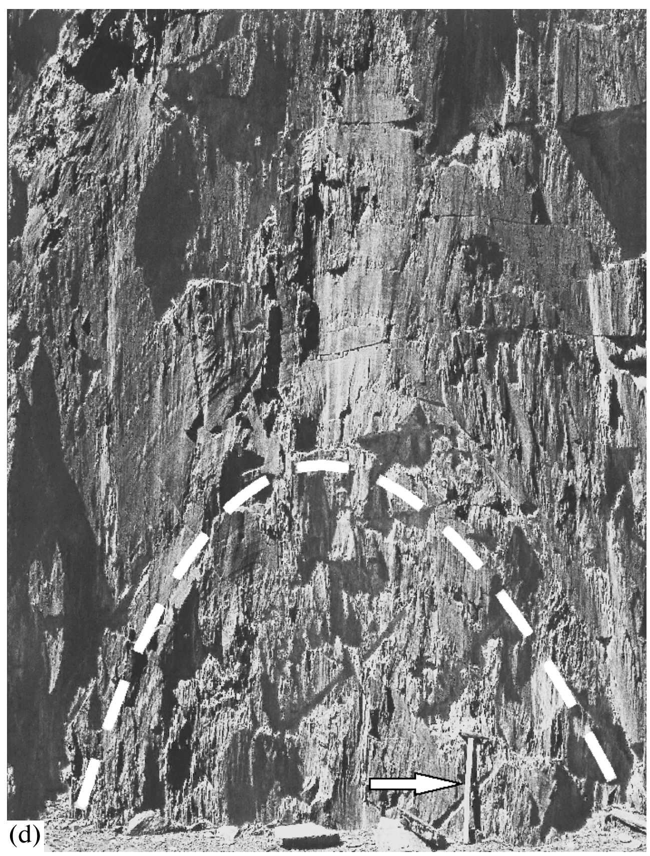


Fig. 4. Contd.

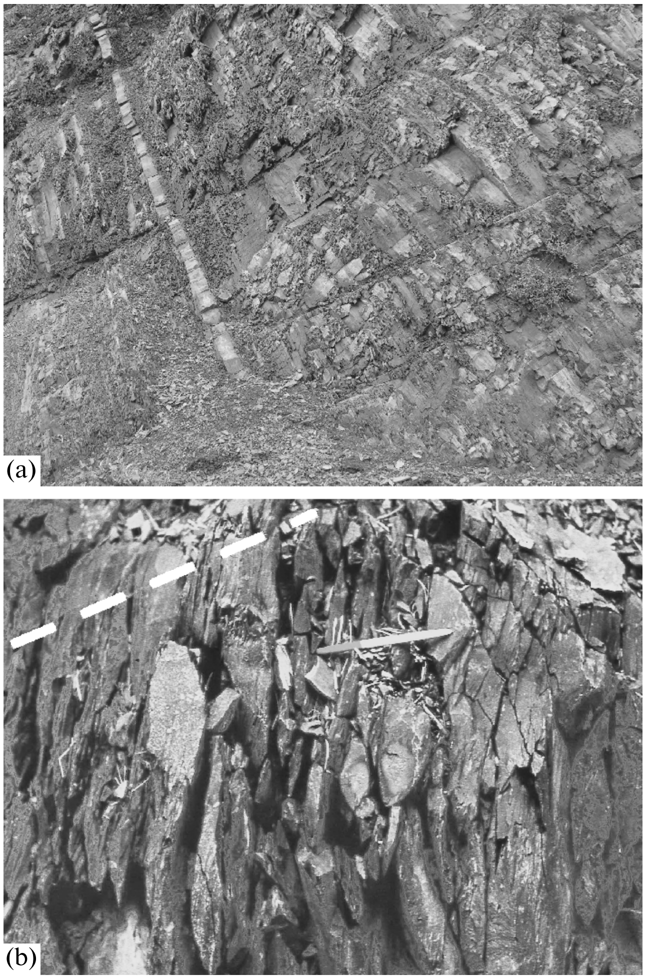


Fig. 5. Irregularly cleaved rocks in the Bezhita depression. (a) Clayey rocks without cleavage (the sandy bed is 20 cm thick); (b) cleaved rocks (the pencil is 15 cm long; the dotted line shows the sedimentation bedding direction).

structures in the shales are often shaded by the cleavage and, therefore, recognized scarcely.

Comparison of mudstones and shales revealed appreciable differences between them. They represent end members of the clayey rock series with transitional varieties. They were subjected to various degrees of postdiagenetic alteration. Changes in their macroscopic appearance are accompanied by several transformations of the mineral composition of rocks.

DISTRIBUTION OF CLAY MINERALS IN ROCKS OF THE PROFILE

Study of about 100 clay mineral samples from different parts of the section and profile showed that the study region includes the layer silicates similar to those in the Terek River section (Gavrilov et al., 1999). The trend of their distribution over the area and section is also similar in both regions.

As is evident from Fig. 2b, rocks of the profile demonstrate a distinct change of clay mineral assemblages (Gavrilov and Tsipursky, 1987; Gavrilov, 2005). For example, in contrast to the Terek River profile, the monoclinal bedding zones, where the influence of secondary alterations upon rocks is primarily governed by the load of the overlying sequences, include the hydromica–chlorite, hydromica–kaolinite, and mixed (hydromica–chlorite–kaolinite) assemblages. Rocks of different formations are mainly characterized by the clay mineral assemblages, and their proportions differ significantly in the Toarcian–Bathonian section (Figs. 2, 3).

When passing from the monoclinal zone to the cleaving and folding zone, the relatively diverse clay mineral assemblage gives way to the monotype hydromica (sericite)–chlorite assemblages. Kaolinite was not detected in any sample. Here, sericite or hydromica is the major mineral, and chlorite prevails in rare samples. At the same time, the hydromica–chlorite assemblage is also typical of rocks in the southern Agvali–Khiva SFZ and clayey rocks in the Bezhita Formation.

Analysis of the structural features of hydromicas and sericites within the profile shows that the number of smectite layers in them is not constant. In the Toarcian and Middle Jurassic rocks of the monoclinal zone, the hydromicas usually contain approximately 5–10% of smectite layers (up to 15% in some layers). The content of expandable layers is less than 5% in some samples (sericite). Moreover, vertical regularity in the distribution of smectite is missing. The formations include similar micaceous minerals in terms of the expandable component. For example, this component is no less than 5–10% in mudstones of the Igatli Formation. At the same time, the content of expandable interlayers is less than 5% in some samples from the Tsudakhar and Batlukh formations.

When passing southward from the monoclinal zone to more intensely folded and cleaved zones (Fig. 2), the clay minerals show a rapid decrease in the content of expandable layers. For example, rocks from the northern part of the flexure (Fig. 2, II) and box fold zone include sericite containing less than 5% of the expandable component. This component disappears from rocks in the southern areas located near the arc-shaped fold zone. Also, micas of the polytype modification 1M disappear at the same level in areas located a little farther south. The arc-shaped and steep fold zones (Fig. 2a, III, IV) include nonexpandable sericites. Thus, the southern Agvali–Khiva SFZ already comprises the clay mineral assemblage, which is widespread south of the Metlyuta–Akhtychai SFZ. In areas located to the south of the Lateral Ridge anticlinorium (i.e., south of the Metlyuta–Akhtychai SFZ), clayey rocks from the Bezhita depression, include sericites containing less than 5% of the expandable layers, while hydromicas contain as much as 5–10% (10–15% in one sample) of the expandable layers (Fig. 2a, V).

The Lower–Middle Jurassic section shows a sufficiently distinct variation trend of polytype modifications of micaceous minerals. As is evident from Fig. 2c, the uppermost parts of the section are dominated by hydromicas of polytype 1M. The amount of modification $2M_1$ increases gradually downward the section. This trend corresponds to rock age in the monoclinal zones. In the intensely folded zones, increase in the content of $2M_1$ hydromicas is already observed in the coeval Toarcian rocks in accordance with the intensification of folding and cleaving. Moreover, only polytype $2M_1$ is recorded in the most dislocated and cleaved Toarcian rocks.

The middle Liassic sequence, which underwent the maximal folding and cleaving (Fig. 2c), contains only sericite of the polytype modification $2M_1$. It was here in a number of shale samples established the presence of two phases of sericite with slightly different unit cell parameters.

Rocks of the Bezhita Formation include a blend of hydromicas of polytype modifications 1M and $2M_1$ (predominant component).

The chemical analysis of the sericite and hydromicaceous phases from <0.001 mm fraction revealed transition from the Toarcian and Aalenian rocks to the middle Liassic rocks (i.e., from mudstones to shales) is accompanied by a distinct increase in the content of Al_2O_3. Increase in the contents of Na_2O and TiO_2 is less prominent. In contrast, contents of MgO, FeO, and H_2O are lesser. The SiO_2 variation is complicated, because hydromica and sericite in the samples are associated with an admixture of quartz. Virtually all samples include two varieties of hydromica and sericite—some samples include a blend of polytypes 1M and $2M_1$, while other samples include two $2M_1$ phases (Gavrilov, 2005).

It is noteworthy that the micaceous minerals are characterized by a slightly lower content of K and the simultaneous increase of Na, particularly in the lower and middle Liassic portions of the section. A part of K is likely replaced by Na. In other words, the sericite is subjected to paragonitization. As in the Terek River section, a part of K is likely replaced by ammonium in this area.

Synchronously with the alteration of hydromicas, polytype modifications of chlorite in the section are replaced according to the scenario in other regions (Karpova, 1972; and others). However, the constant presence in the samples of hydromica interferes with the determination of polytypism of chlorite. As well as in sections of the river Terek, this makes it impossible to establish the exact ratio of different modifications of chlorite. At the same time, the X-ray study of samples makes it possible to characterize the structural peculiarities of chlorite in different parts of the Lower–Middle Jurassic section. For this purpose, we examined several X-ray powder diffraction patterns of the clay fraction preparations. The results revealed variation in parameter b of the unit cell of chlorite from 9.24 Å for the Middle Jurassic rock samples in the monoclinal zone to 9.29–9.30 Å for the middle Liassic rocks in the Metlyuta–Akhtychai SFZ. This trend suggests that the Fe content in chlorites has a positive correlation with the degree of cata- and metagenetic transformation of rocks. The relatively high Fe content in chlorites is also indicated by the microprobe data on shales (Gavrilov, 2005).

CHARACTERISTICS OF DEFORMATION STRUCTURES

Both macroscopic and microscopic examination of the cleavage was carried out in the Jurassic terrigenous rock profile. The macroscopic examination was accomplished for the rock splitting mode, orientation of cleavage planes, and their relationship with rock bedding. Cleavage manifestation zones were identified in sections. The microscopic examination was conducted for the morphological cleavage type. Quantitative estimation of the degree of rock deformation during the development of this structure was carried out. In total, more than 250 thin sections were examined. The study revealed that, like rocks in the Terek River section, the Jurassic rock section is dominated by intergranular cleavage (Gavrilov et al., 1999).

Zones with various types of deformations appreciably differ in terms of cleaving (Fig. 2e). Cleavage is missing in rocks of the monoclinal zone.

Cleavage appears in the flexure and box fold zone. In this part of the profile, the rock deformation value rapidly increases to 10–15%, but one can also see rocks without deformation structures.

The development of cleavage is maximal in the profile segment marked by distinct folding of beds: the CS value is as much as 20% in the southern Agvali–Khiva SFZ and reaches 25% in the Metlyuta–Akhtychai SFZ.

Cleavage is irregularly developed in the southern Bezhita depression: the CS value based on cleavage varies from 0 to 15% and reaches 20% in some places. Figure 6 presents photomicrographs showing different degrees of rock deformation in this portion of the profile.

The thin sections show that the cleavage direction does not often coincide in the silty and clayey interbeds. This is a rather common feature. Such interrelations suggest the following conclusion: in most cases, the cleavage was developed at the prefolding stage of the longitudinal contraction of beds. The cleavage was rearranged and refined later in the course of folding. We can suppose that the lithostructural composition of clay minerals underwent appreciable transformations even at the prefolding stage of rock existence.

Results of K–Ar measurements in bulk samples (rock) and fine fractions from the Lower and Middle Jurassic rocks of the Northeastern Caucasus (Avar Koisu River area)

Sample no.	K, %	Ar_{ord}, mm^3/g	T, Ma	Sample no.	K, %	Ar_{ord}, mm^3/g	T, Ma
682f	3.88	0.04387	270	1193r	3.05	0.03224	253
682r	2.71	0.02648	235	1193f	4.07	0.03787	225
684f	3.67	0.06088	383	51r	2.22	0.01824	200
685r	2.22	0.02235	242	51f	3.9	0.03355	209
267f	3.91	0.03256	202	37r	4.72	0.0312	162
1167f	4.42	0.03717	204	37f	5.71	0.0461	196
46r	3.11	0.0249	195	674f	5.27	0.03647	175
46f	5.02	0.0377	183	32r	2.06	0.0077	93.5
48f	3.62	0.03178	213	32f	4.21	0.0205	122
1542r	2.84	0.04366	358	29r	2.49	0.00841	85
1543r	2.89	0.03264	270	29f	4.05	0.02089	128
1543r	2.97	0.03079	249	20r	2.09	0.0133	156
1572f	5.87	0.046	191	20f	3.66	0.0102	70
1573f	5.03	0.04351	210	253r	2.53	0.01883	182
1573r	3.07	0.0333	260	253f	3.86	0.0249	158.8
1577f	5.85	0.04939	205	222f	4.13	0.031	184
1577r	3.38	0.0368	230	229r	2.31	0.0205	213
1578f	5.31	0.03984	183	229f	2.76	0.03035	262
1574f	4.64	0.04809	249	237r	4.07	0.0249	151
1574r	3.08	0.03434	266	237f	4.1	0.04084	239
45Af	5.6	0.03937	172	242f	4.21	0.03438	199
1532r	3.43	0.03367	236	1221r	2.68	0.013737	127.3
1532f	4.61	0.0382	201	1221f	4.06	0.014318	88.5
1523r	2.68	0.02798	250	1228r	2.63	0.017153	160
1523f	4.07	0.0377	224	1228f	3.56	0.019113	133
1535r	4.46	0.04537	244	1227r	2.95	0.020892	173.5
1535f	5.92	0.05561	228	1227f	3.93	0.018018	114
1529r	4.06	0.03981	236	1218r	2.77	0.01373	123
1529f	5.79	0.04996	209	1218f	4.08	0.01504	93
1177f	3.49	0.02977	207	826f	5.2	0.04016	188
1177r	2.09	0.02172	249	826r	4.2	0.02303	135
690r	2.35	0.02482	253	1238f	3.63	0.02496	172
690f	3.15	0.0278	214	1238r	2.4	0.02377	217
1165f	5.42	0.04294	193	1242f	5.53	0.04042	179
1157r	2.89	0.02808	234	1242r	4.06	0.03683	219
1157f	4.17	0.03743	217	663f	5.97	0.0221	93
1155f	4.37	0.03881	215	663r	5.18	0.02431	117
1155r	3.12	0.03215	247				

Note: Letter designations in sample numbers: (r) rock; (f) fraction <0.001 mm.

RADIOLOGICAL AGE OF ROCKS IN DIFFERENT PARTS OF THE PROFILE

The results of study of the K–Ar isotope system in rocks of the profile are presented in Fig. 2d and the table.

Geochemical data indicate that significant alterations are almost missing in the isotope system of rocks in the monoclinal bedding zones. The measured radiological age of rocks is approximately 250 Ma, which corresponds to the Early Triassic. The "age" of the clay fraction of rocks is about 200 Ma, which is nearly 50 Ma younger (Late Triassic). Dating of one sample yielded 383 Ma (Late Devonian). Stratigraphic age of this rock interval in the monoclinal zone corresponds to the latest Toarcian–Bathonian, i.e., about 180–165 Ma. Thus, the radiological age of these rocks is approximately 30–90 Ma older than the stratigraphic age.

In the southern Agvali–Khiva SFZ, the lithotextural alterations of clay minerals (sequential transition to the sericite–hydromica–chlorite assemblage, prevalence of micas $2M_1$ over 1M, and complete domination of $2M_1$) are marked by a sufficiently rapid intensification of cleavage and changes in the isotope characteristics of rocks—appearance of a sufficiently distinct trend of their rejuvenation. This process is accompanied by increase in their stratigraphic age.

When passing from the Agvali–Khiva to the Metlyuta–Akhtychai SFZ, the alterations become more prominent. The CS value becomes maximal (up to 25%) in the profile, and the KI value of micas reaches 0.22. In contrast, the radiological age of samples from the northern part of this zone is minimal and less than 100 Ma (70 Ma in some places; Table, sample 20). As mentioned above, the stratigraphic age of rocks in this area is approximately 183–185 Ma, which corresponds to the late Pliensbachian. Thus, "rejuvenation" of rocks due to their intense transformation and partial loss of the radiogenic Ar can be as much as 100 Ma or more. However, these values are not extreme ones for the Jurassic terrigenous complex in the Greater Caucasus: a radiological age of 25–50 Ma was recorded previously in the studied profile of the Terek River basin (Bujakaite et al., 2003; Gavrilov et al., 2000, 2001).

The southern part of the profile intersects the northern zone of the Bezhita depression filled with the Toarcian sediments that are very irregularly subjected to secondary transformations: this zone includes sectors with mudstones that resemble the coeval rocks of the northern monocline in the Agvali–Khiva SFZ (Fig. 5a). In some places, however, one can see intense dislocations and development of cleavage (Fig. 5b). The radiological age of samples in this area increases to 150–250 Ma; i.e., here again begins to affect the ancient age of the provenance.

ALTERATIONS OF ORGANIC MATTER AND CARBONATE MINERALS IN ROCKS OF THE PROFILE

Increase in the degree of secondary transformations of deposits from the monoclinal bedding zone to the intensely dislocated one is accompanied with appreciable changes in all parameters of rock composition. For example, the profile shows dramatic alterations of OM. Reflectance of vitrinite shows a wide variation. The upper Toarcian–lower Aalenian rocks from the upper portion of the monoclinal section (Batlukh Formation) includes plant remains and coal interbeds with a reflectance (R^0) of 1.12–1.15, which corresponds to the end stage of fat coals and the initial coke stage of OM alteration. In the cleaved shale (middle Liassic) zone, R^0 increases to 8–8.5; i.e., the degree of OM alteration already reached the anthracite stage (Gavrilov and Tsipursky, 1987; Gavrilov, 2005). Physical properties of rocks also change along this direction: the density of clayey rocks is 2.5–2.6 g/cm^3 in the northern part of the monoclinal zone and reaches 2.7–2.72 g/cm^3 in the middle Liassic (most altered and cleaved) rocks.

Intense reworking of the clayey rocks under the influence of increasing P–T parameters, in particul, stress loads, impact on the mineral composition of diagenetic concretions therein. Under high P-T conditions, siderite in concretions became unstable and was metasomatically replaced by other minerals. This process promoted the formation of specific fine-grained quartz–chlorite nodules that often contain abundant pyrite dissemination owing to the decomposition of siderite and the consequent release of Fe (Gavrilov, 1982, 2005). This trend is recorded well in horizons of coeval rocks with a similar facies composition. They extend from the monoclinal bedding zones to the intense dislocation and cleavage development zone (Figs. 2, 5b). As is evident from Fig. 2, chemical composition of concretions vary appreciably in different parts of the profile. In the northern part of the monoclinal zone with siderite concretions, the contents of CO_2 and FeO (consequently, siderite) vary slightly; the SiO_2 content (15–20%) reflects the presence of siliciclastic material in the concretions; the contents of MgO and MnO are insignificant (they are included partly as isomorphic admixture in siderite and partly as a component of clay minerals in sediments entrapped during the growth of nodules); and CaO occurs in the calcite admixture (its weak reflexes are recorded in diffractograms). The profile segment with distinct signs of cleavage shows an appreciable alteration in the composition of concretions: the SiO_2 content increases drastically to 60% or more. In contrast, decrease in the contents of CO_2 and FeO is considerable. Moreover, concretions from the middle Liassic shales contain only traces of CO_2. The most notable compositional variations in concretions are recorded within a narrow kilometer-scale interval.

As is evident from the figure, lithogeochemical characteristics of the Jurassic terrigenous (siliciclastic) rocks in the profile commonly underwent considerable transformations. However, the alterations are gradual in some places (monoclinal zone) and very abrupt in other (sufficiently narrow) zones.

DISCUSSION

Data presented above testify to intense transformations of the mineral composition of rocks of Jurassic terrigenous complex, particularly, in its lower and oldest horizons. These transformations accompanied by a partial loss of the radiogenic Ar provoked a significant decrease in the radiological age of rocks, relative to the stratigraphic age. As is evident from Fig. 2, the most dramatic variations in the mineral, textural-structural, and geochemical characteristics of rocks are observed at the transition from the monoclinal bedding zones to the intense deformation and cleavage development zones.

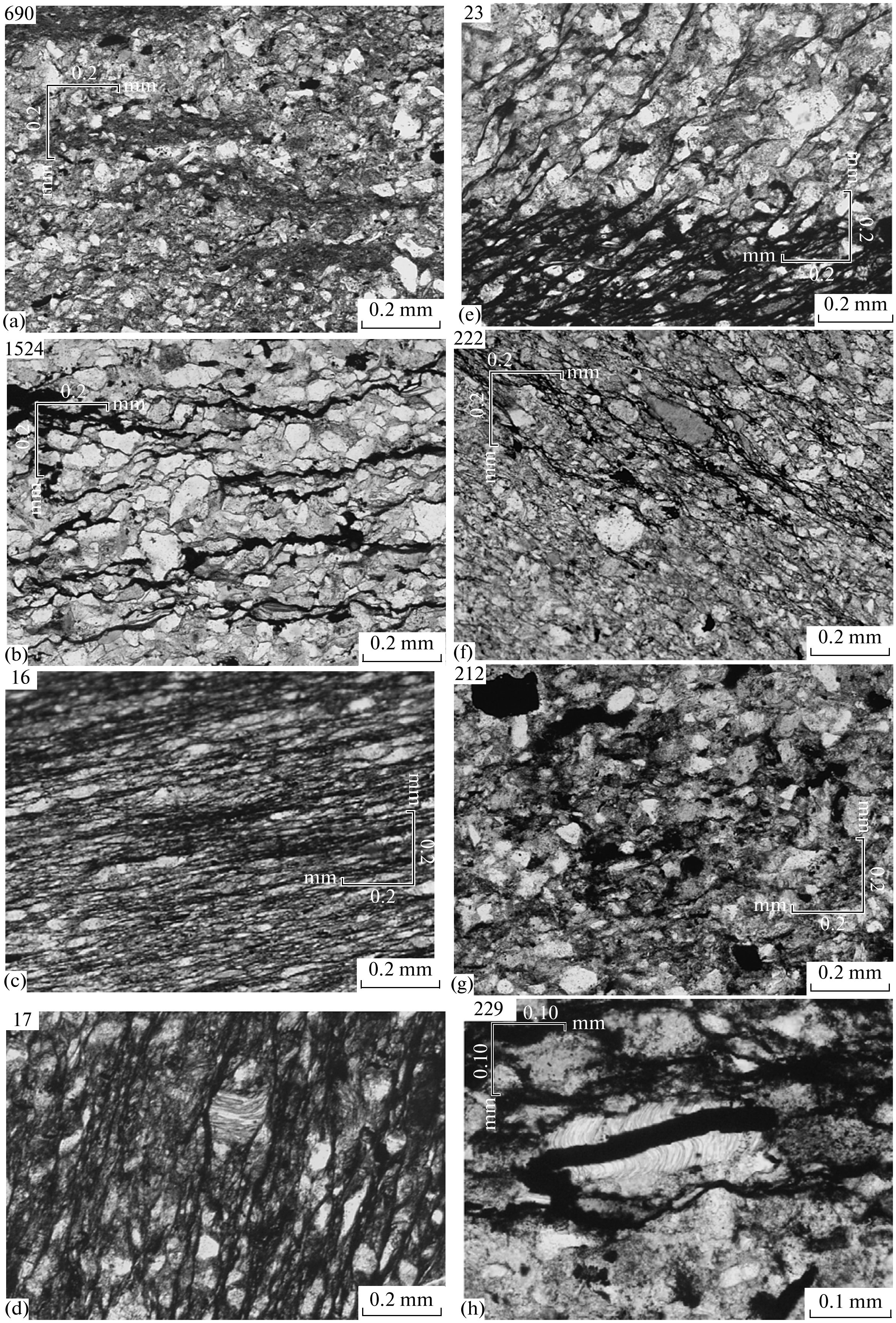
Rocks exposed along the profile were influenced by three factors: geostatic load, temperature, and lateral stress. Influence of these factors on changes in the mineral composition of rocks is discussed in (Bujakaite et al., 2003).

In the monoclinal zone, transformations of rocks are mainly provoked by geostatic load and temperature increasing with depth. In this zone, physical parameters of clay minerals and geochemical isotope parameters behave differently. In the Lower–Middle Jurassic section, the clay mineral composition is notably variable. The hydromica–chlorite assemblage is developed in the upper and lower portions of the section; the amount of micaceous minerals increases with depth; and the middle portion is dominated by kaolinite. The distribution of clay minerals, at least in the middle and upper portions of the section, was appreciably governed by the primary lithofacies constraints of rock formation. As for the lower portion of the section, where the facies properties of the Batlukh and Ratlub formations are similar, we can assume that kaolinite was present in the Ratlub Formation at the initial stage of sedimentation. However, geostatic load of the overlying sequences (5 km of the Toarcian–Bathonian rocks and no less than 3 km of the Upper Jurassic–Cretaceous sequences) destroyed the lower portion and promoted the formation of new authigenic silicate minerals (mainly, micaceous varieties). In general, the monoclinal zone demonstrates the following variation downward the section (from north to south): rocks with a clear predominance of hydromicas of the polytype modification 1M over $2M_1$ give way gradually and regularly to a different type, in which the content of hydromicas of the polytype 1M is slightly higher or approximately equal to that of $2M_1$. Hence, the sedimentary material underwent certain changes in the course of burial under the influence of higher P–T. However, as is evident from Figs. 2 and 3, the radiological age of rocks did not change appreciably, probably, because the sedimentary micaceous minerals turned out to be sufficiently conservative and resistant to recrystallization. In general, they retained the "age signature" of sedimentary material in the provenance. At the same time, the rocks were conserved in sufficiently closed systems: traces of a large-scale redistribution of material, quartz veins, and so on are missing.

A significantly different pattern is observed in the cleavage development zone. Here, one can see numerous traces of sedimentary mineral dissolution accompanied by transport of the dissolved material: pressure shadows include "beards" of various authigenic silicate minerals; authigenic mica flakes are formed along the cleavage planes; and veinlets with quartz or quartz–chlorite infill (Alpine-type veins) are formed. These facts testify to a significantly large-scale migration of matter. Thus, rock system in the cleavage development zone becomes more open relative to the monoclinal zone. Migration of some components is also evident from the metasomatic replacement of carbonate (siderite) concretions by the quartz–chlorite–sulfide mass. In other words, SiO_2, several cations, and sulfur were introduced to the concretions, while the siderite decay product (CO_2) was removed from the system. New conditions of stress (intense lateral pressure) fostered the recrystallization of sedimentary material. The K–Ar system was sensitive to all these processes of change in the mineral composition of rocks. The notable renewal of mineral composition provoked a loss of the radiogenic Ar thus causing the rock "rejuvenation".

As noted in (Gavrilov, 2005), stress pulses were not rare phenomena during great tectonic events and rearrangements. They began to appear even in the sedimentation basin of the Greater Caucasus. Some pulses (probably, not the most intense ones) were synsedimentary processes. Therefore, the oldest rocks of the Jurassic section underwent a greater number of stress pulses relative to the stratigraphically younger counterparts and, consequently, turned out to be more intensely cleaved. The appearance of cleavage in a sedimentary sequence promotes the development of entirely special anisotropic properties (vertical anisot-

Fig. 6. Photomicrographs of rocks from various parts of the profile with different degrees of cleavage manifestation. (a, b) Rocks from the monoclinal zone without signs of cleavage: (a) silty mudstone from the Bathonian rocks at the section top (clayey lenses are traces of bioturbation); (b) clayey–coaly siltstone from the Toarcian rocks at the section base (Ratlub Formation)—black bands indicate coaly substance; (c–e) cleaved shales in the intensely folded zones (Metlyuta–Akhtychai SFZ); (f, g) clayey–silty rocks in the Bezhita depression: (f) with imperfect cleavage, (g) without traces of cleavage; (h) authigenic silicate minerals in pressure shadows.


690
(a)
0.2 mm
23
(e)
0.2 mm
1524
(b)
0.2 mm
222
(f)
0.2 mm
16
(c)
0.2 mm
212
(g)
0.2 mm
17
(d)
0.2 mm
229
0.10 mm
(h)
0.1 mm

ropy) that are quite different from those in nearly horizontal deposits. We assume that the development of a perfect (nearly vertical) cleavage in the sedimentary sequence fosters the formation migration pathways for solutions that can escape from the rock system during the subsequent stress pulses. Therefore, as compared to the noncleaved stratified rocks, the cleaved sedimentary sequence is much more favorable for rearrangement of the mineral composition of rocks under the influence of intense lateral pressure. This factor is likely responsible for the lowest radiological ages (late Pliensbachian, Metlyuta–Akhtychai SFZ) recorded for the oldest rock sequences in the profile with the most perfect cleavage. These age estimates reflect an influence of the "youngest" stress pulses on both rocks and the K–Ar system.

In the Bezhita depression, one can see an irregular development (up to the point of absence) of cleavage over the area. In other words, secondary processes are attenuated in this zone, relative to the Metlyuta–Akhtychai SFZ. The degree of deformation again increases beyond the Bezhita depression and further southward on the northern slope of the Main Caucasus Range. As shown in (Simanovich et al., 2004), cleavage is developed well in the Toarcian–Aalenian rocks in the Samur River basin and its right tributary (Akhtychai River). At the same time, the KI value in the most intensely cleaved rocks is 0.30 (0.27 and 0.29 in two samples); i.e., the KI value does not fall down to the minimum value, as in the Metlyuta–Akhtychai SFZ. The minimal values of the radiological age were obtained for bulk samples (137 and 148 Ma) and <0.001 mm fraction (151 Ma). The remaining samples yielded higher values (more than 160 Ma). Two samples (<0.001 mm) yielded 259 and 262 Ma. Thus, as compared to the middle Liassic sequence along the Avar Koisu River profile, even the most altered rocks in the study region are marked by a lower degree of rejuvenation. Analytical data on the Jurassic rocks of the adjacent Samur River basin (Simanovich et al., 2004) show that the lowest values of the radiological age are related to the oldest (lower and upper Toarcian) rocks exposed in an anticline core in the region.

Thus, data on rock sections of the Avar Koisu River area and the Samur River basin suggest the following empirical regularity: growth of the stratigraphic age of rocks is accompanied by intensification of their transformation due to a stronger impact of temperature and pressure (stress, in particular), resulting in intense rearrangement of both mineral composition and structural-textural peculiarities of rocks. These processes are accompanied by decrease in the radiological age of rocks. Reasons for this trend require a special discussion.

One can assume that the burial of rocks into a high P–T zone would be accompanied with both mineralogical and radiological age rearrangement of rocks, as was demonstrated for the Gulf Coast in (Perry, 1974). However, the data presented above suggest a different conclusion: despite certain alterations in the mineral composition of rocks, significant downsection variations did not occur in the radiological age of the kilometer-scale Lower–Middle Jurassic sequence in the monoclinal zone.

The mineralogical-geochemical and textural-structural characteristics observed at present in rocks along the geological profile of the Avar Koisu River were formed in the course of their long-term accumulation. As demonstrated in (Frolov, 1965; Gavrilov 1994, 2005), a large river played the main role in the delivery of sedimentary material to the northeastern flank of the Greater Caucasus basin during Early and Middle Jurassic. Sources of sedimentary material (provenances) were located both in the proximal zone of the Paleozoic and Triassic sequences of the Scythian plate and in the distal areas of the East European Platform. Moreover, the regional tectonic and paleogeographic reconstruction, which took place approximately at the Aalenian/Bajocian boundary, did not basically affect the character of sedimentation in the basin. The clayey portion of the supplied material was represented by hydromicas mainly composed of 10–20% expandable interlayers dominated by the polytype modification 1M. The sedimentary basin also accumulated both chlorite and some kaolinite; the latter actively formed in the lacustrine-boggy systems in the subaerial delta during certain stages (regressive episodes) and later transported to basin. Consequently, the amount of kaolinite increased drastically in marine rocks of some stratigraphic intervals.

Based on analysis of the distribution of minerals in the heavy and light fractions of sandy rocks in the Jurassic sections, Grossgeim (1961) made the following conclusions: sedimentary material in the eastern part of the basin was delivered from north; sedimentary materials in the Early and Middle Jurassic were generally similar; and they mainly represented decomposition products of the sedimentary and volcanosedimentary complexes in the Scythian plate.

The composition of sandstones and gritstones provides additional information pertaining to the source of material for the Jurassic sedimentary sequences in the Avar Koisu region. The Toarcian and Aalenian sandstones are represented here by the lithoclastic quartz graywackes that are similar to those in the Sumur–Akhtychai interfluve area (Simanovich et al., 2004). The graywackes are composed of quartz (40–60%), plagioclases (5–10%), K-feldspars (from a few grains to 2%), and rock clasts (30–50%). The clasts are represented by clays, weakly metamorphosed micaceous shales, cherts, and effusives. The accessory minerals are represented by zircon, tourmaline, leucoxene, and others.

Frolov (1965) scrutinized the issue of provenances in Dagestan and suggested that they included metamorphic (probably, Early–Middle Paleozoic) rocks, granitoids, and slightly metamorphosed or nonmetamorphosed (Upper Paleozoic–Lower Mesozoic) sedimentary and effusive sequences.

In the upper portion of the section within the monoclinal zones, the common radiological age of rocks is 200–250 Ma and appreciably older in some places. We believe that this value reflects fairy well the age of rocks in the provenances that delivered material to sedimentation basin over a long period (middle Liassic–Bathonian). There are no grounds to doubt that the oldest (late Pliensbachian and early Toarcian) rocks that are exposed in the southern part of the profile were also produced by the similar sedimentary material and initially characterized by similar radiological ages. The significant "rejuvenation" of the radiological age of rocks (up to 70 Ma) was caused by their intense secondary alterations.

We assume that postsedimentary alterations of sedimentary sequences took place according to the following scenario.

The early Liassic trough in the Greater Caucasus accumulated the terrigenous sedimentary material, the age of which was mainly governed by the Paleozoic–Triassic age of rocks in the Scythian plate. Initially, sediments were accumulated in a relatively narrow trough that was expanding in the Early and Middle Jurassic. Morphology of the basin was governed considerably by synsedimentary faults (Nelkh and others). Therefore, the trough basement was likely marked by a terraced relief with subsided southern blocks. The terraces could serve as a rigid stop during the development of stress. Therefore, rocks in the southern part of these faults underwent more intense secondary transformations (in particular, stronger cleaving) than rocks in the northern parts of the basin.

Let us note the following stages of the Greater Caucasus evolution related to compressive stress that provoked a radical change in the mineral composition of rocks. In the Early and Middle Jurassic history, the terminal Aalenian–early Bajocian period was marked by the most intense tectonic process—transition of the passive continental margin to an active one. This process led to initiation of subduction. Consequently, the continental margin was subjected to compression, uplift, and folding (Lomize and Panov, 2001; Panov and Lomize, 2007; and others). This deformation phase was supplemented with other phases that significantly contributed to the Jurassic rock structure. Among them, the main phases are represented by the pre-Callovian, Coniacian–early Santonian, and late Alpian (post-Middle Eocene) episodes (Panov and Lomize, 2007).

In addition to the main phases of deformation that affected Lower–Middle Jurassic deposits, there were weaker but probably also significant events, which influenced the nature of mineralogical–geochemical transformation of rocks. The early Toarcian (Azhgirei, 1963; Gavrilov, 2005; Leonov, 1969, 2007) and some other phases represent such events.

Sub vertical cleavage was responsible for the mainly "Caucasian" strike of dikes in the Azerbaijan and Dagestan sectors of the Greater Caucasus along the Main Caucasus Range. Age of the first dike generation is estimated as Liassic (Kashkai, 1976). Thus, the subvertical fracturing of rocks (protocleavage), which controlled the pathway for the magmatic melt percolation and dike formation, was already developed in the Liassic. According to Kashkai, processes of dynamometamorphism also took place 127–132 Ma (i.e., in the Hauterivian–Barremian, according to the Geological Time Scale 2008). This conclusion is based on the K–Ar and Rb–Sr datings of shales from the Filizchai, Katsdag, and Kyzyldere deposits.

One should also bear in mind the following point: synsedimentary growth of large folds took place in limestones of Dagestan in the Late Cretaceous–Early Paleogene, as suggested by numerous large-scale slumpings of sedimentary masses from limbs of these folds (Moskvin and Semikhatov, 1956). They were likely related to the impact of compressive stress.

Thus, the present-day mineral and geochemical-isotopic compositions of the Lower–Middle Jurassic rocks in the Eastern Caucasus were produced by the influence of several phases of compression in the course of a long period.

Comparison of the radiological age values obtained for rocks from the central sector of the Greater Caucasus (Terek River profile) and the adjacent eastern sector (Avar Koisu River profile) suggest the following conclusions. The Terek profile is marked by a more significant (up to 50 Ma) rejuvenation (the age is lower for some samples). The age of counterparts in the Eastern Caucasus is estimated as no less than 70 Ma, suggesting that this Caucasian sector was likely located in the Cenozoic in a specific "tectonic shadow," where compressive stresses (probably related to the Arabian plate pressure) were slightly weaker than in the western areas.

Studies similar to those in the present work should be continued further to reconstruct a more complete scenario of postsedimentary transformations of the Jurassic terrigenous complex in the Eastern Caucasus and to elucidate its geochemical parameters. The Avar Koisu River profile should be extended across the Main Caucasus Range to its southern slope.

CONCLUSIONS

We carried out detailed structural-geological and mineralogical-geochemical investigations of the Jurassic terrigenous (siliciclastic) rock complex in the Eastern Caucasus. Along the Avar Koisu River profile that is oriented transversely to the strike of the Jurassic deposits, the degree of layer dislocation increases southward from the monoclinal bedding zone to the intensely folded zones. Deformation of beds is accompanied by the development of cleavage, which is lacking in the monoclinal zone and is perfect in the Metlyuta–Akhtychai SFZ. Intensification of cleaving along the profile is nonlinear: cleaving is most intense in the proximal zones of large regional faults. They appeared as synsedimentary structures in the Jurassic and existed over a long time.

From north to south toward the axial part of the Greater Caucasus, one can see a gradual intensification of postsedimentary rock transformations, which are expressed as alteration of the mineral and chemical composition of rocks. The clay minerals are subjected to notable alterations: the hydromica–chlorite–kaolinite assemblage developed in the northern part of the profile gives way to the sericite–chlorite variety; expandable interalyers are missing in the layer silicates; hydromicas of the polytype modification 1M, which prevail in the northern part of the profile, are replaced by modification $2M_1$ in the southern part; and the KI value also increases along the same direction. Moreover, density of the clayey rocks increases from approximately 2.5 g/cm^3 for mudstones to 2.7–2.72 g/cm^3 for the cleaved shales. The reflectance of vitrinite R^0 increases from approximately 1.12 (end of the fat coal stage) to 8–8.5 (anthracite stage).

In accordance with variations in the characteristics of rocks, diagenetic carbonates (mainly siderite) disappear from the section base. In the northern part of the profile, siderite makes up diagenetic concretions. In the cleavage development zone, however, siderite becomes unstable and is metasomatically replaced by silica and sulfide minerals.

Cleavage and rock transformations mentioned above are irregular and less intense in the upper Toarcian rocks of the Bezhita depression in the southernmost part of the profile.

Transformations of rocks are accompanied by variations in their K–Ar age. The initial age of sediments, which reflects the age of provenance, is estimated as Carboniferous–Triassic or older. However, intense secondary transformations of rocks accompanied by the recrystallization of silicate minerals and the loss of radiogenic Ar provoked a decrease in the measured rock age, which can vary from 100 to 200 Ma in different parts of the region. Transformations of rocks were mainly caused by the influence of compressive stress. During the existence of the Jurassic terrigenous complex, stress pulses occurred several times since the Liassic and continued up to the Cenozoic.

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