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Textural–Structural, Mineralogical, Isotopic, and Age Characteristics of Jurassic Terrigenous Rocks of the Northwestern Caucasus (the Belaya River Section)

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Abstract—Results of the comprehensive study of structural, lithological, mineralogical, and isotopic characteristics of Lower Jurassic rocks exposed in the Belaya River valley (Adygeya) in meganticlinorium of the Greater Caucasus are presented. Deformation microstructures were studied. Lithological and textural–structural changes in sequences related to intense secondary transformations should affect the state of isotopic systems of rocks. To reveal basic trends in the evolution of isotopic systems, investigation using the K–Ar method was carried out. Clay fraction (less than 1 μm) separated from rocks and bulk samples were analyzed. Cleavage development, approximate value of rock contraction, and isotopic characteristics are compared with the available data on alteration of clay mineral assemblages. Relationship between the degree of rock deformation at the microlevel and calculated K–Ar ages has been established. K–Ar systems of clayey rocks indicate the age of cleavage formation and correspond to the Bajocian–Bathonian contraction period.

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Study of the character and timing of secondary transformations of the Jurassic terrigenous complex in the Greater Caucasus allow us to assess the dynamics of the formation of this major mountainous structure. We carried out comprehensive petrostructural and isotopic–geochemical studies of sedimentary sequences along a system of profiles across the terrigenous complex of the Caucasus. Results of the study of rocks exposed in the Belaya River valley are presented in this work.

Isotopic studies were carried out in the Caucasus to establish the possibility of the K–Ar dating of tectonic events based on terrigenous clayey rocks.

The study region belongs to the Arkhyz–Guzeripl structural–facies zone, SFZ (Fig. 1). Structural-facies zones are characterized by a definite type of Lower and Middle Jurassic sections extending over considerable distances along the strike and rapidly giving way to each other across the strike of the Greater Caucasus (Panov et al., 1987).

The Arkhyz–Guzeripl SFZ corresponds to the western elevated area of the northern slope of the Greater Caucasus basin. Lower–Middle Jurassic rocks within this zone fill several graben-shaped depressions. In some places, they are retained as small outliers at the crest of uplifts. Lower–Middle Jurassic rocks of the northern wide slope of the basin are characterized by smaller thickness compared to southern zones. The Arkhyz–Guzeripl SFZ is characterized by the coarser-grained composition of rocks, presence of local hiatuses, and more distinct stratification compared to eastern regions (Panov, 1976).

The studied profile located in the western Arkhyz–Guzeripl SFZ extends over 10 km from south to north along the Belaya River valley upstream of the Settlement of Guzeripl (Fig. 1).

The Veriyut Formation unconformably overlies the pre-Jurassic basement in the Belaya River valley. The basal horizon is composed of fine-pebble conglomerates and sandstones. It is overlain by a sequence of dark gray micaceous–silty mudstones with interlayers and lenses of sandstones and sideritic concretions. Based on single finds of ammonites, the lower part of the sequence corresponds to the upper Sinemurian, whereas the main part matches the lower Pliensbachian (Panov et al., 1964). The total thickness of the Veriyut Formation in this region is 100–200 m.

The Chuba Formation (J_1pb_2) characterized by substantial facial variability overlies (sometimes with erosional hiatus) rocks of the Veriyut Formation. In the Belaya River basin, the Chuba Formation represents a sequence of flyschoid alternation of mudstone, siltstone, and fine-grained sandstone with an indistinct basal conglomerate interlayer. Members of massive medium-grained sandstones occur at the base and in the middle part of the formation. The thickness of the formation in the Belaya River section is 370–420 m.

A thick sequence of clayey–silty rocks of the middle and upper Toarcian and Aalenian (Tuba Formation) overlies rocks of the Chuba Formation. The basal layer

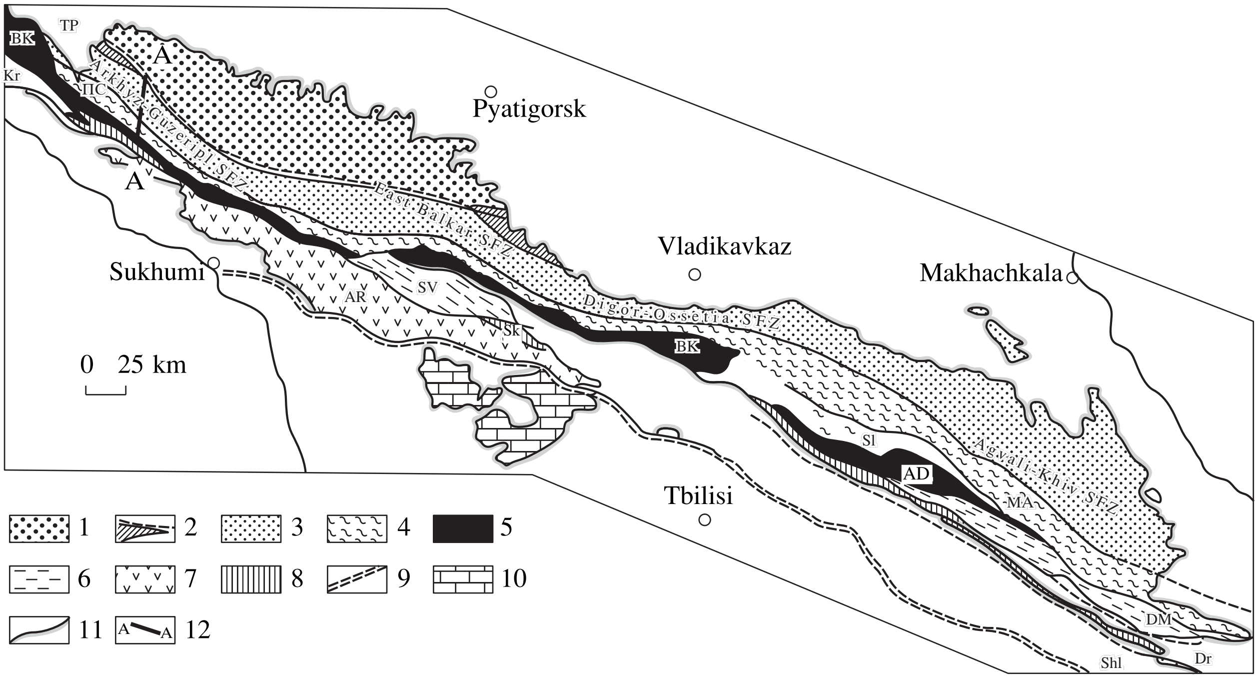

Fig. 1. Scheme of the structural–facies zonation of the northwestern Greater Caucasus for the Early–Middle Jurassic (Panov and Gushchin, 1987).

(1) Epi-Hercynian Scythian Plate; (2) transitional Tyrnauz–Pshekish suture zone (TP); (3–8) Greater Caucasus in the Early Jurassic and Aalenian: (3) northern slope, (4) northern framing of the axial trough: (Ps) Pseashkha, (MA) Metlyuta-Akhtychai, and (Sp) Speroz zones, (5) axial trough: (BK) Bzyb–Kazbek and (AD) Alazan-Didindakh zones, (6) southern framing of the axial trough: (SV) Svanetia and (DM) Dalichai-Mazin zones, (7, 8) southern slope: (Kr) Krasnaya Polyana, (AR) Abkhazo-Rachin, (Sk) Sakauri, (Sh) Shekin, and (Dr) Durudzhi zones; (9) Kakhetia–Lachkhum suture zone; (10) Transcaucasian median massif; (11) boundaries of Lower–Middle Jurassic rocks; (12) position of the studied section.

of this sequence in the Belaya River valley consists of crinoid limestones. The main part is composed of black mudstones with siderite concretions. In some places, the lower part of mudstones includes alternations with siltstones. The thickness of the sequence makes up 1800 m (Rostovtsev, 1967).

The rocks are intricately dislocated, folded, and intersected by steep faults (Fig. 2a). Often only one limb is observed, whereas another one is truncated.

METHODS

We studied rock samples taken from Lower–Middle Jurassic rocks along the Belaya River valley. We examined in thin-sections the character and specific features of deformed microstructures, such as intergrain cleavage, accretion trails in pressure shadows, mineral veins. We also determined the approximate value of rock deformation.

Intergrain cleavage is a plane microstructure formed by plane–parallel alternation of flat fine-dispersed aggregates of layered silicates, ore minerals, organic matter (cleavage zones), and rock zones composed of larger clastic grains with the admixture of fine-dispersed grains of different mineral compositions often predominated by quartz, calcite, and chlorite (microlithons) (Talitskii and Galkin, 1988). This microstructure promotes the development of anisotropy of mechanical properties in rocks.

To assess the intensity of intergrain cleavage in rocks and to determine the approximate value of contraction, we used the scheme elaborated by V. G. Talitskii for the correlation of cleavage with rock deformation at the level of mineral grains (Gavrilov et al., 1999). The first signs of cleavage appear at 5–7% contraction of rock. A distinct structure is observed at 10–12% deformation. Cleavage zones penetrate the rock at 20–25% deformation. The formation of intergrain cleavage is related to nonuniform structure of rocks at the grain level. Rock contraction is accompanied by increase in pressure along grain contacts oriented perpendicularly to contraction and intense dissolution of matter. Insoluble residue accumulated in dissolution zones makes up cleavage zones.

The mineral composition of clayey rocks was determined on fractions <1 μm by the standard method using a DRON-2 diffractometer. The X-ray phase analysis was applied to determine the degree of mica crystallization known as the Kübler crystallinity index (Gavrilov, 2005).

The content of radiogenic argon was measured in weighed samples (60–90 mg by the isotope dilution method using a MI 1201IG mass spectrometer com-

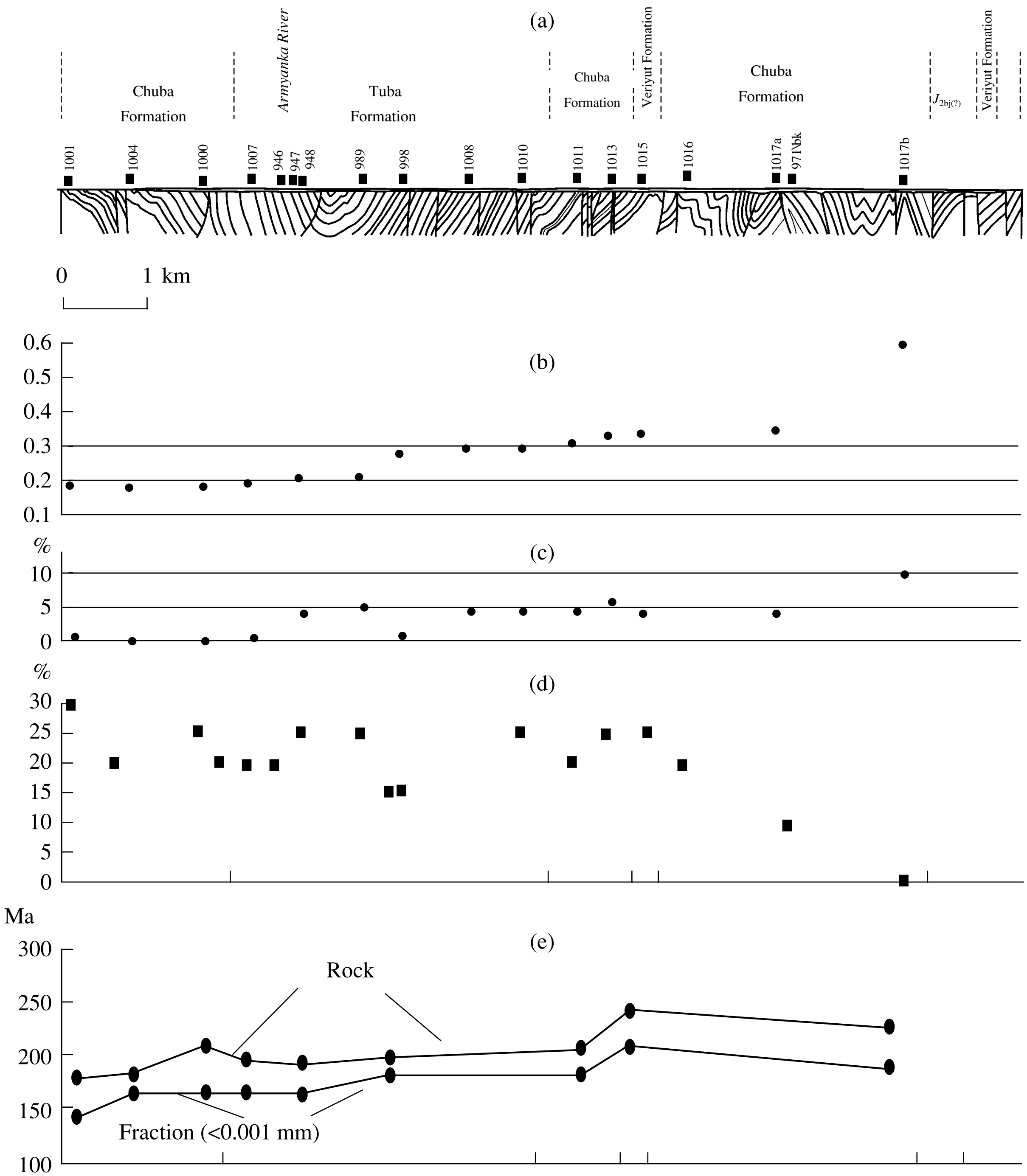

Fig. 2. Geological profile along the Belaya River and structural–textural, mineralogical, and K–Ar characteristics of rocks. (a) Geological profile (N.I. Prutskii); (b) variations in the crystallinity index of micas; (c) number of swelling layers in micaceous minerals; (d) distribution of the degree of contraction based on cleavage; (e) K–Ar ages of rocks (Ma).

plex. Samples were melted at 1600–1800°C. Purity of the tracer (monoisotope ^{38}Ar) was 97.5%. Error of the radiogenic argon measurement did not exceed ±1%. The content of atmospheric argon was 5–10%. Error of the potassium concentration measurement was less than 1%.

Error of age determination (2–2.5%) was controlled by the convergence of parallel (replicate) measurements in samples and by the reproducibility of analyses of standard samples. Ages were determined using 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} (Dalrymple, 1979).

We analyzed bulk samples and fractions <1 mm. Fine fractions readily undergo postsedimentary processes (Vinogradov et al., 2000) and record an isotopic age closest to the timing of rock transformation. Coarser fractions are likely to retain isotopic signatures of the provenance.

CHARACTERISTICS OF DEFORMATION MICROSTRUCTURES

Rocks in the studied section are affected by cleavage to a variable extent (Figs. 3a–3f). One can see rocks without any signs of deformation, with first signs of cleavage (Fig. 3b), and with perfect cleavage zones (Figs. 3d–3f).

Figure 2e illustrates the intensity of rock contraction assessed by cleavage. The character of cleavage is different in individual blocks bounded by ruptures. In the northern part of the profile, cleavage is less developed, and the approximate contraction of rocks does not exceed 10% (Figs. 3a–3c). Often rocks are not affected by deformation at all. Further south, cleavage becomes more intense, and contraction increases to 20–25% (Fig. 3f). In places along cleavage zones, one can observe authigenous mica oriented parallel to the cleavage zones and formed together with them.

Upon passing from one layer to another, all cleavage-bearing thin sections exhibit the refraction of cleavage zones. According to (Talitskii, 1989), the studied cleavage can be attributed to the prefolding structure developed at the longitudinal contraction stage (Fig. 3h). The prefolding cleavage formation is also confirmed by the presence of fan-shaped cleavage (Fig. 3g). In some places, cleavage is confined to the finer-grained interlayers, because intergrain cleavage is more rapidly formed in the fine-clastic rocks in the course of the joint deformation of layers of fine- and coarse-clastic rocks (Galkin, 1988).

The thin-sections also show mineral veins of different compositions and microstructures related to local tension, i.e., accretion trails (Galkin, 1988), in pressure shadows near large pyrite grains.

Accretion trails in pressure shadows are most often composed of fibrous crystals extending parallel to cleavage zones. Hence, such microstructures belong to a single deformation stage (Fig. 3k), because they are in the same strain field.

Short accretion trails and well-developed cleavage is the most observed association in thin sections (Fig. 3k). This is related to the redeposition of material in pressure shadows at later stages of cleavage formation (Galkin, 1988). The association of structures mainly related to rock dissolution suggests that the formation of accretion trails at this stage of postsedimentary alteration proceeded from the rock material. Only perfect cleavage is observed in some thin sections (Galkin, 1988) (Fig. 3d), because the dissolved material was removed and redeposited in other places.

The length of accretion trails suggests the relative intensity of tensile strain, which is determined by the relationship between inclusion dimension and accretion trail length. The length of accretion trails is greater in samples taken in southern parts of the profile relative to samples taken in northern parts.

Mineral veins have different relationships with other deformation structures. In thin sections, one can see different relationships of minerals and microfissures with the deformation structures described above. The most widespread type is represented by equant quartz crystal veins, which intersect cleavage zones.

In some places, the veins extend parallel to cleavage. The formation of a vein begins with the formation of a microfissure (Ramsey and Huber, 1987). In rock with plane elements (cleavage zones) arranged at a high angle to tension direction, microfissures appear along these plane elements and are later filled with the mineral substance. Together with cleavage zones refracted at the boundary of layers, mineral veins can change their direction. In this case, mineral veins formed during the folding of layers after the appearance of cleavage zones. The veins are made up of equant quartz crystals; i.e., they are similar to veins described above in terms of composition and structure. The appearance of veins, dimension and shape of quartz grains, and their formation after cleavage zones indicate that the veins described above formed at one stage.

Like accretion trails, zonal veins (Fig. 3m) usually exhibit two zones, which record two formation stages. Vein walls include thin zones of quartzite crystals, while the central zone contains fibrous quartz crystals. Some veins are separated by a suture into two symmetric parts (Fig. 3n). Such veins grew from walls to the center. They were filled successively with calcite and quartz crystals. The extension direction of veins did not change in the course of their filling, but the composition of solutions (fluids) percolating in rocks did change. Fibrous silica crystals are formed during a gradual growth of crystals under conditions of space deficiency. They are stable only at a temperature below 350°C. Therefore, based on this natural thermometer, one may contend that the temperature of rock deformation did not exceed 350°C (Galkin, 1992).

Some places incorporate veins of two different generations (Fig. 3l). They do not necessarily exhibit a clear zonation. Sometimes, crystals of different minerals do not make up any well-defined zones. Such veins are formed under constantly varying conditions.

Small fibrous veins often observed inside individual grains formed at one stage under calm conditions of deformation. They consist of parallel elongated fibrous calcite crystals oriented along the strike of cleavage zones. As in the case with accretion trails, one may con-

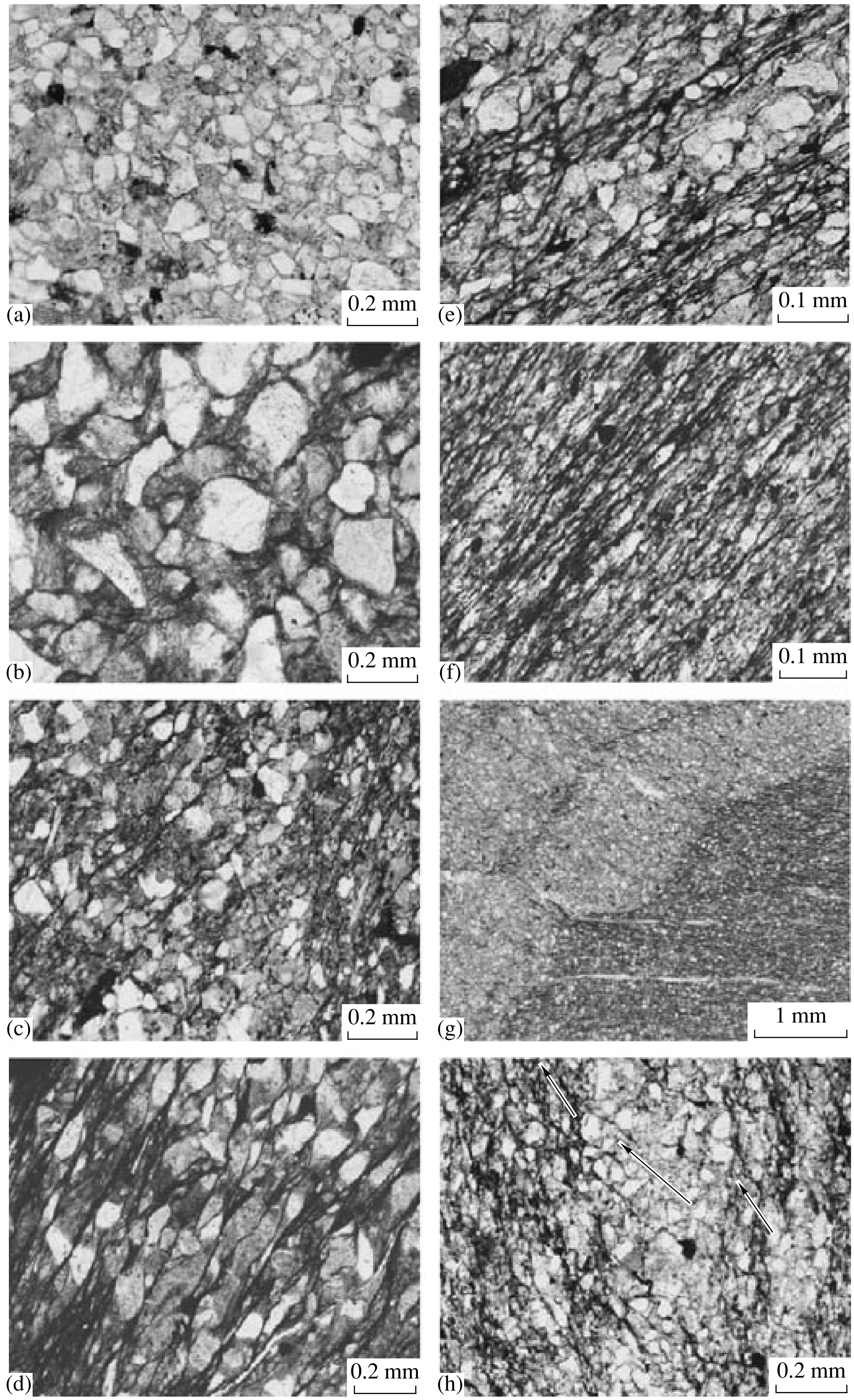

Fig. 3. Photomicrographs of rocks from different parts of the geological profile. Different degrees of rock deformation (approximate value of contraction based on cleavage, %): (a) 0; (b) 5; (c) 10; (d) 15; (e) 20; (f) 25; (g) fan-shaped cleavage; (h) refraction of cleavage zones; (i–k) accretion trails; (l, m) mineral veins; (n) syntaxial vein.

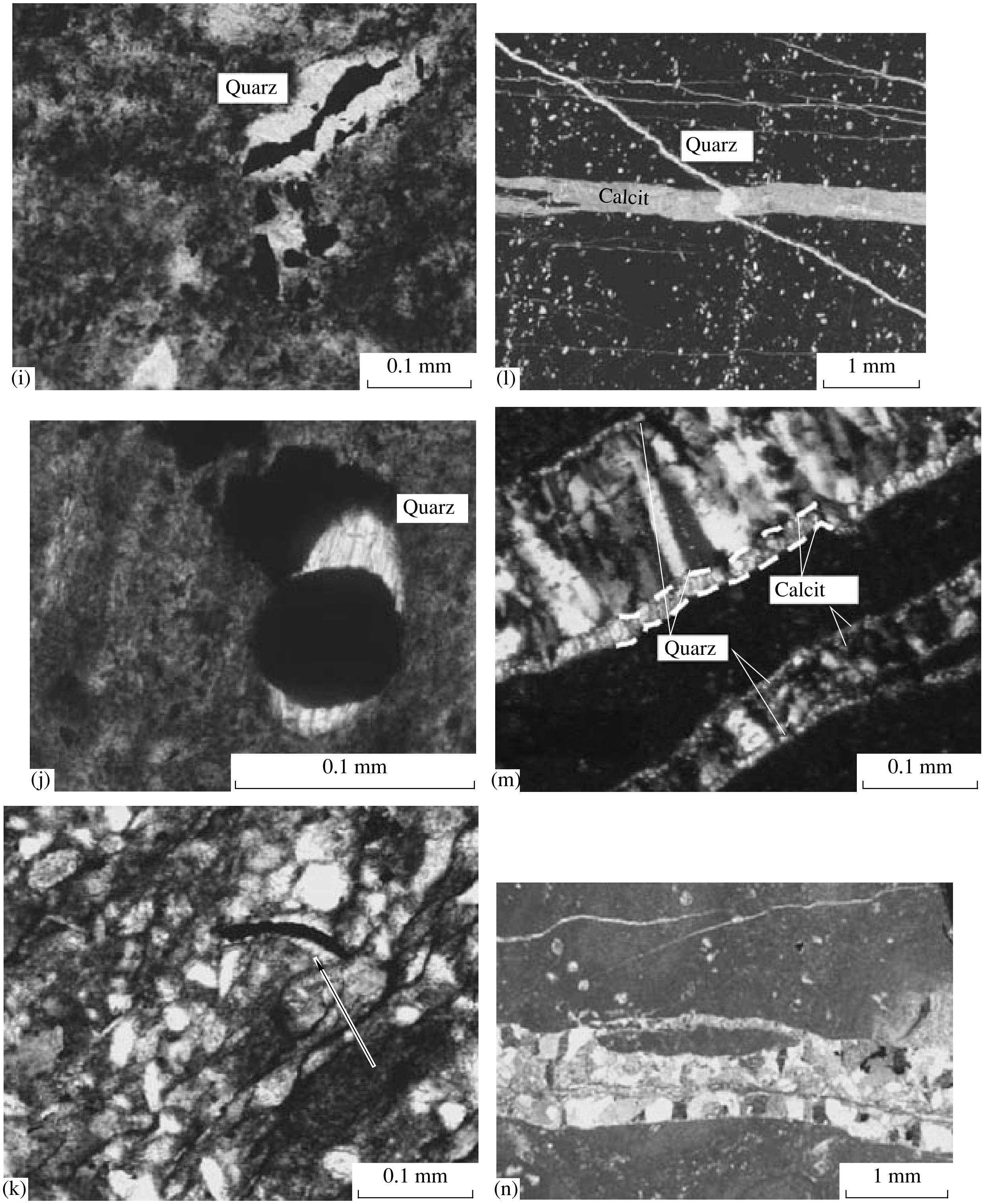

Fig. 3. (Contd.)

tend that they formed together with cleavage zones owing to dissolution of the host rock material.

In general, the intensity of rock deformation regularly varies along the profile and increases from north to south along the axis of the Greater Caucasus.

CHARACTERISTICS OF CLAY MINERALS

The mineral composition of clayey sequences of the western Arkhyz–Guzeripl SFZ was studied in sections along the Belaya River south and north of the Settlement of Guzeripl (Gavrilov, 2005). All the studied samples exhibited rather monotonous mineral composition (sericite or hydromica and chlorite), because the rocks underwent substantial postsedimentary alterations. Consequently, primary mineral assemblages with the potential presence of kaolinite and mixed-layered structures changed significantly, resulting in unification of the mineral composition of clayey rocks from different horizons of the sequence. Jurassic rocks in the northern part of the studied section are less altered. However, the fragmentary character of exposures of Jurassic bedrocks in this area hampers reconstruction of the distribution of clay minerals.

Index of mica crystallinity in the studied section was determined by the Kübler method (Kübler, 1964). The index is most applicable for rocks subjected to substantial postdiagenetic transformations. This feature is characteristic of the studied profile.

The degree of postsedimentary transformation shows a positive correlation with the intensity and clearness of the first low-angle basal reflection of illite. According to (Kübler, 1964), the reflection width at half height, i.e., index of crystallinity (IC), of illite can be used as a measure of the degree of postsedimentary transformation of sedimentary rocks. The IC value determined by the Kübler method has an inverse correlation with the degree of rock transformation (degree of mica crystallinity).

The IC value of micaceous minerals varies along the profile (Fig. 2b). At the base of the section, the IC value gradually increases from 1.9 at the southernmost point of the Jurassic rock zone to 3.5 in the northern area. It is noteworthy that the content of mica with swelling interlayers is negligible in the southern part of the section and as much as 5–10% at the northern margin near the Settlement of Guzeripl (Fig. 2c). According to (Simanovich et al., 2004), the Kübler index corresponds to orogenic catagenesis and metagenesis). As in the Belaya River section, variations in the IC value and concentration of swelling interlayers in the studied profile can be related to the southward intensification of secondary rock transformation.

POTASSIUM–ARGON SYSTEMS

Analyses presented in the table show the following regularity: in general, the isotopic age is older in the northern part of the section as compared to the southern part (Fig. 2e). Based on bulk samples, the age corresponds to Triassic (237 ± 4 Ma). Age values based on bulk samples from the southern part fall within 169–207 Ma. Age values calculated for fractions are slightly younger (164–180 Ma), but they also fall within the Jurassic interval.

Results of the K–Ar measurements shown in isochron coordinates (Fig. 4) make up two (northern and southern) clusters. Data on intensely altered rocks of the southern part are approximated by a straight line (Fig. 5). Data points of slightly altered rocks fall on the same line with a great scattering.

Results of K–Ar measurements of bulk samples (b) and fine fractions (f) of clayey rock samples from the Lower–Middle Jurassic terrigenous complex of the Greater Caucasus (the Belaya River region)

Lab. no.	Field no.	K, %	Ar, mm^3/gr	Age, Ma
795	1001b	3.11	0.0226	178
796	1001f	4.04	0.0235	144
797	1004b	2.62	0.0192	180
798	1004f	3.53	0.0233	162
734	1000b	1.98	0.0173	211
733	1000f	3.21	0.0215	164
799	1007b	2.17	0.0170	192
800	1007f	3.53	0.0232	162
791	948b	2.31	0.0179	189
792	948f	3.47	0.0228	161
793	998b	2.15	0.0175	199
794	998f	3.47	0.0256	181
801	1011b	2.24	0.0192	208
802	1011f	3.52	0.026	181
740	1015b	2.28	0.0229	242
739	1015f	3.2	0.0274	207
735	1017b	2.96	0.0268	233
736	1017f	4.54	0.0360	193

The age based on bulk samples always turns out to be older than the value based on fractions (table). The discrepancy can be as much as tens of million years. At the same time, the potassium content in all samples of fine fractions is considerably higher than that in bulk samples (table). The potassium content versus age plot (Fig. 6) shows an opposite trend: inverse correlation of isotopic age with potassium concentration. Such a pattern is characteristic of the early stage of rock transformation and is likely to be related to the influx of potassium from interstitial water to interlayer spaces in clay minerals (illitization) and the appearance of new minerals (Vinogradov et al., 1999, 2000). The younger age of fine fractions is probably related to a large concentration of potassium in them. The concentration of potassium could be a gradual or syncontemporaneous process.

The inverse correlation in the $^{40}Ar_{rad}$ content versus age diagram (Fig. 7), i.e., the smaller the age, the higher the argon content, is not normal for the K–Ar method. This relationship probably indicates the influx of potassium to clayey rocks at a relatively constant argon concentration. The scatter of values in the plot can be accounted for the heterogeneous nature of terrigenous clayey rocks. Therefore, the share of sorbed potassium can differ. As mentioned above, the influx of potassium

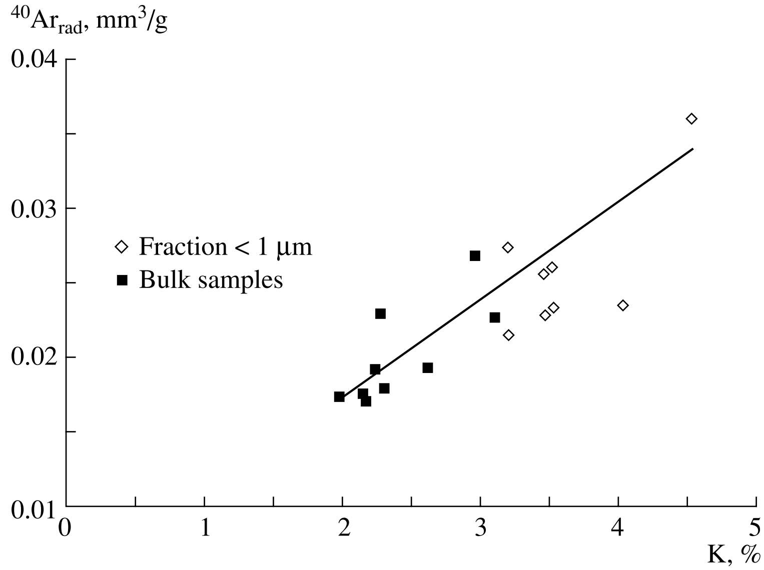

Fig. 4. K–Ar_{rad} ratio measured in fractions and bulk samples.

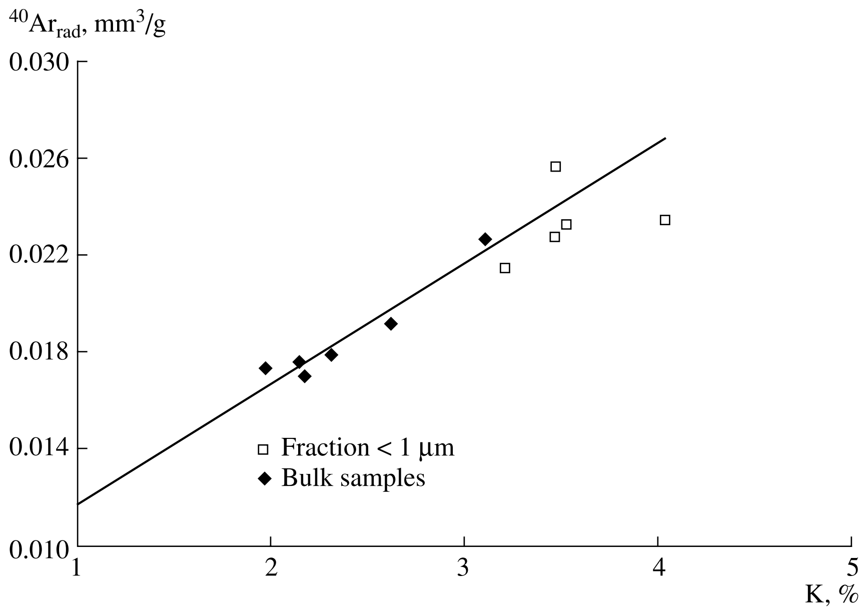

Fig. 5. K–Ar_{rad} ratio measured in samples of intensely altered rocks.

was a one-act process (from the geological point of view).

Thus, K–Ar dates exhibit a distinct trend: decrease in the isotopic age of rocks in the southward direction and stability of the rock age (Fig. 2e) at nearly stratigraphic version in the southern part of the section. Since this part of the section is characterized by the most intense postsedimentary transformations, we may suppose with a great share of probability that the calculated K–Ar value is not stratigraphically significant. This value most likely corresponds to a certain postsedimentary event that was responsible for the formation of cleavage formation, transformation of clay minerals, and variation of rock structures. The event was probably syncontemporaneous relative to the formation of enclosing rocks.

Many researchers (Dotduev, 1989; Koronovskii et al., 1990; and others) maintain that a substantial rearrangement of the structural plan of the Greater Caucasus took place in the Bajocian–Bathonian. Subduction of the substrate of the rift valley under the Scythian

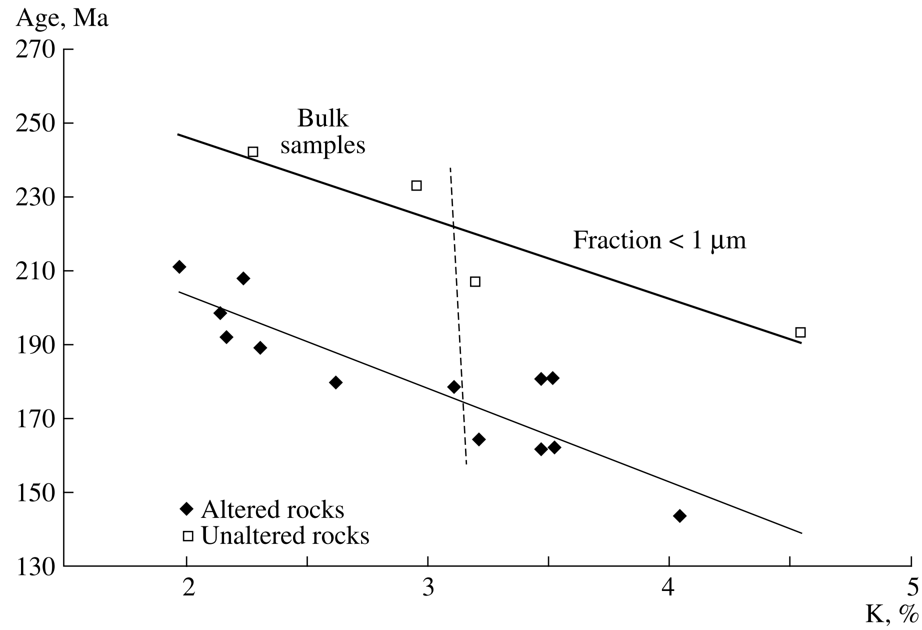

Fig. 6. Dependence of calculated age on the potassium content. Dashed line separates the results for bulk samples and fractions.

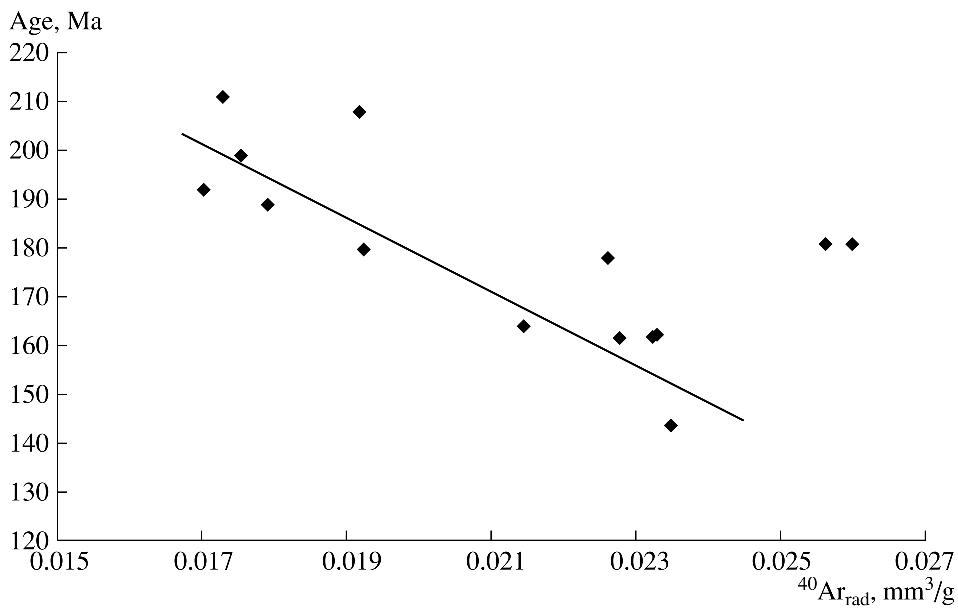

Fig. 7. Dependence of calculated age on the $^{40}Ar_{rad}$ content.

Plate at that time provoked an intense folding of its southern margin.

All the studied rocks were involved in a common process of intense alterations that are best manifested in the southern part of the section (Figs. 6, 7).

DISCUSSION

The studied profile shows regular variation in different characteristics of Lower–Middle Jurassic rocks.

The intensity of rock contraction increases along the southward direction. The oldest rocks of the Veriyut Formation are characterized by the most intense transformations, strong contraction up to 25% (Fig. 3f), and great accretion trails (Fig. 3j). Rocks of the Chuba Formation are exposed in the northern, southern, and central fields. Deformation structures are scarce in these rocks in the northernmost area, but well-developed cleavage zones appear in the southern areas. Deformation of rocks of the Chuba Formation in the southern and central fields is nearly similar. The value of contraction is usually 10–15% (25% in some places). Short accretion trails and mineral veins are encountered. The central part of the profile incorporates rocks of the Tuba Formation with prominent cleavage and numerous mineral veins and accretion trails. The value of contraction averages 10–15% (25%, in some places); i.e., deformation of older rocks is slightly more intense than that of younger rocks. In the northern part of the profile, rocks of the younger Chuba Formation virtually lack deformation structures, whereas rocks of the Veriyut Formation are subjected to very strong deformations.

It should be taken into account that lower horizons of the Jurassic sequence were subject to geostatic pressures. Assessments of such pressure should be based on the total thickness of Mezozoic sediments comprising about 5 km in this segment of the Greater Caucasus.

Variations in the mineral composition of deformed and undeformed sequences indicate that compositional changes in the clayey rocks are also caused by tectonic deformations, which show a positive correlation with the deformation of host rocks.

Similar comprehensive studies of Lower–Middle Jurassic terrigenous rocks were carried out previously in the Terek River region. Different characteristics of sedimentary sequences and the deformation versus rock age dependence were considered in (Bujakaite et al., 2003). Older rocks exposed in the southern part of the region exhibit the most intense deformations and superposed textures formed after the earlier deformation structures, such as plication cleavage and kink zones. Unlike the Belaya River section, the Lower–Middle Jurassic rocks of the Terek River section were more intensely deformed in the course of two deformation stages, because the Belaya River valley is located farther from the maximal strain zones (Pseashkha and Bzyb-Kazbek).

Similar relationships between mineralogical characteristics and the degree of cleavage are also observed in other regions (Alter et al., 1987). In the Cantabrian zone (northwestern Spain), the degree of rock deformation and cleavage development and the composition of clay minerals regularly change from the outer part of the folded zone to its inner part. In the outer zone, transformations of rocks are weak (correspond to the catagenesis/metagenesis boundary) and are characterized by the development of coarse cleavage. When moving to the inner zone, one can observe a well-defined foliated structure; the grade of rock alteration corresponds to metamorphism of the greenschist facies; and the mineral composition of rocks changes—the content of ordered mixed-layered minerals increases, but the concentration of kaolinite and unordered mixed-layered minerals decreases.

All these characteristics regularly vary along the profile from north to south. The degree of rock deformation higher in the southern part of the profile compared to the northern part. This is confirmed by values of contraction and extension, the distribution of the IC value of illite, and the variation of clay mineral assemblage along the profile. Regularities in the distribution of different characteristics of rocks are similar to those in the Lower–Middle Jurassic rock field of the Terek valley (Bujakaite et al., 2003; Gavrilov et al., 2000).

Similar regularities of variations in the mineralogical and structural–textural characteristics of rocks can be related to a common cause of their formation—the impact of strain on rocks. All the data mentioned above confirm the following opinion of the majority of researchers: the present-day appearance of the Lower–Middle Jurassic terrigenous complex of the Greater Caucasus is related to the SW-oriented compression.

Scenario of the evolution of deformation structures in the study region is as follows. The formation of cleavage at the stage of longitudinal contraction of layers was probably followed by the development of calcite accretion trails in pressure shadows, and the formation of intergrain fibrous veins at the late stage of cleavage formation. Since mineral veins formed at one stage are related to the same fluid and characterized by the same composition, we can suppose that calcite zones in zonal veins were also formed at the late stage of cleavage formation.

At the next stage, the layers were folded, and cleavage zones at the boundaries of layers were refracted or arranged in a fan-shaped style at the hinges of folds. This stage was marked by the formation of quartz veins, the further development of accretion trails, and the deformation of rocks at a temperature up to 350°C. Different orientation of quartz veins with respect to cleavage and earlier calcite veins is likely to be accounted for a different orientation of rock layers relative to the direction of extension or for different orientation of the extension axis in different blocks.

Diversity of strain-related microstructures in rocks suggests their deformation in several pulses of compression and extension rather than in one stage. These pulses fostered the appearance of several generations of structure. This conclusion is consistent with the data on Lower –Middle Jurassic rocks of the Greater Caucasus reported in (Gavrilov et al., 1999). Similar investigations of rock sequences on the northern slope of the Greater Caucasus in the Terek River profile also show that rocks were repeatedly subject to stresses. The stage of maximal impact is recorded in K–Ar isotope systems (Bujakaite et al., 2003).

CONCLUSIONS

In general, the Lower–Middle Jurassic rocks of the Belaya River section are less deformed than coeval rocks in the Central Caucasus (the Terek River section).

All the studied rocks were involved in a common process of stress-related transformations. The degree of rock transformations increases along the profile from north to south.

The event responsible for these transformations recorded in K–Ar systems of rocks corresponds approximately to the Middle Jurassic and coincides with the Bajocian–Bathonian compression period.

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