CHAPTER 3:
High Grade Metamorphism of Paleocene Sediments in an Arc-Continent Collision Zone: an Integrated SHRIMP Zircon and Thermochronologic Investigation of the East Flank of the Sredinniy Range, Kamchatka Peninsula

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ABSTRACT

The metamorphic rocks of the Sredinniy Range play a critical yet controversial role in all tectonic models of the Kamchatka Peninsula and the Sea of Okhotsk. Much of the debate centers on the timing of high-grade metamorphism and the nature of the protolith. We performed a reconnaissance-level geo- and thermochronologic investigation of the Kamchatka Complex in the core of the range. We report here the first SHRIMP zircon grain-ages from the metamorphic core of the Sredinniy range. The zircon population yields a highly heterogeneous grain-age distribution from 55 Ma to 2049 Ma. Textural and grain-age heterogeneity indicate a detrital origin for these zircons. The youngest grains (~55 Ma) imply a Paleocene maximum stratigraphic age at least for part of the protolith of Kamchatka complex. We compare grain-age distribution observed in the Kamchatka Complex sample with an unmetamorphosed Lower Eocene sandstone of the Ukelayat Group (Koryak region) deposited along the Eurasian continental margin. The grain-age distributions are surprisingly similar and suggest Kamchatka Complex may represent structurally buried and metamorphosed strata of the northeast Asian margin. A time-temperature history for the Sredinniy Range based on the results of the detrital study, a published Rb/Sr mineral isochron and new fission track and (U-Th)/He data shows the T-t path of these rocks. The data indicate rapid (~90 ºC/Ma) heating and cooling between 55 Ma and 48 Ma follow by apparent gradual (~ 7 ºC/Ma) cooling to the present time. We attribute this rapid heating event to structural burial during collision of the far-traveled Olyutorsky arc.

INTRODUCTION

High grade metamorphic rocks exposed in the Sredinniy Range (Fig. 1) have long played a paramount role in tectonic interpretations of Kamchatka, the Sea of Okhotsk and the adjacent margins of Russia and Japan. Early investigators assigned Precambrian ages to the rocks of the Sredinniy and Ganal ranges based largely on the local occurrence of granulite facies metamorphic rocks. (e.g. German, 1978; Khanchuk, 1985; Marchenko, 1975). Proterozoic and Archean zircon Pb-Pb ages provided additional support for the presence of evolved crust within the high-grade rocks of the Sredinniy (Kuzmin and Chukhonin, 1980) and Ganal ranges (L'vov et al., 1985). Following general acceptance of plate tectonic theory workers argued that the Sredinniy Range was a portion of a larger microcontinental block that composes the basement of the Sea of Okhotsk (Jolivet et al., 1988; Parfenov et al., 1981; Sengor and Natalin, 1996; Zonenshain et al., 1990). This model seems reasonable given that demonstrably Precambrian microcontinental blocks including granulite facies metamorphic rocks compose a significant portion of the continental crust in the Mesozoic orogenic belts of northeastern Russia (Parfenov, 1984; Zonenshain et al., 1990).

Seismic reflection and dredging studies (Burk and Gnibidenko, 1977; Gnibidenko and Khvedchuk, 1982; L'vov et al., 1985) suggest that of the basement Sea of Okhotsk consists of continental rocks. However, conclusions based on this dredging work remain controversial because of the likelihood of ice-rafting. Furthermore, the basement of the central Sea of Okhotsk has not been drilled. Nonetheless, the presumed continental character of this region led researchers to hypothesize the existence of a far-traveled Okhotsk Sea microcontinent, which was accreted to the Asian margin sometime during the Late Cretaceous (Parfenov and Natal'in, 1977; Sengor and Natalin, 1996; Zonenshain et al., 1990). Some workers (Jolivet et al., 1988) have argued that this continent-continent collision zone can be traced as far south as Sakhalin and northeastern Japan.

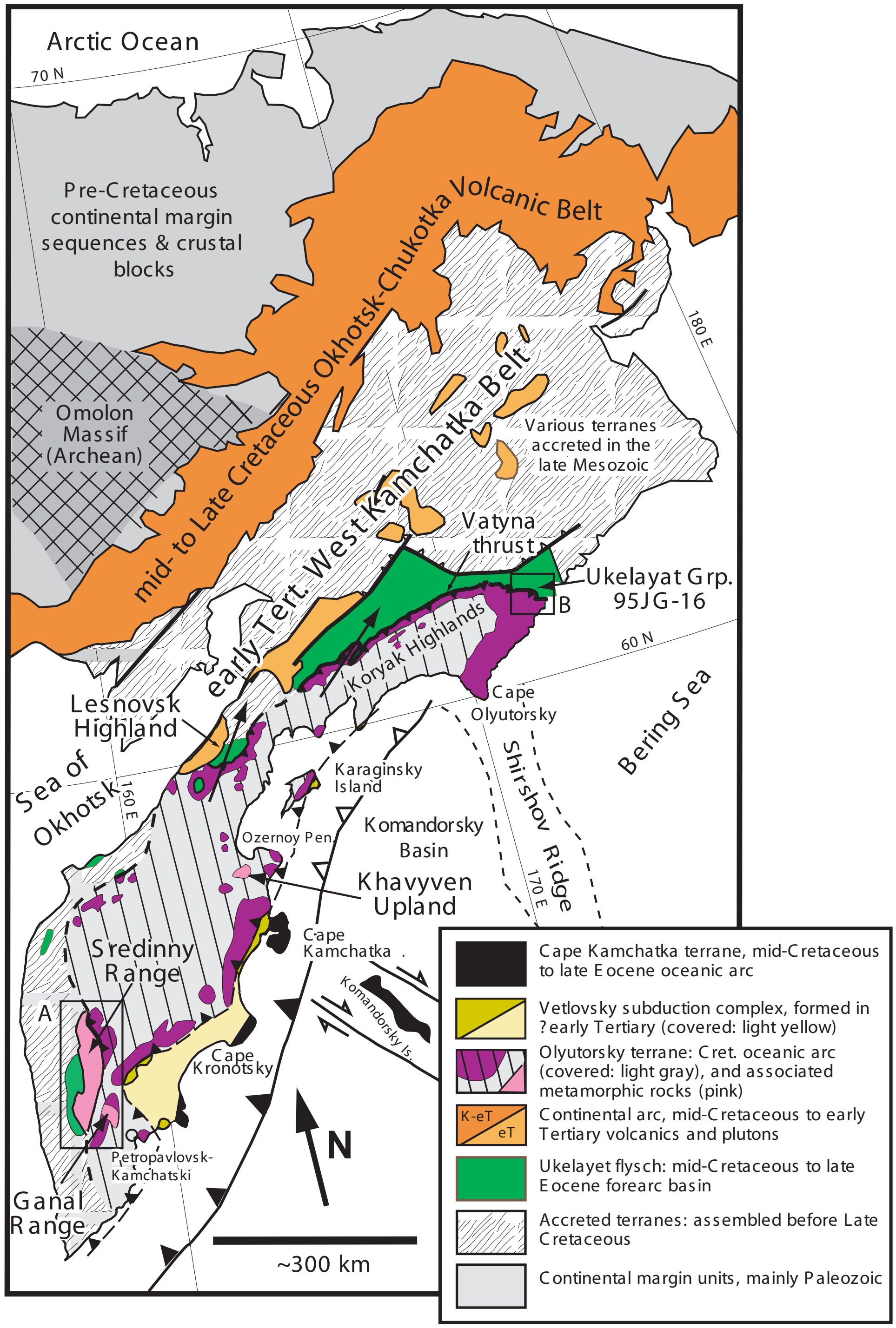


Figure 1. Generalized geologic setting of the Kamchatka Peninsula and Koryak Highlands. Medium to High-grade metamorphic rocks crop out in the Sredinniy, Ganal, and Khavyven Ranges. The location of Ukelayat Group sample (95JG-16) analyzed in this study is shown. After Tilman and Bogdanov (1992), Moore et al. (1992), Zinkevich and Tsukanov (1993), and Shapiro (1995). Boxes show: A) Area of detailed map of the Sredinniy Range (Figure 2) and B) 1995 Field area and sampling region for Ukeleyat Group detrital zircon sample (95JG-16; see text and Figure 3). Heavy arrows alongthe trace of the Vatyna Thrust, are tectonic transport directions determine during previous (1995-1996) field season.

An alternative interpretation is that the Sea of Okhotsk is underlain by an accreted oceanic plateau (Bogdanov and Dobretsov, 2001; Bogdanov and Khain, 2000; Watson and Fujita, 1985). The oceanic plateau hypothesis is presumably drawn from three main observations: 1) the crust in this region is thin (28-30 km) relative to standard continental crust; 2) the velocity structure is arguably more typical of suboceanic crust; and 3) it is overlain by a widespread, relatively undeformed Upper Cretaceous and younger sedimentary cover indicating a rigid, "block-like" character of the crust (Bogdanov and Khain, 2000; Gnibidenko and Khvedchuk, 1982; Worrall et al., 1996). However, there is no direct evidence to support this conclusion given that the inferred plateau does not crop out on land, has never been drilled and the velocity structure is based on either old (Watson and Fujita, 1985) or unpublished data (Bogdanov and Khain, 2000). Furthermore, there are numerous examples of submerged, block-like plateaus, such as the Campbell plateau east of New Zealand or the continental platform beneath the modern Adriatic, which are underlain by complex continental geology, including high grade metamorphic rocks (e.g. Otago schist in the Campbell plateau). Thus, neither thickness of the crust nor its block-like character provides much evidence for the composition and origin of basement of the Sea of Okhotsk.

The metamorphic grade of these rocks indicate that the crust has been deeply exhumed in this area, probably to depths greater than 30 km (Khanchuk, 1985; Savostin et al., 1994). Cooling ages and structural studies (Zinkevich et al., 1993) in the Ganal and Khavyven Ranges indicate that the timing of this exhumation is probably associated, at least in part, with the collision of a far-traveled Cretaceous island arc, called the Olyutorsky arc by (Geist et al., 1994) and the Achaivayam-Valaginskaya arc by Shapiro, (1995). The Olyutorsky arc forms a regionally extensive thrust sheet that covers and obscures much of the deeper geology of Kamchatka. It is now recognized that localized thickening and exhumation in the Sredinniy area has produced a structural window exposing the lower plate over which the Olytorsky arc was obducted (e.g. Geist et al.

1994)(Figure 1). Some components of the northeast Asian margin are clearly recognized within the window, such as a previously accreted Jurassic to Early Cretaceous volcanic arc, called the Kvakhona arc (Bondarenko, 1992). The more deeply seated Sredinniy metamorphic rocks are not as easily classified. They consist mainly of migmatites, gneisses, schists, and intermediate to silicic intrusions, that clearly indicate their continental character. The age of metamorphism remains controversial, with estimates ranging from Early Cretaceous to early Tertiary, and some K-Ar and Rb-Sr geochronologic evidence for two separate (Early Cretaceous and Early Tertiary) metamorphic events (Vinogradov and Grigor'yev, 1996; Watson and Fujita, 1985). Estimates of protolith age for the gneisses range from Precambrian, based on Pb-Pb zircon ages (Kuzmin and Chukhonin, 1980), to Cretaceous, based on inferences from Rb-Sr, K-Ar, Ar-Ar cooling ages (Vinogradov and others, 1988,1991,1996; Bindeman et al. 2001).

We report new isotopic ages that shed light on the protolith of the Sredinniy metamorphic rocks, the age of metamorphism, and the timing and rate of exhumation. Our investigation of the protolith of the Sredinniy gneisses is based on U/Pb dating of individual zircons using the SHRIMP-RG. The exhumation history is determined using a Rb-Sr mineral isochron from the literature (Bondarenko et al., 1993), new fission-track (FT) ages for zircon and apatite, and new (U-Th)/He ages for apatite. Our principal conclusion is that at least some, if not all, of the gneisses in the high-grade core of Sredinniy Range were derived from young sedimentary protolith, as indicated by the presence of a wide range of detrital zircon grain-ages, including some as young as ~55 Ma. This result suggests that Sredinniy metamorphic rocks may be derived entirely from young sedimentary rocks, with no evidence of old Sea of Okhotsk crust.

GEOLOGIC OVERVIEW

The Sredinniy Range (Fig. 2) is one of several exposures metamorphic rocks on the Kamchatka Peninsula (Fig. 1) Ganal and Khavyven ranges represent the other significant exposures of metamorphic rocks (Fig. 1). Outside of these regions the basement Kamchatka Peninsula consists of several virtually unmetamorphosed, exotic terranes accreted at various times from the Eocene to present.

The region has been mapped on 1:2 M, 1:500,000, 1:200,000, and 1:50,000 scales. The 1:2,000,000 maps are readily available abroad, but other sheets remain out of international circulation. The geology is fairly well-studied, however variable usage of stratigraphic terminology, disagreement about the nature of contacts, and structural complexity hamper the understanding of the evolution of the Sredinniy Range. As such there is significant controversy regarding the origin, time of metamorphism, and structural evolution of the rocks in the Sredinniy Ranges. The majority of publications that detail the geology of the Sredinniy Range and provide the necessary background for the ongoing discussion are available only in Russian language. Therefore, we summarize, in several columns, the evolution of stratigraphic terms and major structures for readers unfamiliar with the Sredinniy Range (Fig. 3a-d).

Two end-member approaches have been employed in the interpretation of Sredinniy Range geology throughout the past several decades. Early workers envisioned a single stratigraphic succession with several major unconformities (e.g. Marchenko, 1975; Khanchuk, 1985), but more recent interpretations have favored tectonic juxtaposition of unrelated terranes (Bondarenko, 1992; Rikhtyer, 1995). Vinogradov and Grigoriev (1996) noted, "There has been recent tendency to revise the geological structure of many regions by invoking the accretion hypothesis. In one way this approach is very helpful, because it enable us to subdivide areas of complex structure into distinct accretional complexes and study them independently… but overzealous attempts to identify independent complexes

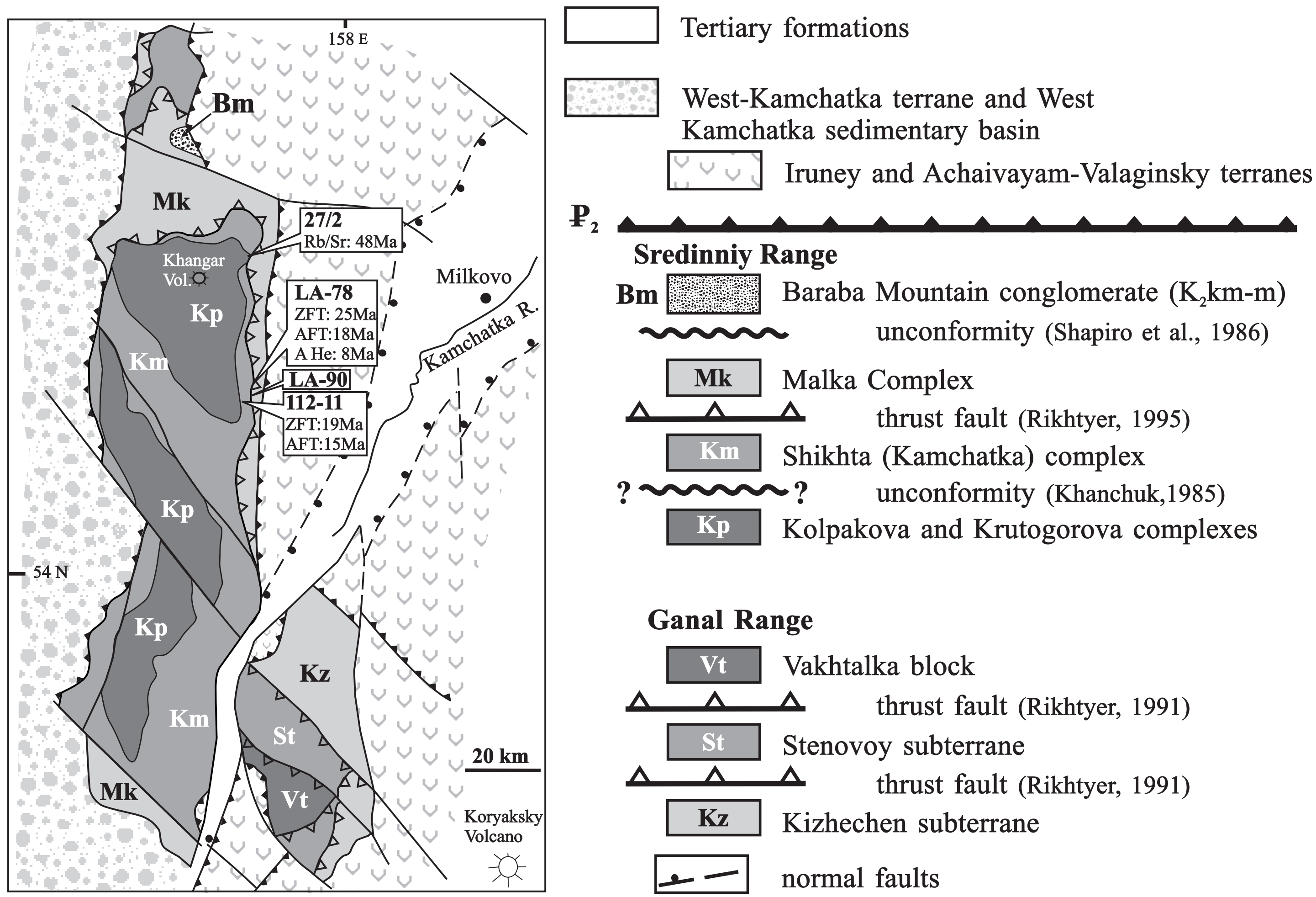


Figure 2. Simplified geologic map of the Sredinniy and Ganal Ranges with accompanying schematic tectonic legend (modified after Zinkevich and Rikhter, 1998) Sample localities with cooling ages are shown (ZFT = zircon fission track, AFT = apatite fission track, AHe = apatite (U-Th)/He).

may result in failure to identify real correlations…" They argue, in essence, that the development Sredinniy Range may actually result from both protracted stratigraphic development and tectonic juxtaposition of terranes.

Stratigraphic Nomenclature

Most of the current stratigraphic divisions have their origins in research carried out in the 50s through 70s and summarized by Marchenko (1975). Descriptions of the lithologies that comprise each "series" are given in figure 3a and 3b. The core of the Sredinniy Range consists of high-grade metamorphic rocks and granites. We define the "Sredinniy core" as the rocks of the Kolpakova, Krutogorova and Kamchatka complexes following Rikhtyer (1995)(Fig. 3d). Granulite facies gneisses make-up the Kolpakova complex. Foliated metalumionous and peralumionous granites define the structural core of the range. In the Khangar volcano region, the Kolpakova and Krutogorova complexes combined compose the Khangar gneiss dome, indicating pre- to syn kinematic emplacement of the Krutogorova granites. The contact between the lower high-grade section and the structurally higher amphibolite-facies metasediments of the Kamchatka Complex is described variably as an unconformity by Khanchuk (1985) and Rikhtyer (1985) or as a low-angle thrust contact by Bondarenko (1992). The contact between the decidedly continental Sredinniy core and the more oceanic Malka Complex metavolcanic and metasedimentary succession (including the Andrianovka, Kheivan, and Khimka units) was similarly interpreted as an unconformity Marchenko (1975) and Khanchuk (1985). Paleozoic spores described by Sivertseva and Smirnova (1974) are commonly cited as evidence for the Paleozoic age of Malka Complex. This is a major misrepresentation of the results of the Sivertseva and Smirnova (1974) study. They discovered both Paleozoic and Mesozoic spores but limited their discussion to the more abundant Paleozoic species. Furthermore they note that Lower Tertiary shales in Kamchatka contain "exotic" Paleozoic spores. Future workers should, therefore, view with caution any Kamchatka

A Marchenko et al. (1976)

Age	Rock Types	Stratigraphic Thickness
J_3-K_1(?)	**Kvakhona Suite:** Schistose- plag-phyric volcanics, albite-epidote-chloriteschists, glaucophane schists, diabase, tuffaceous schists, and other associated volcanogenic sedimentary	2700
J_3-K_1(?)	**Stopol'nik Suite:** Sandstones, siltstones, polymictic meta-siltstones and phyllites with occcasional interbeds of metamorphosed tuffs	2600
PZ_{2-3}	**Khimka Suite:** Qtz-albite-chlorite schists with actinolite, metasandstones	1500
PZ_2	**Kheivan Suite:** Phyllites, metamorphosed oligoclase-bearing sandstones and siltstones	2000
PZ_1	**Andrianovka Suite:** Amphibole, amphibole-plagioclase, and albite-actinolite schists. Quartzites, metamorposed tuffaceous	700-1200
Pr?	**Kamchatka Series:** Mica schists with garnet, staurolite, kyanite. biotite and biotite amphibole	3500
Pr?	**Kolpakova Series:** Biotite, biotite-garnet, biotite amphibole, amphibole-pyroxene gneisses and migmatites, amphibolites and calciphyres	2000

B Khanchuk (1985)

Age	Rock Types	Stratigraphic Thickness
J	**Kvakhona Suite:** Weakly metamorphosed dacites and rarer basalts, tuffs, and conglomerates	2000
PZ_{2-3}	**Alistor Suite:** Amphibole schists after ultramifc and mafic volcanics / **Khimka Suite:** Albite-actinolite schists after tuffs, sandstones and quartzites	800 / 600
	Kheivan Suite: Metamorphosed sandstones and rarer meta- siltstones, conglomerates (Chiefly, sericite-chlorite, biotite and staurolite metamorphic zone)	500-2000
PZ_2	**Andrianova Suite:** Amphibole, epidote-amphibole, and Cpx-amphibole crystalline schists. Amphibolite after mafic volcanics, rare occurrences of metaconglomerate	0-700
	Shikhta Series: Metamorphosed terrigenous deposits with basal conglomerates (chiefly straurolite-sillimanite and biotite-muscovite orthogneisses and migmatites	0-1500
Pr?	**Kolpakova Series:** Retrogressed kyanite, cordierite,cordierite-hyperstene gneisses and ortho-gneisses, rare garnet amphibolites and calciphyres	2500

C Modified after Bondarenko (1992, 1997)

Age	Rock Types	Stratigraphic Thikness (m)
K_2	Iruney Complex	800-1000
K_2-P_1	Khozgon Complex	300-600
K_1-K_2	Kikhchik Complex	800-1500
J_3-K_1	Kvakhona Complex	1500
J_1	Stopolnik Complex	0-700
Tr	Alistor Complex / Andrianov Complex / Khimka Complex	500-1000
D-P	Kamchatka Complex / Kheivan Complex	0-1500
Є-O	Kolpakov Complex	2500

Malka Series

D Rikhter (1995)

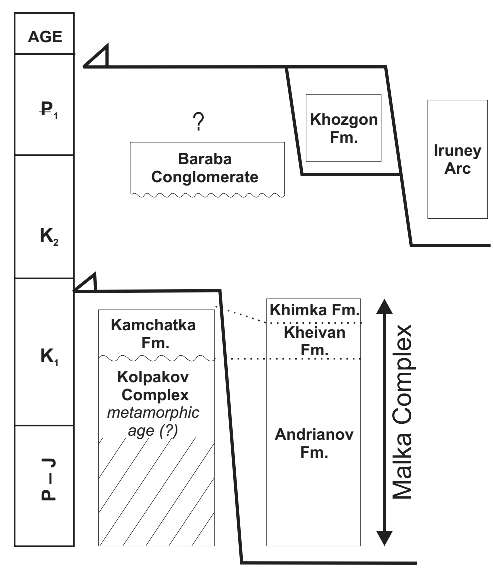


Figure 3. Columnar diagrams showing evolution of stratigraphic names and tectonostratigrphic interpretations for the Sredinniy Range.

stratigraphic scheme based on palynology alone. A third major unconformity is thought to separate the previous units from Jura-Cretaceous metavolcanics and associated metasediments of the Stopol'nik and Kvakhona series (e.g. Bondarenko,1992)

Khanchuk (1985) defined the P-T conditions of metamorphism and substantially revised the stratigraphy of the high-grade core of the Sredinniy Range. He subdivides Marchenko's Kamchatka Series into a lower and upper portion. The lower section, reassigned by Khanchuk (1985) to the upper Kolpakova complex, comprises cordierite-kyanite gneisses with abundant isoclinal folds with west-dipping axial planes. The upper section, characterized by the absence of isoclinal folds and an east-dipping dominant schistosity, consists largely of two-mica schists. Khanchuk (1985) and Rikhter (1995) describe basal conglomerates containing clasts similar appearance to the underlying Kolpakova rocks. The apparent discordance of metamorphic fabrics and conglomeratic horizons suggest an unconformable stratigraphic contact between the Kolpakov and Upper Kamchatka series rocks. To differentiate between these units Khanchuk (1985) renamed the upper section to the Shikhta series. Subsequent works by Khanchuk and Rikhtyer (1985) use the term Shikhta or Shiktiniskaya Series to describe the Upper Kamchatka Series; however, "official" geologic maps and other authors such as Bondarenko and Vinogradov still use "Kamchatka Series" to describe these rocks For consistency with the available maps will use the term Kamchatka Complex to denote the Khanchuk's Shikta Series.

The recognition of the major tectonic boundaries in the core of the range (Zhegalova, 1981) gave rise more recent tectono-stratigraphic interpretations. Bondarenko (1992) and Rikhtyer (1995) define three major structural complexes within the Sredinniy Range: a high-grade core; the Malka Complex; and the Iruney nappe, separated from one another by major thrust faults. These authors argue the Iruney nappe was emplaced on to a composite Sredinniy Core-Malka Complex during the Eocene. They recognize a high-grade core separated by a bounding fault from the Malka series, an assemblage of metamorphosed oceanic and island arc volcanics and associated sediments. Rikhtyer (1995) places the Malka series bounding fault at the base of the Andrianovka unit separating it from the strucutrally lower Kamchatka complex. Bondarenko however includes the Kamchatka Complex within the Malka series reporting a stratigraphic contact between ultramafic volcanics of the Alistor formation and Kamchatka Complex (Bondarenko, 1997).

For purposes this work we have adopted, in a general way, the structural interpretation of Rikhtyer (1995) (Figure 3d) and use a simplified geologic map (figure 2) modified after Zinkevich et al. (1998) to show the salient geologic relationships. The map view shows that the Sredinniy Range is a structural window with highest grade rocks cropping out in the center of the range. Here, the Malka complex is thrust onto the Sredinniy range metamorphic core. As a whole the Sredinniy Range core rocks and Malka Series are thought to compose single, Early Cretaceous metamorphic sequence rather concentrically zoned about the Kamchatka pluton or Krutogorova Complex (Lebedev, 1967) and lacking major breaks in metamorphic grade (Rikhtyer,1995) Reported Rb-Sr whole isochrons (Vinogradov et al., 1988) are used to constrain the timing of metamorphism. The Upper Cretaceous-Paleogene (?) age Baraba Conglomerate (Shapiro et al, 1986) which rests unconformably on the Malka Complex seems compatible with an Early Cretaceous metamorphic age. The applicability of whole-rock Rb/Sr isochron method and the flora constraining the age of the Baraba are problematic. Thus the age of metamorphism of the Malka Complex and Sredinniy Range core rock remain poorly constrained.

Previous Geochronologic Work

Numerous papers describe attempts to constrain the age of protoliths and timing of metamorphism in the Sredinniy Range. Kuz'min and Chukhonin (1980) report a 1.3 Ga Pb-Pb age for the rocks of the Kolpakova complex. L'vov et al. (1985) present Pb-Pb ages from the Yurchik gabbro massif and other gneissic units of the neighboring Ganal Range (within the Vakhtalka block, figure 2) where multiple hand-picked multi-zircon aliquotsz gave ages ranging from 3.20 ± 0.05 Ga to 530 ± 330 Ma. These authors argue that their data provide evidence for Archean and Proterozoic protoliths in the Ganal and Sredinniy ranges, respectively. Vinogradov and coauthors (1988, 1991, 1996) report whole rock Rb/Sr isochrons and rare mineral isochrons from metamorphic rocks of the Kolpakova, Kamchatka, and Malka complexes. Whole rock isochrons yield two crude age populations: Early Cretaceous and Early Tertiary. Bondarenko et al. (1993) report mineral and whole-rock Rb/Sr isochrons ranging from 67 ± 10 Ma to 48 ± 2 Ma from and garnet-bearing orthogneisses hosted by the Kamchatka Complex. The results of extensive K-Ar dating are summarized by Watson and Fujita (1985). For clarity, their "Malkinsk basement" and "Malkinsk granites" are synonymous with rocks of Sredinniy Range. K-Ar data from basement rocks show two prominent peaks at ~100 Ma (n=4) and at 50-60 Ma (n=7). Granites within the Sredinniy range are range from ~10 Ma to 120 Ma (n=43) with a major peak at ~50 Ma (n=13). The data sets contain rare single determinations with older ages up to ~480 Ma. Vinogradov and Grigoriev (1996) commented that the Sredinniy Range K-Ar dating projects were not carried out in a systematic fashion and therefore results should be viewed caution. Finally, Zinkevich et al.(1993) summarize the results of $^{40}Ar/^{39}Ar$ dating of the rocks in Ganal and Khavyven Ranges. They argue age data from the hornblende from metamorphic rocks of the Ganal range indicate prograde metamorphism occurred between 51 and 47 Ma with undeformed post-tectonic intrusions yielding ages in the 42 -35 Ma range.

The Baraba conglomerate rests unconformably on metamorphic rocks of the Malka series (Kolodyazhnyy et al., 1996; Shapiro et al., 1986); Figure 2, 3d) and thus provides important minimum age constraints for the timing of Malka metamorphism. The Baraba contains floral imprints abundant in shaley portions of the stratigraphic sequence. The age of these flora is problematic but generally thought to fall in the Latest Cretaceous

(Campanian) to Paleogene (Shapiro et al.,1986). Accordingly, the metamorphism of the Malka series should be pre-Campanian. We emphasis that the rocks dated for our study are not within the Malka series. Given the new data collected here and the available data in the literature it is possible that the age of metamorphism of Sredinniy core and Malka complex are different, however we feel it is best to defer discussion of this problem until ongoing fission track and $^{40}Ar/^{39}Ar$ dating projects on the Malka and Baraba units are complete. Vinogradov and Grigoriev (1996) report a 62 ± 7 Ma age for phyllites of the Kheivan unit in the upper part of the Malka complex. We see no reason that this age, based on a whole-rock Rb/Sr isochron, can be linked to a discrete event in the history of these rocks, either provenance age or metamorphism. As evidenced by the preceding discussion, there is limited consensus on the timing and cause of metamorphism, in large part due to disparate results of radiometric dating efforts and problematic stratigraphy of overlapping sedimentary sequences.

The eastern flank of the Sredinniy Range is bound by the east-dipping reverse fault which places the Iruney nappe and slivers of a Lower Cretaceous-Paleocene Khozgon Formation (Shapiro et al, 1986) against the Malka complex. Bondarenko (1999) argues for some normal reactivation of this structure following the Middle Eocene collision. Garver et al (2000c) estimate that collision began at 55 Ma and continued through at least 45 Ma based on the detrital FT stratigraphic ages of strata overridden by the arc in central and northern Kamchatka. In the Kamchatka Isthmus area, a deformed section of the Lesnaya Group in the Lesnovsk Highlands (Fig. 1) contains continentally sourced clastics interbedded with olistostromes derived from the overriding Olyutorsky arc thrust sheet. Young (P1) FT grain-age peaks from this syn-orogenic part of the section range from ~55 Ma to ~44 Ma(Garver et al., 2000b; Soloviev et al., 2002 (In press)). The thrust sheet is unconformably overlain by undeformed Kinkil volcanics and cross-cut by undeformed granitic intrusions of the Shamanka Massif which yield 45.5 ± 2.9 Ma (2σ) and 45.3 ± 1.0 Ma (2σ) U/Pb zircon ages, respectively (Garver et al., 2000b).These data tightly bracket the timing of collision to the Middle Eocene.

The Sredinniy Range is a structurally complex region consisting of a high-grade evolved, "continental" core, structurally overlain by Malka Complex metavolcanics significantly more oceanic in character. These complexes form the lower plate of a major thrust system along which the Olyutorsky arc was obducted. Only the timing of arc-continent collision is satisfactorily constrained at the present time.

SHRIMP U/PB ZIRCON GEOCHRONOLOGY

We present U/Pb grain-age data from zircons in an amphibolite-facies gneiss from the upper part of Kamchatka Complex (Marchenko, 1967) (No. 112-11; Figure 2). The specimen consists of plagioclase, quartz, biotite, hornblende and retrograde chlorite with subordinate garnet, zircon, and apatite. In the field the gneiss rock was conditionally interpreted as a meta-igneous rock. However, at the sampling locality the inferred intrusive contact is mylonitized. According to the chemical composition the rock may represent either a diorite by Streicksen classification or plots in the greywacke field for metasediment classification charts. An ε_{Nd} of -5.3 (Bondarenko, unpublished data) for this sample and ubiquitously high Sr_i (>.704) indicate the involvement of relatively old, isotopically evolved crustal material in the formation of Kamchatka Unit. Savostin et al. (1994) suggest the Kamchatka unit experienced metamorphic temperatures on the order of 600 ºC at pressures of 5 to 7 kbar.

Methodology

Zircons were separated using standard crushing and heavy-liquid techniques described in (Garver et al., 2000a). Approximately 100 zircons per sample were mounted in epoxy and polished to their mid-sections. We used transmitted and reflected light microscopy at 20X magnification to identify crack- and inclusion-free regions for subsequent SHRIMP analysis. A cathodoluminescence detector mounted on a JEOL JSM

5600 scanning electron microscope was used to image the fine-scale trace element zonation pattern and illuminate the internal structure of each crystal which has known petrogenetic significance (Hanchar et al., 1992; Hanchar et al., 1993).

Zircons were analyzed on the Stanford-USGS SHRIMP-RG following standard operating procedures (Ireland and Gibson, 1998; Muir et al., 1996). Individual $^{206}Pb^*/^{238}U$ age determinations have analytical precision of ~2%, with better precision for olders grain where the $^{207}Pb^*/^{206}Pb^*$ is more precisely measured. Low U concentration and large variations in count rates, however, result in larger uncertainties. Low abundance of ^{207}Pb in young (<1 Ga) samples result in large uncertainty in $^{207}Pb^*/^{206}Pb^*$; therefore ^{207}Pb corrected $^{206}Pb^*/^{238}U$ ages are reported here. The ^{207}Pb correction assumes that the measured isotopic ratios represent simple mixtures of radiogenic and common lead at the time of crystallization (T_1) with measured $^{207}Pb/^{206}Pb$ used to monitor common lead. Slightly discordant data are extrapolated along a line projected from an estimate of $^{207}Pb/^{206}Pb$ at T_1 (Cumming and Richards, 1975) through the measured data point onto concordia. For old grains (>1Ga) we present common lead corrected $^{207}Pb^*/^{206}Pb^*$ ages. Highly discordant measured data were rejected from the data set. Table 2 lists the data collected for both Kamchatka gneiss and Ukelayat Sandstone samples. Accepted grain-ages are reported in probability density and cumulative probability plots after Brandon (Brandon, 1996).

Several lines of evidence indicate that the zircons of the Kamchatka gneiss are of detrital origin. Cathodoluminescence images reveal a zircon population dominated by structurally simple zircons grains (Fig. 4). SHRIMP analyses of pairs apparent cores and rims failed to demonstrate inheritance of xenocrystic zircon within more structurally complex zircons. Grain-age heterogeneity and the textural heterogeneity of zircon population as a whole indicates the detrital origin of the zircon population (Fig 4,5; Table 2) Grain-scale structural simplicity of this heterogeneous population permits the assumption that minor discordance is related to trace common lead and use of ^{207}Pb

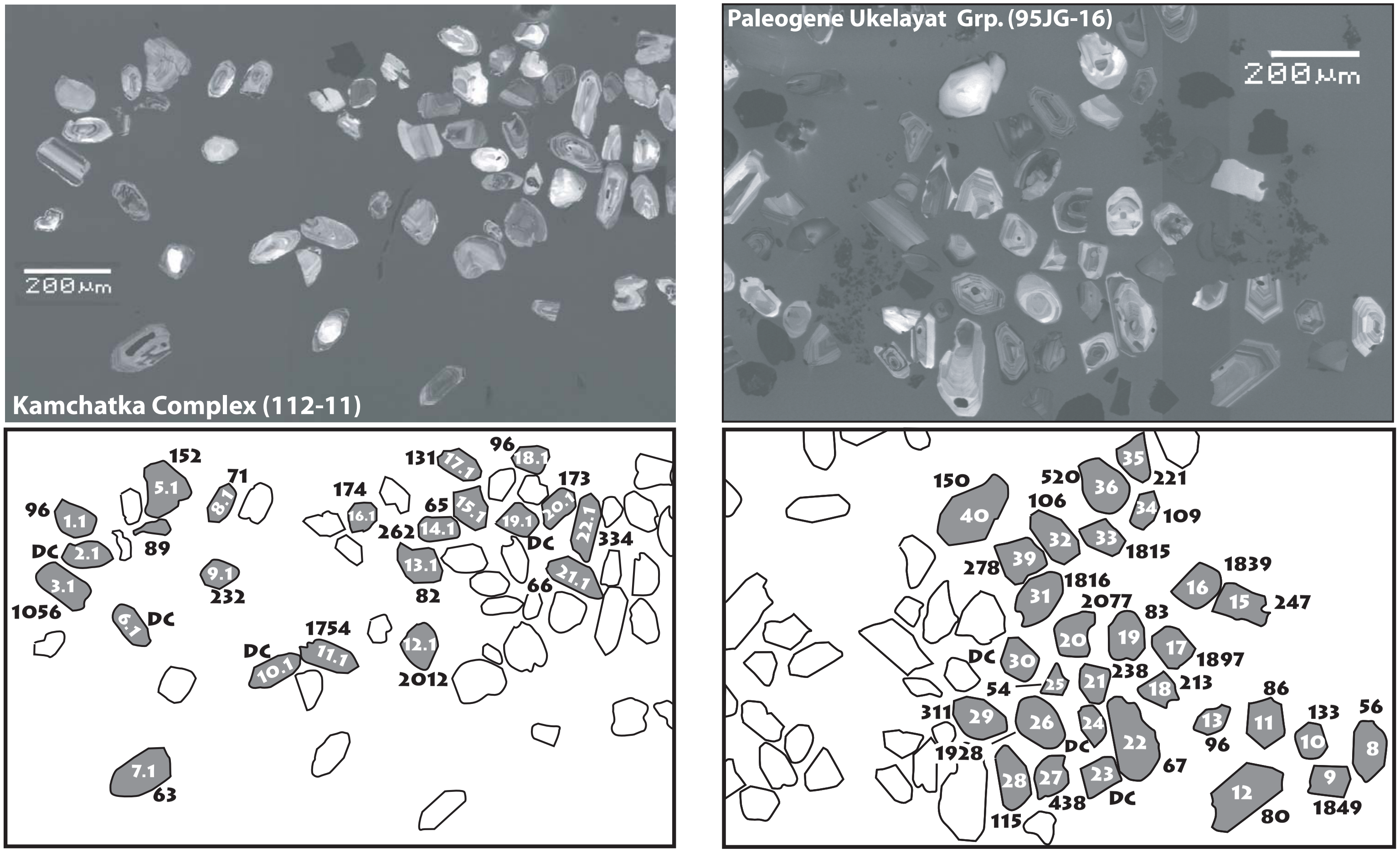


Figure 4. Cathodoluminesce (CL) images illuminating the internal structure of sample zircons from the Kamchatka Complex and Ukelayat Group. Beneath each image an outline sketch of the grain mounts contain spot analysis number in white (See table 2 for data) and age (Ma) in black. "DC" denotes a discordant analysis. Note the internal textural heterogeneity of the Kamchatka Complex zircons exhibited in the CL image is similar to the observed heterogeneity in the Ukelayat sample of known detrital origin. Combined with grain age heterogeneity and Th/U ratios, the observed zircon CL textures suggest this is a detrital population of largely magmatic origin.

corrected grain-ages. The lack of observed correlation between uranium concentration and grain-age suggests that U-correlated differential lead loss is not responsible for the observed heterogeneity. Finally, U/Th ratios greater than 0.1 of young grains rule out a metamorphic origin for the youngest zircons. Ireland and Gibson (1998) use Th/U > 0.4 and U concentration >1000ppm as the metamorphic-magmatic threshold. The youngest grains (Table 2a) pass this more rigorous test as well. We argue that the grain-ages represent igneous crystallization ages and their distribution reflects heterogeneity in sedimentary source region. The magmatic origin youngest population suggests this source region included a magmatic arc which was active into the Paleogene. We argue that the youngest concordant grain-age (55.2 ± 3.3 Ma) constrains the maximum stratigraphic age of the sedimentary protolith of the Kamchatka gneiss to the Paleocene. Our results suggest metamorphism of the Kamchatka complex which necessarily postdates the stratigraphic age of the protolith, is significantly younger than previous workers have argued (e.g. Rikhtyer, 1995).

For comparison with Early Cenozoic NE Asian margin sediments we analyzed detrital zircon grain-age distribution (n=45) from a sandstone in the Eocene section of the Ukelayat Group (Garver et al., 2000c). The Ukelayat Group and its correlatives the Lesnovsk and Khozgon Groups contain thick marine clastics, mainly turbidites, which accumulated along the northeast Asian margin prior to the collision of the Olyutorsky Arc (Garver et al., 2000c; Shantser et al., 1985; Solov'ev et al., 2001).After the onset of collision this sedimentary sequence continued to accumulate in a foredeep in west of an actively advancing obducted arc. Detrital zircon fission track studies (Garver et al. 2000c; Soloviev et al., 2001) and concomitant sandstone petrography studies show that sandstones were derived from a continental arc setting. The sample used for comparison (95JG-16, Matysken River) is known to contain young FT grain-ages which are used to constrain the stratigraphic age of the unit to the Early Eocene (Figure 6). Coincidence of the youngest U/Pb grain-ages and the youngest (P1) FT peak (Fig. 6) demonstrates that

112-11: Shikhta Complex Paragneiss

Labels	U/ppm	Th/ppm	Th/U	Pb*/ppm	Isotopic Ratios (± 1σ)				Age (Ma, ± 1σ)
Grain-ages <1.0 Ga									
						^{207}Pb / ^{206}Pb	**^{238}U / ^{206}Pb**		**^{206}Pb / ^{238}U Age**
112-11-2	160	94	0.59	4		0.0454 ± 0.0043	46.88 ± 2.07		**136.7 ± 6.0**
112-11-5	306	347	1.13	7		0.0498 ± 0.0030	55.27 ± 2.05		**115.4 ± 4.3**
112-11-6	747	237	0.32	31		0.0529 ± 0.0013	24.03 ± 1.05		**262.5 ± 11.2**
112-11-7	642	465	0.72	14		0.0470 ± 0.0020	51.64 ± 2.43		**123.9 ± 5.8**
112-11-8	149	86	0.58	5		0.0618 ± 0.0034	29.46 ± 1.29		**212.2 ± 9.2†**
112-11-9	107	56	0.52	1		0.0478 ± 0.0068	108.71 ± 5.30		**59.0 ± 2.9**
112-11-10	154	56	0.36	7		0.0509 ± 0.0028	22.82 ± 1.16		**276.8 ± 13.8**
112-11-11	76	49	0.65	2		0.0466 ± 0.0047	40.18 ± 3.22		**159.0 ± 12.6**
112-11-12	361	167	0.46	16		0.0541 ± 0.0020	23.05 ± 1.06		**273.1 ± 12.4**
112-11-14	581	367	0.63	11		0.0488 ± 0.0019	58.24 ± 3.44		**109.7 ± 6.4**
112-11-15	377	156	0.41	15		0.0519 ± 0.0022	24.90 ± 1.46		**253.7 ± 14.6**
112-11-16	153	46	0.30	4		0.0474 ± 0.0030	36.67 ± 1.46		**173.9 ± 6.9**
112-11-17	79	40	0.51	3		0.0531 ± 0.0037	25.98 ± 1.51		**242.8 ± 13.9**
112-11-19	890	377	0.42	33		0.0512 ± 0.0011	27.36 ± 1.17		**231.3 ± 9.7**
112-11-22	330	157	0.47	6		0.0503 ± 0.0030	59.80 ± 3.10		**106.6 ± 5.5**
112-11-25	8	0	0.01	0		0.1367 ± 0.0483	108.80 ± 12.67		**52.3 ± 7.1†**
112-11-26	407	169	0.42	4		0.0469 ± 0.0034	112.05 ± 7.85		**57.3 ± 4.0**
112-11-27	190	145	0.76	2		0.0520 ± 0.0047	88.80 ± 5.43		**71.8 ± 4.4**
112-11-28	837	429	0.51	8		0.0502 ± 0.0030	115.82 ± 6.83		**55.2 ± 3.3**
112-11-18c	1037	21	0.02	25		0.0477 ± 0.0017	37.98 ± 1.83		**167.9 ± 8.0**
112-11-18r	387	397	1.03	14		0.0478 ± 0.0019	33.63 ± 2.10		**189.4 ± 11.7**
112-11-23c	616	233	0.38	12		0.0487 ± 0.0018	49.29 ± 1.94		**129.5 ± 5.1**
112-11-23r	1141	730	0.64	22		0.0474 ± 0.0015	56.64 ± 3.31		**113.0 ± 6.5**
112-11-1.1	362	230	0.63	6		0.0487 ± 0.0030	66.31 ± 2.54		**96.4 ± 3.7**
112-11-2.1	184	107	0.58	3		0.0584 ± 0.0035	74.69 ± 2.47		**84.6 ± 2.8†**
112-11-4.1	1276	294	0.23	17		0.0492 ± 0.0013	71.65 ± 3.66		**89.2 ± 4.5**
112-11-5.1	368	178	0.48	9		0.0512 ± 0.0018	41.77 ± 2.00		**152.1 ± 7.2**
112-11-6.1	1278	175	0.14	34		0.0532 ± 0.0009	35.82 ± 1.96		**176.7 ± 9.5†**
112-11-7.1	530	285	0.54	5		0.0485 ± 0.0022	100.92 ± 2.36		**63.5 ± 1.5**
122-11-8.1	1312	413	0.32	14		0.0487 ± 0.0014	90.00 ± 3.84		**71.1 ± 3.0**
122-11-9.1	58	48	0.83	2		0.0504 ± 0.0037	27.27 ± 0.82		**232.3 ± 7.0**
112-11-10.1	195	87	0.45	4		0.1483 ± 0.0075	59.80 ± 4.31		**93.4 ± 6.8†**
112-11-13.1	262	205	0.78	4		0.0440 ± 0.0028	78.83 ± 1.71		**81.6 ± 1.8**
112-11-14.1	691	254	0.37	29		0.0524 ± 0.0010	24.17 ± 0.74		**261.0 ± 7.9**
112-11-15.1	212	149	0.70	2		0.0480 ± 0.0038	99.41 ± 3.79		**64.5 ± 2.5**
112-11-16.1	880	301	0.34	24		0.0494 ± 0.0015	36.55 ± 1.26		**174.0 ± 6.0**
112-11-17.1	258	124	0.48	6		0.0505 ± 0.0026	48.75 ± 2.08		**130.6 ± 5.5**
112-11-18.1	306	258	0.84	5		0.0494 ± 0.0028	64.21 ± 3.78		**99.5 ± 5.8**
112-11-19.1	1108	108	0.10	164		0.1137 ± 0.0009	6.71 ± 0.32		**848.3 ± 37.4†**
112-11-20.1	1868	543	0.29	50		0.0500 ± 0.0008	36.76 ± 1.20		**172.9 ± 5.6**
112-11-21.1	948	842	0.89	11		0.0478 ± 0.0017	96.67 ± 3.72		**66.3 ± 2.5**
112-11-22.1	189	177	0.94	12		0.0506 ± 0.0019	18.84 ± 0.76		**334.4 ± 13.1**
112-11-23.1	836	54	0.06	138		0.1453 ± 0.0011	6.13 ± 0.41		**890.6 ± 55.9†**
112-11-24.1	1052	832	0.79	12		0.0476 ± 0.0015	96.57 ± 1.95		**66.4 ± 1.3**
Grain-ages >1.0 Ga									
					206%	**^{206}Pb / ^{238}U**	**^{207}Pb / ^{235}U**	**^{207}Pb / ^{206}Pb**	**^{207}Pb / ^{206}Pb Age**
112-11-1	1184	204	0.17	400	0.02	0.3368 ± 0.0139	5.338 ± 0.223	0.1150 ± 0.0005	**1879.4 ± 7.7**
112-11-3	159	124	0.78	56	0.14	0.3031 ± 0.0116	4.678 ± 0.203	0.1119 ± 0.0019	**1831.0 ± 30.6**
112-11-4	348	298	0.86	152	0.02	0.3690 ± 0.0278	6.432 ± 0.494	0.1264 ± 0.0010	**2048.9 ± 14.1**
112-11-13	301	160	0.53	106	0.06	0.3188 ± 0.0155	5.210 ± 0.265	0.1185 ± 0.0012	**1934.3 ± 17.9**
112-11-20	255	76	0.30	87	0.01	0.3288 ± 0.0120	5.486 ± 0.214	0.1210 ± 0.0012	**1971.0 ± 17.1**
112-11-21	156	81	0.52	58	0.32	0.3399 ± 0.0190	5.487 ± 0.327	0.1171 ± 0.0017	**1912.1 ± 26.8**
112-11-24	420	54	0.13	133	0.14	0.3181 ± 0.0205	5.094 ± 0.343	0.1161 ± 0.0015	**1897.5 ± 23.1**
112-11-3.1	192	44	0.23	33	0.02	0.1759 ± 0.0072	1.808 ± 0.082	0.0745 ± 0.0012	**1056.1 ± 31.3**
112-11-11.1	236	134	0.57	75	-0.05	0.2910 ± 0.0098	4.306 ± 0.160	0.1073 ± 0.0013	**1754.3 ± 22.0**
112-11-12.1	242	95	0.39	88	0.02	0.3422 ± 0.0130	5.842 ± 0.232	0.1238 ± 0.0009	**2012.2 ± 13.4**

† Rejected discordant grain-age

Table 2: Kamchatka (112-11) and Ukelayat (95JG-16) U/Pb grain-ages. Single grain data are reported in two formats depending on the uncorrected grain-ages. For grain-ages >1.0Ga all reported data have been corrected for common lead contamination with measured ^{204}Pb is used to monitor common lead. For these grains ^{207}Pb / ^{206}Pb ages are reported. For grain-ages less the 1.0 Ga, uncorrected isotopic ratios are reported. The individual grain-ages are ^{207}Pb corrected $^{206}Pb^{*}$/ ^{238}U ages..

95JG16: Paleocene Ukelayat Group sandstone

Grain-ages <1.0 Ga

Labels	U/ppm	Th/ppm	Th/U	Pb*/ppm	Isotopic Ratios (± 1σ) ^{207}Pb / ^{206}Pb	Isotopic Ratios (± 1σ) ^{238}U / ^{206}Pb	Age (Ma, ± 1σ) ^{206}Pb / ^{238}U Age
95JG16-1	110	113	1.03	4	0.0472 ± 0.0050	30.74 ± 1.22	**209.3 ± 8.3**
95JG16-3	192	174	0.91	5	0.0621 ± 0.0060	49.06 ± 4.88	**129.6 ± 12.8†**
95JG16-4	90	69	0.77	2	0.0491 ± 0.0058	57.26 ± 2.48	**113.0 ± 4.9**
95JG16-6	353	213	0.60	5	0.0486 ± 0.0033	76.90 ± 2.95	**84.4 ± 3.2**
95JG16-8	247	120	0.49	2	0.0409 ± 0.0042	116.87 ± 4.45	**56.2 ± 2.2**
95JG16-10	222	93	0.42	5	0.0517 ± 0.0031	48.44 ± 2.52	**132.9 ± 6.9**
95JG16-11	365	147	0.40	5	0.0476 ± 0.0029	75.92 ± 3.22	**85.6 ± 3.6**
95JG16-12	323	133	0.41	4	0.0501 ± 0.0055	81.30 ± 3.70	**79.7 ± 3.6**
95JG16-13	400	684	1.71	8	0.0471 ± 0.0025	67.45 ± 3.14	**96.3 ± 4.5**
95JG16-15	33	37	1.14	2	0.0433 ± 0.0072	26.16 ± 1.42	**246.5 ± 13.3**
95JG16-18	259	184	0.71	9	0.0496 ± 0.0021	30.06 ± 1.20	**213.4 ± 8.4**
95JG16-19	120	50	0.42	2	0.0538 ± 0.0050	77.74 ± 3.22	**82.9 ± 3.5**
95JG16-21	165	220	1.33	8	0.0505 ± 0.0027	26.91 ± 1.26	**237.7 ± 11.0**
95JG16-22	247	110	0.44	3	0.0515 ± 0.0038	97.35 ± 4.01	**66.5 ± 2.7**
95JG16-23	851	48	0.06	111	0.1088 ± 0.0020	7.39 ± 0.62	**771.0 ± 61.8†**
95JG16-24	105	45	0.42	10	0.0721 ± 0.0080	12.01 ± 0.72	**507.7 ± 29.6†**
95JG16-25	207	125	0.60	2	0.0520 ± 0.0049	119.39 ± 8.78	**54.2 ± 4.0**
95JG16-27	173	86	0.50	13	0.0531 ± 0.0022	14.32 ± 0.52	**438.3 ± 15.4**
95JG16-28	435	525	1.21	10	0.0517 ± 0.0023	56.12 ± 3.01	**114.9 ± 6.1**
95JG16-29	69	104	1.51	5	0.0517 ± 0.0032	20.39 ± 0.95	**311.3 ± 14.3**
95JG16-30	118	116	0.98	4	0.0666 ± 0.0042	40.47 ± 2.73	**155.9 ± 10.4†**
95JG16-32	526	243	0.46	9	0.0485 ± 0.0025	60.98 ± 4.02	**106.2 ± 7.0**
95JG16-34	475	198	0.42	8	0.0480 ± 0.0023	59.30 ± 2.74	**109.3 ± 5.0**
95JG16-35	73	54	0.74	3	0.0568 ± 0.0045	28.61 ± 1.34	**222.1 ± 10.3**
95JG16-36	206	117	0.57	18	0.0584 ± 0.0017	11.92 ± 0.43	**519.8 ± 18.2**
95JG16-37	179	87	0.48	3	0.0501 ± 0.0051	73.99 ± 8.56	**87.5 ± 10.1**
95JG16-38	248	67	0.27	22	0.0611 ± 0.0015	10.99 ± 0.50	**560.3 ± 24.5**
95JG16-39	194	145	0.75	9	0.0521 ± 0.0019	22.88 ± 0.92	**278.1 ± 11.0**
95JG16-40	19	16	0.84	1	0.0590 ± 0.0117	42.61 ± 2.48	**149.6 ± 8.9**
95JG16-41	117	55	0.47	7	0.0697 ± 0.0046	18.12 ± 1.21	**342.0 ± 22.3**
95JG-16-1.1	579	162	0.28	8	0.0493 ± 0.0019	73.76 ± 2.03	**86.7 ± 2.4**
95JG-16-2.1	494	317	0.64	6	0.0517 ± 0.0023	88.35 ± 4.83	**72.2 ± 3.9†**
95JG-16-3.1	271	86	0.32	3	0.0975 ± 0.0081	113.16 ± 2.58	**53.1 ± 1.3†**
95JG-16-4.1	507	702	1.39	28	0.0591 ± 0.0039	21.86 ± 1.24	**285.9 ± 16.0†**
95JG-16-5.1	112	156	1.40	5	0.0525 ± 0.0034	28.86 ± 1.92	**219.1 ± 14.4**
95JG-16-7.1	172	100	0.58	3	0.0493 ± 0.0045	58.23 ± 4.19	**109.6 ± 7.9**
95JG-16-8.1	148	91	0.62	3	0.0575 ± 0.0049	63.79 ± 3.74	**99.1 ± 5.8†**
95JG-16-9.1	850	111	0.13	20	0.0506 ± 0.0014	40.66 ± 1.69	**156.3 ± 6.4**
95JG-16-10.1	31	31	1.00	2	0.0528 ± 0.0054	16.98 ± 1.04	**369.4 ± 22.2**

Grain-ages >1.0 Ga

Labels	U/ppm	Th/ppm	Th/U	Pb*/ppm	%f206	^{206}Pb / ^{238}U	^{207}Pb / ^{235}U	^{207}Pb / ^{206}Pb	^{207}Pb / ^{206}Pb Age
95JG16-2	59	22	0.38	20	0.02	0.3172 ± 0.0162	5.218 ± 0.307	0.1193 ± 0.0028	**1945.7 ± 42.7**
95JG16-5	107	79	0.74	35	0.02	0.2866 ± 0.0136	3.895 ± 0.204	0.0986 ± 0.0017	**1597.5 ± 32.2**
95JG16-7	122	99	0.81	47	0.07	0.3322 ± 0.0156	5.097 ± 0.267	0.1113 ± 0.0020	**1820.3 ± 32.3**
95JG16-9	144	73	0.51	52	0.02	0.3356 ± 0.0121	5.233 ± 0.209	0.1131 ± 0.0015	**1849.4 ± 24.3**
95JG16-14	218	39	0.18	72	0.02	0.3291 ± 0.0114	5.393 ± 0.201	0.1188 ± 0.0012	**1938.9 ± 17.4**
95JG16-16	673	82	0.12	192	0.02	0.2899 ± 0.0102	4.493 ± 0.168	0.1124 ± 0.0010	**1838.6 ± 16.2**
95JG16-17	270	388	1.44	112	0.14	0.3158 ± 0.0137	5.056 ± 0.236	0.1161 ± 0.0014	**1897.1 ± 22.2**
95JG16-20	589	300	0.51	246	0.01	0.3807 ± 0.0126	6.742 ± 0.234	0.1284 ± 0.0009	**2076.6 ± 13.0**
95JG16-26	80	89	1.10	32	0.02	0.3153 ± 0.0149	5.136 ± 0.272	0.1181 ± 0.0022	**1928.3 ± 33.9**
95JG16-31	1403	56	0.04	403	0.04	0.2976 ± 0.0151	4.556 ± 0.236	0.1110 ± 0.0006	**1816.2 ± 9.1**
95JG16-33	56	11	0.19	16	0.02	0.2917 ± 0.0115	4.463 ± 0.228	0.1110 ± 0.0031	**1815.2 ± 51.7**
95JG-15-6.1	78	33	0.42	31	0.02	0.3690 ± 0.0129	6.391 ± 0.277	0.1256 ± 0.0027	**2037.8 ± 38.3**

† Rejected discordant grain-age

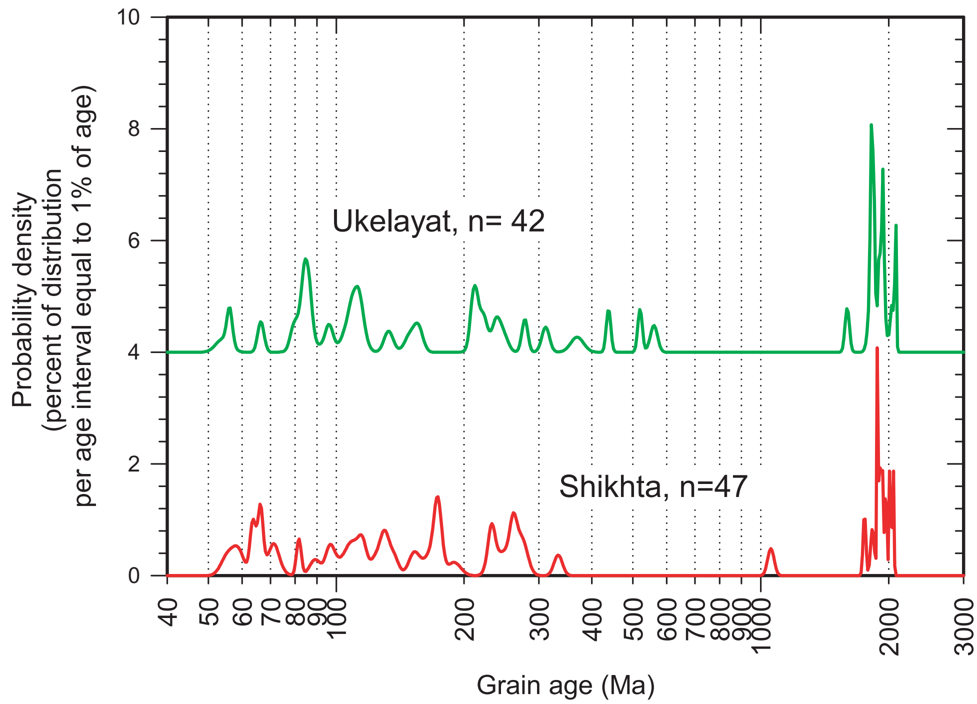


Figure 5. Probability density plots of U/Pb grain ages from the Kamchatka gneiss (112-11). Plots are constructed after Brandon (1996)

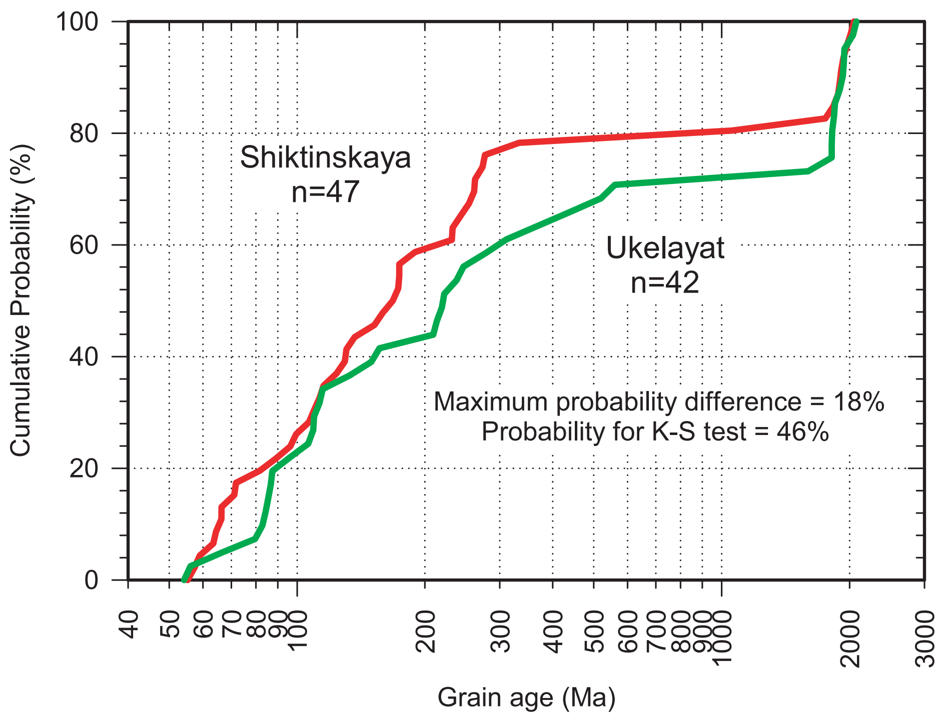


Figure 7. Comparison of cumulative probability distributions for U/Pb grain ages of the Kamchatka and Ukelayat sequences. The Kolmogorov-Smirnov statistic (P(KS)) is a nonparametric test of the degree of misfit of two independent populations. Here P(KS) = 46% implies a high degree of likelihood that these zircons in these two units were derived from the same parent population.

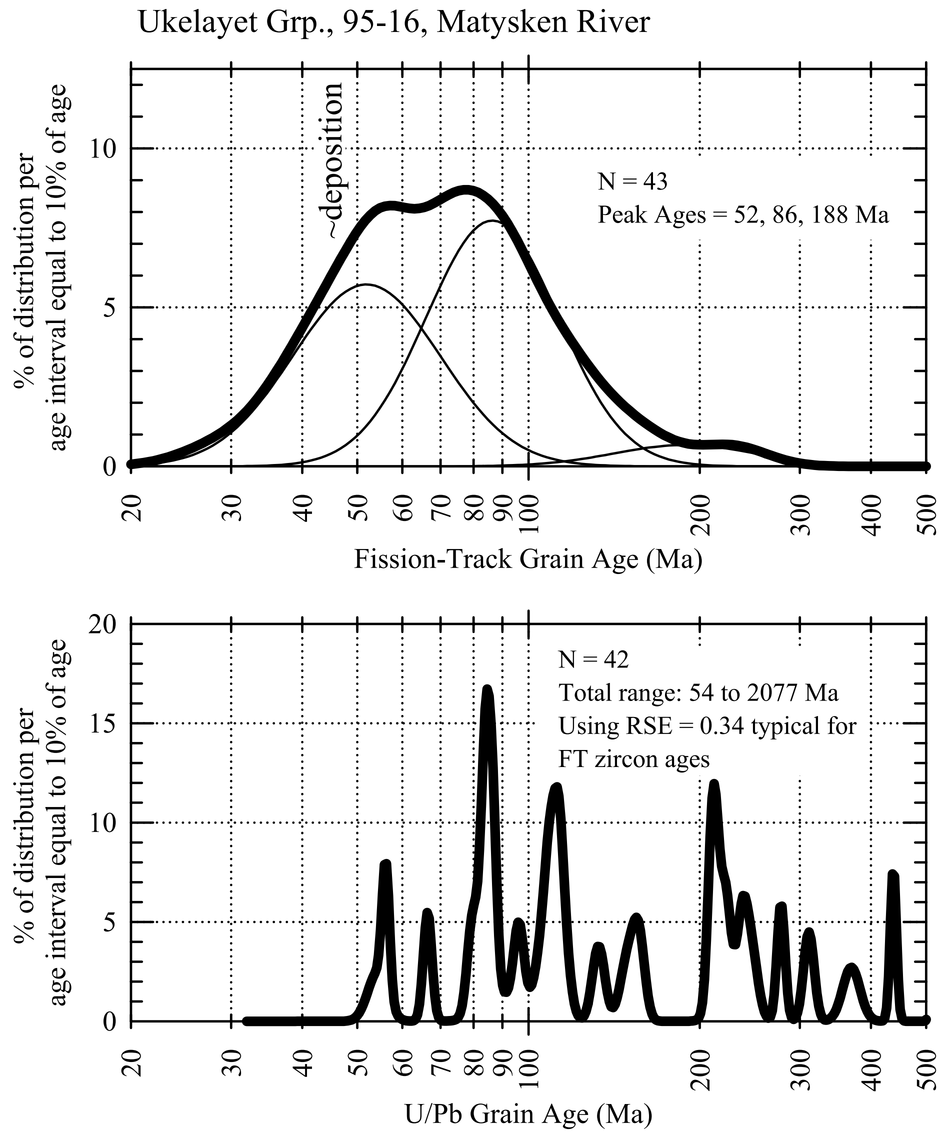


Figure 6. Probability Density for zircon fission track and U/Pb grain-ages from Ukelayat sandstone. Peaks fitted to the fission track grain-age distributions are generally taken to represent the age of component populations in the source region. The concordance of several of the youngest U/Pb grain-ages and the FT young peak (P1) supports the first-cycle volcanic origin of the youngest FT peak (Garver et al., 1999).

the young grains do in fact represent first-cycle volcanic zircons, as proposed by Garver et al. (2000c).

The range and overall distribution of zircon U/Pb grain-ages within the Kamchatka gneiss sample and the Ukelayat sample is remarkably similar (Fig. 5). Visual inspection of the grain-age probability density plots suggests that many of the zircon grain-ages are shared in common. In detail, the Early Cenozoic through Early Mesozoic and Early Proterozoic distributions are similar in terms of range and magnitude of probability density. The most notable divergence of the two data sets occurs in the occurrence of Paleozoic zircons in the Ukelayat sample. We use a Komologorov-Smirnov statistic as a rigorous test of the similarity of the distributions (Fig. 7). The K-S statistic is a non-parametric method for comparing cumulative probability distributions. The degree of misfit between the two distributions is measured by the maximum vertical separation between the cumulative probability plots. P(KS) gives the probability that random chance alone might produce the observed difference in two distributions drawn from the same parent population (i.e. sedimentary source region). For our case P(KS) = 46%, which means that the differences between the two distributions could be due to chance alone.

We conclude, based on the observed grain-age similarity, that the Kamchatka Complex gneisses where produced by high-grade metamorphism of a sedimentary protolith similar to those of the Ukelayat Group. Other workers have suggest that the Kolpakova gneisses are metamorphosed greywackes (Predovskiy, 1970) Our work, however, provides the first direct evidence to support this conclusion. Additionally, these data provide constraints on the stratigraphic age of the protolith. We argue that the Kamchatka complex is a Paleocene correlative of the sediments deposited along the northeast Asian margin (e.g. Ukelayat, Lesnaya, and Khozgon) which suffered high-grade metamorphism. From this perspective the Kamchatka complex represents a structurally-buried and metamorphosed portion of the Early Cenozoic Russian margin. Our findings do not rule out the existence of older rocks in the Sredinniy range core within the Kolpakova complex.

Clearly, the age of metamorphism of our Kamchatka gneiss sample must postdate the ~55 Ma age of the youngest represented detrital grains. This event is similar temporally to and spatially compatible with metamorphism related to collision of the Olyutorsky arc (Garver et al., 1999, Soloviev et al., 2002)

THERMOCHRONOLOGY

An essential component of this investigation is continued critical evaluation of geo- and thermochronologic data published in the Russian literature begun by Watson and Fujita (1985). Our data yield a surprising prediction for the age of the sedimentary protoliths of the Kamchatka series. The data set allows us to model Pb-Pb ages yielded by these heterogeneous grain-age zircon populations. The following equation was used to approximate the $^{207}Pb/^{206}Pb$ for a bulk dissolution experiment:

$$\frac{^{207}Pb}{^{206}Pb}_{bulk} = \sum_{i=1}^{n} \frac{(Pb*_i)(^{207}Pb_i/^{206}Pb_i)}{\sum_{i=1}^{n}(Pb*_i)}$$

where, for a given analysis, $Pb*_i$ and $^{207}Pb_i / ^{206}Pb_i$ are concentration of radiogenic lead and measured isotopic ratio, respectively (Table 1). We assume isotopic ratios and radiogenic lead are homogenous within each analyzed grain, all crystals are of equal mass and these data are statistically representative of the entire population. While in detail these assumptions may be inaccurate, the results of this simple model are instructive. Old grains have radiogenic lead concentrations that are up to two orders of magnitude greater than the young populations which disproportionately weights older components and yields geologically meaningless bulk dissolution $^{207}Pb/^{206}Pb$ ages. The synthetic bulk $^{207}Pb/^{206}Pb$ ratio for the Kamchatka sample would be 0.1018 equivalent to a ~1.66 Ga $^{207}Pb/^{206}Pb$ age. Bulk analysis of the Ukelayat sample zircons would produce a ratio of

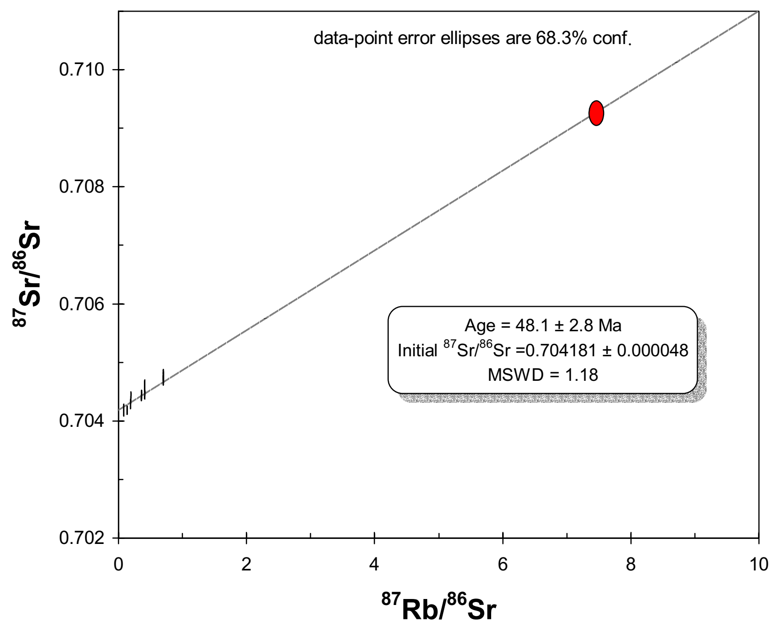
0.1056 or a ~1.73 Ga $^{207}Pb/^{206}Pb$ age. For gneisses, old Pb-Pb ages may alert us to the presence of old zircons within a population. However, in the absence of uranium isotopic measurements it is impossible to verify concordance and assess reliability of the given age data. In the case of heterogeneous detrital populations the Pb-Pb method produces ages that have no geological significance. We emphasis that Precambrian Pb-Pb ages reported in the literature (Kuzmin and Chukhonin, 1980; L'vov et al., 1985) most likely are reflect systematic age bias imparted by highly radiogenic Precambrian grains on an otherwise heterogeneous detrital population, not a real Precambrian protolith age.

The whole rock Rb-Sr isochron method has been widely applied in attempts to constrain the timing of metamorphism of the Sredinniy range. (Vinogradov and Grigor'yev, 1996; Vinogradov et al., 1991; Vinogradov et al., 1988) have reported multiple whole rock isochrons from gneisses and metaplutonic rocks of the Sredinniy Range. In early works (1988,1991) the Vinograodov group provides no statistical support for evaluation of the isochron fits. Vinogradov and Grigror'ev (1996) present isochron fits from 14 whole rock sample suites. In general, whole rock Rb/Sr isochrons even those with producing good linear arrays give apparent ages which are geologically meaningless mixtures of protolith and parent ages (e.g. Dickin, 1997). A more suitable methodology for constraining the age of metamorphism is the Rb/Sr mineral isochron as isotopic equilibration over the volume of a hand sample is a more credible assumption than isotopic equilibrium over $10^1 km^3$ to $10^2 km^3$ as necessitated by the whole-rock method. We re-calculate isochrons from biotite-whole rock pairs using data reported by Vinogradov et al. (1991). Three samples yield a range of ages from 56.2 to 51.2 Ma. . The applicability the whole rock isochron method for constraining metamorphic age of metasediments is predicated on complete isotopic homogenization over the volume from which the whole samples were taken during metamorphism. Indeed, the scale of strontium isotopic homogenization is often significantly smaller than the volume over which sampling occurred even under magmatic conditions (Roddick and Compston, 1977). Vinogradov and Grigoriev (1996) report a biotite-only isochron from a larger suite of hand samples (n=7) which yields a 47 ± 2 Ma isochron. We argue that the excessive scatter of this isochron (MSWD=9.7) indicates the process of widespread $^{87}Sr/^{86}Sr$ homogenization was incomplete during growth of metamorphic biotite. This finding suggests whole rock data do not provide credible evidence for the timing of metamorphism of the Sredinniy Range. We argue instead that there is evidence only for partial homogenization of metasediments derived an isotopically evolved (Sr_i ~ 0.706-0.707) source region(s).

Bondarenko et al. (1993) report a Rb-Sr mineral isochron age of 48 ± 3 Ma for a metamorphosed garnet plagiogranite hosted in the Kamchatka gneisses, located about 35 km to the north of our U/Pb sample locality along the contact between the Kamchatka and Andrianovka Units. The rock is dominated by plagioclase with minor amphibole, garnet, and biotite. Because of it's high Rb/Sr, biotite has the largest control on the slope of the isochron. Jenkins and co-workers (Jenkin et al., 2001; Jenkin et al., 1995) reevaluate the Rb-Sr closure temperature for mineral isochrons from a plagioclase-biotite schist. Where biotite is present in minor amounts, their work suggests a closure temperature of 350 +/- 50 ºC. We have chosen to use the Bondarenko et al. (1993) mineral isochron data (Fig. 8) to construct of the time-temperature history presented here. We have omitted Vinogradov and Grigor'ev's (1996) biotite-only age because of excessive scatter and have chosen not to use the biotite-whole rock pairs because insufficient data are available to statistically support the calculated slope of these isochrons.

Apatite and Zircon Fission Track Data

Fission track dating is based on the decay of trace ^{238}U in zircon and apatite by spontaneous nuclear fission resulting crystal lattice damage trails or fission tracks. Above a compositionally- and cooling rate- dependant effective closure temperature the damage



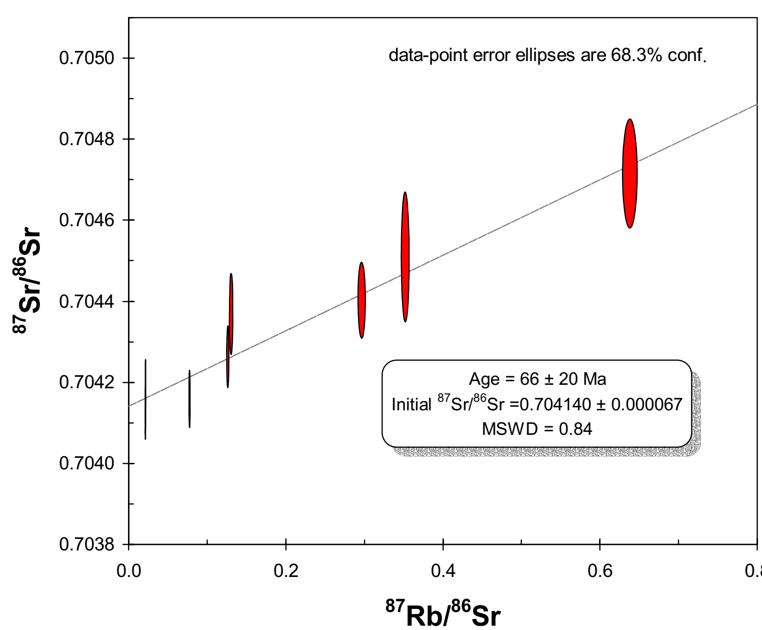


Figure 8. Re-calculated Rb-Sr mineral isochron from a garnet plagiogranite dike which cross cuts high grade rocks of the Sredinniy Range (Bondarenko et al., 1993). These data yield a mineral isochron age of 48.1 ± 2.8 Ma. Biotite exerts the greatest control on the slope of the isochron. A samples excluding biotite yield good linear array yet the clustering of $^{87}Rb/^{86}Sr$ values produces large errors in apparent age (66 ± 20 Ma). Isochrons are calculated using Ludwig's IsoplotEX (http://www.bgc.org/kl.html).

trials are completely annealed. Below the effective closure temperature the number of fission tracks is a function of uranium concentration and elapsed time. By counting the number of fission spontaneous tracks for a known uranium concentration, it is possible to date the timing of a cooling below the effective closure temperature. Zircons and apatites were analyzed using the external detector method described by Garver et al. (2000c).

Our Kamchatka gneiss samples gives zircon and apatite fission track ages of 19 and 15 Ma, respectively. Apatite and Zircons from a zoned mafic-ultramafic intrusion (Left-Andrianovka massif) which have debated contact relationships with the Kamchatka gneiss give ~ 25 Ma ZFT ages and ~18 Ma AFT ages. Assuming ~10 °C/m.y. cooling rate and annealing and diffusion properties we estimate an effective fission track closure temperatures between 225 to 240 °C for zircon (Brandon and Vance, 1992) and 105 to 117 °C (Laslett et al., 1987).

(U-Th)/He Methodology

(U-Th)/ He dating is based on the α-decay of ^{235}U, ^{238}U and ^{232}Th nuclides. Like the FT system above a compositionally and cooling rate dependant closure temperature daughter He atoms are completely expelled from the crystal lattice. He was extracted by CO_2 laser heating of optically-pure single and multiple crystal aliquots in ~1mm Pt foil "micro-ovens" at ~1000 °C (House et al., 2000). Degassesd helium was measured by ^3He isotope dilution with a Balzers quadropole mass spectrometer following cryogenic purification and concentration. Foil packets containing the apatite crystals were then dissolved in ^{229}Th- and ^{233}U-spiked HCl in Teflon bombs. U and Th concentration contents were then measured by isotope dilution on a Finnegan Element 2 high-resolution ICP-MS (analytical uncertainties of 1-2% for U-Th content) Grain size measurements were used to correct for α ejection following (Farley et al., 1996), similar to Farley et al. (1996). Apatites of Left-Andrianovka intrusion yield (U-Th)/He ages of 8

Ma. Assuming cooling rates of ~10C/m.y. we estimate an apatite (U-Th)/He closure temperature of 60 to 70 °C (Farley, 2000).

DISCUSSION

The data described above are used to construct a time-temperature path for the Kamchatka gneisses on the east flank of the Sredinniy Range (Fig. 9). Metamorphism must be younger than 55 ± 2 Ma, which is the age of the youngest U/Pb grain ages in the Kamchatka gneiss. The biotite Rb-Sr age of 48 ± 2 Ma indicates cooling from peak metamorphic conditions through 350°C. Together these data imply a ~ 10 m.y period during which the Kamchatka complex was deposited, underwent peak metamorphism at 600 °C and 5 kb (Savostin et al., 1994) and cooled to below ~350 °C. The short duration of this metamorphic event indicate that heating and cooling were both rapid, with average rates of about 90°C/m.y. Subsequent cooling occurred at a much slower rate of about 7°C/m.y. There is some evidence for slightly faster cooling rates between 25 and 15 Ma, but we are reluctant at this time to attach much significance to this feature of the cooling path.

Our preferred interpretation is that metamorphism occurred when the Olyutorsky arc overrode the Asian margin. The Sredinniy Range data clearly show not only rapid structural burial, but also fast exhumation following peak metamorphism. At present there is no clear evidence to determine how the Sredinniy metamorphic rocks were exhumed, whether by tectonic thinning or by erosion. Numerous workers in this area have commented the Sredinniy metamorphic culmination appears to grade outward without any noticeable structural break (Lebedev, 1967; Rikhtyer, 1995). Our reconnaissance in the area leads us to agree with this conclusion, although more detailed work is needed to resolve the contribution of normal faulting to exhumation of the Sredinniy metamorphic rocks. One prediction is that if erosion were dominant, there should be a significant quantity of sediment shed on flanking basins to the east in the Sea of Okhotsk.

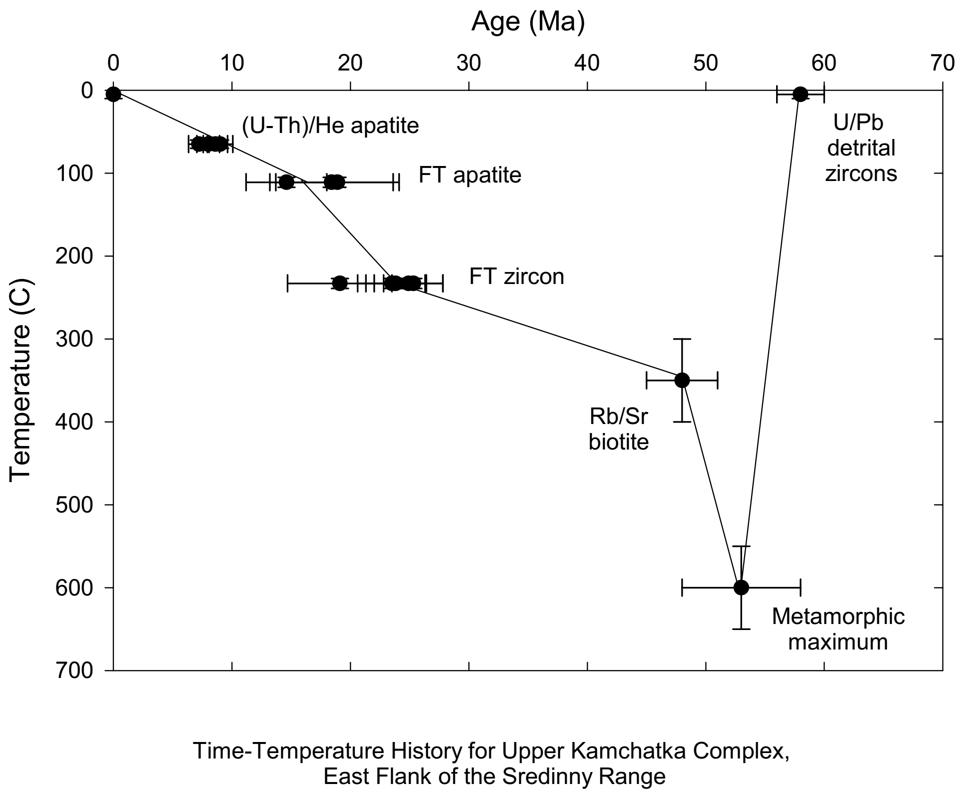


Figure 9. Time-temperature history for Kamchatka complex. Table I describes the data and sources used for construction of this plot.

System	Age	Temperature
Apatite (U-Th)/He (Peter Reiners, this study)	**~ 8 Ma***	**65 ± °5 C** (Farley, 2000)
Apatite Fission Track (This study)	**~ 15 Ma** **~ 18 Ma***	**111 ± 6 °C** (Laslett et al., 1987)
Zircon Fission Track (This Study)	**~ 19 Ma** **~ 25 Ma***	**233 ± 6 °C** (Brandon and Vance, 1992)
Rb/Sr Biotite (Bondarenko et al., 1992)	**48 ± 3 Ma**	**350 ± 50 °C** (Jenkins et al., 1995; 2001)
Metamorphic Maximum (Savostin et al., 1992)	**56 - 48 Ma**	**600 °C**
Protolith Straitgraphic Age (This study)	**< 56 ± 3 Ma**	**0 °C**

Table 1: Cooling ages from the eastern flank of the Sredinniy Range including age data effective closure temperature sources. Sample localities are shown on figure 2.

Our preliminary conclusion is that exhumation occurred mainly by erosion of orogenic topography formed during the Olyutorsky collision. What is interesting is that metamorphic rocks are only locally exposed along the Olyutorsky collision zone. We have focused here on the Sredinniy Range, but results from other metamorphic culminations in Kamchatka are instructive. Ar-Ar ages for hornblende indicate cooling of the Ganal metamorphic culmination between 51 and 47 Ma, and the Khavyven metamorphic culmination at 55 Ma (Zinkevich et al., 1993). Other areas show little to no evidence of deep exhumation. In fact, apatite FT ages from the northern part of the Olyutorsky collision zone in the southern Koryak Mountains indicate less than 5 km of exhumation following the collision (Garver et al., 1998)

Thus, we are left to consider for why some areas along the collisional suture were deeply exhumed and others were not. A recent passive seismic experiment has provided a refined view of crustal thickness beneath the peninsula (Levin et al., 2001) (Fig. 10). The thickest crust beneath Kamchatka lies beneath the Sredinniy Range, which exposes the most deeply exhumed rocks in Kamchatka, the Sredinniy metamorphic terrane. The data presented here indicates that these high-grade rocks were metamorphosed during the Eocene at depths as great as 30 km. This observation suggests that the crust attained maximum thickness of ~68km during the collision event to account for the 30 km depth of metamorphism of rocks exposed at the surface and another ~38 km to the base of the present crust. Such thick crust would have been associated with relatively high topography, like that of the Andean Alti Plano. Conversely, the presence of extensive marine stratigraphy during the Eocene (Gladenkov et al., 1997) suggests that the topography of Kamchatka was probably fairly low at that time. We propose an alternative interpretation, that exhumation of the Sredinniy Range was driven by tectonic underplating during the Eocene collision of the Olyutorsky arc. By this process, crustal thickness would not have to exceed 30 km as long as underplating and exhumation occurred at approximately the same rate.

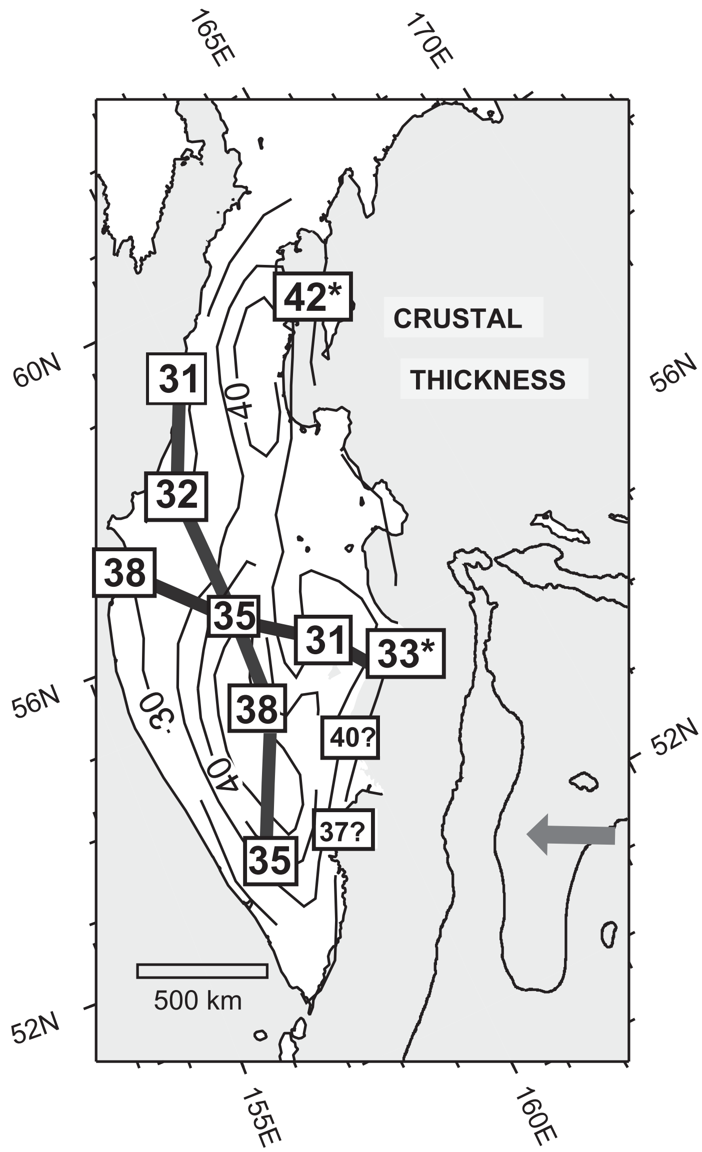


Figure 10. Crustal thickness map of Kamchatka generated by receiver function analysis of distant earthquakes (Levin et al., 2001). Individual thickness measurements are given in black boxes. Crustal thickness contours are from Bogdanov and Khain (2000). The deeply exhumed rocks of the Sredinniy Range occur in the region of the thickest crust of the Kamchatka Peninsula.

REFERENCES CITED

Bogdanov, N. A., and Dobretsov, N. L., 2001, Okhotsk Oceanic Volcanic Plateau, *in* 7th Zonenshain International Conference on Plate Tectonics, Moscow, p. 498.

Bogdanov, N. A., and Khain, V. E., 2000, Explanatory Notes: Tectonic Map of the Sea of Okhotsk Region: Moscow, Institue of the Lithosphere of Marginal Seas, RAS, 171 p.

Bondarenko, G. Y., 1992, The Jurassic-Valangin Stage of the Evolution of Kamchatka [Ph. D. thesis]: Moscow State University and Geological Instiute, Moscow.

-, 1997, Ul'traosnovnyye i osnovnyye metavulkanity sredinnogo khrebta kamchatki; polozheniye v razreze i obstanovka formirovaniya. Ultramafic and mafic metavolcanic rocks of Sredinny Ridge, Kamchatka; sequential development and formation conditions: Byulleten' Moskovskogo Obshchestva Ispytateley Prirody, Otdel Geologicheskiy, v. 72, no. 3, p. 32-40.

Bondarenko, G. Y., Kuznetsov, N. B., Savostin, L. A., Smolyar, M. I., and Sokolov, S. Y., 1993, Izontopnyy vozrast granatovykh plagiogranioidov sredinnogo khrebet, Kamchatki. Isotopic age of garnet plagiogranites in the Central Kamchatka Range: Doklady, RAN, v. 330, no. 2, p. 233-236.

Brandon, M. T., 1996, Probability density plots for fission-track grain-age samples: Radiation Measurements, v. 26, no. 5, p. 663-676.

Brandon, M. T., and Vance, J. A., 1992, Tectonic evolution of the Cenozoic Olympic subduction complex, Washington State, as deduced from fission track ages for detrital zircons: American Journal of Science, v. 292, no. 8, p. 565-636.

Burk, C. A., and Gnibidenko, H. S., 1977, The structure and age of acoustic basement in the Okhotsk Sea, *in* Talwani, M., and Pitman, W. C., III, eds., Island arcs, deep sea trenches and back-arc basins: Washington, American Geophysical Union, p. 451-461.

Cumming, G. L., and Richards, J. R., 1975, Ore lead isotope ratios in a continuously changing Earth: Earth and Planetary Science Letters, v. 28, no. 2, p. 155-171.

Dickin, A. P., 1997, Radiogenic Isotope Geology: Cambridge, UK, Cambridge University Press, 490 p.

Farley, K. A., 2000, Helium diffusion from apatite; general behavior as illustrated by Durango fluorapatite: Journal of Geophysical Research, B, Solid Earth and Planets, v. 105, no. 2, p. 2903-2914.

Farley, K. A., Wolf, R. A., and Silver, L. T., 1996, The effects of long alpha-stopping distances on (U-Th)/He ages: Geochimica et Cosmochimica Acta, v. 60, no. 21, p. 4223-4229.

Garver, J. I., Brandon, M. T., Bernet, M., Brewer, I., Soloviev, A. V., P.J.J., K., and Meyer, N., 2000a, Practical consideration for using detrital zircon fission track thermochronology for provenance, exhumation studies, and dating sediments, *in* The 9th International Conference of Fission-track dating and Thermochronology, Lorne, Australia, p. 109-111.

Garver, J. I., Brandon, M. T., and Soloviev, A. V., 2000b, Eocene Collision of the Olutorsky terrane, Kamchatka, Russia, *in* EOS-Transactions, p. F1243.

Garver, J. I., Bullen, M. E., Brandon, M. T., Soloviev, A. V., Ledneva, G. V., and Bogdanov, N. A., 1998, Age and thermal history of the Ukelayet flysch and its bearing on the timing of collision of the Olutorsky terrane, Northern Kamchatka, Russian Far East, *in* Seventh International Zoneshain Conference, Moscow, Russia, p. 173-174.

Garver, J. I., Soloviev, A. V., Bullen, M. E., and Brandon, M. T., 2000c, Towards a more complete record of magmatism and exhumation in continental arcs using detrital fission track thermochronometry: Physics and Chemistry of the Earth, Part A, v. 25, no. 6-7, p. 565-570.

Geist, E. L., Vallier, T. L., and Scholl, D. W., 1994, Origin, transport, and emplacement of an exotic island-arc terrane exposed in eastern Kamchatka, Russia: Geological Society of America Bulletin, v. 106, no. 9, p. 1182-1194.

German, L. L., 1978, Drevneyshiye kristallicheskiye kompleksy Kamchatki: Moscow, Izd. Nedra,, 124 p.

Gladenkov, Y. B., Shantser, A. Y., Chelebayeva, A. I., Sinel'nikova, V. N., Antipov, M. P., Ben'yamovskiy, V. N., Brattseva, G. M., Polyanskiy, B. V., Stupin, S. I., and Fedorov, P. I., 1997, Nizhniy paleogen Zapadnoy Kamchatki; stratigrafiya, paleogeografiya, geologicheskiye sobytiya. Lower Paleogene of western Kamchatka; stratigraphy, paleogeography, geological events: Trudy - Rossiyskaya Akademiya Nauk, Geologicheskiy Institut, v. 488, p. 367.

Gnibidenko, H. S., and Khvedchuk, I. I., 1982, The tectonics of the Okhotsk Sea: Marine Geology, v. 50, no. 3-4, p. 219-261.

Hanchar, J. M., Miller, C. F., Harrison, T. M., and Ryerson, F. J., 1992, Zircon zonation patterns as revealed by cathodoluminescence and backscattered electron images; implications for interpretation of complex crustal histories, *in* Third V. M. Goldschmidt conference, Reston, VA, p. 1-13.

Hanchar, J. M., Rudnick, R. L., and Hensen, B. J., 1993, Revealing hidden structures; the application of cathodoluminescence and back-scattered electron imaging to dating zircons from lower crustal xenoliths, *in* International workshop ; The xenolith window to the lower crust, Sydney, Australia, p. 289-303.

House, M. A., Farley, K. A., and Stockli, D., 2000, Helium chronometry of apatite and titanite using Nd-YAG laser heating: Earth and Planetary Science Letters, v. 183, no. 3-4, p. 365-368.

Ireland, T. R., and Gibson, G. M., 1998, SHRIMP monazite and zircon geochronology of high-grade metamorphism in New Zealand: Journal of Metamorphic Geology, v. 16, no. 2, p. 149-167.

Jenkin, G. R. T., Ellam, R. M., Rogers, G., and Stuart, F. M., 2001, An investigation of closure temperature of the biotite Rb-Sr system; the importance of cation exchange: Geochimica et Cosmochimica Acta, v. 65, no. 7, p. 1141-1160.

Jenkin, G. R. T., Rogers, G., Fallick, A. E., and Farrow, C. M., 1995, Rb-Sr closure temperatures in bi-mineralic rocks; a mode effect and test for different diffusion models: Chemical Geology, v. 122, no. 1-4, p. 227-240.

Jolivet, L., Cadet, J. P., and Lalevee, F., 1988, Mesozoic evolution of Northeast Asia and the collision of the Okhotsk microcontinent: Tectonophysics, v. 149, no. 1-2, p. 89-109.

Khanchuk, A. I., 1985, Evolutsiya Drevney Sialicheskoy Kory v Octrovoduzhnoy Sisteme Vostochnoy Asii: Vladivostok, Nauka, 135 p.

Kolodyazhnyy, S. Y., Zinkevich, V. P., Luchitskaya, M. V., and Bondarenko, G. Y., 1996, Priznaki vyazko-plasticheskogo techeniya v mezozoyskikh barabskikh konglomeratakh Sredinno-Kamchatskogo massiva. Indicators of visco-plastic flow in the Mesozoic Baraba conglomerates, Central Kamchatka Massif: Byulleten' Moskovskogo Obshchestva Ispytateley Prirody, Otdel Geologicheskiy, v. 71, no. 6, p. 15-30.

Kuzmin, M. I., and Chukhonin, A. P., 1980, Precambrian age of gneisses of the Kamchatka Pluton: Doklady, Earth Science sections AN USSR, v. 251, p. 61-63.

Laslett, G. M., Green, P. F., Duddy, I. R., and Gleadow, A. J. W., 1987, Thermal annealing of fission tracks in apatite: Chemical Geology; Isotope Geoscience Section, v. 65, no. 1, p. 1-13.

Lebedev, M. M., 1967, Verkhnemelovyye kristallicheskiye slantsy Kamchatki. The upper Cretaceous schists of Kamchatka: Sovetskaya Geologiya, v. 4, p. 57-69.

L'vov, A. B., Neelov, A. N., Bogomolov, E. S., and Mikhailova, N. S., 1985, Age of metamorphic rocks of Ganal Range of Kamchatka: Soviet Geology and Geophysics, v. 26, no. 7, p. 42-49.

Marchenko, A. F., 1967, Geologic Map of the USSR, Sheet N-57-XIV: VSEGEI, scale 1:200,000.

-, 1975, O tektonicheskoi prirode, vozraste i strukturnom polozhenie metamorficheskikh kompleksov Kamchatki, On the tectonic nature, age and structural position of metamorphic complexes of Kamchatka, Voprosi magmatizma i tektoniki Dal'nevo Vostoka, Questions of Magmatism and Tectonics of the Far East: Vladivostok, Nauka, p. 234-246.

Muir, R. J., Ireland, T. R., Weaver, S. D., and Bradshaw, J. D., 1996, Ion microprobe dating of Paleozoic granitoids; Devonian magmatism in New Zealand and correlations with Australia and Antarctica: Chemical Geology, v. 127, no. 1-3, p. 191-210.

Parfenov, L. M., 1984, Kontinental'niye okraini i ostrovniye dugi mezozoid severo-vostoka azii, Continental Margins and Island Arcs of the Mesozoid of North-East Asia: Novosibirsk, Nauka, 183 p.

Parfenov, L. M., and Natal'in, B. A., 1977, Mesozoic-Cenozoic tectonic evolution of northeastern Asia: Transactions (Doklady) of the U.S.S.R. Academy of Sciences: Earth Science Sections, v. 235, no. 1-6, p. 89-91.

Parfenov, L. M., Natal'in, B. A., Voynova, I. P., and Popeko, L. I., 1981, Tectonic evolution of active continental margins along the northwestern margin of the Pacific Ocean: Geotectonics, v. 15, no. 1, p. 54-67.

Predovskiy, A. A., 1970, Geochemical Reconstruction of the Original Composition of the Metamorphic Volcanogenic-Sedimentary Rocks of the Pre-Cambrian: Apatites, Trudy, Geological Institute, Academy of Sciences, USSR: Moscow, Nauka, 116 p.

Rikhtyer, A. V., 1995, Structure of the metamorphic complex of the central Kamchatka Massif: Geotectonics, v. 29, no. 1, p. 65-72.

Roddick, J. C., and Compston, W., 1977, Strontium isotopic equilibration; a solution to a paradox: Earth and Planetary Science Letters, v. 34, no. 2, p. 238-246.

Savostin, L. A., Kuznetsov, N. B., Bondarenko, G. Y., Perchuk, A. L., and Gerya, T. V., 1994, New data on the relations between the Kamchatka and Andrianov complexes, central Kamchatka: Transactions (Doklady) of the U.S.S.R. Academy of Sciences: Earth Science Sections, v. 327A, p. 53-58.

Sengor, A. M. C., and Natalin, B. A., 1996, Paleotectonics of Asia: fragements of a synthesis, *in* Yin, A., and Harrison, M., eds., The Tectonic Evolution of Asia: London, Cambridge University Press, p. 486-641.

Shantser, A. Y., Shapiro, M. N., Koloskov, A. V., Chelebayeva, A. I., and Sinel'nikova, V. N., 1985, Evolyutsiya struktury Lesnovskogo podnyatiya i yego obramleniya v kaynozoye (Severnaya Kamchatka). Evolution of Lesnovsk Rise structure and its frame in the Cenozoic, northern Kamchatka: Tikhookeanskaya Geologiya = Pacific Geology, v. 1985, no. 4, p. 66-74.

Shapiro, M. N., 1995, The Upper Cretaceous Achaivayamian-Valginian volcanic arc and kinematics of the North Pacifc plates: Geotectonics, v. 29, no. 1, p. 52-64.

Shapiro, M. N., Raznitsyn, Y. N., Shanster, A. E., and Lander, A. V., 1986, Struktura severo-vostochnogo obramleniya massiva metamorficheskikh porod sredinnigo khrebta Kamchatki (Structure of the northeastern framing of the Kamchatka's Sredinniy Ridge metamorphic massif), Ocherki po Geologii Vostoka SSSR (Articles on the Geology of Eastern USSR): Moscow, Nauka, p. 5-21.

Sivertseva, I. A., and Smirnova, A. N., 1974, O nakhodke paleozoyskikh spor v metamorfizovannykh otlozheniyakh Kamchatki. Paleozoic spore finds recovered from the metamorphic rocks of Kamchatka: Geologiya i Geofizika, v. 1974, no. 6, p. 126-128.

Solov'ev, A. V., Garver, J. I., and Shapiro, M. N., 2001, Fission-Track Dating of Detrital Zircons from Sandstone of the Lesnaya Group, Northern Kamchatka: Stratigraphy and Geological Correlations, v. 9, no. 3, p. 293-303.

Soloviev, A. V., Shapiro, M. N., Garver, J. I., Shcherbinina, E. A., and I.R., K.-B., 2002 (In press), New age data from the Lesnaya Group: a key to understanding the timing of arc-continent collision: The Island Arc, v. 11, no. 1.

Vinogradov, V. I., and Grigor'yev, V. S., 1996, Rb-Sr ages of rocks in the Median Ridge of Kamchatka: Transactions (Doklady) of the Russian Academy of Sciences, Earth Science Section, v. 343A, p. 80-86.

Vinogradov, V. I., Grigor'yev, V. S., and Kastrykina, V. M., 1991, Vosrast metamorficheskikh porod fundamenta Kamchatki: Sovetskaya Geologiya, v. 1991, no. 7, p. 58-65.

Vinogradov, V. I., Grigor'yev, V. S., and Leytes, A. M., 1988, Vozrast metamorfizma porod Sredinnogo khrebta Kamchatki: Izvestiya Akademii Nauk SSSR. Seriya Geologicheskaya, v. 1988, no. 9, p. 30-38.

Watson, B. F., and Fujita, K., 1985, Tectonic evolution of Kamchatka and the Sea of Okhotsk implications for the Pacific Basin, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the Circum-Pacific region: Houtson, TX, Circum-Pacific Council for Energy and Mineral Resources, p. 333-348.

Worrall, D. M., Kruglyak, V., Kunst, F., and Kuznetsov, V., 1996, Tertiary tectonics of the Sea of Okhotsk, Russia: Far-field effects of the India-Eurasia collision: Tectonics, v. 15, no. 4, p. 813-826.

Zhegalova, G. V., 1981, Melange in the massifs of the gabbro-norite-cortlandite complex of the Sredinnyy [Middle] Range of central Kamchatka: Geotectonics, v. 15, no. 3, p. 273-278.

Zinkevich, V. P., Rikhter, A. V., and Fugzan, M. M., 1993, 40Ar/ 39Ar dating of East Kamchatka metamorphic rocks: Transactions, v. 335, no. 2, p. 78-82.

Zinkevich, V. P., Rikhter, A. V., and Tsukanov, N. V., 1998, Accretion tectonics and geodynamics of Kamchatka-Sakhalin region: Virtual Geology, no. 04 March 1998, p. http://geo.tv-sign.ru/virtugeo/articles/tsukanov/articl.htm.

Zonenshain, L. P., Kuzmin, M. I., Natapov, L. M., and Page, B. M., 1990, Geology of the USSR; a plate-tectonic synthesis, Geodynamics Series Vol. 21: Washington, DC, American Geophysical Union,, 242 p.