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Fission-Track Dating of Detrital Zircons from Sandstone of the Lesnaya Group, Northern Kamchatka

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Abstract—Flyschoid deposits of the Lesnaya Group that are exposed within northern Kamchatka are almost barren of identifiable fossils. The group is considered to be of the Late Cretaceous age on the basis of geological correlation. Ages of detrital zircons from nine sandstone samples of the Lesnaya Group are determined using the fission-track dating. The youngest population of colorless idiomorphic zircon crystals, which experienced no secondary annealing, is from 43.7 ± 3.4 to 58.1 ± 4.2 Ma old. Morphological features of zircons allow us to relate their formation to the volcanic activity synchronous to accumulation of the Lesnaya Group flysch. Hypabyssal intrusions and blocks of older rocks that experienced rapid exhumation from the depth, where thermal parameters exceeded the blocking temperature, could be the source rocks for younger zircons. The age of the youngest zircon population can be interpreted as corresponding to sedimentation time of the Lesnaya Group that lasted, according to our data, until the mid-Middle Eocene.

Key words: *fission-track dating, detrital thermochronology, zircon, Lesnaya Group, northern Kamchatka.*

INTRODUCTION

The dating of flyschoid deposits in Boreal provinces, which contain almost unidentifiable organic remains, is a difficult problem of geochronology and stratigraphy. Some papers published in western countries during the past decade demonstrated that the problem could be solved with the help of the detrital thermochronology based on the fission-track dating of zircon and apatite grains from sedimentary rocks. The method is shown to be useful for establishing ages of those deposits, dating of which on the basis of paleontological remains is highly conjectural.

In our study, we applied the detrital thermochronology for elucidating the deposition period of the flyschoid Lesnaya Group constituting the core of the Lesnaya Upland in northern Kamchatka.

LESNAYA GROUP: BRIEF DESCRIPTION

The Lesnaya Group is distinguished in western slopes of the Sredinnyi Range of the Kamchatka Isthmus (Fig. 1). It is composed of sandy–clayey flyschoid sediments deposited along the continental slope of Eurasia and occurring now as the autochthonous Lesnaya thrust sheet intensely dislocated and overridden by the siliceous–volcanogenic Irunei unit related in origin to the Olyutorskii island arc (Santonian–Maastrichtian, probably Danian) (*Geologicheskaya karta...*, 1989; Shantser *et al.*, 1985; Fedorchuk and Izvekov, 1992). Immediately below the Lesnaya thrust fault, the group includes exotic blocks of siliceous–volcanogenic deposits that yield impoverished assemblages of Campanian–Maastrichtian radiolarians (Shapiro and Fedorov, 1985). Origin of those blocks is debatable.

Considerable deformations and the uniform composition of sediments lacking macrofauna are unfavorable for the correct interpretation of rock succession, and inferences on their age are mainly based on dates obtained for some localities and on the correlation with lithologically similar deposits occupying an analogous structural position in other parts of the region. In particular, there were found some Santonian–Campanian inocerams and Maastrichtian–Danian assemblages of agglutinated benthic foraminifers (*Geologicheskaya karta...*, 1989). Fedorchuk and Izvekov (1992) reported in addition on some occurrences of the Late Cretaceous and Eocene nannoplankton in mudstone beds of the Lesnaya Group. The group correlates with an upper part of the Cretaceous Omgon Group in the western coast of Kamchatka (*Geologicheskaya karta...*, 1989), with the Khozgon Formation of the southern Sredinnyi Ridge that yields Campanian radiolarians (Shapiro *et al.*, 1986), and with the Ukelayat flysch of the southern Koryak Upland, where its stratigraphic range is thought to be spanning the Upper Cretaceous, Paleocene, and basal Eocene (Ermakov and Suprunenko, 1975; Bogdanov *et al.*, 1987; Garver *et al.*, 1998; Solov'ev *et al.*, 1998). The Lesnaya Group is assigned to the Upper Cretaceous in the geological maps available.

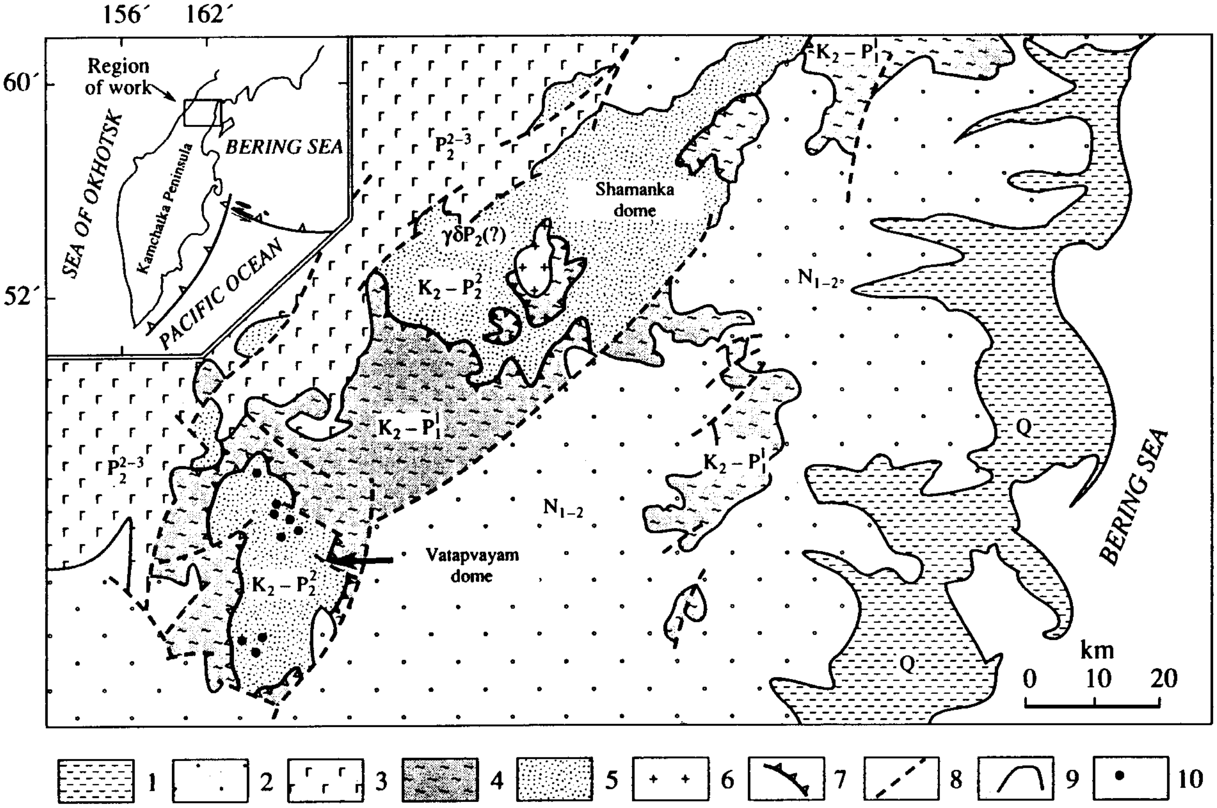

Fig. 1. Simplified geological structure of the study area (*Geologicheskaya karta...*, 1989, with modifications): (1) Quaternary deposits; (2) Central Kamchatka volcanic belt (N_{1-2}); (3) Western Kamchatka volcanic belt (P_2^{2-3}); (4) exposures of the Irunei Formation (K_2-P_1^1); (5) exposures of the Lesnaya Group (K_2-P_2^2); (6) Shamanka Massif of the Middle Eocene granite; (7) Lesnaya thrust fault; (8) other faults; (9) stratigraphic contacts; (10) sampling sites.

The upper age limit of the Lesnaya Group is inferable from the age of the neoautochthon composed of unconformably lying terrestrial volcanics of the Kinkil Formation that is attributed to the Middle Eocene on the basis of K/Ar dates ranging from 37 to 47 Ma (Gladenkov *et al.*, 1991). In upper reaches of the Shamanka River, conglomerates of the Upper Eocene contain pebbles of granite intruding the Lesnaya Group, Irunei Formation, and thrust fault separating them (Shantser *et al.*, 1985).

Data on the Lesnaya Group age are controversial but very important for the analysis of the regional geology. In this connection, we dated detrital zircon from the Lesnaya Group sandstones.

PRINCIPLES OF DETRITAL THERMOCHRONOLOGY

At the beginning of the 1960s, American researchers suggested a new method of the mineral age determination based on the density calculation of fission-tracks originated by spontaneous decay ^{238}U nuclei during the geological history of a mineral (Price and Walker, 1963; Fleischer, Price, and Walker, 1975). In Russia, the method was termed as the dating based on tracks of the uranium nuclear debris (Shukolyukov *et al.*, 1965). In this work, we use the original term "fission-track dating".

The development of fission tracks in a mineral can be compared with the accumulation process of radiogenic isotopes in the course of radioactive decay. The annealing (disappearance) of tracks in most minerals happens at the temperature of more than 300°C, i.e., the tracks appear and survive in crystals only if the rock is cooled below a particular temperature called "the closure temperature". The closure temperature is different in various minerals, and this allows the fission-track dating to be applied for studying thermal events related to orogeny and volcanism in active geodynamic settings of the Earth. The fission-track ages of zircon and apatite are most frequently used for solving geological problems (Wagner and Van den Haute, 1992).

We used the detrital thermochronology in our work, as it offers a chance to establish the cooling time of rocks in provenances, which supplied sedimentary sequences with detrital minerals (Hurford *et al.*, 1984; Baldwin *et al.*, 1986; Brandon and Vance, 1992; Garver and Brandon, 1994; Carter *et al.*, 1995). The cooling of rocks in a provenance can be associated with different geological processes, e.g., with the exhumation of rocks from a large depth or with volcanic activity; the redeposition of older sediments is also a possibility. In the works mentioned above, the fission-track age of individual detrital zircons was determined in order to distinguish subsequently their populations (Galbrain and Green, 1990; Brandon, 1992; Brandon, 1996) that arrived in the sedimentary basin from different provenances and had different ages. As was shown, the fission-track age of detrital zircons that escaped a secondary annealing, could be used for establishing the age of terrigenous sedimentation. The youngest population of zircon grains defines the age of sedimentation, when the latter was synchronous to volcanism that developed in immediate vicinity of the sedimentation site (Brandon and Vance, 1992; Garver and Brandon, 1994). In particular, the youngest zircon population marks the lower time limit of the sedimentation cessation, and this is very important for the analysis of accumulation history of the Lesnaya Group and geodynamics of Kamchatka at the Mesozoic–Cenozoic boundary.

AGE OF ZIRCONS FROM SANDSTONES OF THE LESNAYA GROUP

We selected nine sandstone samples (each 4–8 kg in weight) of the Lesnaya Group within the area of the Vatapvayam dome: three samples in the southwestern part (Mt. Gechanana) and six samples in the northeastern part (the northern slope of the Levaya Lesnaya River valley) of the latter (Fig. 1). Zircons were extracted from sandstone at the Laboratory of Accessory Minerals, the Institute of the Lithosphere of Marginal Seas, Russian Academy of Sciences. The zircon ages were measured at the Laboratory of Fission-Track Dating, the Union College (Schenectady, NY, USA). The method of an external detector was applied when dating (Hurford and Carter, 1991). Peculiarities of the technical treatment of samples to be dated are characterized in notes to Table 2.

From 45 to 90 zircon grains from each sample were dated (Table 2). Presented as an example are calculation data and ages for individual zircon grains from Sample L10 (Table 1). The program "Zetaage 4.7" by M.T. Brandon (Yale University, USA) was applied for calculating the age of zircon grains. The program is available for any user at the site http:\\love.geology.yale.edu/~brandon.

Ages of zircon grains vary within a wide range in all samples (for instance, Sample L10 in Table 1, Fig. 2b), thus suggesting that zircons arrived to the basin of sedimentation from different provenances, and that we deal with several zircon populations different in age. To separate different populations, we applied the method described earlier (Galbraith and Green, 1990; Brandon, 1992; Brandon, 1996). According to this method, the measured ages of individual grains characterize several zircon populations (this is correct, as the studied zircons are of different morphology), and distribution of ages in each population obeys the same model law. We used the binomial approximation in our study. The model parameters and, in particular, the position of distribution peaks for individual populations is assessed using the maximum-likelihood method. The number of populations is chosen according to the error minimization criterion (criterion 2) for the assessed parameters. To separate populations of different age in our study, we applied the program Binomfit 1.8 by Brandon (Yale University, USA) that uses the algorithm by Galbrain (1988). The program is available for any user at the site http:\\love.geology.yale.edu/~brandon.

The results of subdividing populations of zircon grain from nine samples are given in Table 2 (Fig. 2a, b, c). Two populations were selected from samples L1 and L13, and three populations from the others. These groups of populations (peaks in Fig. 2a, b, c) minimize errors of assessed parameters best of all, whereas smaller or greater amounts of "peaks" used on calculations considerably deteriorate the result. It should be pointed out that the peak "width" (W) that characterizes the relative standard deviation varies from 19 to 29% proving the result validity (Brandon, 1996).

Thus, the analysis of distribution of fission-track ages measured for nine rock samples revealed three zircon populations of different age: (P1) 44–58 Ma, (P2) 71–93 Ma, and (P3) 104–176 Ma (Table 2).

As the individual zircon grains from each sample show widely variable ages (Fig. 2a, b, c), we can assume that they, when arrived in the basin, have never been heated up to or above the temperature (about 215–240°C) able to cause the track system closure (Brandon and Vance, 1992). Consequently, these zircons characterize the time range of rock cooling in provenances.

Zircons of the youngest population are mainly represented by colorless idiomorphic crystals. This morphological feature allows a suggestion that zircons of this kind formed during the volcanic activity synchronous to accumulation of the Lesnaya Group, and appeared in the basin of sedimentation shortly after their formation. Accordingly, the youngest zircon population is interpreted as characterizing the accumulation period of the Lesnaya Group that lasted (see Fig. 2d) from the latest Paleocene (58.1 ± 4.2 Ma) to the mid-Middle Eocene (43.7 ± 3.4).

Zircons from older populations are more diverse in morphology. Smoothed crystal fragments dominate among them, whereas rounded grains and idiomorphic crystals are rare. Zircons of these populations (P2, P3, Table 2) have been likely derived from other provenances and characterize the cooling history of parental rocks under impact of different geological processes (Garver *et al.*, in press). It is likely that their provenances were in the Okhotsk-Chukchi volcano-plutonic belt originated above the different-age terranes. It is

Table 1. Calculated parameters of fission tracks in zircon grains, Sample L10. First plate L10a, etching time 15 hours (see notes for Table 2)

Grain number	ρs	Ns	ρi	Ni	Area	U ± 2se		Grain age	Age* ±95%
1	5.44	45	4.48	37	12	133	44	75.2	47.5–119.7
2	6.00	62	4.26	44	15	127	39	87.0	58.1–131.4
3	4.90	54	6.17	68	16	184	46	49.3	33.7–71.7
4	5.42	56	5.71	59	15	170	45	58.8	39.9–86.5
5	5.81	44	5.15	39	11	153	50	69.8	44.2–110.5
6	9.51	59	9.51	59	9	284	76	61.9	42.3–90.7
7	5.66	78	8.71	120	20	260	50	40.2	30.0–53.8
8	4.84	40	4.48	37	12	133	44	66.9	41.6–107.7
9	4.72	39	4.84	40	12	144	46	60.4	37.8–96.5
10	11.6	64	17.8	98	8	530	111	40.6	29.0–56.4
11	7.50	62	7.14	59	12	213	57	65.1	44.7–94.8
12	7.74	48	4.52	28	9	135	51	105.6	65.0–174.9
13	8.22	34	7.26	30	6	216	79	70.1	41.6–118.7
14	4.45	46	3.58	37	15	107	35	76.9	48.7–122.0
15	10.7	118	6.44	71	16	192	47	102.5	75.5–140.2
16	5.56	69	8.87	110	18	265	53	39.0	28.2–53.3
17	10.1	104	6.58	68	15	196	49	94.4	68.7–130.6
18	6.05	50	4.23	35	12	126	43	88.2	56.1–140.2
19	4.96	41	3.14	26	12	94	37	97.2	58.1–165.6
20	11.4	94	7.62	63	12	227	59	92.1	66.1–129.3
21	6.17	51	6.17	51	12	184	52	61.9	41.1–93.4
22	10.1	111	6.89	76	16	206	49	90.2	66.5–122.9
23	9.92	82	12.9	107	12	386	78	47.6	35.0–64.3
24	9.19	95	7.06	73	15	211	51	80.5	58.5–111.1
25	6.33	109	7.14	123	25	213	40	54.7	41.9–71.4
26	8.03	166	7.50	155	30	224	38	66.1	52.5–83.1
27	6.53	72	5.26	58	16	157	42	76.8	53.4–110.8
28	5.97	37	3.87	24	9	115	47	95.0	55.4–166.1
29	4.11	34	2.18	18	12	65	30	116.0	64.0–218.1
30	6.99	53	6.73	51	11	201	57	64.4	42.9–96.7
31	11.5	95	10.4	86	12	310	69	68.4	50.3–93.0
32	7.35	76	5.32	55	15	159	44	85.4	59.4–123.4
33	4.06	28	1.74	12	10	52	30	142.5	70.9–306.9
34	8.42	58	4.93	34	10	147	51	105.1	67.7–165.8
35	6.41	53	3.75	31	12	112	40	105.3	66.4–169.9
36	5.17	57	3.99	44	16	119	36	80.1	53.0–121.7
37	8.39	52	4.84	30	9	144	53	106.7	66.9–173.5
38	5.20	43	9.31	77	12	278	65	34.7	23.2–51.2
39	11.7	97	7.86	65	12	235	60	92.1	66.4–128.6
40	4.23	35	6.05	50	12	180	52	43.5	27.3–68.4
41	10.2	84	7.26	60	12	216	57	86.5	61.2–123.0
42	8.89	98	6.44	71	16	192	47	85.3	62.0–117.9
43	4.66	61	4.05	53	19	121	34	71.2	48.3–105.2
44	7.18	89	6.21	77	18	185	43	71.5	51.9–98.7
45	6.82	47	1.60	11	10	48	28	257.7	134.1–546.2

Note: Density of tracks in the external detector (low-uranium mica) ρd = 4.08 ± 2.98 path/cm^{-2} × 10^5.

Table 1. (Contd.)

Grain number	ρs	Ns	ρi	Ni	Area	U ± 2se		Grain age	Age* ±95%
46	7.40	51	6.82	47	10	201	60	67.9	44.6–103.3
47	4.30	74	3.25	56	25	96	26	82.5	57.4–119.3
48	4.60	38	3.39	28	12	100	38	84.6	50.6–143.3
49	11.8	73	3.06	19	9	91	41	235.6	142.1–411.9
50	6.29	52	4.84	40	12	143	46	81.1	52.6–126.0
51	6.82	94	4.43	61	20	131	34	96.1	68.7–135.3
52	10.5	87	3.39	28	12	100	38	191.7	124.5–304.6
53	5.01	69	2.54	35	20	75	26	122.5	80.5–189.9
54	6.53	54	2.66	22	12	79	33	151.8	91.4–261.6
55	4.19	26	3.39	21	9	100	44	77.3	41.8–144.3
56	6.35	70	7.89	87	16	233	52	50.4	36.1–70.1
57	7.98	66	5.81	48	12	171	50	85.8	58.2–127.5
58	5.13	53	8.03	83	15	237	54	40.1	27.7–57.4
59	3.82	79	4.11	85	30	121	27	58.2	42.1–80.3
60	7.74	80	4.45	46	15	131	39	108.3	74.3–159.5
61	6.53	54	5.81	48	12	171	50	70.3	46.7–106.2
62	6.41	53	6.89	57	12	204	55	58.2	39.1–86.4
63	4.16	43	4.35	45	15	129	39	59.8	38.3–93.1
64	5.94	86	2.63	38	21	78	25	140.4	94.9–211.8
65	3.41	61	2.62	47	26	77	23	81.0	54.4–121.5
66	4.87	47	5.08	49	14	150	44	60.0	39.2–91.6
67	6.53	54	3.99	33	12	118	41	101.9	64.9–162.4
68	4.23	35	5.81	48	12	171	50	45.7	28.6–72.3
69	5.32	55	2.52	26	15	74	29	131.2	81.1–218.0
70	5.52	76	5.66	78	20	167	39	61.0	43.7–85.0
71	1.52	84	1.74	96	80	51	11	54.8	40.2–74.5
72	6.00	62	7.16	74	15	212	51	52.5	36.7–74.8
73	5.22	36	5.81	40	10	171	55	56.4	34.8–90.8
74	6.89	57	8.35	69	12	247	61	51.8	35.6–74.8
75	5.13	53	6.19	64	15	183	47	51.9	35.2–76.1
76	5.00	31	4.84	30	9	143	52	64.6	37.8–110.6
77	5.81	48	1.69	14	12	50	26	210.3	115.4–411.1
78	4.60	38	6.05	50	12	179	51	47.7	30.3–74.2
79	7.84	81	5.71	59	15	169	45	85.7	60.3–122.3
80	4.96	41	4.35	36	12	129	43	71.2	44.3–114.8
81	5.64	70	6.21	77	18	183	43	56.9	40.4–80.0
82	3.54	39	4.63	51	16	137	39	48.0	30.7–74.3
83	4.43	61	2.54	35	20	75	26	108.4	70.5–169.6
84	5.81	48	6.05	50	12	179	51	60.1	39.5–91.3
85	3.87	32	4.11	34	12	121	42	58.9	35.1–98.5
86	7.18	99	3.77	52	20	111	31	118.4	83.7–169.5
87	4.17	23	2.54	14	8	75	40	102.0	50.6–214.1
88	6.24	43	2.18	15	10	64	33	176.5	97.1–341.1
89	6.53	54	2.54	21	12	75	33	158.9	95.0–276.7
90	3.43	71	1.11	23	30	33	14	190.3	118.2–318.7

Note: Density of tracks in the external detector (low-uranium mica) ρd = 4.12 ± 2.97 path/cm^{-2} × 10^{5}; U content in glass-dosimeter (CN-5) 12.17 ppm; factor Z = 305.1 ± 6.91; the area unit is 6.89 cm^{-2} × 10^{-7}; ρs is density of ^{238}U spontaneous decay tracks, Ns/cm^{-2} × 10^{-6}; Ns is calculated number of spontaneous decay tracks; ρi is density of induced fission tracks Ni/cm^{-2} × 10^{6}; Ni is calculated number of induced fission tracks; U is uranium content, ppm; ±se is standard error of the U content determination; age*—interval of age determination ±95%.

Table 2. Fission-track ages of detrital zircons from sandstones of the Lesnaya Group (northern Kamchatka)

Sample number	Number of grains dated	Age of populations (BinomFit v.1.8—Brandon, 1996)		
		P1	P2	P3
L1	45	46.0 ± 2.7		107.3 ± 7.0
		Nf = 22.1		Nf = 22.9
		W = 22%		W = 25%
L2	90	48.1 ± 5.0	78.1 ± 5.8	116.0 ± 8.6
		Nf = 6.1	Nf = 47.4	Nf = 36.6
		W = 19%	W = 22%	W = 23%
L4	90	58.1 ± 4.2	83.3 ± 6.3	130.5 ± 14.9
		Nf = 32.6	Nf = 46.1	Nf = 11.4
		W = 23%	W = 24%	W = 24%
L9	90	47.0 ± 3.8	70.8 ± 5.7	104.0 ± 11.9
		Nf = 16.9	Nf = 50.4	Nf = 22.7
		W = 19%	W = 21%	W = 25%
L10	90	53.9 ± 3.4	87.5 ± 6.2	176.5 ± 23.8
		Nf = 35.7	Nf = 45.3	Nf = 9.0
		W = 21%	W = 22%	W = 29%
L11	90	50.4 ± 5.6	70.6 ± 6.6	109.7 ± 25.0
		Nf = 17.9	Nf = 58.7	Nf = 13.4
		W = 22%	W = 24%	W = 26%
L12	67	43.7 ± 3.4	70.6 ± 4.4	107.0 ± 12.2
		Nf = 11.3	Nf = 44.6	Nf = 11.1
		W = 19%	W = 22%	W = 23%
L13	89	55.5 ± 3.5	93.0 ± 4.8	
		Nf = 30.4	Nf = 58.6	
		W = 21%	W = 23%	
L17	90	54.5 ± 10.4	84.6 ± 6.5	134.6 ± 18.9
		Nf = 4.0	Nf = 58.9	Nf = 27.0
		W = 20%	W = 20%	W = 24%

Note: (Nf) number of grains statistically attributed to a given population; (W) relative standard deviation of a peak (characteristics peak "width" expressed in percent, after Brandon, 1996). The age determination error $\pm 1\sigma$ corresponds to the standard deviation of the mean peak position for Nf grains. Zircons are dated using the external detector method (Hurford and Carter, 1991). Zircon grains were pressed into FEP Teflon *MT* plates 2 × 2 cm^2 in size. Two plates were prepared for each sample. The abraded plates were polished with diamond paste (9 and 1 μm) and Al$_2$O$_3$ paste (0.3 μm) at the final stage. The plates were etched by NaOH-KOH compound at the temperature of 228°C during 15 (first plate) and 30 hours (second plate). After etching, the plates covered with detector (mica with a low U content) were exposed to irradiated under the thermal neutron flux of 2×10^{15} neutron/cm^2 (reactor of the Oregon University). The zircon age standards Fish Canyon Tuff (FCT) and Buluk Tuff (BL), and also the glass-dosimeter (CN-5) with known U content (Hurford, 1998) were irradiated simultaneously with samples. Microscope Olympus BH-P with an automated system and digital plotting board (maximum magnification ×1256, dry method) was used to calculate density of tracks. Z-factor calculated on the basis of 10 age standards (6 FCT and 4 BL) is 305.01 × 6.91 (Hurford, 1998).

important to note that old zircon grains (> 500 Ma) and grains with a high U content (> 500 ppm) usually show the very high density of fission tracks, and their dating appears to be impossible. Moreover, the metamict, usually Precambrian zircons dissolve under long chemical etching applied in our procedure of sample treatment (see explanations for Table 2). Thus, we were unable to get information about the Early Paleozoic and Precambrian zircons from the Lesnaya Group, though they definitely occur in rocks.

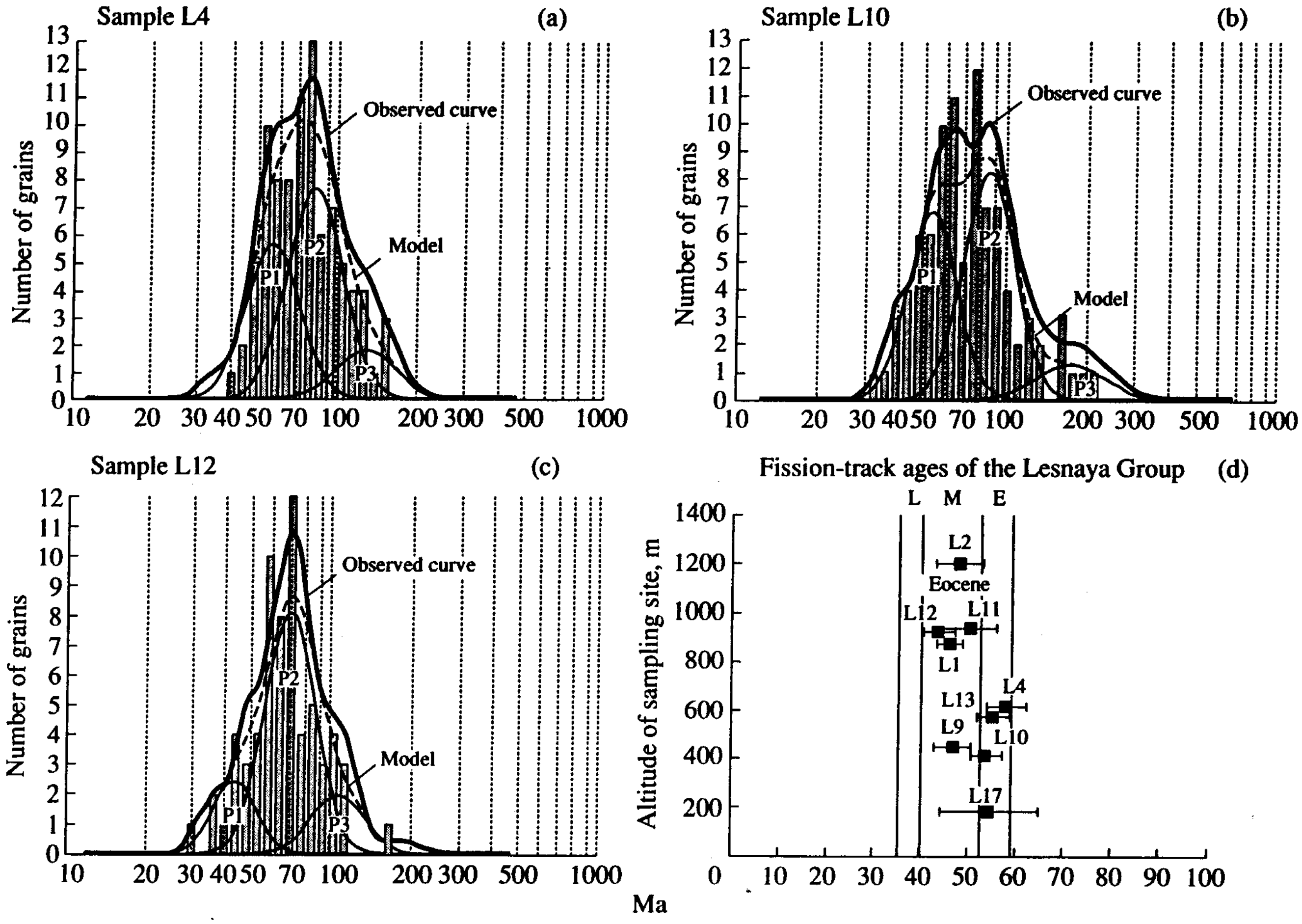

Fig. 2. Histograms (a, b, c,) of fission-track ages of detrital zircon from sandstone samples of the Lesnaya Group: the observed (solid line) and model (dashed line) curves, the later estimated using the BinomFit 1.8 program by Brandon (1996); P1, P2, and P3 are peaks of different-age populations (see Table 1) fitting the model curves; (d) ages of young zircon populations distinguished in the studied samples (age determination error is ±1σ) versus altitude of sampling sites. The fission-track ages of young zircon populations are interpreted as indicators of accumulation time of the Lesnaya Group (see text for explanations). Eocene substages: (E) early, (M) middle, and (L) late. Indices L1, L2, etc., correspond to sample numbers in Table 2.

COMPOSITION OF SANDSTONE FROM THE LESNAYA GROUP

The Lesnaya sandstones were previously studied by Shapiro *et al.* (1993). Since the knowledge of the rock composition is important for understanding the nature of provenances, we studied the composition of the samples, zircons from which were used for age determinations (Table 3).

All the studied sandstone samples are compositionally similar (Table 3) and, according to the classification by Pettijohn *et al.* (1976), they are typical graywackes having 23–35% of fine-grained matrix. Among grains, there are rock fragments (36–47%), quartz (27–33%), and feldspar (21–31%). According to the average composition, the samples (Q30F26L44, Fig. 3a) corresponds to lithic graywackes (Pettijohn *et al.*, 1976) or feldspar–quartz graywackes (Shutov *et al.*, 1972). Their feldspar fraction predominantly consists of plagioclase monocrystals, whereas feldspar aggregates make up only 15–35% in total. Alkali plagioclase (albite) represents up to 5–30% of all feldspars. Individual aggregates of plagioclase and quartz are also present. Monocrystalline quartz shows clear undulating extinction and abundant dusty inclusions. Its clear unstrained grains are rare. Polycrystalline grains make up 15–30% of the total quartz fraction. Ore and colored minerals are very rare. The latter are often represented by small flakes of white and brown mica and, occasionally, by amphibole. Large rounded zircon grains are most common among the colored minerals.

Clasts of volcanic rocks, devitrified glass included, slightly dominate over sedimentary lithic fragments (Fig. 3b). Volcanic clasts with felsitic and microlitic textures prevail over those with granular texture. Only feldspar was found in volcanic rocks as small phenocrysts. Sedimentary rocks are represented mainly by mudstone, siltstone, and siliceous–clayey rocks probably representing original tuffs (Table 3). Chert, sandstone, coaly mudstone, shale, siltstone, and plant debris

Table 3. Composition of sandstone samples from the Lesnaya Group

Sample	Qm	Qp	Qq	P	F	K	Lvl	Lvm	Lvf	Lvv	Lm	Lssh	Lsa	Lss	Lsch	Lst	Ls	Op	nOp	U	T	Mtx	Aut	Age*
L12	62	21	9	55	16	1	9	18	27	19	2	4	23	7	4	7	9	–	1	6	300	89	9	43.7 ± 3.4
L1	63	12	4	68	22	1	8	22	25	22	6	5	20	5	2	6	–	3	1	5	300	116	17	46.0 ± 2.7
L9	62	12	3	62	24	1	3	9	29	16	2	2	35	15	9	4	1	–	–	11	300	119	27	47.0 ± 3.8
L2	75	16	14	52	7	–	2	14	27	8	7	8	34	4	10	5	2	2	2	11	300	83	8	48.1 ± 5.0
L11	64	17	3	72	6	1	6	18	30	15	3	4	30	8	7	7	1	1	–	7	300	89	22	50.4 ± 5.6
L10	66	19	3	65	18	–	4	23	24	13	2	1	32	6	7	9	–	2	–	6	300	102	14	53.9 ± 3.4
L17	83	11	3	75	14	–	4	14	18	44	2	1	9	3	3	5	3	1	2	5	300	97	3	54.5 ± 10.4
L13	66	17	4	58	10	–	10	28	14	39	6	–	16	1	9	10	3	–	–	9	300	96	7	55.5 ± 3.5
L4	75	15	3	63	4	–	12	16	25	33	5	4	18	4	4	9	–	–	–	10	300	132	36	58.1 ± 4.2

Note: Main detrital components: Qm, monocrystalline quartz; Qp, polycrystalline quartz; Qq, quartzite; P, Ca-plagioclase (colored); F, Na-albite (uncolored); K, potassium feldspar; Lvl, volcanics with lath-shaped crystals; Lvm, microlitic volcanics; Lvf, felsitic volcanics; Lvv, devitrified glass; Lm, metamorphic rocks; Lssh, shale; Lsa, mudstone, aleuropelite; Lss, mudstone, sandstone; Lsch, chert; Lst, fine-grained tuffaceous–sedimentary rock; Lso, other sedimentary rocks, bioclasts included; Op, ore mineral; nOp, colored mineral (mica, amphibole, pyroxene, etc.); U, unidentifiable grains; T, total number of counted points; Mtx, matrix (cement included); Aut, secondary minerals.

* Age of the youngest zircon population interpreted as indicator of accumulation time of the Lesnaya Group.

are found as individual grains. Persistent but insignificant admixture of metamorphic rocks is represented by phyllite, greenschist, mica schist, and micaceous quartzite clasts (Table 3b).

DISCUSSION

Fission-track ages of individual zircon grains from deposits of the Lesnaya Group vary widely from 44 to 176 Ma. The fact suggests that deposits of the group have not been heated after deposition above the critical temperature of the track system closure in zircons (215–240°C). Hence, the upper horizons of the Lesnaya Group, where zircons yielded the age value of 43.7 ± 3.4 Ma, cannot be older than the middle Eocene. This considerably changes the formerly accepted age of the Lesnaya Group, the accumulation period of which should be extended to the lower half of the middle Eocene. We emphasize that this inference does not contradict any direct age interpretation of the Lesnaya Group. Moreover, the dates obtained enable correlation of the Lesnaya Group with the Ukelayat flysch sequence, the upper part of which is quite reliably attributed to the Eocene on the basis of fission-track dating (Garver *et al.*, 1998; Solov'ev *et al.*, 1998).

Some consequences of new dating results require a brief discussion. The time interval, during which zircons the youngest zircon population was transported from provenances to the sedimentation basin, could be as long as several million years (Brandon and Vance, 1992; Garver *et al.*, 1999). In our case, however, the difference between the age of young zircons (about 45 Ma) and sedimentation time cannot be as great, since deposits of the Lesnaya Group are unconformably overlapped by volcanics of the Kinkil' Formation, the lower horizons of which are characterized by the oldest K/Ar date of 46.5 ± 0.8 Ma (Gladenkov *et al.*, 1991). Hence, the fission-track age of young zircons coincides within the limits of analytical error (3–4 Ma in our runs) with the time of sedimentation. There are known some other regions, where the young zircon population was associated with volcanism synchronous to sedimentation in the flysch trough (Brandon and Vance, 1992; Garver and Brandon, 1994). In our case, this assumption finds confirmation in morphology of zircon grains. The studied zircons of the youngest population are mainly colorless, idiomorphic crystals of typical volcanogenic origin, which did not experience an appreciable transportation and arrived in the basin soon after their cooling. The morphology of older zircons is more diverse: grains of moderate roundness grade are dominant, whereas grains and idiomorphic crystals are rare. The age range of the youngest zircon population from different samples (43.7 ± 3.4–58.1 ± 4.2 Ma) indicates the stratigraphic range of the interval sampled and, probably, the duration of the synchronous volcanism. The Paleocene volcanics known in the western coast of Kamchatka (Gladenkov *et al.*, 1997) can be considered as source rocks of young zircons accumulated in the Lesnaya Group. In the current structure of the peninsula, volcanics of that age are exposed in the Utkholokskii and Khairyuzov capes, as well as near the Shamanka River mouth.

Thin beds of fine tuffs are present among deposits of the Lesnaya Group. Sandstone beds with a considerable amount of pyroxene and amphibole among dominant clasts of volcanic rocks were also detected in some sections of the Lesnaya Group (Grechin, 1979). Lenticular members of tuffaceous sandstones and tuffs are described among the Ukelayat trough deposits correlative with the Lesnaya Group (Ermakov and Suprunenko, 1975), and volcaniclastic varieties are distinguished among sandstone beds of variable composition (Ermakov and Suprunenko, 1975; Kazimirov *et al.*, 1987). We should emphasize, however, that the fresh tuffaceous material has not been recognized in thin sections of the studied sandstone samples. Clasts resembling in morphology ash particles, or rock fragments with pumiceous structure have not been distinguished as well. Quartz grains having habit typical of phenocrysts in acid volcanics are absent. Zonal plagioclase crystals are also unknown in these rocks. Pyroxene, amphibole, and titanomagnetite represent a minor part of the heavy fraction (Shapiro *et al.*, 1993). It should be noted as well that we sampled thick beds of medium- to coarse-grained sandstones angular mudstone fragments. All these features are characteristic of the fluvial turbidite facies of submarine fans, which show minimal grading and sorting of detrital material. Most grains are angular, and soft rocks like mudstones are frequent among them. These characteristic features of the studied sandstones exclude a possibility to explain the absence of fresh tephra by its reworking and disintegration during a long transportation.

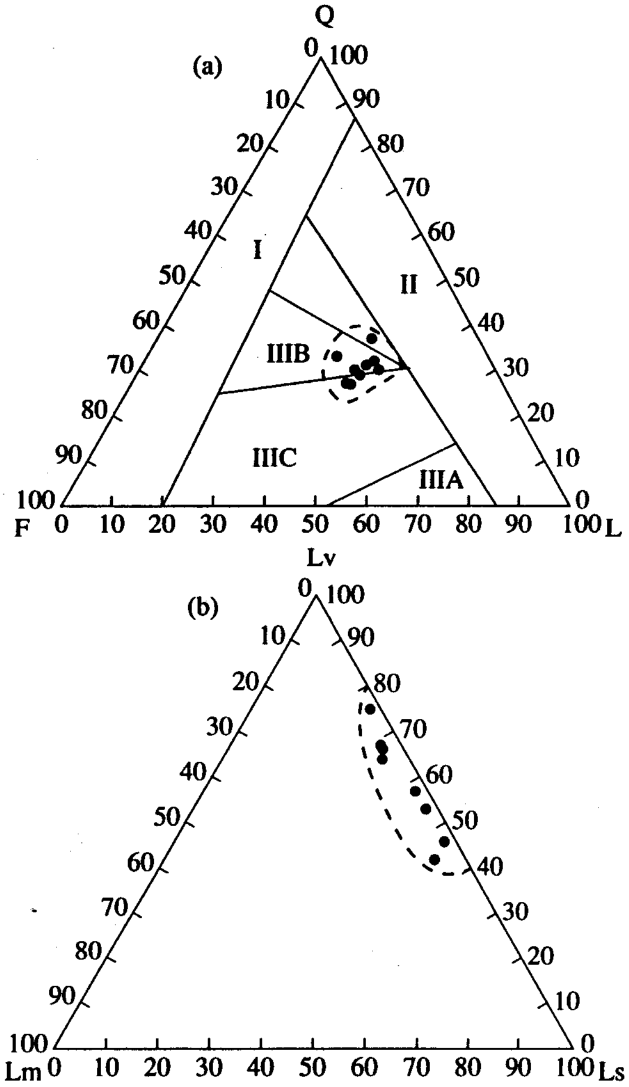

Fig. 3. FLQ diagram (a) for sandstones of the Lesnaya Group: Q, quartz (without silicate rock and quartzite), F, feldspar, L, rock fragments. Fields in the diagram correspond to following type provenances (Dickinson *et al.*, 1979): (I) continental massifs; (II) orogens; (III) magmatic arcs eroded poorly (A), deeply (B), or moderately (C). Dashed contours outlines the compositional field of the Lesnaya Group sandstones.

Lm-Lv-Ls diagram (b) characterizing proportions of lithic clasts in sandstones of the Lesnaya Group: (Lm) metamorphic, (Lv) volcanogenic, and (Ls) sedimentary rocks; dashed line limits the compositional field of the Lesnaya Group sandstones.

Thus, we suspect that the volcanic source is not the only possible explanation for origin of the young zircon population, the fission-track age of which was concurrent to sedimentation time of the upper parts of the Lesnaya Group. It is likely as well that voluminous hypabyssal acid to intermediate intrusions, which originated in the provenance at the end of the Paleocene and in the first half of the Eocene, but had no relation to the synchronous volcanism, could be taken for the additional source of zircons. If the intrusive activity was synchronous to the rising of landmasses subjected to denudation, then most of igneous rocks could be brought to the erosion surface in the middle Eocene. Abundant feldspar and subordinate quartz–feldspar (including micropegmatite) intergrowths occurring among clasts of the sandstones sampled could be derived from such intrusive rocks. If the intrusive bodies were formed at a depth of 2–3 km, then the time interval between the zircon formation and its appearance in sediments would be not greater than the determination error of fission-track ages, provided that the bodies rose up to the surface at 500–1000 m/m.y. If the hypabyssal intrusions happened to be the main source of young zircons, we meet certain difficulties by interpreting variations in the average age of young zircon populations in different samples. If we assume that they indicate ages of sampled sediments, this would mean the constant rate of rising of intrusive bodies to the surface during the whole period of accumulation of the Lesnaya Group. In such a case, the provenance should be eroded down to the depth of 5 km during 10 m.y. so that the older intrusions would be eroded completely, while younger intrusive bodies were brought to the surface. Admitting such a deep erosion, we may expect considerable changes in composition of sandstone with time. However, we do not see changes of that sort in sampled sandstones. Hence, it more probable that we sampled a narrow stratigraphic interval of the youngest beds of the Lesnaya Group, and the age variations of young zircon populations reflect changes in the drainage areas that supplied the basin of sedimentation with detrital material. In this case, the land rise could be slower and the erosion not so deep.

Zircons, the fission-track age of which is synchronous or almost synchronous to sedimentation, may appear in the provenance as the result of a rapid exhumation of young intrusions and any zircon-bearing rocks from the depth, where the temperature exceeded the blocking one. If the exhumation rate exceeded 2000 m/m.y. and the geothermal gradient in the provenance was 50°C, then the time difference between the zircon cooling in the initial collector and its burial in sediment was not greater than 3 m.y. As the Lower Paleogene sequences of the western Kamchatka coast are represented by coarse molasses (Gladenkov *et al.*, 1997), a fast rise and deep erosion of individual blocks in the provenance are quite possible. The high geothermal gradient assumed above is plausible, because manifestations of the Paleocene–Eocene volcanism are known in the western Kamchatka. In this case, we should assume a considerable differentiation of tectonic movements that would mean that the most frequent zircons (population P2) are derived from rocks cooled in the Late Cretaceous, some others (population P3) are related in origin to the basement salients, which experienced the pre-Late Cretaceous thermal impact, and the young population (P1) characterizes blocks which rapidly rose from the depth, where the temperature exceeded the blocking one. In this case, the variable average ages of young zircon populations from different samples can be explained by different exhumation rates of individual blocks.

The newly established upper limit of the Lesnaya Group is important for understanding its relationships with the Paleocene–lower Eocene molasses of the western Kamchatka coast (Gladenkov *et al.*, 1997). According to our data, the upper part of the Lesnaya Group and molasses of the western Kamchatka could be considered as facies analogues of the Paleocene–early Eocene time. In such a case, it is understandable why the latter do not occur above the Lesnaya Group. At the same time, facies transitional between the molasses and Lesnaya Group have never been described, though Grechin (1979) mentioned individual thin coal measures occurring among deposits of the Lesnaya Group and suggesting possible facies interrelations between molasse and flysch. Searching for facies of this kind is an important problem to be solved. Moreover, new data imply important tectonic consequences: folding of the Lesnaya Group and formation of the Lesnaya thrust fault, an important tectonic suture, happened during a short period of time about 45 Ma ago, when sediments in the upper part of the Lesnaya Group were still unconsolidated. Data on the folded structure of the Lesnaya Group suggest that deformations affected the pliant sediments (Shapiro and Solov'ev, 1999).

We hope the information presented may give impetus to a new study and reinterpretation of many problems of regional geology.

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REFERENCES

Baldwin, S.L., Harrison, T.M., and Burke, K., Fission-Track Evidence for the Source of Accreted Sandstones, Barbados, *Tectonics*, 1986, vol. 5, pp. 457–468.

Bogdanov, N.A., Vishnevskaya, V.S., Kepezhinskas, P.K., Sukhov, A.N., and Fedorchuk, A.V., *Geologiya yuga Koryakskogo nagor'*ya (Geology of the Southern Koryak Upland), Moscow: Nauka, 1987.

Brandon, M.T., Decomposition of Fission-Track Grain-Age Distributions, *Am. J. Sci.*, 1992, vol. 292, pp. 535–564.

Brandon, M.T., Probability Density Plot for Fission-Track Grain-Age Samples, *Radiation Measurements*, 1996, vol. 26, no. 5, pp. 663–676.

Brandon, M.T. and Vance, J.A., Tectonic Evolution of the Cenozoic Olympic Subduction Complex, Western Washington State, as Deduced from Fission Track Ages for Detrital Zircon, *Am. J. Sci.*, 1992, vol. 292, pp. 565–636.

Carter, A., Bristow, C., and Hurford, A.J., The Application of FT Analysis to the Dating of Barren Sequences: Examples from Red Beds in Scotland and Thailand, *Non-Biostratigraphic Methods of Dating and Correlation*, Dunay, R.E. and Hailwood, E.A., Eds., *Geol. Soc. London. Spec. Publ.*, 1995, no. 89, pp. 57–68.

Dickinson, W.R. and Suczek, C.R., Plate Tectonics and Sandstone Composition, *Bull. Am. Assoc. Petrol. Geol.*, 1979, vol. 63, pp. 2164–2182.

Ermakov, B.V. and Suprunenko, O.I., Structure and Formation Conditions of Late Cretaceous and Miocene Flysch Formations in the Koryak–Kamchatka Region, *Sov. Geol.*, 1975, no. 12, pp. 53–65.

Fedorchuk, A.V. and Izvekov, I.N., New Data on the Structure of the Northern Sredinnyi Range in Kamchatka, *Izv. Ross. Akad. Nauk, Ser. Geol.*, 1992, no. 12, pp. 147–151.

Filatova, N.I., *Periokeanicheskie vulkanicheskie poyasa* (Peri-Oceanic Volcanic Belts), Moscow: Nedra, 1988.

Fleisher, R.L., Price, P.B., and Walker, R.M., Nuclear Tracks in Solids, *University of California Press*, Berkeley (CA), 1975.

Galbraith, R.F., Graphical Display of Estimates Having Differing Standard Errors, *Technometrics*, 1988, vol. 30, pp. 271–281.

Galbraith, R.F. and Green, P.F., Estimating the Ages in a Finite Mixture, *Nuclear Tracks Radiation Measurements*, 1990, vol. 17, no. 3, pp. 197–206.

Garver, J.I. and Brandon, M.T., Fission-Track Ages of Detrital Zircon from Mid-Cretaceous Sediments of the Methow-Tyaughton Basin, Southern Canadian Cordillera, *Tectonics*, 1994, vol. 13, no. 2, pp. 401–420.

Garver, J.I., Brandon, M.T., Roden-Tice, M., and Kamp, P.J.J., Exhumation History of Orogenic Highlands Determined by Detrital Fission-Track Thermochronology, *Exhumation Processes: Normal Faulting, Ductile Flow and Erosion*, Ring, U., Brandon, M.T., Lister, G.S., Willett, S.D., Eds., *Geol. Soc. London. Spec. Publ.*, 1999, no. 154, pp. 283–304.

Garver, J.I., Bullen, M.E., Brandon, M.T., *et al.*, Age and Thermal History of the Ukelayat Flysch and Its Bearing on the Timing of Collision of the Olyutorskii Terrane, Northern Kamchatka, Russian Far East, *6th International Zonenshain Conference, Moscow, Russia*, Moscow: Inst. Oceanol. Ross Akad. Nauk, 1998, pp. 173–174.

Garver, J.I., Soloviev, A.V., Bullen, M.E., and Brandon, M.T., Volcanism and Exhumation of the Okhotsk-Chukotka Arc (Russia) Revealed by Detrital Fission-Track Ages of Zircon, *Physics and Chemistry of the Earth* (in press).

Geologicheskaya karta SSSR. Masshtab 1 : 1000000 (novaya seriya). List O-57 (58)–Palana. Ob"yasnitel'naya zapiska (Geological Map of the Soviet Union, Scale 1 : 1000000, Sheet O-57 (58)–Palana. Explanatory Notes), Leningrad: Vses. Geol. Inst., 1989.

Gladenkov, Yu.B., Shantser, A.E., Chelebaeva, A.I., *et al.*, *Nizhnii paleogen Zapadnoi Kamchatki (stratigrafiya, paleogeografiya, geologicheskie sobytiya)* (Lower Paleogene of Western Kamchatka: Stratigraphy, Paleogeography, and Geological Events), Moscow: GEOS, 1997.

Gladenkov, Yu.B., Sinel'nikova, V.N., Shantser, A.E., Chelebaeva, A.I., *et al.*, *Eotsen Zapadnoi Kamchatki* (The Eocene of Western Kamchatka), Moscow: Nauka, 1991.

Grechin, V.I., Upper Cretaceous Volcano-Sedimentary Formations in Various Structural Zones of Kamchatka, *Osadkonakoplenie i vulkanizm v geosinklinal'nykh basseinakh* (Sedimentation and Volcanism in Geosynclinal Basins), Moscow: Nauka, 1979, pp. 130–149.

Hurford, A.J., Zeta: the Ultimate Solution to Fission-Track Analysis Calibration Or Just an Interim Measure?, *Advances in Fission-Track Geochronology*, Kluwer, 1998, pp. 19–32.

Hurford, A.J. and Carter, A., The Role of Fission-Track Dating in Discrimination of Provenance, *Geol. Soc. London. Spec. Publ.*, 1991, no. 57, pp. 67–78.

Hurford, A.J., Fitch, F.J., and Clarke, A., Resolution of the Age Structure of the Detrital Zircon Populations of Two Lower Cretaceous Sandstones from the Weald of England by Fission-Track Dating, *Geol. Mag.*, 1984, vol. 121, pp. 269–277.

Kazimirov, A.D., Krylov, K.A., and Fedorov, P.I., Tectonic Evolution of Marginal Seas: Evidence from the Southern Koryak Upland, *Ocherki po geologii Severo-Zapadnogo sektora Tikhookeanskogo tektonicheskogo poyasa* (Geological Sketches on the Northwestern Sector of Pacific Tectonic Belt), Moscow: Nauka, 1987, pp. 200–225.

Pettijohn, F.J., Potter, R., and Siever, R., *Sand and Sandstone*, Heidelberg: Springer, 1972.

Price, P.B. and Walker, R.M., Fossil Tracks of Charged Particles in Mica and the Age of Minerals, *J. Geophys. Res.*, 1963, vol. 68, pp. 4847–4862.

Shantser, A.E., Shapiro, M.N., Koloskov, A.V., *et al.*, The Cenozoic Structural Evolution of the Lesnaya Uplift and Adjacent Territories (Northern Kamchatka), *Tikhookean. Geol.*, 1985, no. 4, pp. 66–74.

Shapiro, M.N. and Fedorov, P.I., Basalts in the Cretaceous Terrigenous Sequence of the Sredinnyi Range in Kamchatka, *Izv. Vyssh. Uchebn. Zaved., Geol. Razv.*, 1985, no. 5, pp. 22–29.

Shapiro, M.N. and Solov'ev, A.V., Structure and Evolution of the Lesnov Overthrust (Northern Kamchatka), *Tikhookean. Geol.*, 1999, vol. 18, no. 6, pp. 71–82.

Shapiro, M.N., Markevich, P.S., Grechin, V.I., and Konstantinovskaya, E.A., The Cretaceous–Paleogene Sandstones of Kamchatka: Composition and Problems of Provenance, *Litol. Polezn. Iskop.*, 1993, no. 1, pp. 36–49.

Shapiro, M.N., Raznitsyn, Yu.N., Shantser, A.E., and Lander, A.V., Northeastern Structures around the Metamorphic Massif in the Sredinnyi Range of Kamchatka, *Ocherki po geologii Vostoka SSSR* (Studies on Geology of the Eastern Soviet Union), Moscow: Nauka, 1986, pp. 5–21.

Shukolyukov, Yu.A., Krylov, I.N., Tolstikhin, I.N., and Ovchinnikova, G.V., Uranium Fission-Tracks in Muscovite, *Geokhimiya*, 1965, no. 3, pp. 291–301.

Shutov, V.D., Kossovskaya, A.G., Murav'ev, V.I., *et al.*, *Grauvakki* (Graywackes), Moscow: Nauka, 1972.

Solov'ev, A.V., Brandon, M.T., Garver, J.I., *et al.*, Collision between the Olyutorskii Island Arc and Eurasian Continental Margin: Kinematic and Age Aspects, *Dokl. Akad. Nauk*, 1998, vol. 360, no. 5, pp. 666–668.

Wagner, G.A. and Van Den Haute, P., *Fission-Track Dating*, Kluwer, 1992.