Russian Geology
and Geophysics
Vol. 45. Mi>. II. pp. 1292-1302. 2004

Geolotfiva
i Gei>fizika
UDC552.24(1/9)

FORMATION OF THE EAST KAMCHATKAN ACCRETIONARY PRISM BASED ON FISSION-TRACK DATING OF DETRITAL ZIRCONS FROM TERRIGENE ROCKS

A.V. Solov'ev, M.N. Shapiro*, J.I. Garver**. and A.V. Lander***

Institute of Lithosphere of Marginal and Inner Seas of the RAS,
22 Staromonetny per., Moscow, 119180. Russia
** United Institute of Physics of the Earth, 10 id. Bol'shaxa Gruzinskaya. Moscow, 123810, Russia*
*** Geological Department, Union College, Schenectady, New York, USA*
**** International Institute of Earthquake Prediction Theory and Mathematical Geophysics of the RAS,*
79 Varshavskoe Shosse, Bldg. 2, Moscow, 113566, Russia

Fission-track ages were determined from detrital zircons from sandstones of the Drozdov and Stanislavskaya Formations and Tyushev Series of the Kumroch Range, eastern Kamchatka. The age of the young zircon population in the sandstones of the Orozdov Formation (Kumroch Range) is late Late Paleocene (from 55.9±4.4 to 57.7±3.5 Ma). The Drozdov Formation was deposited in the late Paleocene and continued to accumulate in the Early Eocene. The age of young zircon populations in the coarse-clastic sequence of the Stanislavskaya Formation (40.7±3.1; 40.913.9; 42.4+1.9 Ma) indicates that it accumulated as late as middle Bartonian. The age of young zircon populations in the sandstones of the Tyushev Series (from 50.0+2.9 to 38.1±3.4 Ma) is much older than the age of the sandstones themselves (Early-Middle Miocene, 24-11 Ma). Therefore, in the Early Miocene, the Tyushev Series accumulated a distance from central Kamchatka, volcanic activity was intense at that time.

There are three tectonic zones within the East Kamchatkan accretionary prism: Stanislavskaya, Vetlovaya, and Tyushev. The Stanislavskaya zone, represented by terrigenous units, are interpreted as deposits of the accretionary prism that originated after the Ozernoe-Valagin arc collided with the Eurasian margin. The Vetlovaya zone was formed by offscraping cover strata from the oceanic crust that separated the Ozernoe-Valagin and Kronotsky arcs in the middle Paleocene to late Miocene. Deposits of the Tyushev zone formed the Oligocene-Miocene cover of the "aseismic" Kronotsky Range, which was active following the demise of the Kronotsky arc. Units of the Tyushev zone became part of the East Kamchatkan accretionary prism after the Late Miocene collision of the Kronotsky block with Kamchatka.

Fission-track dating, zircon, tectonic evolution, East Kamchatkan accretionary prism

INTRODUCTION

Kamchatka is a classical example of an active convergent margin and its history is dominated by collision of terranes. Its structure has been formed by processes of suprasubduction accretion interrupted by short episodes of island-arc-continent collisions. The structure of eastern Kamchatka terranes is related to two intraoceanic island arcs, Ozernoe-Valagin and Kronotsky, separated by a zone of east-vergent imbricate structures (Fig. 1). This structural zone is here referred to as the Cenozoic East Kamchatkan accretionary prism. The Cenozoic history of this part of the region is difficult to interpret largely due to the lack of well-dated terrigenous strata. The terrigenous strata of the East Kamchatkan accretionary prism outcrop in the Kumroch Range, where sandstone samples were

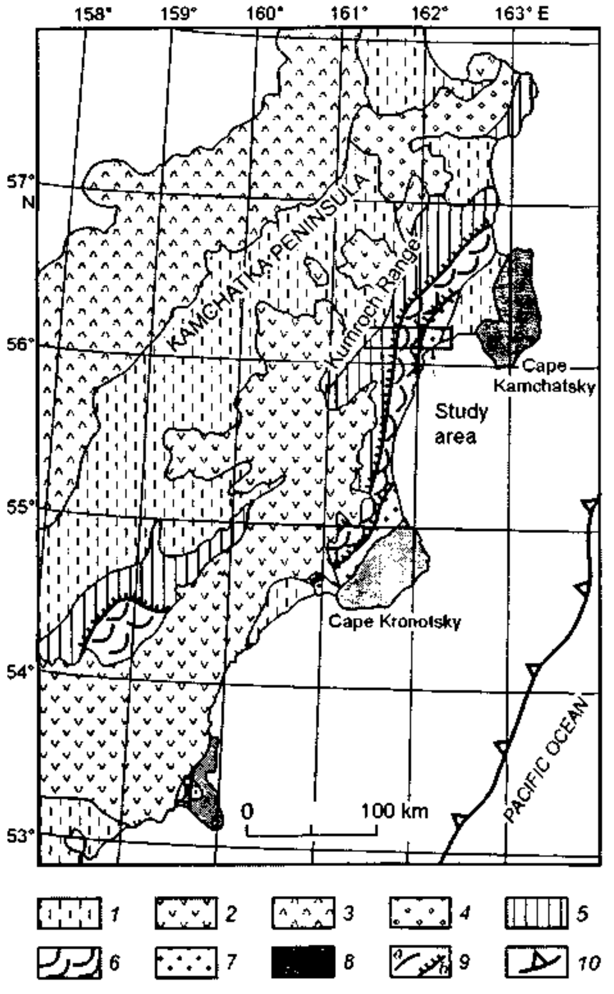

Fig. 1. The scheme of tectonic structure of southeastern Kamchatka (modified after [1-3]). ***1*** **— Quaternary deposits;** ***2*** **— East Kamchatkan volcanic belt (Pliocene-Quaternary);** ***3*** **— Central Kamchatkan volcanic belt (Oligocene-Quaternary);** ***4*** **— Oligocene-Miocene terrigene deposits; 5 — volcanic formations of the Ozernoe-Valagin island arc and its terrigene cover (Late Cretaceous-Early Eocene);** ***6, 7*** **— East Kamchatkan accretionary prism:** ***6*** **— terrigene deposits of the Stanislavskaya (Middle-Late Eocene) and Vetlovaya (Paleocene-Early Eocene) zones, 7 — terrigene-volcanogenic deposits of the Tyushev zone (Oligocene-Miocene);** ***8*** **— terrigene-volcanic formations of the Kronotsky island arc (Late Cretaceous-Eocene);** ***9*** **— geologic boundaries (a) and major thrusts** ***(b); 10*** **— recent zone of subduction.**

taken for analysis. The age of detrital zircons isolated from sandstones was determined by fission-track dating. In this study, the clastic sediments were not heated over 220-240 °C after accumulation, so the fission-track age of the youngest zircon grains is a constraint on depositional age and in many cases is close to the age of sedimentation. This paper reports data on the fission-track age of detrital zircons from the sandstones sampled from the Drozdov and Stanislavskaya Formations and Tyushev Series exposed in the Kumroch Range. This dating allows reconstruction of the evolution of the East Kamchatkan accretionary prism.

GEOLOGIC SETTING

The Kumroch Range is the easternmost range in a series of ranges in southeastern Kamchatka. It consists of four fault-bounded elongate structure zones (Fig. 2). The western (Khapitsa) zone is comprised of island-arc volcanites of ihe Khapitsa Formation depositionally overlain by flysch of the Drozdov Formation both of which

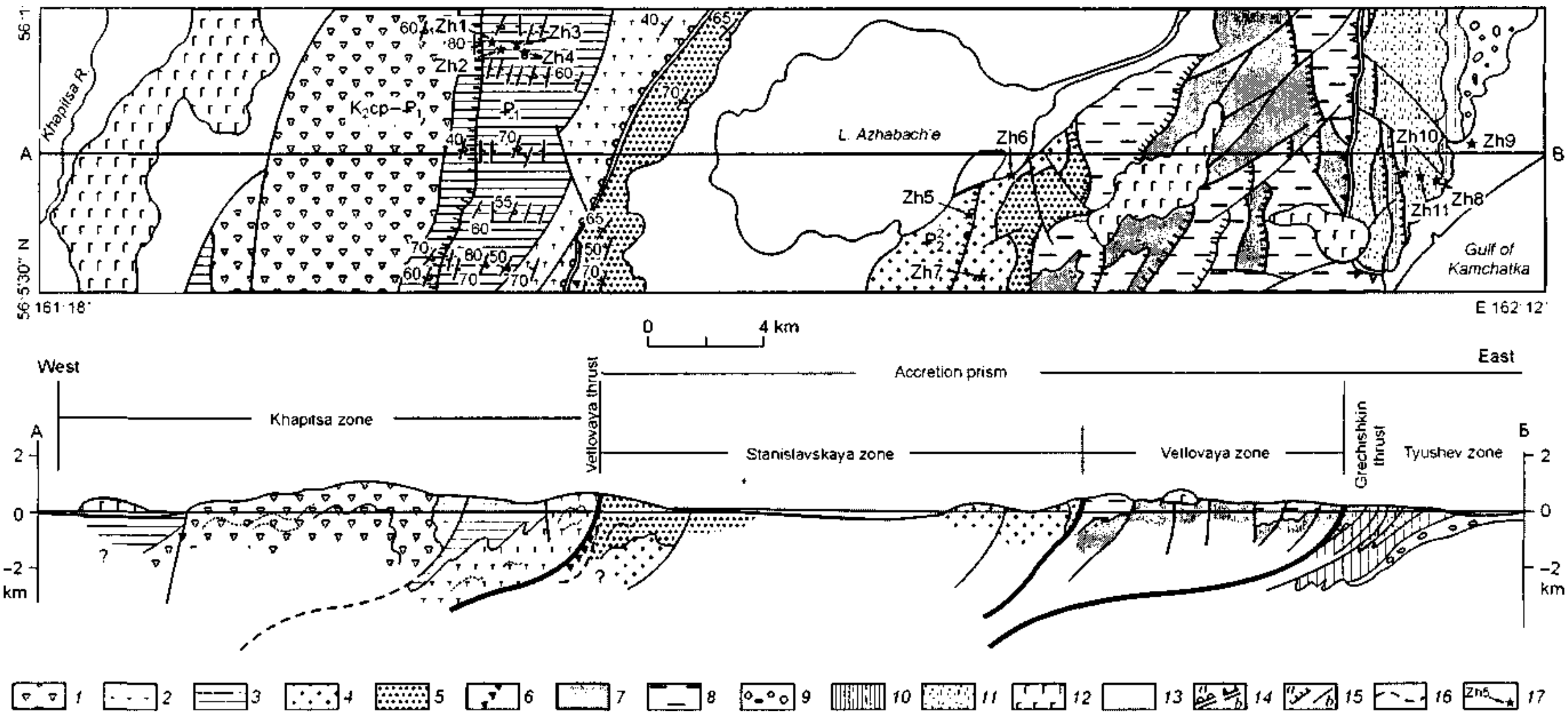

Fig. 2. Geologic structure of the Kumroch Range south of the Kamchatka River compiled after [1, 4,5] and a schematic geologic profile along the A—B line. Khapitsa zone: *1,2* — Khapitsa Formation: *I* — agglomcratic tuffs and basalts, *2* — psammitic and pelitic tuffs; *3* — Drozdov Formation. Stanislavskaya zone: *4—6* — Stanislavskaya Formation: *4* — coarse-grained sandstones and gravelstones, 5 — flysch, *6* — olistostromes. Vetlovaya zone: *7,8* — Vetlovaya Formation: 7 — siliceous aleuropelites, *8* — aleuropelites. Tyushev trough: *9-11* — Tyushev Series: *9* — conglomerates, *10* — Chazhma and Talovaya Formations, *11* — Olenin Formation; *12,13* — Quaternary deposits: *12* — basalts, *13* — loose deposits; *14* — most important sutures: *a* — Vetlovy thrust, *b* — Grechishkin thrust; *15* — other disjunctives: *a* — reverse faults and thrusts, *b* — normal faults and strike-slip faults; *16* — internal structure (on profile); *17* — sampling locality and number of specimen.

are deformed into folds overturned to the east. A few samples with radiolarians from the Khapitsa Formation, from the northern part of the Kumroch Range, restrict deposition to the Campanian and early Paleocene [6]. Published reconstructions based on gcochemical and paleomagnetic data, suggest that the Khapitsa Formation formed within the intra-occan island arc (Ozernoe-Valagin paleoarc) [3. 6, 7]. Sandstones of the Drozdov Formation are quartz-feldspar graywackes derived from a continental margin [8]. The Drozdov Formation is of Paleocene-Eocene age, as inferred from comparison with the Tal'nikovo Formation of the Valagin Range, which contains age-diagnostic planktonic foraminifers [9].

Together, the next three zones form the East Kamchatkan accretionary prism. The westernmost. Stanislavskaya zone, south of the Kamchatka River, largely coincides with the modern Lake Azhabach'ye depression (see Fig. 2). This zone has imbricate structures and is comprised of terrigenous rocks of the Stanislavskaya Formation (after the Stanislavskaya River in the Gamchen Range). The formation has two sub-divisions: the base of the section consists of massive coarse-clastic sandstones locally grading into conglomerate and small-pebble conglomerates; upsection the unit is largely flysch. The composition of the Stanislavskaya sandstones is dominated by lithic fragments of volcanic and chert, similar to rocks of the Khapitsa Formation. The age of the Stanislavskaya Formation is poorly known. It is inferred to be Paleocene on the basis of spore-pollen complexes, sandy benthic foraminifers and incorrect correlation of the upper flysch to the Drozdov Formation [10].

The Khapitsa and Stanislavskaya zones are separated by the significant Vetlovaya thrust (see Fig. 2): along this structure olistostromes with elastics of the Khapitsa and Drozdov Formations occur as part of the Stanislavskaya Formation. This finding implies a relatively gentle synsedimentary thrust which originally separated these zones. South of Lake Azhabach'ye, numerous lenses of Khapitsa-like tuffs arc interbedded with sandstones of the Stanislavskaya Formation.

The next eastward structural zone includes rocks of the Kumroch Range, which is usually called Vetlovaya after the Vetlovaya River. The Vetlovaya Series is represented chiefly by aleuropelites. siliceous aleuropelites. and fine-grained sandstones with lenses of chert, jasper, pelitomorphic limestones, and oceanic basalts [11]. The structure of the zone is dominated by a series of east-directed thrusts. The internal structure of most slices is monoclinic, and siliceous members lie, as a rule, structurally below terrigenous units. Steep dips are predominant, and small disharmonic folds and random complexes of the type of sedimentary melanges with blocks of cherts and basalts in aluropelitic groundmass are common. A few samples with of radiolarians and planktonic foraminifers indicate that the Vetlovaya Series is Paleocene and Lower Eocene [11].

The boundary between the Stanislavskaya and Vetlovaya zones is sharp (see Fig. 2) but less distinct than tectonic boundaries between other zones. Moreover, where the top of the Stanislavskaya Formation is terrigenous members of the Vetlovaya Series, the transition between these divisions is gradual. In places, such as northern Kumroch, the Slanislavskaya Formation is regarded as being at the top of the Vetlovaya Series.

Immediately south of the Kamchatka River, the eastern boundary of the Vetlovaya zone is the Grechishkin overthrust [5, 12], along which the Vetlovaya series is thrust over Oligocene-Miocene flysch of the Tyushev Series, separating the peninsula (fragments of the Kronotsky paleoarc) from the rest of Kamchatka (see Fig. 1). Most of the Tyushev zone is a gentle west-inclined monocline but near the Grechishkin thrust it is quite complicated with folds and thrust slices. Much of the section is characterized by mollusk fauna but at the bottom lies a poorly dated conglomerate member composed of green rhyolite tuffs, the rocks typical of the Paleocene Tarkhovo Formation of the Kamchatka Peninsula.

DETRITAL FISSION-TRACK DATING: METHODS AND RESULTS

Detrital thermochronometry. based on the determination of age of solitary zircon grains by the fission-track method (zircon fission-track dating) (13, 14], allows resolution of '"poorly dated" clastic sequences, stratigraphic correlation, and location and characterization of clastic sources [15-18]. Fission-track dating of a mineral is based on the determination of the number of tracks formed by the spontaneous fission of uranium nuclei ($U^{2;l8}$) that have accumulated in the mineral since cooling [13, 19], Track accumulation in crystals is a process similar to accumulation of daughter isotopes from parent isotopes in minerals. Track stability is governed mainly by temperature, and tracks form and are retained in the crystals that cooled below the "effective closure temperature". The closure temperature corresponds to the point when more than 50% of the tracks become stable 114]. Assuming monotonic cooling in geologic settings (cooling rate of 1 to 30 °C/Myr), the effective temperature of closure for zircon is 215-240 °C 120].

Fission-track thermochronometry permits dating of single zircon grains. Thus, heterogeneous populations from different source terranes with different thermal histories can be distinguished. Rock formation and cooling in source terranes results from different geologic processes, two of which are highlighted here. First, volcanic rocks and

Table 1

Track Ages **of Detrital Zircon Populations from Terrigene Deposits of Kumroch** Range, Eastern **Kamchatka**

Sp. no.	kiL>i its, l tin	*Nt*	Age of zircon populations. Ma		
			PI	P2	P3
Zhl	Drozdov	55	66.7±5.0 (48.7%)	127.7 ±9.7 (51.3%)	—
Zh2	»	50	57.7±3.5 (65.2%)	128.2 ± 13.0 (34.8%)	—
Zh3	»	50	55.9±4.4 (33.9%)	83.8 ± 7.3 (46.6%)	137.2± 17.4 (19.6%)
Zh4	»	45	68.3±6.2 (49.4%)	110.8 ± 11.2 (50.6%)	—
Zh5	Stanislavskaya	50	40.9±3.9 (22.4%)	61.7 ±5.1 (55.0%)	80.8± 12.8 (22.6%)
Zh6	»	45	42.4± 1.9 (100.0%)	—	—
Zh7	»	45	40.7±3.1 (62.7%)	62.6 ±6.8 (37.3%)	—
Zh8	Tyushev Series	40	38.1±3.4 (32.5%)	73.2 ± 6.9 (56.4%)	141.5 ±42.7 (11.1%)
ZhlO	»	50	43.3±2.4 (72.1%)	94.4 ± 10.5 (27.9%)	—
Zhll	»	50	50.0±2.9 (68.3%)	108.1 ± 10.5 (31.7%)	

Note. Nt is the number of dated zircon grains in the specimen. PI, P2, and P3 are the zircon populations calculated by Binomfit 1.8 [23, 24]. The ages are given in Ma, a dating error is ±1a, parenthesized percentage is the number of grains of a given population of the total number of dated grains *(Nt).* Zircons are dated by the method of outer detector [14], described in detail in [16]. The zircon grains were pressed into FEP TeflonMT plates 2x2 cm in size. Two plates were prepared for each specimen. The plates were roughed out with emery cloth (800 grit) and then polished with diamond pastes (9 and 1 |ini) and AI:O, paste 0.3 um at the final stage. The plates were chemically etched with NaOH-KOH at 228 °C for 14-18 hours (1st plate) and 18-22 hours (2nd plate). The etched plates were covered with a detector (U-poor mica) and radiated in a flow of thermal neutrons of about 210'- neutrons/cm^2 (reactor of Oregon University). Simultaneously with the specimens, zircon age standards were irradiated (Fish Canyon Tuff, FCT, and Buluk Tuff, BL) and the dosimeter glass with a known content of U (CN-5) [25]. To calculate the tracks, we used the microscope Olympus BH-P with an automated system and digital plotting board, maximum magnification x1600, dry assay. The z-factor [25] calculated from 12 age standards (FCT-7, BL-5) was equal to 345.09+8.44 (A.V. Solov'ev).

near-surface intrusions cool quickly, are eroded and zircons from these rocks are transported to nearby sedimentary basins. This permits their use for constraining the age of poorly dated terrigenous strata [15-17. 21. 22]. Second, when blocks are exhumed from depth, they "cool" at a certain time [14, 15], and the rocks pass through the closure temperature for fission tracks in zircon (215-240 °C [20]). Since this time, tracks accumulate, and the age determined from these minerals corresponds to the time since rock cooling.

Detrital zircons from terrigenous deposits usually have a wide age range. The youngest population or "minimal age" is the most important [15], because it constrains the lower age range of sedimentation. We use detrital thermochronometry to date terrigenous deposits of the East Kamchatkan accretionary prism.

Results of zircon fission-track dating. Sandstones were sampled (6-10 kg) from the strata of the Drozdov and Stanislavskaya Formations and Tyushev Series (see Fig. 2, Table 1). Zircons were separated by a standard procedure at the Laboratory of Accessory Minerals of the Institute of Lithosphere of Marginal and Inner Seas of the RAS and Union College (Schenectady. NY, USA). The methodology is described in the note to Table 1. Forty to fifty grains of zircon were analyzed from each sample. To calculate the age of zircon grains, we used the program Zetaage 4.7 [23, 24]. The ages of grains in all samples are distributed in a wide range; therefore, several heterochronous populations of zircon occur in the sandstones. We separated the heterochronous population using Binomfit 1.8 [24]*.

The presence of several zircon populations (Fig. 3) suggests that, after the rocks were deposited, they have not been heated to temperatures that exceed the fission-track system closure in zircon, i.e. 215-240 °C [20]). This is corroborated by field observations of the lithology and structure of terrigenous deposits: The rocks do not contain metamorphic minerals formed over 200 °C nor do they have cleavage typical of this temperature range (and higher). Thus, the zircon fission-track dating of the analyzed units reflects the time of their original cooling of the source

* The programs used for the calculations are available from http://www.geology.yale.edu/--brandon/

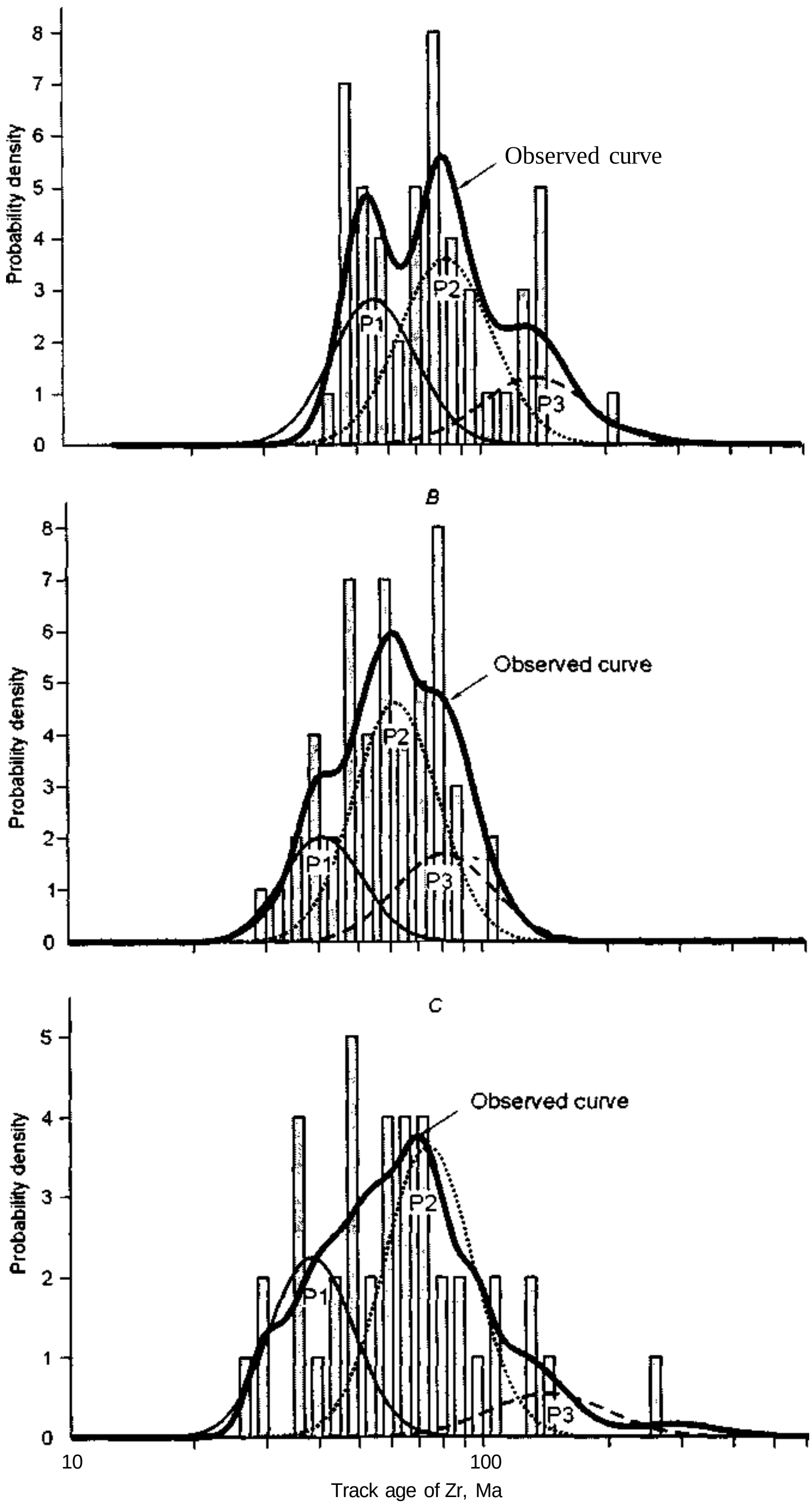

Fig. 3. Patterns of distribution of track ages of zircon grains from terrigene deposits of Eastern Kamchatka. PI, P2, and P3 are peaks of heterochronous zircon populations (see Table 1) distinguished by Binomfit 1.8 [24]. *A* — Sp. Zh3 — sandstone, Drozdov Formation; *B* — sp. Zh5 — sandstone, Stanislavskaya Formation; *C* — sp. Zh8 — sandstone, Tyushev Series.

rocks. Fission-track dating of the youngest zircon population yields the lower bound for the time of sedimentation ol the host sandstones.

The age of the youngest population of zircon grains is close to the age of deposition, if volcanic activity occurred during sedimentation [16. 17. 20-22]. In the orogenic zones that experienced fast exhumation and erosion, subsurface intrusions are exhumed and eroded rather quickly. Thus, it may take a few million years for the zircon grains cooled in a subsurface intrusion to be eroded, exposed, and delivered to nearby basins.

DISCUSSION

Drozdov Formation. To date detrital zircons, four samples of medium-grained sandstones were taken. The fission-track ages of zircons are heterogeneous, with two to three age populations recognized in each sample (see Table 1, Fig. 3, *A).* Most likely, sampled sandstones were not heated over the temperature of fission-track system closure, and the age of zircons corresponds to the time of source rock cooling. The age of the young population of zircon in sample Zh2 (57.7±3.5 Ma) and Zh3 (55.9±4.4 Ma) corresponds to the Thanetian. and therefore the sandstones cannot be older than Early Eocene. In specimens Zhl (66.7±5.0 Ma) and Zh4 (68.3±6.2 Ma) the age of the young population is Maastrichtian. It is likely that in the Early Eocene, a number of zircon sources fed the Drozdov sandstones. In general, the results obtained do not contradict the comparative analysis of the Drozdov and Tal'nikovo Formations.

Clastic sediment of the Drozdov Formation was derived from the Eurasian continental margin, where blocks of the Okhotsk-Chukchi volcanic belt were exhumed and eroded, including granitic intrusions [16, 22]. The composition of the sandstones of the Drozdov Formation as well as the age of the young population of zircons in the sandstones suggests correlation with the younger units of the Lesnaya Group, now well-exposed at the isthmus of the Kamchatka Peninsula [17, 26]. However, the Drozdov Formation occupies a different structural position, stratigraphically overlapping the volcaniclastic strata of the Ozemoe-Valagin island arc, whereas the Lesnaya Series forms a thrusted autochthon that is overlain by an allochthonous volcanic arc.

Stanislavskaya Formation. We determined cooling ages of detrital zircons from three samples of coarse-grained volcanic-lithic sandstones of the Stanislavskaya Formation (see Table 1, Fig. 3, *B).* The young population in the three specimens (Zh5, Zh6, Zh7) is upper Middle Eocene. It means that the sampled unit cannot be older than Bartonian. Thus, it is not reasonable to correlate the Stanislavskaya and Drozdov Formations. Correlation of the Kumroch Range with the Tundra Formation of the Kronotsky Peninsula is more likely. The Tundra Formation is represented by massive coarse-clastic sandstones concordantly overlain by a flysch member, the fauna-containing Chazhma Formation of Oligocene age [12].

There are several inferences about the source of Middle Eocene zircons in the Stanislavskaya Formation. The character of its sediments excludes long transport of the elastics. As inferred from clastic composition, the main source was the Ozernoe-Valagin arc, where the age of the youngest volcanics are middle Paleocene. One possibility is that elastics of the Stanislavskaya Formation (more exactly, the coarse-clastic sediment) were produced by quickly exhumed tectonic slices and wedges from sufficiently deep levels of the arc, where the temperatures exceeded the closure temperatures of zircon. Alternately, the zircons with Middle Eocene ages could be transported to the basin from the West Kamchatkan-Koryakian (KinkiT) volcanic belt, characterized by active volcanic activity at that time *[2].* Simultaneously, high levels of the Ozernoe-Valagin arc were eroded, from where zircon came, which was of Early Paleocene and Late Cretaceous age typical of the volcanites of the Khapitsa Formation.

Tyushev Series. Three samples of sandstones were analyzed from the upper flysch of the Tyushev Series section faunally dated by the Lower-Middle Miocene (20-12 Ma) [10]. Two or three age populations of zircon are present in the specimens (see Table 1. Fig. 3, C). The age of the young population is middle Lower Eocene to upper Middle Eocene (35-52 Ma). In this case, sandstone deposition is much younger than the youngest population of zircon. This finding means that neither tephrogenic zircon nor material from the fast rising "hot" blocks were delivered to the sediment simultaneously with sedimentation. The Miocene is a period of intense volcanism. partly explosive, in the Central Range of Kamchatka 127]. The source for the terrigenous sediments of the Tyushev Series is probably the inactive Kronotsky arc rather than active volcanics in western Kamchatka, otherwise we would have seen a young population of grain ages. In the first half of the Miocene, the Kronotsky arc was rather far apart from Kamchatka. The youngest igneous rocks of this arc are Eocene volcanites and subsurface intrusions of the Stolbov and Kronotsky Series, which could be the source of the young population zircons in the Tyushev sandstones. One of the specimens contains several grains of relatively old zircon (Late Jurassic-Early Crelaccous). A possible source for these grains is the Pikezh sandstones of the Afrikan Series that is evidently related to the erosion of the continental block [28].

HISTORY OF THE EAST KAMCHATKAN ACCRETIONARY PRISM

New zircon fission-track ages from the terrigenous rocks of the Kumroch Range combined with the known data allow a new depth to our understanding of the history of the Eastern Kamchatkan accretionary prism.

This history can be traced discontinuously from the Campanian when in the northern Pacific about 2000-3000 km southeast of that margin of Eurasia the Ozernoe-Valagin and Kronotsky island arcs began to form due to oceanic subduction [29]. The Ozernoe-Valagin arc. with the subduction zone inclined oceanward. occurred at the margin of the Pacific plate during the Campanian, Maastrichtian. In the early Paleocene it was transported rapidly toward the northeastern margin of Eurasia. The Kronolsky arc. at least, until the middle Paleocene did not move northward. There, the subduction zone was inclined landward, and the arc itself was likely at the margin of the Eurasian or North-American plates until the middle Eocene. The arcs are inferred to be connected by an elongate transform fault.

Active volcanism in the Ozernoe-Valagin arc ceased in the middle Paleocene [9] (Fig. 4, *A).* The change of setting recorded in the Khapitsa Formation and then by the Drozdov implies: 1) subduction beneath the arcs terminated; and 2) that the arc was close enough to the continent to receive continental detritus. The fission track ages for the zircons from the Drozdov sandstones of the Kumroch Range support the stratigraphic correlation of this unit to the Tal'nikovo Formation of the Valagin Range, whose Paleocene-Lower Eocene age is constrained by planktonic foraminifera. Deformation of the arc followed deposition of the Drozdov Formation (see Fig. 4. *B).* In the Valagin Range, first deformation of the Ozernoe-Valagin arc is documented by the sub-Snatol Fm. unconformity in the range 50-45 Ma [9].

The Kronotsky arc began its northern translation approximately at the time when volcanic activity ceased in the Ozernoe-Valagin arc or even later when this arc became part of Eurasia. The fast northerly translation of the Kronotsky arc was initiated due to the demise of a trench to the south and initiation of a trench to the north (see Fig. 4, *B).* In the late Eocene (40-35 Ma) volcanic activity in the Kronotsky arc ceased, and it continued its northwestern translation as a within-plate "aseismic" ridge on the Pacific plate (see Fig. 4, *C, D).* Since then, convergence between the Pacific plate and Eurasia has been accommodated by subduction along the leading edge of Kamchatka. The development of this subduction zone was terminated by the Kronotsky arc-Kamchatka collision in the late Miocene, which is suggested by a regional pre-Pliocene discontinuity and establishment of a regionally extensive tectonic suture, the Grechishkin thrust (see Fig. 4. *E).* The system of steep imbricated thrusts and east-overturned folds of the Stanislavskaya. Vetlovaya, and Tyushev Formations, can be considered a thrust belt structurally formed between the collisions of the Ozernoe-Valagin and Kronotsky arcs with Eurasia, i.e.. from middle Eocene to late Miocene.

This structural prism is distinguished by its tripartite structure reflecting three different environments in which these rocks accumulated. The oldest rocks of the Vetlovaya Series make up the central tectonic zone and are represented chiefly by hemipelagic sediments, to a lesser extent pelagic sediments and oceanic basalts of the Paleocene and Early Eocene. Most likely, these are sediments of the basin that separated the Ozernoe-Valagin and Kronotsky arcs (see Fig. 4. *A-C).* Subduction of the lithosphere of this basin beneath Kamchatka led to the partial offscraping of these sediments, most of which seemed to be imbricated into the subduction zone.

The terrigenous rocks of the lower Slanislavskaya Formation were derived from erosion of the Ozernoe-Valagin island-arc terrane and reflect the contrasting relief produced either by the collision of the Ozernoe-Valagin arc with Eurasia or by the origin of a new subduction zone outboard of this island-arc terrane. New ages of the coarse-clastic rocks of the Stanislavskaya Formation (younger than 40 Ma) exclude their direct connection with the collision of the Ozernoe-Valagin arc, which occurred earlier (no later than 45 Ma). Therefore, we suggest that coarse-clastic deposits of the Stanislavskaya Formation record a new zone of subduction along the northeastern margin of the Eurasian continent. Prior to this event (approximately from 45 to 40 Ma) the approach of the Pacific plate to Eurasia was compensated by subduction beneath the Kronotsky arc. At the initial stage of formation of the accretionary prism most of its volume formed at the expense of the elastics of the Ozernoe-Valagin arc (Stanislavskaya Formation) supplied to the trench from an elevated continental margin (see Fig. 4, *C, Cl).* Later, the prism was accreted chiefly at the expense of the subducted plate (Vetlovaya Series) (see Fig. 4, *C. D).*

Simultaneously with the formation of an accretionary prism along the continent margin, an apron of terrigenous deposits accumulated on the slopes of the Kronotsky uplift to form the Tyushev Series (see Fig. 4. *C. D).* The youngest age of zircons (older than 38 Ma) from the Tyushev sandstones suggests that the terrigenous and tephrogenic material from the continent was not deposited this far outboard until middle Miocene. This hypothesis is in agreement with other data indicating a Pliocene age lor uplift of the Kronotsky -Kamchatka collision. At the beginning of this collision, some part of the Kronotsky cover was stripped off its basement and added to the East Kamchatkan accretionary prism (see Fig. 4. *E)* as its third component, the Tyushev tectonic zone in the east.

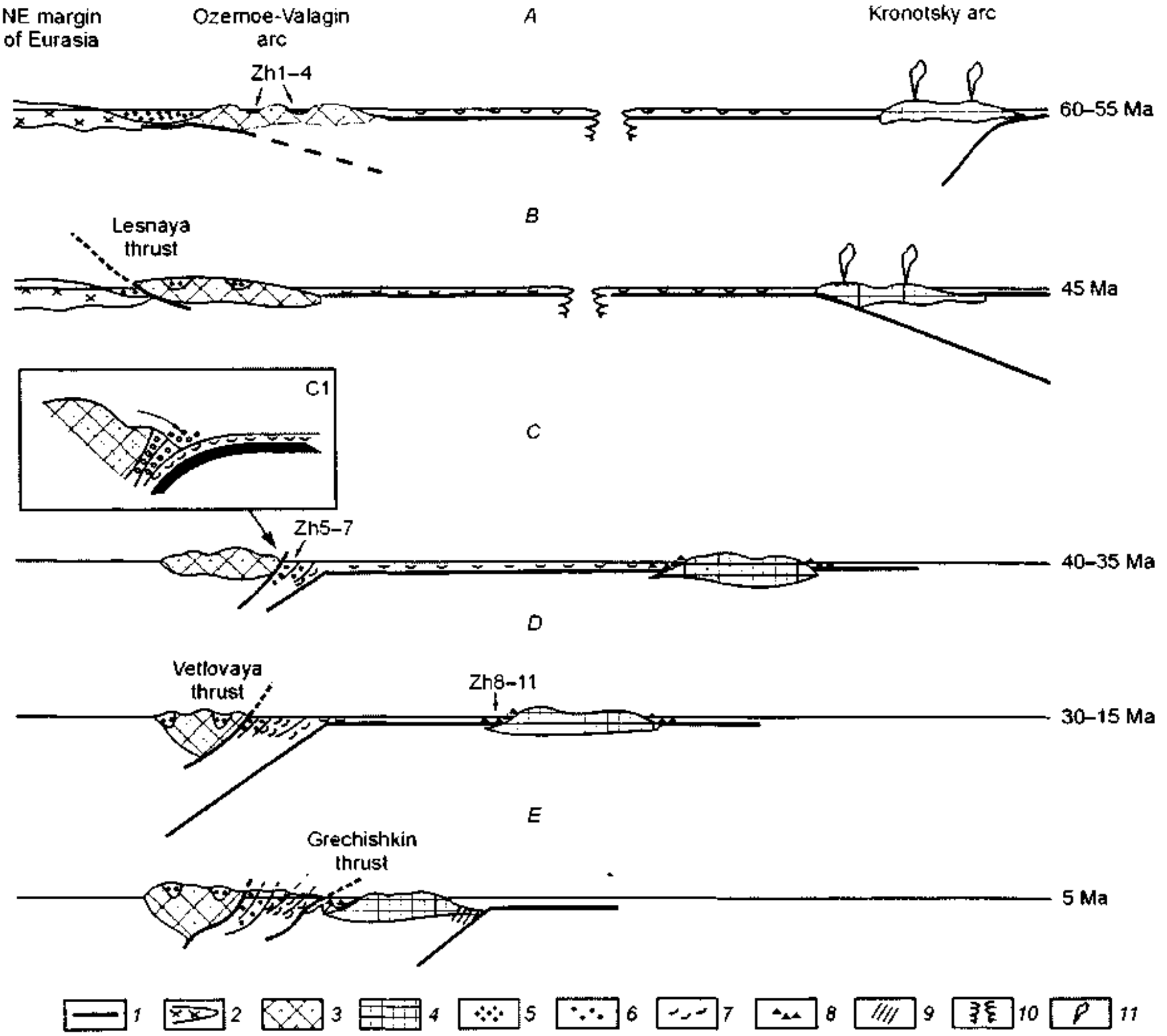

Fig. 4. Out-of-scale schema of formation of the East Kamchatkan accretionary prism. *A. Late Paleocene* (60-55 Ma). Ceased subduction beneath the Ozernoe-Valagin arc, accumulation of the cover of this arc (Drozdov Formation), accumulation of deposits of the Vetlovaya Series in the basin between the arcs, subduction of the Pacific plate beneath the Kronotsky arc. The arcs seem to belong to different plates. *B. Middle Eocene* (45 Ma). Collision of the Ozernoe-Valagin arc with Eurasia, formation of the Lesnaya thrust [26], inversion of subduction beneath the Kronotsky arc. *C. Middle-Late Eocene* (40-35 Ma). Termination of the subduction beneath the Kronotsky arc and transformation of the arc into a within-plate rise on the Pacific plate, the start of subduction of the Pacific plate beneath Kamchatka, accumulation of the Stanislavskaya Formation. *D. Oligocene-Middle Miocene* (30-15 Ma). Accumulation of the terrigene cover on the slopes of the Kronotsky rise (Tyushev Series), continued subduction of the Pacific plate beneath Kamchatka and accretion of the prism by offscraping of the Vetlovaya Series. *E. Pliocene* (5 Ma). Collision of the Kronotsky arc with Kamchatka, stripping the cover (Tyushev Series) off the slope of the Kronotsky rise and addition of this cover to the accretionary prism. *I* — oceanic crust; *2* — continental basement of western Kamchatka; *3* — Ozernoe-Valagin arc and related terrane in the structure of Kamchatka; *4* — Kronotsky arc; *5-8* — terrigene complexes: 5 — Lesnaya and Drozdov, *6* — Stanislavskaya, 7 — Vetlovaya, *8* — Tyushev; 9 — recent accretionary prism; *10* — spreading center; // — volcanic activity.

CONCLUSIONS

1. The age of ihe young population of zircons in sandstones of the Drozdov Formation (Kumroch Range) corresponds to the end of the Late Paleocene (55.9±4.4; 57.7±3.5 Ma). The Drozdov Formation began to form in the late Paleocene and continued in the Early Eocene. The fission-track data do not contradict correlation between the Drozdov Formation with the Late Paleocenc-Early Eocene Tal'nikovo Formation of the Valagin Range.

2. The age of young zircon populations in the coarse-clastic rocks of the Stanislavskaya Formation (40.7±3.I: 40.9+3.9; 42.4±1.9 Ma) indicates that its deposition was no earlier than the middle Bartonian. Therefore, correlation between the Stanislavskaya and Drozdov Formations is probably not tenable. It is more reasonable to correlate the Stanislavskaya Formation of the Kumroch Range with the Tundra Formation of the Kronotsky isthmus.

3. The young populations of zircons in the Tyushev sandstones (from 50.0+.2.9 to 38.1±3.4 Ma) is much older than the age of the sandstones themselves (Lower-Middle Miocene, 24-11 Ma). This means that we see no evidence of post-Eocene sources of zircon related to volcanic activity within the source region of the Tyushev sandstones. Hence, the Central Range of Kamchatka, characterized by intense volcanism, could not be a source and instead the Tyushev Series formed at the expense of erosion of the Kronotsky uplift (within-plate "aseisrnic" ridge), where volcanism ceased in the Eocene.

4. The specific division of the East Kamchatkan accretionary prism into three longitudinal tectonic zones (Stanislavskaya, Vetlovaya, and Tyushev) that mirror three stages of its formation. The Stanislavskaya zone formed at the lime of high relief when a new zone of subduction began to form after the Kronotsky arc had died. The Vetlovaya zone originated somewhat later as a result of long-term erosion (and structural slicing) of the cover of the oceanic basin that separated the Ozernoe-Valagin and Kronotsky arcs from middle Paleocene to late Miocene. The Tyushev zone is the cover, partly derived from its basement, of the "aseismic" Kronotsky Range, the former Kronotsky are, collided with Kamchatka in the late Miocene.

We are grateful to N.A. Bogdanov for valuable advice, to G. Bazarkin (TINRO). D.M. Ol'shanetsky, and O.V. Rodionov, for help with field work.

This work was supported by grant 02-05-64967 from the Russian Foundation for Basic Research and by grant OPP-9911910 (Garver) from the National Science Foundation (USA).

REFERENCES

1. *The USSR Geological Map. Scale 1:1.000,000 (new series). Sheet O-57 (58) — Palana: Explanatory note* [in Russian], 105 pp.. VSEGEI. Leningrad. 1989.

2. Bogdanov. N.A., and V.E. Khain (eds.). *Explanatory note to the Tectonic Map for Region of the Sea of Okhotsk at a scale of 1:2,500,000* [in Russian), 193 pp., ILOiVM RAN, Moscow, 2000.

3. Shapiro, M.N., The Late Cretaceous Achavayam-Valagin volcanic arc (Kamchatka) and kinematics of the North Pacific plates, *Geotektonika,* 1. 58-70. 1995.

4. Khotin, M.Yu., *Effusive-tujfaceous-silica formation of Cape Kamchatsky* [in Russian], 196 pp.. Nauka, Moscow, 1976.

5. Shapiro, M.N., B.I. Slyadnev, and A.V. Lander, Imbricate structure of the northern East Kamchatka anticlinorium. *Geotektonika,* 1, 84-98, 1984.

6. Zinkevich, V.P., E.A. Konstantinovskaya. N.V. Tsukanov, A.V. Rikhter, V.S. Kamenetskiy. R. Magakyan. A.V. Sobolev, S.F. Karpenko. S.A. Garanina. L.V. Danushevskiy, N.N Kononkova, M.V. Portnyagin, G.M. Kolesov. and T.V. Romashova, *Accretionary tectonics of Eastern Kamchatka* [in Russian], 272 pp., Nauka. Moscow, 1993.

7. Shapiro, M.N., D.M. Pechersky, and A.V. Lander, Velocities and directions of the absolute motion of subduction zones in the geologic past, *Geotektonika,* 2, 3-13, 1997.

8. Shapiro, M.N.. P.V. Markevich. V.I. Grechin, and E.A. Konstantinovskaya. Upper Cretaceous and Lower Paleocene sandstones of Kamchatka: composition and problems of sources. *Litologiya i Poleznye lskopaemye.* 6, 94-106. 1992.

9. Bakhteev, M.K., V.N. Ben'yamovsky. N.Yu. Bragin, O.A. Moro/.ov, S.R. Tikhomirova, and A.E. Shantser, New data on Mesozoic-Cenozoic stratigraphy of East Kamchatka (Valagin Ridge). *Stratigrafna. Geologiciieskava Korrelyatsiya,* 2. 6, 77-84, 1994.

10. *Resolutions of operating interdepartmental regional stratigraphic meetings on Paleogene and Neogene of eastern Russia — Kamchatka, Koryak Upland, Sakhalin, and Kurils. Explanatory note to stratigraphic schemes* [in Russian), 114 pp., GEOS. Moscow. 1997.

I 1. Tsukanov, N.V.. *Tectonic development of the near-ocean zone of Kamchatka in the Late Mesoz.oic-Earlx Cenozoic* |in Russian]. 104 pp.. Nauka. Moscow. 1991.

12. Bakhteev. M.K.. O.A. Morozov. and S.R. Tikhomirova, Structure of ophiolitc-free collision suture of East Kamchatka — Greehishkin thrust zone, *Geotektonika.* 3. 74-85. 1997.

13. Faure. G.. Dating methods based on study of fission-fragment tracks and other radiation disturbances, in *Principles of isotope geologx* [Russian translation). 353-175. Mir. Moscow. 1989.

14. Wagner. G.A.. and P. Van Den Haute. *Fission-Track Dating.* 285 pp.. Kluwer Academic Publishers. 1992.

15. Garver. J.I.. M.T. Brandon. M. Roden-Tice. and P.J.J. Kamp. Exhumation history of orogenic highlands determined by detrital fission-track thermochronology, in U. Ring. M.T. Brandon. G.S. Lister, and S.D. Willelt ieds.). *Exhumation Processes: Normal Faulting. Ductile Flow and Erosion. Geological Society London. 1999. Special Publications.* **154.** 283-304. 1999.

16. Garver. J.I.. A.V. Soloviev, M.E. Bullen. and M.T. Brandon. Towards a more complete record of magmatism and exhumation in continental arcs, using detrital fission-track thermochronometry. *Phxs. Chem. Earth.* Pan A. 25. 6-7, 565-570, 2000.

17. Solov'ev. A.V., G.I. Garver, and M.N. Shapiro. Age of detrital zircons in sandstones of the Lesnaya Formation, northern Kamchatka, from fission-track data, *Stratigrafiya. Geologicheskaya Korrelyatsixa. 9,* 3. 89-00. 2001.

18. Solov'ev. A.V., Solution of tectonic problems by detrital fission-track thermochronometry, in *Proceedings >/ the All-Russian scientific conference on Geologx. Geochemistry, and Geophysics around Transition from 20th :o 21st Century, vol. 1: Tectonics, stratigraphy, and lithologx* [in Russian], 95-97. Svyaz'-Print, 2002.

19. Fleisher, R.L., P.B. Price, and R.M. Walker, *Nuclear tracks in solids,* 605 pp.. University of California Press. Berkeley, CA. 1975.

20. Brandon, M.T., and J.A. Vance, Tectonic evolution of the Cenozoic Olympic subduction complex, western Washington State, as deduced from fission track ages for detrital zircon, *Amer. J. Sci.,* **292.** 565-636, 1992.

21. Garver. J.I., and M.T. Brandon, Fission-track ages of detrital zircon from mid-Cretaceous sediments of he Methow-Tyaughton basin, southern Canadian Cordillera, *Tectonics,* 13. 2. 401^20, 1994.

22. Shapiro, M.N., A.V. Solov'ev, J.I. Garver, and M.T. Brandon, Zircon sources in terrigene sequences of he Cretaceous and Early Paleogene of the West Kamchatkan-Ukelayat zone. *Litologiya i Poleznye Iskopaemye.* -. 374-389. 2001.

23. Brandon, M.T., Decomposition of fission-track grain-age distributions, *Amer. J. Sci..* **292,** 535-564. 1992.

24. Brandon, M.T.. Probability density plot for fission-track grain-age samples. *Radiation Measurements,* 26. -V 663-676. 1996.

25. Hurford. A.J., Zeta: the ultimate solution to fission-track analysis calibration or just an interim measure? - *Advances in Fission-Track Geochronologx.* 19-32. Kluwer Academic Publisher, 1998.

26. Solov'ev, A.V., M.N. Shapiro, and J.I. Garver, Lesnaya tectonic massif, northern Kamchatka. *reotektonika*, 6, 45-59, 2002.

27. Avdeiko, G.P., S.V. Popruzhenko. and A.A. Palueva. Tectonic development and volcano-tectonic .gionalization of the Kuril-Kamchatkan island-arc system, *Geotektonika.* 4, 64-80. 2002.

28. Shapiro, M.N.. and M.Yu. Khotin, Late Cretaceous quartz-feldspar sandstones of eastern Kamchatka. *-.rologiya i Poleznye Iskopaemye,* 5, 67-74, 1973.

29. Levashova. N.M.. *Kinematics of Late Cretaceous and Cretaceous-Paleogene ensimatic island arcs of • .imchatka: PhD thesis* [in Russian], 22 pp., GIN, Moscow. 1999.

Editorial responsibility: V.A. Vernikovsky

Received 5 June 2003