



AGE AND COMPOSITION OF EOCENE SANDSTONES IN WESTERN KAMCHATKA: APPLICATION TO THE STUDY OF PROVENANCE FOR PETROLEUM RESERVOIRS OF THE SEA OF OKHOTSK

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ABSTRACT. The lithology, composition, U-Pb LA-ICP-MS ages of detrital zircons from sediments of the Western Kamchatka Basin (Russian Far East) provide important insight into paleogeography and tectonic setting of the Sea of Okhotsk in the Eocene. Our study is based on mapping, structural observations, descriptions of the sections and lithology, composition of the sandstones, and U-Pb LA-ICP-MS dating and morphology analysis of detrital zircons from the Eocene sandstones of the Western Kamchatka Basin. The provenance for the sandstones is mainly associated with orogen recycling in magmatic arcs. The analysis of heavy minerals indicates mafic to sialic sources. The mafic terranes of the Asian margin on the west or/and Olyutorka-Kamchatka ensimatic island arc affected the mechanism transferring the basic material to the Western Kamchatka Basin in the Eocene. The sialic clasts originated from continental blocks of the Asian margin and the Okhotsk-Chukotka volcanic belt.

New data allow us to prove that the erosion of the Okhotsk-Chukotka belt had a significant influence on the sedimentation system in the north of the Sea of Okhotsk in the Eocene. We can assume that the Paleo-Penzhina River system already existed in the Eocene. The existence of the sialic sources in Eocene allows us to assume the possibility of finding the good quality collectors in the Eocene deposits of the Western Kamchatka Basin and the north of the Sea of Okhotsk.

KEYWORDS: detrital zircons; morphology; U-Pb LA-ICP-MS dating; provenance; Eocene; Western Kamchatka Basin; Sea of Okhotsk

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ВОЗРАСТ И СОСТАВ ЭОЦЕНОВЫХ ПЕСЧАНИКОВ ЗАПАДНОЙ КАМЧАТКИ: РЕКОНСТРУКЦИЯ ИСТОЧНИКОВ СНОСА ДЛЯ НЕФТЕГАЗОНОСНЫХ КОЛЛЕКТОРОВ ОХОТСКОГО МОРЯ

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АННОТАЦИЯ. Литология, состав, U-Pb LA-ICP-MS возраст зерен обломочного циркона из осадочных пород Западно-Камчатского бассейна (Дальний Восток России) дают важную информацию о палеогеографии и тектонической обстановке в Охотском море в эоцене. Исследование основано на картировании, структурных наблюдениях, описании разрезов и литологии, составе песчаников, U-Pb LA-ICP-MS датировании и морфологическом анализе обломочного циркона из эоценовых песчаников Западно-Камчатского бассейна. Основным источником сноса песчаника был рециклированный ороген с влиянием магматической дуги. Анализ тяжелых минералов указывает на смесь материала из базитовых и сиалических источников. Террейны основного состава Азиатской окраины с запада и/или Олюторско-Камчатская энсиматическая островная дуга с востока поставляли основной материал в Западно-Камчатский бассейн в эоцене. Источниками сноса сиалических обломков были континентальные блоки на окраине Азии и Охотско-Чукотский вулканический пояс.

Новые данные доказывают, что эрозия Охотско-Чукотского пояса оказала существенное влияние на осадконакопление на севере Охотского моря в эоцене. Можно предположить, что речная система Палео-Пенжины уже существовала в эоцене. Наличие сиалических источников в эоцене позволяет предположить возможность обнаружения качественных коллекторов в эоценовых отложениях Западно-Камчатского бассейна и севера Охотского моря.

КЛЮЧЕВЫЕ СЛОВА: обломочный циркон; морфология; U-Pb LA-ICP-MS датирование; источники сноса; эоцен; Западно-Камчатский бассейн; Охотское море

ФИНАНСИРОВАНИЕ: Полевые работы финансировались компанией PetroKamchatka PLC. Исследования проведены при поддержке РФФИ (гранты № 13-05-00485_а, № 12-05-31299 мол_а) в рамках госзадания Геологического института РАН (проект № ФММГ-2023-0009). U-Pb датирование детритовых цирконов проводилось в Arizona LaserChron Center по гранту NSF-EAR 0732436.

1. INTRODUCTION

The Sea of Okhotsk is a frontier basin that has generated significant interest in the viability of petroleum systems originating and hosted within the Eocene strata [Gladenkov, 1980; Khvedchuk, 1993; Harbert et al., 2003]. Huge (14 billion barrels (1.9 billion tons) of oil and 96 trillion cubic feet (2.7 trillion cubic meters) of gas) petroleum resources in the northern Sakhalin Island have heightened interest in the petroleum potential of the Sea of Okhotsk as a whole [Kharakhinov, 2010; Khisamutdinova et al., 2018; Stoupakova et al., 2021; Kalinin et al., 2022]. In [Mel'nikov et al., 2022] the available geological and geophysical data served as a basis for making quantitative assessment of the total initial resources of the Kamchatka Krai as on 01.01.2022, which was 499.8 million tons of hydrocarbon equivalents (geological) (Fig. 1).

A critical piece of the puzzle is the quality of the sandstone reservoir that hosts matured petroleum reserves. For instance, high-quality arkose reservoir rocks of the Sakhalin system occur within long-lived perideltaic deposits of the

Amur River, which drains a vast area (~1.85M km²) of the Russian Far East comprising the evolved continental basement. The question is whether the Sakhalin Island is a unique reservoir structurally related to the Sakhalin-Hokkaido shear zone [Rozhdestvenskiy, 1982; Worrall et al., 1996] or there are other viable high-quality host-rock systems within the Okhotsk Basin. This paper interrogates sediment provenance and the paleogeography of sediment dispersal systems exposed in the Western Kamchatka as a predictive model for occurrence of reservoir quality rocks in the circum-Okhotsk region.

Northeast Asia includes the Paleozoic to Cenozoic oceanic and arc terranes that have been swept into the margin during the Late Jurassic to Tertiary (Fig. 2) [Nokleberg et al., 2001; Khanchuk, 2006]. A dominant geological feature along this margin is the Cretaceous Okhotsk-Chukotka volcanic belt (OCVB), which is a prominent subduction-related magmatic province formed as a part of this terrane collage. The OCVB represents a laterally extensive Andean-style arc that persisted along the southern margin of the

western and northern edge of what is now the modern boundary of the Sea of Okhotsk and Bering Shelf [Nokleberg et al., 2001]. The modern studies indicate that the Middle Albian to Early Campanian (106–77 Ma) magmatic activity in the OCVB was highly discontinuous [Akinin, Miller, 2011; Tikhomirov et al., 2012; Akinin et al., 2022]. The volcanism was terminated by the 76–78 Ma plateau basalts [Hourigan, Akinin, 2004], which mark a change in the geodynamic setting from frontal subduction to the regime of a transform margin with local extension [Akinin, Miller, 2011]. Since the Cretaceous, the OCVB has been a main mountain chain on the North-East Asian margin that shed clastic material off toward the marginal seas and the paleo-Pacific.

The Sea of Okhotsk region (Fig. 2) remains a geologic frontier. The Sea of Okhotsk is floored almost exclusively by a thin crust of debated affinity. The material dredged from bathymetric highs and the velocity structure form the basis for interpretation of basement geology of the Sea

of Okhotsk. Given the paucity of direct evidence, leading models reveal significant disparities in: 1) captured oceanic plateau [Watson, Fujita, 1985; Bogdanov, Dobretsov, 2002]; 2) accreted microcontinental block [Parfenov, Natal'in, 1977; Konstantinovskaia, 2001], or 3) extended continental framework of accreted terranes [Hourigan, 2003; Schellart et al., 2003; Verzhbitsky, Kononov, 2006].

Collided-block models hold that an allochthonous microcontinent or oceanic plateau collided with the margin of northeastern Asia in the Late Cretaceous, resulting in the cessation of magmatism in the Andean-style Okhotsk-Chukotka belt [Parfenov, Natal'in, 1977; Konstantinovskaia, 2001; Bogdanov, Dobretsov, 2002]. Both [Parfenov, Natal'in, 1977; Konstantinovskaia, 2001] argued that the microcontinental block extends on land on the Kamchatka Peninsula. However, these models are inconsistent with a more recent model demonstrating the Eocene high-grade metamorphism of northeast Russia sediments within the Sredinniy Range [Hourigan et al., 2009].

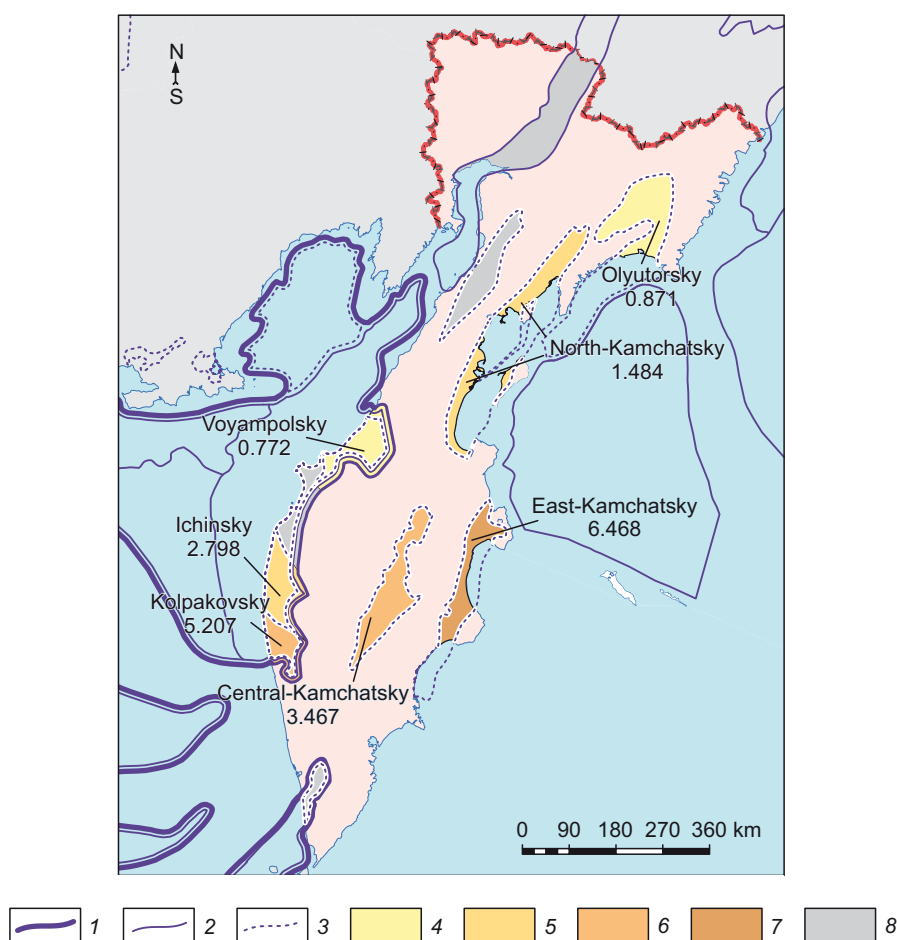


Fig. 1. Density map of the total initial HC resources of the Kamchatka Region as on January 1, 2022 after [Mel'nikov et al., 2022]. Borders of oil and gas geological zoning: 1 – provinces; 2 – regions; 3 – areas. Density of total initial recoverable resources, hydrocarbon equivalents thousand t/km²: 4 – up to 1; 5 – from 1 to 3; 6 – from 3 to 6; 7 – more than 6; 8 – uncertain prospects.

Рис. 1. Карта плотности начальных ресурсов углеводородного сырья Камчатского края на 01.01.2022 г. по данным [Mel'nikov et al., 2022].

Нефтегазogeологическое районирование: 1 – провинции; 2 – районы; 3 – области. Плотность начальных суммарных извлекаемых ресурсов, в углеводородном эквиваленте тыс. т/км²: 4 – до 1; 5 – от 1 до 3; 6 – от 3 до 6; 7 – более 6; 8 – неопределенные перспективы.

An alternative view is that the Omgon-Palana belt (north and west of the Sredinnyy Range) acts as a collision zone separating the Sea of Okhotsk plate from the West Kamchatka microplate. [Bogdanov, Chekhovich, 2002] argue that a fragment of an ancient oceanic plateau makes up the Sea of Okhotsk microplate, while the West Kamchatka plate is a quasi-continental crust [Bogdanov, Chekhovich, 2002].

Finally [Hourigan, 2003; Verzhbitsky, Kononov, 2006] propose a back-arc extensional model with basement geology made up of a variety of the Mesozoic terranes. [Schellart et al., 2003] assume the occurrence of slab rollback based on the east-southward-propagating extensional zone that has progressively extended since the Eocene [Hourigan, 2003].

In this context, the provenance composition of the Eocene sediments in the Western Kamchatka Basin (Fig. 3) should provide insight into the Early Paleogene paleogeography of the Sea of Okhotsk. Each model outlined above provides

a unique prediction for the composition, provenance and dispersal patterns within the Sea of Okhotsk. This study is the first to integrate mapping, structural observation, regional lithostratigraphy correlation and sandstone composition with U-Pb LA-ICP-MS provenance analysis of detrital zircons from the Eocene sandstones of the Western Kamchatka Basin.

2. TERRANES IN THE BASEMENT OF THE WESTERN KAMCHATKA BASIN

The basement of the Kamchatka can be subdivided into four terranes: Ukelayat-Omgon (UOM), Olyutorka-Kamchatka (OKA), Vetlovskiy (VT), and Kronotskiy (KRO) (see Fig. 2) [Nokleberg et al., 2001; Khanchuk, 2006]. The deposits of the Western Kamchatka Basin rest on Ukelayat-Omgon (UOM) and Olyutorka-Kamchatka (OKA) terranes [Shapiro, Soloviev, 2009]. The Ukelayat-Omgon terrane (UOM) consists of strongly deformed (tightly folded) Cretaceous – Middle

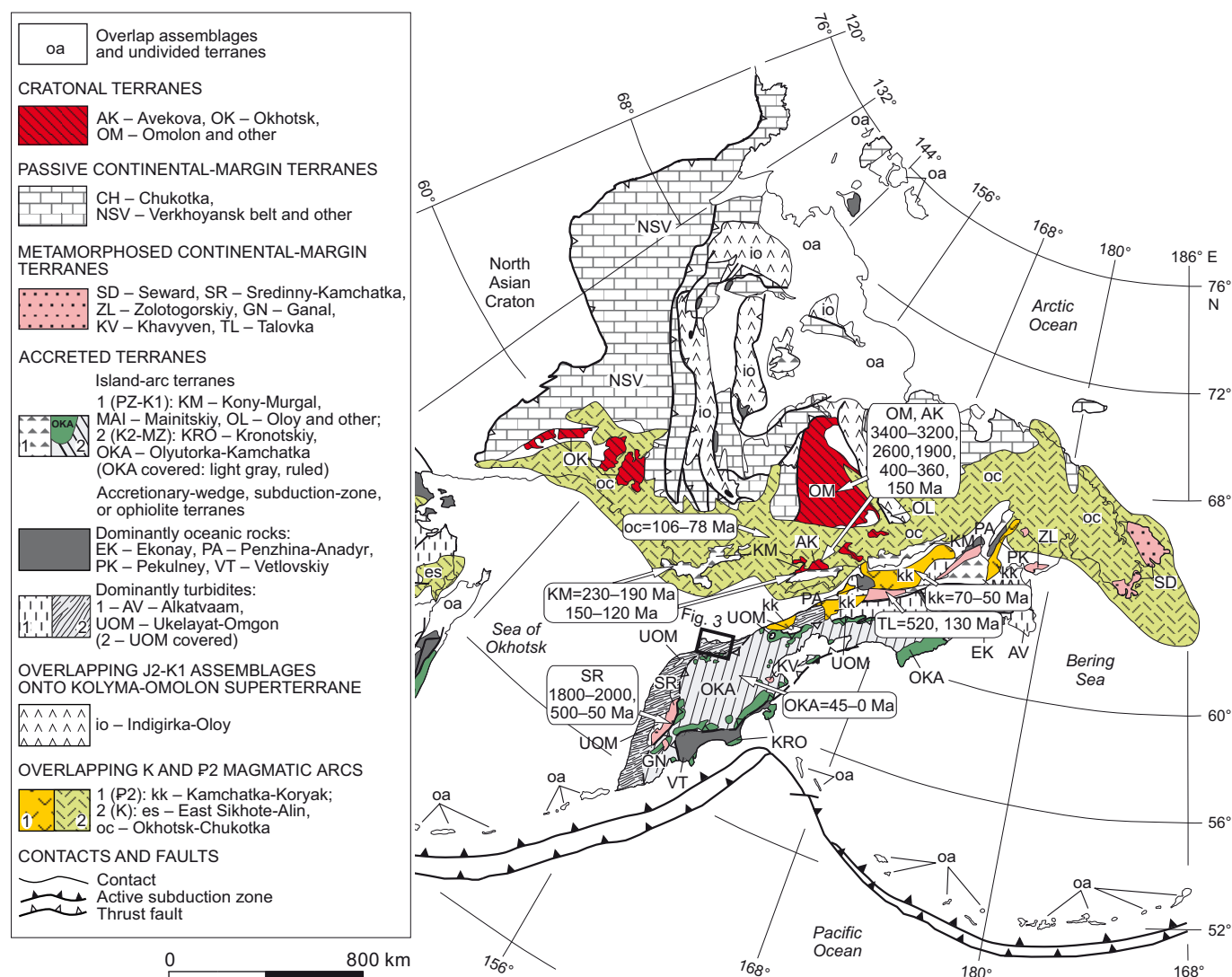


Fig. 2. The tectonostratigraphic terranes and overlap assemblages of the Russian Far East (modified after [Nokleberg et al., 2001; Hourigan et al., 2009]).

Рис. 2. Тектоностратиграфические террейны и перекрывающие их комплексы Дальнего Востока России (по [Nokleberg et al., 2001; Hourigan et al., 2009], с изменениями).

Eocene continent-derived flysch-like sediments [Garver et al., 2000]. The deposits of the Ukelayat-Omgon terrane were accumulated along the continental margin of the northeast Asia. The Omgon Range of Western Kamchatka contains the Middle to Upper Cretaceous sequence of flysch with tectonic inclusions of the Jurassic – Cretaceous oceanic rocks inferred to have been imbricated together in an accretionary prism [Soloviev et al., 2006]. The accretionary prism resulted from subduction of the Pacific paleo-oceanic plate (Izanagi) under the Eurasian continental margin and was attended by volcanism in the inboard Okhotsk-Chukotka

volcanic belt. Internal imbrication was completed by the Maastrichtian (~70 Ma) as indicated by apatite fission-track ages that record cooling and exhumation of this crustal block [Soloviev et al., 2006]. The Olyutorka-Kamchatka terrane (OKA), composed of the Late Cretaceous to Paleocene basalt, chert, intermediate volcanics and associated volcanogenic sediments, has been interpreted as an island arc. The allochthonous island arc units and continental margin strata are juxtaposed along a ~1500 km-long suture zone (see Fig. 2). The northeast, central and south-west segments of this fault are referred to as the Vatyina

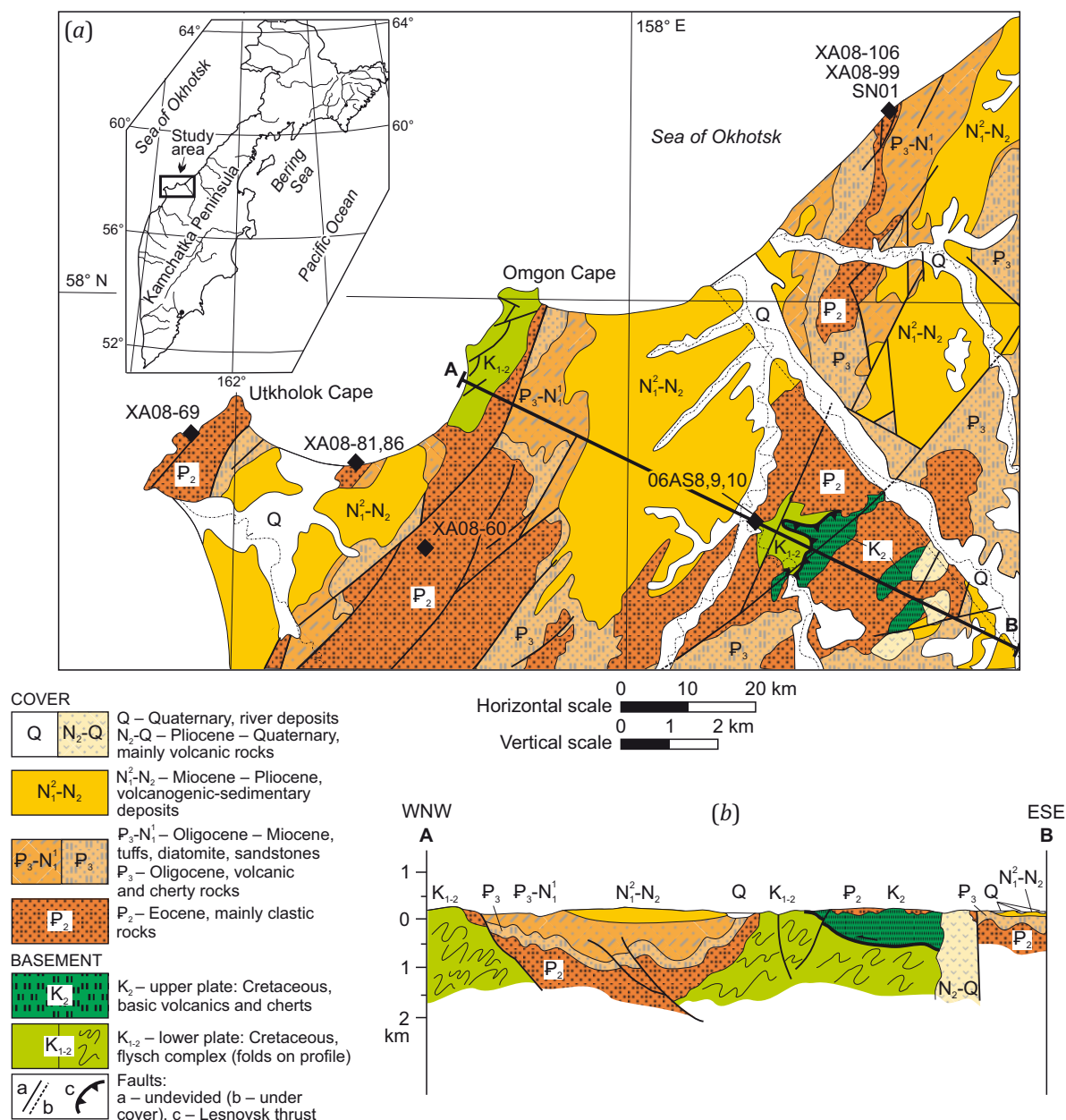


Fig. 3. The geological map (modified after [Litvinov et al., 1999]) (a) and cross section of the Western Kamchatka study area (b). The cross section has been drawn using the unpublished seismic data obtained by PetroKamchatka Ltd. The samples under study are shown by rhombuses.

Рис. 3. Геологическая карта (по [Litvinov et al., 1999], с изменениями) (a) и разрез исследуемой территории на Западной Камчатке (b). Разрез составлен с использованием неопубликованных сейсмических данных PetroKamchatka Ltd. Образцы для исследования показаны ромбами.

thrust (Koryak Highlands), the Lesnovsk thrust (Lesnovsk Highlands in the Kamchatka Isthmus), and the Andrianov thrust (Sredinnyi Range), respectively [Soloviev et al., 2001; Hourigan et al., 2009]. The forearc sediments of Ukelayat-Omgon terrane were deformed in the Eocene (52–46 Ma) because of collision between the Olyutorka-Kamchatka terrane and northeastern Asian margin [Soloviev et al., 2002, 2011].

3. GEOLOGY OF THE WESTERN KAMCHATKA BASIN

The Pre-Tertiary rocks in Western Kamchatka generally occur as isolated exposures (Fig. 3) [Litvinov et al., 1999]. The Lesnovsk thrust which separated the Ukelayat-Omgon and the Olyutorka-Kamchatka terranes from each other is observed in erosional windows (Fig. 3, 4). The eastern part of the Sea of Okhotsk and the western Kamchatka Peninsula are occupied by the Western Kamchatka Basin

filled with the Cenozoic sediments [Litvinov et al., 1999]. The Tertiary rocks in Western Kamchatka are poorly exposed, and the outcrops are difficult to access due to limited infrastructure. The best-described are those located along the coastal cliffs. These outcrops are most critical for understanding of the structure of the Tertiary complexes, which is, in turn, significant for interpretation of geodynamics of the Sea of Okhotsk and reliable assessment of its petroleum resource potential.

The previous geological mapping revealed that the Cenozoic sequences of the Western Kamchatka Basin are deformed into simple folds with the NNE-trending axes [Geological Map..., 1965]. According to [Litvinov et al., 1999] the Tertiary sediments fill grabens and rest upon the erosional surface of the highly deformed pre-Cenozoic basement. It has been recently shown that the Tertiary sediments of western Kamchatka experienced significant fold-thrust

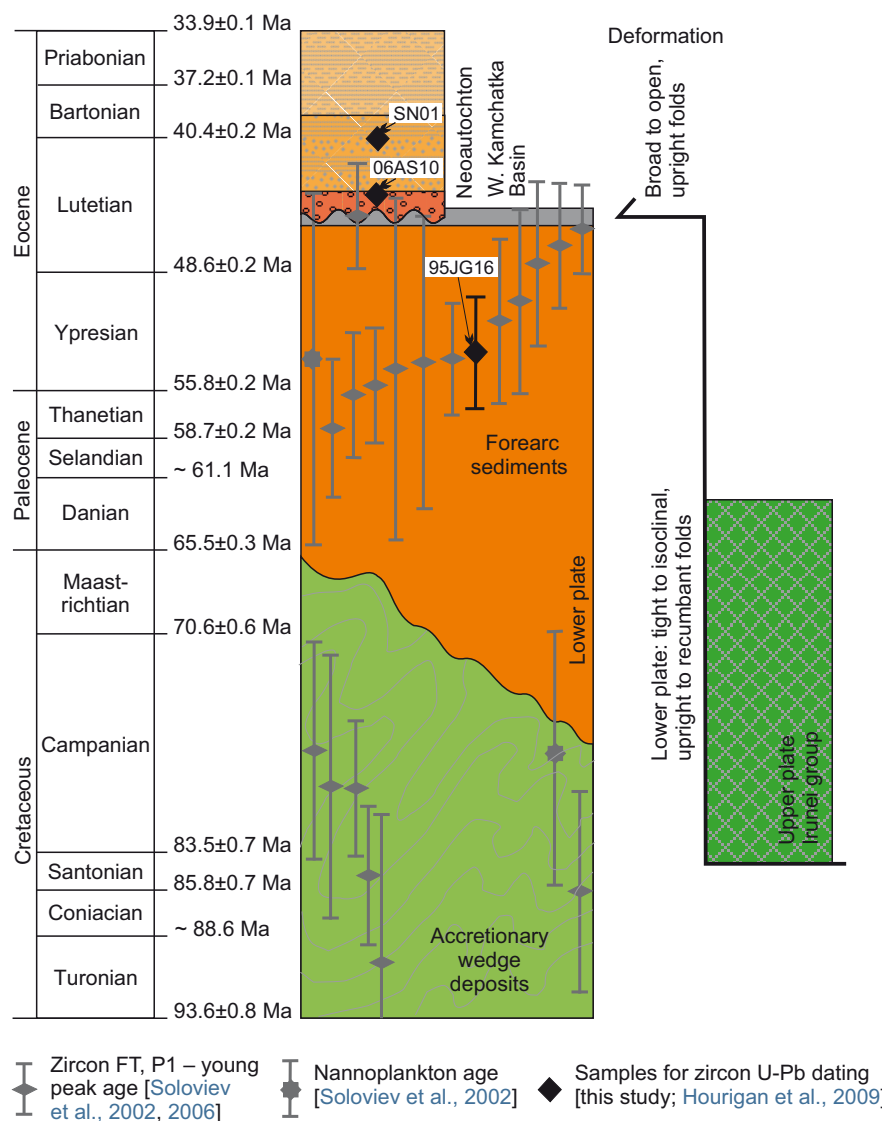


Fig. 4. The tectonostratigraphic column for the Western Kamchatka Basin: the relationship between lower plate, upper plate and cover. The stratigraphic chart is from [Ogg et al., 2008].

Рис. 4. Тектоностратиграфическая колонка Западно-Камчатского бассейна: соотношение автохтона, аллохтона и неоавтохтона. Стратиграфическая схема составлена по [Ogg et al., 2008].

deformations [Mazarovich et al., 2010]. The Oligocene – Lower Miocene sequences demonstrate isoclinal superposed folds, thrusts, and duplex structures characteristic of the compression regime (see Fig. 3). The last stage of strong deformations occurred in the mid-Miocene and may represent a response to termination of collision between the Eastern Peninsulas (Kronotskaya) island arc zone and the eastern Kamchatka Peninsula [Verzhbitsky, Soloviev, 2009].

[Gladenkov, 1980; Gladenkov et al., 1997] report a generalized stratigraphy of the West Kamchatka basin, marked by the Eocene – Pliocene strata overlying the Cretaceous strata, which consist mostly of deep marine turbidites and organic-rich mudstone. The Eocene part of the succession is largely nonmarine and consists of a 500 m thick fining-upward succession of predominantly coarse clastic material interbedded with coal and organic-rich shales. A 3000 m thick succession of the Upper Eocene-Oligocene sandstone, coal and shale beds in the Western Kamchatka Basin is capped by a thick, laterally widespread mudstone. The 4000–4500 m thick Miocene section with a sandstone-rich unit (>1000 m) at the base is thought to have been deposited in shallow marine shelf environments. It is overlain by an approximately 500 m thick interval of tuffaceous cherty rocks that underlie a 2000–2500 m thick sequence of interbedded sandstone, conglomerate and diatomite. The uppermost Miocene-Pliocene section consists of interbedded sandstone and coal. In the Western Kamchatka Basin, this succession consists of the Eocene – Lower Oligocene nonmarine-shallow marine sequence, overlain by the much thicker Oligocene-Upper Miocene upward-shoaling progradational slope to shelf sequence. [Oleinik, 2001] consider the Eocene-Miocene rocks as the major Miocene transgressive sequence ranging from tidal-to-shelf environments at the bottom of the section to slope facies.

Scout reports from the onshore gas-condensate fields of the Western Kamchatka Basin also place the interval

of interest in the Paleogene section, unconformably overlying the Upper Cretaceous strata [Belonin et al., 2003]. The sedimentary section in these onshore areas is subdivided into five lithostratigraphic sequences: (1) the alluvial Khulgun formation; (2) the alluvial-lagoonal Napana formation; (3) the nearshore shelf Snatol formation; (4) the coastal plain Kovachin formation; (5) the deep-water shelf Kuluven and Viventek formations. We collected ten (10) sandstone samples from the lower part of the Paleogene section (Khulgun, Napana and Snatol formations). The locations of the samples under analysis and discussion are shown in Fig. 3, 4 and their exact locations and ages are listed in Table 1.

4. SANDSTONE COMPOSITION

Poorly sorted and angular to slightly rounded grains, together with quartz, plagioclase and mica point to proximal orogenic sources that contained mostly volcanic rocks and some sedimentary rocks which are present as abundant lithic fragments therein (Fig. 5; App. 1, Table 1.1, 1.2). Volcanic lithic fragments are dominated by variable amounts of mafic to felsic volcanic rocks and devitrified glasses. Sedimentary and metasedimentary rocks also form an important component of the sandstones. These are mostly fragments of siltstone, fine-grained sandstones, cherts and metaquartzites (Fig. 5; App. 1, Table 1.1). The sandstones are quartz-feldspar graywackes [Pettijohn, 1975] or lithic arenites [Folk et al., 1970]. The sandstones were mainly derived from orogen recycling in magmatic arcs [Fig. 5] [Dickinson, 1985].

Heavy minerals include variable percentages of zircon, apatite, rutile, leucoxene, sulphides, ilmenite, garnet, black spinel (App. 1, Table 1.3). All samples can be divided by sulfide content into high-, medium- and low-sulphide groups. According to [Pettijohn, 1975], all diagnosed minerals were divided into three groups: indicator minerals for acid rocks – zircon, apatite, rutile, tourmaline; indicator

Table 1. Location and age of the Eocene sandstone samples (Western Kamchatka)

Таблица 1. Места отбора образцов и информация о возрасте палеогеновых песчаников (Западная Камчатка)

Field number	Latitude, N	Longitude, E	Map unit	Age
95JG16	61°41'57"	171°47'51"	Ukelayat group	Early Eocene
XA08-106	58°16'53"	158°42'30"	Snatol fm.	Middle Eocene
XA08-99	58°16'42"	158°42'16"	Snatol fm.	Middle Eocene
SN01	58°16'40"	158°42'07"	Snatol fm.	Middle Eocene
XA08-69	57°47'44"	156°51'57"	Cape Zubchaty fm.	Paleocene (?)
XA08-81	57°46'03"	157°19'20"	Khulgun fm.	Paleocene (?)
XA08-86	57°46'06"	157°19'51"	Snatol fm.	Middle Eocene
XA08-60	57°43'29"	157°40'22"	Snatol fm.	Middle Eocene
06AS10	57°41'27"	158°19'44"	Napana fm.	Middle Eocene
06AS09	57°41'26"	158°19'48"	Napana fm.	Middle Eocene
06AS08	57°41'25"	158°19'51"	Napana fm.	Middle Eocene

Note. The detrital zircons from samples highlighted bold were dated by U-Pb LA-ICP-MS method.

Примечание. Обломочные цирконы были датированы методом U-Pb LA-ICP-MS из образцов, выделенных жирным шрифтом.

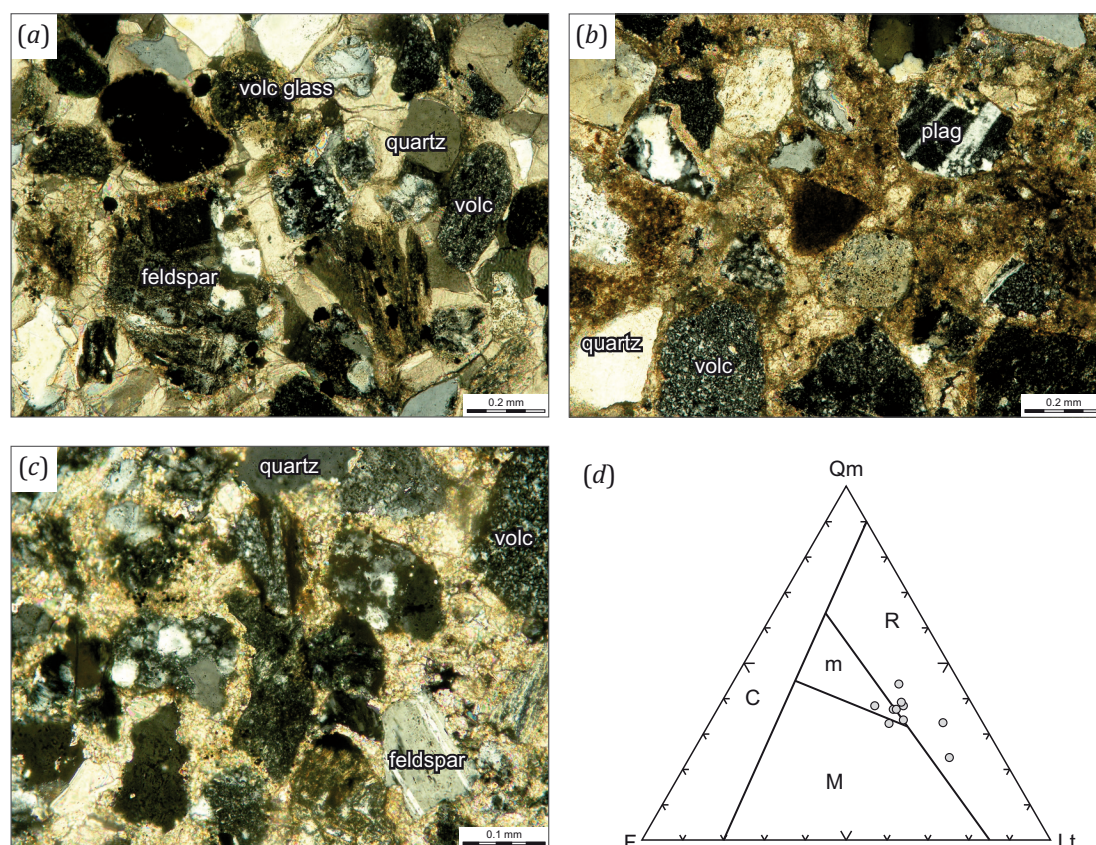


Fig. 5. Photomicrographs (a–c) and point-count data (d) for the Eocene sandstones from the Western Kamchatka Basin. (a) – sample XA08-81, x-polars; (b) – sample AS06-9, x-polars; (c) – sample XA08-106, x-polars; (d) – ternary diagram shows monocrystalline quartz (Qm), feldspar (F), total lithic (Lt) composition and provenance fields: C – continental block, R – recycled orogen, M – magmatic arc, m – mixed [Dickinson, 1985].

Рис. 5. Микрофотографии (a–c, скрещенные николи) и данные точечного подсчета (D) для эоценовых песчаников Западно-Камчатского бассейна.

(a) – образец XA08-81; (b) – образец AS06-9; (c) – образец XA08-106; (d) – треугольная диаграмма показывает состав монокристаллического кварца (Qm), полевого шпата (F), суммарного литического материала (Lt) и поля источников сноса: C – континентальный блок, R – рециклированный ороген, M – магматическая дуга, m – смешанный [Dickinson, 1985].

minerals for basic rocks – pyroxene, ilmenite (leucoxene), spinel; other minerals. It should be noted that pyrite dominates quantitatively in this group. An insignificant amount of garnet probably indicates the presence of high-aluminous granitoids or metamorphic rocks. It should be noted that minerals typical for metamorphic sources were not detected in samples.

Obviously, there are at least two sources of erosion within the study area: acid and basic igneous rocks. Zircon and apatite are most common in sialic rocks. Basic rocks are mostly characterized by anatase, pyroxene, ilmenite, along with leucoxene, chromite and rutile. Hence, the analysis of heavy minerals indicates a mixture of materials derived from mafic and sialic sources.

5. DETRITAL ZIRCON DATA

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a table, heavy liquids, and a magnetic separator. Samples were processed so that all zircons were retained in the final heavy mineral fraction. The separations

were made in the Laboratory of mineralogical and fission-track analysis (Geological Institute of Russian Academy of Sciences).

The analysis of detrital zircon morphology [Pupin, 1980; Belousova et al., 2006] indicates that subalkaline (calc-alkaline) granitoids played a key role in the formation of the Western Kamchatka Basin in the Eocene, with an insignificant participation of high-aluminous muscovite-bearing granites (App. 2, Table 2.1; Fig. 2.1, 2.2).

Detrital zircons from two sandstone samples were dated by the LA-ICP-MS method at the Arizona LaserChron Center (100 single grain ages per sample). Sample locations are listed in Table 1, description of analytical methods is given in App. 3, measured isotopic ratios and interpreted ages and Concordia diagrams are presented in Suppl. 1 (see article page online). The U-Pb ages from each sample are plotted on relative age probability distribution diagrams [Ludwig, 2008] in Fig. 6. The relative age probability distribution diagrams for detrital grains younger than 500 Ma provide a more detailed comparison of the younger populations of zircons in the samples (Fig. 6).

Grain U-Pb ages of detrital zircons are scarce for the Sea of Okhotsk region. A lone detrital zircon dataset is published for the Early Eocene sample (95JG16) from the Ukelayat Basin [Reiners et al., 2005; Hourigan et al., 2009]. Detrital zircon in modern sand (sample Amur) of the Amur River [Safonova et al., 2010] is used for comparison as "fingerprint" of the intracontinental zircon provenance in northeast Russia. Finally, a compilation of $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb SHRIMP ages for the Okhotsk-Chukotka volcanic belt

[Akinin, Miller, 2011; Akinin et al., 2020, 2022] is useful for characterization of the expected zircon age range for arc-derived detritus.

All of the samples from the Sea of Okhotsk region have a few Archean grains, but the age distributions have a significant percentage of 2.0–1.8 Ga zircons (14–24 % of the populations). The Amur sample alone has 8 % of 2.0–1.8 Ga zircons. The presence of the Early Proterozoic zircons indicates that the source region likely included the Siberian

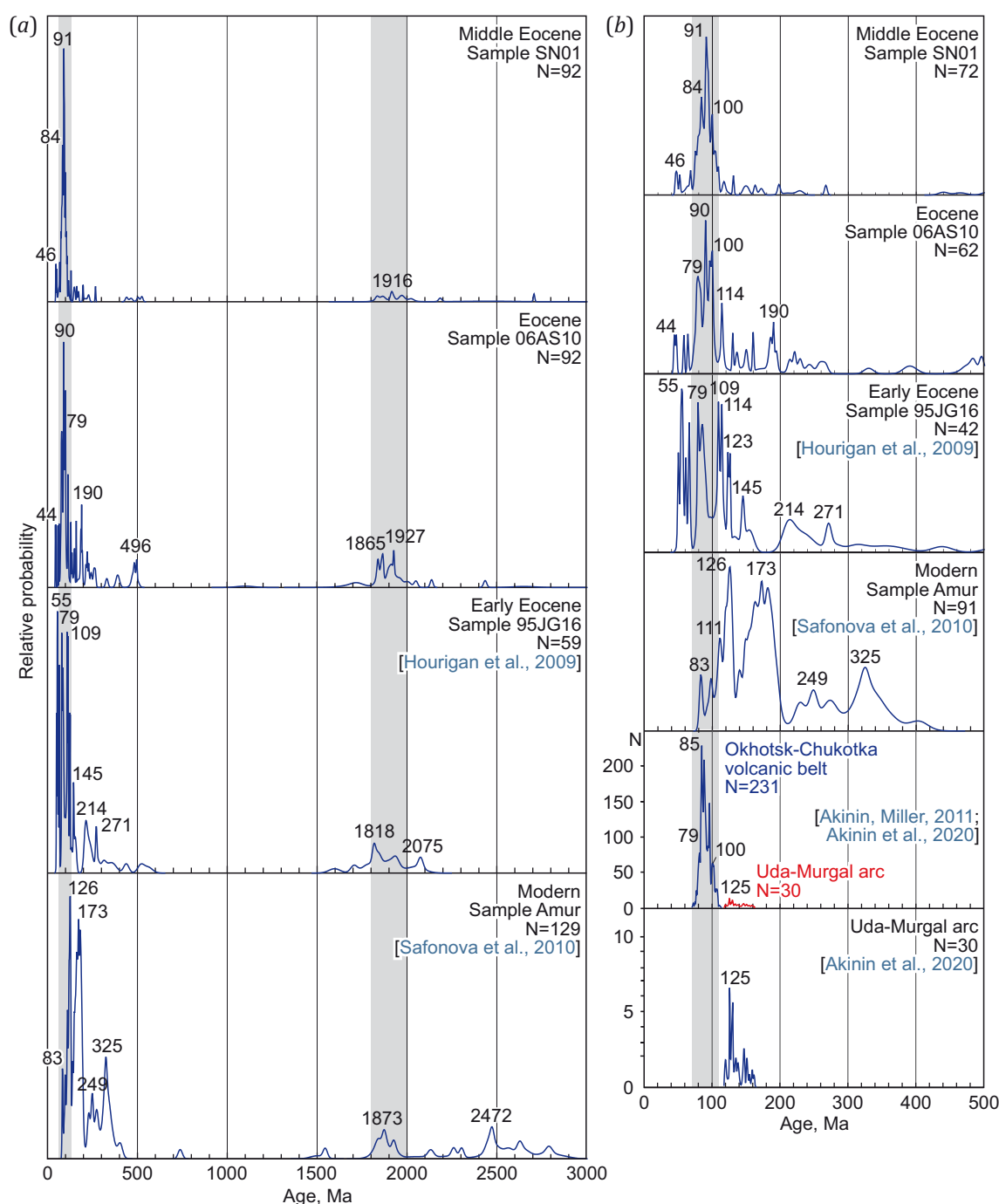


Fig. 6. Comparison of the ages of the detrital zircons from the Sea of Okhotsk region based on age probability plots: 0–3000 Ma (a), 0–500 (b). See text for details.

Рис. 6. Сравнение распределения значений возраста обломочного циркона по образцам из Охотоморского региона на основе графиков плотности вероятности: 0–3000 млн лет (a), 0–500 млн лет (b). Подробности см. в тексте.

Craton, which shows a peak in magmatic activity at 1900 Ma [Rosen, 2002]. In the Sea of Okhotsk region there are the Avekova, the Okhotsk and the Omolon cratonic terranes [Nokleberg et al., 2001]. The Okhotsk and the Omolon terranes are interpreted as those derived from the North Asian (Siberian) Craton [Nokleberg et al., 2001]. The 1.9–1.8 Ga old zircons occur in metamorphic and migmatitic rocks of the Okhotsk [Kuz'min et al., 2009], Omolon and Avekova [Khanchuk, 2006] terranes. The recent study confirms the global episode of crust formation at 2.0–1.8 Ga, which gave rise to the Columbia supercontinent [Safonova et al., 2010].

The Paleozoic zircons are not present in significant abundance in the studied deposits. The Middle Eocene sample (06AS10) exhibits a small peak (3 % of the population) at ~500 Ma. The Late Paleozoic – Early Mesozoic zircons (~400–215 Ma) in the modern Amur sand could be derived from the Mongol-Okhotsk orogen [Safonova et al., 2010].

A set of ages, spanning the Mesozoic and Cenozoic (~250–45 Ma), is the most abundant zircon age population (~52–74 %). The zircons older than 110 Ma are present in large percentages (~47 %) only in the Amur sample, but samples from the northern part of the Sea of Okhotsk region contain much less zircons (~10–25 %) of this age (~250–110 Ma). The northeast margin of Russia is characterized by the occurrence of long-term island arc and continental arc magmatism that can account for the observed Mesozoic zircon ages [Khanchuk, 2006; Miller et al., 2002; Khanchuk et al., 2025]. The peak (~110–77 Ma) is significant in all samples (~22–54 %) with exemption of the Amur sample (5 %) (Fig. 6). The Okhotsk-Chukotka Volcanic Belt (OCVB) was active from about 106 to 77 Ma

[Akinin, Miller, 2011; Tikhomirov et al., 2012]. In particular, the Cretaceous grain-ages can be related to the OCVB formation sources.

Both scattered volcanic rocks in the Koryak Highlands [Ledneva, Matukov, 2009] and volcanic belt in the Western Kamchatka (see Fig. 2, kk – overlapping magmatic arc) show the early Cenozoic activity. These sources may account for the zircons younger than 77 Ma. The Early Eocene zircons (~55 Ma) are typical for the sample (95JG16) from the Ukelayat Basin [Hourigan et al., 2009]. Four grains from the sandstones of the Western Kamchatka Basin date back to the Middle Eocene (~48–44 Ma). The Kinkil (Western Kamchatka) volcanic belt was active contemporaneously with deposition in Western Kamchatka Basin in the Middle Eocene.

6. INTERPRETATIONS

The study of the sandstones sampled near the base of the Western Kamchatka Basin suggests that the provenance for the sandstones is mainly associated with orogen recycling in magmatic arcs (see Fig. 5) [Dickinson, 1985]. The analysis of heavy minerals indicates a mixture of mafic and sialic materials. The only possible provenance for sialic material is the terranes of northeastern Asian margin and the Okhotsk-Chukotka volcanic belt built on these terranes (see Fig. 2). This conclusion is supported by the north-northeast paleocurrent directions [Khisamutdinova et al., 2016]. On the one hand, the mafic clastics from the east were probably derived from the Olyutorka-Kamchatka ensimatic island-arc collided with continental margin in the Eocene. On the other hand, the mafic terranes of Asian margin could shed off sediments towards the Western Kamchatka Basin from the west.

Table 2. K-S test results for samples from the Sea of Okhotsk region
Таблица 2. Результаты К-С теста для образцов из Охотоморского региона

K-S P-values using error in the CDF				
	SN01	06AS10	95JG16	Amur
SN01		0.001	0.004	0.000
06AS10	0.001		0.780	0.000
95JG16	0.004	0.780		0.001
Amur	0.000	0.000	0.001	

Note. The data are presented for sample 95JG16 [Reiners et al., 2005; Hourigan et al., 2009] and for sample Amur [Safonova et al., 2010]. The K-S test is a non-parametric method for comparing cumulative probability distributions. P(KS) gives the probability that random chance alone might produce the observed difference in two distributions derived from the same parent population. A low test probability, such as P(KS)<0.05, would indicate that the differences between the two distributions are significant and that the samples are not similar in terms of their age population. If P(KS)>>0.05, then the differences are just a factor of random chance. To apply the K-S test to the data, we used the algorithm from [Guynn, Gehrels, 2010]. Values that pass the K-S test at 95 % confidence level and not rejected are shown in yellow.

Примечание. Приведены данные для образцов 95JG16 [Reiners et al., 2005; Hourigan et al., 2009] и Амур [Safonova et al., 2010]. Тест Колмогорова–Смирнова представляет собой непараметрический тест, применяемый для сравнения кумулятивного распределения вероятностей. Значению P(KS) соответствует вероятность того, что уже сама случайность может быть причиной различия двух распределений, выведенных из одной и той же исходной совокупности. Низкая вероятность теста при P(KS)<0.05, будет означать, что разница двух распределений существенна, и что образцы не являются однородными с точки зрения возрастного состава популяции. Если же P(KS)>>0.05, то различие является просто фактором случайности. Для применения теста Колмогорова–Смирнова к данным мы использовали алгоритм, приведенный в работе [Guynn, Gehrels, 2010]. Значения, прошедшие тест Колмогорова – Смирнова при уровне доверительной вероятности 95 % и не попавшие в выбраковку, показаны желтым цветом.

The morphology of detrital zircons indicates that the dominant provenance of the Eocene subalkaline (calc-alkaline) granitoids was the Western Kamchatka Basin with a small amount of high-aluminous muscovite granites. We correlate the morphologies of detrital grains, observed in CL-images, with ages of zircons (Fig. 7). The crystals with morphologies L5 and S10 are typical for subalkaline (calc-alkaline) and alkaline granitoids and have ages similar to the OCVB age (Fig. 7, a, sample SN01). Some crystals exhibit elongation attributed to volcanic sources, for example, L5 – 84.1 ± 2.1 Ma, L5 – 81.1 ± 2.3 Ma (Fig. 7, a). Sample 06AS10

contains zircons with a larger age difference (Fig. 7, b). The crystal (Q1 – 44.0 ± 1.3) is definitely related to the Kinkil (Western Kamchatka) volcanic belt.

The Kolmogorov-Smirnov (KS) statistical test was used to further assess the similarity of distributions of the U/Pb LA-ICP-MS ages of single grains, with the results presented in Table 2 (Fig. 8). According the K-S test, the sample from the modern Amur sand is different from other samples. The distributions of the detrital zircon ages are similar in samples 95JG16 and 06AS10. It is an unusual and important observation because sample 95JG16 was collected from

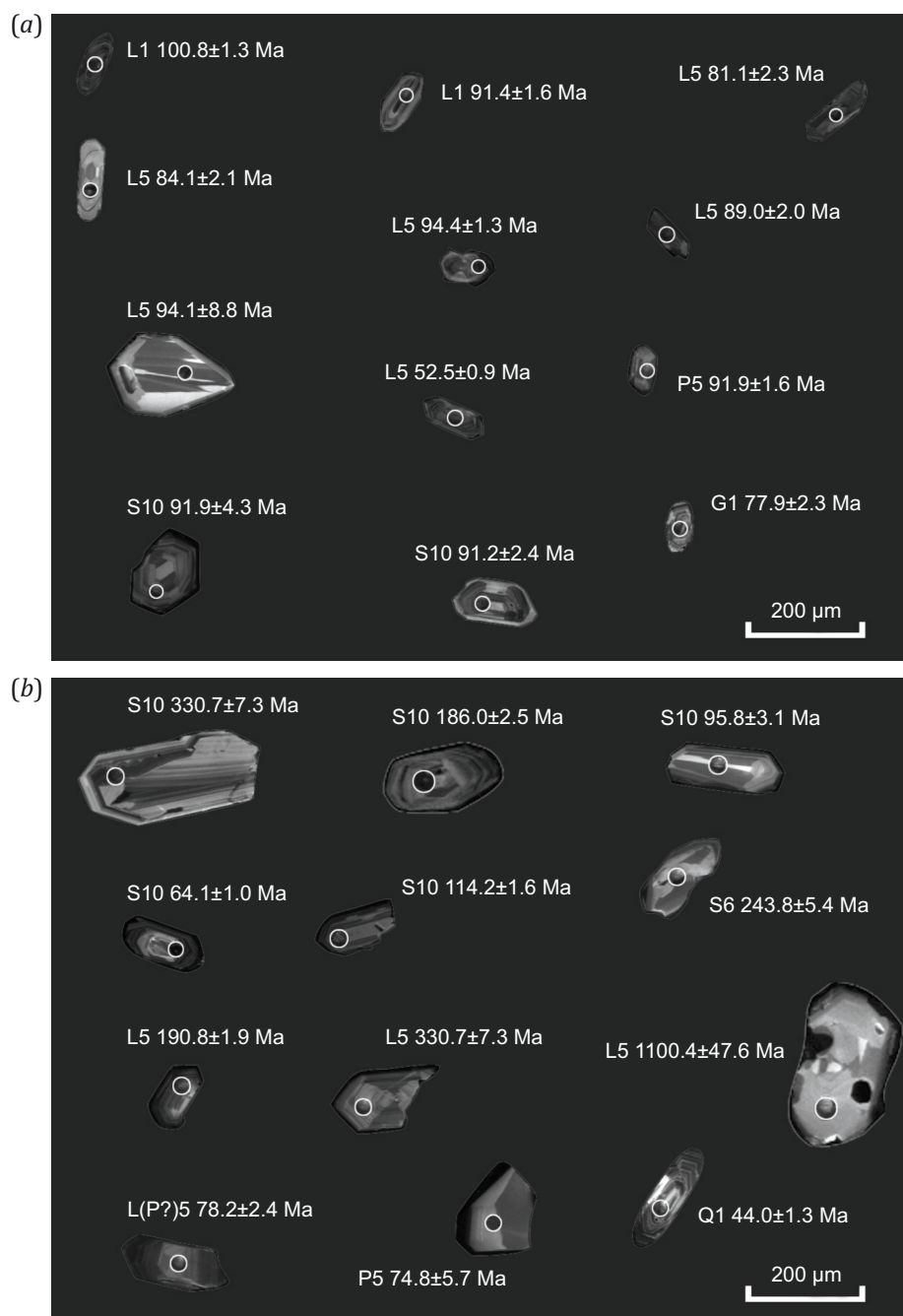


Fig. 7. Correlation of morphology of detrital zircons on the CL-image with ages. (a) – sample SN01, (b) – sample 06AS10.

Рис. 7. Сопоставление морфологии обломочных цирконов на CL-изображениях с возрастом: (a) – образец SN01, (b) – образец 06AS10.

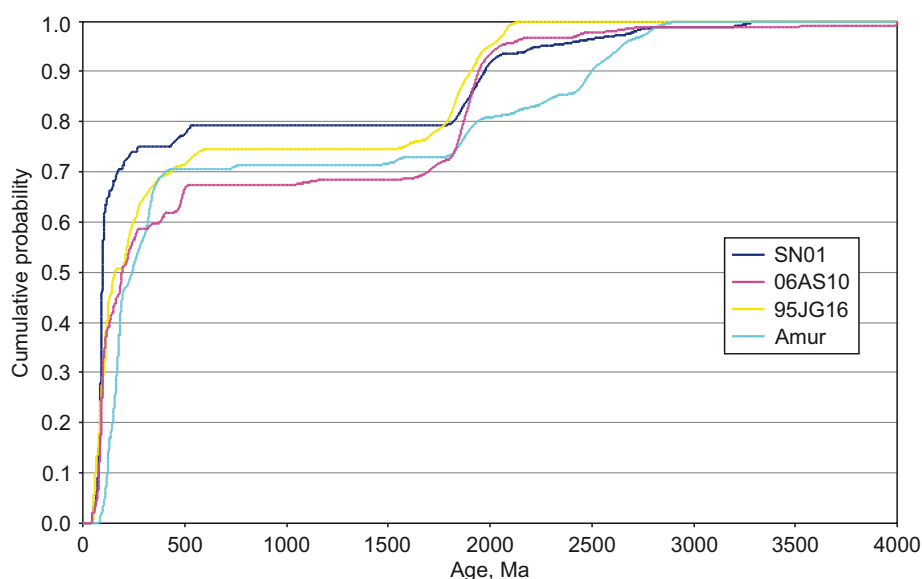


Fig. 8. Comparison of detrital ages distributions in samples from the Sea of Okhotsk region based on the cumulative age probability plot.

Рис. 8. Сравнение распределения значений возраста обломочного циркона в образцах из Охотоморского региона на кумулятивном графике вероятности возраста.

the forearc sediments deposited before the arc-continent collision event in the Middle Eocene [Soloviev et al., 2002]. Sandstone sample 06AS10 has been taken near the base of the Western Kamchatka Basin. The sedimentation in this basin started after the collision of the Olyutorka-Kamchatka island-arc terrane with northeastern Asian margin. The new detrital zircon data allow us to speculate that depositional system along the northern Kamchatka segment of the Asian margin was not dramatically affected by arc-continent collision, because collision in this area occurred at a low crustal level, and the suture is only shallowly exposed (~3–4 km) [Shapiro et al., 2008; Soloviev, Garver, 2012]. The difference between samples 06AS10 and SN01 could be explained by their stratigraphic positions (see Fig. 4) and provenance evolution up the section. The sources were more various in the beginning of sedimentation in the Western Kamchatka Basin and similar to deposition in the preexisting forearc basin. The provenance is becoming more uniform up the section, and the OCVB starts to dominate as a source for clastics (see Fig. 6, sample SN01).

Thereby, new data allow us to prove that sedimentation in the Western Kamchatka Basin started in the Eocene, and the Okhotsk-Chukotka volcanic belt, terranes of the northeastern Asian margin and the Olyutorka-Kamchatka island-arc terrane shed off clastic material towards this basin. We can speculate that the Paleo-Penzhina River system has already existed in the Eocene.

7. CONCLUSIONS

The study of the sandstones near the base of the Western Kamchatka Basin suggests that the provenance for the sandstones is mainly associated with orogen recycling in magmatic arcs. The presence of rutile, black spinel, anatase and pyroxene in heavy fraction may indicate the erosion

of basic rocks; the prevalence of these minerals also indicates a significant effect of the source. The mafic terranes of the Asian margin on the west or/and the Olyutorka-Kamchatka ensimatic island arc supply the basic material to the Western Kamchatka Basin in the Eocene. By the presence of zircon and apatite, we can also suggest the existence of granitoids in the area of erosion. The provenances of the sialic clasts were continental blocks in Asian margin and the Okhotsk-Chukotka volcanic belt. The existence of the sialic sources in the Eocene allows us to assume the possibility of finding the good quality collectors in the Eocene deposits of the Western Kamchatka Basin in the north of the Sea of Okhotsk.

According to the analysis of the morphology of zircon we can make the following conclusion: subalkaline (calc-alkaline) granitoids with a small proportion of high-aluminous muscovite granites are dominant in provenances for the Western Kamchatka Basin in the Eocene. This conclusion is consistent with the results of dating of detrital zircons from sediments of the Western Kamchatka Basin. The Eocene deposits contain detrital zircons whose ages are similar to the age of the Okhotsk-Chukotka volcanic belt, which is known for large amounts of calc-alkaline igneous rocks, including contaminated mantle-crust granitoids [Akinin, Miller, 2011].

Most of the clastic material was transported from the north and northeast. The erosion of the Okhotsk-Chukotka belt had a significant influence on the Eocene sedimentation, where the longitudinal clastic material transport dominated over the transfer across the main strike of the structures. Thus, we can assume that the Paleo-Penzhina River system has already existed in the Eocene, and, perhaps, even earlier after the formation of the Okhotsk-Chukotka volcanic belt.

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9. CONTRIBUTION OF THE AUTHORS

All authors made an equivalent contribution to this article, read and approved the final manuscript.

10. DISCLOSURE

The authors declare that they have no conflicts of interest relevant to this manuscript.

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APPENDIX 1

Table 1.1. Composition of the Eocene sandstones from Western Kamchatka**Таблица 1.1.** Состав эоценовых песчаников Западной Камчатки

Sample	Qm	Qp	Qq	P	Lvl	Lvm	Lvf	Lvv	Lm	Lssh	Lsa	Lss	Lsch	Lst	Lso	Op	nOp	U	T	Mtx	Aut
					Lv					Ls											
95JG-16	52	7	4	62	9	12	28	17	6	2	56	6	4	17	3	1	2	12	300	125	6
XA-08-106	64	30	21	65	34	12	17	30	0	6	0	0	0	9	0	4	1	7	300	78	6
XA08-99	62	41	10	57	21	9	25	41	2	6	0	0	0	7	0	0	7	12	300	120	14
SN-01	60	22	5	26	10	4	5	30	15	0	0	5	10	0	0	2	2	4	200	51	11
XA08-69	70	37	7	67	17	4	26	34	0	8	0	0	7	2	0	8	3	10	300	96	17
XA08-81	71	24	30	55	12	25	23	21	12	6	0	5	0	0	0	5	4	7	300	104	4
XA08-86	70	38	15	48	15	23	26	24	7	12	0	4	0	0	0	7	2	9	300	130	25
XA08-60	38	20	2	25	0	0	0	0	0	5	0	0	0	0	0	0	0	10	100	150	7
AS-06-10	57	16	10	20	16	2	18	28	10	4	0	8	19	0	0	0	0	3	200	63	17
06AS-09	74	31	43	56	15	17	34	10	1	7	0	0	0	0	0	0	4	8	300	98	5
06AS-08	69	41	37	48	13	19	27	15	2	9	0	0	0	0	0	0	8	12	300	108	8

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

Примечание. Qm – монокристаллический кварц; Qp – поликристаллический кварц; Qq – кварциты неясного происхождения; P – полевошпат; фрагменты мелкозернистых пород: Lv – вулканыты, Lvl – вулканыты с лейстовидной текстурой (главным образом основного и промежуточного состава), Lvm – породы с микролитической текстурой (в основном андезиты, дациты и их аналоги), Lvf – кислые породы с фельзитовой текстурой, Lvv – рекристаллизованное стекло и микролиты, Lm – метаморфические породы (включая метакварциты), Ls – осадочные породы, Lssh – сланцы, Lsa – аргиллит и алевропелит, Lss – алевролит и мелкозернистый песчаник, Lsch – чёрты, Lst – туфф, туфогенный силицилит, а также туфогенные аргиллиты, Lso – прочие осадочные породы (карбонат, уголь), Op – рудные минералы, nOp – цветные минералы, U – фрагменты неизвестной породы; T – общее число определений гранулометрического состава в шлифе, Mtx – матрица и цемент, Aut – аутигенные минералы.

Table 1.2. Percentage of rock-forming minerals in Eocene sandstones of Western Kamchatka**Таблица 1.2.** Процентное соотношение породообразующих минералов эоценовых песчаников Западной Камчатки

Sample	T	Q, %	F, %	L, %	L (vms)	V, %	M, %	S, %	V(lmf)	Vl, %	Vm, %	Vf, %	Mtx, %
AS-06-10	200	37	10	53	94	63	11	26	33	48	6	46	24
SN-01	200	43	13	44	79	62	19	19	19	53	21	26	20
XA-08-106	300	33	23	44	108	86	0	14	63	54	19	27	21
XA08-99	300	37	20	43	111	86	2	12	55	38	16	46	29
XA08-69	300	38	24	38	98	83	0	17	47	36	9	55	24
XA08-81	300	34	19	47	104	78	12	10	60	20	42	38	26
XA08-86	300	38	17	45	111	79	6	15	64	23	36	41	30
XA08-60	100	64	28	8	5	0	0	100	0	–	–	–	60
06AS-09	300	37	19	44	84	90	1	9	66	23	26	51	25
06AS-08	300	39	17	44	85	87	2	11	59	22	32	46	26
95JG-16	300	21	12	58	160	41	4	55	49	18	24	58	29

Note. Total components values are calculated using the formulas: $Q\% = (Qm + Qp) / T \times 100$; $F\% = P / T \times 100$; $L\% = (Qq + Lv + Lm + Ls) / T \times 100$; $L(vms) = Lv + Lm + Ls$; $V\% = Lv / Lvm \times 100$; $M\% = Lm / Lvm \times 100$; $S\% = Ls / Lvm \times 100$; $V(lmf) = Lvl + Lvm + Lvs$; $Vl\% = Lvl / Vlmf \times 100$; $Vm\% = Lvm / Vlmf \times 100$; $Vf\% = Lvf / Vlmf \times 100$; $mtx\% = mtx / (mtx + T) \times 100$.

Примечание. Суммарные значения компонентов рассчитываются по формулам: $Q\% = (Qm + Qp) / T \times 100$; $F\% = P / T \times 100$; $L\% = (Qq + Lv + Lm + Ls) / T \times 100$; $L(vms) = Lv + Lm + Ls$; $V\% = Lv / Lvm \times 100$; $M\% = Lm / Lvm \times 100$; $S\% = Ls / Lvm \times 100$; $V(lmf) = Lvl + Lvm + Lvs$; $Vl\% = Lvl / Vlmf \times 100$; $Vm\% = Lvm / Vlmf \times 100$; $Vf\% = Lvf / Vlmf \times 100$; $mtx\% = mtx / (mtx + T) \times 100$.

Table 1.3. Composition of heavy minerals of the Eocene sandstones (Western Kamchatka)**Таблица 1.3.** Состав минералов тяжелой фракции в эоценовых песчаниках (Западная Камчатка)

Mineral	Sample									
	XA-08-106	XA-08-99	SN-01	XA-08-69	XA-08-81	XA-08-86	XA-08-60	AS-06-10	AS-06-09	AS-06-08
Zircon	11	24	17	29	3	3	8	4	22	34
Apatite	–	2	m	–	–	5	–	1	m	–
Rutile	4	3	2	3	2	2	20	4	4	4
Anatase	–	m	–	–	m	m	–	m	–	m
Tourmaline	–	m	–	–	m	–	–	–	1	–
Leucoxene	26	39	–	m	24	1	–	–	29	15
Sulphide	20	7	13	16	60	67	63	75	–	14
Clinopyroxene	–	–	1	36	–	–	m	m	–	–
Orthopyroxene	–	m	2	–	–	m	2	–	–	m
Amphibole	–	–	–	–	m	–	5	–	m	–
Ilmenite	10	–	10	6	9	21	–	–	–	4
Spinel	17	15	12	7	m	–	m	14	26	21
Garnet	12	10	10	3	2	1	2	2	18	8
Black ore mineral	–	–	33	–	–	–	–	–	–	–

Note. m – single marks.

Примечание. m – единичные знаки.

APPENDIX 2

MORPHOLOGY OF THE DETRITAL ZIRCON

After the mineralogical analysis, zircon crystal morphology was analyzed using Pupin's method [Pupin, 1980]. J.P. Pupin found the variability of zircon crystal forms depending on conditions in which granitoids are formed. It is found that chemical composition of the medium affects the growth and development of the pyramidal crystal faces, while temperature affects the prismatic faces. According to this, a classification has been proposed for the main types and subtypes of zircon forms depending on temperature (IT index) and alkali/alumina ratio in mineral-forming medium (index IA). The first one shows the rate of crystallization and presence of volatile components in the melt, the second one shows the heterogeneity of the medium and the evolution of its chemical composition [Pupin, 1980]. This method of the analysis of detrital zircons can also be used for the reconstruction of the features of the granitoids in granitoid provenance (for example, [Dunkl et al., 2001]). Based on the J.P. Pupin's chart [Pupin, 1980], a typological chart was developed by [Belousova et al., 2006] classifying zircons by belonging to the type of granitoids. With the help of this chart it was determined which types of granitoids are eroded.

A fraction sized – 0.07 mm was used to analyze the morphology as the most representative from the point of preservation of the crystal forms of zircon. The counting was performed only among the euhedral grains. In average, for all the samples it was about 35 % for unrounded lightly colored and colorless euhedral crystals of different morphological type, which are valid for counting, about 45 % for

half-rounded grains and about 20 % for rounded grains, so as the grains from detrital rocks were studied.

The initial classification of zircons [Pupin, 1980] was modified to make counting easier. Morphological types with a similar structure were grouped excluding elongation factor; each group was named by the leftmost morphological type from the classification (App. 2, Table 2.1, Fig. 2.1, 2.2). Counting was performed on 100–250 grains depending on the content of zircon in the sample. The result of the counting shows five morphological types of zircons dominating in the samples – H, L4, S9, S15, S25 (App. 2, Table 2.1, Fig. 2.1, 2.2). The content of other morphotypes of zircon is insignificant.

Let us consider which kind of rocks could supply the Eocene sedimentary basin with zircons of the predominant morphological types. According to the classification [Belousova et al., 2006], H-type zircons are common for high-aluminous muscovite-bearing S-type granites. L4-type zircons come from hybrid (contaminated) monzonites and alkali granites. S9 and S15-type zircons are typical for contaminated subalkaline and alkaline granites of I-type, including calc-alkaline subduction-related ones. S25-type zircons are common for alkaline granitoids and I-type tholeiitic granites.

Thus, the morphology of detrital zircons indicates that subalkaline (calc-alkaline) granitoids were dominant in the provenance of the Western Kamchatka Basin in the Eocene, with a small amount of high-aluminous muscovite-bearing granites.

Table 2.1. Contents of detrital zircons (%) of different morphological types [Pupin, 1980] in the Eocene sandstones from the Western Kamchatka

Таблица 2.1. Содержание зерен обломочного циркона (%) разных морфологических типов [Pupin, 1980] в эоценовых песчаниках Западной Камчатки

Sample	Morphological type																					
	B	AB4	AB5	A	H	L1	L3	L4	G1	I	Q2	S6	S7	S9	R2	S15	S19	R4	S22	S24	S25	R5
XA08-106	0	0	0	0	7	7	2	27	1	0	2	0	0	14	1	17	3	0	4	2	13	0
XA08-99	0	0	0	0	5	1	1	22	11	0	3	0	2	20	1	20	3	0	2	2	6	1
SN01	1	0	1	1	4	4	0	22	0	3	8	4	2	9	1	23	1	0	3	4	8	1
XA08-69	0	0	0	0	17	2	1	14	2	1	4	0	1	22	2	11	4	0	0	2	14	3
XA08-81	1	0	0	0	6	1	0	24	0	0	0	8	0	36	0	17	0	0	0	0	7	0
XA08-86	0	0	0	0	7	6	1	25	5	5	2	1	4	15	1	17	0	0	1	1	9	0
06AS10	0	1	1	0	6	6	1	19	4	3	4	1	4	15	0	13	5	1	7	4	4	1
06AS09	0	0	0	0	18	2	3	23	2	0	3	2	5	18	0	9	4	0	2	0	9	0
06AS08	0	0	0	0	16	5	0	20	0	0	0	7	1	13	0	12	1	0	0	8	17	0

Note. The symbols of the morphological types correspond to domain joins: B=B, AB4=AB4, AB5=AB5, A=A, H=H+Q1, L1=L1+L2+S1+S2, L3=L3+S3, L4=L4+L5+S4+S5, G1=G1+P1, I=I+R1, Q2=Q2+Q3+Q4, S6=S6+S11, S7=S7+S8+S12+S13, S9=S9+S10+P2+S14, R2=R2+R3, S15=S15+P3+S20+P4, S19=S19, R4=R4, S22=S22+S23+J2+J3, S24=S24+J4, S25=S25+P5+J5+D, R5=R5+F. The dominating morphological types of zircons are highlighted in bold.

Примечание. Символы морфологических типов соответствуют присоединениям к доменам: B=B, AB4=AB4, AB5=AB5, A=A, H=H+Q1, L1=L1+L2+S1+S2, L3=L3+S3, L4=L4+L5+S4+S5, G1=G1+P1, I=I+R1, Q2=Q2+Q3+Q4, S6=S6+S11, S7=S7+S8+S12+S13, S9=S9+S10+P2+S14, R2=R2+R3, S15=S15+P3+S20+P4, S19=S19, R4=R4, S22=S22+S23+J2+J3, S24=S24+J4, S25=S25+P5+J5+D, R5=R5+F. Доминирующие морфологические типы цирконов выделены жирным шрифтом.

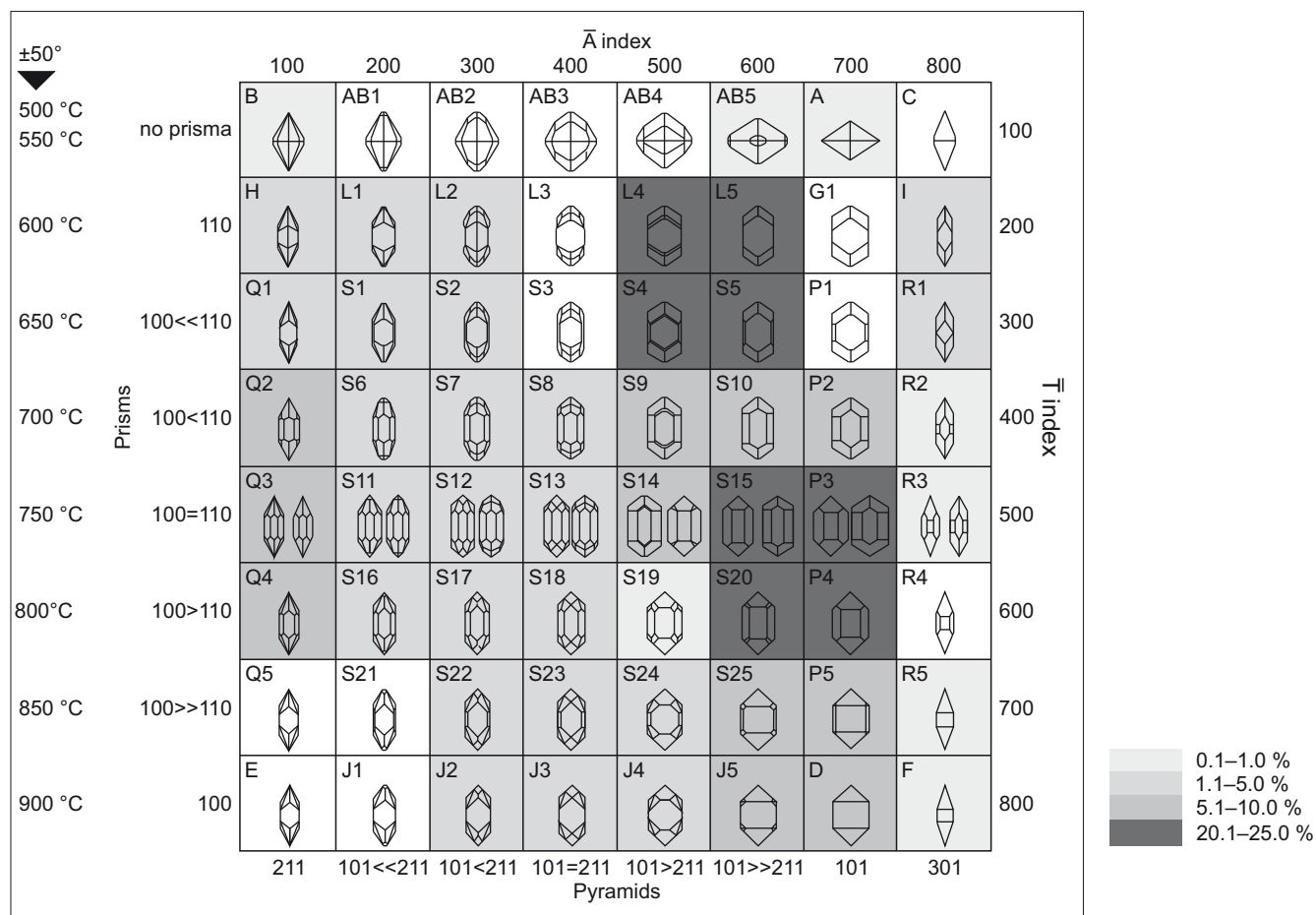


Fig. 2.1. The content of detrital zircons (%) of different morphology for sample SN01 is shown by colors (App. 2, Table 2.1). Zircon typological classification and corresponding geothermometric scale proposed by [Pupin, 1980]. Index A reflects the Al/alkali ratio, controlling the development of zircon pyramids, whereas temperature affects the development of different zircon prisms.

Рис. 2.1. Содержание детритового циркона (%) различной морфологии в образце SN01 показано в цвете (Прил. 2, Табл. 2.1). Типологическая классификация цирконов и соответствующая геотермометрическая шкала, предложенная в работе [Pupin, 1980]. Индекс А отражает соотношение алюминия и щелочей, контролирующее развитие пирамидальных простых форм, в то время как температура оказывает влияние на развитие призм.

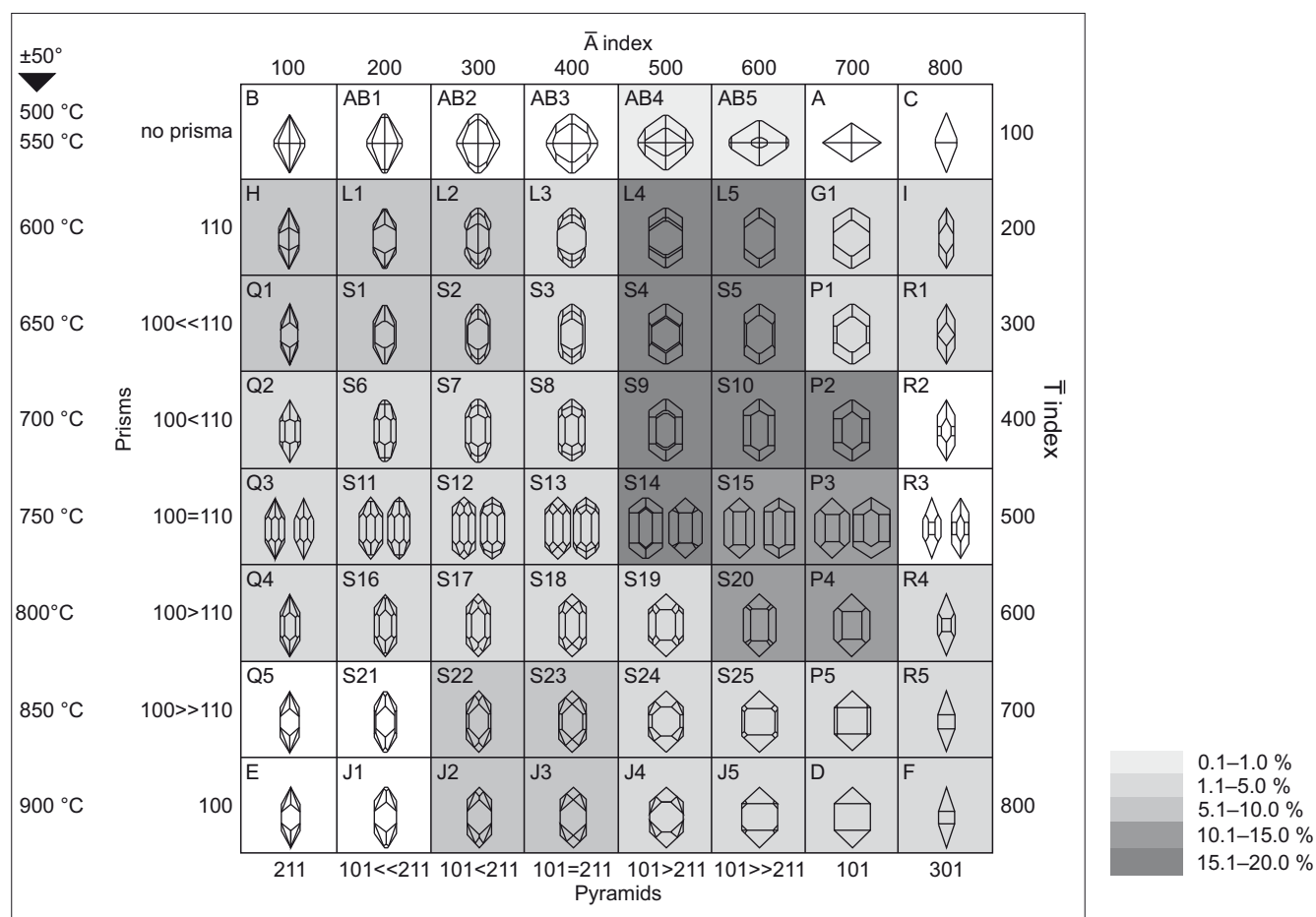


Fig. 2.2. The content of detrital zircons (%) of different morphology for sample 06AS10 is shown by colors (App. 2, Table 2.1). Zircon typological classification and corresponding geothermometric scale proposed by [Pupin, 1980]. Index A reflects the Al/alkali ratio, controlling the development of zircon pyramids, whereas temperature affects the development of different zircon prisms.

Рис. 2.2. Содержание детритового циркона (%) различной морфологии в образце 06AS10 показано в цвете (Прил. 2, Табл. 2.1). Типологическая классификация цирконов и соответствующая геотермометрическая шкала, предложенная в работе [Pupin, 1980]. Индекс А отражает соотношение алюминия и щелочей, контролирующее развитие пирамидальных простых форм, в то время как температура оказывает влияние на развитие призм.

APPENDIX 3

U-Pb GEOCHRONOLOGIC ANALYSIS OF DETRITAL ZIRCONS (Nu HR ICP-MS)

A large split of zircons (generally 1000–2000 grains) was incorporated into a 1" epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts were sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis.

U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) in the Arizona LaserChron Center [Gehrels et al., 2006, 2008]. The analyses involve ablation of zircon with a New Wave UP193HE Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 30 microns. The ablated material is carried in helium into the plasma source of a Nu HR ICP-MS, which is equipped with a flight tube of sufficient width so that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors with $3 \cdot 10^{11}$ Ohm resistors for ^{238}U , ^{232}Th , $^{208}\text{Pb}/^{206}\text{Pb}$, and discrete dynode ion counters for ^{204}Pb and ^{202}Hg . Ion yields are ~0.8 mv per ppm. Each analysis consists of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30-second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~15 microns in depth.

For each analysis, the errors in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ result in a measurement error of ~1–2 % (at 2σ level) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also result in ~1–2% (at 2σ level) uncertainty in age for grains that are >1.0 Ga and substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages occurs at ~1.0 Ga.

^{204}Hg interference with ^{204}Pb is accounted for measurement of ^{202}Hg during laser ablation and subtraction of ^{204}Hg according to the natural $^{202}\text{Hg}/^{204}\text{Hg}$ of 4.35. This Hg cor-

rection is not significant for most of the analyses because our Hg backgrounds are low (generally ~150 cps at mass 204).

Common Pb correction is accomplished by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from [Stacey, Kramers, 1975]. Uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$ are applied to these compositional values based on the variation in Pb isotopic composition in modern crystal rocks.

Inter-element fractionation of Pb/U is generally ~5 %, whereas apparent fractionation of Pb isotopes is generally <0.2 %. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with the known age of 563.5 ± 3.2 Ma (2σ error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1–2 % (2σ) for both $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages.

Concentrations of U and Th are calibrated relative to our Sri Lanka zircon, which contains ~518 ppm of U and 68 ppm Th.

The analytical data are reported in Suppl. 1. The uncertainties shown in these tables are at the 1-sigma level and include only measurement errors. The analyses with >20 % discordancy (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages) or >5 % reverse discordancy are not included.

The resulting interpreted ages are shown on Pb*/U concordia diagrams and relative age-probability diagrams using the routines involved in Isoplot [Ludwig, 2008]. The age-probability diagrams show each age and its uncertainty (for measurement error only) as a normal distribution, and sum all ages from a sample into a single curve. Composite age probability plots are made from an in-house Excel program (available from www.geo.arizona.edu/alc) that normalizes each curve according to the number of constituent analyses so that each curve contains the same area and then stacks the probability curves.