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Sources of Zircons from Cretaceous and Lower Paleogene Terrigenous Sequences of the Southern Koryak Upland and Western Kamchatka

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Abstract—The mineral composition of sandstones from Cretaceous–Lower Paleocene terrigenous sequences of the western Kamchatka–Ukelayat zone (southern Koryak Upland, western Kamchatka) suggests that the Okhotsk–Chukot volcanogenic belt and fragments of the Uda–Murgal island arc served as the most probable provenance. Fission-track dating of zircon showed that sandstones from this zone contain detrital zircon of several different-age populations. Fission tracks in zircon grains were nor subjected to secondary ignition. The age of young zircon population coincides with the biostratigraphic age of host sequences. Thus, results of dating of detrital zircon grains from sandstones, which did not experience heating above 215–240°C, indicate that this method is appropriate for dating fossil-free terrigenous sequences. The young zircon population in the sandstones is related to erosion of plagiogranite and diorite intrusions of the Uda–Murgal arc and outer zone of the Okhotsk–Chukot volcanic belt exposed at the day surface owing to differential vertical movements and rapid exhumation of blocks.

The southern Koryak Upland located north and northwest of the Olyutor zone composed of Upper Cretaceous siliceous–volcanogenic sequences (Bogdanov *et al.*, 1987) hosts the Ukelayat trough (Central Koryak structural-facies zone) (Ermakov and Suprunenko, 1975). The trough is filled with highly deformed Upper Cretaceous and Lower Paleogene sandy–shaly sequences frequently of the flyschlike appearance (Ermakov *et al.*, 1974; Kazimirov *et al.*, 1987; Chekhovich, 1993). Terrigenous sequences, close in age and lithology, are developed in the Kamchatka Isthmus (Lesnaya Group and Getkilnin Formation) and also occur as isolated salients of the pre-Eocene basement in southern areas of western Kamchatka (Omgon Group, Mainach and Tal'nitsa formations) (*Geologiya SSSR*, 1964; *Geologicheskaya karta…*, 1989; Grechin, 1979) (Fig. 1). We define the distribution area of these sequences as the western Kamchatka–Ukelayat zone. Its probable continuation is represented by exposures of Upper Cretaceous sequences on western slopes of the Sredinnyi Range south of the Ichi River (Kikhchik Group, Khozgon Formation). Most researchers consider terrigenous sequences of the western Kamchatka–Ukelayat zone as sediments accumulated at the foot of the continental slope of Eurasia (Ermakov and Suprunenko, 1975; Til'man and Bogdanov, 1992; Sokolov, 1992; Shapiro, 1995; Chekhovich, 1993; *Ob"yasnitel'naya zapiska…*, 2000). The terrigenous sedimentation basin probably existed from the Cretaceous to the mid-Eocene when Upper Cretaceous and Lower Paleocene siliceous–volcanogenic rock complexes of the Olyutor–Kamchatka island-arc system was accreted to Eurasia (Shapiro, 1995; Soloviev *et al.*, 1998).

Terrigenous sequences of the western Kamchatka–Ukelayat zone contain occasional macrofaunal remains. Their dating was mainly based on microfaunal and microfloral fossils (benthic foraminifers, radiolarians, and nannoplankton). The age determination was promoted by the application of the detrital thermochronology method (Brandon and Vance, 1992; Garver and Brandon, 1994; Garver *et al.*, 1999). The use of the fission-track method for dating zircons from terrigenous sequences of southern Koryak Upland and western Kamchatka showed that sandstones enclose several populations of detrital zircon (Garver *et al.*, 1998, 2000; Soloviev *et al.*, 2001). Fission-track ages of zircons from the studied sequences correspond to their cooling in parental rocks of the provenance. Inasmuch as the sedimentary sequence is not older than enclosed zircons, fission-track measurements of the youngest population provide the younger age limit of host sandstones. This provides an opportunity to estimate both spatial and temporal variations of sandstone composition and, thus, to study the nature and evolution of the provenance.

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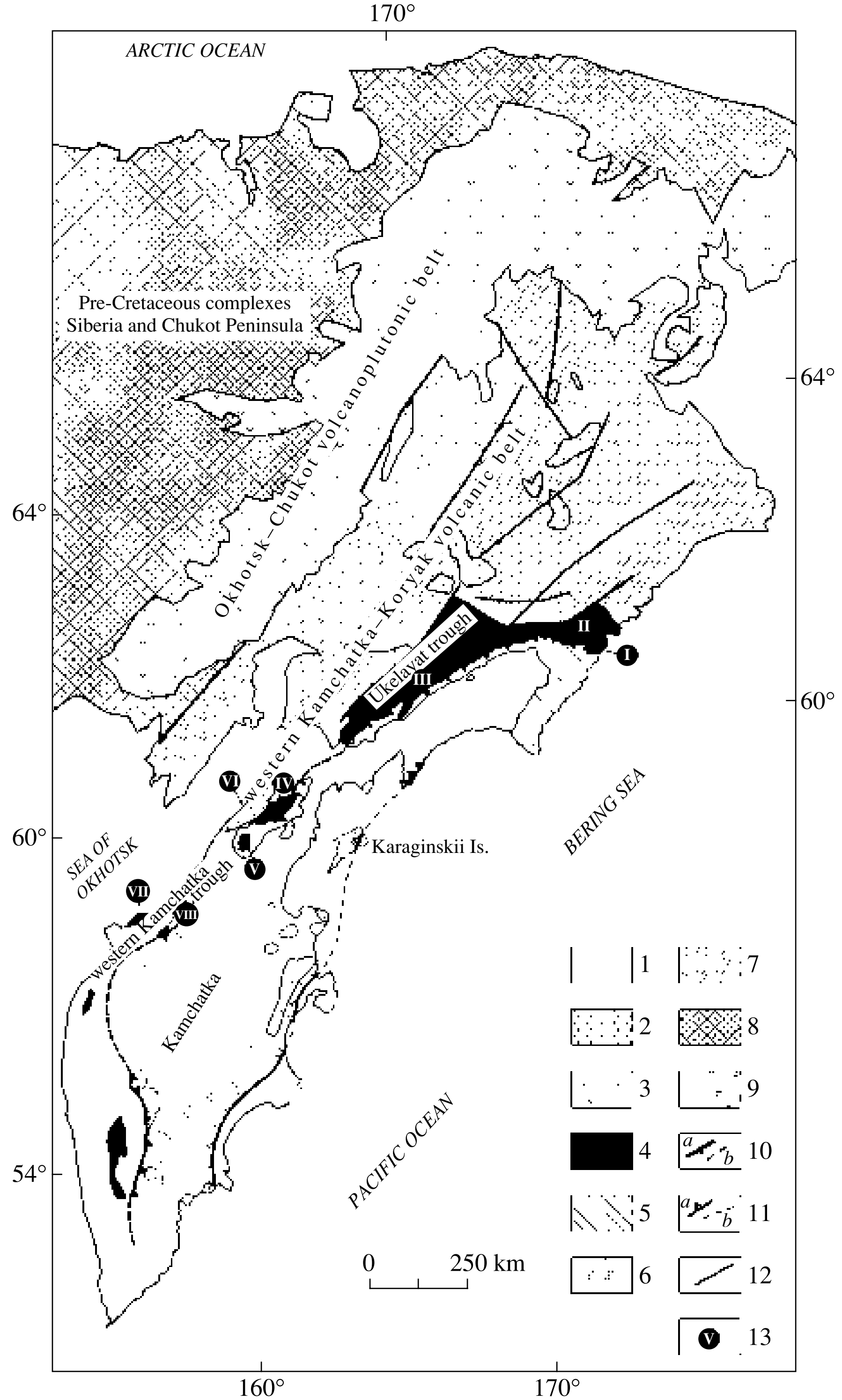

Fig. 1. Tectonic structure of Northeast Russia (modified after Til'man and Bogdanov, 1992; Shapiro, 1995; *Ob"yasnitel'naya zapiska…*, 2000). (1) Cenozoic cover of the southern Koryak Upland and Kamchatka; (2) western Kamchatka–Koryak volcanic belt (Eocene–Oligocene); (3) Okhotsk–Chukot volcanic belt (Cretaceous); (4) western Kamchatka–Ukelayat zone (Cretaceous–Eocene); (5) Olyutor–Kamchatka island-arc system (Late Cretaceous–Paleocene); (6) Kronotsk island arc (Late Cretaceous–Eocene); (7) terranes accreted in the Mesozoic; (8) pre-Cretaceous rock complexes of Siberia and Chukot Peninsula; (9) metamorphic rock complexes of Kamchatka; (10, 11) regional thrusts: (10) Vatyna–Lesnaya: (*a*) proven, (*b*) assumed, (11) Tyushevsk–Govena: (*a*) proven, (*b*) assumed; (12) other faults; (13) location and number of the study area.

BRIEF CHARACTERISTICS OF TERRIGENOUS SEQUENCES IN THE WESTERN KAMCHATKA–UKELAYAT ZONE

Terrigenous sequences of the western Kamchatka–Ukelayat zone were studied on the southern Koryak Upland (Ukelayat flysch, Fig. 1, areas I–III), Kamchatka Isthmus (Lesnaya Group, Fig. 1, areas IV, V), and western coast of Kamchatka (Omgon Group, Fig. 1, areas VII, VIII). In addition, we examined some sandstone samples from the Getkilnin (Fig. 1, area VI) and Snatol (Fig. 1, area VII) formations and from a melange block beneath the Lesnaya thrust (Fig. 1, area IV).

In terms of lithology, the Ukelayat and Lesnaya sandy–argillite groups are similar. They are mostly composed of distal turbidites and contourites that are intensely deformed into small folds and barren of macrofaunal remains. Therefore, reference sections of these units were never described and their thickness was only arbitrarily estimated. Their lower boundary is also unknown. The Ukelayat Group forms an autochthon of the Vatyna–Vyvenka thrust (Til'man and Bogdanov, 1992; Soloviev *et al.*, 1998), and the Lesnaya Group composes an autochthon of its southwestern continuation, i.e., the Lesnaya thrust (Shantser *et al.*, 1985; Shapiro and Soloviev, 1999). Based on benthic foraminifers, the age of the Ukelayat Group is possibly Late Cretaceous–Early Eocene (Ermakov *et al.*, 1974). Nannoplankton from argillites of the Lesnaya Group indicates its Paleocene–earliest Eocene age (Fedorchuk and Izvekov, 1992; Shapiro *et al.*, 2001).

Tectonic melange at the Lesnaya thrust base is observed in the Lesnaya River basin (Fig. 1, areas IV, V), where the sandy–argillite matrix in the Lesnaya Group rocks encloses size-variable blocks of tuff, chert, basalt, and sandstone (Shantser *et al.*, 1985; Shapiro and Soloviev, 1999). The sandstone is similar to the counterpart from the Lesnaya Group, except for a higher quartz content and occasional occurrence of chert and inoceram coquina beds. We consider these blocks outliers of the lower Lesnaya Group or easterly facies zones now overlapped by the Lesnaya thrust.

The Ukelayat Group has no stratigraphic contacts with other pre-Pliocene rock complexes (Bogdanov *et al.*, 1987), whereas the Lesnaya Group is unconformably overlain by Eocene Snatol and Kinkil formations (Shantser *et al.*, 1985; Gladenkov *et al.*, 1991) and is intruded by Middle Eocene granites (Fedorchuk and Izvekov, 1992; Soloviev *et al.*, 2000).

The Omgon Group in the synonymous ridge area (Fig. 1, area VII) is represented by flysch with abundant conglomerate and gravelstone beds. The latter can be considered the shallow shelf facies or proximal (riverbed) facies of the submarine fan. Judging from diverse faunal and floral remains described from these layers (*Geologiya SSSR*, 1964), the first assumption is more probable. The fauna and flora suggest that terrigenous sediments of the Omgon Group accumulated during the Albian–Early Senonian (Coniacian) interval. An imbricate structure of the area inhibits the subdivision of the Omgon Group into smaller units. The Omgon Group domain includes exposed tectonic sheets composed of Jurassic–Cretaceous basalts and cherts (Bondarenko and Sokolkov, 1990; Bogdanov *et al.*, 1991; Soloviev *et al.*, 2000). They are overlain with a sharp unconformity by the Middle Eocene Snatol Formation (*Geologicheskaya karta…*, 1989), the basal part of which is composed of conglomerates.

In the Sedanka Settlement area (Fig. 1, area VIII), sandstones and argillites of the Mainach Formation of the Omgon Group (*Geologicheskaya karta…*, 1989) are overlain by a pillow basalt unit with the cherty bed at its base. No faunal remains are found in the flysch unit. Therefore, its belonging to the Mainach Formation (Omgon Group) is rather arbitrary.

The Getkilnin Formation exposed at the sea coast north of the Lesnaya Settlement (Fig. 1, area VI) is largely composed of medium- to coarse-grained sandstones with thin interbeds of carbonaceous siltstones. Based on faunal and floral remains sampled in northern coastal areas, the formation is referred to the Paleocene (Gladenkov *et al.*, 1997). It is overlain by Middle Eocene Kinkil volcanic rocks (*Geologicheskaya karta…*, 1989).

COMPOSITION OF SANDSTONES

The composition of detrital material from sandstones examined in 29 thin sections is shown in Tables 1 and 2. All studied sandstone samples belong to the graywacke class (Pettijohn *et al.*, 1976), i.e., the matrix composes 25 to 35 vol %. Most of the clasts are angular.

In line with classification by Shutov *et al.* (1972), all sandstones correspond to the quartzofeldspathic and feldspathic–quartzose graywackes and mostly include clasts of quartz, feldspar, and fine-grained rocks. Fragments of colored minerals are rare and consist of small mica flakes. Ore minerals are extremely rare (up to 1%). Clasts are mainly composed of various volcanic or sedimentary rocks. Some grains (up to 5%) are composed of fine-grained mineral aggregates of unclear genesis. Clasts of metamorphic rocks (quartzites and micaceous shales) are rare (up to 3%) but ubiquitous.

Fragments of volcanic rocks can be divided into four groups. The first three groups are characterized by the presence of laths or microlithic and felsitic textures. The fourth group consists of weathered glass, which is a groundmass of volcanic rocks. Clasts of groups 1–3 correspond, in general, to basalts, andesites, and rhyodacites. The composition of weathered glass was not determined.

Fragments of sedimentary rocks mainly consist of argillite (up to 25%). Fine-grained tuffogeneous rocks, clayey–siliceous tuffites, and less common ash tuffs are subordinate. Cherts, which are most stable among sedimentary rocks, are rare (1–4%, sometimes up to 7%). This is typical of rocks from the Omgon Cape section

Table 1. Composition of sandstones from the western Kamchatka–Ukelayat zone

Sample	Qm	Qp	Qq	P	Lvl	Lvm	Lvf	Lvv	Lm	Lssh	Lsa	Lss	Lsch	Lst	Lso	Op	nOp	U	T	Mtx	Aut
					Lv					Ls											
(I) Ukelayat zone (Anastasiya Bay area)																					
JG93-2	48	6	2	100	5	19	18	14	–	2	51	2	2	11	–	5	3	12	200	129	18
(II) Ukelayat zone (Il'pi and Matysken rivers area)																					
JG95-7	32	3	5	74	30	65	15	20	1	2	24	3	1	11	–	2	–	12	300	87	14
JG95-41	13	7	9	83	14	62	17	10	2	2	41	–	21	10	1	–	–	8	300	120	–
JG95-16	52	7	4	62	9	12	28	17	6	2	56	6	4	17	3	1	2	12	300	125	6
JG95-19	29	5	3	98	13	38	31	26	–	3	29	1	2	7	2	1	2	10	300	87	9
JG95-29A	13	22	4	34	24	23	11	24	–	1	80	12	12	28	2	–	1	9	300	110	6
(III) Ukelayat zone (Tapel'vayam River area)																					
96JG-21	77	26	4	99	3	11	14	5	7	1	22	–	3	21	2	–	2	3	300	56	3
96JG-7	57	10	2	86	6	10	25	13	6	–	49	5	5	16	–	–	–	10	300	120	40
96JG-14	57	10	6	88	5	31	25	10	8	2	21	4	7	8	1	–	2	15	300	158	4
96JG-20	64	17	1	92	7	9	28	19	6	2	19	4	5	16	1	–	2	8	300	81	21
(IV) Lesnaya Uplift (Shamanka dome)																					
Sh3/99	46	5	–	37	2	14	15	10	4	4	21	11	12	12	–	–	2	5	200	67	28
Sh2/99	89	17	2	81	12	24	40	25	10	8	29	17	10	22	–	–	5	7	400	160	3
Sh15/99	49	8	8	51	–	11	27	14	7	2	1	3	6	5	–	–	–	8	200	70	11
(V) Lesnaya Uplift (Vatapvayam dome)																					
L12	62	21	9	72	9	18	27	19	2	4	23	7	4	7	9	–	1	6	300	89	9
L1	63	12	4	91	8	22	25	22	6	5	20	5	2	6	–	3	1	5	300	116	17
L9	62	12	3	87	3	9	29	16	2	2	35	15	9	4	1	–	–	11	300	119	27
L2	75	16	14	59	2	14	27	8	7	8	34	4	10	5	2	2	2	11	300	83	8
L11	64	17	3	79	6	18	30	15	3	4	30	8	7	7	1	1	–	7	300	89	22
L10	66	19	3	83	4	23	24	13	2	1	32	6	7	9	–	2	–	6	300	102	14
L17	83	11	3	89	4	14	18	44	2	1	9	3	3	5	3	1	2	5	300	97	3
L13	66	17	4	68	10	28	14	39	6	–	16	1	9	10	3	–	–	9	300	96	7
L4	75	15	3	69	12	16	25	33	5	1	18	4	4	9	–	–	–	11	300	132	36
(VI) Western Kamchtaka (eastern coast of the Sea of Okhotsk)																					
Sh34/99	71	19	4	63	7	22	16	28	2	4	10	12	9	19	–	–	3	9	300	107	58
Sh22/99	47	12	3	50	5	9	8	8	2	2	19	7	10	9	–	–	1	8	200	51	33
(VII) Western Kamchtaka (Omgon Ridge)																					
OM3	23	1	5	88	12	38	14	37	3	4	26	13	–	23	3	–	2	8	300	98	12
OM39	28	4	3	60	25	60	18	25	7	1	12	15	3	28	–	1	7	3	300	56	9
OM27	19	1	–	99	5	30	23	43	–	3	35	9	–	13	3	4	3	10	300	106	10
OM24	34	9	4	84	22	43	11	37	3	6	13	2	4	17	2	–	2	7	300	86	2
(VIII) Western Kamchtaka (Rossoshina River valley)																					
OM48	47	2	–	84	3	25	19	33	2	4	34	9	4	14	5	1	4	10	300	123	8

Notes: Roman numbers designate sampling areas shown in Fig. 1.

(Qm) monocrystalline quartz; (Qp) polycrystalline quartz; (Qq) quartzites of unclear origin; (P) feldspar; fragments of fine-grained rocks: (Lv) volcanics, (Lvl) volcanics with the lath texture (mainly mafic and intermediate), (Lvm) rocks with the microlitic texture (mainly andesite, dacite, and their analogues), (Lvf) acid rocks with the felsitic texture, (Lvv) recrystallized glass barren of microlites, (Lm) metamorphic rocks (including metaquartzites), (Ls) sedimentary rocks, (Lssh) shales, (Lsa) argillite and aleuropelite, (Lss) siltstone and fine-grained sandstone, (Lsch) cherts, (Lst) tuff, tuffogene silicilith, and tuffogene argillites, (Lso) other sedimentary rocks (carbonate, coal), (Op) ore minerals, (nOp) colored minerals, (U) undetermined rock fragments; (T) total number of determinations of grain composition in thin section, (Mtx) matrix and cement, (Aut) authigenic minerals.

Table 2. Composition of sandstones from the western Kamchatka–Ukelayat zone

Sample	T	Q	F	L	L(vms)	V	M	S	V(lmf)	Vl, %	Vm, %	Vf, %	%mtx	Age, Ma
(I) Ukelayat zone (Anastasiya Bay area)														
JG93-2	300	19	33	48	124	45	–	55	42	12	45	43	22	44.8 ± 3.7
(II) Ukelayat zone (Il’pi and Matysken rivers area)														
JG95-7	300	13	25	62	172	75	1	24	110	27	59	14	22	43.9 ± 3.6
JG95-41	300	10	28	62	180	57	1	42	93	15	67	18	29	49.8 ± 8.0
JG95-16	300	21	21	58	160	41	4	55	49	18	24	58	29	51.3 ± 6.3
JG95-19	300	12	33	55	152	71	–	29	82	16	46	38	22	54.5 ± 3.7
JG95-29A	300	13	11	76	217	38	–	62	58	41	40	19	27	66.1 ± 6.3
(III) Ukelayat zone (Tapel’vayam River area)														
96JG-21	300	36	33	31	89	37	8	55	28	11	39	50	16	58.0 ± 3.2
96JG-7	300	23	29	48	135	40	4	56	41	15	24	61	29	59.4 ± 2.3
96JG-14	300	24	29	47	122	58	7	35	61	8	51	41	34	61.8 ± 3.7
96JG-20	300	27	31	42	116	54	5	41	44	16	20	64	21	73.3 ± 3.2
(IV) Lesnaya Uplift (Shamanka dome)														
Sh3/99	200	25.5	18.5	56	105	39	4	57	31	6	45	49	25	51.6 ± 5.0
Sh2/99	400	27	20	53	197	51	5	44	76	16	32	52	29	54.1 ± 8.9
Sh15/99	200	32.5	25.5	42	76	68	9	23	38	–	29	71	26	86.1 ± 6.1
(V) Lesnaya Uplift (Vatapvayam dome)														
L12	300	31	24	45	129	57	2	41	54	17	33	50	23	43.7 ± 3.4
L1	300	26	30	44	121	64	5	31	55	15	40	45	28	46.0 ± 2.7
L9	300	26	29	45	125	46	2	52	41	7	22	71	28	47.0 ± 3.8
L2	300	35	20	45	121	42	6	52	43	5	33	62	22	48.1 ± 5.0
L11	300	28	26	46	129	53	2	45	54	11	33	46	23	50.4 ± 5.6
L10	300	29	28	43	121	53	2	45	51	8	45	47	25	53.9 ± 3.4
L17	300	32	30	38	106	75	2	23	36	11	39	50	24	54.5 ± 10.4
L13	300	29	23	48	136	67	4	29	52	19	54	27	24	55.5 ± 3.5
L4	300	31	23	46	127	68	4	28	53	23	30	47	31	58.1 ± 4.2
(VI) Western Kamchtaka (eastern coast of the Sea of Okhotsk)														
Sh34/99	300	31	21	48	129	57	2	41	45	16	49	35	26	58.5 ± 4.9
Sh22/99	200	31	25	44	79	38	3	59	22	23	41	36	20	59.0 ± 4.3
(VII) Western Kamchtaka (Omgon Ridge)														
OM3	300	10	29	61	173	58	2	40	64	19	59	22	25	80.0 ± 4.1
OM39	300	12	20	68	194	66	4	30	103	24	58	18	16	85.3 ± 4.2
OM27	300	7	33	60	164	62	–	38	58	9	52	39	26	99.8 ± 5.8
OM24	300	16	28	56	160	71	2	27	76	29	57	14	22	102.0 ± 18.9
(VIII) Western Kamchtaka (Rossoshina River valley)														
OM48	300	16	28	56	152	53	1	46	47	6	53	41	29	79.5 ± 8.0

Notes: Age with asterisk designates the age of youngest zircon population (Table 3). Roman numbers designate sampling areas shown in Fig. 1.
Total component values are calculated using formulas:
$Q = (Qm + Qp + Qq)/T \times 100$; $F = P/T \times 100$; $L = (T - Q - F)/T \times 100$; $L(vms) = Lv + Lm + Ls$; $V = Lv/(Lv + Lm + Ls) \times 100$; $M = Lm/(Lv + Lm + Ls) \times 100$; $S = Ls/(Lv + Lm + Ls) \times 100$; $V(lmf) = Lvl + Lvm + Lvs$; $Vl = Lvl/Vlmf \times 100$; $Vm = Lvm/Vlmf \times 100$; $Vf = Lvf/Vlmf \times 100$; $\%mtx = mtx/(mtx + T) \times 100$.

where the terrigenous Omgon Group overlies with presumable unconformity Jurassic–Early Cretaceous cherty–basaltic sequences (Bondarenko and Sokolkov, 1990). Coalified plant detritus is also common in these rocks.

Feldspars are mainly represented by plagioclase monocrystals. The alteration degree of plagioclases is variable. They vary from pure, almost colorless monocrystals, which are visually similar to quartz grains, to varieties almost completely replaced by secondary minerals (albite, sericite, epidote, and others). Pure colorless and, simultaneously, twinned plagioclase grains are rare. Aggregates of relatively fresh plagioclase grains most likely of intrusive genesis are common. The albite content amounts to 5–30% of the total plagioclase content. Plagioclase frequently forms clusters with quartz. Potassic feldspar occurs only as single grains and, therefore, is excluded from calculations. Its low abundance is also confirmed by results of feldspar dyeing in thin sections.

Quartz is mainly monocrystalline and usually highly deformed (distinct undulatory extinction). It is frequently highly blurred. Clusters with feldspars are subordinate. Undeformed pure grains with rare smoothed edges, which are typical of rhyolites, are practically absent. Relatively large polycrystalline aggregates of quartz are usually disordered and cannot be referred to metamorphic structures. The group of quartzose clasts also includes fine-grained aggregates of quartz grains (Qq), except for grains, which can undoubtedly be referred to metamorphic rocks based on orientation and admixture of micaceous minerals.

Newly formed authigenous minerals in sandstones are mainly represented by carbonates partly replacing the matrix and, sometimes, mineral grains.

RESULTS OF FISSION-TRACK DATING OF ZIRCONS

Principles of the Detrital Thermochronology

The fission-track dating of zircons is based on the measurement of density of tracks left by products of spontaneous fission of U^{238} nuclei, which accumulate in the mineral during the geological history (Price and Walker, 1963). Physical principles of the method are described elsewhere (Shukolyukov *et al.*, 1965; Fleischer *et al.*, 1975). The accumulation of tracks in zircon with time is a process similar to the accumulation of radiogenic isotopes as a result of radioactive decay. The track stability is controlled, first of all, by temperature; i.e., tracks are formed and preserved in crystals cooled below the effective closure temperature. The statistically effective closure temperature corresponds to the moment when more than 50% of tracks become stable (Wagner and Van Den Haute, 1992). If we assume that the sample uniformly cools under conditions typical of geological processes (the cooling rate of 1 to 30°C/Ma), the effective closure temperature for zircon will be equal to 215–240°C (Brandon and Vance, 1992).

Detrital thermochronology is based on fission-track dating of fragments of zircon and apatite grains from terrigenous and tuffogeneous rocks. This method makes it possible to discriminate thermal events responsible for provenance evolution and reveal the relationships between endogenic (magmatism, volcanism, orogeny) and exogenic (erosion, sedimentation) processes. First studies dedicated to this problem were performed approximately 15 years ago (Hurford *et al.*, 1984; Baldwin *et al.*, 1986). Nowadays, the detrital thermochronology is a popular tool in the study of depositional and tectonic processes in many regions of the world (Brandon and Vance, 1992; Garver and Brandon, 1994; Carter *et al.*, 1995; Garver *et al.*, 1999, 2000).

Inasmuch as the fission-track dating allows us to determine the age of individual mineral grains, it becomes possible to discriminate their different-age populations related to different provenances. Rock cooling in provenances can occur during different geological processes. For instance, volcanism and near-surface intrusions are characterized by cooling of newly formed minerals synchronously with their formation process, whereas the fission-track age of minerals can be significantly rejuvenated (relative to the age of mineral formation and host rocks) during exhumation of rocks from deep levels.

As was shown in several works, the fission-track age of detrital zircons, which did not experience secondary ignition, can be used for determining the age of terrigenous sediment accumulation. The age of the youngest population of zircon grains is close to that of sediment accumulation in case that synchronous volcanic activity occurred nearby during sedimentation (Brandon and Vance, 1992; Garver and Brandon, 1994; Garver *et al.*, 2000; Shapiro *et al.*, 2001; Soloviev *et al.*, 2001). In orogenic belts, which experienced rapid rise and erosion, exhumation of near-surface intrusions occurs during a sufficiently short period. Therefore, the time interval between crystallization of zircon grains in the near-surface intrusion and their sedimentation in the adjacent basin is considered to be several million years (Brandon and Vance, 1992; Garver and Brandon, 1994).

Fission-Track Age of Zircons from the Western Kamchatka–Ukelayat Zone

In total, 41 sandstone samples (4 to 10 kg each) were collected in eight areas of the western Kamchatka–Ukelayat zone (Fig. 1). Zircon grains were extracted from sandstones in the Laboratory of Accessory Minerals, Institute of the Lithosphere of Marginal Seas, RAS. The zircon age was measured in the Laboratory of Fission-Track dating, Union College (Schenectady, New York, United States). The method of an external detector was used for age measurements (Hurford and Carter, 1991). Zircon grains were pressed into FEP Teflon MT plates of 2×2 cm^2 in size. Two plates were prepared for each sample. Plates were abraded and then polished using diamond pastes (9 and 1 μm) and Al_2O_3 paste (0.3 μm) at the terminal stage. Chemical leaching of plates was performed using NaOH–KOH at 228°C during 15 h (first plate) and 30 h (second plate). After chemical leaching, plates were covered by the detector (low-uranium mica) and irradiated in a thermal neutron flow of approximately

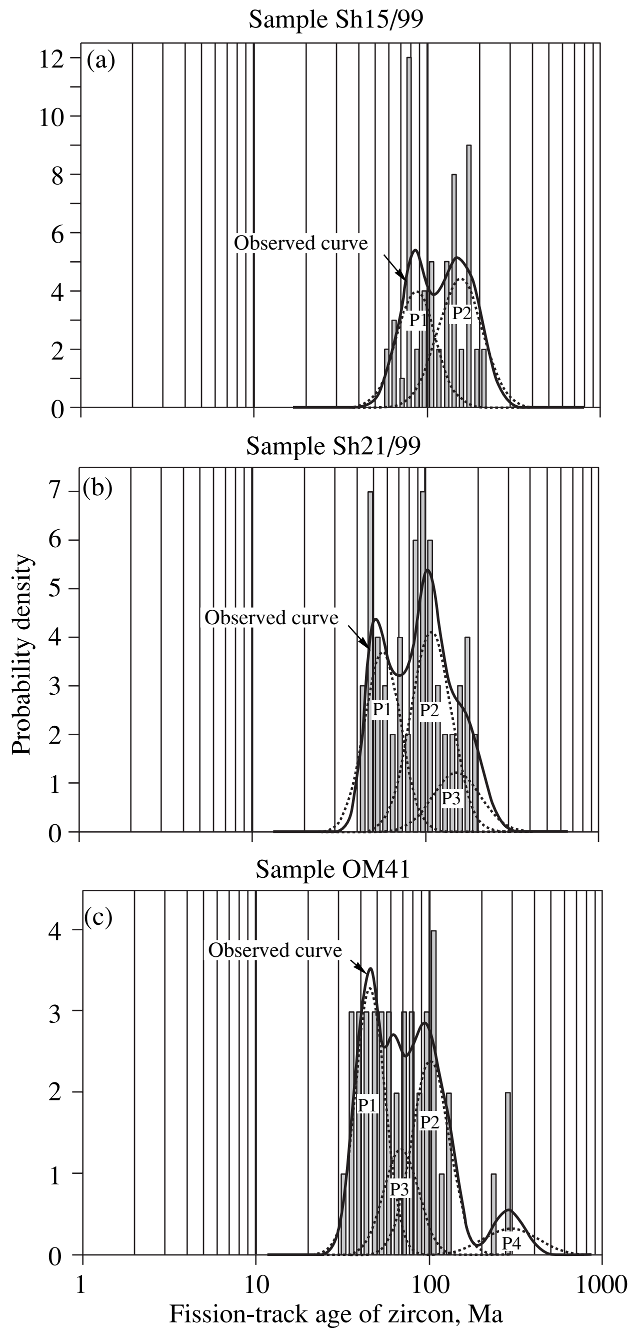

Fig. 2. Distribution of fission-track ages of zircon grains from some sandstone samples (a, b, c). Sample locations: (Sh15/99) Lesnaya Group (block), (Sh21/99) Lesnaya Group, (OM41) Snatol Formation (Table 1). (P1, P2, P3, P4) peaks of different-age populations (Table 1) defined using the Binomfit 1.8 program (Brandon, 1996).

2×10^{15} neutron/cm^2 in the reactor of the Oregon University. Age standards for zircon (Fish Canyon tuff, FCT and Buluk tuff, BT) and glass dosimeter (CN-5) with known uranium content (Hurford, 1998) were also irradiated together with samples. The tracks were counted using an Olympus BH-P microscope with an automatic system and a digital plotting board at the highest magnification of 1256X (dry method). The Z factor calculated from ten age standards (six FCT samples and four BT samples) was equal to 305.01 ± 6.91 (Hurford, 1998).

From 10 to 90 zircon grains were dated for each sample (Table 3). The Zetaage 4.7 program by M.T. Brandon (Yale University, USA) was used to calculate the age of zircon grains. The age of separate grains is scattered within a wide interval (Fig. 2), which indicates the presence of several different-age zircon populations. In our study, we used Brandon's Binomfit 1.8 program supplemented by Galbraith's algorhytm (1988) for the discrimination of different-age populations. The Zetaage 4.7 and Binomfit 1.8 programs are available for every anonymous user at http:\\love.geology.yale.edu/~brandon.

From two to four different-age zircon populations are present in all studied samples (Table 3). The study of apatite from the same samples and secondary minerals from argillites allows a conclusion that terrigenous sequences were not heated after sedimentation to temperatures above 215–240°C (Garver *et al.*, 1998, 2000). Thus, the age of zircon populations reflects thermal events in the provenance.

Tables 3 and Fig. 4a show that the age of the youngest population in studied samples falls into a wide interval: from latest Albian to the mid-Eocene. At first approximation, this interval corresponds to the integral age interval of studied sequences estimated by independent biostratigraphic methods.

The oldest fission-track ages obtained for young-population zircons from the Omgon sandstones are 102 ± 18.9 to 80.0 ± 4.1 Ma. The age of the Omgon Group determined by the molluscan fauna and floral remains is estimated at the Albian–Early Senonian (Coniacian), i.e., 110–87 Ma (*Geologiya SSSR*, 1964). According to the fission-track dating of zircon (with consideration for the measurement error), the age interval of the Omgon Group should be widened at least to the Campanian (84 Ma), because sandstones should be younger than the youngest zircon grains in these rocks. The age of young zircon population from sandstones of the Snatol Formation is 45.2 ± 3.2 Ma, which corresponds to the Middle Eocene age of this formation. (Gladenkov *et al.*, 1997).

The study also provided the first age estimate for the Mainach Formation exposed in the Rossoshina River valley (Fig. 1, area VIII). The young zircon population is dated back to 77.7 ± 6.6 and 79.5 ± 8.0 Ma. Thus, these dates confirmed the validity of a conclusion that the Mainach Formation exposed in this area should be included into the Omgon Group.

The age of the young zircon population from the melange block developed after the Lesnaya Group rocks (Fig. 1, area IV) is equal to 86.1 ± 6.1 Ma. This value is close to that of the host block composed of Campanian rocks (83.5–71.5 Ma) based on the nannoplankton-based age estimate (Shapiro *et al.*, 2001). In

Table 3. Fission-track ages of detrital zircons from sandstones of the western Kamchatka–Ukelayat zone

Sample	Group, formation	Nt	Age of zircon population		
			P1	P2	P3
(I) Ukelayat zone (Anastasiya Bay area)					
JG93-2	Ukelayat	10	47.8 ± 3.7 (90%) W = 0.22	–	166.0 ± 56.5 (10%) W = 0.39
(II) Ukelayat zone (Il'pi and Matysken rivers area)					
JG95-7	Ukelayat	46	43.9 ± 3.6 (42%) W = 0.26	76.4 ± 6.3 (58%) W = 0.31	–
JG95-41	Ukelayat	46	49.8 ± 8.0 (38%) W = 0.28	89.3 ± 15.4 (51%) W = 0.27	151.9 ± 57.4 (11%) W = 0.31
JG95-16	Ukelayat	43	51.3 ± 6.3 (41%) W = 0.30	85.7 ± 9.4 (54%) W = 0.27	188.2 ± 56.2 (5%) W = 0.29
JG95-19	Ukelayat	78	54.5 ± 3.7 (50%) W = 0.25	97.7 ± 7.2 (50%) W = 0.28	–
JG95-39	*Ukelayat*	*37*	*57.8 ± 3.7 (91%)* *W = 0.30*	–	*134.5 ± 50.8 (9%)* *W = 0.31*
JG95-29A	Ukelayat	50	66.1 ± 6.3 (59%) W = 0.35	112.2 ± 14.7 (41%) W = 38%	–
(III) Ukelayat zone (Tapel'vayam River area)					
96JG-18	*Ukelayat*	*32*	*54.8 ± 2.8 (39%)* *W = 0.15*	*88.3 ± 6.2 (43%)* *W = 0.16*	*155.6 ± 13.4 (18%)* *W = 0.17*
96JG-21	Ukelayat	20	58.0 ± 3.2 (53%) W = 0.16	105.6 ± 7.1 (47%) W = 0.19	–
96JG-7	Ukelayat	32	59.4 ± 2.3 (29%) W = 0.12	118.3 ± 5.3 (45%) W = 0.17	241.9 ± 15.7 (26%) W = 0.20
96JG-14	Ukelayat	15	61.8 ± 3.7 (26%) W = 0.13	104.8 ± 8.0 (12%) W = 0.16	139.4 ± 13.7 (30%) W = 0.18
96JG-15	*Ukelayat*	*21*	*64.8 ± 2.3 (71%)* *W = 0.14*	*129.6 ± 9.6 (12%)* *W = 0.12*	*189.4 ± 13.7 (17%)* *W = 0.15*
96JG-4	*Ukelayat (block)*	*20*	*66.2 ± 3.1 (56%)* *W = 0.16*	–	*169.0 ± 11.1 (44%)* *W = 0.21*
96JG-6	*Ukelayat*	*20*	*69.1 ± 3.0 (55%)* *W = 0.14*	*137.7 ± 7.4 (45%)* *W = 0.16*	–
96JG-20	Ukelayat	20	73.3 ± 3.2 (40%) W = 0.12	119.6 ± 5.8 (36%) W = 0.12	189.3 ± 16.1 (24%) W = 0.17
96JG-13	*Ukelayat*	*15*	*78.2 ± 4.1 (47%)* *W = 0.15*	–	*173.0 ± 8.9 (53%)* *W = 0.16*
96JG-3	*Ukelayat*	*30*	*83.0 ± 3.3 (61%)* *W = 0.16*	*129.0 ± 7.1 (32%)* *W = 0.16*	*378.7 ± 54.7 (7%)* *W = 0.23*
96JG-25	*Ukelayat*	*30*	*87.9 ± 4.5 (40%)* *W = 0.14*	*124.9 ± 6.1 (40%)* *W = 0.13*	*206.9 ± 14.1 (20%)* *W = 0.18*
(IV) Lesnaya Uplift (Shamanka dome)					
Sh3/99	Lesnaya	60	51.6 ± 5.0 (27%) W = 0.26	86.7 ± 8.9 (55%) W = 0.28	131.4 ± 29.2 (18%) W = 0.31
Sh2/99	Lesnaya	75	54.1 ± 8.9 (16%) W = 0.27	73.9 ± 13.9 (26%) W = 0.26	132.6 ± 9.2 (58%) W = 0.31
Sh21/99	*Lesnaya*	*60*	*56.1 ± 3.8 (37%)* *W = 0.26*	*106.0 ± 11.5 (47%)* *W = 0.27*	*150.3 ± 34.2 (16%)* *W = 0.32*
Sh15/99	Lesnaya (block)	59	86.1 ± 6.1 (44%) W = 0.24	155.3 ± 11.0 (56%) W = 0.30	–

Table 3. (Contd.)

Sample	Group, formation	Nt	Age of zircon population		
			P1	P2	P3
(V) Lesnaya Uplift (Vatapvayam dome)					
L12	Lesnaya	67	43.7 ± 3.4 (17%) W = 0.19	70.6 ± 4.4 (67%) W = 0.22	107.0 ± 12.2 (16%) W = 0.23
L1	Lesnaya	45	46.0 ± 2.7 (49%) W = 0.22	–	107.3 ± 7.0 (51%) W = 0.25
L9	Lesnaya	90	47.0 ± 3.8 (19%) W = 0.19	70.8 ± 5.7 (56%) W = 0.21	104.0 ± 11.9 (25%) W = 0.25
L2	Lesnaya	90	48.1 ± 5.0 (7%) W = 0.19	78.1 ± 5.8 (53%) W = 0.22	116.0 ± 8.6 (40%) W = 0.23
L11	Lesnaya	90	50.4 ± 5.6 (20%) W = 0.22	70.6 ± 6.6 (65%) W = 0.24	109.7 ± 25.0 (15%) W = 0.26
L10	Lesnaya	90	53.9 ± 3.4 (40%) W = 0.21	87.5 ± 6.2 (50%) W = 0.22	176.5 ± 23.8 (10%) W = 0.29
L17	Lesnaya	90	54.5 ± 10.4 (5%) W = 0.20	84.6 ± 6.5 (65%) W = 0.20	134.6 ± 18.9 (30%) W = 0.24
L13	Lesnaya	89	55.5 ± 3.5 (34%) W = 0.21	93.0 ± 4.8 (66%) W = 0.23	–
L4	Lesnaya	90	58.1 ± 4.2 (36%) W = 0.23	83.3 ± 6.3 (51%) W = 0.24	130.5 ± 14.9 (13%) W = 0.24
(VI) Western Kamchtaka (eastern coast of the Sea of Okhotsk)					
Sh34/99	Getkilnin	60	58.5 ± 4.9 (32%) W = 0.25	98.1 ± 8.1 (53%) W = 0.27	173.6 ± 26.7 (15%) W = 0.32
Sh22/99	Getkilnin	60	59.0 ± 4.3 (45%) W = 0.26	107.0 ± 10.8 (48%) W = 0.27	192.1 ± 73.0 (7%) W = 0.32
(VII) Western Kamchtaka (Omgon Ridge)					
OM3	Omgon	75	80.0 ± 4.1 (95%) W = 0.26	175.7 ± 50.5 (5%) W = 0.37	–
OM39	Omgon	74	85.3 ± 4.2 (95%) W = 0.24	167.8 ± 33.6 (5%) W = 0.27	–
OM30	*Omgon*	*46*	*90.6 ± 9.0 (53%)* *W = 0.32*	*151.3 ± 17.3 (47%)* *W = 0.27*	–
OM27	Omgon	75	99.8 ± 5.8 (83%) W = 0.29	187.0 ± 27.9 (17%) W = 0.34	–
OM24	Omgon	75	102.0 ± 18.9 (19%) W = 0.24	142.2 ± 12.0 (68%) W = 0.26	248.2 ± 28.8 (13%) W = 0.27

			P1	*P2*	*P3*	*P4*
OM41	*Snatol*	*42*	*45.2 ± 3.2 (39%)* *W = 0.20*	*68.3 ± 13.0 (18%)* *W = 0.23*	*101.2 ± 9.7 (36%)* *W = 0.25*	*293.0 ± 60.7 (7%)* *W = 0.37*

Sample	Group, formation	Nt	P1	P2	P3
(VIII) Western Kamchtaka (Rossoshina River valley)					
OM50	*Mainach*	*65*	*77.7 ± 6.6 (50%)* *W = 0.23*	*96.6 ± 11.4 (46%)* *W = 0.24*	*198.3 ± 64.8 (4%)* *W = 0.38*
OM48	Mainach	70	79.5 ± 8.0 (30%) W = 0.24	108.0 ± 12.3 (50%) W = 0.26	179.3 ± 28.0 (20%) W = 0.33

Notes: Italic designates samples, for which composition was not determined (Tables 1, 2). Roman numbers designate the sampling areas shown in Fig. 1.

(Nt) number of dated zircon grains in the sample. (P1, P2, P3, P4) zircon populations calculated using the Binomfit 1.8 program (Brandon, 1992, 1996). The age is given in Ma, measurement error is ±1σ. Percents in parentheses correspond to the ratio between number of grains of a given zircon population and total number of dated zircon grains (Nt). (W) relative standard deviation of the peak, i.e., characteristics of the peak width (Brandon, 1996).

the Tapel'vayam area (Fig. 1, area III), where the fission-track age of young zircon grains falls into the interval of 54.8 ± 2.8–87.9 ± 4.5 Ma, no independent age estimates exist for host sandstones. The same is true for the Il'pi–Matysken area (Fig. 1, area II) where zircon is dated back to 43.9 ± 3.6–66.1 ± 6.3 Ma. Nevertheless, the integral age estimate of these partly overlapping intervals corresponds to that obtained for the Ukelayat flysch from benthic foraminifers (Ermakov *et al.*, 1974; Ermakov and Suprunenko, 1975).

The sampled part of the Lesnaya Group yields the young population of zircons with fission-track ages of 43.7 ± 3.4–58.1 ± 4.2 Ma. This precisely corresponds to the Paleocene–Eocene age of the group determined by nannofossils (Shapiro *et al.*, 2001). The upper age limit should be lowered to 46–47 Ma, because the age of rhyolites from the Kinkil Formation, which unconformably overlies the Lesnaya Group, and granodiorites of the Shamanka Massif, which intrudes the Lesnaya Group, is estimated by the U–Pb, Rb–Sr, K–Ar, and fission-track methods at 44–46 Ma (Soloviev *et al.*, 2000).

Based on biostratigraphic methods (mollusks and foraminifers), the Getkilnin Formation containing young zircon grains (58.5 ± 4.9 and 59.0 ± 4.3 Ma) is correlated with the Danian–Thanetian (approximately 63–56 Ma) time (Gladenkov *et al.*, 1997).

Thus, zircon was constantly delivered to sediments during the long-term (from the mid-Cretaceous to the mid-Eocene, ~60 Ma) period of accumulation of the thick terrigenous sequence in western Kamchatka and the Ukelayat trough. The final cooling stage of the zircon was close to that of its precipitation. This allows the age of young zircon population from sandstone to be used for an approximate age estimation of sandstones.

Zircon of older populations in examined sandstones is from 70 to 350 Ma old. Most grains are younger than 200 Ma (Fig. 4b). The age of zircons (P2) from sandstones of the Ukelayat and Lesnaya groups is estimated at 75–130 Ma (Garver *et al.*, 2000), whereas zircons from sandstones of the Omgon Group are dated back to 97–190 Ma (Soloviev *et al.*, 2000). The age of zircons of the third population (P3) reflects older thermal events, although the interpretation of these data is very ambiguous.

DISCUSSION

General Data on Provenance Position

Despite some differences in sandstone composition in some areas, we follow previous researchers (Ermakov and Suprunenko, 1975; Kazimirov *et al.*, 1987; Til'man and Bogdanov, 1992; Sokolov, 1992) and assume that terrigenous sequences of this zone were deposited in a common basin bounded in the west by Northeast Asia. Noteworthy is an insignificant share of cherts (particularly jaspers), basalts, pyroxenes, amphiboles, and titanomagnetites amid the detrital material in sandstones. The Lesnaya and Omgon groups are characterized by the assemblage of accessory minerals (mainly zircon and apatite) that are most typical of erosion products of acid magmatic rocks (Shapiro *et al.*, 1993). It indicates that the provenance did not include Upper Cretaceous–Danian marginal-sea and island-arc siliceous–volcanogenic rocks that make up the Olyutor–Kamchatka paleoarc. Based on paleomagnetic data, the latter was located in the terminal Cretaceous–initial Paleogene far to the south of Northeast Asia and joined the continent only in the Middle Eocene (Soloviev *et al.*, 2000).

The analysis of prevalent structures in sandstones of the Ukelayat and Lesnaya flysch groups indicates that a significant role during their accumulation belonged to currents oriented both along the continental margin (northeast–southwest) and in the northwest–southeast direction (Garver *et al.*, 1998, 2000; Soloviev *et al.*, 2001). No signs of currents oriented in the opposite direction are recorded. In Kamchatka, the southeastward basin deepening is confirmed by the successive replacement of shallow-water sediments by deeper water ones in the same direction (e.g., the Paleocene Getkilnin Formation and Lesnaya Group, as well as the Upper Cretaceous Omgon Group and blocks in melange).

The absence of any significant amount of siliceous rocks or products of erosion of mafic and ultramafic complexes in the detrital material suggests that the North Koryak thrust-and-fold structure was not the main source of terrigenous material for the Ukelayat trough and western Kamchatka as well. Judging from the wide development of neoautocthonous shallow-water rocks of the uppermost Cretaceous–Lower Paleogene (Sokolov, 1992), this area represented a vast island shelf that served as a transit zone for the detrital material from the inner part of Asia. It seems that the Okhotsk–Chukot volcanogenic belt and fragments of the Uda–Murgal volcanic arc were most probable sources of the detrital material and zircon.

Variations in Composition of Sandstones and Their Interpretation

By the dominant composition of terrigenous components, sandstones containing zircon grains used for the fission-track dating are subdivided into two main groups differing, first of all, in quartz content (Fig. 3a). The first group includes sandstones from the Lesnaya Group, Ukelayat area (Tapel'vayam sector), Getkilnin Formation, and melange-hosted block beneath the Lesnaya thrust. The quartz content in the detrital material of this group makes up 23–35%. The second group is represented by Omgon and Ukelayat sandstones from the Il'pi–Matysken area and is characterized by the quartz content of 7–21%. In most diagrams, these groups form separate fields (Figs. 3b, 3c).

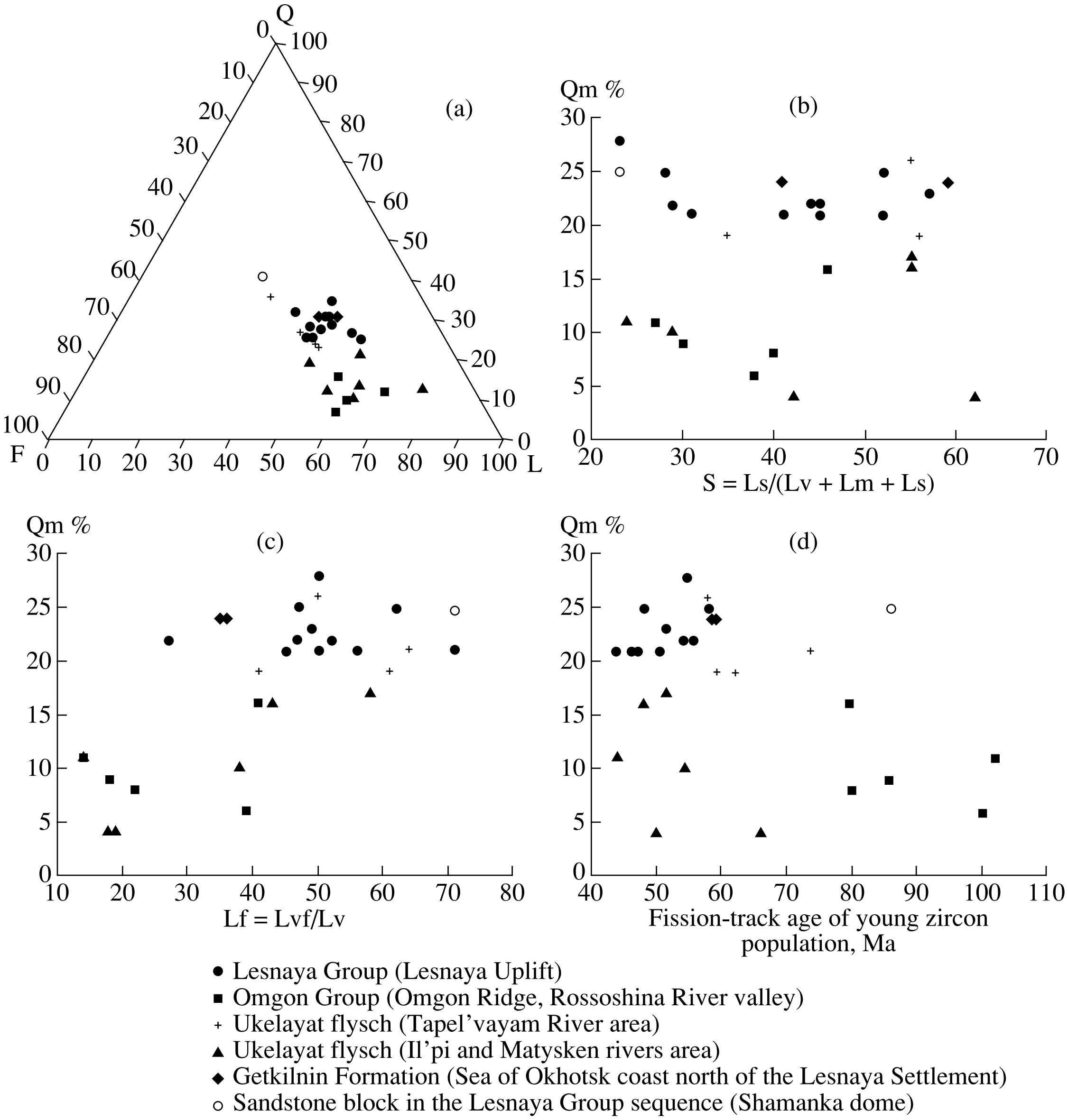

Fig. 3. Composition of sandstones from the western Kamchatka–Ukelayat zone. (a) QFL diagram: (Q) quartz, (F) feldspar, (L) rock fragments; (b) quartz vs. sedimentary rock fragments correlation; (c) quartz vs. felsitic correlation volcanics; (d) quartz vs. young zircon population correlation.

In the Lesnaya and Ukelayat (Tapel'vayam area sector) sandstones, felsitic sandstones prevail over microlithic ones, whereas the content of rocks with well-developed laths does not exceed a few percents. In sandstones from the Ukelayat (Matysken River section) and Omgon areas, microlithic rocks are prevalent, whereas rocks with laths compose up to 10%. Sandstones in the melange-hosted block are characterized by the lack of fragments of rocks with laths, whereas microlithic grains are slightly prevalent sandstones from the Getkilnin Formation. The Omgon sandstones have a high content of vitrophyric grains and tuffogeneous rocks.

It is apparent that the available data are insufficient to make any conclusion on the sandstone composition and age relationship (Fig. 3d). One can only suppose that either the composition of sandstones from the western Kamchatka–Ukelayat zone was not noticeably altered during its 60-Ma-long history or the evolution is masked by local variations. For instance, the quartz content can be low both in Upper Cretaceous (Omgon Group) and Paleocene–Eocene (Il'pi–Matysken) rocks (Fig. 3d). Similarly, high contents of this component are recorded in both Paleocene–Eocene sequences (Lesnaya Group, Tapel'vayam sector) and Campanian rocks (melange-hosted block). The lack of any regularity in the evolution of sandstone composition gives no chance to reconstruct the development of the presumable provenance and compare it with the well-known history of the Okhotsk–Chukot volcanic belt and neighboring structures. Most probably, no any drastic changes in the paragenesis of eroded rocks occurred during this evolution. This assumption is consistent with the concept suggesting that the main watershed of Northeast Asia coincided with the axis of the Okhotsk–Chukot volcanic belt since the Albian time (Filatova, 1988). The lack of a distinct dependence of composition of sandstones from the western Kamchatka–Ukelayat zone on their age emphasizes the inefficiency of this lithological feature for regional stratigraphic correlation.

Origin of Quartz Grains

One can assumed with a fair degree of confidence that most quartz and zircon grains were derived from a common source. It is apparent that most quartz grains in studied rocks are not related to the erosion of rhyiolitic volcanic rocks. This is evidenced by the quartz habit. Nevertheless, Fig. 3c shows a certain positive correlation between contents of quartz and acid volcanics (Lvf), indicating that sources of quartz were at least spatially close to those of acid volcanics. The endowment of quartz derived from older sandy sequences in the studied rocks was also insignificant. Redeposited quartz grains are usually well rounded. This feature is not observed in the studied thin sections. In addition, no correlation between contents of quartz and sedimentary rock clasts is observed (Fig. 3b). Therefore, it is unlikely that most quartz grains were derived from low-temperature stringers in slightly metamorphosed sandy–clayey sequences. Of course, eroded metamorphic rocks delivered quartz to sedimentary basins, but the content of detrital metamorphic rocks suggests that the share of such quartz was insignificant. Finally, the habit of quartz grains and sufficiently wide distribution of feldspar and quartzofeldspathic aggregates indicates that zircon was mostly derived from plagiogranite, granodiorite, and diorite intrusions. In the case of the Omgon Group, this assumption is also supported by the wide occurrence of diorite and plagiogranite pebbles in sandstone-hosted conglomerates lenses.

Age Similarity of Sandstones and Their Young Zircon Population

The age similarity of young zircon population and host sandstones may be caused by the influence of synchronous (relative to terrigenous sequence accumulation) volcanism and the tuffogeneous origin of zircon; i.e., cooling and deposition of zircon grains coincide in time (Brandon and Vance, 1992; Garver and Brandon, 1994; Garver *et al.*, 1999). This assumption is favored by synchronism of sedimentation in the western Kamchatka–Ukelayat zone and volcanism in the Okhotsk–Chukot belt during the Albian to mid-Campanian time. Younger volcanics are dominated by basalts and could not serve as a zircon source. Later, in the terminal Maastrichtian(?)–Paleocene, volcanic centers also existed in westernmost Kamchatka (Gladenkov *et al.*, 1997). This notion is supported by the domination of euhedral nonrounded crystals in the young zircon population (Garver *et al.*, 2000; Soloviev *et al.*, 2001).

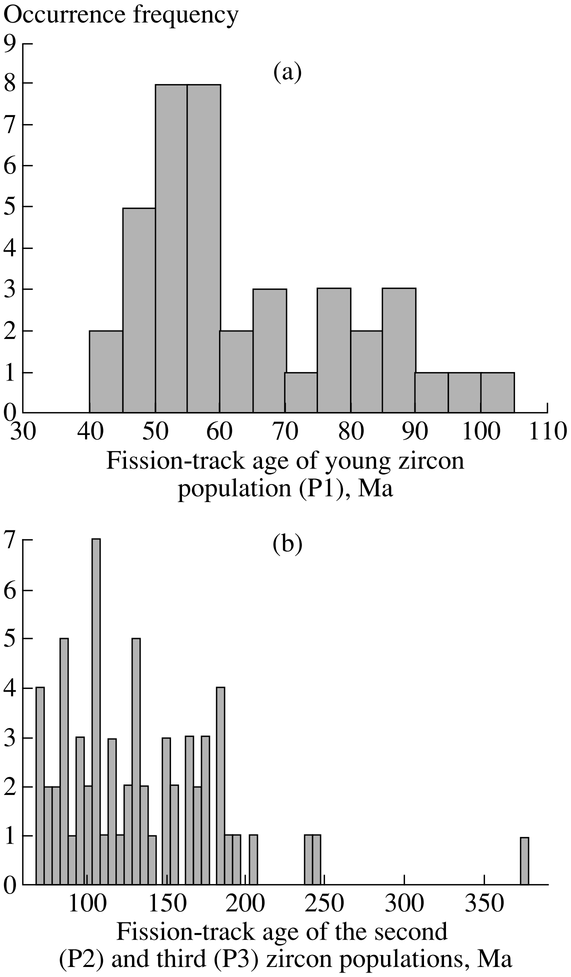

Fig. 4. (a) Distribution of fission-track ages of young (P1), see Table 3, and (b) second + third (P2 + P3) zircon populations in sandstones from the western Kamchatka–Ukelayat zone.

The sandstones, however, lack any tuffogeneous components, such as fragments of fresh glass and pumice, quartz typical of acid volcanics, zoned plagioclases, as well as pyroxenes, amphiboles, and titanomagnetites. Hence, either the tuffogeneous material was completely reworked during transportation or its content in the considered rocks was initially negligible. Both assumptions are difficult to prove. The first assumption is inconsistent with the following fact: most examined sandstones are immature. The clasts are angular and most grains are composed of unstable components, such as volcanics, argillites, and tuffs. The only component, for which the tuffogeneous origin can be assumed, are fragments of weathered decomposed glass (approximately 2–15%). Nevertheless, the lack of correlation between contents of glass and quartz grains makes their connection with detrital zircon unlikely as well.

In any case, the assumption on volcanic origin of young zircons cannot be universal for sandstones of the western Kamchatka–Ukelayat zone. It can be valid for some young zircons from the Omgon Group, which is synchronous with the Okhotsk–Chukot volcanic belt located at a distance of 300 km. Any significant centers of Early Eocene acid and intermediate volcanism have not been recorded northwest of Kamchatka and the Ukelayat Ridge, whereas a significant share of sandstones from the Lesnaya and Ukelayat groups contain zircon grains of this age. On the other hand, the late Danian–early Thanetian volcanic centers were located in northwestern Kamchatka (Gladenkov *et al.*, 1997). If they supplied the Lesnaya Group with zircons, other elements of ash should also be well preserved in its rocks. Therefore, we believe that some alternative hypothesis is needed to explain the origin of young zircon in the considered rocks.

Synchronism in the cooling of zircon grains and their burial in sediments can also be explained by a rapid (3–5 mm/yr) exhumation of blocks from deep levels in areas with a high geothermal gradient (approximately 0.1°C/m). Such gradients are recorded in modern volcanic areas (Palmason, 1981; Genshaft and Saltykovskii, 1999). High uplift rates are typical of watershed areas of large mountainous systems (Kukal, 1987; Brandon *et al.*, 1998; Garver *et al.*, 1999). Since the terminal Cretaceous, watershed between the Pacific and Arctic basins in Northeast Asia approximately coincided with the Okhotsk–Chukot belt and served as a provenance for the considered sequences. Volcanic processes (mainly basaltic extrusions) in this zone continued until the mid-Eocene (Filatova, 1988). Thus, the crust could retain high temperature till that time. This period was also marked by the differential uplift of numerous blocks of the Okhotsk–Chukot belt, the exhumation of granitoid massifs and, sometimes, pre-Albian basement of volcanic structures. The highly differentiated topography of the belt at that time is indicated by the absence of coeval deposits that are developed only beyond the study region. In this case, the exhumation of zircon-bearing rocks from depths of 2–3 km, where the temperature was higher than the value needed for blocking the track formation, could occur during a period of only 1–2 Ma. If the provenance was drained by rivers with a large catchment area, some zircon grains from such blocks should always enter the detrital material.

It should be emphasized that we are discussing only differential movements of some blocks of the provenance, which did not provoke a large-scale exposition of deep metamorphic layers of the Earth's crust, rather than its general rise.

The influx of older zircon populations was related to erosion of blocks, which were exhumed at the normal rate.

CONCLUSIONS

(1) Fission-track dating of zircons from Upper Cretaceous and Lower Paleogene sandstones of the western Kamchatka–Ukelayat zone showed that these rocks enclose detrital zircon, which avoided secondary ignition, and all samples yield from two to four populations of such zircon grains.

Based on independent biostratigraphic methods, the age of young zircon population coincides, within error limits, with the age of host rocks. In all samples, the integral age interval of zircons from young population corresponds to the integral age interval of examined terrigenous sequences. Hence, fission-track dating of zircon from sandstones, which did not experience heating above the temperature of 215–240°C, can be considered as an appropriate method for dating fossil-free sequences.

(2) Sandstones from the western Kamchatka–Ukelayat zone corresponded to quartzofeldspathic and feldspathic–quartzose graywackes (Shutov *et al.*, 1972). They contain fragments of quartz, plagioclase, volcanic (mainly intermediate and acid) rocks, sedimentary rocks (mainly argillites and tuffites), and some amount of metamorphic rocks and granitoids. Quartz is generally observed as monocrystalline grains probably derived from intrusive bodies that served as the main source for most zircon grains.

(3) The Okhotsk–Chukot volcanic belt and fragments of the Uda–Murgal arc were the potential provenance for terrigenous sequences of the western Kamchatka–Ukelayat zone.

Synchronism in the cooling of young zircon population and its burial in sediments can be explained by its tuffogeneous origin. The habit of zircon grains from this population is consistent with such interpretation. However, sandstones lack other components that could be considered with a sufficient confidence as elements of fresh tephra.

One can hardly assume that this tephra could completely be reworked, because all examined sandstones are immature and dominated by physically unstable mineral grains. Therefore, we assume that the synchronous cooling and burial of zircon grains due to their tuffogeneous origin cannot be considered the only possible hypothesis.

(4) We propose that the young zircon population in sandstones is derived from eroded plagiogranite and diorite intrusions of the Uda–Murgal arc and outer zone of the Okhotsk–Chukot volcanic belt exposed owing to differential vertical movements and rapid exhumation of some blocks.

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