Detrital zircon U-Pb geochronology of Mesozoic sandstones from the Lower Yana River, northern Russia

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ABSTRACT

The formation of the Amerasian Basin of the modern Arctic remains enigmatic in terms of both timing and method of formation. Most models used to describe its formation involve movement of the Arctic Alaska-Chukotka microplate across the basin’s current location. Detrital zircon U-Pb geochronology has been shown to be an inexpensive yet powerful method by which the tectonic correlation and proximity between multiple terranes over geologic time can be approximated. Five detrital zircon samples were collected from Late Jurassic sandstones from the Lower Yana River area and compared to previous results from detrital zircons collected from nearby Triassic strata. Jurassic samples had detrital zircon age populations of 147–210 Ma, 223–396 Ma, 1639–2183 Ma, and 2281–3116 Ma. Comparison of all detrital zircon ages from the Lower Yana River to those dated from Triassic and Jurassic sandstones of Chukotka, the Verkhoyansk fold-and-thrust belt, and the In’yali-Debin synclinorium supports the interpretation that Chukotka was separated from the Kular area during the Triassic. Jurassic detrital zircon age populations suggest that the Anyui Ocean had closed by the Tithonian, bringing Chukotka to a location where it could be fed by similar depositional systems as the Verkhoyansk fold-and-thrust belt and the Lower Yana River area. Sedimentological and detrital data presented here also suggest that the Yana fault does not represent a regional suture between the Kolyma-Omolon superterrane and the Siberian craton.

INTRODUCTION

The tectonic history responsible for formation of the major basins of the Arctic has long been a topic of debate despite an increasing body of research. These efforts typically focus on the Amerasian Basin and its internal Canada Basin (see review in Lawver and Scotese, 1990) since the Eurasian Basin, located more proximal to the Barents Shelf, is younger and has a more easily interpreted tectonic history (Fig. 1A). Seafloor spreading models utilize multiple interpretations of the movement and function of prominent features in and around the Amerasian Basin, including the Lomonosov Ridge, the Alpha and Mendeleev Ridges, the Chukchi Cap, the Northwind Ridge, and the Arctic Alaska-Chukotka microplate (Fig. 1A). The Arctic Alaska-Chukotka microplate includes the North Slope and Seward Peninsula of Alaska, as well as Chukotka, the New Siberian Islands, Wrangel Island, and the East Siberian Shelf of northeast Russia. Because of access difficulties to the Arctic basins, most studies are limited to research of the landmasses surrounding the Amerasian Basin. More specifically, detrital zircon geochronology has been shown to be a powerful tool for determining sedimentary provenance and for tectonic reconstructions when source regions can be identified (Andersen, 2005; Carrapa, 2010). Studies of modern river systems have shown that along a river transect, input of zircons from downstream sources can overprint upstream sources, despite higher erosive rates in the headwaters (Cawood et al., 2003). Though headwater zircon preservation may diminish downstream compared to more proximal sources, these signatures are present nonetheless and require long-distance transport. Results from a study of detrital zircons from sedimentary rocks in the Verkhoyansk Range of Siberia require transport of zircons for thousands of kilometers as well as persistence of the river responsible for deposition for up to 200 m.y. (Prokopiev et al., 2008). A similar study of marine and fluvial sandstones collected in the Colorado Plateau of the U.S. Cordillera suggests transport of detrital zircons from source regions in eastern and central Laurentia at times as far away as the Appalachian orogen along a transcontinental river system with headwaters in the southern Appalachian Mountains (Dickinson and Gehrels, 2009). These studies provide strong support that long-distance transport of detrital zircons is possible under the right circumstances. With the advent of laser-ablation–multicollector inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS), the cost of individual zircon grain dating has gone down, along with a concomitant rise in accuracy, speed, and ease of analysis.

The Lower Yana River area, describing the general area east of the Kular Dome surrounding the Yana fault and lower Yana River, was selected for this study because it is located between the Verkhoyansk fold-and-thrust belt and the Arctic Alaska-Chukotka microplate, two areas that are well studied and have abundant detrital zircon U-Pb data for the Mesozoic. Several studies by Miller et al. (2006, 2008, 2010) have already compared detrital zircon geochronologic results from several areas surrounding the Amerasian Basin. Our data will serve as a supplement to the ongoing formation of a comprehensive Mesozoic detrital zircon data set (i.e., Miller et al., 2012), and will add insight from Jurassic samples to the Mesozoic tectonic setting of northern Siberia and the Arctic. For brevity, the Lower Yana River area will be referred to as the Kular area, as it only includes data collected along the Yana River east of the Kular Dome.

GEOLOGICAL FRAMEWORK

Arctic Tectonics

Similarities of stratigraphic records, magnetic anomalies, basin correlations, and seismic
profiles comparing northern Alaska to the Canadian Arctic Islands all support an opening of the Canada Basin involving counterclockwise rotation of the Alaskan portion of the Arctic Alaska-Chukotka microplate away from an original position along the Canadian Arctic Islands, with proposed rifting ages from the Early Jurassic to the Early Cretaceous (Emby, 1990; Embry and Dixon, 1994; Grantz and May, 1983; Grantz et al., 1979; Lawver et al., 2002) (Fig. 1B). While there is an abundance of support for the pre–Canada Basin location of northern Alaska adjacent to the Canadian Arctic Islands, there is less well-documented evidence for the original location of Chukotka. According to the rotational model, Chukotka and the Siberian Shelf were attached to the North Slope of Alaska akin to their current geometry and experienced a similar rotational movement away from an original location along the northern Canadian Arctic Islands near Greenland with strike-slip or transform motion along the Lomonosov Ridge during the Mesozoic (i.e., Embry, 1990; Lawver and Scotese, 1990; Grantz et al., 1979).

However, under current interpretations regarding the Mesozoic location of Arctic landmasses, it is not possible to restore the Arctic Alaska-Chukotka microplate back to this prerift position if it is treated as a rigid, coherent block, due to large overlap of prerift landmasses and significant space problems during continental drift (Miller et al., 2006). Using detrital zircon geochronologic data, Miller et al. (2006, 2008, 2010) suggested that the Arctic Alaska-Chukotka microplate must have been a unified fragment in the late Paleozoic and that Chukotka was instead located closer to the Barents Shelf and Ural Mountains prior to formation of the Amerasian Basin, according to similarities in detrital zircon ages from Upper Paleozoic strata collected from Wrangel Island, the Lisburne Peninsula, and the Seward Peninsula of Alaska. A model presented by Miller et al. (2006) and later expanded upon in Miller et al. (2008, 2010, 2011) shows an updated pre–Amerasian Basin location for the various pieces of the Arctic Alaska-Chukotka microplate, where Chukotka and Wrangel Island were located more proximal to Baltic and east of the Uralides during sedimentation prior to rifting. Permian–Triassic rifting provided the basin in which sediments of Chukotka and Wrangel Island, derived from the Taimyr Peninsula and Ural Mountains, were deposited and severed Baltican sedimentation from the rest of the Arctic Alaska-Chukotka microplate. Miller et al. (2006) also used linear arrays of normal faults from bathymetric data to support later formation of the Makarov Basin involving rift formation parallel to the Lomonosov Ridge and orthogonal to the Canadian Arctic Islands, consistent with previous studies (i.e., Sweeney et al., 1982; Taylor et al., 1981; Vogt et al., 1982). Under this reconstruction, Pacific-directed move-out of subduction zones found along northern Eurasia was associated with rifting parallel to the Barents Shelf, resulting in formation of the Amerasian Basin during the Cretaceous (Miller et al., 2010). This rifting event was also correlated with as much as 100% extension of the Siberian Shelf in an east-west direction and movement of Chukotka along a transform boundary represented by the modern South Anyui zone (Miller et al., 2006, 2008). A prerift location of Chukotka closer to the Taimyr region also ties in with another reconstruction by Kuzmichev (2009) involving rotation of Chukotka and Arctic Alaska about two separate poles, where Chukotka experienced...
clockwise rotation away from the Lomonosov Ridge margin concurrently with counterclockwise rotation of the North Slope of Alaska away from the Canadian Arctic Islands, though retaining their connection near the modern Chukchi Sea. The specific movement pathway of the various pieces of the Arctic move in this model by way of an opening parallelogram in order to overcome various geometrical problems such as the modern acute angle between Chukotka and western Alaska and the rectangular shape of the Makarov Basin (Kuzmichev, 2009). Under this model, the South Anyui suture zone turns south within the “Chroma Loop” to connect with the Kolyma Loop on the outer border of the Kolyma-Omolon superterrane, which is thought to have collided with the Siberian platform in the Late Jurassic, rather than turning north toward the Anjou Islands, as is more commonly suspected (e.g., Spektor et al., 1981; Parfenov et al., 1993, and references within; Kuzmichev, 2009), or continuing west toward the Taimyr Peninsula (Sokolov et al., 2002).

While the specifics of movement for the various pieces of the modern Arctic are controversial, conclusions from Miller et al. (2006, 2008, 2010, 2011) regarding the close proximity between Chukotka and the Taimyr Peninsula or Uralian sources prior to the Triassic have particular merit because this geometry alleviates the problem of overlap between the Arctic Alaska-Chukotka microplate and Greenland created by closing the Amerasian Basin using the rotational model. The Chukotka part of the Arctic Alaska-Chukotka microplate is assumed to have reached its final position during the Late Cretaceous along the northern Kolyma-Omolon superterrane, which deformed passive-margin sequences along the eastern edge of the Siberian craton to form the Verkhoyansk fold-and-thrust belt in the Late Jurassic (Fig. 1). The South Anyui zone represents a suture between Chukotka and northern Russia, though the specifics of this suture are still a topic of much debate. While the main body location of the suture is generally agreed upon, the location of the suture around and west of the New Siberian Islands is very much in question (see review in Kuzmichev, 2009).

Kular Dome

The Kular Dome is located at ~70.0°N, 134.3°E, ~135 km south of the Laptev Sea and ~30 km west of the Lower Yana River and Ust’ Kuyga, Siberia (Fig. 2). In this area, granites of the Kular pluton intrude Paleozoic metasediments and Mesozoic sandstones of the Kular-Nera slate belt (Parfenov, 1991) (Fig. 3). The Kular Range contains multiple Early Cretaceous (103 Ma) biotite granite plutons (Layer et al., 2001) that crop out in multiple exposures along a northeast-southwest trend. Within our field area, the unit surrounding the Kular pluton is a biotite- and muscovite-rich andalusite-bearing metapelite, which displays top-down shear away from the pluton, involving gently plunging stretched andalusites and mantled porphyroblasts, suggestive of extensional emplacement conditions during intrusion of the pluton. These metametapelites likely formed under local moderate-temperature, low-pressure conditions associated with intrusion of the Kular pluton, as suggested by prevalence of andalusites. The next units outward from the pluton are Triassic sandstones with shale interbeds that display open folds along axes paralleling the long direction of the Kular granite (Figs. 2 and 3). Triassic sandstone units are separated from Jurassic sandstone units in the Kular area by the Yana fault, which has traditionally been interpreted as a local reverse fault within the Kolyma-Omolon superterrane, a branch of the Adycha-Taryn suture fault, or a part of the Chai-Yuryue-Indigirka suture fault (Khudoley and Prokopiev, 2007; Konstantinovsky, 2007; Oxman, 2003; Parfenov, 1991) (Figs. 2 and 3). The Adycha-Taryn thrust fault, located west of the Kular-Nera slate belt (Fig. 2), is more commonly interpreted to represent the regional suture between the Siberian craton and the Kolyma-Omolon superterrane, though the Chai-Yuryue-Indigirka reverse fault system, located directly east of the Kular-Nera slate belt, has also been interpreted as a suture. The Jurassic sediments southeast of the Yana fault are openly folded along axes striking approximately east-west and are cut by several southward-vergent thrust faults with minor displacement.

Stratigraphy

Geologic maps of northeastern Russia place the Kular Dome and Triassic sequences of the Kular area within the Kular-Nera slate belt, which has traditionally been described as an ~900–1200 km long belt of Late Permian, Triassic, and Early Jurassic black shale and turbidite deposits, which extend from the Laptev Sea in the northwest to the Sea of Okhotsk in
The southeastern Polousnyy synclinorium is separated from the Verkhoyansk fold-and-thrust belt by the Adycha-Taryn fault zone (Khudoley, 1979; Oxman, 2003; Konstantinovsky, 2007). To the west, the Kular-Nera slate belt is described by the detrital zircon data described by Miller et al. (2012) and this text, though generally younger, with maximum depositional ages suggested by detrital zircon assemblages.

In the Kular area, the relevant stratigraphy for this geochronology study includes Triassic sandstone sequences of the Kular-Nera slate belt. Well-preserved ammonites are also found within Triassic rocks of the Kular area, which further preclude deposition within a turbidite flow like those described for the Kular-Nera slate belt. Three Triassic units have been mapped in our field area previously based on their paleontological ages, T\textsubscript{3} (Late Triassic), J\textsubscript{ox} (Oxfordian), J\textsubscript{km} (Kimmeridgian), and J\textsubscript{t} (Tithonian) (Oleshko, 1981). All observed Triassic units were lithologically similar, despite age differences, though different from Jurassic units, which were also generally identical in terms of lithology. Eight thin sections were prepared using two samples from T\textsubscript{3} and six from J\textsubscript{ox}, though several outcrops were studied in the field from all mappable units. Unfortunately, in-place sedimentary outcrop was difficult to find away from the Yana River, so most data collection and observation occurred along a transect of this river from Ust’ Kuyga to the Kyuchus mining operation near the confluence with the Kyuchus tributary (Fig. 3). Due to the similarities in lithology between all Triassic units and all Jurassic units, for descriptive purposes, all mapped units will be referred to as either Triassic or Jurassic sandstones.

Triassic sandstones found west of the Yana fault have 20%–25% lithics, mostly metamorphic fragments and minor chert, 35%–40% quartz, mostly monocrystalline with few polycrystalline grains, 20%–25% feldspars, 2%–15% opaque iron-oxide material, likely diagenetic hematite, and occasional (<1%) calcite rhombs. Total biotite with minor associated muscovite may locally comprise as much as 10% of sample volume, though it is in general much less common. All grains are generally medium sized and angular with poorly defined grain boundaries. Laminated black shales and red-colored mudstone interbeds, generally <1 mm thick, are also common and often show thin, soft-sediment, fluid-supported slump folds with wavelengths of 1 m or less, and occasional cross-beds, rip-up clasts of partially lithified mud, and burrows. Ripple marks are also exposed, which, together with structures described previously, are in agreement with deposition in a delta or prodelta environment just offshore and are inconsistent with deposition in a continental slope environment commonly invoked for deposition of the Kular-Nera slate belt. Well-preserved ammonites are also found within Triassic rocks of the Kular area, which further preclude deposition within a turbidite flow like those described for the Kular-Nera slate belt.

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samples yield a magmatic arc as the most likely provenance, according to diagrams developed by Dickinson et al. (1983) (Fig. 5), though the lack of volcanioclastic grains in Triassic samples suggests that a mixed source may more accurately describe the source for Triassic rocks.

Jurassic units east of the Yana fault are fine to coarse grained and have a high amount of muddy matrix. Grains are angular and poorly sorted, with sizes ranging from <30 µm to 0.5 mm. Samples are composed of 20%–35% matrix, 5%–10% lithic fragments with subequal proportions of volcanioclastic grains and chert, 20%–30% quartz, mostly monocrystalline, 30%–35% feldspars, and minor amounts of white mica, biotite, and diagenetic hematite. Volcanioclastic lithic fragments are basaltic or andesitic and show characteristic plagioclase-rich matrix (Fig. 6). Bedding of Jurassic units is massive, with beds 5–6 m thick, showing abundant laminated organic-rich black shale interbeds and occasional conglomerate lenses up to 2 m in diameter containing aligned, rounded lithic clasts. Wood fragments were also noticed in some sections, supporting a depositional location near the continent. Flat, rounded rip-up clasts similar to those found in Triassic units were also common along both the top and bottom of beds in Jurassic units. Reverse grading was visible in multiple locations, along with prevalent slump folding and abundant 1–2-m-thick conglomerate lenses, suggesting the likelihood of rapid subaqueous fan deposition potentially within a prodelta environment, with preservation of wood and faunal assemblages within the delta plain segment of an overall prograding delta system. Impressive flute casts several centimeters in thickness were also commonly visible on the underside of tilted layers, suggestive of a paleocurrent toward the SE upon restoration of bedding (Fig. 4B). Four previously mapped units were adopted for this study based on previously published palaeontological ages and new detrital zircon ages from J3ox, J3km, and J3t occurring within our field area. These units are exposed as open folds striking approximately east-west within northward-vergent imbricated thrust packages east of the Yana fault (Fig. 3). Unit thicknesses range from 0.6 to 1.3 km (Oleshko, 1981). A QmFLt plot based on multiple 300 point-count analyses of thin sections suggests that a continental source is most likely for Jurassic samples (Dickinson et al., 1983) (Fig. 5), though different from Triassic sedimentation due to prevalence of volcanioclastic grains in Jurassic samples.

GEOCHRONOLOGY

Geochronologic analysis of detrital zircons was performed on seven samples (two Triassic, five Jurassic) collected along the Yana River south of Us’ Kuyga (Fig. 3) using LA-MC-ICP-MS at the University of Arizona LaserChron Center. Samples were crushed and separated using standard gravimetric and magnetic separation techniques at West Virginia University. Following separation, grain mounts were created and polished at the LaserChron Center and were imaged using reflected light and cathodoluminescence (CL). No fewer than 100 grains per sample were randomly ablated using a 35-µm-diameter laser. For every five sample grains ablated, one standard grain (also added to each mount) was targeted. For this study, standard R33 was used, which yields an isotope dilution–thermal ionization mass spectrometry (ID-TIMS) age of 419.3 ± 0.4 Ma (Black et al., 2004). Individual zircon grain ages were determined using 238U/206Pb ratios for grains younger than 1.4 Ga and 207Pb/206Pb ratios for grains older than 1.4 Ga, due to higher precision within these respective ranges (Gehrels and Pullen, 2010). Analyses with greater than 30% discordance or greater than 5% reverse discordance between 238U/206Pb and 207Pb/206Pb ages were discarded. Of the grains ablated, 87% had a U/Th ratio less than 3, indicating a magmatic source (Hoskin and Black, 2000). For more detailed information on the analytical process, see review of operating procedure in Gehrels and Pullen (2010) and Gehrels et al. (2006).

Results from geochronologic analysis of the Kular samples are listed in Appendix 1 of the GSA Data Repository1 and are shown in probability density plots in Figure 7. Detrital zircon data from the Kular area are plotted in Figure 8 along with data compiled from previous studies in areas surrounding the Amerasian Basin.

1GSA Data Repository item 2012336, which includes Appendices 1 (full detrital results from the Lower Yana River area) and 2 (compiled detrital age ranges from various publications), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado 80301, USA.
DISCUSSION

When possible, age ranges and peak ages using complete data sets from all samples were calculated with AGEPICK and compiled into sets of representative age ranges for each location (Appendix 2 [see footnote 1]; Fig. 8). Most representative age ranges were based on multiple samples. Detrital zircon populations were compiled from the literature from multiple sources surrounding the Amerasian Basin and are described in the following sections, though zircons collected in northern Chukotka and along the Dyanyshka River within the Verkhoyansk fold-and-thrust belt are most relevant to this discussion (Fig. 1).

Zircons from Chukotka’s Triassic 5.5-km-thick sequences of distal turbidites (Bychkov, 1994) near Bilibino, Russia, were dated by Miller et al. (2006) and were supplemented with Jurassic zircons from nearby massive, well-cemented arkosic sandstones collected north of Bilibino to Pevek (Miller et al., 2008). Pennsylvanian–Jurassic detrital zircon samples diagnostic of Siberian cratonal passive-margin sequences collected from the central Verkhoyansk fold-and-thrust belt were described in greater detail by Prokopiev et al. (2008) and Miller et al. (2006). Units of the Verkhoyansk fold-and-thrust belt are well exposed along the Dyanyshka River just east of the Vilyui graben. Triassic samples from this area were from the Tolbon and Khedalichen Formations, which were previously dated as Anisian-Ladinian and Carnian-Norian based on faunal data (Gradstein et al., 2004).
Triassic Detrital Zircon Data

Results from the Triassic samples of the Kular area (Miller et al., 2012) are in agreement with interpretations by Miller et al. (2006, 2008) that detrital zircon data from Chukotka and western Alaska place these areas closer to the Taimyr Peninsula and the Verkhoyansk fold-and-thrust belt than to the Canadian Arctic during the early Mesozoic. This observation is based on abundance of detrital zircons in Chukotka likely derived from Uralian sources and a higher degree of similarity of detrital zircon populations between Chukotka and Siberian areas than between Chukotka and Laurentian areas (Fig. 8). In Triassic samples, Chukotka and western Alaska display a different range of zircon ages than the Verkhoyansk Range, while Triassic data from Kular show similarities to both Chukotka and Verkhoyansk. Specifically, both Kular and Chukotka Triassic samples have 225–260 Ma and 730–850 Ma zircons that are absent from Verkhoyansk Triassic samples (Fig. 8). However, both Kular and the Verkhoyansk Range lack 800–1000 Ma and 1000–1315 Ma zircon populations that are present in Triassic Chukotka samples (Miller et al., 2006). The presence of Permian–Triassic zircons in Kular and Chukotka is significant since granitic rocks of this age are uncommon in northern Siberia. Potential source areas for Permian–Triassic zircons are the southern Taimyr Mountain range, where doleritic sills aged 220–230 Ma and 250 Ma A-type granites are common (Walderhaug et al., 2005; Vernikovsky et al., 2003), and the widespread Siberian Traps south of Taimyr, which contain mafic volcanics with mean ages of ca. 250 Ma (Dalrymple et al., 1995; Reichow et al., 2002; Renne and Basu, 1991). Though mafic sources are unlikely to contribute substantial amounts of detrital zircons to sedimentary samples, widespread syenite and quartz syenite intrusions with mafic components not exceeding 15% total content, as well as lesser quartz monzonite, subalkaline granite, alkaline syenite, and granite are found in the northwestern Taimyr Peninsula (Vernikovsky et al., 2003). These intrusions have been dated via U-Pb analysis of zircons and have a likely emplacement age of 241–249 Ma, i.e., coeval or shortly following Siberian Trap magmatism, and are suggested to be related to the Permian–Triassic northern Eurasian superplume that generated the Siberian Traps (Vernikovsky et al., 2003). Assuming a Taimyrian source, zircons of these ages were likely carried northward along the paleo–Taimyr River system (Miller et al., 2012) which supplied elastic material to the northern part of the platform (modern coordinates), the Kular area, and to the Polousnyy synclinorium, but...
not to the more southern Verkhoyansk region, which was fed mostly by the paleo–Lena River (Prokopiev et al., 2008). Permian–Triassic zircons are also absent from the Sadlerochit Mountains and Sverdrup Basin data (Miller et al., 2006) (Fig. 1), despite other similarities to Triassic data from the Arctic Alaska-Chukotka microplate. More important for Triassic detrital zircon data is the lack of 730–850 Ma zircons in the Verkhoyansk Range, but their presence in both Kular and Chukotka. In Miller et al. (2006), these zircons are suggested to have also been from the Taimyr region as age ranges of zircons are within error of samples collected from granitic and metamorphic rocks of the Central Belt of Taimyr (Pease et al., 2001; Pease and Vernikovsky, 2000, and references within). Another potential source for zircons of this age is the Baikalia region (Transbaikalia and Prebaikalia) to the south, which is known to have granitic intrusions ranging in age from 772 to 831 Ma, though the lack of zircons of this age in the Verkhoyansk Range suggests that the Taimyr region is a more likely source for Chukotka and Kular. Zircons in the range of 850–1000 Ma and 1000–1315 Ma are prevalent in Triassic Chukotka samples (Miller et al., 2006) but are conspicuously absent from both Kular and the Verkhoyansk Range. Interestingly, zircons of this age were also seen in Triassic samples from Wrangel Island, western Alaska (Lisburne Hills), and eastern Alaska (Sadlerochit Mountains and the Sverdrup Basin) (Fig. 8), though percentages of this age range are greatly diminished relative to late Paleozoic samples from the same areas (Miller et al., 2010). Though all three areas have Precambrian zircons of varying age ranges (Fig. 8), differences in younger populations of zircons (less than 400 Ma) suggest that Chukotka and western Alaska may have shared sedimentation sources that were different from those feeding eastern Alaska during the Triassic. Decreased amounts of Late Proterozoic zircons found in Triassic samples from Chukotka and Wrangel Island relative to upper Paleozoic samples from the same areas suggest a change from Baltican deposition in the Paleozoic to a Taimyr or Uralian source in the Late Permian–Triassic (Miller et al., 2010). The presence of Middle to Late Proterozoic zircons in Upper Paleozoic samples from Chukotka and Wrangel Island suggests a prior connection to intrusions found in Baltica that is further supported by deposition in these areas across Upper Paleozoic platformal sediments underlain by Neoproterozoic rocks of the Timanides also associated with Baltica (Bingen et al., 2008, and references within; Miller et al., 2010). Triassic samples from Kular, Chukotka, and Verkhoyansk all contain zircons in the range of 1600–2100 Ma, which match basement ages from the Siberian craton. Similarities between all three sites (Chukotka, Kular, and Verkhoyansk) suggest that they shared some sedimentation sources during the Triassic, though Chukotka and to a lesser extent, the Kular region seem to have been fed by more varied sources, because they contain zircons from age ranges not seen in the Verkhoyansk Range. These interpretations, including the similarity of detrital zircon ages collected from Chukotka to igneous ages from the Taimyr Peninsula and similarity between Chukotka and Kular area detrital zircon data, put Chukotka closer to northern Russia and the Barents Shelf prior to development of the Amerasian Basin, supporting original conclusions by Miller et al. (2006, 2008, 2010).

### Jurassic Detrital Zircon Data

Deposition of the Kular Jurassic units must have occurred following initiation of collision between the incoming Kolyma-Omolon superterrane and the Siberian craton based on differences between Triassic and Late Jurassic Kular detrital data. Potential sources for the 162 Ma peak seen in Jurassic samples are the Selenga (135–295 Ma), Uda-Murgal, and Stanovoy (96–203 Ma) subduction-related arcs that formed during subduction of the Mongol-Okhotsk Ocean plate under the North Asian cratonic margin (Parfenov et al., 2009). The Selenga volcanic-plutonic belt was also suggested to have provided detrital zircons of similar ages found in the Verkhoyansk fold-and-thrust belt along the Dyanyshka River, having traveled northward along the paleo–Lena River system (Prokopiev et al., 2008). Presence of volcanioclastic lithic fragments in Jurassic samples is further indication of an arc source for these younger zircons, and the low percentage of volcanioclastic fragments is in agreement with the low numbers of Middle–Late Jurassic zircons in Jurassic samples (average of 2% Main belt–aged zircons per sample), supportive of diminishing percentages caused by the long distances traveled, overprint of upstream sources by downstream sources (Cawood et al., 2003), and influence from the incoming Kolyma-Omolon superterrane. The Kular area was situated closer to the colliding terrane than was the Dyanyshka River (Verkhoyansk in Fig. 1A), which remained more insulated from the effects of collision with the Kolyma-Omolon superterrane in the Jurassic. Samples collected from Jurassic units in the In’yali-Debin synclinorium, located directly east of the central Kular-Nera slate belt (Fig. 1A), show a nearly identical zircon age distribution to the Kular area samples, despite being located some 650 km to the southeast (Fig. 8), suggesting the likelihood of a similar arc source for Middle Jurassic zircons. Western zircon source areas for older detrital grains are compatible with the interpretation that the Kular-Nera belt was a series of eastward-deposited continental-slope fans, which likely also applies to deposition within the In’yali-Debin terrane. This interpretation is further supported by the presence of SE-directed paleocurrent indicators seen in Jurassic strata along the Yana River, as described earlier.

In’yali-Debin sediments have been described as synorogenic and are inferred to have been deposited synchronously with collision of the Kolyma-Omolon superterrane from the east (Oxman, 2003), which could be a potential source for the Late Jurassic–aged zircons found both in the In’yali-Debin and Kular areas, as previously described. Differences in the detrital signal strength between the In’yali-Debin and Kular areas may be related to their large geographical

### TABLE 1. KOLMOGOROV-SMIRNOV (K-S) TEST RESULTS FOR ALL SAMPLES FROM THE KULAR AREA WITH AGES YOUNGER THAN 229 Ma REMOVED (AGE OF THE YOUNGEST TRIASSIC ZIRCON)

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Note: Zircons younger than 229 Ma are not considered because they represent additions based on depositional age. Specific P-values discussed in text are emphasized in bold. See Figure 3 for sample locations.
separation. Both the In’yali-Debin terrane and Kular lack a 450–550 Ma range of zircons (commonly attributed to the Central Asia fold belt) that is present in the Verkhoyansk Range, supporting a disconnect between parts of the paleo-Lena River and the Kular Nera terrane caused by deformation associated with the impending Kolyma-Omolon superterrane collision.

**Triassic to Jurassic Transition**

The differences in Triassic and Jurassic Kular detrital signatures suggest a large disturbance in the sedimentation system for northern Russia between 242 Ma and 167 Ma. While Triassic and Jurassic detrital data are relatively consistent in the Dyanyshka River area of the Verkhoyansk Range, with the only major changes being the expected addition of younger signatures to the Jurassic samples and the loss of zircons older than 2300 Ma, the Kular and Chukotka Triassic detrital signatures are different from their Jurassic counterparts despite close proximity of sample collection within each area (Fig. 8). A K-S test of only Kular ages older than 229 Ma (the age of the youngest Triassic zircon dated) from both Triassic and Jurassic samples supports two different populations based on calculated P values (Table 1). Upon removal of all zircons with ages younger than 229 Ma (the Jurassic input pulse), the highest P value when comparing Jurassic Kular samples to Triassic Kular samples was 0.106. Triassic samples collected from the Kular area include a dominant 400–500 Ma signature and a smaller 730–850 Ma signature, which are completely absent from Jurassic samples collected from the same area (Figs. 7 and 8). These age ranges are most likely representative of source regions in the Central Asian fold belt, which were cut off from deposition in the Kular area and In’yali-Debin (which also lacks Central Asian fold belt signatures in Jurassic samples) by the Late Jurassic (Fig. 1A) due to compressional deformation to the west in the Verkhoyansk fold-and-thrust belt, blocking eastward flow input from the paleo-Taimyr River system.

Though Taimyr (560–850 Ma and 885–940 Ma; Pease et al., 2001; Pease and Vernikovsky, 2000, and references within) and Baltica (900–2000 Ma, with greatest proportions in the range of 1400–1800 Ma; Miller et al., 2010, and references within) zircon ages from 750 to 1000 Ma and 1000–1300 Ma are present in Triassic samples from Chukotka and western Alaska (Miller et al., 2006), suggesting close proximity between these areas in the Triassic, they are present in diminished amounts relative to their Paleozoic counterparts (Miller et al., 2010). By the Jurassic, none of the samples from similar geographic locations near modern northern Russia (South Anyui suture, Chukotka, Verkhoyansk, Kular, Stolbovoi Island, and In’yali-Debin) displays zircons with ages ranging from 750 to 1300 Ma at all (Miller et al., 2010). This suggests that by the Jurassic, these areas had likely become more closely linked geographically than they were in the Triassic and that they were also separated from the source of the Middle–Late Proterozoic zircons by this time. Chukotka, Verkhoyansk, and the Kular areas are, however, similar in terms of other age distributions and prominent peak ages in Triassic samples (Fig. 8), indicating some similarity in sedimentation systems during the Triassic and further evidence that Chukotka was not separated from northern Siberia during the Triassic, as is suggested by the rotational model. Chukotka, however, may have begun separation from Baltic sources by the Triassic due to rifting along northern Siberia, separating Baltic and Uralian sediments from Chukotka and the Taimyr regions. This separation is evidenced by diminished percentages in 1000–1300 Ma detrital zircons from Triassic samples collected in Wrangel Island, Lisburne Hills, Alaska, and Chukotka as compared with late Paleozoic samples collected from the same areas (Miller et al., 2010), though it is noted that Uralian sources for Chukotka sediments cannot be ruled out (Miller et al., 2006). These data are also consistent with conclusions of Miller et al. (2006), who stated that source regions for Permian–Triassic zircons found in Triassic samples of Chukotka could have included the Taimyr region or a Uralian source, provided they included river systems passing through the Taimyr and Siberian Trap regions. Incorporating Jurassic detrital zircon data into emplacement models for Chukotka suggests that by the Tithonian, Chukotka was situated north of the Kular area, which is in agreement with the Miller et al. (2008) conclusion that the South Anyui suture must have begun to form by the Tithonian, closing the Anyui Ocean. The youngest age in Kular Jurassic sediments is ca. 160 Ma, and Kular Jurassic data match Chukotka Jurassic data, precluding separation of the two areas by an oceanic basin by the Late Jurassic, despite likely separation in the Triassic. Further evidence supporting closure of the South Anyui Ocean by the Tithonian is the presence of detrital zircons with likely source areas from south of the South Anyui suture (1.7–2.1 Ga) found in Late Jurassic samples from Chukotka (Miller et al., 2008).

Kular and Chukotka appear to have similar detrital zircon signatures for the Jurassic despite differences in the Triassic. Neither one has zircons older than 2200 Ma in Triassic samples; they both have zircons ranging in age from 1600 to 2800 Ma, with wide age ranges older than 2200 Ma and a matching age peak at 1920 Ma, in Jurassic samples, matching Aldan Shield ages seen in Triassic Verkhoyansk data. The Aldan Shield is commonly invoked as a source of Precambrian zircons because it represents the largest exposure of Precambrian basement in the Siberian platform (Glebovitsky and Drugova, 1993). The change in sedimentation source that added older zircon populations by the Late Jurassic (possibly Aldan Shield or equivalent basement) affected both Kular and Chukotka, suggesting connection to a sedimentation system that had previously only reached the Verkhoyansk area. Absence of the 2200–3000 Ma signature in the Verkhoyansk Jurassic samples suggests both a change in the paleo-Lena River deposition (as suggested in Prokopiev et al., 2008), as this age range was present in Triassic samples, and also that the paleo–Lena River was not responsible for transport of Aldan Shield zircons to Chukotka and the Kular area in the Jurassic. It could be that as collision with the Kolyma-Omolon superterrane began, it formed a NW-SE–oriented watershed where sediments from the Aldan Shield could have traveled up the northeast edge of the continent, bypassing the paleo–Lena River. So, in the Triassic, this extra sedimentation source was likely just moving eastward into the basin, and most sediments to Kular were coming through the Verkhoyansk area along the paleo–Lena River (Prokopiev et al., 2008) or along the paleo–Taimyr River system (Miller et al., 2012). Following Jurassic accretion, this new pathway from the Aldan Shield could have bypassed the paleo–Lena River to the east and supplied an additional older population to both Chukotka and Kular.

**Tectonic Implications of Detrital Zircon Data**

Extensive work performed around the Canada Basin supports a Late Jurassic–Early Cretaceous opening, which is at odds with detrital data presented here if the Alaskan and Chukotkan portions of the Arctic Alaska–Chukotka microplate are treated as a coherent block during opening of the Canada Basin. Resolutions to this problem involve either rifting of the Arctic Alaska-Chukotka microplate away from the Canadian Arctic Islands earlier, during the Middle to Late Jurassic, as one coherent block similar to the rotational model (Fig. 1B), or separation of the Alaskan and Chukotkan portions of the Arctic Alaska-Chukotka microplate, which would allow Chukotka to be near the Kular area during opening of the Canada Basin. Due to the strong support for Late Jurassic–Early Cretaceous opening of the Canada Basin involving rifting of the North Slope of Alaska away from
CONCLUSIONS

In recent years, detrital zircon studies focusing on Wrangel Island and the Chukotka Peninsula have suggested that the Chukotka part of the Arctic Alaska-Chukotka microplate may have been closer to Siberia during the Neocene than previously considered. Detrital zircon geochronology performed in the Kular area of northern Siberia provides an important sedimentological link among previous studies performed in the Verkhoyansk fold-and-thrust belt, Chukotka, (Miller et al., 2006, 2008, 2010; Prokopiev et al., 2008), and In’yl’-Debin regions (A. Prokopiev, 2012, personal obs.). Detrital zircon data presented here show that the paleo-Lena River system likely provided sediments to the Kular area during the Triassic, as demonstrated by the similarity in the detrital zircon data sets between the Kular area and the Dyanshinka River system of the Verkhoyansk fold-and-thrust belt, though the paleo-Taimyr River system also likely provided sediment to the Kular area in the Triassic, according to similarities to detrital zircon records of Chukotka. The detrital zircon record from Triassic sediments of Chukotka suggests a depositional source from Baltica that is not present in Kular or the Verkhoyansk fold-and-thrust belt, though Taimyr and Siberian sources are also evident, putting Chukotka near the Taimyr Peninsula and Barents Shelf in the Triassic (Miller et al., 2006). By the Late Jurassic, collision between the Kolyma-Omoilon superterane and the Siberian craton disrupted deposition in the Dyanshinka and Kular areas. Comparison of these results with those collected from landmasses surrounding the modern Amerasian Basin provides support for the separation of the Chukotka part of the Arctic Alaska-Chukotka microplate from the Baltic sources in the Late Triassic–Early Jurassic and involving dextral strike-slip movement of Chukotka along the northern Siberian Shelf to a position more proximal to the Kular area by the Middle–Late Jurassic. Detrital zircon age peaks seen in Kular samples also match well with global records for prominent zircon age peaks, contributing to the global supercontinent cycle record of zircon preservation (Condie and Aster, 2009). Sedimentological and detrital data collected from the Kular area are also strong evidence against the presence of a large regional suture represented by the Yana fault in the Kular area.

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