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Research Article

New age data from the Lesnaya Group: A key to understanding the timing of arc-continent collision, Kamchatka, Russia

Alexei V. Soloviev,[1,*] Mikhail N. Shapiro,[2] John I. Garver,[3] Ekaterina A. Shcherbinina[4] and Igor R. Kravchenko-Berezhnoy[4]

[1]*Institute of the Lithosphere of Marginal Seas, Russian Academy of Sciences, Staromonetny per., 22, Moscow 109180, Russia, (email: solov@ilran.ru)* [2]*Institute of the Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya, 10, Moscow 123810 GSP, Russia,* [3]*Geology Department, Union College, Schenectady, NY 12308–2311, USA, and* [4]*Geological Institute, Russian Academy of Sciences, Pyzhevskiy per., 7, Moscow 109017, Russia*

Abstract The Lesnaya Group is part of a thick, poorly dated turbidite assemblage that sits in the footwall of a regionally extensive collision zone in which the Cretaceous–Paleocene Olutorsky island arc terrane was obducted onto continental margin basin strata. Nannoplankton from 18 samples from the upper part of the Lesnaya Group yield Paleocene through Middle Eocene assemblages. Detrital zircons from nine sandstone samples have a young population of fission-track ages that range from 43.7 ± 3.4 to 55.5 ± 3.5 Ma (uppermost Paleocene to Middle Eocene). The deformed footwall rocks of the Lesnaya Group and the overlying thrusts of the Olutorsky arc terrane, are unconformably overlain by neoautochthonous deposits which are Lutetian (lower Middle Eocene) and younger. Together, these new data indicate that thrusting, which is inferred to have been driven by collision of the Cretaceous–Paleocene island arc with north-eastern Asia, took place in the mid-Lutetian, at about 45 Ma.

Key words: collision, Eocene, fission-track dating, Kamchatka, nannoplankton, zircon.

INTRODUCTION

The timing of collision of outboard island arc terranes in Kamchatka has been debated for years. Central to the debate is the age of deformed units involved in the hanging wall of the collision zone, as well as the age of post orogenic units. The Vatyna thrust (also Lesnaya thrust) defines a nearly continuous north-south suture zone exposed over nearly 800 km in Kamchatka. This suture zone places an oceanic island arc over strata of the Eurasian continental paleomargin. At the time of collision, the margin was an Andean style continental arc, which shed detritus into flanking basins to the east (Bogdanov *et al.* 1999; Garver *et al.* 2000b). The island arc that collided has a number of names that have appeared in published reports, but most common are the Olutorsky Arc, Olutorsky terrane, or the Achaivayam–Valaginsky Arc; we use Olutorsky terrane in this paper. This oceanic arc is well dated as Upper Cretaceous in age, based on a number of occurrences of *Inoceramus* and microfossils in the host strata, as well as radiometric ages on igneous rocks (Ledneva *et al.* 2000). Locally, the Olutorsky terrane contains strata as young as Paleocene. The footwall of the collision zone is almost everywhere which includes poorly dated marine turbiditic strata of the Ukelayat, Lesnaya, or Hosgon Groups (regional names from north to south in Kamchatka). The key to determining the timing of collision is a better understanding of the age of these poorly fossiliferous units because they sit in the collision zone, and locally these strata contain olistoliths inferred to have been derived from the island arc sequence.

*Correspondence.

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The Lesnaya Group is exposed in the Lesnaya uplift on the Kamchatka Isthmus and it forms the autochthon of the Lesnaya thrust, which can be traced northward to the Vatyna thrust. Allochthonous rocks in the collision – the Olutorsky terrane – are comprised in this area of volcanic rocks and chert of the Santonian–Maastrichtian Irunei Formation (Shantser *et al.* 1985; Markovsky 1989; Shapiro & Soloviev 1999) (Fig. 1). The age of the Lesnaya thrust is constrained by the age of the rocks involved in deformation and to the oldest overlap strata. However, for some time there has been considerable uncertainty as to the ages of footwall rocks, thus casting suspicion on the assigned ages of overlap sequences which are inferred from long-ranging floral assemblages. As such, the age of the Lesnaya Group is crucial in resolving the timing of this deformation.

Prior to recognition of the nearly horizontal Lesnaya thrust, the Lesnaya Group was believed to be Upper Cretaceous in age largely because the unfossiliferous flysch of the Lesnaya Group was seen as being *stratigraphically* overlain by well-dated Upper Cretaceous strata of the Irunei Group (Markovsky 1989; Shantser *et al.* 1985), and many hold this view despite new data that has emerged from this area. After the overthrust was first recognized, it was inferred to have developed sometime between the Late Maastrichtian to Early Eocene (Shantser *et al.* 1985). New data suggesting that the Lesnaya Group is actually younger than previously thought (Fedorchuk & Izvekov 1992; Soloviev *et al.* 2001) has opened the question of the entire collision zone for re-examination. This paper presents new data regarding the age of the Lesnaya Group and provides esti-

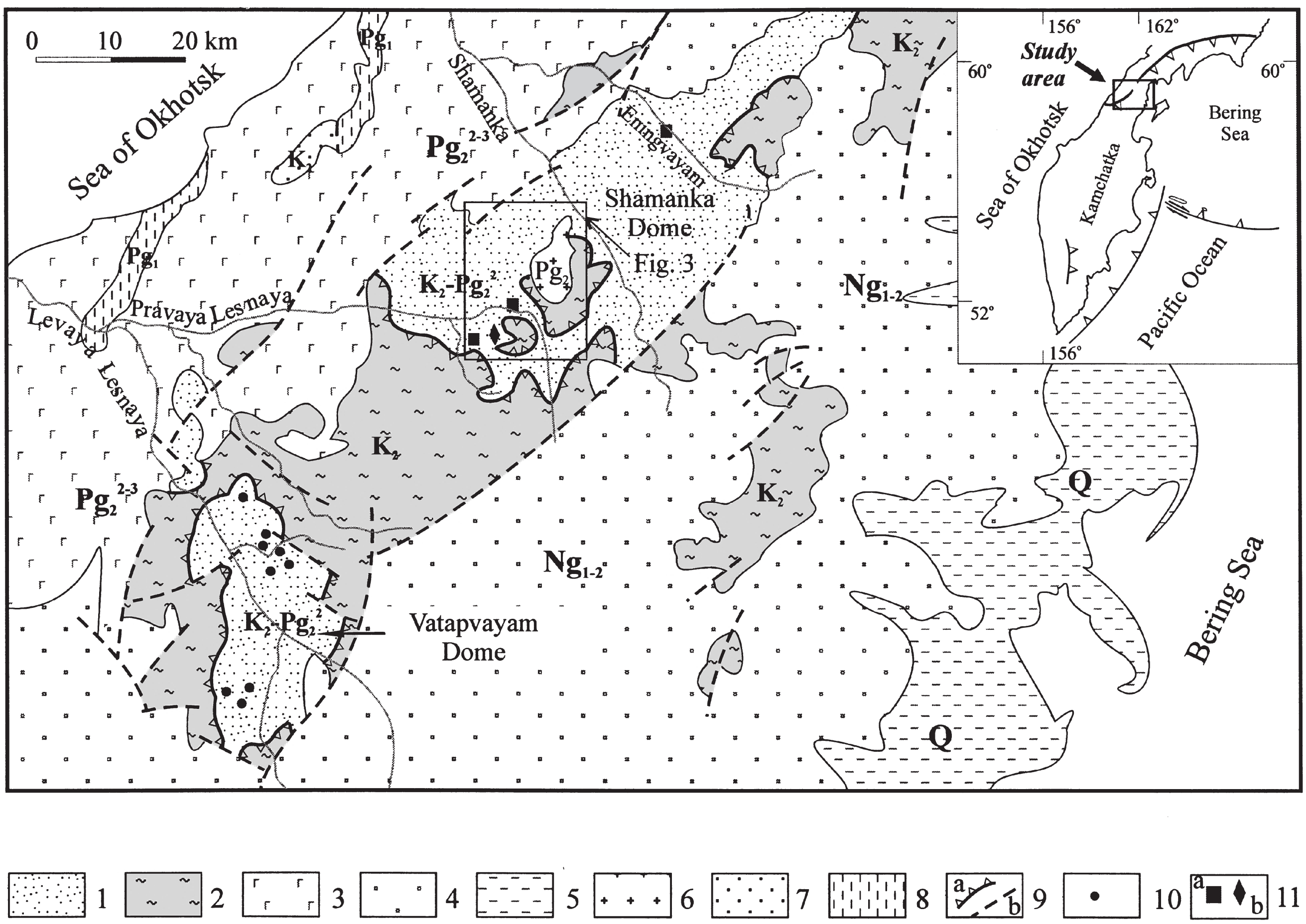

Fig. 1 Schematic map showing the geological structure of the Kamchatka Isthmus. 1, autochthonous complex, Lesnaya Group (Upper Cretaceous (?) – Middle Eocene); 2, allochthonous complex, Irunei Formation (Upper Cretaceous); 3–6, neoautochthonous complex: 3, extrusives of the Kinkil Formation, Middle to Upper Eocene (West Kamchatka volcanic belt); 4, Upper Eocene to Lower Miocene sedimentary sequences and Miocene to Pliocene volcanites of the Central Kamchatka belt; 5, unconsolidated Quaternary deposits; 6, Shamanka granite massif; 7, 8, pre-Eocene terrigenous complexes of unclear structural setting at the base of the West Kamchatka belt: 7, Talnichskaya Formation (Upper Cretaceous); 8, Getkilninskaya Formation (Paleocene); 9, Lesnaya thrust (a) and other faults (b); 10, stations at which Lesnaya sandstones were sampled for fission-track analysis on zircon; 11, (a) localities sampled for nannofossils from the Lesnaya Formation and (b) blocks in melange below the Lesnaya thrust.

mates of the duration of tectonic events related to arc-continent collision. These data were acquired from rocks in the upper reaches of the Pravaya Lesnaya River (Fig. 1).

LESNAYA GROUP

GENERAL LITHOLOGY AND FIELD OCCURRENCE

The Lesnaya Group is represented by terrigenous flysch of thin- to thick-bedded distal turbidite and contourite lithofacies. Sandstones of the Lesnaya Group are generally quartzofeldspathic graywackes that in general have a greater proportion of quartz and feldspar than of rock fragments. The rock fragments are represented by roughly equal amounts of various extrusive volcanic fragments and fine-grained sedimentary rocks, but most samples also contain a minor percentage of schist fragments (see also Shapiro *et al.* 1993). Heavy-mineral separates are dominated by apatite and zircon. A number of flutes, grooves and ripples observed and measured in the field indicate that the primary transport direction was west to east, and therefore to a first approximation, the source region of interest lay toward the Asian continental margin, and it is likely that this clastic material was derived in part from the Okhotsk–Chukotka Continental arc (see Garver *et al.* 2000b).

Where we studied the Lesnaya Group in detail (Lesnaya, Shamanka and Eningvayam drainages, Fig. 1), the strata are represented by sandstone-dominated flysch with thin interbedded mudstone, siltstone and fine-grained sandstone. Thick (1–2 m) beds of gray, coarse- to medium-grained sandstone commonly display typical Bouma sequences (Ta-c) in their upper part and basal sole marks. Sandstones have a polymict composition typical of the Lesnaya Group ($25_{Q}22_{F}53_{L}$, averaged from four samples). They are intercalated by thin layers of black mudstone and siltstone commonly with abundant fine coalified plant detritus. The fine-grained layers are dominated by mudstone alternating rhythmically with thin (3–15 cm) siltstone beds and less commonly, fine-grained sandstone beds. The siltstone and sandstone layers display either no lamination or show fine parallel lamination with sharp upper and lower contacts.

The base of the Lesnaya Group is not exposed and deformation is pervasive enough that continuous stratigraphic sections are non-existent and for these reasons thickness estimates are difficult to make. In the western part of the study area, deformed rocks of the Lesnaya Group are unconformably overlain by felsic extrusives and volcanoclastics of the Eocene Kinkil Formation, which forms the base of the neoautochthonous stratigraphic section (Shantser *et al.* 1985; Gladenkov *et al.* 1991). In the south-west part of the Lesnaya dome (Levaya Lesnaya River) the Lesnaya Group is unconformably overlain by marine sediments of the middle Eocene Snatolski Formation (Markovsky 1989). In the area of the Lesnaya uplift, the Lesnaya Group, the Irunei Formation and the Lesnaya thrust, are all intruded by granitic rocks of the Shamanka massif.

The Lesnaya Group shows pervasive deformation throughtout the study area. The rocks are deformed with small, west-vergent folds, commonly overturned and hinges are commonly faulted. Internal disruption of the stratigraphy is locally pervasive and in these cases the unit is best considered broken formation or melange. Unfortunately, the lithologic uniformity, lack of marker beds and structural complexity have prevented measurement of a continuous stratigraphic section. Typically, sandstones and shale occurs as a mono-lithologic sedimentary melange (Shapiro & Soloviev 1999). Lithologically and structurally, the Lesnaya Group differs dramatically from both the structurally overlying Irunei rocks (Olutorsky terrane) and from the non-marine volcanoclastic neoautochthonous deposits which show only very simple broad folds and tilting. This structural and lithologic contrast allows easy mapping of the regional relationships of rocks (Shantser *et al.* 1985; Markovsky 1989).

EARLY AGE ASSIGNMENTS AND REGIONAL CORRELATION

The Lesnaya Group has customarily been inferred to be Cretaceous in age due to a complicated set of historical circumstances. Initially, this age assignment was based on inferred stratigraphic continuity between the Lesnaya Group and the overlying well dated Irunei Formation (Markovsky 1989). Yet in all the cases that we know of, to the layers that had been interpreted to be ‘transitional beds’ are actually mylonites and cataclacite of the Lesnaya thrust (Shantser *et al.* 1985; Shapiro & Soloviev 1999). The rocks in the fault are commonly underlain by sedimentary melange (200–400 m thick) with a mudstone matrix and blocks of tuff, chert, basalt and sandstone. Some of the sedimentary blocks contain *Inoceramus* shell fragments. Formerly, these exotic blocks were viewed as lenses within the Lesnaya Group stratigraphy and the *Inoceramus* and radiolaria from the blocks were taken as evidence of a Cretaceous age for the Lesnaya Group (Markovsky 1989). These blocks are now inferred to be tectonic inclusions of upper plate rocks that occur in the fault zone.

The ages of late igneous intrusions have also complicated the original age assignment for the Lesnaya Group. During the original regional mapping of this area, Yu. A. Novoselov dated the Shamanka granitic massif which intrudes deformed rocks of the Lesnaya Group, as well as the overlying thrust sheets of the Olutorsky terrane. The granitic rocks yielded K/Ar whole rock ages of 75 and 78 Ma (see Markovsky 1989). Even at the outset, these ages were suspect because field relationships, indicate that the Shamanka granite fed a series of subvolcanic bodies that are linked to the extrusive rocks (below) of the moderately well-dated subaerial volcanics of the Eocene Kinkil Formation (Shantser *et al.* 1985).

Attribution of Lesnaya Group to the Cretaceous was supported by the age of lithologically similar deposits elsewhere in Kamchatka. For example, on Cape Omgon, on the western edge of Kamchcatka, the marine strata of the Omgon Group contain two main units, separated by a minor unconformity, into the lower Talnichskaya Formation and the upper Mainach Formation. The latter contains a late Turonian through Santonian mollusk assemblage (Markovsky 1989). In this context, a loose correlation with the poorly dated rocks of the Lesnaya Group and the well-dated rocks of the Omgon Group seemed to be supported by this regional correlation.

The closest lithological counterpart to the Lesnaya Group is the Ukelayat Group, which extends in a wide belt in central to northern Kamchatka just inboard of the Olutorsky terrane. In general this thick and widespread turbidite assemblage is poorly dated, but Upper Cretaceous and Paleocene through lower Eocene strata are locally recognized on the basis of benthic foraminifera assemblages (Yermakov & Suprunenko 1975). However, in the context of regional mapping campaigns, virtually all of the Ukelayat Group was mapped as Upper Cretaceous and everywhere it occurred in the footwall of the collision it was inferred to be Cretaceous as well. Part of this age assignment was undoubtedly due to the fact that the well-dated Upper Cretaceous rocks of the structurally overlying Olutorsky terrane implied a similar Upper Cretaceous or older assignment as discussed above for the Lesnaya area. However, fission-track (FT) age determination on detrital zircons show a considerable part of the sequences previously assigned Upper Cretaceous age are actually Lower Paleogene (Soloviev *et al.* 1998; Garver *et al.* 2000b).

Cenozoic age data for the Lesnaya Group were first reported by Fedorchuk and Izvekov (1992). We obtained a few nannofossils from a mudstone sample from their collection, which indicate an Eocene to Oligocene age. However, the paucity of the nannofossil assemblage in this single sample, the fact that the sample was unique and the lack of a precise geographical location for this sample, diminished the significance of this result. Therefore, the available data had thus been, until recently, insufficient for reliable dating of the youngest strata of the Lesnaya Group.

NEW DATA FOR THE AGE OF THE LESNAYA GROUP

FT AGES OF DETRITAL ZIRCONS

To constrain the minimum depositional age of sandstones of the Lesnaya Group, we applied the detrital thermochronology method based on the dating of detrital zircon from sandstones (Garver & Brandon 1994; Garver *et al.* 1999). Fission-track dating is based on the density of spontaneous fission tracks created by ^{238}U fission fragments that disrupt the crystal lattice (Fleischer *et al.* 1975), and it allows the cooling age of individual zircon grains to be determined (Wagner & van den Haute 1992). Fission-track dating of detrital zircon grains from sandstones makes it possible to discriminate age populations of grains (Galbraith & Green 1990; Brandon 1996) supplied to the depositional basin from different sources and had not suffered heating above temperatures sufficient to cause partial annealing (~200–250°C) (Brandon 1996). The age of the youngest zircon population defines the lower age limit for deposition and may approximate the depositional age in sediments that have a volcanic or partial volcanic source (Brandon & Vance 1992; Garver & Brandon 1994; Garver *et al.* 1998; Garver *et al.* 1999). In studies where the source included active volcanism, this young age is commonly referred to as the 'FT depositional age' because it can closely approximate the time of deposition (i.e. Garver *et al.* 1999, 2000a,b).

Nine sandstone samples from the south-western part of the Lesnaya uplift were collected and analyzed using the detrital FT methodology (Fig. 1). Zircons were dated using standard methods for FT dating using an external detector (Table 1, Garver *et al.* 2000a). Zircons were extracted using standard separation procedures. All samples were crushed, pulverized and then passed over a Gemeni table (Gemeni, Queensland, Australia), passed through tetrobromethane, a Franz magnetic separator (S.G Frantz, Trenton, NJ, USA), and finally methylene iodide. Zircon grains were mounted in 2 × 2 cm^2 squares of tetraflouroethylene-perflouroalkoxyethene (PFA) Teflon (Toray Industries, Osaka, Japan). During polishing, each mount was first cut with 800 grit wet sandpaper, and then polished successively on 1 μm, 9 μm diamond paste, and then finished using a 0.3-μm Al_2O_3 paste. Mounts were etched in a eutectic NaOH–KOH mixture at 228°C for 15 h (mount one) and 30 h (mount two). Etch times were varied due to poor etching efficiency due to disintegration of old metamict grains which subsequently affected the quality of the chemical etchant. After etching, mounts were covered with a low-uranium mica detector and irradiated with thermal neutrons at Oregon State University with a nominal fluence of 2×10^{15} n/cm^2, along with a zircon standards (Fish Canyon Tuff (FCT), Buluk Tuff (BT)) and a reference glass dosimeter CN-5 (Hurford 1998). Fission-tracks were counted on an Olympus BH-P microscope (Olympus, Tokyo, Japan) fitted with an automated stage and digitizing tablet. Total magnification was 1250× (100× objective, 1.0 tube factor, 12.5 oculars). A Zeta factor of 305.01 ± 6.91 was as computed from 10 age standards (six FCT and four BT member samples) (Hurford 1998).

For each sample, 45–90 zircon grains were dated. Fission-track ages were computed using the program Zetaage 4.7 (available from: ftp://love.geology.yale.edu/pub/brandon/FT_PROGRAMS) (Brandon 1996). Individual grain ages span a broad age range (Fig. 2) and each sample has several different age populations of zircon. To discriminate the populations by age, we used the program Binomfit 1.8 (Galbraith 1988) (available from: ftp://love.geology.yale.edu/pub/brandon/FT_PROGRAMS) (Brandon 1996).

Zircon FT ages from the nine samples show three distinct grain-age populations (P1, P2 and P3) for each sample: P1, 44–58 Ma; P2, 71–93 Ma; and P3, 104–176 Ma (Table 1). The youngest population is crucial to understanding the age of the Lesnaya Group, because this population constrains depositional age. The youngest population (P1) covers the range from 43.7 ± 3.4 to 58.1 ± 4.2 Ma (Paleocene and Middle Eocene), and therefore parts of the Lesnaya Group must be Paleocene and Middle Eocene or younger. It is probable that young FT ages represent a population of grains from nearly contemporaneous volcanism in the source region. This inference is supported by the fact that volcanic grains are common in the fraction of lithic fragments in the sandstones (Garver

Table 1 Fission-track ages of detrital zircon from the Lesnaya Group (northern Kamchatka)

Sample No.	Number of grains dated	Age of zircon population (± 1 σ) P1 (Ma)	P2 (Ma)	P3 (Ma)
L1	45	46.0 ± 2.7 Nf = 22.1		107.3 ± 7.0 Nf = 22.9
L2	90	48.1 ± 5.0 Nf = 6.1	78.1 ± 5.8 Nf = 47.4	116.0 ± 8.6 Nf = 36.6
L4	90	58.1 ± 4.2 Nf = 32.6	83.3 ± 6.3 Nf = 46.1	130.5 ± 14.9 Nf = 11.4
L9	90	47.0 ± 3.8 Nf = 16.9	70.8 ± 5.7 Nf = 50.4	104.0 ± 11.9 Nf = 22.7
L10	90	53.9 ± 3.4 Nf = 35.7	87.5 ± 6.2 Nf = 45.3	176.5 ± 23.8 Nf = 9.0
L11	90	50.4 ± 5.6 Nf = 17.9	70.6 ± 6.6 Nf = 58.7	109.7 ± 25.0 Nf = 13.4
L12	67	43.7 ± 3.4 Nf = 11.3	70.6 ± 4.4 Nf = 44.6	107.0 ± 12.2 Nf = 11.1
L13	89	55.5 ± 3.5 Nf = 30.4	93.0 ± 4.8 Nf = 58.6	
L17	90	54.5 ± 10.4 Nf = 4.0	84.6 ± 6.5 Nf = 58.9	134.6 ± 18.9 Nf = 27.0

Fission-track ages of detrital zircon from the Lesnaya Group deposits (northern Kamchatka). N_f = calculated number of grains in a specific peak or fraction. Uncertainties cited at ± 1SE.

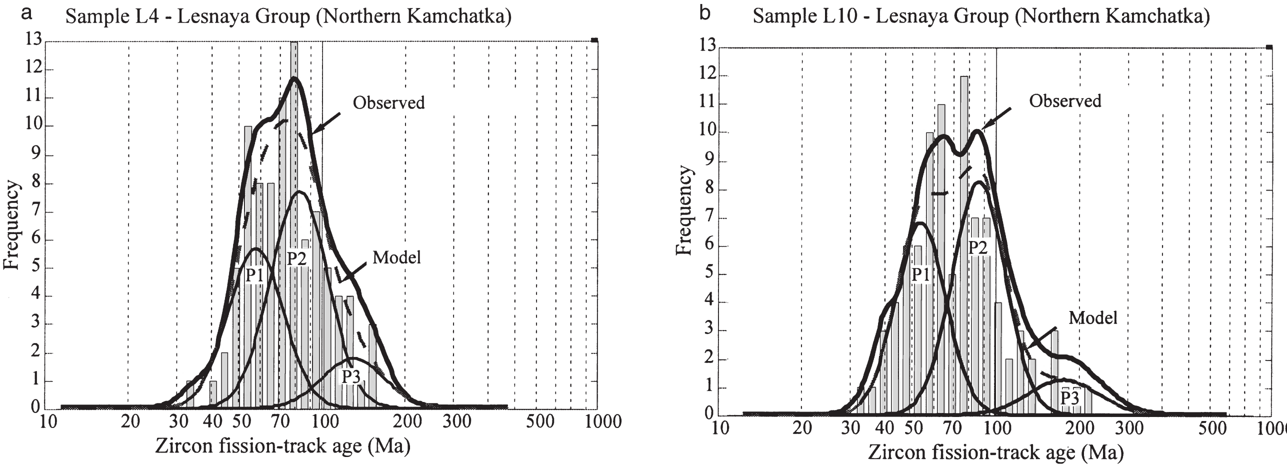

Fig. 2 Plots showing distribution of fission-track zircon ages from selected samples of Lesnaya Group sandstones. Heavy solid line is the observed probability density plot. Model computed using Zetaage 4.7 (Brandon 1996). P1, P2, P3—peaks of different age populations (see Table 1), identified by BimonFit 1.8 (Brandon 1996). Histogram depicts the number of grains of a given age in a sample.

& Brandon 1994; Garver *et al.* 1998; Garver *et al.* 2000b). The older populations give information about the cooling history of rocks in the source area. For the Ukelayat Group to the north, P2 is inferred to represent exhumation of the spine of the Okhotsk–Chukotka belt, which is the nearly contemporaneous Andean-style continental arc (Garver *et al.* 2000b).

A crucial question in the type of analysis is the thermal history of the host strata, because significant heating can cause partial annealing or even full erasure of the FT. In our case, we have direct evidence that sandstones of the Lesnaya Group did not experience temperatures high enough to cause partial annealing of FT. We dated apatite grains from the same samples (by FT) and we discovered that the apatites are commonly not reset, indicating that the maximum temperature reached was *c.* 100 to 110°C or less (Soloviev *et al.*, in press), which is well below the temperature required to partially anneal FT in zircon (*c.* 200°C for grains with α-damage; Garver & Bartholomew 2001). A detrital suite of zircon grains would be expected to have a wide range of grain ages and uranuim plus thorium concentrations, which determine total α-damage in a crystal. Because α-damage affects the stability of FT in zircon, one would expect variable resetting of zircon grains in a detrital sample subjected to elevated temperatures. Therefore, in the case of a partially annealed sample, multiple populations would be likely. For this reason, estimates of the thermal history are crucial to establishing the validity of such data.

Detrital FT analysis yielded Paleocene and Eocene ages (P1) from detrital zircon from the Ukelayat Group, which is stratigraphically correlative with the Lesnaya Group and occurs in structurally similar setting in northern Kamchatka (Garver *et al.* 1998; Soloviev *et al.* 1998; Garver *et al.* 2000b).

NANNOPLANKTON

The dramatic changes in inferred depositional ages of the Lesnaya Group owing to the P1 ages from the pioneering FT ages, initiated new collection of rocks for biostratigraphic analysis. In view of the virtually total lack of macro- and microfossils in the Lesnaya rocks, this study focused on calcareous nannofossils. The first nannofossils results were reported by Fedorchuk and Izvekov (1992). From a mudstone sample collected by these workers in the northern part of the Lesnaya uplift, we identified *Cyclicargolithus floridanus*, which constrains the age to the Middle Eocene–Oligocene. This determination was the first indication that at least the upper part of the Lesnaya Group was Tertiary in age. Our new data are from the central part of the Lesnaya uplift (Pravaya Lesnaya River area, Fig. 3).

In this area, we collected 46 samples from the most friable and least cleaved mudstones. Of this suite of 46, only 12 yielded sparse nannofossils (Table 2). In most of the successful samples collected along the Veaitymlyvayam River, nannofossils are represented by single species with a likely range in the Early Paleogene. Samples 9902–5, 9902–7, and 9902–11 contain sporadic *Micula decussata* (Upper Cretaceous–Paleocene), *Sphenolithus primus/moriformis* (Paleocene–

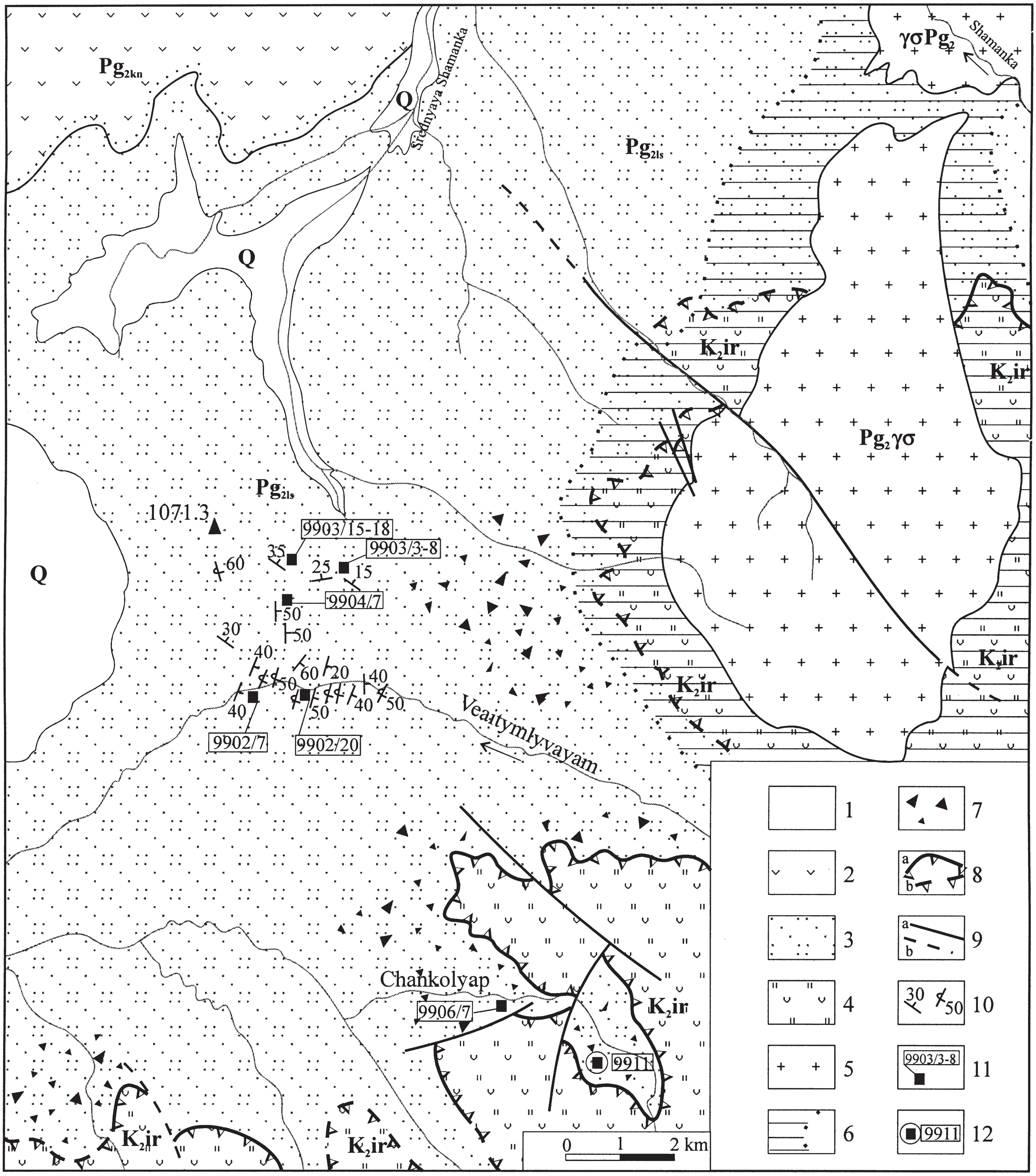

Fig. 3 Structure of the western and south-western surroundings of the Shamanka granite massif. 1, unconsolidated Quaternary deposits; 2, Kinkil Formation; 3, Lesnaya Group; 4, Irunei Formation; 5, granodiorite; 6, hornfels and its outer boundary; 7, the larger areas of mélange underneath the Lesnaya thrust; 8, Lesnaya thrust (a) proven and (b) inferred; 9, other faults; 10, dip and strike of rocks; 11, stations sampled for nannofossils from the Lesnaya Group; 12, same, from blocks in melange underneath the thrust.

Miocene), *Neochiastozygus* sp. (Paleocene), *Watznaueria barnesae* (Upper Jurassic–Paleocene). The fact that these species occur together suggests the Paleocene age for the host rocks.

A number of samples (9902–20, 9903–11, 9903–15, 9903–18, 9904–7), however, are clearly younger. The strata from which samples 9902–20, 9903–11 and 9903–18 were collected are definitely

Table 2 Nannofossils from the Lesnaya Group in the Veaitymlyvaiam and Chankolyap drainages

Nannoplankton species	Sample number 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					x		x		x									
Coccolithus pelagicus								x			x							
Sphenolithus primus/moriformis	x			x		x					x			x				
Dictyococcites bisectus									x			x						
Reticulofenestra umbilicus									x	x								
R. hagii									x									
R. dictyoda													x					
Helicosphaera compacta					x													
Chiasmolithus cf. Nitidus									x									
Zygrhablithus bijugatus						x												
Micula decussata			x															
Neochiastozygus sp.		x																
Thoracosphaera sp.									x							x	x	x
Watznaueria barnesae	x																	
Reinhardtites anthophorus															x			
Eiffellithus turriseffeli																	x	

no older than the Middle Eocene and, in all likelihood, are upper middle Eocene, as evidenced by the presence of *Reticulofenestra umbilicus* s.l., *Helicosphaera compacta* and *Dictyococcites bisectus*. These samples are no younger than the Early Oligocene which is the upper limit for *Reticulofenestra umbilicus*.

All of the nannofossil data taken together from the Pravaya Lesnaya River area thus suggest that these deposits of the Lesnaya Group are most likely Paleocene to Middle Eocene. However, these results do not preclude that the sampled stratigraphic interval might be somewhat broader: the upper limit remains poorly constrained, because it cannot be asserted with confidence that the youngest nannofossil assemblage corresponds to the uppermost strata of the Lesnaya Group.

Another sampling area (Chankolyap River; Fig. 3) is confined to melange in the autochthon immediately below the Lesnaya thrust several kilometers to the south. In this area, the Lesnaya thrust and associated melange below it are well exposed. The mudstone-sandstone matrix of the melange in the Lesnaya Group hosts numerous blocks of various sizes (a few meters to several hundred meters), most of which are sandstone or alternating sandstone, siltstone, and mudstone. In one of the blocks (St. 9911) the internal stratigraphy was documented and studied (Fig. 4). This fragment

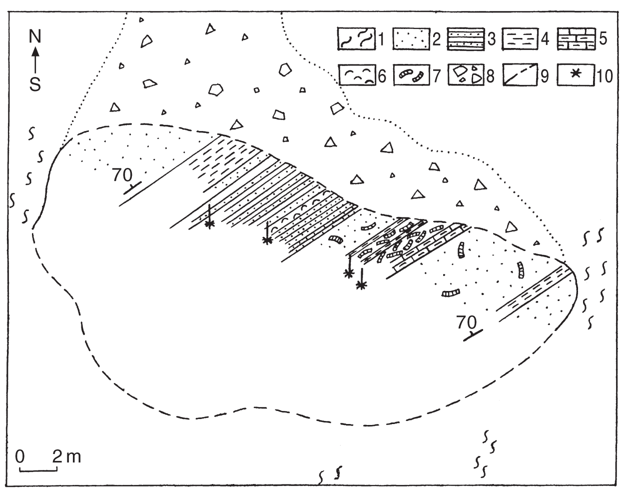

Fig. 4 Structure of a block in melange below the thrust on the south slope of the Chankolyap Creek in its upper reaches. 1, Lesnaya mudstone enclosing the block; 2–7, strata in the block: 2, sandstones; 3, alternating (flysch-like) sandstones and silty mudstones; 4, mudstones; 5, calcareous mudstones; 6, cherts; 7, isolated fragments of *Inoceramus* prisms and coquina; 8, coarse-block talus on the slope below the block; 9, inferred and proven boundaries of the block; 10, samples with nannoplankton.

consists of alternating sandstone, siltstone, and mudstone and is structurally and lithologically similar to typical strata of the Lesnaya Group, but it contains thin chert lenses and fragments of *Inoceramus* confined to sandstone beds. Four siltstone samples from this section yielded sporadic nannofossils of Santonian–Campanian age. In this same area, mudstones in the melange matrix of the Lesnaya Group yielded a *Sphenolithus moriformis*, a Cenozoic coccolith covering a broad age interval (Lower Eocene to Miocene). Therefore, some of the clasts in this melange are Cretaceous in age, but mixing probably post-dated Tertiary deposition of part of the Lesnaya Group (mudstone matrix). This finding also supports other studies that deposition of strata of the Lesnaya and the Ukalayat Groups occurred over a interval from the Upper Cretaceous to the Eocene (Yermakov & Suprunenko 1975; Garver *et al.* 2000b).

DISCUSSION

The nannoplankton ages from mudstones of the Lesnaya Group correspond well to the FT depositional ages (P1) from the detrital zircons from the sandstones of the Lesnaya Group. As the sandstones contain volcanic lithic fragments, we are encouraged that the FT depositional age closely approximates the time of deposition. This inference is further supported by the similarity of P1 to the nannoplakton ages. Taken together, these ages, obtained independently from a number of sites using different methods, suggest that the upper part of the Lesnaya Group is largely Eocene in age, and if the FT depositional age is any clue, it is likely that the deposition occurred between about 55 and 45 Ma (mainly Early to Middle Eocene). One prediction of this important finding is that because the zircons that comprise the P1 peak are volcanic, single-grain uranium-lead ages on grain in this population should indicate that not only did they cool at this time, they crystallized at this time as well.

Obviously the youngest rocks of the Lesnaya Group cannot be younger than the base of the neoautochthonous (overlap) assemblages which are exposed to the south, west, and north-west of the main part of exposures of the Lesnaya Group. The Snatolsky Formation makes up the base of the neoautochthon sequence to the south and west of the Lesnaya uplift. In the type section (along the western coast of Kamchatka), the Snatolsky Formation corresponds to the upper part of the Lutetian and lower part of the Bartonian, based on microfossils and foraminifers (i.e. upper part of Middle Eocene; see Gladenkov *et al.* 1997; Gladenkov *et al.* 1998). However, farther inland on the western slopes of the Lesnaya uplift, Upper Eocene to Lower Oligocene mollusks occur in the Snatolsky Formation and the underlying conglomerates have pebbles of Shamanka granite and yield Upper Eocene flora (Shantser *et al.* 1985). The simple interpretation from these observations is that the Snatolsky Formation is diachronous and may progressively onlap eastward. If so, the implication is that the early deposits of the Snatolsky Formation were nearly coeval the upper Lesnaya Group to the east, but the Snatolsky Formation onlapped rocks during and after collision.

In the north-western part of the Lesnaya uplift, the base of the neoautochthonous assemblage consists of subaerial volcanic rocks of the Kinkil Formation, whose outcrops are mapped as far as the Sea of Okhotsk coast and several hundred kilometers along the coast. Radiometric dates for volcanic rocks of the Kinkil Formation exposed near the Cape Kinkil range from 37.4 ± 0.6 to 46.5 ± 0.8 Ma (K/Ar method—whole-rock), falling between Lutetian and Priabonian (Middle to Late Eocene) (Gladenkov *et al.* 1991). A single radiometric measurement for the Kinkil volcanic rocks from the axial part of the Kamchatka Isthmus corresponds to the upper part of the Lutetian (K/Ar, 46.4 Ma) (Fedorchuk & Izvekov 1992). In the vicinity of the Rekinniki Bay, the Kinkil volcanic rocks yield considerably older ages, 46.7 ± 2.7–51.3 ± 11 Ma, corresponding to the Ypresian and Lutetian stages (Early to Middle Eocene) (Gladenkov *et al.* 1998).

The Shamanka granite massif is closely linked tightly to the lower horizons of the Kinkil Formation via a system of minor satellite stocks and subvolcanic bodies and it intrudes deformed rocks of the Lesnaya Group (Shantser *et al.* 1985). The minimum age for the pluton is constrained by the base of the conglomerate sequence bearing Upper Eocene flora which passes upsection into sandstones that host Upper Eocene to lower Oligocene faunas (Shantser *et al.* 1985). These conglomerates contain abundant pebbles of the Shamanka granites, which sets pre-Upper Eocene to Oligocene age limit for both the massif and associated felsic extrusives of the Kinkil Formation.

Therefore, the oldest neoautochthonous assemblages of the Kamchatka Isthmus are Middle Eocene in age and include at least the upper half of the Lutetian. Note that FT dates for the young

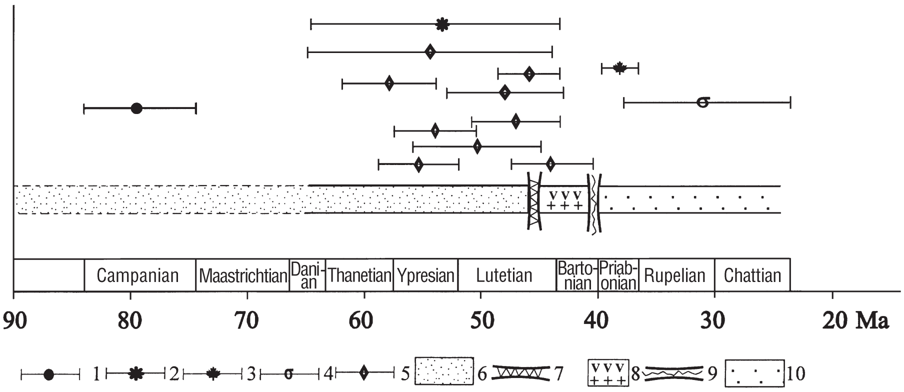

Fig. 5 Chronology of geological events in the central part of the Lesnaya thrust for the Campanian through Oligocene interval. 1–4, intervals constraining the age of paleontological complexes: 1, nannoplankton from terrigenous blocks in melange underneath the thrust at the Chankolyap Creek (St. 9911); 2, nannoplankton from the Lesnaya Group on the right side of the Veaitymlyvayam River (St. 9902, 9903, 9904); 3, floras from the lower part of the Shamanka Formation., after (Shantser *et al.* 1985); 4, mollusk faunas from the upper part of the Shamanka Formation, after (Shantser *et al.* 1985); 5, the age of the young zircon population from the Lesnaya sandstones, interval showing analytical error ($\pm 1\,\sigma$); 6, accumulation of the Lesnaya Group; 7, deformation of the Lesnaya Group, formation of the Lesnaya thrust, uplifting, and erosion; 8, accumulation of the Kinkil Formation and granite emplacement; 9, uplift and deep erosion involving exhumation of the Shamanka massif; 10, transgression and accumulation of the Shamanka Formation.

zircon population in some Lesnaya sandstone samples coincide within analytical error with the oldest published K/Ar ages for the Kinkil extrusives (Gladenkov *et al.* 1991), the sandstones being themselves clearly the same age as, or younger than, the cooling ages of zircons they host. Considering these data, we conclude that the time between the termination of deposition of the Lesnaya Group and the onset of deposition of the Kinkil Formation must have been very rapid, perhaps no longer than several million years (Fig. 5). This time interval (Lutetian, or Middle Eocene) included the last deposition, and then deformation including thrusting which was presumably the collision of the island arc.

Despite our efforts, the maximum age of the Lesnaya Group remains poorly constrained. Most rocks of the Lesnaya Group are likely to be Cenozoic, but it is likely that its lower part is Upper Cretaceous in age, as is the case in the Ukelayat flysch to the north (Garver *et al.* 2000b). The inference that the Lesnaya Group has these older ages is indirectly supported by the Campanian age of a block in the melange underlying the thrust, which is lithologically similar to typical sandstones typical of the Lesnaya Group. This block is inferred to be a fragment of the lower horizons of the Lesnaya Group exhumed during the formation of the Lesnaya thrust and related tectonic structures of the autochthon. If this is true, the total age span of the Lesnaya Group would thus correspond to the Campanian through the lower part of the Middle Eocene. This interval is virtually identical to the age span of the flysch sequences of the Ukelayat Group in the Koryak Highlands, which make up the autochthon of the Vatyna–Vyvenka thrust (Yermakov & Suprunenko 1975; Bogdanov *et al.* 1987; Garver *et al.* 1998; Soloviev *et al.* 1998; Garver *et al.* 2000b).

CONCLUSIONS

Data on the age of detrital zircon from Lesnaya sandstones and independent nannofossil determinations from Lesnaya mudstones suggest that most part of the section of this group is Paleocene to the lower half of Eocene. It is likely, however, that lower units of the Lesnaya Group (including some blocks in the melange under the Lesnaya thrust) are Upper Cretaceous. The total age span of the Lesnaya Group possibly corresponds to the late part of the Upper Cretaceous through to the Middle Eocene, and if so, this range would be identical to the age interval of the flysch sequences of the Ukelayat basin in the southern part of the Koryak Highland (Garver *et al.* 2000b).

These timing constraints suggest that only several million years passed between the end of deposition of the Lesnaya Group and the onset of deposition of the Kinkil Formation in the Middle Eocene. This time interval accommodated complex deformation of the Lesnaya Group and overthrusting along the Lesnaya thrust by at least 50 km. Provided these processes result from collision of the Olutorsky Island arc with north-eastern Asia, this event, pivotal to Kamchatka geological history, must have taken place at about 45 Ma.

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