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Detrital Zircon U-Pb Data for Jurassic–Cretaceous Strata from the South-Eastern Verkhoyansk-Kolyma Orogen—Correlations to Magmatic Arcs of the North-East Asia Active Margin

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Citation: Prokopiev, A.V.; Ershova, V.B.; Stockli, D.F. Detrital Zircon U-Pb Data for Jurassic–Cretaceous Strata from the South-Eastern Verkhoyansk-Kolyma Orogen—Correlations to Magmatic Arcs of the North-East Asia Active Margin. *Minerals* **2021**, *11*, 291. <https://doi.org/10.3390/min11030291>

Academic Editor:
Rubén Díez-Fernández

Received: 15 January 2021

Accepted: 8 March 2021

Published: 11 March 2021

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Abstract: We performed U-Pb dating of detrital zircons collected from Middle–Upper Jurassic strata of the Sugoi synclinorium and Cretaceous rocks of the Omsukchan (Balygychan-Sugoi) basin, in order to identify their provenance and correlate Jurassic–Cretaceous sedimentation of the south-eastern Verkhoyansk-Kolyma orogenic belt with various Magmatic belts of the north-east Asia active Margins. In the Middle–Late Jurassic, the Uda-Murgal Magmatic arc represented the Main source area of clastics, suggesting that the Sugoi basin is a back-arc basin. A Major shift in the provenance signature occurred during the Aptian, when granitoids of the Main (Kolyma) batholith belt, along with volcanic rocks of the Uyandina-Yasachnaya and Uda-Murgal arcs, became the Main sources of clastics deposited in the Omsukchan basin. In a final Mesozoic provenance shift, granitoids of the Main (Kolyma) batholith belt, along with volcanic and plutonic rocks of the Uyandina-Yasachnaya and Okhotsk-Chukotka arcs, became the dominant sources for clastics in the Omsukchan basin in the latest Cretaceous. A broader comparison of detrital zircon age distributions in Jurassic–Cretaceous deposits across the south-eastern Verkhoyansk-Kolyma orogen illustrates that the Sugoi and Omsukchan basins did not form along the distal eastern portion of the Verkhoyansk passive Margin, but in the Late Mesozoic back-arc basins.

Keywords: North-east Asia; Verkhoyansk-Kolyma orogen; Magmatic belts; Late Mesozoic sedimentary basins; Sugoi synclinorium; Omsukchan (Balygychan-Sugoi) basin; detrital zircons

1. Introduction

For almost 400 million years during the Early Paleozoic–Mesozoic, the Pacific Margin of NE Asia was characterized by the initiation, evolution, termination, and revival of Magmatic arcs in response to subduction and collisional processes along the complex, long-lived north-east Asia active Margins (Figure 1). Fragments of the Paleozoic Magmatic arcs, such as the Maya-Abkit and North-Okhotsk arcs, are scattered within continental blocks of the Kolyma-Omolon Superterrane in the central part of the Verkhoyansk-Kolyma orogenic belt. In the Mesozoic, several arc Magmatic belts formed during closure of the Oymyakon Ocean and the resulting collision of the Kolyma-Omolon Superterrane and Siberia, including the Main (Kolyma), Uyandina-Yasachnaya, Northern, and Transverse Magmatic belts (e.g., [1–12] and references therein). To the north (in present-day coordinates), the Svyatoi Nos-Oloy and New Siberian-Chukotka Magmatic belts formed during closure of the South Anyui Ocean and formation of the Novosibirsk-Chukotka orogenic belt (e.g., [2,3,5,6,11–18], and references therein). The coeval Magmatic belts also formed to the south along the

paleo-Pacific Margin, known as the Uda-Murgal and Okhotsk-Chukotka volcanic-plutonic belts (Figure 1) (e.g., [1,2,11,19,20] and references therein).

Figure 1. Schematic Map illustrating the locations of the Main Paleozoic–Mesozoic Magmatic belts of the north-east Asia active Margin. Modified after [1].

A number of coeval Late Mesozoic sedimentary basins of varying sizes formed across NE Asia in response to this tectonic and Magmatic activity, but their geological histories are poorly understood due to the lack of geological constraints on their tectonic settings, paleogeographic affinities, and sedimentary provenance. Clastic sedimentation within these basins occurred synchronously with Magmatic activity across the north-east Asia active Margin; therefore, their sedimentary fill and provenance can be used to constrain the history of Magmatic activity within this region.

Detrital zircon provenance studies have been an effective and widely-used approach for reconstructing linkages between sedimentary basins and their tectono-magmatic source regions, providing independent constraints on the affinity of rocks in provenance regions and their tectonic settings. Here we present the first detrital zircon U-Pb data from Mesozoic rocks in the Sugoi and Omsukchan (Balygychan-Sugoi) basins, located in the south-eastern part of the Verkhoyansk-Kolyma orogenic belt in north-east Asia in order to reconstruct the provenance and tectonic evolution of this key part of NE Asia.

2. Geological Setting

2.1. Kolyma-Omolon Superterrane

The composite Kolyma-Omolon Superterrane (microcontinent), located in the eastern part of the Verkhoyansk-Kolyma orogen, comprises a collage of fault-bounded blocks (terrane) of various geodynamic origins [5,6,8–10,12]. In the vicinity of the study area, the tectonic basement units are mainly associated with the Prikolyma, Omolon, and Omulevka terranes (Figure 2). The Prikolyma Terrane is composed of intensely deformed Paleoproterozoic to Carboniferous rocks, overlain by less deformed Permian and Mesozoic clastic and volcanoclastic rocks (e.g., [5,8,21–24]). The Omolon Terrane comprises Archean to Paleoproterozoic metamorphic basement (e.g., [25,26]), unconformably overlain by Mesoproterozoic to Ordovician clastic and carbonate rocks. The uppermost part of the succession of the Omolon Terrane comprises Devonian to early Mississippian arc-related volcanic rocks of the Kedon Formation (North-Okhotsk arc) and late Mississippian clastic rocks [5,8,27–30]. The Omulevka Terrane, in general, consists of Cambrian to Triassic clastic and carbonate rocks, but the Rassokha and Uvyazka blocks in the eastern part of the terrane contain Early Silurian arc-related felsic magmatic rocks [31] and Middle Devonian trachyte plutons [32].

2.2. Main Paleozoic–Mesozoic Magmatic Belts of the NE Asia Active Margin

2.2.1. Maya–Abkit Magmatic Belt

Fragments of this magmatic belt are represented by Early Paleozoic magmatic and volcanic rocks. Late Ordovician arc-related granites exposed across the south-western Okhotsk Terrane with a zircon U-Pb crystallization ages of 445.7 ± 1.5 Ma, 447 and 451 Ma [33]. Early to Middle Silurian syenite and granite intrusions are associated with slab-window related asthenospheric upwelling across the Omolon-Taigonos area, with zircon U-Pb crystallization ages of 433–425 Ma [34]. In the South Verkhoyansk region, Ordovician mafic dikes and sills with baddeleyite U-Pb ages of 445–458 Ma have been reported [35–37], while Ordovician arc-related volcanic and volcanoclastic rocks occur in the Omulevka Terrane [38–40]. SHRIMP zircon U-Pb dating of small island arc-type granitic plutons within the Rassokha block of the Omulevka Terrane yielded a crystallization age of 440 ± 2 Ma [31] (Figure 1).

2.2.2. North Okhotsk Magmatic Belt

This belt of Devonian–Early Carboniferous volcanic rocks was recognized by Parfenov et al. [6] and Badarch et al. [41] (Figure 1). Devonian–Early Carboniferous subduction-related effusive rocks of the Kedon Complex, including trachybasalts, trachyandesites, rhyolites, trachyrhyolites, tuffs and volcanoclastic rocks with thicknesses from 1250 to 4350 m, have been documented in the Omolon Terrane and southern part of the Prikolyma Terrane e.g., [11,28]. The ages of these rocks were established on the basis of fossil fauna and zircon U-Pb ages. Rhyolites yielded U-Pb zircon ages of 402 and 387 Ma [27], while felsic intrusions are 335 and 338 Ma in age [29,30].

Upper Devonian (Frasnian to Famennian) volcanic and sedimentary rocks are exposed in the south-western and central parts of the Okhotsk Terrane, comprising 1300 meters of rhyolitic to andesitic lavas, tuffs, and volcanoclastic rocks [42–45]. Arc-related granitoid plutons gave zircon U-Pb ages of 375 Ma [45].

Figure 2. Main geological units of the Prikolyma Terrane and Sugoi synclinorium (modified [21]). Inset Map shows location of the region and Main tectonic units.

2.2.3. Main (Kolyma) Batholith Belt

This SE-NW-oriented Magmatic belt extends for more than 1000 km along the axial part of the Verkhoyansk-Kolyma orogenic belt and orthogonal to the Sea of Okhotsk coast and to the strike of older subduction-related Magmatic belts (Figure 1) (e.g., [2,46–48]). It is formed by a few hundred biotite-hornblende granodiorite and granite plutons of varying sizes, along with numerous felsic dikes. Both S- and I-type granites are present (e.g., [1,48]), coeval to the Uyandina-Yasachnaya volcanic rocks exposed in the north-east of the Main (Kolyma) belt. The geodynamic setting for the Main (Kolyma) belt remains a Matter of debate. Some studies have proposed that it was formed in response to the

collision of the Kolyma-Omolon Superterrane with Siberia (e.g., [2,6–8,49,50]), while others claimed that it represents the product of subduction-related Magmatism (e.g., [1,48,51,52]). U-Pb crystallization ages of the plutons vary from 165 to 144 Ma, with a predominant mode at about 150 Ma [1,48,53]. The plutons exhibit a younging trend to the north-west, which has been attributed to oblique subduction followed by transpressive collision of the Kolyma-Omolon Superterrane with the Siberian Craton Margin [52]. Numerous biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages between 143–138 Ma [50] reflect the timing of cooling in response to tectonic unroofing and exhumation during collision between the Superterrane and the Craton. In the north-west, the Main belt joins the Northern belt (see below), thereby forming an arcuate composite Magmatic belt, referred to as the Kolyma loop.

2.2.4. Northern Batholith Belt

This WSW-ENE-oriented Magmatic belt stretches for over 650 km at an acute angle to the north-western termination of the Main (Kolyma) belt to form the northern flank of the composite Kolyma loop (Figure 1) (e.g., [3,5,50]). Most plutons in this belt consist of diorites to monzonites with minor granites and granodiorites – all classified as I-type arc granitoids. These intrusions are interpreted to have been emplaced in a suprasubduction setting (e.g., [5,50]). Zircon U-Pb ages from Major plutons range from 140 to 129 Ma [1], younging in an eastward direction, while $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the plutons vary from 144 to 123 Ma [50].

2.2.5. Uyandina-Yasachnaya Magmatic Belt

This belt represents a 150 km-wide Magmatic arc, paralleling the Main Kolyma batholithic belt on its NE flanks and stretching for nearly 1000 km across the axial portion of the Verkhoyansk-Kolyma orogenic belt (Omulevka Terrane and adjacent areas of the In'yali-Debin and Polousnyi synclinoria), as far as the southern Prikolyma Terrane (Figure 1). The arc consists of Oxfordian–Tithonian volcanic and volcanoclastic rocks, varying in thickness from a few hundred meters to a Maximum of 3500 m. The volcanic rocks are dominated by andesite, basalt, andesite-basalt, and more acidic varieties, including rhyolite. Tuffs of various types and compositions are common. The Uyandina-Yasachnaya Magmatic arc has been interpreted as being related to subduction associated with closure of the Oymyakon Ocean, although the polarity of the subduction zone remains debated (e.g., [1–3,5,8,51]). The ages of the volcanoclastic rocks, constrained by fossils and zircon U-Pb dated at 153–150 Ma [1,12,50,52], are nearly coeval with those of the Main (Kolyma) belt granitoids described above.

2.2.6. Uda-Murgal Magmatic Belt

This Magmatic belt extends for over 2000 km along the Sea of Okhotsk coast from Uda Bay to the northern extremity of Kamchatka, but is generally less than 100 km wide (Figure 1). It has an arc affinity and is composed of volcanic and volcanoclastic rocks including andesites, basaltic andesites, rhyolites, dacites, basalts, and tuffs, with thicknesses ranging from 3000 to 7000 m (e.g., [2,19,54,55]). There are contrasting interpretations and models for the age of the Uda-Murgal Magmatic belt. According to Parfenov [2], the Uda-Murgal volcanic arc existed from the Permian to the Early Cretaceous on the basis of volcanic rocks of Late Permian–Jurassic age (as indicated by fossils) described from the Taigonos Peninsula, Late Triassic to Late Jurassic age from the Koni Peninsula, and Early to Late Jurassic age from the Pyagin Peninsula. Parfenov [2] also recognized the Triassic–pre-Albian Uda and Koni-Murgal continental Magmatic arcs along the north-western and northern Margins of the Sea of Okhotsk. However, within the Uda-Murgal Magmatic belt, Sokolov [56] documented the older Late Paleozoic–Early Mesozoic Koni-Taigonos Magmatic arc that is superimposed by the younger Late Jurassic–Early Cretaceous Uda-Murgal arc. The Kobayume graben, in the back-arc region of the Uda-Murgal arc, contains up to 800 m of basalt, basaltic andesite, and tuffs [57], which Prokopyev et al. [58] suggested to have formed during extension in the back-arc region of the Uda-Murgal arc. Biakov

et al. [59–61] reported calc-alkaline volcanics of the late Middle–Late Permian age in the east of the Okhotsk Terrane and ascribed them to the Okhotsk-Taigonos volcanic arc, although they could have alternatively been assigned to the Uda-Murgal Magmatic belt. Mesozoic diorite and granodiorite plutons and volcanic rocks have yielded zircon U-Pb ages of 160–100 Ma (e.g., [1,62] and references therein). Late Paleozoic–Early Mesozoic volcanics of the Uda-Murgal Magmatic belt mainly comprise basalts and andesites [2,54,55] containing very few zircons, thus accounting for the lack of Late Paleozoic–Early Mesozoic detrital zircon U-Pb age modes in sedimentary samples [1]. Along the south-eastern Margin of the belt in the Uda Gulf of the Sea of Okhotsk, 176–178 Ma basaltic andesites and andesites ($^{40}\text{Ar}/^{39}\text{Ar}$ [63]) and 181 ± 2 Ma granites (zircon U-Pb [64]) have been reported.

2.2.7. Svyatoi Nos–Oloy Magmatic Belt

This Magmatic belt extends for more than 1200 km along the coasts of the Laptev and East Siberian Seas in the Svyatoi Nos Cape area, along the northern Margin of the Verkhoyansk-Kolyma orogenic belt (Figure 1). The belt can be divided into two branches: the Svyatoi Nos and Oloy. The Svyatoi Nos branch (e.g., [2,5,9]) is composed of Late Jurassic–Early Cretaceous andesites, tuffs, and greywackes with thicknesses exceeding 400 m (e.g., [5,65]). They were intruded by minor granitoid plutons and dikes with U-Pb ages of 114–112 Ma and 119–111 Ma, respectively [65]. A bulk of this branch has been buried beneath younger Cenozoic sedimentary strata along the Margin of the Laptev Sea.

The eastern portion of the belt—the Oloy branch—is located between the Kolyma, Omolon, and Bolshoy Anyui rivers, south of the South Anyui suture [5,8,9,14,39]. It consists of mafic, intermediate, and acidic volcanic rocks, associated volcanoclastic rocks, and small plutons. An Early Cretaceous age of the volcanoclastic rocks was constrained by fossils and corroborated by zircon U-Pb ages ranging from 150 to 137 Ma [1]. Dacites yielded a zircon U-Pb crystallization age of 174 Ma, while other granodiorite-diorite plutons were dated at 142–139 Ma [66].

The composite Svyatoi Nos–Oloy Magmatic belt was formed during closure of the South Anyui Ocean, resulting in the collision of the Arctic Alaska–Chukotka Superterrane with the Siberian Margin [5,65]. The Late Jurassic–Early Cretaceous volcanic and volcanoclastic rocks are consistent with the characteristics of a continental arc, while the Aptian–Albian granitoids in the Svyatoi Nos Cape area and Berriasian–Valanginian granodiorites of the Oloy branch reflect either the final Magmatic phase of the Magmatic arc or the incipient continental collision and formation of the Novosibirsk–Chukotka orogeny (e.g., [16,18]).

2.2.8. New Siberian–Chukotka Magmatic Belt

This Magmatic belt extends for more than 2000 km from the south-western part of the New Siberian Islands archipelago to the lower reaches of the Kolyma River and Chukotka (Figure 1). This Magmatic belt sits outboard from the Svyatoi Nos–Oloy Magmatic belt and was emplaced within the Arctic Alaska–Chukotka Superterrane. While granite plutons of the New Siberian Islands yielded U-Pb ages as old as 121–144 Ma [67] and $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages at 113–105 Ma [49], zircon U-Pb ages obtained from granitoid plutons in Chukotka gave systematically younger ages ranging from 121 to 100 Ma [1,62,68–77].

2.2.9. South Verkhoyansk Magmatic Belt

This N-S-oriented Magmatic belt attains a length of 400 km in the central portion of the Verkhoyansk orogenic belt in the back-arc region of the Uda-Murgal and Okhotsk–Chukotka arcs (Figure 1). The granitoids it contains were emplaced during two major pulses of subduction-related magmatism and deformation in the region at 125–120 Ma (Early Cretaceous) and 95–90 Ma (early Late Cretaceous) [44,78,79].

2.2.10. Okhotsk-Chukotka Magmatic Belt

The Okhotsk-Chukotka Magmatic belt is the largest in north-east Asia, extending over 3000 km from the north-western corner of the Sea of Okhotsk coast as far as the eastern termination of Chukotka, with a width of 100 to 400 km (Figure 1). This voluminous volcanic arc is composed of a thick succession of volcanic and volcanoclastic rocks with a Maximum thickness of up to several kilometers. The belt is interpreted as an Andean-type continental Magmatic arc [1,2,4,77,80,81]. The Aptian–Late Cretaceous age of the volcanic and volcanoclastic rocks were determined by fossil flora, while zircon U-Pb and mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the volcanic and plutonic rocks clustered between 106–76 Ma [1,62,73,74,76,77,81–86].

2.3. Sugoi Synclinorium and Omsukchan Basin

The Sugoi synclinorium is located within the south-eastern part of the Verkhoyansk-Kolyma orogenic belt and is separated by Major faults from the Omulevka, Prikolyma, and Omolon terranes of the Kolyma-Omolon Superterrane (microcontinent). To the east of the Sugoi synclinorium (in present-day coordinates), the Khetagchan anticlinorium comprises Triassic clastic deposits. Similarly, the Balygychan anticlinorium to the south also Mainly contains Triassic clastic deposits and is separated from the Sugoi synclinorium by a series of faults. A Major sinistral strike-slip fault separates the Sugoi from the In'yali-Debin synclinorium to the south-west, which exposes a thick succession of Triassic–Jurassic strata [87–89] (Figures 2 and 3).

The Sugoi synclinorium comprises mostly Jurassic clastic strata attaining a total thickness of up to 2700 m [87] (Figure 4), with small outcrops of Upper Triassic rocks in the cores of anticlines. The thickness of Jurassic rocks is likely an overestimation due to superimposed shortening. The Marat Formation (up to 800 m, Lower Jurassic) comprises siltstone and mudstone with interbeds of limestone. The Memechen Formation (600–1000 m) and the Oktyabrin Formation (up to 700 m, Middle Jurassic) comprise sandstone, siltstone, and mudstone. The Kuchukan Formation (150–200 m, Upper Jurassic) is represented by intercalating sandstone, siltstone, and mudstone [87] (Figure 4). The age of the formations is constrained by fossil findings [87].

The Sugoi synclinorium has been considered the easternmost continuation of the In'yali-Debin synclinorium [87]. The paleogeographic association and tectonic setting of these Jurassic and Triassic clastic strata is debated. The In'yali-Debin synclinorium has been considered as part of the Polousnyi-Debin Terrane of the Kolyma-Omolon Superterrane [5,6,8,9], with Upper Triassic–Jurassic clastics deposited along the south-western Margin of the Kolyma-Omolon Superterrane prior to its accretion to Siberia in the Late Mesozoic. However, detrital zircon U-Pb age data from Triassic–Jurassic strata in the In'yali-Debin synclinorium were used to suggest that these strata were deposited along the eastern Verkhoyansk passive Margin of Siberia [90]. Alternatively, Parfenov and Nokleberg [8,9,89] proposed that the Mesozoic rocks of the Sugoi synclinorium were deposited within the Marginal sea associated with the Kolyma-Omolon Superterrane or in the back-arc basin of the Uda-Murgal arc [87].

The Omsukchan basin [89] (also known as the Balygychan-Sugoi basin [87]) stretches in a meridional direction for over 300 km from the Sea of Okhotsk to the middle course of the Kolyma River, with a Maximum width of the exposure belt of 50 km (Figures 2 and 3). The basin comprises a Massive section of continental Cretaceous volcanic and volcanoclastic rocks, reaching thicknesses of 5300 to 9500 m [87] (Figure 5), with an angular unconformity separating Cretaceous rocks of the Omsukchan basin from intensely deformed Triassic and Jurassic rocks of the Sugoi synclinorium [87]. Cretaceous rocks are also deformed with local cleavage development. However, structural trends and orientation of the Omsukchan basin are roughly orthogonal to the axial traces of the Sugoi synclinorium (Figures 2 and 3). The Hauterivian–Barremian rocks are rhyolite, tuffs, tuffaceous sandstone, and shale. The oldest Aptian deposits of the Omsukchan basin comprise rhyolite, ignimbrite, and shale in the lower part and siltstone, andesite, and basalt in the middle part, grading

to sandstone and siltstone in the upper part of the basal succession. The lower Albian rocks are predominantly clastic with intercalated andesitic tuffs and basalt flows. Upper Albian to lower Cenomanian deposits comprise andesite, tuffs, tuffaceous sandstone, and conglomerate, which are overlain by upper Cenomanian tuffs, rhyolite, dacite, and sandstone. The lower part of the Turonian–Campanian succession consists of tuffs, rhyolite, dacite, and sandstone, while the upper-most portion is Mainly sandy in composition (Figure 5). The ages of the Omsukchan basin deposits are Mainly based on fossil flora [4] and rare K-Ar, Rb-Sr and U-Pb dates [87]. Zircon U-Pb dating yielded ages of 132–134 Ma for rhyolites of the Askold Formation, while dacites and rhyolites of the Shorokh Formation gave ages of 82–86 Ma [91] (Figure 5). The Omsukchan basin sedimentary strata were intruded by Late Cretaceous felsic and Mafic plutons and dikes (Figures 2, 3 and 5). The Cretaceous Omsukchan basin is overlain by Paleogene continental deposits above an angular unconformity.

Figure 3. Geological Map of the boundary zone between the southern Prikolyma Terrane and northern Sugoi synclinorium (modified [87,88]). See Figure 2 for location.

Figure 4. Generalized stratigraphic column of the Sugoi synclinorium and Omsukchan basin with position of dated samples.

Formations: as - Askold, ar - Arylakh, ul - Ulik, gl - Galimov, ag - Aigur, tp - Toptan, zr - Zorin, kh - Kakhovka, nd - Nadezhda, sr - Shorokh, dz - Dzhagyn

Figure 5. Schematic geological section of the Omsukchan basin (data from [87]). The stratigraphic age of 17AP29 and 17AP36 are shown based on their Maximum depositional ages.

The origin of the Omsukchan basin is still debated. Belyi [4] considered the Omsukchan basin as an orthogonal branch of the Okhotsk-Chukotka volcanic belt. However, only its upper parts (late Albian–Campanian) are coeval with the Okhotsk-Chukotka

volcanic belt, while the Aptian–lower Albian succession is contemporaneous with the Uda-Murgal Magmatic belt [1,87]. In contrast, Parfenov [3], Kuznetsov, and Livach [92] interpreted the Omsukchan basin as a piggy-back basin with the Verkhoyansk-Kolyma orogenic belt. However, most recent studies have considered the basin as rift-related [93–98].

3. Materials and Methods

In order to elucidate the provenance and tectonic setting of the strata of the Sugoi synclinorium and Omsukchan basin, six clastic rock samples were collected from Jurassic–Cretaceous strata of the Sugoi synclinorium and Omsukchan basin (Figures 5 and 6), as well as one sample from the cross-cutting Arangass granite pluton along the Kolyma River (Figure 3, Table 1).

Figure 6. (a–f) Photos of the outcrops of the studied rocks. The star shows the location of the sample.

Table 1. Summary of locations of analyzed samples.

Sample Number	Latitude	Longitude	Stratigraphic Age; Formation
17AP01	N63°02′52.1″	E152°33′05.1″	Upper Jurassic; Kuchukan Formation [87]
17AP04	N63°14′27.5″	E152°34′15.3″	Middle Jurassic; Memechen Formation [87]
17AP05	N63°19′03.2″	E152°34′34.0″	Upper Jurassic; Kuchukan Formation [87]
17AP25	N64°13′02.7″	E154°27′16.1″	Aptian [87]; Ulik Formation
17AP29	N64°37′42.1″	E154°01′19.5″	Younger than Coniacian—this study; Late Carboniferous–Early Permian; Monkhaidyn Formation [87]
17AP36	N64°42′37.6″	E153°58′51.7″	Younger than Campanian—this study; Late Carboniferous–Early Permian; Monkhaidyn Formation [87]
17AP07	N63°28′07.5″	E152°52′53.8″	Arangass pluton. Cretaceous (86–87 Ma—this study) Coniacian

All samples were analyzed at the UTChron geochronology facility at the Department of Geological Sciences at the University of Texas, Austin, TX, USA. Samples underwent

conventional heavy mineral separation and were grain mounted (no polishing) on one-inch round epoxy pucks with double-sided tape. All grains were depth-profiled using a Photon Machines Analyte G2 ATLex 300si ArF 193 nm Excimer Laser, equipped with a Helix two-volume ablation cell using procedures of Marsh and Stockli [99]. The ablated aerosols were transported using He carrier gas to a Thermo Fisher Element2 single collector, Magnetic sector-ICP-MS for isotopic determinations. GJ1 was used as primary zircon standard ($^{206}\text{Pb}/^{238}\text{U}$ 601.7 ± 1.3 Ma, $^{207}\text{Pb}/^{206}\text{Pb}$ 607 ± 4 Ma; [100]) and interspersed every 4–5 unknown analyses for elemental and depth-dependent fractionation. Plešovice (337.1 ± 0.4 Ma, [101]) was used as a secondary standard to monitor data quality. No common Pb correction was applied due to Hg interference. Data reduction was performed using the IgorPro [102] based Iolite 3.4 software with Visual Age data reduction scheme [103]. All uncertainties are quoted at 2σ . For data interpretations, $^{206}\text{Pb}/^{238}\text{U}$ ages were used for zircons < 1 Ga, while $^{207}\text{Pb}/^{206}\text{Pb}$ ages were used for older zircons. Detrital and Magmatic zircon U-Pb analytical results tables are provided in Supplementary Materials. Histograms were constructed using the detzrcr software (version 1.0, University of Oslo, Oslo, Norway) [104].

4. Results

4.1. Petrography of Studied Rocks

Sample 17AP01

This is a fine- to medium-grained, poorly sorted arkosic arenite (Figure 7). Quartz contribute 25–30% of total grain population. Grains are angular to sub-angular. Feldspar grains are angular to sub-angular and up to 40–50%. Lithic grains comprise 20–15% and are Mainly volcanic in composition. Cleavage is observed.

Figure 7. Petrography of the studied rocks. Qu–quartz, Fsp–feldspar, Lv–lithic volcanic grains, Ol–olivine.

Sample 17AP04

This is a fine-grained silty arkosic arenite (Figure 7). Quartz grains are angular to sub-angular and contribute 50–60% of total grain population. Feldspar grains are angular to sub-angular up to 40–50%. Lithic grains are rare. Cleavage is observed.

Sample 17AP05

This is a fine-grained arkosic arenite with secondary carbonate cement (Figure 7). Quartz grains are angular to sub-angular and contribute 50–60% of total grain population. Feldspar grains are angular to sub-angular up to 40–50%. Lithic grains are rare. Cleavage is observed.

Sample 17AP25

This is a medium- to coarse-grained lithic arenite with the Majority of lithic grains (30–35%) being volcanic in composition (Figure 7). Quartz and feldspar grains are angular to sub-angular and contribute 40–45% and 20–30%, respectively.

Sample 17AP29

This is a medium- to coarse-grained tuffstone (Figure 7). Clastic grains are Mainly lithic volcanic grains and olivine.

Sample 17AP36

This is a silty fine-grained arkosic arenite. Due to the widespread carbonatization and dissolution, the quantity of original clastic grains is difficult to calculate.

Sample 17AP07

This is an alkaline granite porphyry, which contains potassium feldspar (45–66%), quartz (20–15%), albite (3–25%), hornblende, riebeckite, aegirine, and biotite (20%).

4.2. U–Pb Dating of Detrital Zircons

A sample 17AP04 was collected from fine-grained silty arkosic arenite of the Middle Jurassic Memechen Formation (Figures 3, 4, 6 and 7, Table 1). The zircon age distribution is characterized by a subsidiary component of Precambrian zircons (28%) that form a minor peak at 1860 Ma (Figure 8). The Paleozoic grains (16%) group around 380–430 Ma. The youngest zircons form a dominant age peak at 170 Ma (56% of the dated grains) (Figure 9).

Samples 17AP01 and 17AP05 were collected from Upper Jurassic (Kuchukan Formation) fine- to medium-grained poorly sorted arkosic arenite and fine-grained arkosic arenite, respectively (Figures 3, 4, 6 and 7, Table 1). Precambrian zircon Make up a subsidiary portion (26%) of all analyses that yielded U–Pb ages from 1740 to 2000 Ma (Figure 8). Only 15% of zircons are of Paleozoic age, forming two minor peaks at 320 and 380–430 Ma. A significant number of detrital zircons (~60%) yielded Jurassic ages, with a distinct peak at 170 Ma and subordinate peak at 186 Ma (Figure 9).

Sample 17AP25 was collected from an Aptian medium- to coarse-grained lithic arenite of the Ulik Formation (Figure 5, Table 1). While Precambrian zircons (8%) do not represent a prominent peak (Figure 8) and Paleozoic grains (15%) only form minor peaks in the age range 310–425 Ma, Mesozoic zircons represent the bulk (77%) of the total population, with Major peaks at 144 and 187 Ma (Figure 9).

Two samples (17AP29 and 17AP36) were analyzed from the Monkhaidyn Formation, previously considered to be Late Carboniferous–Early Permian in age [105] (Figures 2 and 3, Table 1) on the basis of unsubstantiated fossil evidence. Precambrian zircons (16%) form two subsidiary age peaks at 1860–1890 Ma and 1950–2050 Ma (Figure 8), while Paleozoic zircons constitute 46% and 20 % of the dated population in sample 17AP29 and 17AP36, respectively. Detrital ages of Paleozoic zircons from sample 17AP29 form two peaks at 309 and 395–465 Ma, while, in sample 17AP36, three minor peaks exist at 260–299, 381, and 430 Ma. Mesozoic grains Make up 39% and 72% of the dated detrital zircons in samples 17AP29 and 17AP36, respectively. The youngest zircons from both samples are Late Jurassic and Late Cretaceous in age and fall into two Major peaks at 155–158 Ma and 88–90 Ma (Figure 9).

Figure 8. Kernel Density Estimation (KDE) plot showing all U-Pb detrital zircon data from the Middle–Upper Jurassic and Cretaceous samples analyzed in this work. The Main sources of detrital zircons are shown in color.

Sixteen zircons from the alkaline granite porphyry of the Arangass pluton (sample 17AP07) (Figures 2 and 3, Table 1, Table S1) yielded a weighted average zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 86.9 ± 0.79 Ma (Figure 10A), while seven concordant zircon grains yielded a U-Pb concordia age of 86.7 ± 0.8 Ma (Coniacian) (Figure 10B).

Figure 9. Kernel Density Estimation (KDE) plot showing young (60–530 Ma) U-Pb detrital zircon data from the Middle–Upper Jurassic and Cretaceous samples analyzed in this paper. The Main sources of detrital zircons are shown in color.

Figure 10. Age of alkaline granite porphyry from the Arangass pluton: (A) Weighted average of LA-ICP-MS U-Pb zircon dating (86.9 ± 0.79 Ma, 16 grains). (B) Concordia plot of LA-ICP-MS U-Pb analyses from sample 17AP07. Ellipses overlap concordia and each other with a concordia age [106,107] of 86.7 ± 0.8 Ma (small dotted ellipse) (7 zircon grains).

5. Discussion

The distributions of detrital zircon U-Pb ages from three Jurassic rocks of the Sugoi synclinorium exhibit very similar provenance signatures (Figures 8 and 9). Precambrian zircons are not abundant, represent a subsidiary component of the zircon population

(<28–10%) (Figure 8), and cluster predominantly between 1800–2000 and 2500–2800 Ma. Metamorphic complexes in the basement of the Omolon Terrane, located to the north-east of the Sugoi synclinorium, represent a possible source for the Archean and Paleoproterozoic zircons (e.g., [26,108,109]) (Figures 2 and 3). Zircons of these ages could also be sourced from the southern part of the Prikolyma Terrane, based on comparable detrital zircon age signatures (1750–2800 Ma) in Devonian–Carboniferous strata from that region [21]. The Maya-Abkit Magmatic belt, in the eastern part of the Omulevka Terrane [31] and Omolon-Taigonos area [34], possibly represents the source area for the 420–430 Ma old zircon (Figures 8 and 9). Zircons of comparable ages have also been reported from Devonian–Carboniferous clastic rocks across the southern part of the Prikolyma Terrane [21].

The Majority of the dated zircon grains (60–77%) from Jurassic strata cluster at 170 Ma (Figure 9). Hence, the Main clastic provenance signal points to sourcing from Middle Jurassic felsic Magmatic rocks located close to the Sugoi synclinorium. Early–Middle Jurassic volcanic and volcanoclastic rocks have only been reported from the Uda-Murgal Magmatic arc, located to the south of the Sugoi basin. However, the Late Paleozoic–Early Mesozoic rocks of the Uda-Murgal arc are dominated by andesites and basalts, with a conspicuous absence of felsic rocks (e.g., [2,54,55]). This implies a paucity of zircons, Manifested by the absence of Middle Jurassic detrital zircon U-Pb age dates from the Uda-Murgal Magmatic arc in the eastern part of the Verkhoyansk-Kolyma orogenic belt [1]. The nearest well-dated Early–Middle Jurassic basaltic andesites, andesites and granites have been reported from the south-western Margin of the Uda-Murgal arc (Uda Gulf of the Sea of Okhotsk [63,64]), 1400 km to the south-west of the Sugoi basin. Our new detrital zircon U-Pb data, characterized by an abundance of Middle Jurassic zircons, indicate that Middle Jurassic Magmatic activity occurred within the Uda-Murgal arc, but that felsic Magmatic rocks have either been subsequently eroded or are now completely buried beneath younger Cretaceous rocks of the Okhotsk-Chukotka Magmatic belt. These findings strongly support the hypothesis that the Sugoi basin represented a back-arc basin of the Uda-Murgal arc. Subordinate components of Precambrian and Paleozoic detrital zircons were likely derived from minor erosional input from continental terranes framing the Sugoi basin to the north, west, and east (in present-day coordinates).

Aptian rocks of the Omsukchan basin are characterized by dominant zircon peaks at 144 and 183 Ma, implying erosion and sourcing of first-cycle volcanic rocks from the Main (Kolyma) Magmatic belt and the Uyandina-Yasachnaya arc, along with the Uda-Murgal arc, respectively. In addition, these Aptian strata show a greater abundance of Paleozoic and Precambrian grains in comparison with Jurassic strata of the Sugoi basin, pointing to input from the continental Omolon, Prikolyma, and Omulevka terranes (Figures 8 and 9). An increase in erosion rates across the Kolyma-Omolon Superterrane, Main (Kolyma) Magmatic belt, and Uyandina-Yasachnaya arc can be attributed to the final collisional phase between the Kolyma-Omolon Superterrane and Siberia. This is consistent with zircon (U-Th)/He thermochronometric data from the southern part of the Prikolyma Terrane, confirming an episode of rapid cooling and exhumation at 137 Ma [110]. The Omsukchan basin most likely represented an Early Cretaceous [95–98] small rift, oriented orthogonal to the Uda-Murgal arc. In contrast to the Jurassic deposits of the Sugoi basin, the Lower Cretaceous strata of the Omsukchan basin do not contain abundant Middle Jurassic zircons, implying that erosion of Jurassic sedimentary strata and coeval volcanics did not extensively contribute to the clastic provenance in the Early Cretaceous.

The source area of clastics within the Omsukchan rift basin dramatically changed in the latest Cretaceous. These Late Cretaceous strata are characterized by dominant components of Late Jurassic (155–158 Ma) and early Late Cretaceous (88–90 Ma) detrital zircons (Figures 8 and 9). The Late Jurassic (155–158 Ma) component correlates with Magmatic rocks reported from the Main (Kolyma) batholith belt and volcanic rocks of the Uyandina-Yasachnaya arc (Figure 1) (e.g., [1,48,52,53]). The youngest, syn-depositional detrital zircon peak at 88–90 Ma (Figures 8 and 9) Matches the ages of volcanic rocks, volcanoclastic rocks, and granitoid plutons of the Okhotsk-Chukotka Magmatic belt (Figure 1) (e.g., [1]).

Granite porphyry of the Arangass pluton yielded a similar age (86–87 Ma; this study) and was intruded during the final phases of Magmatic activity within the Okhotsk-Chukotka volcanic belt (e.g., [1,81,86]).

Erosional unroofing of terranes along the south-eastern Margin of the Kolyma-Omolon Superterrane significantly increased during the Late Cretaceous, which was possibly related to a second episode of cooling starting at ~104 Ma, as reported by zircon (U-Th)/He ages from the Prikolyma Terrane [110]. Paleoproterozoic detrital zircons, with predominant age peaks at 1860–2050 Ma, were likely derived from metamorphic basement complexes in the Omolon Terrane [26,108,109] (Figure 8) or could alternatively have been recycled from Devonian–Carboniferous sedimentary strata deposited across the southern part of the Prikolyma Terrane [21]. The Ordovician–Silurian zircons were possibly sourced from the Maya-Abkit Magmatic belt (Figures 8 and 9), which contains volcanic rocks dated at 433–425 Ma and 440 ± 2 Ma in the Omolon-Taigonos area [34] and in the Rassokha block of the Omulevka Terrane [31], respectively (Figures 1 and 2). Alternatively, abundant 425–450 Ma zircons have also been reported from Emsian–Eifelian sandstones of southern Prikolyma [21] and could also be the source of similarly aged zircons in the Omsukchan basin. The potential sources for Devonian–Carboniferous detrital zircons could be Devonian–Early Carboniferous subduction-related volcanic rocks of the Kedon Complex and co-magmatic felsic intrusions within the North Okhotsk Magmatic arc [27–30], which have a widespread distribution across the Omolon Terrane. Alternatively, these zircons could also be sourced from Magmatic rocks from the Uvyazka block in the north-eastern part of the Omulevka Terrane (395 ± 2.9 Ma, U–Pb, [32]), or from reworking of Devonian–Carboniferous strata across the Prikolyma Terrane, where 333–405 Ma zircons are abundant [21]. Potential sources of the subordinate ~260 Ma zircon age component are the Okhotsk-Taigonos volcanic arc or erosion and reworking of Late Permian clastic rocks from the Balygychan (Ayan-Yuryakh) anticlinorium [61] (Figures 1 and 2).

The provenance areas for the 299–309 and ~500 Ma old detrital zircons remains enigmatic due to an absence of documented coeval Magmatic and tectonic events across the north-east Asia active Margin [1].

Two samples (17AP29 and 17AP36) were collected from the Monkhaidyn Formation, previously considered as Late Carboniferous–Early Permian [105], but which our data have conclusively shown to be Late Cretaceous in age. The young detrital zircon modes indicate Coniacian (17AP29) and Campanian (17AP36) Maximum depositional age estimates. The presence of these Cretaceous ages provide evidence for a northward extent of the Omsukchan basin for more than 35 km, covering the south-eastern part of the Prikolyma Terrane (Figures 2 and 3).

Jurassic strata of West Verkhoyansk and the In'yaly-Debin synclinorium are dominated by detrital zircon U–Pb age components of 280–287 Ma, 480 Ma, and 1830–1960 Ma (Figure 11), indicative of source areas located along the southern Margin of the Siberian continent [90,111]. The absence of Neoproterozoic and Mesoproterozoic grains is a diagnostic Manifestation of the “Siberian Gap” [111,112]), representing a period of tectonic quiescence during formation of the Siberian Craton basement [90,111]. Furthermore, Jurassic rocks of the West Verkhoyansk area and the In'yaly-Debin synclinorium were deposited by the paleo-Lena River on the Verkhoyansk passive Margin of Siberia [90,111]. In contrast, the Main source regions for clastic Jurassic strata of the Sugoi synclinorium and Cretaceous rocks of the Omsukchan basin were the Magmatic belts associated with the north-east Asian active Margin and, to a lesser extent, with continental blocks of the Kolyma-Omolon Superterrane (Figure 12).

Figure 11. Comparison between detrital zircon ages from Jurassic sandstones of West Verkhoyansk, In'yali-Debin synclinorium, Sugoi synclinorium, and Cretaceous rocks of the Omsukchan basin. The Main sources of detrital zircons are shown in color.

Figure 12. Palaeogeographic Maps of NE Asia for the Middle—early Late Jurassic (A) and Hauterivian—Late Cretaceous (B) (modified from [6,111,113]). Main Jurassic and Cretaceous sedimentary basins: SG—Sugoi, OB—Omsukchan, ID—In'yali-Debin, PS—Polousnyi, VB—Vilyui, PB—Priverkhoyansk, ZR—Zyryanka. Terranes: PT—Prikolyma, OT—Omolon, O—Omulevka, WV—West Verkhoyansk. Magmatic belts: UM—Uda-Murgal, OCVB—Okhotsk-Chukotka, UY—Uyandina-Yasachnaya, MB—Main (Kolyma), NB—Northern, SO—Svyatoi Nos-Oloy, SV—South Verkhoyansk.

6. Conclusions

U–Pb dating of detrital zircons from Middle–Upper Jurassic clastic rocks of the Sugoi synclinorium and Cretaceous clastic and volcanoclastic rocks of the Omsukchan basin across the south-eastern Verkhoyansk–Kolyma orogenic belt has revealed new insights regarding the Mesozoic tectonic and paleogeographic evolution of the area. The salient insights and conclusions are:

1. Middle–Upper Jurassic rocks of the Sugoi back-arc basin were likely sourced from the Uda–Murgal arc;
2. The Uda–Murgal arc comprised Early–Middle Jurassic felsic Magmatic rocks, which were either subsequently eroded or completely buried beneath younger Cretaceous rocks of the Okhotsk–Chukotka Magmatic belt;
3. Aptian deposits were Mainly sourced from the Main (Kolyma) batholith belt and Uyandina–Yasachnaya arc;
4. A Major change in provenance occurred during the Late Cretaceous in the Omsukchan basin, as reflected by the arrival of clastic input derived from granitoids of the Main (Kolyma) batholith belt, volcanic, and plutonic rocks of the Uyandina–Yasachnaya and Okhotsk–Chukotka arcs and with a significant addition of clastic Material from the uplifted Kolyma–Omolon Superterrane;
5. Comparison of detrital zircon U–Pb age distributions of Mesozoic rocks in the Sugoi and Omsukchan sedimentary basins suggests that they were not deposited along the Verkhoyansk passive continental Margin of Siberia;
6. Our data allow us to assign new depositional ages to non-fossiliferous volcanoclastic rocks across the south-eastern Prikolyma Terrane and revise Late Carboniferous–Early Permian to Late Cretaceous. As a consequence, the northern boundary of the Omsukchan basin should be moved farther northward, covering older deformed rocks of the Prikolyma Terrane;
7. This study provides new insights into the evolution of sedimentary basins and their relations to Magmatic belts across the north-east Asia active Margin and could be used to inform larger scale paleotectonic and paleogeographic reconstructions of NE Asia.

7. Future Work

The Jurassic–Cretaceous provenance models proposed here are based on U–Pb dating of detrital zircons and sandstone petrography. Further work to study Mesozoic sedimentation requires acquiring additional U–Pb zircon data from Triassic, Jurassic, and Cretaceous clastic and volcanoclastic rocks of this region, accompanied by geochemistry of Magmatic rocks and Lu–Hf study of detrital zircons. This will subsequently improve our understanding of the Mesozoic history of the north-east Asia active Margin.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2075-163X/11/3/291/s1>, Table S1: Results of U–Pb dating of detrital zircons.

Author Contributions: A.V.P., investigation, writing—original draft preparation; V.B.E., investigation, editing; D.F.S., investigation, editing. All authors have read and agreed to the published version of the Manuscript.

Funding: U–Pb dating was supported by the project “Changes at the Top of the World through Volcanism and Plate Tectonics: A Norwegian–Russian–North American collaboration in Arctic research and education: NOR–R–AM 2”. Interpretation of isotopic data of Jurassic rocks was supported by the Russian Science Foundation (grant No. 20-17-00169). Interpretation of isotopic data of Cretaceous rocks and interpretation of isotopic data was supported by the Russian Foundation for Basic Research (RFBR) (grant No. 19-05-00945). Field work was partly supported by DPMGI SB RAS (project No. 0381-2019-0001).

Data Availability Statement: Not applicable.

Acknowledgments: The authors are most grateful to Vladimir Shpikerman and Vasilii Proskurnin (Karpinskiy Russian Geological Research Institute, St. Petersburg, Russia) for their help in conducting field work. We would like to thank Lisa Stockli for analytical assistance. We thank three anonymous reviewers for their constructive comments, suggestions, and corrections, which very much helped to improve the Manuscript. We are grateful to James Barnet for correcting the English.

Conflicts of Interest: The authors declare no conflict of interest.

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