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Lesnaya Nappe, Northern Kamchatka

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Abstract—The Lesnaya–Vatyn nappe (southern Koryakia, Kamchatka) was formed as a result of the collision between a Cretaceous island arc and the Eurasian continent. The Cretaceous marginal marine and island-arc complexes are obducted along this suture onto the Cretaceous-Paleogene deposits of the Eurasian continental margin. The suture is overridden by the neoautochthonous volcanics of the Kinkil' belt and cut by intrusions. Fission-track zircon dating of the autochthonous clastics (Lesnaya Group) along with nannoplankton datings showed that it was formed before the middle of the Middle Eocene. The Neoautochthon (Kinkil' Formation) of the Lesnaya–Vatyn thrust and the intrusion that cuts it (Shamanka massif) are dated as 45 Ma. Therefore, the Lesnaya thrust was emplaced at 45-46 Ma during less than 1 Ma. A collision model is proposed.

INTRODUCTION

Northeast Asia is a collage of noncoeval heterogeneous terranes docked up to Eurasia during the Mesozoic and Cenozoic [1, 2, 4, 16, 17, 19, 20, 25, 47, 51]. The last, accreted to Northeast Asia, is a belt of intensely deformed volcaniclastics that extends into Kamchatka from the front of the Olyutorsky zone (Fig. 1). This belt is composed of Cretaceous marginal marine and island-arc rock associations [1, 19, 21, 25, 26, 28] that presently rest upon a heterogeneous basement [3, 16]. Paleomagnetic data suggest that the island-arc sequences were deposited 20° south of the part of the continent [11, 13] to which they are currently welded. It is obvious that the arc had drifted over a considerable distance within an oceanic plate(s) before it collided with the continent [12, 22, 23, 34] and both were deformed, giving rise to an extensive collisional suture [14, 21, 23, 30, 32]. At the same time, there is no final answer to the question of where and how the collision actually took place. The answer depends largely upon the precise dating of the collision. It is believed that the collision between a Cretaceous island arc and the Asian continent induced changes in North Pacific plate kinematics the extinction of the Kula-Pacific Ridge, and led to a veer of the Pacific plate drift direction [38]. Thus, the precise dating of the collision between the Late Cretaceous arc and Eurasia is important for the understanding of the tectonic processes that took place along the northern periphery of the Pacific Ocean during the first half of the Cenozoic.

LESNAYA–VATYN THRUST FAULT

The Lesnaya–Vatyn thrust fault (Fig. 1) is among the largest sutures in Northeast Asia; it is traceable in southern Koryakia and Kamchatka [1, 14, 19, 21, 25, 30, 32]. The thrust fault separates the Cretaceous-Eocene deposits of the Eurasian continental margin [1, 10, 20, 22] and the Cretaceous marginal marine and island-arc complexes [1, 28]; in southern Koryakia, it is referred to as the Vatyn–Vyvenka [14, 21]; and on the Kamchatka Isthmus, as the Lesnaya thrust [30, 32].

Along the Vatyn-Vyvenka thrust fault, Upper Cretaceous cherty volcanics are obducted as a thin-skinned nappe onto the Cretaceous-Paleogene terrigenous flysch of the Ukelayat trough [10, 21] deposited at the foot of the Asian continental slope. The nappe emplacement was dated as (1) Maastrichtian (the age of the matrix of the subthrust olistostrome (?) as determined from benthic foraminifers [15]); (2) Middle Eocene (the age of the youngest autochthonous strata as determined from benthic foraminifers [10] and fission-track datings on detrital zircons [22, 33, 46]); or (3) Middle Miocene (the age of the oldest angular unconformity [6] mapped in the nearest vicinity of the thrust fault, on the Il'pin Peninsula [28]). The main difficulty in determining the nappe emplacement time is the absence of pre-Pliocene neoautochthonous complexes.

The Lesnaya thrust fault (Fig. 1b) on the Kamchatka Isthmus is a southward extension of the Vatyn–Vyvenka fault. It is also associated with the thin-skinned nappe of Upper Cretaceous cherty volcanics overriding the strongly deformed flysch of the Lesnaya Group [30, 32]. An important difference between the Kamchatka Isthmus and the front of the Olyutorsky zone is the wide occurrence of neoautochthonous rock complexes, which provide a possibility to determine the upper time limit of thrust emplacement during the arc-continent collision. The lower time limit of this process coincides with the age of the youngest autochthonous

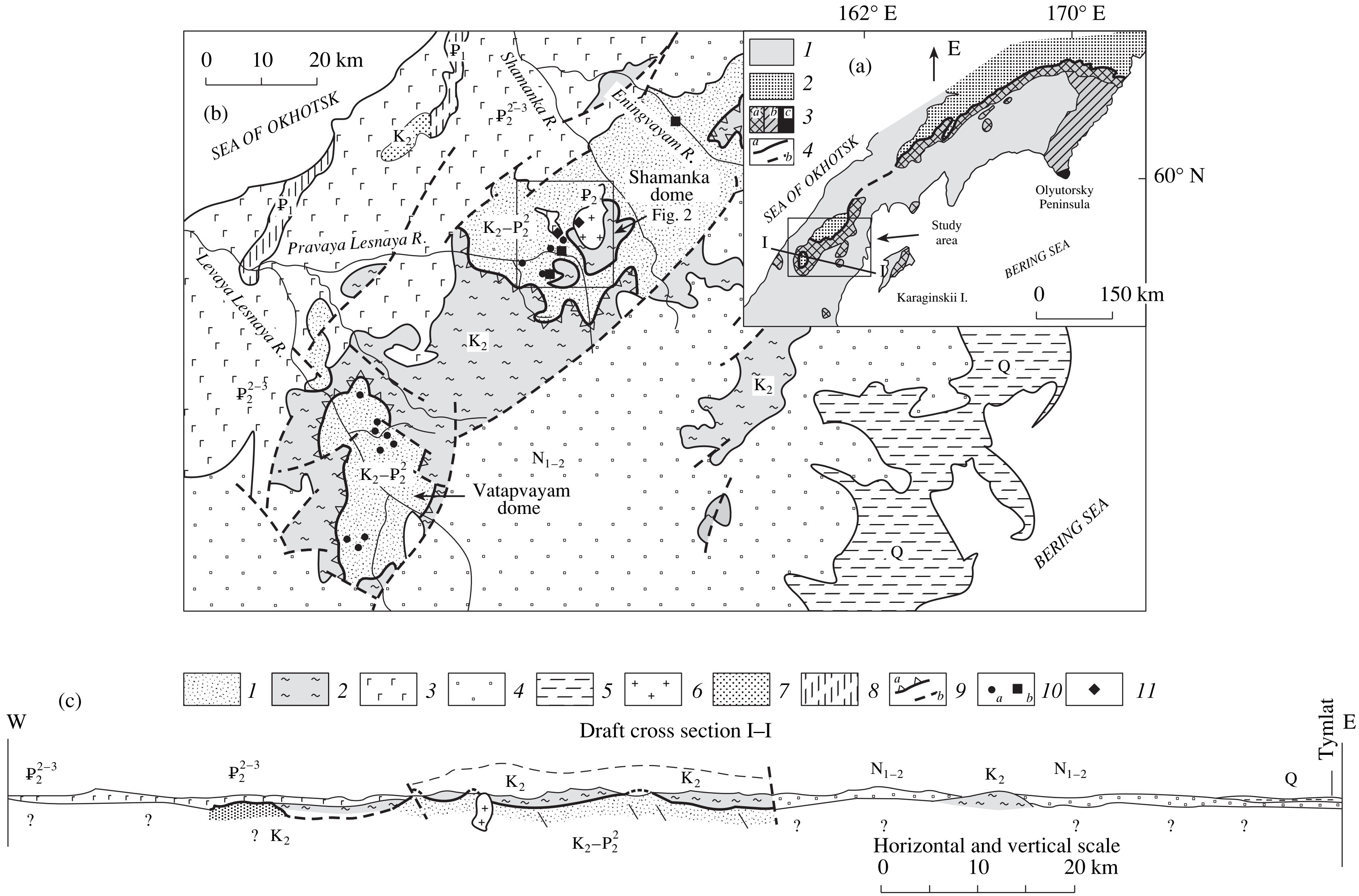
162° E
170° E
60° N
(a)
E
1
2
3
4
a
b
c
SEA OF OKHOTSK
Olyutorsky Peninsula
Study area
BERING SEA
Karaginskii I.
I
0
150 km
(b)
0 10 20 km
SEA OF OKHOTSK
Shamanka R.
Eningvayam R.
Pravaya Lesnaya R.
Levaya Lesnaya R.
Shamanka dome
Fig. 2
Vatapvayam dome
BERING SEA
K2
K2–P22
N1–2
Q
(c)
W
E
Tymlat
Draft cross section I–I
Horizontal and vertical scale
0 10 20 km
1 2 3 4 5 6 7 8 9 10 11

Fig. 1. Geologic structure of the Lesnaya–Vatyn collisional suture: (a) Position of the Lesnaya–Vatyn thrust fault in the structural framework of the Olyutorsky zone and northern Kamchatka, modified after [1]; (b) Draft map of the Kamchatka Isthmus; (c) Draft geologic cross section I–I. (a) (*1*) Cenozoic deposits; (*2*) Cretaceous–Paleogene deposits of the Ukelayat–Lesnaya trough; (*3*) Cretaceous cherty volcanics: (*a*) of the frontal Olyutorsky zone and Kamchatka Isthmus, (*b*) Olyutorsky Range, (*c*) Olyutorsky Peninsula; (*4*) Lesnaya–Vatyn thrust fault: (*a)* proven, (*b*) inferred. (b) and (c): (*1*) Autochthonous complex—Lesnaya Group (Upper Cretaceous?–Middle Eocene); (*2*) allochthonous complex—Irunei Formation (Upper Cretaceous); (*3–6*) Neoautochthonous complex: (*3*) Middle–Upper Eocene volcanics of the Kinkil' Formation (West Kamchatkan volcanic belt), (*4*) Upper Eocene–Lower Miocene sedimentary strata and Miocene–Pliocene volcanics of the Central Kamchatka belt, (*5*) loose quaternary sediments, (*6*) Shamanka granitoid massif; (*7, 8*) west Kamchatkan clastic complexes: (*7*) Talnich Formation (Upper Cretaceous), (*8*) Getkilnin Formation (Paleocene); (*9*) faults: (*a*) Lesnaya thrust fault, (*b*) other faults; (*10*) sampling sites: (*a*) sandstones of the Lesnaya Group for fission-track zircon dating, (*b*) samples for nannofossil identification from the Lesnaya Group; (*11*) sampling sites for isotopic dating.

or allochthonous deposits. New datings of rocks from the autochthonous and neoautochthonous complexes enabled us to determine the thrust emplacement time.

CHARACTERISTICS OF ROCK COMPLEXES MAPPED ON THE KAMCHATKA ISTHMUS

Structure and Age of the Autochthon of the Lesnaya Thrust

The autochthon of the Lesnaya thrust is composed of terrigenous flysch [31, 32, 33]. It consists of distal turbidite and contourite facies. Occasional directive structures (lingular hieroglyphs and asymmetrical microdunes) suggest a western source of clastic material [23]. The flysch is compressed into west-vergent folds and frequently crushed into tectonic mélange [23, 32]. The base of the group is not exposed, and there are no descriptions of its sequences or reliable thickness estimates. Structurally above it are the allochthonous cherty volcanics, usually separated by a mylonite zone. The mylonites are underlain by a tectonic mélange zone (200–400 m) with a matrix of the rocks of the Lesnaya Group that carry tuff, chert, basalt, and sandstone blocks. These blocks were previously interpreted as lenses in the Lesnaya sequence, and the inoceramid and radiolarian finds in them were cited in support of its Cretaceous age [5]. The Lesnaya sequence lacks macrofauna, is poor in radiolarians, and presents foraminifers as scarce agglutinated forms of a wide age range. Calcareous nannoplankton is the only group of fossils in the sequence that enables its reliable dating. *Cyclicargolithus floridanus* (as identified by E.A. Shcherbinina), extracted for the first time from a Lesnaya mudstone sample collected in the Eningvayam River basin, indicates a time interval of Middle Eocene-Oligocene; also, the Upper Cretaceous nannoplankton was identified from other samples collected in the study area [27]. Thus the age of the Lesnaya Group remained disputable until recently.

We determined the age of the Lesnaya Group by two independent methods: detrital thermochronology and nannoplankton identification (by E.A. Shcherbinina from the Geological Institute (GIN), Russian Academy of Sciences).

Detrital thermochronology. Detrital thermochronology is based on the track dating of separate detrital mineral grains (zircon, apatite) from sedimentary rocks. Track dating is based on counting the density of fission tracks from the spontaneous fission of uranium (U^{238}) accumulated in the mineral during its geologic history [39, 48]. Fission track accumulation in a mineral over time is a process similar to the accumulation of radiogenic isotopes as a result of radioactive decay. Track stability is guided largely by temperature, that is, the tracks are formed and retained in the crystals cooled down below the annealing temperature. Statistically, the annealing (effective for closure) temperature corresponds to the moment when more than 50% of the tracks become stable [50]. Assuming that a sample cools monotonously under typical geologic conditions (at a rate of 1 to 30°C/Ma), the annealing temperature for zircons will be 215–240°C [37].

The principal advantage of detrital thermochronology is the opportunity to trace the relationship between endogenic (magmatism, volcanism, orogeny) and exogenic (erosion, sedimentation) processes in time. The first data obtained using this technique were published 15 years ago [42]. At present, detrital thermochronology is a popular instrument for studying sedimentary and tectonic processes in various regions of the world [22, 24, 33, 37, 41, 44-46].

Because fission-track dating enables the ages of individual mineral grains to be determined, it provides the possibility of distinguishing noncoeval grain populations related to different provenances. The cooling of rocks in the source areas is due to various geologic processes. On the one hand, volcanic rocks and surficial intrusions cool rapidly and are destroyed by erosion, therefore zircons from these rocks quickly get into sedimentary basins. This makes them suitable for dating clastic sequences barren of fossils [24, 33, 37, 44–46]. On the other hand, the blocks pushed upward from the interior cool down at a certain moment, namely, when they rise above the closure (annealing) temperature of the fission-track system [45, 50]. It is from this moment on that fission track formation and accumulation in mineral crystals begins, and the age determined from these minerals will correspond to the cooling time.

Thirteen sandstone samples (4–10 kg each) were collected in the Vatapvayam and Shamanka domes (Fig. 2, see Fig. 1) of the Lesnaya high. Zircons were extracted from sandstones in the Laboratory of Accessory Minerals of the Institute of the Lithosphere of Marginal Seas, Russian Academy of Sciences. Zircon ages were determined in the Fission-Track Dating Lab-

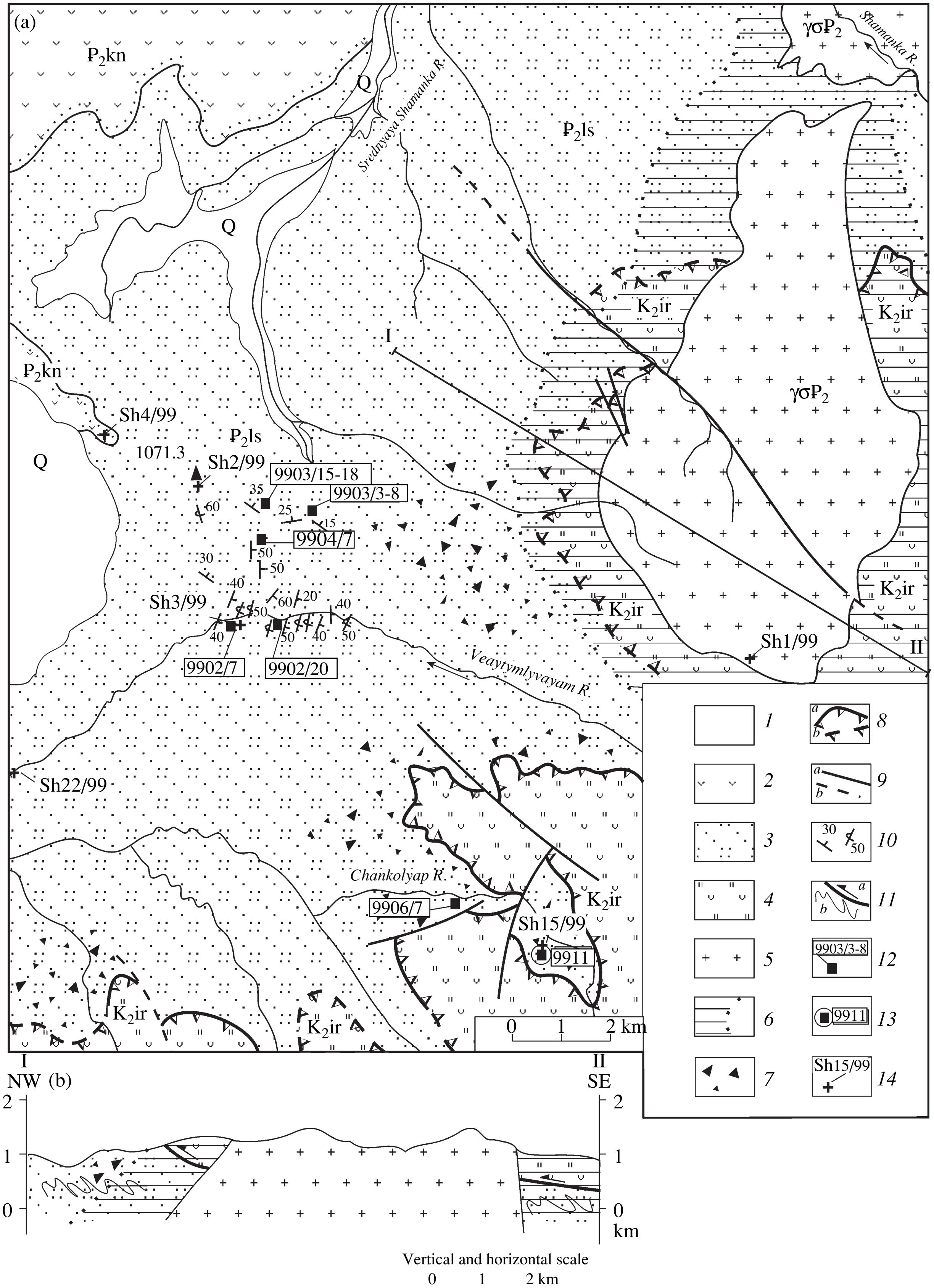
(a)
₽2kn
Q
Srednyaya Shamanka R.
₽2ls
γσ₽2
Shamanka R.
K2ir
I
II
Sh4/99
1071.3
Sh2/99
9903/15-18
9903/3-8
9904/7
Sh3/99
9902/7
9902/20
Sh1/99
Veaytymlyvayam R.
Sh22/99
Chankolyap R.
9906/7
Sh15/99
9911
0 1 2 km
NW (b)
SE
km
Vertical and horizontal scale
0 1 2 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Fig. 2. Western and southwestern surroundings of the Shamanka granitoid massif, modified after [30, 34]: (a) Draft geologic map, (b) Draft cross section I–II. (*1*) Quaternary sediments, (*2*) Kinkil' Formation (Middle Eocene); (*3*) Lesnaya Group (Paleocene–Middle Eocene); (*4*) Irunei Formation (Santonian–Maastrichtian0; (*5*) Middle Eocene granodiorites; (*6*) hornfelses and their areal extent; (*7*) largest mélange fields in the autochthon of the Lesnaya thrust; (*8*) Lesnaya thrust fault: (*a*) mapped, (*b*) inferred in the hornfels field; (*9*) other faults: (*a*) mapped, (*b*) inferred; (*10*) strike and dip symbols, (*11*) on the cross section: (*a*) fault plane of the Lesnaya thrust fault, (*b*) folding in the autochthon; (*12*) nannoplankton sampling sites from the Lesnaya Group and sample numbers; (*13*) nannoplankton sample from a block in the subthrust mélange; (*14*) numbers of samples for dating by various geochronological methods.

oratory of the Union College (Schenectady, NY, USA). The specific features of the sample preparation and dating procedure are described in the captions for Table 1. From 45 to 90 zircon grains were dated from each sample (Table 1). Zircon ages were calculated using Zetaage 4.7 software designed by M.T. Brandon (Yale University, USA). The ages of individual grains in all samples vary in a wide range, and this suggests that sandstones contain several noncoeval zircon populations. These populations were discriminated using a Binomfit 1.8 software created by M.T. Brandon (Yale University, USA) using an algorithm from [43].[1]

[1] The software used for calculations is available at http:\\love.geology.yale.edu/~brandon.

Fission-track distribution from 12 samples enables the recognition of three noncoeval zircon populations: P1, 44–58 Ma; P2, 71–106 Ma; and P3, 104–176 Ma (Table 1). Studies of apatite grains from the same samples suggest that the tracks in apatites were not annealed or were partially annealed [49]. Consequently, the temperature of the Lesnaya sediments after accumulation never exceeded 80–120°C (that apatite track system closure temperature) [50]. It follows that the fission tracks in zircons were not annealed, because the zircon track system closure temperature is estimated at 215–240°C [37, 50]. The youngest population P1 is dated in the interval between 43.7 ± 3.4 and 58.1 ± 4.2 Ma (Fig. 5), that is, this zircon population was last cooled in the interval between the latest Paleocene to

Table 1. Fission-track ages of detrital zircons from the Lesnaya sandstones (northern Kamchatka)

No	Group, formation	Nt	Ages of zircon populations		
			P1, Ma	P2, Ma	P3, Ma
Lesnaya High (Shamanka Dome)					
Sh3/99	Lesnaya	60	51.6 ± 5.0 (27%)	86.7 ± 8.9 (55%)	131.4 ± 29.2 (18%)
Sh2/99	Lesnaya	75	54.1 ± 8.9 (16%)	73.9 ± 13.9 (26%)	132.6 ± 9.2 (58%)
Sh21/99	Lesnaya	60	56.1 ± 3.8 (37%)	106.0 ± 11.5 (47%)	150.3 ± 34.2 (16%)
Sh15/99	Lesnaya (block)	59	86.1 ± 6.1 (44%)	155.3 ± 11.0 (56%)	–
Lesnaya High (Vatapvayam Dome)					
L12	Lesnaya	67	43.7 ± 3.4 (17%)	70.6 ± 4.4 (67%)	107.0 ± 12.2 (16%)
L1	Lesnaya	45	46.0 ± 2.7 (49%)	–	107.3 ± 7.0 (51%)
L9	Lesnaya	90	47.0 ± 3.8 (19%)	70.8 ± 5.7 (56%)	104.0 ± 11.9 (25%)
L2	Lesnaya	90	48.1 ± 5.0 (7%)	78.1 ± 5.8 (53%)	116.0 ± 8.6 (40%)
L11	Lesnaya	90	50.4 ± 5.6 (20%)	70.6 ± 6.6 (65%)	109.7 ± 25.0 (15%)
L10	Lesnaya	90	53.9 ± 3.4 (40%)	87.5 ± 6.2 (50%)	176.5 ± 23.8 (10%)
L17	Lesnaya	90	54.5 ± 10.4 (5%)	84.6 ± 6.5 (65%)	134.6 ± 18.9 (30%)
L13	Lesnaya	89	55.5 ± 3.5 (34%)	93.0 ± 4.8 (66%)	–
L4	Lesnaya	90	58.1 ± 4.2 (36%)	83.3 ± 6.3 (51%)	130.5 ± 14.9 (13%)

Note: No is sample number; Nt, number of dated zircon grains in the sample; P1, P2, and P3 are zircon populations discriminated using BinomFig v 1.8 software [35, 36]. Ages are given in Ma, age determination error corresponds to ±1σ. Percentages in parentheses correspond to the proportion of the grains of this population in the whole dated grain number (Nt). The zircons are dated using the external detector technique [50]. Zircon grains were mounted in FEP Teflon™ disks 2×2 cm^2 in size. Two disks were prepared for each sample. The mounted samples were rough-ground on an abrasive disk and then polished using 9 micron and 1 micron diamond pastes and 0.3 micron Al_2O_3 paste at the final stage. Then the grain mounts were etched by NaOH-KOH eutectic at a temperature of 228°C during 15 hours (first disk) and 30 hours (second disk). After etching, the grain mounts were covered by external detectors (low-U mica flakes) and irradiated by a thermal neutron flux of about 2×10^{15} neutron/cm^2 (Oregon State University reactor). Zircon age standards (Fish Canyon Tuff, FCT and Buluk Tuff, BL) and a glass dosimeter with established uranium content (CN-5) [40] were irradiated together with the samples. Fission tracks were counted under an Olympus BH-P microscope with an automatic system and a digitizer tablet, maximum magnification 1256x, dry method. ζ-factor [40] as calculated from 10 age standards (6 FCT and 4 BL samples) was 305.01 ± 6.91.

Table 2. Nannoplankton from the Lesnaya Group in the headwaters of the Pravaya Lesnaya River (Northern Kamchatka)

Nannoplankton species	Sample numbers																	
	9902-1	9902-5	9902-7	9902-11	9902-20	9903-4	9903-5	9903-6	9903-11	9903-15	9903-16	9903-18	9904-7	9906-7	9911-7	9911-8	9911-12	9911-17
Cyclicargolithus floridanus					■		■		■									
Coccolithus pelagicus								■			■							
Sphenolithus primus/moriformis	■			■		■					■			■				
Dictyococcites bisectus									■			■						
Reticulofenestra umbilicus									■	■								
R. haqii									■									
R. dictyoda													■					
Helicosphaera compacta					■													
Chiasmolithus cf. nitidus									■									
Zyghablithus bijugatus						■												
Micula decussata			■															
Neochiastozygus sp.		■																
Thoracosphaera sp.									■									
Watznaueria barnesae	■															■	■	■
Reinchardtites anthiphorus															■			
Eiffellithus turriseffeli																	■	
Prediscosphaera sp.																■		

the mid-Eocene. Considering that deposits are always younger than the clasts they consist of, the sampled portion of the Lesnaya Group cannot be older than the latest Paleocene to Early Eocene.

Nannoplankton studies. The main nannoplankton sampling site is located in the headwaters of the Pravaya Lesnaya River (Figs. 1, 2). At this site, 46 samples were collected from the softest and the least cleaved argillites. Rare nannoplankton forms were found in 12 of them (identified by E. A. Shcherbinina, Table 2) [34]. In most samples from the Lesnaya Group, nannoplankton occurs as single forms generally within the Early Paleogene time span. Samples 9902-1, 9902-5, 9902-7, and 9902-11 contain *Micula decussata, Sphenolithus primus/moriformis, Neochiastozygus* sp., and *Watznaueria barnesae* indicative of the Paleocene age of host rocks. The deposits represented by samples 9902-20, 9903-11, and 9903-18 are not older than the Middle Eocene, most probably the upper part, as obvious from the presence of *Reticulofenestra umbilicus*, *Helicosphaera compacta*, and *Dictyococcites bisectus*, and not younger than the Early Oligocene (the upper limit of the *Reticulofenestra umbilicus* zone). Some samples contain species of a wide stratigraphic range. For example, *Cyclicargolithus floriadanus* and *Helicosphaera compacta* encountered in Sample 9902-20 indicate the Middle Eocene-Oligocene time interval; combined *Sphenolithus moriformis* and *Zygrhablithus bijugatus*, Eocene–Oligocene; and *Coccolithus pelagicus* and *Sphenolithus primus/moriformis,* latest Danian–Middle Miocene.

To summarize, the nannoplankton species extracted from the Lesnaya argillites suggest the Paleocene–Middle Eocene age of these deposits (Fig. 5).

The age of the clastic blocks in the Lesnaya Group. The Chankolyap Creek headwater area (Fig. 2) exhibits a well exposed Lesnaya thrust fault and a thick subthrust mélange zone, where the sandstone–mudstone matrix of the Lesnaya Group contains numerous blocks of various size (from a few meters to one or two hundred meters); the bulk of these blocks here are composed of clastic rocks. One such block (site 9911, see Fig. 2) is composed of sandstones, siltstones, and mudstones with thin chert lenses and fragmentary prismatic layers of inoceramids [34]. The sandstones are similar in composition with those of the Lesnaya Group. Four samples of mudstones (argillites) from this block contain single nannoplankton forms (Table 2) of Santonian–Campanian age. The matrix of the mélange at this site is composed of younger rocks, considering the presence of *Sphenolithus moriformis*, a Cenozoic form

Table 3. U-Pb isotopic data for zircons from samples Sh1/99 and Sh4/99

Grain type	Grain weight, mg	Pb_c, pg	U, g/t	$^{206}Pb_m$/^{204}Pb	$^{206}Pb_c$/^{208}Pb	Apparent ages, Ma: $^{206}Pb^*$/^{238}U	$^{207}Pb^*$/^{235}U	$^{207}Pb^*$/$^{206}Pb^*$
Sh1/99								
5A	31	6	241	571	9.6	45.6 ± 1.3	45.7 ± 1.6	51 ± 49
5A	32	11	216	310	5.9	45.3 ± 1.3	45.3 ± 2.2	46 ± 88
5A	29	8	303	502	7.7	45.3 ± 1.1	44.9 ± 1.5	20 ± 55
1Br	11	9	471	283	5.9	45.2 ± 1.8	45.5 ± 2.6	63 ± 99
5Ar	29	9	386	556	3.6	45.4 ± 0.9	45.5 ± 1.1	52 ± 37
Sh4/99								
5Ar	31	6	1301	3200	21.9	47.1 ± 0.3	47.6 ± 0.5	71 ± 15
5Ar	32	11	3151	4100	20.3	46.1 ± 0.3	46.4 ± 0.5	61 ± 20
5Ar	36	11	1915	2690	20.3	44.9 ± 0.3	46.1 ± 0.5	105 ± 16
5Ar	66	8	1809	9180	13.1	61.7 ± 0.4	78.9 ± 0.6	637 ± 7
5Ar	70	12	1462	5900	19.9	61.1 ± 0.4	80.1 ± 0.7	692 ± 10

Note: Analyses were made by G. Jarels (Arizona State University, USA) on a mass-spectrometer using isotopic dilution technique. Asterisks indicate radiogenic Pb. Grain type: A = ~100 micron, B = ~200 micron, r = 5 : 1 elongate grains; grain numbers are given for all grain types. $^{206}Pb/^{204}Pb$ is the incorrect measured ratio; $^{206}Pb/^{208}Pb$, correct measured ratio. Concentrations have a 25% error resulting from grain weight determination error. The following constants were used: $^{238}U/^{235}U = 137.88$; decay constants: $^{235}U = 9.8485 \times 10^{-10}$, $^{238}U = 1.55125 \times 10^{-10}$. Errors correspond to $\pm 2\sigma$ (95%). Lead blank contamination was 2 to 10 pg; uranium, <1 pg. The interpreted ages for concordant grains are $^{206}Pb^*/^{238}U$ if the age is < 1.0 Ga and $^{207}Pb^*/^{206}Pb^*$, if the age is >1.0 Ga. The interpreted ages for discordant grains are projected from 100 Ma (see Fig. 3).

of a wide stratigraphic range (Lower Eocene–Miocene), in the mudstones.

The fission-track dating of zircons extracted from sandstones from the same block (site 9911, sample Sh15/99) showed the presence of two populations (Table 1). The young zircon population is dated 86.1 ± 6.1 Ma, which corresponds to the Coniacian–Santonian. We believe that the sampled block is a fragment of the lower flysch horizons exhumed during the Lesnaya thrust emplacement. Therefore, the overall age of this group is estimated as Santonian to earliest Middle Eocene (Fig. 5).

Structure and Age of the Allochthon of the Lesnaya thrust

The allochthon of the Lesnaya thrust is complexly built; it consists of numerous slices, which make it difficult to compile the reference sections of cherty-volcanic sequences [5, 9].

On the western slope of the Lesnaya high, the cherty volcanic sequence consists of two members with predominant pillow basalts and jaspers in the lower part and fine tuffs and cherts, in the upper. Small (several centimeters to several meters) folds are not typical for the allochthon, and folds with amplitudes of several meters to several tens of meters are rarely found in outcrops. Large folds in the allochthonous complexes of the Lesnaya high have a generally NE trend; near the Lesnaya thrust fault, however, they acquire conformity with its fault plane and exhibit a steep westward dip on the western flank of the Vatapvayam dome and a gentle southeastward dip in the southern part of the eastern flank [32].

Until recently, the age of the cherty volcanics of the Lesnaya high was determined largely from inoceramids, which were dated either as Santonian–Campanian or as Campanian, depending on their preservation [5]. In recent years, these were supplemented by the datings of radiolarians from the cherts, most of which indicate a Campanian–Maastrichtian age of the host rocks (T.N. Palechek, unpublished).

Structure and Age of the Neoautochthonous Complexes of the Lesnaya Thrust

The neoautochthonous complexes of the Lesnaya thrust comprise the Shamanka granodiorite massif and volcanic rocks of the Kinkil’ Formation. The Shamanka intrusion cuts the Lesnaya thrust zone, giving rise to hornfelses along the Lesnaya clastics, the cherty volcanics, and the thick mylonite zone between them on the divide between the Shamanka and Pravaya Lesnaya rivers (Fig. 2) [34].

The Shamanka massif is composed of medium- to coarse-crystalline and, in places, porphyritic plagiog-

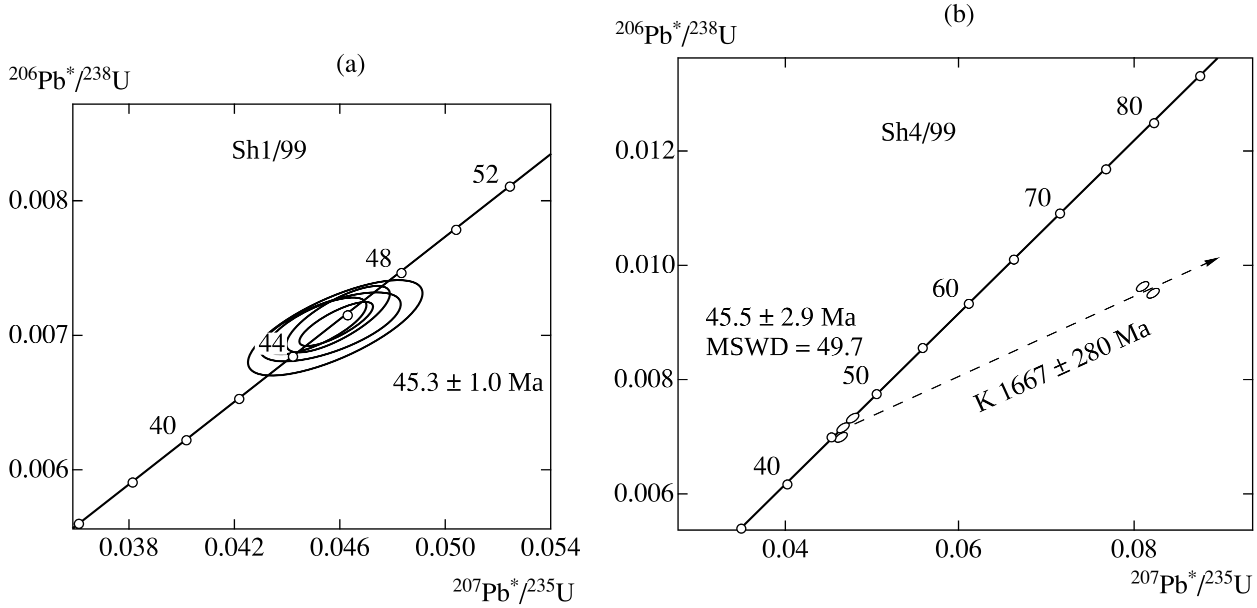

Fig. 3. U/Pb isochron diagrams: (a) for the Shamanka granodiorites (sample Sh1/99); (b) for the rhyolites at the base of the Kinkil Formation (sample Sh4/99).

ranites and granodiorites with numerous stratified host rock, granodiorite, porphyry diorite, and diabase xenoliths. The massif extends N–S and has a gentle northwestern and subvertical eastern contact. To the northwest, the intrusion is rimmed by a stockwork of dikes of varying composition and, somewhat farther, by a series of subvolcanic rhyolite bodies compositionally similar to the Kinkil' rhyolites. Pebbles and bounders of granitoid and hornfels are present in the Upper Eocene conglomerates to the east of the intrusion [30].

Samples for datings were collected from medium granodiorites, composed of acid plagioclase (dominant), quartz, and subordinate potassium feldspar. The mélanes are represented by fresh, light brown biotite and green amphibole, sometimes by partially replaced biotite. Zircon grains are included in the biotite and surrounded by pleochroic halos.

Granodiorite sample Sh1/99 was collected in the southern part of the massif (Fig. 2). The age of the granodiorites was determined by U/Pb, Rb/Sr, and K/Ar methods. U/Pb datings from five zircon batches (Table 3) lie on a concordia (Fig. 3a). It is obvious that the zircons do not contain xenogenic components. The age was determined as 45.3 ± 1.0 Ma. Rb/Sr isochron was plotted on 3 points (biotite, hornblende, and plagioclase) (Table 4, Fig. 4). The isochron parameters are: age 44.4 ± 0.1 Ma, $(^{87}Sr/^{86}Sr)_0$ = 0.70388 ± 0.00003, MSWD = 23.3. Biotite and hornblende from the same sample (Sh1/99) were dated by the K/Ar method (Table 5). The biotite age is 47.0 ± 1.3 Ma; the hornblende age, 44.0 ± 2.5 Ma. Note that the datings obtained by different methods exhibit a good convergence (Fig. 5). The only exception is the K/Ar biotite age, which is older by approximately 6%, probably due to an excessive amount of radiogenic argon, adsorbed

Table 4. Rb/Sr datings of sample Sh1/99 (granodiorite from the Shamanka massif)

Mineral	Rb, g/t	Sr, g/t	$^{87}Rb/^{87}Sr$	$^{87}Sr/^{86}Sr$	Age, Ma	Mineral pair	Age, Ma	$(^{87}Sr/^{86}Sr)_0$
Plagioclase (Pl)	6.314	759.0	0.02410 ± ± 0.00007	0.70388 ± ± 0.00002	44.4 ± 0.1 $(^{87}Sr/^{86}Sr)_0$ = = 0.70389 ± ± 0.00003 MSWD = 23.3	Plagioclase–Hornblende	47.1 ± 1.1	0.70386 ± ± 0.00002
Hornblende (Hb)	9.566	15.86	1.7447 ± ± 0.0016	0.70503 ± ± 0.00002		Plagioclase–Biotite	44.37 ± 0.04	0.70386 ± ± 0.00002
Biotite (Bi)	325.4	3.240	295.72 ± ± 0.25	0.89023 ± ± 0.00003		Biotite–Hornblende	44.35 ± 0.04	0.70393 ± ± 0.00002

Note: Rb and Sr abundances were determined by isotope dilution technique using mixed $^{85}Rb/^{84}Sr$ spike. Isotopic ratios were measured on a Micromass Sector 54 mass-spectrometer. Operation was controlled by measuring international strontium standard SRM 987. Strontium isotopic composition was normalized for $^{86}Sr/^{88}Sr$ = 0.1194. The datings were obtained by V.N. Golubev (Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences).

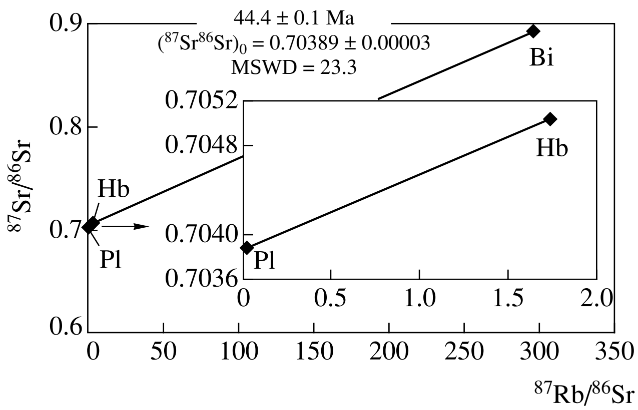

Fig. 4. Rb–Sr isochron diagram for the Shamanka granodiorites (sample Sh1/99). Pl—plagioclase, Hb—hornblende, Bi—biotite.

during secondary alteration. The U–Th/He apatite age is 40.3 Ma (as determined by P. Rhyner, California Institute of Technology, USA), corresponds to the time when the intrusion was exposed to erosion surface. For further geological modeling, we adopted the age of the Shamanka intrusion as 44.4 Ma (Middle Eocene, Lutetian).

The Kinkil' volcanics rest with a pronounced angular unconformity upon the Lesnaya flysch and, according to [5, 30], also upon the Irunei cherty volcanics. These volcanics occur as a wide belt extending along the western coast of Kamchatka to the north of the Palana River mouth. The Kinkil' belt consists largely of subaerial basalts and andesites geochemically similar to the products of Andean-type volcanic belts [8, 29]. On the basis of scarce flora finds in sedimentary intervals and relationships with better dated sediments, the Kinkil' Formation was dated as Eocene [7]. The K/Ar whole-rock age of the volcanics ranges within 37–51 Ma [8], but these dates, as well as geochemical data, characterize the rocks exposed on the Sea of Okhotsk coast. In the immediate vicinity of the study area, the Kinkil' sequence is acid-to-basic, beginning with rhyolites and crowned by basalts [30].

To determine the age of the Kinkil' Formation, basal biotite-bearing rhyolites were sampled (Sh4/99) from a small isolated field surrounded by the outcrops of the Lesnaya Group (Fig. 2). The rhyolites are bedded almost horizontally above the unconformably underlying, strongly deformed deposits of the Lesnaya Group. The sample consists of a felsitic matrix with small quartz, feldspar, opacitized amphibole, and dark-brown biotite phenocrysts. The rhyolites were dated by U/Pb, K/Ar, and fission-track methods; the U/Pb age was determined on five zircon batches (Table 3, Fig. 3). The datings on three batches lie close to the concordia (Fig. 3b); two batches yielded ages shifted away from the concordia, probably due to the contamination of the parent melt with ancient zircons crustal complexes. From three points, the age of the rhyolites was determined as 45.5 ± 2.9 Ma (Fig. 3b). The upper intercept

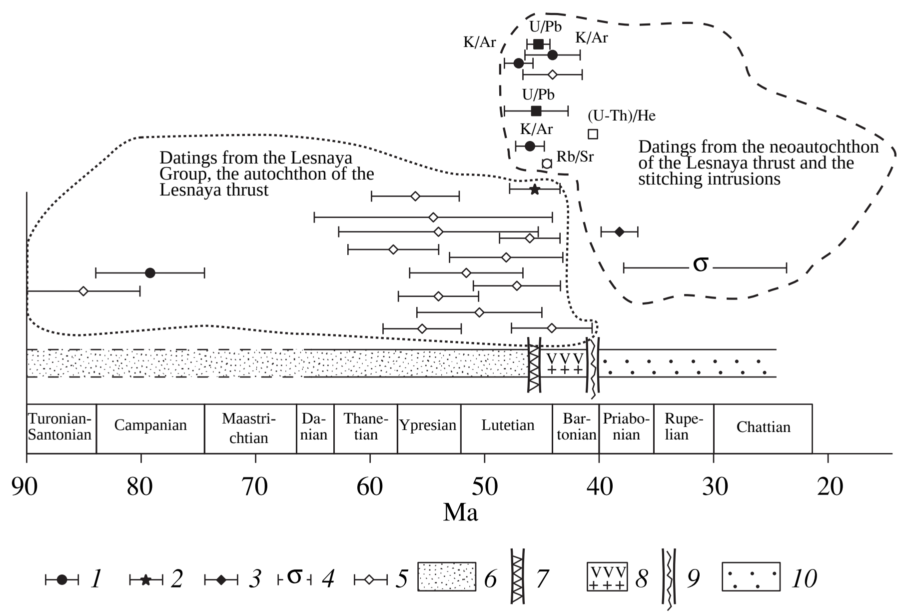

Fig. 5. Chronology of geologic events in the central Lesnaya high in the interval from the Campanian to Oligocene. (*1–4*) Intervals dated by fossils: (*1*, *2*) nannoplankton: (*1*) from a block of clastic rocks in the subthrust mélange of the Lesnaya Group [34], (*2*) from the Lesnaya Group [34], (*3*) flora from the base of the Shamanka Formation [30], (4) mollusks from the top of the Shamanka Formation [30]; (*5*) age of a young zircon population from the Lesnaya sandstones, interval corresponds to identification error; (*6*) accumulation of the Lesnaya Group; (*7*) deformation of the Lesnaya Group, Lesnaya thrust emplacement, uplift, and erosion; (*8*) accumulation of the Kinkil' Formation and granite emplacement; (*9*) uplift and deep scour resulting in the surface exposure of the Shamanka massif; (*10*) transgression, accumulation of the Kinkil' formation.

Table 5. K-Ar datings of biotite and hornblende from sample Sh1/99 (granodiorites from the Shamanka massif) and biotite from sample Sh4/99 (Kinkil' rhyolite)

Sample No	Mineral	Potassium, % ±1σ	$^{40}Ar_{rad}$, ng/g ±1σ	Age, Ma ±1.6σ
Sh1/99	Biotite	6.67 ± 0.06	22.0 ± 0.3	47.0 ± 1.3
Sh1/99	Hornblende	0.54 ± 0.01	1.65 ± 0.06	44.0 ± 2.5
Sh4/99	Biotite	6.75 ± 0.06	21.8 ± 0.3	46.0 ± 1.3

Note: Radiogenic argon content was measured on a MI-1201 IG mass-spectrometer using isotope dilution technique with ^{38}Ar as a spike, and potassium content was measured by flame spectrophotometry. The following constants were used: $\lambda_k = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K = 0.01167$ (at.%). The datings were performed by M.M. Arakelyants and V.A. Lebedev (Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences).

of the discordia (1667 ± 280 Ma) suggests the presence of xenogenic material captured from host rocks. The K/Ar biotite age of the same sample (Sh4/99) is 46.0 ± 1.3 Ma (Table 5), which coincides with the zircon age within the error. Zircon (44.0 ± 2.6 Ma) and apatite (44.3 ± 5.7 Ma) ages were determined by fission-track dating (Table 6). We assume the age of the captured xenoliths to be 1700 Ma (Proterozoic); the age of the rhyolite melt, 45.5 Ma; and the age of its cooling below 240°C, 44.0 Ma (Middle Eocene, Lutetian).

LESNAYA THRUST EMPLACEMENT MODEL

The Lesnaya thrust emplacement was preceded by a long independent development of the autochthonous and allochthonous complexes (Fig. 6, I). The Lesnaya Group is composed largely of distal turbidites and contourites accumulated at the foot of the NE Asian continental slope [10, 16, 19]. The bulk of the Irunei Formation was accumulated near an island arc and a marginal sea that separated the arc from the Eurasian margin [9, 11, 13, 19]. As a result of collision between the arc and Asian margin, the top of the island-arc crust, composed predominantly of volcanics and associated sediments, was obducted onto the continental margin and overrode the sediments deposited on the continental slope and continental rise.

A hypothetical version of Lesnaya thrust emplacement model implies that, as the lithospheric plates converged, the thin (2–5 km) and strongly faulted island-arc slab was scraped off its basement and pushed 50–100 km up the continental slope, deforming the underlying sediments of the Lesnaya Group. However, the offscraping of a thin island-arc slab from the basement as a result of general lithospheric compression and its subsequent movement up the slope hardly seems possible. Moreover, the structural patterns of the allochthonous and autochthonous complexes are apparently independent [23]. The folded structure of the autochthon is truncated by the Lesnaya thrust plane. Deformations in the allochthon, accompanied by greenschist metamorphism, precede the main thrust plane formation and are also truncated by the thrust. Therefore, we propose a different thrust emplacement model.

The ongoing subduction of the oceanic lithosphere beneath the island arc must have finally induced the outer edge of the Late Cretaceous turbidite–contourite apron of NE Asian margin to start plunging into the trench (Fig. 6II). The abrupt thickening of sediments on the downgoing slab led to their offscraping; as a result, an accretionary prism sourced from the continent rather than the arc was formed (Fig. 6III). Subduction beneath the arc ceased on the approach of the thick and light continental lithosphere of the upper part of the continental slope [10]. The ongoing plate convergence led to the strong compression of the island-arc lithosphere, rapid uplift of the island arc, and the gravitational destabilization of the newly formed uplift. Its upper parts slid down rapidly toward the newly formed accretionary prism as a succession of thin-skinned slices and thereby give rise to the Lesnaya thrust (Fig. 6IV, 6V). This model complies well with the arc-continent collision model proposed by Konstantinovskaya [12].

Table 6. Fission-track datings of the Kinkil' rhyolite (sample Sh4/99)

Mineral	ρ_s	Ns	ρi	Ni	ρd	N	χ^2	Age, Ma	–1σ	+1σ	U ± 2 se
Zircon	6.39	1071	7.04	1181	2.81	20	100	44.0	–2.5	+2.6	300.5 ± 25.3
Apatite	0.47	185	1.57	612	28.4	14	99.7	44.3	–5.0	+5.7	22.1 ± 2.0

Note: ρs is the density of ^{238}U spontaneous fission tracks (cm^{-2} × 10^{-6}); Ns, counted number of spontaneous fission tracks; ρi, density of ^{235}U induced fission tracks (cm^{-2} × 10^{-6}); Ni, counted number of induced fission tracks; ρd, density of tracks in external detector (low-U mica) (cm^{-2} × 10^{-5}); N, number of dated grains; χ^2, probability in per cent. Z-factor [40] for zircons, calculated from 10 age standards (Fish Canyon tuff and Buluk tuff) is 305.01 ± 6.91 (±1 se). Z-factor for apatite, calculated from 7 age standards (Fish Canyon tuff and Buluk tuff), is 104.32 ± 3.35 (±1 se). The samples were irradiated in a thermal neutron flux of about 2×10^{15} neutron/cm^2 for zircons and 8×10^{15} neutron/cm^2 for apatites (Oregon State University reactor). Age standards and a dosimeter glass with established U content (CN = 5 for zircons and CN = 1 for apatites) were irradiated simultaneously with the samples. Tracks were counted under an Olympus BH-P microscope with an automatic system and digitizer tablet, maximum magnification 1562.5×, dry method.

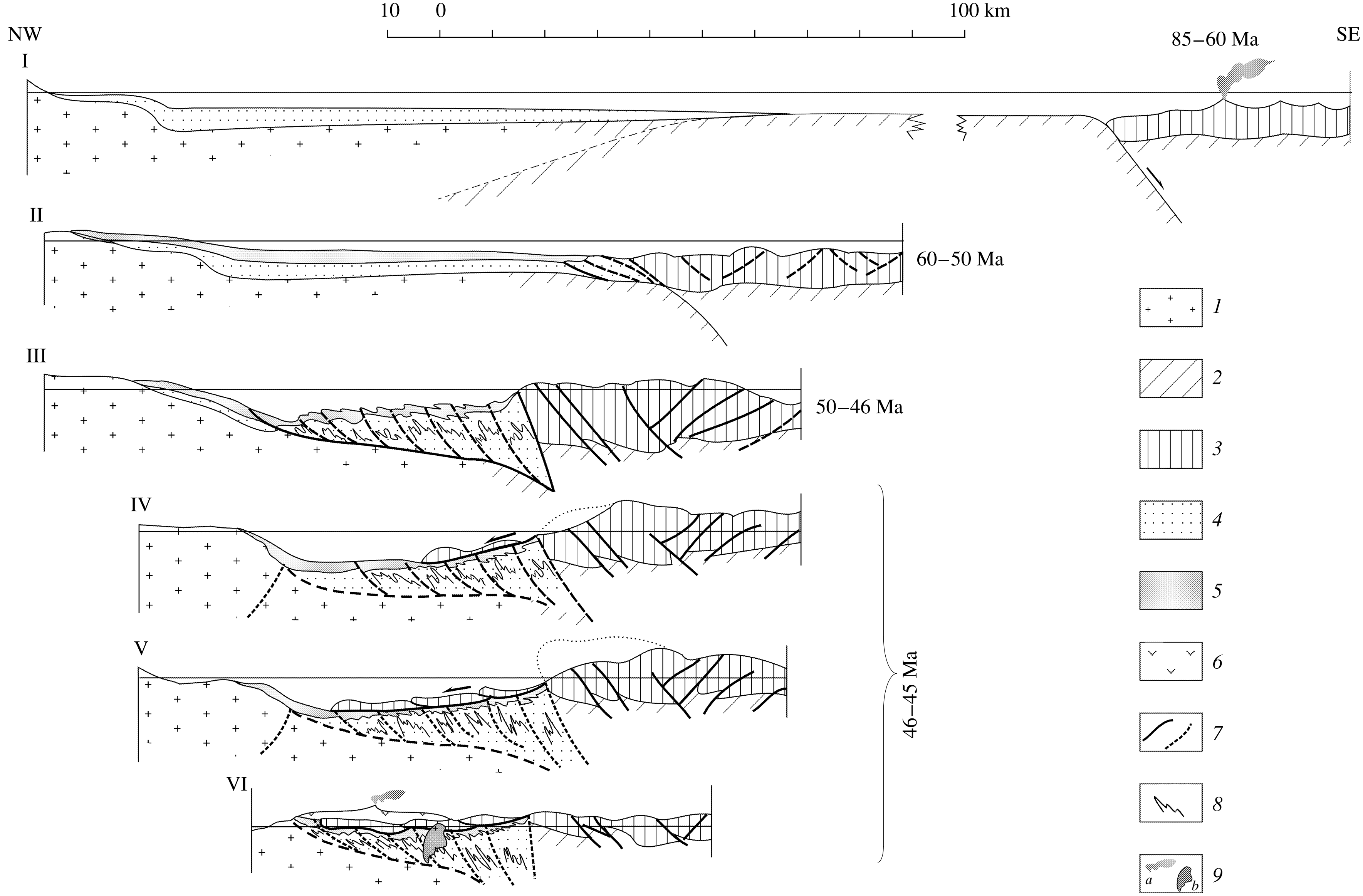

Fig. 6. Model of the Lesnaya thrust emplacement (Northern Kamchatka). Vertical scale is conventional. (*1*) Continental crust of the Eurasian margin; (*2*) oceanic and marginal marine crust; (*3*) Late Cretaceous island-arc complexes (allochthon); (*4*) Cretaceous–Lower Paleocene marginal turbidites (autochthon, Lesnaya Group); (*5*) Upper Paleocene–Eocene marginal turbidites (autochthon, Lesnaya Group); (*6*) Middle Eocene volcanics of the Kinkil' Group; (*7*) faults; (*8*) folding in the autochthon; (*9*) postcollisional: (*a*) volcanism, (*b*) intrusions.

CONCLUSIONS

Based on nannoplankton and fission-track detrital zircon datings, the autochthonous clastics of the Lesnaya thrust were deposited from the Santonian–Campanian to the earliest Middle Eocene inclusive. The youngest zircon population in the sampled sandstones of the Lesnaya Group cooled down and was reworked not earlier than 46 Ma (Fig. 5). The Lesnaya sandstones are similar in age to the young zircon population to the sandstones of the northern Ukelayat trough (Matysken River basin) [22, 33, 46].

The Shamanka granodiorite massif intruded the deformed autochthonous deposits, Lesnaya thrust zone, and the lower part of the allochthonous slice no later than 44.4 Ma (a set of isotopic datings) (Fig. 5). The basal rhyolites of the Kinkil' Formation started to accumulate no later than 45.5 Ma (a set of isotopic datings) (Fig. 5). Absolute datings suggest that the Shamanka granodiorites are comagmatic with the lower Kinkil Formation.

The end of deposition of the autochthonous Lesnaya Group and the beginning of deposition of the neoautochthonous complexes coincide in time within the instrumental error. This means that the deformation of the Lesnaya Group, Lesnaya thrust emplacement, post-thrusting uplift, and erosion took place rapidly, during 1 Ma or sooner. Considering that the displacement along the Lesnaya thrust fault is more than 50 km [23, 32], the allochthon displacement velocity probably exceeded 5 cm/yr. Such a velocity exceeds the rate of relative convergence of the Pacific plate and Eurasia (North America) early in the Middle Eocene [38]. Probably, the northeastward movement of the allochthon did not directly reflect plate convergence, but was caused by the gravity slide of thin slices from a previously formed uplift (Fig. 6). The obtained dating of the Lesnaya thrust is closely contemporaneous with the most pronounced regional unconformity in the Cenozoic sequence of Kamchatka, recorded at the base of the Snatol' Horizon (middle Lutetian) [7]. Therefore, thrust emplacement on the Kamchatka Isthmus obviously reflects an important collision event.

To summarize, the following hypothesis is proposed. If the Lesnaya–Vatyn suture formation (45 Ma) marked the end of the collision between a Late Cretaceous arc and a continental margin, this event preceded by 2 Ma a major change (sa. 43 Ma) in the kinematics of North Pacific oceanic plates and probably caused it.

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