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Local Tectonics and Sedimentation in Grabens of the Central Russian Aulacogen (East European Platform)

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Abstract—The influence of local tectonic processes that determined individual development of each particular graben in the Central Russian aulacogen is best reflected in the asynchronous appearance of compositionally different clastic materials in their sedimentary sections, which accumulated with variable intensity. Against the background of the stable composition of the clastogenic framework of the terrigenous Molokovo Group, there are intervals of the sedimentary section from tens to a few thousands of meters thick, where the heavy fraction of sandstones is highly enriched (35–95%) with acute-angled epidote grains. Several features (relative instability of epidote in the hypergenesis zone, angular and fresh appearance of clasts, absence of correlation between the epidote influx and content of the main rock-forming components) imply the formation of epidote anomalies owing to local sources. Analysis of probable geodynamic mechanisms, which could determine development of the Central Russian aulacogen and its grabens, structure and composition of the upper part of the consolidated crust, made it possible to assume that the specific clastic material originates from epidote-rich blastomylonites occurring among metamorphic rocks of the basement in form of strata with anomalous petrogeophysical properties. Comparison between crystals and grains of epidote from blastomylonites and sediments shows that they are characterized by similar habit, sizes, and optical parameters and contain 25–30% of the pistacite component, which is typical of secondary epidote that forms pseudomorphs after biotite and amphibole under conditions of partial melting. Regularities in the distribution of epidote-rich intervals in the sedimentary section are explained by relations between attitude elements of planes of Neoproterozoic normal faults and Paleoproterozoic blastomylonite strata, which served as local sources of clastic material. The same factor also determined the facies properties of sedimentary complexes and structural evolution of sedimentation basins. Crosscutting normal faults stimulated the formation of grabens with the rheologically determined subsidence limit (Molokovo type), particularly, in situations characterized by the gentle attitude of blastomylonite bodies. In such a situation, the subsidence of granitoid rocks into the denser amphibolite substrate was limited by isostatic leveling forces. Under the stationary regional strain field after reaching the subsidence limit, grabens of this type experienced lateral extension, which resulted in the accumulation of regressive sedimentary successions with the irreversible transition from the lacustrine to the fluvial–proluvial facies. Such grabens are characterized by the one-act manifestation of the local source of clastics regardless of the structure development stage. The development of more expedient (in terms of energy) normal faults along blastomylonite strata (Roslyatino type) did not disturb the isostatic equilibrium and resulted in the formation of narrow deep grabens, where depositional environments remained virtually unchanged. The epidote influx was in progress during the entire life of the accommodation space, since progressive deepening of the graben stimulated constant activity of its local source.

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Interrelation between tectonic and sedimentary processes is realized at different hierarchical levels (from the general geodynamic position of sedimentation areas to local structures) and at different stages of the detrital material life (from its mobilization and transport to fixation and transformation into rock). All these diverse long-term or catastrophic ("avalanche") events are realized in similarly different-scale tectonosedimentary systems. The last term is explicitly never used, although precisely it determined spatial sizes and energetics of relationships between tectonic and sedimentary processes.

In this work, the tectonosedimentary system is understood as a sphere of the activity of processes with the obligatory participation of structure formation and sedimentation (Chamov, 2013a). Their cause-and-effect interrelation can be determined as tectonosequential sedimentation or tectonics reflected in sedimentary successions.

Different scales of structure-forming processes determine the hierarchical organization (hierarchy) of tectonosedimentary systems (TSS), which characterize different-size structural-morphological regions. For example, development of tectonosedimentary systems associated with lithospheric plates is determined by global tectonics, while development of provinces and their parts depends on regional tectonics. From the practical point of view, the tectonosedimentary systems controlled by local tectonic processes, which result in the realization of forces provided by the regional stress field corresponding to a particular geological object, are most important. Initiation, development, geometry, and, frequently, composition of local forms is completely determined by local reaction of the geological medium to the tectonic impact of a higher order.

This work is dedicated to some aspects of the influence of local tectonics on structure formation and sedimentation in the Central Russian aulacogen, which represents the Neoproterozoic composite structure in the Central Russian–Belomorian province of the East European Platform (Fig. 1a).

The formation of the aulacogen is owed to large-scale crustal layering due to regional shear movements in the Neoproterozoic (Chamov, 2013b). Local regularities/heterogeneities in the basement structure determined the formation of genetically related and structurally isolated grabens in the strike-slip fault zones (Fig. 1b). Despite the general similarity of processes, each graben represents an autonomous tectonosedimentary system, which is reflected in individual facies features of its sedimentary infill.

Variations in local extension forces determine the formation of grabens of two different structural-facies types. The first type includes wide (tens to a few hundreds of kilometers) and relatively shallow grabens not deeper than 3.5 km, where the sedimentary section reflects distinctly the regressive replacement of facies: gray-colored sediments of deep lakes by fluvial–proluvial subaerial redbeds. Such basins are mostly confined to the southwestern flank of the aulacogen (Fig. 1c). The second type is represented by narrow (a few tens of kilometers) and deep (5 km or, probably, deeper) grabens known only at the northeastern flank of the aulacogen, where sections are composed of alternating deepwater (gray-colored sediments) and shallow-water (variegated sediments) lacustrine facies.

Influence of local tectonics indicating the individual development of each graben is reflected in asynchronous and different (in pattern and intensity) manifestation of the influx of specific clastic material represented by abundant acute-angled epidote grains (Fig. 1c) to sedimentary sections.

Epidote is a chemically unstable mineral readily corroded up to its complete dissolution in the hypergenesis zone, particularly, under the influence of the aggressive fluid. The fresh appearance and angular shapes of examined epidote grains indicate the closeness of its source to the sedimentation basin. Inasmuch as sediments in grabens reflect the initial sedimentation cycle and grabens themselves represent basement structures, only its epidote-rich rocks could serve as such a source. Among metamorphic rocks of the basement, epidote is widespread only in Paleoproterozoic blastomylonites as a rock-forming mineral along with quartz, feldspars, hornblende, biotite, and sphene.

It should be emphasized that the examined Upper Riphean terrigenous rocks are barren of volcanogenic components, which prevents from explaining the appearance of epidote by the hypothetical Late Riphean magmatism.

These considerations led to the assumption that epidote of sandstones originates, probably, from blastomylonites of the basement (Chamov et al., 2010). However, the above work did not interpret this phenomenon in detail at that time and propose tectonosedimentary model explaining the appearance of blastomylonites in the erosion area and the position of epidote-rich intervals in the sedimentary section.

RESULTS

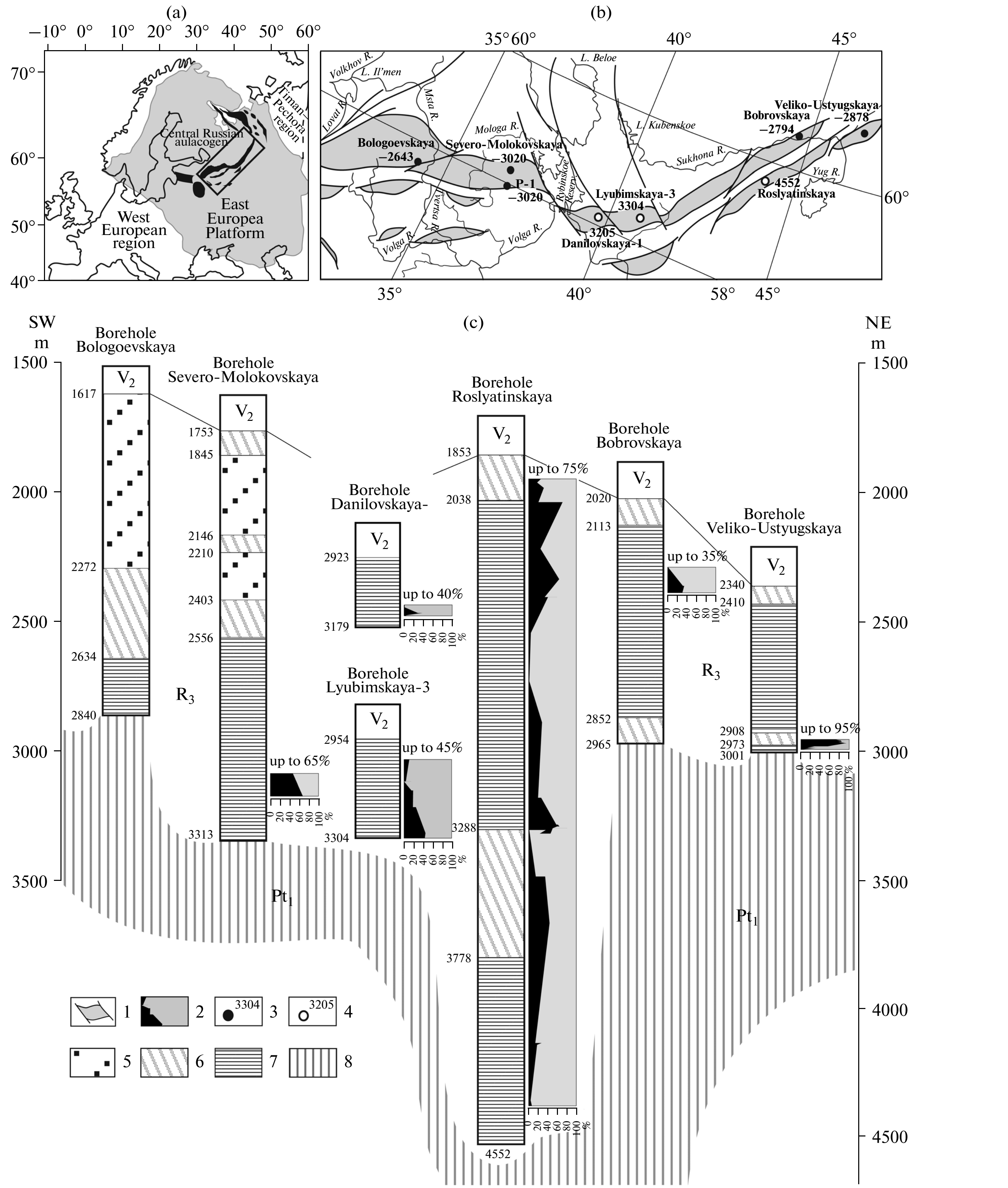
Clastogenic Framework of Sandstones and Epidote Anomalies in Their Composition

The facies types of red- and gray-colored rocks of the Neoproterozoic Molokovo Group, which fill grabens of the Central Russian aulacogen, are similar in composition. They are represented by oligomictic and arkosic feldspar–quartz sandstones, feldspar–quartz siltstones, and variably silty chlorite–hydromica–kaolinite mudstones (Chamov et al., 2010). They also demonstrate a similar polycomponent composition of clayey matter in the sandy–silty rocks and mudstones. The general lithostructural immaturity of sediments and typical presence of fragments of metamorphic basement rocks imply the closeness of clastogenic material sources.

According to the whole-rock chemical analysis of rocks, their composition remained virtually unchanged during the entire period of accumulation of the Molokovo Group, although diagrams illustrating ratios between the main oxides reflect some progressive maturing of material. Noteworthy is the distribution of the Na_2O/K_2O ratio in rocks. Regardless of their type, it varies from 0.85 to 2.00 in basement rocks, remains at the level of 0.5 in the gray-colored sequence, and sharply and regularly decreases upsection in the Vendian and Cambrian interval of the platform sedimentary section beginning from the red-colored sequence.

The heavy faction of gray-colored and variegated arkosic sandstones, which fill grabens of the Central Russian aulacogen, includes similarly moderate concentrations of hornblende, sphene, zircon, tourmaline, staurolite, and ore minerals.

Against the background of the stable composition of the clastogenic framework of rocks in the Molokovo Group, the sharp enrichment of some intervals of the sedimentary section with acute-angled epidote grains, which constitute 35–95% of the heavy fraction of sandstones, appeared to be particularly contrasting. Thickness of such “epidote intervals” varies from a few tens to 2000 m (Table 1, Fig. 1c).


(a)
−10° 0° 10° 20° 30° 40° 50° 60°
70° 60° 50° 40°
Central Russian aulacogen
Timan-Pechora region
West European region
East Europea Platform
(b)
35° 60° 40° 45°
Volkhov R.
L. Il'men
Lovat R.
Msta R.
Mologa R.
L. Beloe
L. Kubenskoe
Sukhona R.
Yug R.
Tversa R.
Volga R.
Rybinskoe Reserv.
Bologoevskaya −2643
Severo-Molokovskaya −3020
P-1 −3020
Lyubimskaya-3 3304
3205 Danilovskaya-1
Veliko-Ustyugskaya −2878
Bobrovskaya −2794
4552 Roslyatinskaya
60°
35° 40° 58° 45°
(c)
SW m
NE m
1500 2000 2500 3000 3500 4000 4500
Borehole Bologoevskaya
V_2
1617 2272 2634 2840
Borehole Severo-Molokovskaya
1753 1845 2146 2210 2403 2556 3313
up to 65%
Borehole Danilovskaya-
2923 3179
up to 40%
Borehole Lyubimskaya-3
2954 3304
up to 45%
Borehole Roslyatinskaya
1853 2038 3288 3778 4552
up to 75%
Borehole Bobrovskaya
2020 2113 2852 2965
up to 35%
Borehole Veliko-Ustyugskaya
2340 2410 2908 2973 3001
up to 95%
0 20 40 60 80 100 %
R_3
Pt_1
1 2 3 3304 4 3205
5 6 7 8

The general regularity in the distribution of detrital epidote within an anomalous interval consists in the increase of its notable concentrations in the heavy fraction in the lower part, their maximum values in the middle part, and gradual decrease in the upper part of its section. Usually, the section includes single such interval, although at least three intervals are observable in the Roslyatino borehole drilled down to the depth of 4552 m (Fig. 1c).

Position of "epidote intervals" in sedimentary sections of grabens can be divided into three types: (1) Molokovo type with such intervals located near the basement (boreholes Severo-Molokovskaya, R-1, Velikoustyugskaya); (2) Bobrov type with intervals located tens to hundreds of meters above the basement (boreholes Bobrovskaya, Danilovskaya-1); and (3) Roslyatino type with the interval corresponding to the entire sedimentary section or its largest part (boreholes Roslyatinskaya, Lyubimskaya-3).

Morphology of Epidote Grains in Sediments

The transparent thin sections demonstrate that epidote grains are represented by virtually unrounded grains, frequently angular with acute edges (Fig. 2).

Comparison between sandstones from different parts of the Molokovo graben reveals no regular changes in the epidote grain sizes from the marginal part of the graben toward its axial part. For example, one field in the thin section of sandstone from the marginal part of the graben includes grains ranging in size from 0.05 to 0.20 mm across (Fig. 2a). At the same time, precisely these rocks contain most angular (spicular) and large (approximately 0.3 × 0.3 mm) epidote grains (Fig. 2b). Rocks from the central and marginal parts of the graben are characterized by the similar degree of roundness and sorting of epidote grains. One field of the thin section includes grains varying in size from 0.07 to 0.35 mm across (Fig. 2c). Poor roundness of grains is also evident from the presence of their elongated specimens 0.10 × 0.25 and 0.10 × 0.35 mm in size (Figs. 2c and 2d, respectively), i.e., grains with the elongation coefficient of 2.5 and 3.5, respectively.

Some epidote grains contain relicts of primary minerals (Figs. 2e, 2f).

Morphology of Epidote Grains in Blastomylonites

In blastomylonites, epidote is formed during the replacement of hornblende or biotite (Fig. 3). Its crystals are from 0.1 to 0.5 mm across and comparable in size with their counterparts in sandstones of the sedimentary cover.

The characteristic well-expressed crystallographic outlines of epidote imply its formation in the partial melting environments. The late formation of epidote is emphasized by rounded or strongly corroded relicts of host protolith minerals in its crystals (Figs. 3a, 3e, 3f, 3h). In addition, epidote grains exhibit tortuous boundaries at their contacts with quartz and feldspars (Figs. 3a, 3c). Such relations indicate the following succession in crystallization: hornblende–biotite–epidote–quartz + feldspar.

Like epidote, sphene represents a newly formed mineral in blastomylonites. Sphene forms usually crystal accumulations along the periphery of amphibole grains, although it may also be represented by isolated rhomboid crystals. Locally, its crystals are located immediately near the newly formed epidote crystals (Fig. 3e).

These observations combined with U–Pb isotopic age of sphene (1750 ± 10 Ma) made it possible to determine the time of dynamometamorphism, which produced the blastomylonites. It is remarkable that the isotope signature of sphene coincides with concordia, which unambiguously indicates that it represents a newly formed mineral (Chamov et al., 2010).

Chemical Composition of Epidote Grains

For testing the assumption that detrital epidote grains from sandstones of the Molokovo Group and blastomylonites are related to each other, their chemical compositions were compared.

With this purpose, fresh euhedral light green epidote crystals were sampled from metamorphic rocks and its sand-sized (0.10–0.25 mm) subeuhedral grains with similar optical properties were extracted from the heavy fraction of sedimentary rocks. The chemical composition of grains was determined in uncovered thin sections with a CAMEBAX microprobe. Each epidote grain was analyzed at three randomly selected points in its marginal and central parts. Table 2 presents the results of the microprobe chemical analysis and calculated formula units.

According to the recommended nomenclature of epidote minerals (Ambruster et al., 2006), which is based on the detailed crystallochemical formula $(A1A2)_2(M1M2M3)_3[Si_2O_7][SiO_4](O4)(O10)$, occupation of positions A_n, M_n by cations and positions O4, O10 by additional anions, the mineral epidote species under consideration belong to the clinozoisite sub-

Fig. 1. The Central Russian aulacogen: (a) position in the Central Russian–Belomorian province of the East European Platform, (b) schematic tectonic structure, (c) structure of the sedimentary cover. (1) Grabens; (2) concentrations of detrital epidote in the heavy fraction of sandstones, %; (3, 4) holes and depths: (3) abandoned in the basement and altitudes of their top, (4) abandoned in the sedimentary cover and relative depths according to drilling; (5–7) Molokovo Group (Neoproterozoic, R_3): (5) red-colored sandstones of rift valleys, (6) variegated sandy–silty–clayey sediments of small lakes, (7) gray-colored silty–clayey sediments of deep lakes; (8) basement rocks (Paleoproterozoic, Pt_1).

Table 1. Epidote concentrations, boundaries of intervals with the heavy fraction of sandstones enriched with epidote, and relative (according to drilling) depths of main interfaces and borehole bottoms

Interval, m	Epidote concentration, wt %	Data sources (geological reports)
Severo-Molokovsakaya (Riphean top 1753 m, basement top 3193 m, hole bottom 3313 m)		
3077–3084	60	L.D. Tsvetkov, N.P. Chamov, V.V. Kostylev, et al., *Detailed Investigation of the Geological Section Recovered by the Severo-Molokovskaya Parametric Hole. Object 065*, Yaroslavl: Nedra, 2001. Measurements of epidote concentrations by mineralogist V.V. Kostyleva (GIN RAN).
3077–3084	62	
3077–3084	45	
3157–3164	60	
3157–3164	65	
3157–3164	62	
3157–3164	60	
Danilovskaya-1 (Riphean top 2923 m, basement top is not recovered, hole bottom 3179 m)		
2894–2899	1	N.A. Usanov, *Results of Exploration Drilling for Oil and Gas in the Danilovskaya Area in 1967–1976*, Yaroslavl: YANGR, 1979. Measurements of epidote concentration in YANGR.
2950–2954	1	
2954–2958	2	
3079–3087	29	
3079–3087	28	
3079–3087	38	
3125–3130	7	
3130–3134	5	
3130–3134	4	
3134–3139	22	
3134–3139	4	
3134–3139	3	
3146–3153	6	
Lyubimskaya-3 (Riphean top 2954 m, basement top is not recovered, hole bottom 3304 m)		
2956–2965	1	N.A. Kagarmanyan, T.S. Eikina, and O.A. Mazur, *Geological Report with Results of Exploration Drilling for Oil and Gas in the Lyubimskaya Area (Yaroslavl Region)*, Yaroslavl: YANGR, 1975. Measurements of epidote concentration in YANGR, VNIGNI, OTsL.
2956–2965	0	
2956–2965	2	
2956–2965	7	
2965–2985	1	
2985–2901	1	
2985–2901	11	
3038–3050	4	
3038–3050	14	
3080–3088	15	
3080–3088	18	
3158–3163	18	
3158–3163	14	
3158–3163	24	
3277–3280	43	
3301–3304	42	
3301–3304	42	
3301–3304	21	

Table 1. (Contd.)

Interval, m	Epidote concentration, wt %	Data sources (geological reports)
Roslyatino (Riphean top 1853 m, basement top is not recovered, hole bottom 4552.1 m)		
1929–1933	24	I.F. Gorbachev, *Report with Results of the Roslyatinskatya Parametric Hole Drilling in the Babushkin Area of the Vologda Region*, Yaroslavl: YANGR, 1973. Measurements of epidote concentrations by mineralogists V.A. Savinova and V.M. Desyatov (YANGR); intervals of 3158–3163 and 3301–3304 m, at VNIGNI.
1942–1945	16	
1961–1964	29	
2020–2022	19	
2022–2024	65	
2200–2206	23	
2316–2321	59	
2384–2388	31	
2384–2388	55	
2388–2392	37	
2523–2525	4	
2711–2715	1	
2867–2881	26	
3158–3163	18	
3158–3163	14	
3158–3163	24	
3266–3271	53	
3266–3271	56	
3271–3275	59	
3271–3275	57	
3271–3275	55	
3275–3280	46	
3275–3280	74	
3275–3280	46	
3301–3304	42	
3301–3304	42	
3301–3304	21	
3284–3289	33	
3284–3289	32	
3284–3289	1	
3465–3468	14	
3465–3468	11	
3465–3468	10	
3465–3468	23	
3468–3471	32	
3645–3648	40	
4109–4112	13	
4109–4112	25	
4116–4120	16	
4334–4338	4	
4371–4338	6	

Table 1. (Contd.)

Interval, m	Epidote concentration, wt %	Data sources (geological reports)
Bobrovskaya-1 (Riphean top 2020 m, basement top 2964.5 m, hole bottom 2991 m)		
2045–2055	2	V.M. Eremina, *Geological Report on Results of the Bobrinskaya-1 Parametric Hole Drilling in the Nyuksenitsa Area of the Vologda Region*, Yaroslavl: YANGR,, 1974. Measurements of epidote concentrations by mineralogists V.A. Savinova and V.M. Desyatov (YANGR).
2045–2055	1	
2277–2292	34	
2277–2292	37	
2365–2377	33	
Velikii Ustyug (Riphean top 2340 m, basement top 3001 m, hole bottom 2991 m)		
2949–2952	89	V.M. Eremina, *Geological Report on Results of the Veliko-Ustyugskaya Parametric Hole Drilling in the Velikii Ustyug Area of the Vologda Region*, Yaroslavl: YANGR, 1974. Measurements of epidote concentrations by mineralogists V.A. Savinova and V.M. Desyatov (YANGR).
2949–2952	73	
2949–2952	80	
2949–2952	95	
2949–2952	77	
2952–2956	86	
2952–2956	80	
2952–2956	98	
2952–2956	93	
2952–2956	1	
2952–2956	88	
2956–2962	90	
2956–2962	66	
2956–2962	75	
2956–2962	58	
2956–2962	79	
2956–2962	52	
2956–2962	60	
2956–2962	95	
2956–2962	82	
2963–2966	99	
2963–2966	96	
2973–2977	63	
2973–2977	37	
2977–2984	22	
2977–2984	42	
2977–2984	40	
2985–2992	2	
2985–2992	30	
2985–2992	14	
2985–2992	3	

Calculated laboratory values of epidote concentrations are rounded up to the nearest whole number. In diagrams (Fig. 1), values are attributed to the center of sampling intervals.

group. Main valences are A1 = M^{2+}, A2 = M^{2+}, and M3 = M^{3+}, where A1 = Ca, A2 = Al, and M3 = Fe^{3+}.

The pistacite component, the value of which reflects its thermodynamic formation conditions, represents an important criterion for determining the origin of epidote (Dawes and Evans, 1991; Pribavkin et al., 2010; Schmidt and Thompson, 1996; Tulloch, 1979). The higher values of this component are characteristic of magmatic epidote.

Table 2 and Figure 4 present the data on contents of the pistacite component in epidote crystals from blastomylonites and detrital epidote grains. It is seen that the grains are characterized by the maximum scatter in contents of this component, although its fields are overlapped within the selection. Both crystals and grains contain 25–30% of the pistacite component, which is characteristic of secondary epidote that forms pseudomorphs after biotite and amphibole (Dawes and Evans, 1991; Pribavkin et al., 2010; Smirnov and Zin'kova, 1993, Tulloch, 1979).

DISCUSSION

As follows from the above data, the substantial enrichment of the heavy fraction in sandstones with detrital epidote does not affect the composition and relative contents of the main rock-forming components in them. Such a property combined with the fresh appearance of fragments implies the existence of

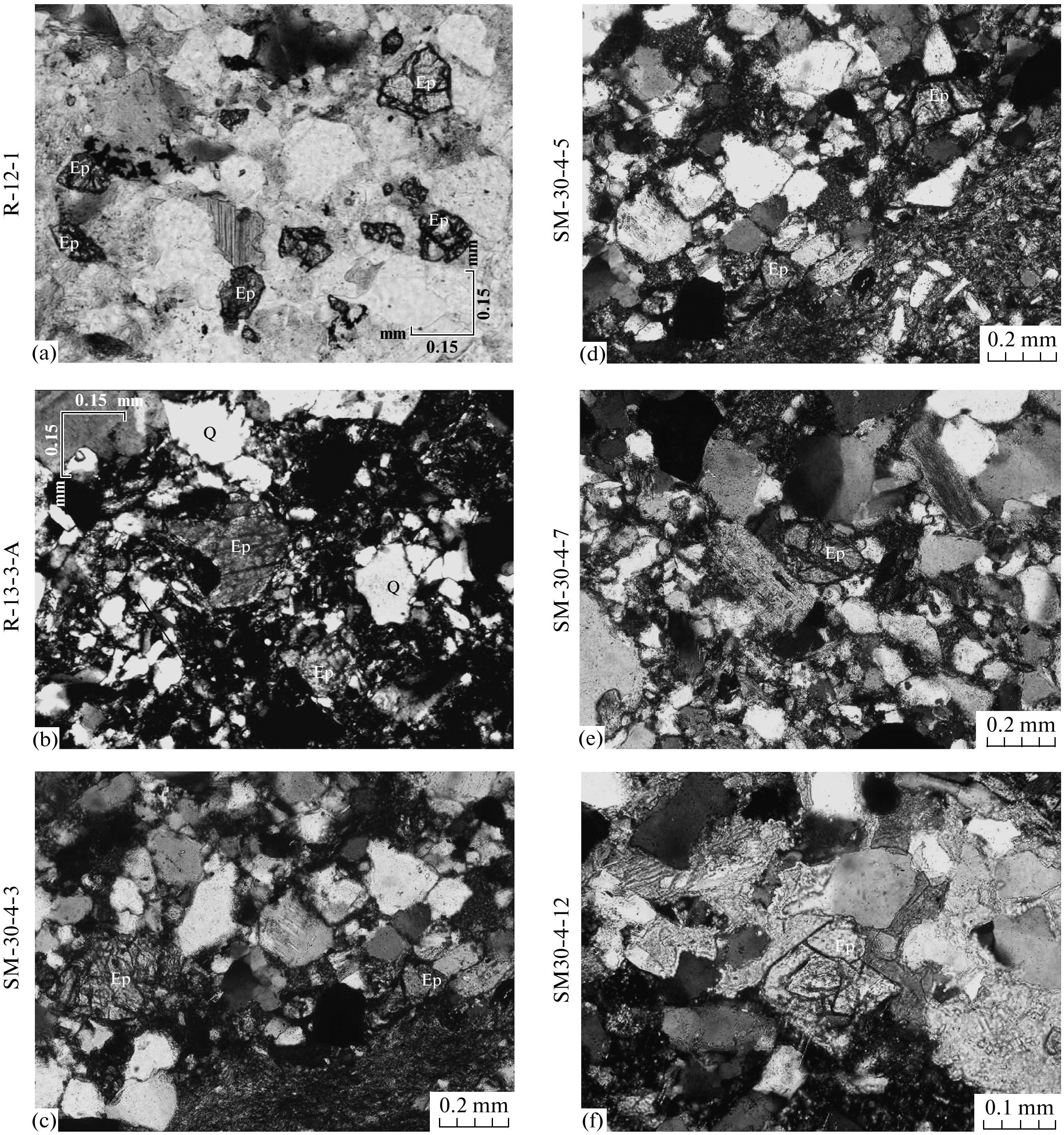


Fig. 2. Epidote (Ep) grains in transparent thin sections of sandstones from the gray-colored sequence of the Molokovo Group (Molokovo graben).
(a, b) Southern wall, Borehole R-1; (c–f) central part of the graben, Borehole Severo-Molokovskaya. Crossed nicols except for (a).

a local source immediately near the sediment accumulation area, which yielded variable contributions to sediments in different parts of the graben. The comparative analysis of epidote crystals and grains in sandstones of the sedimentary cover is consistent with the assumption that it originates from blastomylonites of the basement.

Let us consider conditions, which could be responsible for the appearance of Paleoproterozoic metamorphic epidote-bearing rocks in the erosion zone, where they serve as local sources of detrital material for sediments filling grabens in the Neoproterozoic.

The normal faults determine the formation of the asymmetrical accommodation space during their ini-

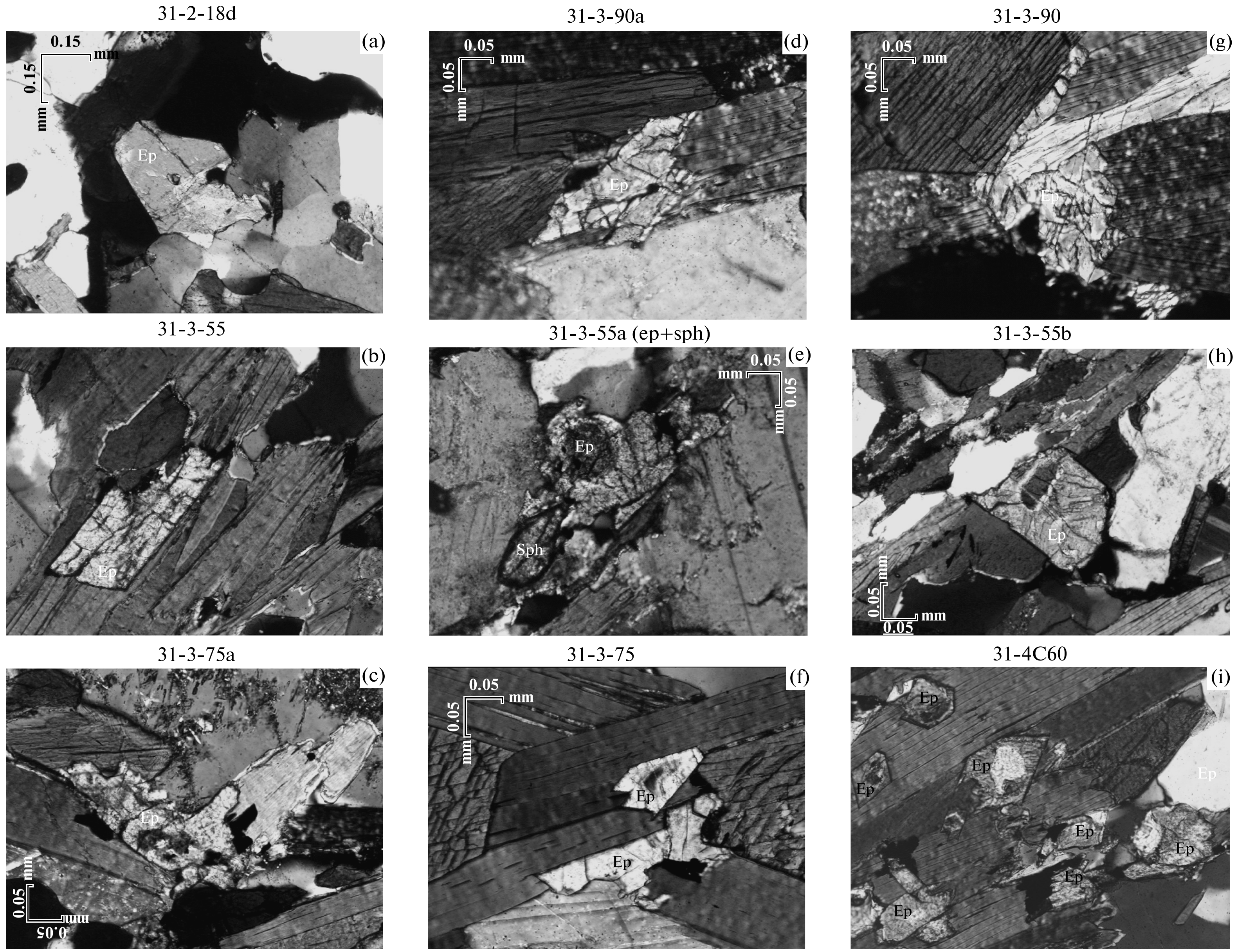


Fig. 3. Epidote (Ep) and sphene (Sph) in thin sections of blastmylonites from the tectonic melange group (Molokovo graben).

Table 2. Chemical composition of epidote (wt %) and crystallochemical coefficients (f.u.)

Oxide	Sandstones						Blastomylonites		
	interval 3157–3164 m						interval 3157–3164 m		
	SM 30/4, 90-100			SM 31/2, 0-10			SM 31/3, 50-55		
	epidote grains						epidote crystals		
	1	2	3	1	2	3	1	2	3
SiO_2	38.73	38.77	38.66	38.38	38.44	38.45	38.89	38.61	38.96
Al_2O_3	23.34	24.35	23.93	24.58	24.33	23.61	23.87	24.35	24.10
FeO	13.40	11.82	12.86	11.83	12.74	13.20	11.86	12.04	12.08
MnO	0.16	0.14	0.11	0.12	0.34	0.12	0.13	0.21	0.17
MgO	0.01	0	0	0	0	0	0	0	0.02
CaO	22.79	22.81	22.73	22.76	22.58	22.73	22.82	23.05	23.02
Sum	98.43	97.89	98.29	97.67	98.43	98.11	97.57	98.26	98.35
Formula units									
Si	3.01	3.00	3.00	2.98	2.98	2.99	3.02	2.99	3.01
Al	2.14	2.22	2.19	2.25	2.22	2.17	2.19	2.22	2.19
Fe	0.87	0.77	0.83	0.77	0.82	0.86	0.77	0.78	0.78
Mn	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Mg	0	0	0	0	0	0	0	0	0
Ca	1.90	1.89	1.89	1.89	1.87	1.9	1.9	1.91	1.9
Ps	28.95	25.62	27.61	25.46	27.09	28.41	26.07	25.97	26.24

Analyses were performed at GIN RAN with a CAMEBAX electron probe microscope, analyst G.V. Karpova. Values are normalized for O = 12, OH = 1.

tiation, where rocks of the downthrown block form a bottom inclined toward the fault, while its plane surface forms a steep slope, which becomes the local source of detrital material in the immediate vicinity to the graben. Inasmuch as grabens represent structural elements of the basement, as it was shown above, only epidote-rich blastomylonites of the basement could become a source of specific clastic material.

It is important to determine the attitude mode of blastomylonites among basement rocks and outline scenarios of their exhumation to the erosion level, which would be consistent with regularities observed in the localization of epidote-rich intervals in the sedimentary section.

Attitude Modes of Blastomylonites

Yu.B. Konoval'tsev was the first to identify blastomylonites at the basement of the Central Russian aulacogen (Chamov et al., 2010; Chamov, 2013). On the basis of the seismic refraction data, he established the presence of crustal layers approximately 400 m thick with anomalously low P-wave velocities (5.0–5.7 km/s). One of such layers was defined at the base of the Molokovo graben, where subsequent drilling to a depth of approximately 350 m recovered migmatized amphibolites, migmatites (enderbites), and blastomylonites of the tectonic melange group. At the southern footwall of the Molokovo graben, the refraction wave method did not revealed the low-velocity refracted wave, which implies the absence of the anomalous layer or significant reduction of its thickness due to erosion.

Analysis of drill core shows that blastomylonites were developed after migmatites, which macroscopically look as typical granitoids. Blastomylonites envelope massive migmatite blocks. Moreover, these rocks demonstrate gradual transitions: gneiss-type structures disappear (become degenerated) as blastomylonites penetrate massive rocks. Directive structures in blastomylonites are characterized by a wide (from low-angle to subvertical) spectrum of dip angles relative to the longitudinal core axis.

By their whole-rock chemical composition, migmatites and blastomylonites are attributed to granitoids associated with collisional processes. In the geodynamic diagram 6Ca + 2Mg + 2Al – 4Si – 11(Na + K) – 2(Fe + Ti) (Batchelor and Bowden, 1985), data points of compositions of these rocks form a continuous "cloud" extended from the field of pre-plate collision to that of the postcollisional uplifting (Chamov et al., 2010). Inasmuch as data points of rocks within the "cloud" (in this and other diagrams) are over-

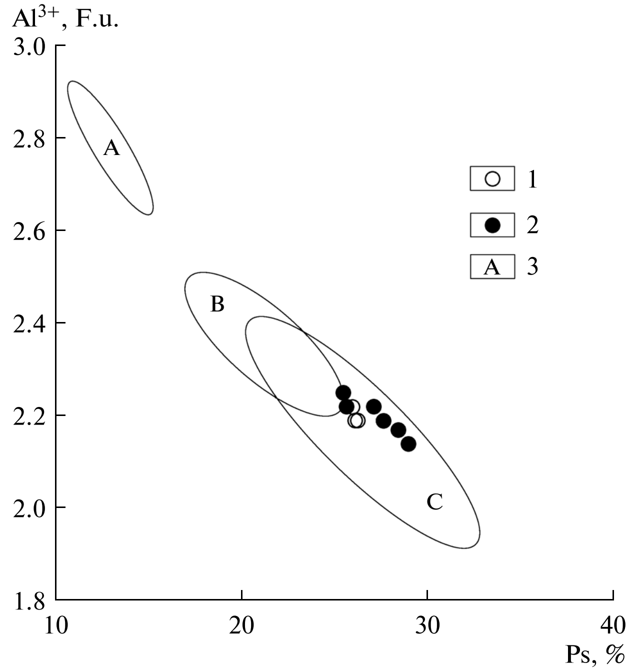


Fig. 4. The pistacite component–Al^{3+} diagram. (1) Epidote in blastomylonites; (2) epidote in sediments; (3) fields of characteristic values, after (Dawes and Evans, 1991; Evans and Vance, 1987; Pribavkin et al., 2009; Smirnov and Zin'kova, 1993; Tulloch, 1979): (A) epidote and clinozoisite after plagioclase, (B) porphyric epidote phenocrysts, (C) epidote after biotite and amphibole.

lapped and demonstrate no trend in the transition from migmatites to blastomylonites, dynamometamorphism that stimulated blastomylonitization is likely an isochemical process.

Genetic Model of Blastomylonites

The presented data offer opportunity to reveal several principal regularities in the structure and structural position of blastomylonites. The main important are the similarity of chemical compositions and the close spatial association of migmatites and blastomylonites. The presence of anomalous intervals composed of blastomylonites suggests high-amplitude movements of crustal blocks in the past.

The available data allow these movements to be related to postcollisional leveling of intracrustal heterogeneities, which resulted from the melting and migmatization of amphibolites (Chamov, 2005, 2013). The appearance of granitoid rocks with a density of approximately 2.9 g/cm^3 at depth among dense ($\geq$3.0 g/cm^3) amphibolites provokes their ascending movement. The superposition of shear deformations induced, for example, by disintegration of the collisional structure on this process results in the appearance of peculiar rock complexes known as metamorphic core complexes (MCC). The core proper is composed of migmatites, while its external framing located in the zone of maximum dynamic stresses (detachment) at the interface between tectonic slices with different values competence is transformed into blastomylonites owing to dynamic metamorphism in the partial melting environments.

The formation of blastomylonites in the metamorphic core complex is evident from mineral parageneses observable in thin sections, where epidote behaves as a late magmatic mineral. Such mineral associations are established among Cretaceous–Tertiary granitoids of the Cordillera hinterland (Zen and Hammarstrom, 1984), which represents a tectonotypical region of MCC development (Coney and Harms, 1984; and others).

The anomalous layers composed of blastomylonites are considered here as relicts of rock associations of detachment zones formed at the interface of tectonic slices (Chamov, 2005, 2013). As follows from the isotopic age of blastomylonites, these processes took place in the Neoproterozoic and characterize the tectonic pre-history of the Central Russian aulacogen formation. By the time of initiation of grabens in the aulacogen in the Neoproterozoic, Paleoproterozoic collisional processes gradually ceased during the long (Mesoproterozoic) period, and the inner structure of the basement probably complicated by the subsequent local deformations was formed completely.

Let us consider the influence of the inner structure of the basement on the structure and sedimentation patterns in Neoproterozoic grabens of the aulacogen.

Dependence of Localization of Epidote-rich Intervals on the Attitude Patterns of Blastomylonite Bodies

Regularities in the position of epidote-rich intervals may be explained by the relation between attitude elements of Neoproterozoic normal fault planes and Paleoproterozoic blastomylonite bodies.

The Molokovo-type intervals, which reflect the influx of epidote to sediments immediately after the formation of the graben and its gradual cessation, are formed under the initially gentle shallow attitude of the blastomylonite layer (Fig. 5a). The downthrown part of the layer becomes a bottom of the graben, while its other wall is exhumed into the erosion zone owing to isostatic uplifting of the downdeep block (Fig. 5b). The subsequent development of the graben results in the burial of the subsided part of the layer, further uplift of the downdeep block, progressive erosion, and exhumation of the upper fragment of the blastomylonite layer from the zone of influence on the growing graben (Fig. 5c).

The Bobrov-type intervals, which are characterized by the influx of epidote from the local source at the late stages of graben development, owe to the deeper position of the blastomylonite layer by the normal fault initiation (Fig. 5d). In such a situation, the base of the graben is composed of rock constituting the upper slice (amphibolites and plagioclasites). The subse-

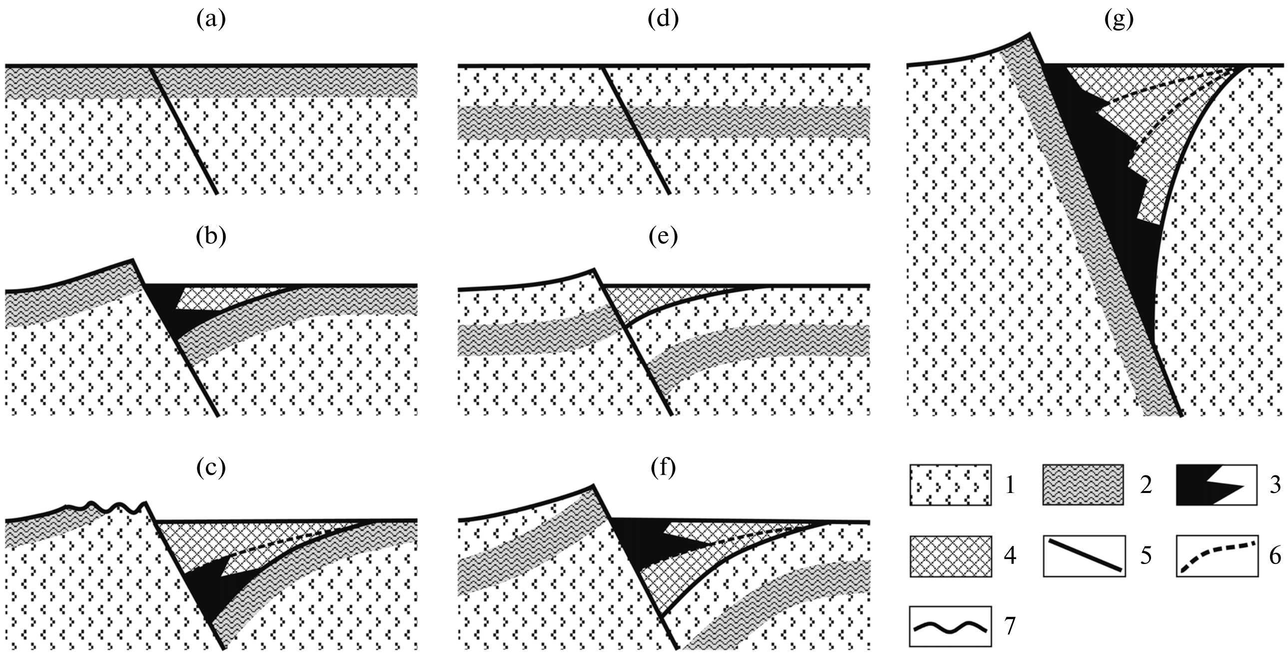


Fig. 5. Formation models of grabens and corresponding types of intervals with elevated epidote concentrations: (a–c) Molokovo, (d–f) Bobrov, (g) Roslyatino. (1, 2) Basement: (1) amphibolites and migmatites, (2) blastomylonites with crystalline epidote; (3) detrital epidote from blastomylonites in the heavy fraction of sandstones; (4) arkosic sediments from the external source; (5) normal faults; (6) intermediate surfaces of the graben bottom; (7) erosional boundaries.

quent deepening of the graben is accompanied by its compensation by sediments without their enrichment with products of blastomylonite layer erosion (Fig. 5e), the influence of which is evident at the late stages of graben development (Fig. 5f).

Locally, the blastomylonite layer fails to reach the zone of erosion and no sediment enrichment with epidote is observed. Such a situation is probably responsible for the absence (no revelation) of epidote-rich intervals in the Borehole Bologoevskaya section (Fig. 1). It should, however, be taken into consideration that the borehole is drilled at the margin of the graben and the complete section of the basin may be similar with the adjacent section recovered by Borehole Severo-Molokovskaya.

In the Roslyatino-type intervals, where the enrichment with epidote is characteristic of the entire sedimentary sequence, are formed when the blastomylonite layer is characterized by the steep attitude and the normal fault is developed along its strike (Fig. 5g). The blastomylonite layer experiences no isolation due to the deepening of the basin and the simultaneous uplift of the footwall. On the contrary, these processes stimulate the intense input of epidote from the local source.

Dependence of Graben Geometry and Facies Composition of Sediments on the Attitude of Blastomylonite Bodies

Relations between the plane attitude of Neoproterozoic normal faults and blastomylonite layers determined the appearance of local sources of detrital material and influenced the structural evolution of the basin and facies organization in sedimentary complexes.

The crossing normal faults stimulated (particularly, in situations with the gentle attitude of blastomylonite bodies) the formation of grabens with the rheologically determined subsidence limit (Molokovo type). At some depth, the isostatic leveling forces prevented from further subsidence of granitoid rocks with a density of 2.9 g/cm^3 into the denser (≥3 g/cm^3) amphibole substrate.

If extension in the region continued to affect grabens after their achievement of the subsidence limit, the further development of structures was determined by their local extension, which resulted in the accumulation of regressive sedimentary successions with transition from the lacustrine to fluvial-proluvial sediments.

The more expedient (in terms of energy) development of normal faults along blastomylonite bodies (Roslyatino type) left the isostatic equilibrium undisturbed and stimulated the formation of narrow deep grabens with depositional environments remaining stable over long periods.

CONCLUSIONS

Variations in local tectonic conditions determined the individual evolution of grabens in the Central Russian aulacogen. Despite the general similarity of processes, which were controlled by the regional strain field, each of these grabens represented an autonomous tectonosedimentary system, which is reflected in structural organization of the accommodation space and facies composition of its sedimentary complexes.

The influence of local tectonics is best expressed in the asynchronous variable enrichment (35–95%) of some intervals of the sedimentary section with acute-angled epidote grains.

Some features (relative instability of epidote in the hypergenesis zone, angular shapes and fresh appearance of clasts, and absence of correlation between the epidote input and content of the main rock-forming components) imply the formation of epidote anomalies owing to local sources. Analysis of the probable geodynamic mechanisms responsible for the development of the Central Russian aulacogen, structure of its grabens, and structure and composition of the upper part of the consolidated crust made it possible to suggest that the specific clastic material originates from the epidote-rich blastomylonites developed among metamorphic complexes of the basement in the form of layers with anomalous geophysical properties. Comparison between epidote crystals and grains from blastomylonites and sediments confirms such an assumption. Indeed, crystals and grains of epidote exhibit similar habit, sizes, and optical properties and contain 25–30% of the pistacite component, which is characteristic of secondary epidote that forms pseudomorphs after biotite and amphibole in the partial melting environments.

Regularities in the localization of epidote-rich intervals in the sedimentary section reflect the processes responsible for the exhumation of blastomylonites into the erosion zone. The influence of the local source of clastic material and, correspondingly, position of epidote-rich intervals in the sedimentary section was determined by relations between attitude elements of planes of Neoproterozoic normal faults and Paleoproterozoic blastomylonite bodies. The same factor affected the facies composition of sedimentary complexes and structural evolution of the sedimentation basin. The crossing normal faults stimulated (particularly, in situations with the gentle attitude of blastomylonite bodies) the formation of grabens with the rheologically determined subsidence limit (Molokovo type). In such a situation, the subsidence of granitoid rocks into the denser amphibole substrate was limited by the isostatic leveling forces. When the regional strain field remained stable after reaching the subsidence limit, grabens of this type experienced lateral extension, which resulted in the accumulation of regressive sedimentary successions with the transition from the lacustrine to fluvial–proluvial sediments. Such grabens are characterized by the one-act manifestation of the local source of clastic material regardless of the structure development stage.

The more expedient (in terms of energy) development of normal faults along blastomylonite bodies (Roslyatino type) left the isostatic equilibrium undisturbed and stimulated the formation of narrow deep grabens with depositional environment remaining stable over long periods. Moreover, the blastomylonite body experienced no isolation due to basin deepening with simultaneous uplift of the footwall; to the contrary, these processes stimulated the enhanced influx of epidote from the local source.

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