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The Mineralogical, Isotope (K–Ar), Structural, and Textural Features of the Jurassic Siliciclastic Complex in Various Tectonic Environments (Greater Caucasus, Chechnya, and Georgia)

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Abstract—The variations in the structural, textural, mineralogical, and geochemical (isotope) features of Lower to Middle Jurassic siliciclastic sediments along the Chanty-Argun River in Mountainous Chechnya and Georgia are discussed. This profile transects areas with various types of deformed sediments, from the northern comparatively weakly deformed and altered zone, to the southern zone of intense deformation and cleavage. Southward along the profile, these alterations are accompanied by the evolution of clay mineral assemblages, as well as polytypic modifications of micas and their crystallinity index. Increasing intensity of rock alteration and cleavage leads to a change of the K–Ar system, which results in a substantially rejuvenated isotope age of the sediments with a simultaneous increase of their stratigraphic age.

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INTRODUCTION

The Jurassic siliciclastic complex occupies a special position in the structure of the Greater Caucasus because it is the largest association with a thickness that reaches 8–10 km in the axial region of the mountain structure; this complex occupies the largest part of its area. This complex was formed for more than 35 Ma from the Early to Middle Jurassic. However, it is rather homogeneous in lithology; sandy clay sediments are predominant, whereas volcanic sedimentary rocks occur in a sharply subordinate amount and limestone is extremely rare. While occupying a significant area of the Greater Caucasus fold structure, the Lower and Middle Jurassic sequences underwent various deformations in various parts and post-sedimentation alterations that were different in intensity.

The study and reconstruction of these processes within the area of this silisiclastic complex and estimation of their dates are very important in order to determine the formation dynamics of both this thickest sedimentary complex and the structure of the Greater Caucasus as whole. Investigation along geological profiles throughout the Lower to Middle Jurassic sediments across the Caucasus trend from the weakly altered zones to the zones with the most altered rocks is the most efficient method to resolve this problem. Previously, similar studies were carried out along the Terek, Central Caucasus, Belaya, Adygea, and Avar Koisu, Dagestan Valleys (Buyakaite et al., 2002, Gavrilov, 2005; Gavrilov et al., 2012; Kushcheva et al., 2007). Simanovich et al. (2004) performed a similar investigation on the right bank of the Samur River in Southern Dagestan.

Here, we describe the results of structural, textural, mineralogical, and isotope studies along the Chanty-Argun Valley in Mountainous Chechnya and Georgia (Fig. 1). While the characteristics of the sedimentary sequences that are transected by the profile along the Terek River reflect environments of sedimentogenesis and alteration that are common in the central part of the Greater Caucasus in the Digoro–Ossetia and Pseashkho structural-facies zones (SFZ) and the profile along the Avar Koisu River reflects those environments in the eastern part of the Greater Caucasus in the Agvali–Khiva and Metlyuta–Akhtycha SFZ, the profile along the Chanty-Argun River is intermediate and transects sediments in the region that is transitional between them. However, we note that the lithological complexes of the sedimentary sequences in the region of the Chanty-Argun River are attracted to those in the Eastern Caucasus.

The previous study of the Lower to Middle Jurassic complex of the Greater Caucasus showed that its rocks were post-diagenetically transformed due to the effects of high temperature and geostatic pressure; however, in the first place, these transformations were caused by pulses of intense stress that resulted in deep mineralogical transformation and cleavage. Gavrilov and Tsipurskii (1987), Gavrilov et al. (1992, 2012), Buyakaite et al. (2003), Gavrilov (2005), and Kushcheva et al. (2007) reported that transformation of

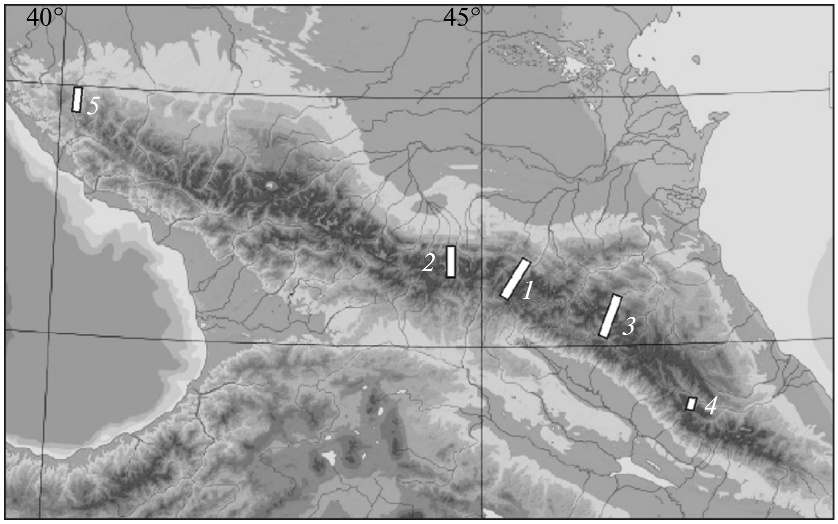


Fig. 1. The physical map of the Greater Caucasus and the sections (geological profiles) across the Jurassic siliciclastic sediments for which the K–Ar age, as well as the structural, textural, and mineralogical characteristics, were determined. (*1*–*5*) Profiles: (*1*) Chanty-Argun River, (*2*) Terek River, (*3*) Avar Koisu River, (*4*) right bank of the Samur River, (*5*) Belaya River.

these sediments consisted of changing clay mineral assemblages and polytypic modifications and the crystallinity index of micas. The formation of cleavage was accompanied by the dissolution of primary terrigenous minerals and crystallization of new minerals with the redistribution of chemical elements or their compounds that was accompanied in particular by changes in the relationship of parental and daughter isotopes. Rearrangement of isotope systems causes new setting of the radiological clock, which allows estimation of the period of post-diagenetic rock transformation with some uncertainty.

Previously, the problem of the evolution of isotope systems in the Lower to Middle Jurassic clay rocks was illustrated by other sediments in the western, central, and eastern parts of the Greater Caucasus. It was established that in these zones, where the sediments are not strongly altered, the isotope age is notably older than the stratigraphic age, reflects to a certain extent the age of rocks in the provenance, and corresponds to the Late and occasionally Middle Paleozoic. In contrast, in cleavage zones, the rocks are rejuvenated for a few tens of millions of years and sometimes for more than 100 Ma as compared with the stratigraphic age.

Different alteration intensities of sequences in various zones were established. Determination of the nature and dynamics of post-diagenetic transformation of the Jurassic siliciclastic complex over an extensive area will allow the modeling of its formation, which in turn will specify the scenario of the development of the Greater Caucasus.

OBJECT AND METHODS

The general type of deformations and the nature of the deformational structure and textures were determined in various parts of the profile while studying the Jurassic siliciclastic complex. Approximately 90 specimens were collected from the sequences with ages from Late Pliencbachian to Bathonian for comprehensive study.

The phase compositions of fractions of less than 0.001 mm of clay rocks were determined using oriented samples and powders of these specimens on DRON-2 (Cu $K\alpha$ radiation) and D8 Advance Bruker diffractometers. Micas, kaolinite, and chlorite were found in various proportions. Integer-valued or close to integer-valued reflections 00*l* with $d(001) \approx 10$ Å that are typical of micas were found in the X-ray diffraction patterns of oriented natural samples. The first basal reflection 001 in the X-ray diffraction pattern of some samples that were saturated in glycerin shifts to higher angles, which indicates expandable layers (2 : 1) in micas (Drits and Sakharov, 1976). According to the classification of micas with different numbers of expandable layers (Omelyanenko et al., 1982), the micas that we studied are divided into two groups: sericites containing less than 5% of expandable layers, and hydromicas, in which the number of expandable layers ranges from 5 to 10%, reaching 15% in some samples.

Some samples were examined with oblique-texture electron diffraction (OTED) to establish the probable distinctions of polytypic modifications of micas and determination of the unit cell dimensions. The samples that contain chlorite were processed to remove this constituent. The examination was performed on an ER-100 electron diffractometer that was operated at the acceleration voltage of 100 kV. The pattern that

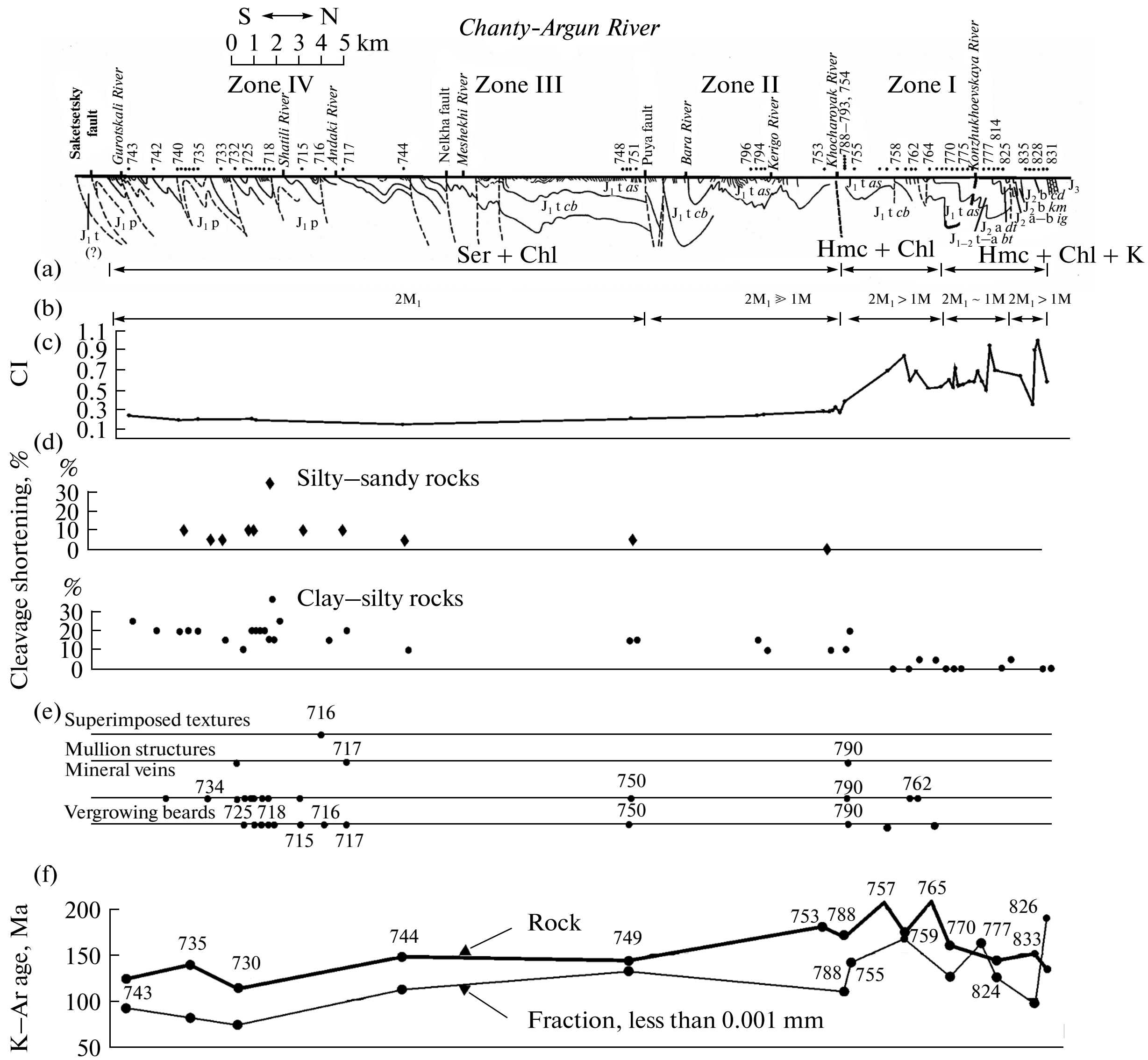


Fig. 2. The geological profile along the Chanty-Argun River, after Gushchin and Panov (1983), and the textural, structural, mineralogical, and geochemical characteristics of the Jurassic siliciclastic sediments. (a) Assemblage of clay minerals: hydromica (Hmc), kaolinite (K), chlorite (Chl), and sericite (Ser); (b) distribution of the 1M and $2M_1$ polytypic modifications of micas; (c) crystallinity index of clay minerals (CI); (d) shortening value, % of cleavage for sandy–silty and silty–clay rocks; (e) textures, structures, veins, and overgrowing beards that resulted from intense post-diagenetic processes; (f) the K–Ar age of rocks determined from the bulk rock (heavy line) and the fraction of less than 0.001 mm (hairline). The numerals are the numbers of samples.

was obtained, which was interpreted by S.I. Tsipursky, revealed 1M and $2M_1$ polytypic modifications of micas whose relationship is substantially variable in different parts of the profile (Gavrilov, 2005).

The crystallinity of the layered silicates is variable in the various parts of the profile. The crystallinity index (CI) is often used to estimate this parameter. Despite some problems (Frey, 1970; Drits et al., 1997) for a great number of measurements, CI shows a statistically reliable pattern, which adequately reflects the variations in the layered silicates. We have determined the CI of micas with a 10 Å half-height peak width as °Δ 2θ (Kübler, 1964; Kisch, 1991). The results that we obtained are given in Fig. 2c.

Quantitative indices are required to estimate the intensity of cleavage due to its nonuniformity within the profile (Talitskii, 1989; Gavrilov et al., 1999; 2012). The first signs of cleavage that were observed in thin sections as separate cleavage zones occuring at a 5–7% shortening deformation; a distinct structure is observed in the rock at 10–15%, and cleavage occurs in the whole rock and appears quite perfect at 20–25%. This scale has been used for approximate estimation of rock deformation at the level of mineral grains (Fig. 2d).

The K–Ar method was the most informative way to reveal the evolution of isotope systems owing to strong alteration. Both the clay fraction of less than 0.001 mm that was selected from the rocks and the rocks themselves were measured. The content of radiogenic Ar was measured from the 60–90 mg samples by the isotope dilution method on a MI 1201IG mass-spectrometer. The samples were melted at 1600–1800°C. The purity of the mono-isotope ^{38}Ar tracer was 97.5%. The uncertainty of the single measurement of the radiogenic Ar content did not exceed ±1%. The proportion of atmospheric Ar was within the range of 5–10%. The uncertainty of the calculated age was 2–2.5%; it was verified by the convergence of repeated measurements of the samples and the reproducibility of the standard measurements. The constants $\lambda_\alpha = 0.581 \times 10^{-10}$ year^{-1}, $\lambda_\beta = 4.962 \times 10^{-10}$ year^{-1}, and ^{40}K/K = 1.167×10^{-4} (Steiger and Jäger, 1977) were used in the calculations. We note that Buyakaite et al. (2002) and Simanovich et al. (2005), who discussed the problem of the alteration of the Early to Middle Jurassic rocks in the Caucasus, investigated the behavior of the Rb–Sr system and showed good convergence of the isotope ages that were determined using these two methods.

STRUCTURAL-FACIES ZONATION, CHARACTER OF BEDDING, AND DISLOCATION DEGREE OF THE LOWER AND MIDDLE JURASSIC SEDIMENTS

The Early and Middle Jurassic paleobasin of the Greater Caucasus was characterized by structural-facies zonation (Leonov, 1966; Panov, 1988; *Yura...*, 1992; Panov and Lomize, 2007). Various structural-facies zones are distinguished by their section type, which implies its stratigraphic volume, completeness of sediments, the mineralogy and chemical composition of the sediments, and its thickness. The zones that were recognized on this basis correspond to certain paleotectonic units of the Greater Caucasus Trough: to the axial trough, i.e., to the northern and southern walls in the Early Jurassic and Aalenian and to the trough system of the northern and southern slopes and the belt of central anticline rises that separate them in the Bajocian and Bathonian (Panov et al., 1988). The structural-facies zones (SFZ) in the western and eastern parts of the Northern Caucasus slightly differ from those characteristic of the Eastern Caucasus segment.

The section along the Chanty-Argun River is located between previously studied profiles along the valleys of the Terek (Central Caucasus) and Avar Koisu (Eastern Caucasus) rivers. The paleogeography of these regions differs. In the Liassic to Aalenian, the Digoro–Ossetia SFZ area within the Central Caucasus segment was a stepped slope of a basin ranging from shallow shelf sediments in the north to comparatively deep-sea sediments in the south. The Pseashkho SFZ corresponded to the northern framework of the axial basin trough. The sedimentary sequences in the eastern (in the first place Dagestan) part of the basin were formed under effects of a large river whose delta complex extended for more than 200 km from SE to NW. The proximal part of the delta front determined the sedimentation within the Agvali–Khiva SFZ and the distal part determined it in the Metlyuta–Akhtychai LTZ.

In general, the character of the Lower and Middle Jurassic sediment sections within the Chechnya part of the basin is intermediate; nevertheless, they are attracted to those in the Eastern Caucasus because lithologically similar regional formations of the Eastern Caucasus that are well defined in the Dagestan sections are identified here. The Lower and Middle Jurassic sediments in the region of the Chanty-Argun River are predominantly deeper-sea facies than those in the section of the Avar Koisu area, viz., the Assab and Igatly Formations (Fig. 3) are represented by distal delta front sediments. The content of psammitic fraction decreases, whereas the thickness increases; thus, the general cyclicity is retained (Frolov, 1965; Panov and Gushchin, 1993; Gavrilov, 2005).

During the Early Bajocian, the delta was repositioned for a distance of few hundred km toward the north because of tectonic rearrangement of the region and strong transgression (Gavrilov et al., 1989; Gavrilov, 2005). The Bajocian–Bathonian sequence consists of marine clay–silty rocks (Fig. 3), which are unconformably overlapped by the Upper Jurassic carbonate sequence.

The geological profile along the Chanty-Argun River intersects from north to south: the Agvali–Khiva SFZ corresponds to the northern trough shoulder, while the Metlyuta–Akhtychai SFZ is the northern framework of the trough. In the opinion of D.I. Panov, the system of large tectonic sheets that belong to the system of the Main Caucasus Ridge, which may have carried to the formation of the Greater Caucasus paleotrough.

Dislocation of the layers notably increases along the profile from north to south. Considering the variable character of the deformations, the cleavage degree of the rocks, the distribution of clay mineral assemblages in the sediments, and the crystallinity index of the mica polytypes, the profile is divided into four zones (Fig. 2). The listed parameters are similar in quality and values within the zone and change in the neighboring zone. Within zone I, the layers are broadly open folded and complicated by faults; only in its northernmost part do the Bajocian and Bathonian sediments form a narrow N-dipping steep monocline. In its deformation character, this zone is closer to the profile along the Terek River than that along the Avar Koisu River, where the layers form a broad gentle dipping monocline. Southward, zone I extends to the mouth of the Khacharoiakhk River, a right tributary of the Chanty-Argun River.

Toward the south the following zones are identified: II before the Pui fault, III between the Pui and

Nelkha faults, and IV south of the Nelkha fault. The dislocation degree of the layers within zone IV is greatest; small (from a few meters to a few tens of meters) folds, predominantly with carinate hinges, are developed here; inclined and rare inverted folds are also found. The sequence is broken by faults with variable amplitudes and contains Alpine-type veins filled with quartz and chlorite.

The rock type also evolves from north to south. The clay rocks within zone I are light and dark gray mudstones, frequently with a brownish tint that depends on the content of organic matter. The sedimentation textures and structures are clearly distinguishable. Solid shales that are broken and split into flattened plates along cleavage planes are abundant in the strongly folded and cleaved zones (especially within the Middle Liassic sequence). Shales are dark gray, frequently almost black. The sedimentation structures are hardly recognized in the cleaved shales.

Mudstones and shales substantially differ in the impact of the post-diagenetic processes and are end members of clay rock series with transitional varieties between them.

THE DISTRIBUTION OF CLAY MINERALS IN THE LOWER AND MIDDLE JURASSIC SEDIMENTS

The distribution of clay minerals within the Lower to Upper Jurassic section along the Chanty-Argun River valley is quite regular and is similar to that within the eastern and western sections. Here, the assemblages that were mainly formed at the sedimentation stage of the Toarcian to Bathonian sediments are retained within zone I, which corresponds to the northern Agvali–Khiva SFZ; the composition of the sediments to a great extent depended on that in the provenance. As demonstrated in Fig. 2a, the hydromica–chlorite–kaolinite assemblage is predominant here. Kaolinite within this section is abundant only in the sediments of the Batlukh Formation; it is minor in the Datuna Formation, while a comparatively small amount was found in the Upper Bajocian and Bathonian siltstones. The amount of chlorite and micas within the section is also variable, as it was established by the relationship of the 7 and 10 Å reflection intensities. The highest content of mica minerals is observed in the lower half of the Batlukh Formation, whereas within the Bajocian and Bathonian sequences, the amount of micas decreases to less than 50%, similar to that along the Avar Koisu River (in deeper parts of the section such relationship was not found).

Mineral assemblages that resulted from the alteration and recrystallization of primary siliciclastic matter are developed in the southern part of the profile (southern Agvali–Khiva and Metlyuta–Akhtychai SFZ, zones II–IV). Towards the south, kaolinite disappears; a number of expandable smectite layers in

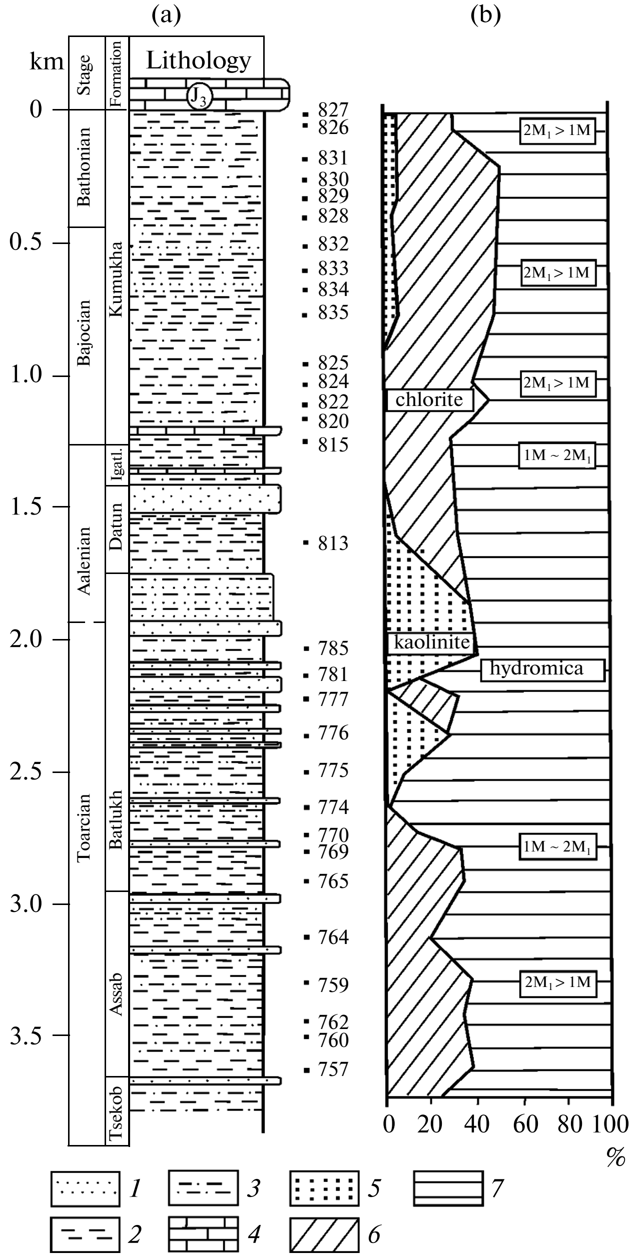


Fig. 3. (a) The lithostratigraphic column of the Toarcian to Bathonian sediments of zone I and (b) the distribution of clay mineral assemblages. (*1*) Sandstones, (*2*) clay sediments, (*3*) clay–silty sediments, (*4*) limestones, (*5*) kaolinite, (*6*) chlorite, (*7*) micas.

hydromicas decreases; a sericite–chlorite assemblage that typical of the most part of the profile occurs.

The distribution of mica polytypes is also distinct. Ten samples from various parts of the profile were examined using electron diffraction (Table 1, samples 730–833; the examination was performed by S.I. Tsipursky). Two mica phases, 1M and $2M_1$, in different relationships are pervasive in siltstones beyond the cleavage zone; cleaved shales contain only $2M_1$

Table 1. The unit cell dimensions of the micas in the Lower to Middle Jurasic sediments in the section along the Chanty-Argun River

Number of the sample	Unit cell dimensions				Polytype modifications of micas and their relationships		Stratigraphic age of the sediments where the samples were collected
	a, Å	b, Å	c, Å	β, deg			
826	5.21	9.03	20.14 10.23	95.7 101.27	$2M_1$ 1M	$2M_1 > 1M$	Bathonian
833	5.21	9.03	20.1 10.21	95.77 101.17	$2M_1$ 1M	$2M_1 > 1M$	Bajocian
824	5.21	9.02	20.1 10.18	95.68 101.26	$2M_1$ 1M	$2M_1 > 1M$	
815	5.21	9.02	20.15 10.23	95.7 101.4	$2M_1$ 1M	$2M_1 \sim 1M$	Aalenian
770	5.21	9.02	20.14 10.23	95.77 101.32	$2M_1$ 1M	$2M_1 \sim 1M$	
759	5.21	9.02	20.15 10.24	95.7 101.22	$2M_1$ 1M	$2M_1 > 1M$	
778	5.21	9.02	20.15 10.21	95.79 101.26	$2M_1$ 1M	$2M_1 \gg 1M$	
775	5.21	9.03	20.08 10.19	95.72 101.18	$2M_1$ 1M	$2M_1 \gg 1M$	Toarcian
735	5.21	9.03	20.12	95.75	$2M_1$		Upper Pliensbachian
730	5.21	9.03	20.1	95.75	$2M_1$		

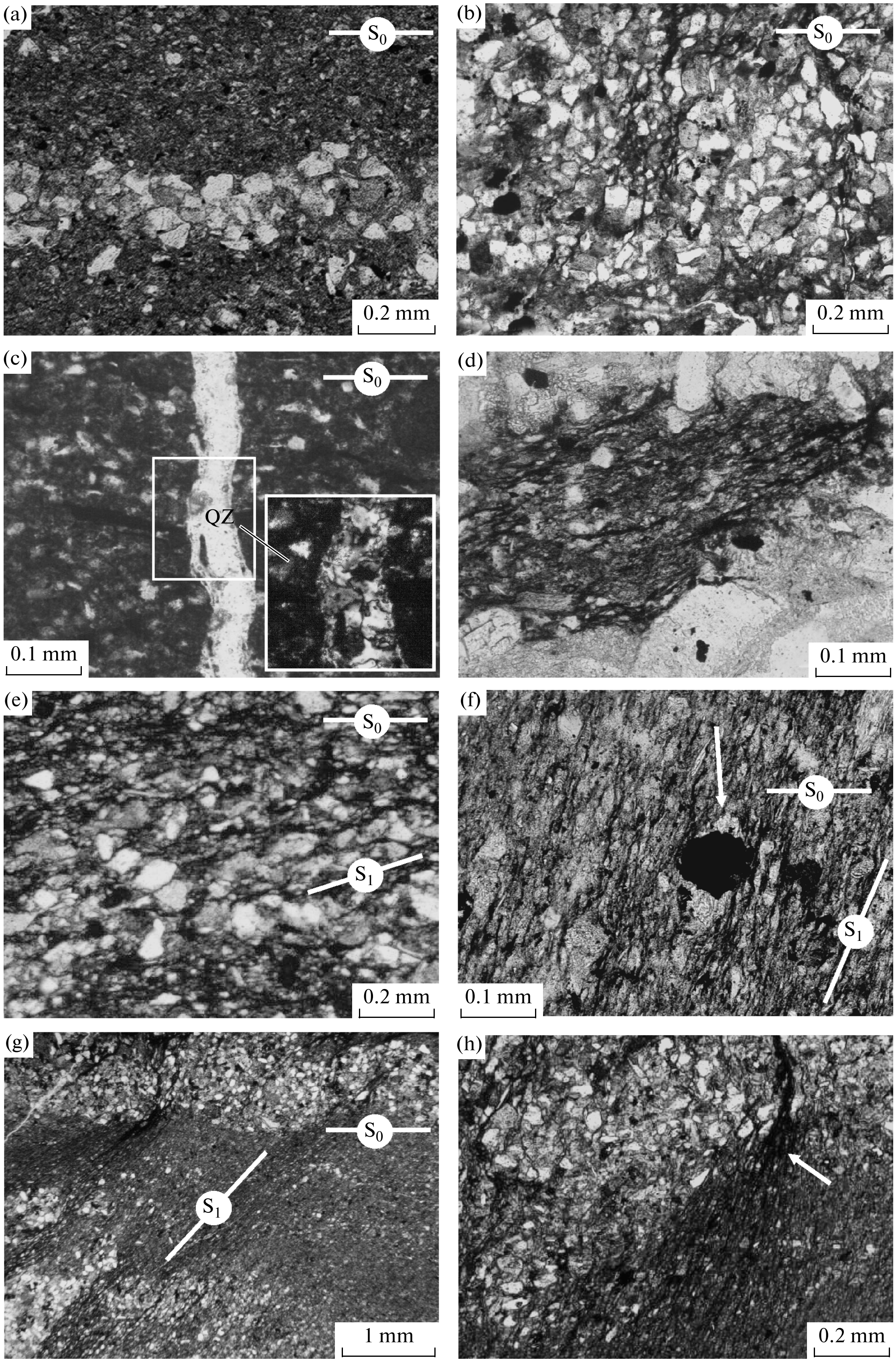
mica of variable composition, which is consistent with the X-ray diffraction patterns. d(001) exceeding 10 Å is highlighted in the X-ray diffraction patterns of some samples, which may indicate NH_4^- that is partly replacing K in the interlayer.

The crystalinity degree of the micas evolves regularly along the profile from north to south. The crystallinity index (CI) within zone I ranges from 0.5 to ~1.0. However, in zone II the CI decreases to 0.3 and in zones III and IV it decreases to 0.19–0.2; in one sample it is 0.15. The area of abrupt changes of clay minerals coincides with the zone of a rapid increase in the degree of cleavage.

Thus, the distribution of clay minerals in the Lower and Middle Jurassic section along the Chanty-Argun River is similar to that identified in North Ossetia and

Fig. 4. Photomicrographs of the rocks from various parts of the profile with different degrees of deformation textures. (S_0) Orientation of bedding, (S_1) orientation of intergrain cleavage, (S_2) orientation of intimate crumpling cleavage, (Qz) quartz, (Chl) chlorite, (Ser) sericite. (A) Deformation textures of rocks in the northern and southern parts of the profile. Zone I: (a) undeformed rock (sample 829), (b) value of shortening deformation less than 5% (sample 826), (c) quartz stringer (sample 759); zone II: (d) value of shortening deformation of 10%, zoned cleavage (sample 753), (e) the same, 15% (sample 795), (f) the same, (sample 790), (g) zoned layer-by-layer cleavage and initial stage of mullions (sample 790), (h) cleavage clusters at the boundary between layers (sample 790). (B) Deformation textures of the rocks in the southern part of the profile (zone IV); bedding is horizontal: (a) layer-by-layer cleavage is accompanied by break of the cleavage zones at the boundary of layers, value of shortening deformation within the sandy and silty intercalations is 5 and 20%, respectively (sample 717), (b) value of shortening deformation of 25% (sample 723), (c) cleavage clusters at the boundary of layers (sample 717), (d) cleavage mullions (sample 727), (e) texture of intimate crumpling cleavage S_2 superimposed onto intergrained cleavage (sample 716), (f) intimate crumpling cleavage S_2 in the crest of a microfold (sample 716), (g) zoned overgrowing beards in the pressure shadows adjacent to large pyrite crystals (sample 723), (h) zoned overgrowing beards composed of fibrous crystals of quartz and sericite (sample 717).

A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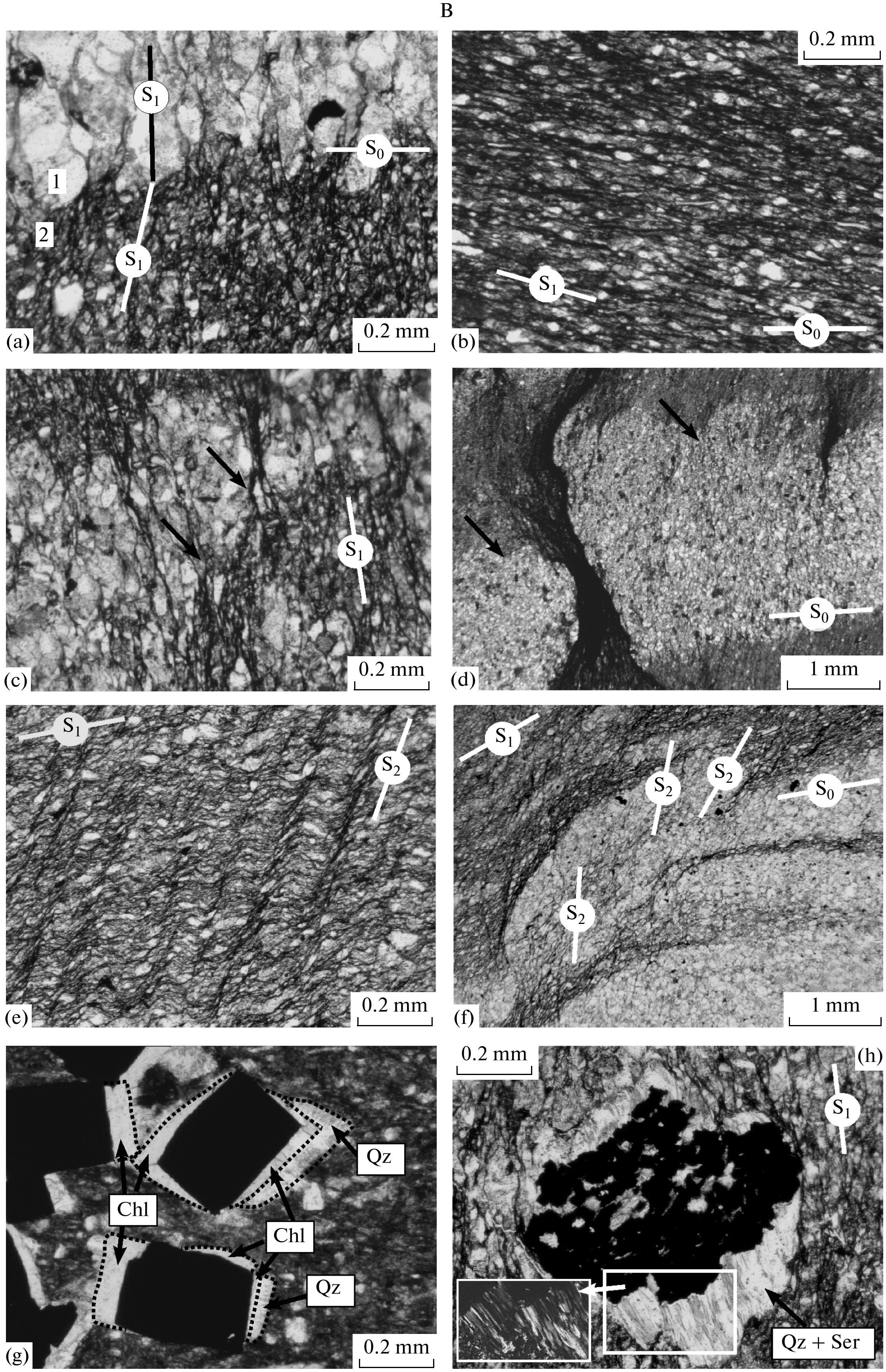
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Fig. 4. (Contd.)

Georgia (the Terek River) and in Dagestan (the Avar Koisu River).

THE CHARACTERISTICS OF DEFORMATION STRUCTURES

The deformation structures in sandstones, siltstones, mudstones, and shales were studied in thin sections. The nature of the deformation structures in the rocks from various zones substantially differs. Deformation structures are absent within the northern zone (zone I, samples 758–777 and 813–831) (Fig. 4A, a); rare dissolution zones with a deformation shortening value of no more than 5% are observed only within the sporadic samples of clay rocks (samples 764 and 826) (Fig. 4A, b). The formation of these dissolution zones is caused by local stress close to faults. Rare thin (<0.1 mm) planar, curved, and branching veinlets filled with isometric crystals of quartz (Fig. 4A, c) that formed as a result of local extension are found within rocks of this zone. The morphology confirms the free growth of crystals in rapidly opened fractures (Kirmasov, 2011).

The zone cleavage is developed almost throughout the rock samples in zone II. The rock is irregularly saturated in cleavage planes; zones with condensed cleavage and cleavage-free zones alternate (Fig. 4A, d). Cleavage is better shown in clay intercalations, whose shortening deformation reaches 10% and sometimes 15% (Fig. 4A, e) and in one sample (790) is up to 20% in separate layers (Fig. 4A, f). Cleavage zones are weaker in sandy layers than those in clay layers.

Talitskii (1989) reported the formation mechanism of the cleavage zones in detail. Different shortening deformation in neighboring layers is caused in the first place by a different level of grain contacts, where strain concentration and dissolution occur. Therefore, when cleavage zones transfer from sandy to clay layers, their number increases, but they become thinner (Fig. 4A, g).

Sometimes, extended cleavage zones separate fragments of more solid siltstone intercalation, where cleavage is absent (Fig. 4A, g). The same pattern can arise at the initial stage of the cleavage mullions, which is a deformation structure that constitutes fragments of coarser-grained intercalations as long bars separated by the cleavage zones (Kirmasov, 2011).

Curved cleavage planes and bunches of these planes are observed at the boundaries of laminas that differ in grain size (Fig. 4A, h). This implies that the cleavage formed at the stage of the pre-fold longitudinal shortening of beds (Talitskii, 1989). In a sample, cleavage zones extend along the axes of small folds without changing in fact their strikes in axes and on limbs. This relationship between cleavage and folds could be caused if cleavage formation continued after folding at the stage of general stress-induced sequence flattening. Other deformation structures, which could be attributed to the same structural paragenesis with cleavage zones, are in particular overgrowing beards in pressure shadows of ore mineral grains. These are symmetrical newly formed mineral aggregates at the opposite margins of inclusions of ore minerals. The overgrowing beards that resulted from local extension (Kirmasov, 2011) are composed of small fibrous quartz crystals and sericite flakes that are oriented parallel to cleavage zones whose length does not exceed 0.05 mm (Fig. 4A, f).

In general, the rocks from zone II are characterized by intermediate shortening deformation (10–15%); however, higher values reaching 20% were noted at the boundary between zones I and II; overgrowing beards, veins, and indications of the initial stage of the mullion formation are identified here.

The shortening deformation of clay rocks and silty sandstones within zone III is approximately 15% and does not exceed 5%, respectively. The cleavage character in the rocks of this zone indicates the cleavage development under the longitudinal shortening of layers. In contrast to the rocks from zone II, deformation structures are observed in all rocks samples of zone III. The cleavage zones were also found within sandy intercalations. This zone is transitional between the two adjacent zones in the character of folds and faults. The rocks within the zone are characterized by intermediate shortening deformation similar to that in the zone II; they can be considered as transitional from relatively weakly to strongly deformed rocks.

The rocks from zone IV are the most intensively deformed throughout the profile along the Chanty-Argun River. The most diverse deformation microstructures are observed here (Fig. 2e). Intense proper cleavage is found in clay rocks with a shortening deformation of greater than 20% (Fig. 4B, b). The deformation structures are more poorly shown in silty sandstones and mudstones. The direction of the cleavage planes within silty and clay interacalations is highly variable, i.e., cleavage is broken at the boundary between layers (Fig. 4B, a), which also indicates a pre-fold origin of the cleavage (Gavrilov et al., 1999). The clusters of cleavage zones are frequently formed via crowding of the cleavage surfaces at the boundaries between layers with different grain sizes (Fig. 4B, c).

Cleavage mullions, which are extended fragments of the siltstone layer that are undeformed inside but displaced relative to each other along the cleavage planes or cleavage bunches (Fig. 4B, d), are common in the rocks of zone IV. The cleavage mullions resulted from irregularly developed cleavage along bedding of layered rocks under stress. In clay rocks, cleavage is dense, whereas within siltstone intercalations it is rare. The further deformation leads to stronger displacement of separate fragments of layers along cleavage planes (Kirmasov, 2011). The cleavage mullions indicate a stronger and longer deformation of these rocks as compared with the rocks in the other parts of the profile.

The rocks that compose this block sometimes show cleavage of intimate crumpling, i.e., cleavage zones separate microlithons within which the earlier texture

Table 2. K–Ar isotope data on the Early to Middle Jurassic bulk rock samples (b) and the fine fraction (f) of clay rocks in the northeastern Caucasus (the region of the Chanty-Argun River)

Number	Number of sample	K, %	Ar, ppm	Age, Ma
1	743b	4.07	0.0203	124
2	743f	4.98	0.0183	92.5
3	735b	2.51	0.01404	139
4	735f	3.89	0.0136	85
5	730b	2.55	0.0117	115
6	730f	4.23	0.0125	75.5
7	744b	2.64	0.0158	148
8	744f	3.06	0.0131	111
9	749f	3.77	0.0205	135
10	749b	2.54	0.01474	143
11	753b	2.59	0.01717	163
12	788f	4.43	0.01997	112
13	788b	2.8	0.02165	189
14	755f	3.8	0.022	143
15	757b	2.52	0.02152	207
16	759b	2.31	0.0162	172
17	759f	4.05	0.028	170
18	765b	2.88	0.025	210
19	770b	3.25	0.0207	157
20	770f	4.33	0.02153	124
21	777f	4.94	0.0329	163
22	824b	2.61	0.015	142
23	824f	4.57	0.02306	125
24	833b	2.16	0.01315	150
25	833f	4.08	0.01578	97
26	826b	4.2	0.02303	136
27	826f	5.2	0.04016	188

of the intergrain cleavage is observed. New cleavage zones (S_2) of various strikes are formed after earlier cleavage zones (S_1) during folding that are caused by a change in the structural geometry of deformation (Fig. 4B, e). The intimate crumpling cleavage is always accompanied by microscopic folding, which results in folding of earlier cleavage zones (Talitskii, 1989).

Cleavage zones are fanned in the hinges of some folds (Fig. 4B, f). The fan-like cleavage zones are zones of intimate crumpling (S_2) that formed before folding; therefore, they are considered to be pre-fold. Intimate crumpling cleavage was not established in all of the samples; therefore, its formation is caused by an elevated strain close to faults or in fold crests. Similar textures were established in similar environments during the study of siliciclastic rocks along the Terek River valley. The intimate crumpling cleavage that is superimposed on the intergrain cleavage in the rocks is caused by the effect of multiple strong stresses on the rock sequence (Gavrilov et al., 1999).

Most of the overgrowing beards that formed in the grain pressure shadows are observed in the rock samples from this block. The abundance and comparatively long length of these deformation structures indicate the greatest deformation value within the studied profile. The overgrowing beards are polymineral and are frequently zoned around large grains of pyrite: inner and outer zones are composed of chlorite and fibrous quartz, respectively (Fig. 4B, g). Some overgrowing beards are composed of fibrous crystals of quartz and sericite (Fig. 4B, h) with an orientation that is close to the strike of the cleavage zones; therefore, they were probably formed in the same stress field and could be attributed to the same structural paragenesis. Different structure of overgrowing beards can indicate variable conditions of rock deformation even within the same block. Therefore, mineralogical zoning does not coincide in various microstructures. Veinlets with various structures and compositions consisting of isometric crystals of calcite and quartz occur within zone IV. Some veinlets that cut both the bedding and cleavage zones indicate that they postdated the cleavage or were formed during cleaving.

As shown in Fig. 2e, the microtextures are widely variable in the rocks of zone IV, which indicates multiple pulses of deformation.

In general, the data that we obtained indicate heterogeneous deformation within the profile from north to south that is towards the axial part of the Caucasus range; the deformation value increases and the texture of the intimate crumpling, zoned stringers, and overgrowing beards in the pressure shadows are observed (Figs. 2d, 2e). The cleavage development started under compression at the initial stage of longitudinal shortening before folding.

The value of the shortening deformation that is determined from the cleavage differs in various rocks. Clay rocks, as a rule, have more cleavage zones than sandy rocks and the observed values of shortening deformation are higher in the former. The cleavage zones become denser and thin at the transition from sandy to clay rocks and form cleavage bunches, as a rule. The deformation of a layered block combines the deformation values at the intragrain, intergrain, layer, and block levels (Talitskii, 1997). Different deformation values at the grain level (according to the degree of intergrain cleavage) results from compensation by heterogeneous deformation at the other levels during folding (the layer level) and displacement along faults of separate blocks (the block level).

The formation of intimate crumpling is caused by changes in the orientation of strain fields during deformation. Stringers of various compositions were formed at the late stage during slight extension. Deformation occurred during several stages affecting sediments from various parts of the profile. The rocks from the south part of the profile are the most deformed as a result of multiple stresses.

RESULTS OF ISOTOPE STUDY

The isotope data are given in Fig. 2f and Table 2. Parameters that are typical of clay minerals indicate weak post-diagenetic alteration of the Lower and Middle Jurassic clay sediments in the northern part of the profile (zone I). Therefore, isotope dating of the rocks corresponds to the age of provenance to a great degree. As is seen from Fig. 2f in accordance with the data from Table 2, the oldest K–Ar age is typical of the Toarcian–Aalenian part of the zone I section, which exceeds 200 Ma in some samples; the isotope age of the Bajocian–Bathonian sediments is younger.

The isotope age decreases regularly in zones II, III, and IV, which are located southwards; the youngest ages were determined in the southernmost part of the profile (75–92 Ma in fractions of less than 0.001 mm, Fig. 2f). We emphasize that the isotope ages that are measured in the fractions are, as a rule, younger than those in the bulk samples (except for occasional samples) throughout the profile.

DISCUSSION

The data that we obtained show substantial differences in the intensity of rock alteration within the profile across the Jurassic siliciclastic sequences in the mountainous part of Chechnya and Georgia. Geostatic pressure, temperature, and stress caused this alteration. Buyakaite et al. (2003), Gavrilov (2005), and Gavrilov et al. (2012) discussed the effect of these factors on the mineralogical, geochemical, structural, and textural features of Jurassic rocks.

The Upper Toarcian to Bathonian sediments with a thickness of approximately 4 km cropped out in the northern part of zone I. Further, they were overlapped by the Upper Jurassic, Cretaceous, and probably Lower Paleogene sequences with an approximate thickness of 3.5 km. Here, geostatic pressure and temperature were crucial in the post-diagentic process without a developed cleavage or with its weak manifestation. As mentioned, assemblages that contain hydromica with a variable content of smectite interlayers (up to 15%), kaolinite, and chlorite are retained in this zone. An impurity of smectite was suggested to occur in the sediments initially, but it was not retained as an individual species. Diverse mineral assemblages indicate the retention of primary assemblages that originated during sedimentation in this zone. These factors probably caused the increasing content of the $2M_1$ polytypic modification of micas in the southern part of the zone as compared with that of polytype 1M. However, no drastic lithological and geochemical changes are observed there.

In contrast, the rocks were substantially transformed within the zones to the south: cleavage increased; clay minerals are represented by a uniform mica + chlorite assemblage; expandable interlayers nearly disappear from the mica (<5%); and the Kübler index decreases, which that indicates an increasing degree of mica crystallinity. The zone of coexisting 1M and $2M_1$ polytypic modifications of mica changes to an area of $2M_1$ modification with a rather rapid transition from the zone of multimineral assemblages to that of a sericite + chlorite assemblage at a distance of several km.

Let us examine the evolution of the isotope age of the rocks along the profile separately. The profile along the Chanty-Argun River transects the Lower and Middle Jurassic sequences that compose the north limb of the Greater Caucasus meganticlinorium; therefore, the stratigraphic age of these sequences decreases northward from the Late Pliensbachian (ca. 190 Ma) to Bathonian (ca. 165 Ma).

In contrast to the stratigraphic data, the isotope dating of the Jurassic rocks indicates that the most ancient K–Ar age is characteristic of the southern zone I (the northern termination of the profile), which reaches 210 Ma in the Aalenian sediments (the Aalenian is dated as 175.6–171.6 Ma). The sediments with some such structural position in the section along the Terek River are of the most ancient K–Ar age, viz., 212–278 Ma, while in the Avar Koisy region it reaches 200–260 Ma.

The younger isotope age of 97–150 Ma is characteristic of the Bajocian to Bathonian sediments in the section along the Chanty-Argun River, which are the youngest in stratigraphy (the Bajocian to Bathonian geochronological interval is dated as 171.6–164.7 Ma). Thus, the isotope age is substantially younger than the stratigraphic age and is comparable with that of rocks in the southern part of the profile that underwent a substantial diagenetic alteration. The young age of 90 Ma was also established in one sample of the Bathonian rocks in the section along the Terek River.

Thus, the evolution of the isotope age shows that the rejuvenated ages are characteristic throughout the southern part (zones II–IV) and northern part of zone I of the profile as compared with the stratigraphic ages. The most ancient isotope ages were obtained in the southern part of zone I (Upper Toarcian) (Fig. 2F).

Polytypic modifications of micas are also distributed within the profile in a non-linear manner. As shown in Fig. 2b, $2M_1$ micas are abundant throughout the southern part of the profile; $2M_1$ micas are dramatically predominant over the 1M modification in the northern and southern parts of zone I; in the middle zone mixed assemblage of micas with approximately identical content of the both polytypes are found.

An evaluation of the composition of the initial sediments that accumulated within the Northern Caucasus segment of the Liassic–Aalenian and Bajocian–Bathonian basins is required to discuss the effects of the post-diagenetic processes on the mineralogical and geochemical characteristics of the rocks.

The Jurassic sediments that were studied along the Avar Koisu River valley (Gavrilov et al., 2012) give the most probable answer. Here, the mineralogical and isotope parameters of silisiclastic sequences differ slightly from those along the Chanty-Argun River: the 1M mica is predominant over the $2M_1$ modification at the section top (including the Bajocian and Bathonian) and the significant isotope age of the rocks is 200–250 Ma. This is due to the existence of a large river delta in the eastern part of the paleobasin from the Liassic to Bajocian. This river transported the main mass of sedimentary material. Although this river migrated northward in the Bajocian–Bathonian, nevertheless it played, as before, a key role in the delivery of sediments to the palereservoir and controlled the character of the accumulated sediments. The isotope data reflects the age of the provenances that are located in the northern areas (Gavrilov et al., 2012).

At the same time, the data that we obtained indicate that the $2M_1$ mica modification is predominant within the Bajocian to Bathonian part of the section, whereas the 1M modification is substantially minor; the isotope age of the rocks is notably rejuvenated. We believe that these changes are due to the following causes.

The structure of the region was rearranged during the Bajocian; in the axial part of the Greater Caucasus a system of rises formed that led to the breakup of the unified basin into southern and northern parts. Therefore, the new provenance areas of silisiclastic material arose in some regions of the northern paleobasin. In particular, this was embodied in the appearance of a different assemblage of accessory minerals in sandy–silty rocks (Bezborodov, 1961). These rises were composed of pre-Bajocian predominantly Liassic siliciclastic sediments, which were substantially post-diagenetically cleaved by that time. Erosion of these rises and the transport of sedimentary material into the reservoir resulted in the predominance of the $2M_1$ mica in sediments. However, the Bajocian–Bathonian $2M_1$ hydromicas contain some expandable interlayers and are poorly crystallized as compared with those from the rock within the cleavage zones (Gavrilov et al., 1999; Gavrilov, 2005). The substantial rejuvenation of the Bajocian to Bathonian rocks that was determined from the isotope study is due to the same cause, as the sediments of the rises from the axial zone of the Greater Caucasus that were transformed due to several pulses of stress were eroded.

As seen in Fig. 2, the major and most drastic changes of the mineralogical, geochemical, structural, and textural characteristics of the Jurassic sediments occur within a comparatively narrow range that is related to one of the large faults (a probable analog of the Suargom faults in the westward areas of the Northern Caucasus). Gavrilov (2005) discussed the probable causes of the origin of these transitional zones in the profile along the Terek River. We suggest the following causes. These large near-Caucasus trending faults were growth faults (landslide bodies could be related to them). The southward areas of the Jurassic trough submerged along these faults during the Liassic and Aalenian. Therefore, the paleobasin slope was stepped with downfaulted southern blocks. Furthermore, this bend of the relief slope acted as fixed stop in the event of stress and the sequences that accumulated in trough south of it were affected by the maximum force of compression, whereas the sequences that were located northward were comparatively weakly transformed. The Pui and Nelkha faults, which are located southward on the profile, appeared to act similarly and caused different degrees of rock alteration in various blocks with the first stress pulses at the initial stage of the Greater Caucasus trough. However, the later pulses of stress caused their deeper transformation, which diffused the lithological and geochemical differences between them and resulted in their unification.

The presented evidence suggests that the studies of cleavage and other secondary textures along the profile on the Chanty-Argun River support its plural formation and consequently, the manifestation of stress pulses. Intimate crumpling of the cleavage within the rocks and the great diversity of microtextures, which are cleavage mullions and different structures of overgrowing beards, indicate multiple deformation pulses. As a result of the several stages of deformation the sediments were transformed to different extents in various parts; the Liassic rocks that were close to the axial part of the paleobasin underwent the strongest and longest-term transformation.

CONCLUSIONS

As a result of a detailed structural, geological, mineralogical, and geochemical study of the Lower and Middle Jurassic siliciclastic complex of the Eastern Caucasus it was established that the dislocation degree of sediments increases from monoclinal or gently folded to the zone of intense folding along the Chanty-Argun River (Chechnya, Georgia) across the area of the Jurassic sediments from north to south. The increasing deformation of sediments was accompanied by the development of cleavage, from its entire absence in the northern part of the profile to perfect cleavage within the sequences of the Metlyuta–Akhtychai SFZ. The strongest cleavage was found within the zones that are close to the great regional faults, which acted over a long period of time and were contemporaneous during the Middle Jurassic.

The intensity of the post-sedimentary transformation increased and the mineralogical and geochemical characteristics of the sediments evolved in the same trend from north to south. The clay minerals were substantially altered; the hydromica + chlorite + kaolinite assemblage that is abundant in the northern part of the profile was altered to a sericite + chlorite assemblage; the swelling out interlayers in micas disappeared; the northern part of the profile is dominated by the 1M polytypic modification, which changes to the $2M_1$ modification in the southern part; and value of the crystallinity index of the micas decreases.

This transformation is accompanied by a change in the K–Ar age. The initial age of the sediments, which reflects the provenance age, is evaluated as Carboniferous to Triassic. The rejuvenation of the sediments due to intense alteration in various parts of the profile reached 100 Ma and more. The Jurassic silicilastic rocks were transformed to a great extent under the effect of stress; multiple pulses of this stress began in the Liassic and continued up to the Cenozoic.

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