Tectonic evolution of the Mesozoic South Anyui suture zone, eastern Russia: A critical component of paleogeographic reconstructions of the Arctic region

Jeffrey M. Amato1, Jaime Toro2, Vyacheslav V. Akinin3, Brian A. Hampton1, Alexander S. Salnikov4, and Marianna I. Tuchkova5

1Department of Geological Sciences, New Mexico State University, MSC 3AB, P.O. Box 30001, Las Cruces, New Mexico 88003, USA
2Department of Geology and Geography, West Virginia University, 330 Brooks Hall, P.O. Box 6300, Morgantown, West Virginia 26506, USA
3North-East Interdisciplinary Scientific Research Institute, Far East Branch, Russian Academy of Sciences, Magadan, Portovaya Street, 16, 685000, Russia
4Siberian Research Institute of Geology, Geophysics, and Mineral Resources, 67 Krasny Prospekt, Novosibirsk, 630091, Russia
5Geological Institute, Russian Academy of Sciences, Pyshevskii per. 7, Moscow, 119012, Russia

ABSTRACT

The South Anyui suture zone consists of late Paleozoic–Jurassic ultramafic rocks and Jurassic–Cretaceous pre-, syn-, and postcollisional sedimentary rocks. It represents the closure of a Mesozoic ocean basin that separated two microcontinents in northeastern Russia, the Kolyma-Omolon block and the Chukotka block. In order to understand the geologic history and improve our understanding of Mesozoic paleogeography of the Arctic region, we obtained U-Pb ages on pre- and postcollisional igneous rocks and detrital zircons from sandstone in the suture zone. We identified four groups of sedimentary rocks: (1) Triassic sandstone deposited on the southern margin of Chukotka; (2) Middle Jurassic volcanogenic sandstone that was derived from the Oloy arc, a continental margin arc, along the Kolyma-Omolon block, south of the Anyui Ocean, a sample of which yielded no pre-Jurassic zircons and a single peak at 164 Ma; (3) suture zone sandstone that yielded Late Jurassic maximum depositional ages and likely predated the collision; and (4) a Mid-Cretaceous syncollisional sandstone that had a maximum depositional age of 125 Ma. These rocks were intruded by postkinematic plutons and dikes with ages of 109 Ma and 101 Ma that postdate the collision. We present a seismic-reflection line through the South Anyui suture zone that indicates south-vergent of thrusting of the Chukotka block over the Kolyma-Omolon block, opposite of most existing models and opposite in the vergence in the Angayucham suture zone, the postulated along-strike equivalent in Alaska. This suggests that Chukotka and Arctic Alaska may have different pre-Cretaceous histories, which could solve space problems with existing reconstructions of the Arctic region. We combine our detrital zircon data and interpretations of the seismic line to construct a new GPlates model for the Mesozoic evolution of the region that decouples Chukotka and Arctic Alaska to solve space problems with previous Arctic reconstructions.

INTRODUCTION

The South Anyui suture zone (Fig. 1) is a remnant of a Mesozoic ocean basin that separated the Arctic Alaska–Chukotka microplate from Siberia and from the arcs and continental blocks that eventually formed the Kolyma-Omolon block of northeastern Russia (Seslavinsky, 1979; Parfenov, 1984). It is a key tectonic boundary for paleogeographic reconstructions of the Arctic region prior to the opening of the Amerasian Basin. Although its western termination is not clear (Franke et al., 2008; Kuzmichev, 2009), it can be traced eastward using outcrops of accretionary complexes, ophiolitic rocks, and magnetic anomalies from the New Siberian Islands (Fig. 1) in the west to at least as far as central Chukotka and, more speculate, to northern Alaska, where it has been correlated with the Angayucham suture zone (Churkin and Trexler, 1981; Nokleberg et al., 2000; Amato et al., 2004). The South Anyui–Angayucham suture has been used to define the present-day southern boundary of the Arctic Alaska–Chukotka microplate (e.g., Fujita, 1978; Silberling et al., 1994), a continental block with an area comparable to that of Greenland. It was displaced by the initial opening of the Arctic basin in Early Cretaceous time (Grantz et al., 1990). Although Arctic Alaska–Chukotka translated across the Arctic to its present location, its initial geometry, initial position, and the kinematics of its trajectory remain elusive. A host of competing models have been proposed through the years (e.g., Lane, 1997; Lawver et al., 2000; Miller et al., 2006; Kuzmichev, 2009; Shephard et al., 2013). The Mississippian to Triassic stratigraphy of the North Slope basin of Alaska matches that of the Canadian Arctic Islands, so that restoring Arctic Alaska to the Canadian Arctic creates an alignment of the basin’s depocenters and produces a reasonable alignment of facies belts (Toro et al., 2004). Also, both margins experienced a simultaneous rift event in the Early Cretaceous Period (Grantz et al., 1990), but it is not clear where to restore Chukotka. A signifi-
significant problem is that the Arctic Alaska–Chukotka microplate is too long to fit comfortably in the Arctic reentrant without considerable overlap of continental crust. Thus, it is likely that Arctic Alaska–Chukotka underwent considerable internal deformation during translation (e.g., Miller et al., 2006; Shephard et al., 2013). Miller et al. (2006) used detrital zircon data from Triassic sandstone of the circum-Arctic to show that the samples from Chukotka and Wrangel Island have provenance signatures from Taimyr, Siberian Traps, and/or the Polar Urals, all regions of current Siberia. Because these detrital zircon data are in sharp contrast with samples from the Canadian Arctic and from northeastern Alaska, which have clear Laurentian affinities, Miller et al. (2006) concluded that Chukotka should be restored adjacent to the Taimyr and North Verkhoyansk, east of the Polar Urals of Russia.

We obtained detrital zircon ages from nine samples of Triassic through Cretaceous sedimentary rocks of the South Anyui suture zone. In these samples, we observe a change in the detrital zircon signature from Triassic to Late Jurassic rocks that coincides temporally with convergence along the margin of the South Anyui Ocean. We also interpret the crustal-scale structure of the region visible in the 2DV deep-crustal seismic line. The seismic data show, contrary to previous models, that the South Anyui suture zone is a south-vergent structural wedge, i.e., the opposite of the coeval Angayucham–Brooks Range orogen of Alaska. Our data from the South Anyui suture zone are interpreted in the context of the Mesozoic evolution of the Arctic region, and we use them to create a new plate-tectonic model developed using the GPlates program of Williams et al. (2012).

### REGIONAL GEOLOGY

#### Crustal Blocks

The geologic framework of northeastern Russia (Fig. 1) is the result of multistage accretion of arcs and continental fragments to the ancient Siberian craton. Relevant reviews of the regional geology include Zonenshain et al. (1990), Nokleberg et al. (2000), and Shephard et al. (2013). The Siberian (or North Asian) craton (Fig. 2) is made of several large Archean (ca. 3.2–2.7 Ga) granite-greenstone blocks assembled during an orogenic event at 2.1–1.8 Ga (Rosen et al., 1994; Gladkochub et al., 2006). Most of the Siberian craton is blanketed by a thick and largely flat-lying Neoproterozoic cover succession (1.8 Ga), early Paleozoic (494–482 Ma), and late Paleozoic (315–290 Ma) granite batholiths (Prokopiev et al., 2008) that characterize the detrital zircon populations of sediment derived from Siberia.
Figure 2. Stratigraphic columns for areas referred to in the text, based on data in Nokleberg et al. (1994), with some minor changes based on this study. Q—Quaternary, T—Tertiary, K—Cretaceous, Jr—Jurassic, Tr—Triassic.
A Devonian rifting event created the eastern passive margin of Siberia (Fig. 2), along which the immense Verkhoyansk clastic prism accumulated from Devonian to Jurassic time (Parfenov, 1991).

The Omolon block (Fig. 1) consists of Precambrian metamorphic and igneous basement ranging in age from 3.4 to 2.0 Ga covered by Neoproterozoic low-grade metasediments and Paleozoic platformal rocks (Fig. 2; Zonen-shain et al., 1990). Together, the Omolon block and its adjacent magmatic arcs and collapsed oceanic basins are referred to as the Kolyma-Omolon block (Fig. 1), and it collided with Siberia to form the Verkhoyansk fold-and-thrust belt (Parfenov, 1991). Along the boundary between the Kolyma-Omolon and the Verkhoyansk prism (Fig. 1), there are two major belts of granitoid plutons emplaced prior to and during the collision: the Main belt, with ages of 152–145 Ma, and the Northern belt, which is 135–127 Ma and strikes east-west, approximately parallel to the South Anyui suture zone (Parfenov, 1991; Layer et al., 2001; Akinin et al., 2009).

The Chukotka block (Fig. 1) of northeastern Russia includes the Chukotka Peninsula, western Chukotka extending perhaps as far west as the New Siberian Islands, and a large section of the East Siberian shelf, including Wrangel Island. It has been traditionally considered a component of the larger Arctic Alaska–Chukotka microplate, which also includes parts of northern Alaska such as the North Slope, Brooks Range, and Seward Peninsula (Moore et al., 1994). Most of Chukotka is covered by a thick succession of deformed Triassic turbidites (Fig. 2) that obscure its older history. Based on a few exposures on the mainland and on Wrangel Island, it appears that basement is composed of late Neoproterozoic crystalline rocks overlain by an early Paleozoic platformal succession (Kos’ko et al., 1993; Natal’In et al., 1999; Amato et al., 2014). Along the north coast of Chukotka, exposures of mid-Devonian granitoid plutons and metavolcanic rocks are interpreted as an arc–back-arc system (Natal’in et al., 1999). The late Paleozoic rocks of Chukotka (Fig. 2) are represented by poorly exposed shallow-water carbonate and clastic rocks that are found either in fault contact or are unconformably overlain by the Triassic succession (Chasovitin and Shpetnyi, 1964; Tuchkova et al., 2009).

Triassic strata on Chukotka (Fig. 2) consist of thick successions (up to 3000 m) of rhythmically alternating mudstone, siltstone, and fine- to coarse-grained sandstone. Lithology is monotonous over large areas, fossils are rare, and the rocks are typically folded and slightly metamorphosed, making their stratigraphic study challenging. Available fossil data, supported by detrital zircon studies, indicate that this sedimentary succession spanned the entire Triassic period from Induan to Norian time, and continued into Lower Jurassic time, where it is cut by a major unconformity (Tibilotov et al., 1982; Tyunkergav and Bychkov, 1987; Bychkov and Solov’yov, 1992; Bychkov, 1994a, 1994b; Tuchkova et al., 2009). Lower Triassic deposits are intruded by abundant gabbro sills (Gelman, 1970). These sills, dated at ca. 252 Ma in eastern Chukotka, have been interpreted to be part of the large igneous province that produced the Siberian Traps (Ledneva et al., 2011). Tuchkova et al. (2009) recognized deep shelf, slope, rise, and deep basin lithofacies at different stages of the Triassic of central Chukotka and mapped their distribution in time and space. These strata were interpreted to represent passive-margin shelf to deep-margin turbidite sedimentation along the continental margin, sourced from a metamorphic complex (Tuchkova et al., 2009). The distribution of facies was used to infer a source to the northeast, possibly in the Canadian Arctic or on the Chukotka Peninsula. Miller et al. (2006) instead showed that the detrital zircon U-Pb ages from these Triassic units point to source areas in the Taymyr Peninsula, the Polar Urals, and Bataica, not the Canadian Arctic or Alaska (Miller et al., 2006).

Above the angular unconformity that caps the Triassic turbidite succession (Fig. 2), there are Upper Jurassic and Lower Cretaceous arkosic sandstone and conglomerate of the Rauchua foreland basin that signal the onset of convergent deformation in the Chukotka fold belt and a switch in sediment provenance to a southerly source (Miller et al., 2008). The Chukotka fold belt is a broad zone of tightly folded Triassic turbidites that locally have multiple slaty cleavages. The S, cleavage, attributed to shortening during closure of the South Anyui suture, is typically subvertical in the area adjacent to the South Anyui zone (Katkov et al., 2005) and south- or southwestern-dipping near the north coast (Miller and Verzhbitsky, 2009; Miller et al., 2009). A subhorizontal cleavage (S2) overprints the older fabrics in the vicinity of the Arlanmaut metamorphic massif (Fig. 3) and has been attributed to Mid-Cretaceous (109–103 Ma) high-strain extensional deformation that was accompanied by widespread granitic magmatism (Miller et al., 2009). It appears that the overall structure of the Chukotka–South Anyui orogen is that of a bivergent convergent system, with south-directed thrusting in the South Anyui zone, as will be demonstrated later in this paper, and north-vergent tectonic transport in the northern part of the Chukotka fold belt.

**South Anyui Suture Zone**

The South Anyui suture zone (Figs. 1, 2, and 3) is a belt of intensely deformed Jurassic and Early Cretaceous lithic sandstone imbricated with volcanic, volcanioclastic, and oceanic rocks, including basalt, chert, and ultramafic rocks, that separates Chukotka from the Kolyma-Omolon block to the south and the Siberian platform to the west (Seslavinsky, 1970, 1979; Natal’in, 1984; Parfenov, 1991; Natal’in et al., 1999; Sokolov et al., 2002, 2008). The South Anyui suture zone was originally recognized by Seslavinsky (1979) based on the geologic maps of Davgai (1984), which revealed ultramafic rocks between the Bolshoi Anyui and Maly Anyui Rivers (Fig. 3). Strong aeromagnetic anomalies outline the exposed part of the South Anyui suture zone and continue to the west across a broad area covered by Neogene deposits and onto the shelf as far as the New Siberian Islands, where ophiolite fragments are also exposed (Kuzmichev, 2009). To the east, the South Anyui suture zone is obscured by extensive Late Cretaceous deposits of the Okhotsk-Chukotka volcanic belt (Fig. 3). The magnetic anomalies are not clear, but on the Chukotka Peninsula, there are small exposures of mafic rocks that have been proposed to belong to the suture (Sokolov et al., 2002). The South Anyui suture zone has also been correlated to the Angayucham suture zone of northern Alaska (Patton et al., 2011).
Figure 3. Geologic map of central Chukotka modified from Gorodinski (1980). The South Anyui suture zone (SASZ) boundaries are mapped under Cenozoic and Cretaceous cover on the basis of aeromagnetic data in Klemperer et al. (2002). The box shows location of Figure 4. OCVB—Okhotsk-Chukotka volcanic belt; Jr—Jurassic.
and Tailleur, 1977; Churkin and Trexler, 1981; Nokleberg et al., 2000), and it may also be present on Saint Lawrence Island on the Bering Shelf (Patton and Csejtey, 1980; Till and Dumoulin, 1994). Thus, in many tectonic models, the South Anyui–Anganyucham suture is one of the unifying features of the Arctic Alaska–Chukotka microplate (e.g., Nokleberg et al., 2000).

The South Anyui suture zone is a critical component of Mesozoic Arctic paleogeographic reconstructions, but there are persistent uncertainties about the geology of this area. The controversial aspects of the South Anyui suture zone are the following: (1) There are multiple exposures of mafic/ultramafic rocks with different compositions, apparent ages, and relationships with host rocks. Some of these mafic/ultramafic complexes may be remnants of the South Anyui Ocean (e.g., Aluchin), others may represent arc basement (Vurguveem complex; Ganelin and Silantyev, 2008), and still others appear to be layered mafic intrusions with ultramafic cumulates (Uyamkanda massif; Lychagin et al., 1992). (2) The ages of these mafic/ultramafic complexes are not well constrained. The majority of the published ages appear to indicate that they are Triassic or even late Paleozoic (Sokolov et al., 2009, 2015), which contradicts models in which they are associated with Jurassic arc complexes or oceanic crust. (3) The orientation of the exposed mafic/ultramafic complexes is not parallel to the inferred suture zone. The South Anyui suture zone trends mainly northeast-southeast, parallel to structural grain of the Chukotka fold belt, but the largest ultramafic complex, the Aluchin complex, has exposures with north-south contacts. There has been some speculation that these orientations result from postaccretionary strike-slip motions parallel to the South Anyui suture zone (Sokolov et al., 2002, 2009). (3) Previous structural models of the South Anyui suture zone emphasize northward emplacement of oceanic rocks onto the Chukotka passive margin (Bondarenko, 2004; Sokolov et al., 2002, 2009), but field observations and seismic data clearly show that some of the structures in the South Anyui suture zone are south-vergent (see fig. 4 in Sokolov et al., 2002; fig. 13 in Sokolov et al., 2009). (4) Late Jurassic volcanic arc rocks are found both in the South Anyui suture zone (Nutesyn arc) and on the northern margin of the Kolyma-Omolon terrane (Oloy arc), yet geochronological data on these rocks are sparse, and there is disagreement as to whether these were intra-oceanic or Andean-type arcs.

Fundamentally, there is agreement that the South Anyui suture zone is the manifestation of the collision between two blocks with different ages, separated by an ocean basin that closed as the result of subduction ending with accretion between the Kolyma-Omolon and Chukotka blocks in the Early Cretaceous Period.

**South Anyui Ocean and Ultramafic Complexes**

Mafic-ultramafic complexes are found at several separate localities in, and near, the South Anyui suture zone, and they have been interpreted as ophiolites or ophiolite fragments. These include the large Aluchin and Vurguveem (or Gromadnesky) complexes, and the smaller Uyamkanda (or Polyarny) and Merzlyui ophiolites (Figs. 3 and 4; see Sokolov et al., 2002, 2009). These complexes consist of various faulted stacks of serpentinitized peridotite and other mafic and ultramafic rocks, including pyroxenite, gabbro, sheeted dikes, basalt-chert successions, and plagiogranites. The Aluchin complex (Fig. 3) also includes blueschist-facies metamorphic rocks (Dovgal et al., 1975). The 40Ar/39Ar analyses from ultramafic rocks in the upper Uyamkanda River (Fig. 4) yielded dates of 257–229 Ma, which are consistent with a Permian or Early Triassic age, although it is not clear whether some of these argon dates provide the age of the protolith or its subsequent metamorphism (Sokolov et al., 2009). Carboniferous 40Ar/39Ar dates were obtained from the Vurguveem ultramafic complex, east of our study area (Fig. 3; Sokolov et al., 2009). Ganelin et al. (2013) obtained a 280 Ma U-Pb zircon date from a cumulate gabbro in the Aluchin complex (Fig. 3). Sheeted dikes in the Aluchin ultramafic complex yielded mainly Triassic 40Ar/39Ar dates (Sokolov et al., 2009; Ganelin et al., 2013). Overall, ultramafic and gabbroic rocks in the region have 40Ar/39Ar dates ranging from ca. 320 Ma to ca. 220 Ma (Sokolov et al., 2015), with a few gabbros at ca. 150 Ma that are likely related to Jurassic arc magmatism, as discussed later herein (Sokolov et al., 2015).

The ultramafic bodies were initially interpreted as ophiolite successions representing the Jurassic South Anyui Ocean that formerly separated Chukotka from the Kolyma-Omolon block or the Siberian craton (e.g., Zonenshain et al., 1990; Parfenov, 1991), and this model has been used in the tectonic models for northeastern Russia (Parfenov, 1991; Nokleberg et al., 2000; Shephard et al., 2013). However, the available geochronology points toward crystallization, and possibly also initial metamorphism of the ophiolites, having taken place in the Permian–Triassic. Furthermore, it has been suggested that some of these rocks crystallized in a suprasubduction setting and represent island-arc lower crust (Ganelin and Silantyev, 2008; Sokolov et al., 2009) or back-arc basin magmatism (Ganelin, 2011); therefore, little direct evidence for the Jurassic seafloor of the South Anyui Ocean has been found so far.

Another issue is that the outcrops of the ultramafic rocks are not everywhere parallel to the suture. In particular, the Aluchin complex (Fig. 3) has a NNE trend, nearly orthogonal to the suture. On the basis of its orientation and late Paleozoic age, Sokolov et al. (2009) assigned the Aluchin ophiolites to the Yarakvaam island-arc terrane, which is distinct from their South Anyui terrane.

**Mesozoic Rocks of the South Anyui Zone**

The following provides a general overview on some of the key Mesozoic clastic strata that are exposed across the South Anyui suture zone (Fig. 4). A simplified version of the geologic map is included that shows the major features of the region (Fig. 5).

Jurassic rocks are exposed throughout the South Anyui suture zone in northeast-southwest-trending belts (Figs. 4 and 5). Upper Jurassic rocks have been reported along the northern margin of the suture zone and consist primarily of calc-alkaline to subalkaline volcanic rocks that are interbedded with
Quaternary Units
- Basalt flows
- Undifferentiated unconsolidated sediment

Post-collisional Units
- Cretaceous granites
- Cretaceous intermediate intrusive rocks
- Cretaceous sedimentary and volcanic rocks of the Ainakhkurgen basin

Arc-related and Syn-collisional Units of the South Anyui Zone
- Cretaceous sedimentary rocks
- Late Jurassic sedimentary rocks
- Jurassic volcanic and volcaniclastic rocks: (Nutesyn Arc)
- Gabbro and ultramafic rocks of the Uyamkanda massif (Jurassic?)

Sedimentary Units of the Oloy Arc
- Mid-Jurassic volcaniclastic sedimentary rocks

Pre-collisional Units-AACM
- Triassic sedimentary rocks of the Chukotka Fold Belt

Pre-collisional Units
- Triassic granitic rocks
- Triassic gabbro
- Merzly ultramafic complex (Permian-Triassic?)
- Vurgueveem ultramafic complex (Permian?)
- Aluchin ophiolite (Permian-Triassic?)
- Upper Paleozoic (?) sedimentary and volcanic rocks

Geochronology Sample Key
All sample numbers 1–32 refer to samples 02An-01 to 02An-32
- 321 = Z321
- 336 = Z336
- 100 = AN100
- Detrital zircon samples
- Other sed samples
- Dated igneous rocks
- Shotpoints on seismic line
- Towns

Figure 4. Geologic map of South Anyui zone based on 1:200,000 scale Russian maps (e.g., Yegorov, 1962; Dovgal, 1964; Gulevitch, 1968) and this study. AACM—Arctic Alaska-Chukotka microplate.
Jurassic rocks in the central part of the suture zone consist primarily of Upper Jurassic siliciclastic strata (interbedded sandstone and siltstone) that were likely deposited in shallow- to deep-marine fan systems (Sokolov et al., 2009). Depositional ages are thought to be Late Jurassic (late Kimmeridgian—early Tithonian) based on faunal remains (Shekhovtsov and Glotov, 2001). Turbidite deposits are Late Jurassic–Early Cretaceous (Tithonian–Valanginian) in age based on fossils (Sokolov et al., 2002; Bondarenko, 2004).

Cretaceous rocks are exposed both in the main parts of the South Anyui suture zone as well as overlying Triassic rocks on the Chukotka block and parts of the Oloy arc rocks (Fig. 4; Dovgal, 1964). A succession of Upper Jurassic–Lower Cretaceous tuffaceous turbidites, tectonic mélangé, and volcanic and sedimentary olistostrome blocks occurs in the southeastern part of the suture zone. These strata are as young as Early Cretaceous (Berriasian–Valanginian), and overlap in part with volcanism and sedimentation associated with the Nutesyn arc.

Lower Cretaceous rocks in the central part of the suture zone consist primarily of siliciclastic strata that were likely deposited in shallow- to deep-marine fan systems (Sokolov et al., 2009). These strata have been reported from the upper parts of an Upper Jurassic–Lower Cretaceous flysch unit and were interpreted to reflect sedimentation in a forearc basin setting and remnant ocean basin (Sokolov et al., 2009). The flysch unit consists primarily of tabular deposits of interbedded sandstone and siltstone and is thought to be as young as Early Cretaceous (Tithonian–Valanginian; Sokolov et al., 2002; Bondarenko, 2004).

Early Cretaceous (Aptian–Albian) volcanic and sedimentary rocks in the Ainakhkurgen basin (Fig. 5; Shekhovtsov and Glotov, 2001) are thought to represent postcollisional overlap assemblages (Nokleberg et al., 1994). Roughly age-equivalent strata are exposed along the southern margin of the suture zone (Dovgal, 1964) and may also represent postcollisional sedimentation.

**Jurassic Volcanic Arcs**

Two Jurassic volcanic arcs existed within the South Anyui Ocean or near its northern and southern margins: the Nutesyn arc of the Chukotka margin and the Oloy arc of the Kolyma-Omolon margin (e.g., Parfenov, 1984; Nokleberg et al., 2000). They initiated at ca. 160 Ma and ceased during collisional closure of the South Anyui Ocean in Mid-Cretaceous time (e.g., Nokleberg et al.,...
and are clearly posttectonic with respect to shortening in the South Anyui-Chu-intrusive rocks though, dated by the U-Pb method, range from 117 to 109 Ma (Parfenov, 1997; Sokolov et al., 2000). The Nutesyn arc of Natal’în (1984) has also been referred to as the Kulpolney arc by Sokolov et al. (2002, 2009). We use the original term, Nutesyn arc, as did Nokleberg et al. (2000) and Shephard et al. (2013), to avoid confusion. This arc system has been correlated to the Koyukuk island arc in Alaska (e.g., Nokleberg et al., 2000). It was originally interpreted as a continental-margin arc (Natal’în, 1984; Parfenov, 1997), but Sokolov (2009, 2015) suggested that it was more likely an island arc. Some workers have proposed that mafic/ultramafic rocks of the Vurguevem complex represent basement to this island arc (Ganelin and Silantyev, 2008). Shephard et al. (2013) showed it as an island arc near Chukotka at 160–150 Ma, which matches our preferred model. Regardless of whether it was oceanic or continental, the arc was likely close to the northern margin of the South Anyui Ocean basin during Late Jurassic time (Zonenshain et al., 1990; Tit’man and Bogdanov, 1992; Nokleberg et al., 2000). In our field area, Nutesyn arc rocks crop out as a narrow belt of andesitic volcanic rocks that are inferred to be Jurassic age based on associated fossils (Radzivill, 1964; Natal’în, 1984). Associated Jurassic–Cretaceous rocks include volcaniclastic sandstone, flysch deposits, and dismembered ophiolite (Sokolov et al., 2002; Bondarenko et al., 2003).

The Oloy arc is Jurassic–Early Cretaceous in age (160–140 Ma; Layer et al., 2001; Shephard et al., 2013) and consists of mafic–siliceous volcanic and sedimentary rocks (e.g., Nokleberg et al., 1994). Lower–Middle Jurassic strata that may predate the Oloy arc are overlain by Late Jurassic–Early Cretaceous (Oxfordian–Valanginian) pyroclastic and volcaniclastic strata associated with the arc (Afizkiy, 1970; Tit’man et al., 1977; Parfenov, 1984; Shekhovtsov, 1991; Parfenov et al., 1993; Nokleberg et al., 1994). Nokleberg et al. (2000) referred to the Oloy arc as a continental margin arc that formed under a south-dipping subduction zone at the southern edge of the South Anyui Ocean, but in their tectonic models, they show it as an island arc near the Kolyma-Omolon block. Shephard et al. (2013) showed it as a continental margin arc at 160–150 Ma, which matches our preferred model.

Cretaceous Magmatism

The rocks of the South Anyui suture zone and the Chukotka fold belt were intruded by numerous Cretaceous plutons and dikes, predominantly of granitic composition. The oldest known is a syenite adjacent to the Aluchin ophiolite with a U-Pb zircon date of 142 Ma (Moll-Stalcup et al., 1995; see also our data herein) that intrudes Jurassic sedimentary rocks (Dovgal, 1964). Most of the intrusive rocks though, dated by the U-Pb method, range from 117 to 109 Ma and are clearly posttectonic with respect to shortening in the South Anyui-Chukotka fold belt (Miller et al., 2009). One granite in the South Anyui suture zone, west of the Orlowka River, yielded a date of 109 ± 3 Ma (Fig. 4; sample AN-100 of Miller et al., 2009). This magmatic event has been attributed to the onset of extensional deformation linked to rifting in the Arctic basin (Miller et al., 2009). Mid-Cretaceous magmatism was followed by regional exhumation, development of an angular unconformity, and eruption of the Okhotsk-Chukotka volcanic belt from 106 to 77 Ma, driven by subduction of the paleo-Pacific Ocean (Akinin and Miller, 2011). The Okhotsk-Chukotka volcanic belt is typically flat-lying and clearly overlaps the South Anyui suture zone and the structures of the Chukotka fold belt.

Timing of Collision

The timing of the collision between the Arctic Alaska–Chukotka microplate and the Kolyma-Omolon block is constrained by crosscutting relationships and 40Ar/39Ar cooling ages. Most plutons that cut folded Jurassic-Cretaceous rocks are 117–109 Ma in age (Miller et al., 2009). Sokolov et al. (2009) reported 40Ar/39Ar dates on greenschists of 119–106 Ma that are inferred to be related to the late stages of the collision. The Okhotsk-Chukotka volcanic belt is largely flat lying and clearly overlapped the South Anyui suture zone and the structures of the Chukotka fold belt after 106 Ma (Akinin and Miller, 2011). Thus, it appears that the collision occurred in Early Cretaceous time prior to 117 Ma. Shephard et al. (2013) used the opening of the Amerasia Basin and the subsequent rotation of the Arctic Alaska–Chukotka microplate as evidence of the closing of the South Anyui Ocean, with a final collision around 126–120 Ma, which matches the existing geochronological data.

METHODS

U-Pb Geochronology

U-Pb geochronology was carried out using two methods. Sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) dating of igneous rocks was conducted at the Stanford–U.S. Geological Survey Ion Probe Facility. The primary beam excavated an area of 25–30 µm across to a depth of ~1 µm. The analytical routine followed Williams (1998) and Strickland et al. (2011). The SQUID program (Ludwig, 2005) was used for data reduction. Isotopic compositions were calibrated by replicate analyses of zircon standard R33, which has an age of 419 Ma (Black et al., 2004). The 206Pb/238U ages were corrected for common Pb using 207Pb. Common Pb compositions were estimated from Stacey and Kramers (1975). We used the SHRIMP-RG to date two crosscutting dikes and to obtain additional ages on detrital zircons from four samples.
IGNEOUS LITHOLOGY AND GEOCHRONOLOGY RESULTS

Jurassic Volcanic Rocks

Late Jurassic volcanic and volcanioclastic rocks crop out over an area of 25 km × 100 km in the study area. Rock types range from rhyolite tuffs to mafic lavas. This unit was included in the Nutesyn arc complex by Natal’n (1984) and is overlain by Early Cretaceous sedimentary rocks that are folded about NW-SE-trending fold axes and intruded by Mid-Cretaceous granitoid plutons.

We sampled a highly altered andesite (02An-7) from this unit for geochemistry, but it was barren of zircon. The rock is gray color, is mostly equigranular, and is dominated by altered plagioclase and amphibole crystals. The presence of relict clinopyroxene suggests that the amphiboles have replaced pyroxenes. A whole-rock XRF analysis from this sample (Table 1) indicates a SiO₂ concentration of 52 wt% with no detectable K₂O and low TiO₂. The classification using the total alikals versus SiO₂ diagram places this rock in the basaltic andesite field. The lack of K₂O may result from hydrothermal alteration.

Cretaceous Intrusions

Numerous stocks and dikes are present in the South Anyui zone. We dated a syenite pluton as well as two dikes that cut deformed Jurassic–Cretaceous sedimentary rocks in order to constrain the timing of deformation and cleavage development in the host rocks.

The syenite, known as the Edegkich pluton (Fig. 4), is from a southern tributary of the Bolshoi Anyui River, to the west of the Aluchin ophiolite (Fig. 3). This pluton cuts Late Jurassic sedimentary rocks. We analyzed zircons from two samples of this pluton using LA-MC-ICP-MS (Table 2). Sample Z321 yielded a weighted mean ⁴⁰Ar/³⁹Ar age of 135 ± 4 Ma (Fig. 6A). The other sample (Sample 2336) yielded a weighted mean age of 144 ± 3 Ma (Fig. 6B). Despite some overlap on a concordia diagram (Fig. 6C), these mean ages are sufficiently different to indicate that they were likely sampled from two separate intrusions, even though they were originally mapped as one. A whole-rock XRF analysis and petrography from one of these samples (Table 1) indicate monzonite to quartz-syenite porphyry composition with Rb, Y, and Nb trace elements, classifying it as a volcanic-arc granitoid (Pearce et al., 1984).

One dike (02An-05) is a fine-grained biotite hornblende granodiorite. It cuts Triassic (Carnian) slates east of the Ustieva River and is located ~5 km east of sedimentary sample 02An-04. It has xenoliths of granite that are 5 mm in diameter. The dike strikes NNW and dips 30° south. It has zircons that are 100–200 by 50 μm with oscillatory zonation and no observed xenocrystic cores. U concentrations are generally high (1000–2000 ppm), and Th/U ranges from ~0.1 to 0.4 (Table 3). All U-Pb data (n = 10) are concordant, with a weighted mean ⁴⁰Ar/³⁹Ar age of 109.9 ± 0.8 Ma (mean square of weighted deviates [MSWD] = 0.5), which excluded two younger outliers (Fig. 6D).
The other dike (02An-11) cuts Early Cretaceous sandstone east of the Ustieva River, and it is located ~3 km from detrital sample 02An-10. The dike is vertical, strikes E-W, and is 8 m wide. It has an andesite composition and is dominated by fine-grained plagioclase and brown hornblende phenocrysts. The dike has xenoliths 5–10 cm in diameter of a coarser-grained hornblende diorite. Granite xenoliths were also observed. Sample 02An-11 has zircons that range from euhedral to rounded, with the rounded zircons yielding much older ages than the youngest zircons; distinct cores were not observed in any of the youngest crystals. U concentrations of the igneous zircons ($n = 7$) were generally low (<200 ppm), resulting in larger uncertainties in $^{206}\text{Pb}/^{238}\text{U}$, though two grains had U concentrations in the ~700–1000 ppm range (Table 3). The $^{238}\text{U}/^{206}\text{Pb}$ ages range from $111 \pm 2$ Ma to $107 \pm 4$ Ma, with one outlying grain at $115 \pm 1$ Ma. Discarding the oldest grain yields a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $109.3 \pm 1.2$ Ma with a MSWD of 0.8 (Fig. 6E). There were 10 analyses that yielded older ages (Table DR4 [see footnote 1]). These include two Middle–Late Jurassic ages, two Triassic ages, two Late Paleozoic ages (Permian and Carboniferous), one Cambrian age at 506 Ma, two Proterozoic ages at 1.72 Ga and 1.95 Ga, and one Archean age at 2.68 Ga. Xenocryst ages match well with detrital zircon ages from sample 02An-02 from the host Cretaceous sandstone (see following).

### SANDSTONE MODAL COMPOSITION AND DETRITAL ZIRCON GEOCHRONOLOGY RESULTS

Compositional trends were determined for sandstone samples collected from four Mesozoic stratigraphic units (Fig. 4). Stratigraphic intervals include (1) Middle–Late Triassic, (2) Jurassic, (3) Late Jurassic, and (4) Mid-Cretaceous. Recalculated data (Table 4) are based on procedures defined by Ingersoll et al. (1984) and Dickinson (1985). The following provides a summary of modal composition trends for each stratigraphic interval; the maximum depositional ages of the samples are listed in Table 5.

#### Chukotka Passive Margin Strata (Middle–Late Triassic)

The Triassic samples were collected from the region north of the South Anyui suture zone that has been previously interpreted as the southern passive margin of Chukotka (e.g., Tuchkova et al., 2009). They are generally fine-grained sandstone and siltstone. Triassic strata (Fig. 7A) are dominated by quartz with subordinate occurrences of lithic fragments and rare feldspar (Q 73%, F 7%, L 20%; Fig. 8). The total quartz composition consists primarily of monocrystalline quartz (Qm), with subordinate polycrystalline quartz (Qp) and relatively minor amounts of chert (C) (Fig. 7). Feldspar grains are rare, with plagioclase (P) being dominant and potassium feldspar (K) relatively less abundant (Qm 90%, P 8%, K 2%; Fig. 8). Lithic fragments consist primarily of metamorphic (Lm) and sedimentary (Ls) grains, with lithic volcanic fragments (Lv) making up a relatively smaller overall percentage (Lm 54%, Ls 30%; Fig. 8). Lithic metasomatic fragments are characterized primarily by xenoliths and schist fragments with lesser occurrences of quartzite and gneiss fragments. Lithic sedimentary fragments consist primarily of mudstone, and lithic volcanic fragments are characterized almost entirely by fine-grained volcanic groundmass.

### TABLE 1. WHOLE-ROCK CHEMISTRY AS DETERMINED BY XRF

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<tr>
<th>Sample</th>
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<th>Z336</th>
<th>Z321</th>
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<tr>
<td>Major oxides (wt%)</td>
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<td>SiO$_2$</td>
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<td>MgO</td>
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Note: Whole-rock major element concentrations were determined by X-ray fluorescence (XRF) spectroscopy. Sample 02An-7 was processed at New Mexico State University, using a Rigaku ZSX wavelength-dispersive spectrophotometer equipped with an end-window Rh target X-ray tube. Samples Z336 and Z321 were processed at North-East Interdisciplinary Scientific Research Institute (NEISRI) (Magadan, Russia) using XRF SRM-25 and VRA-30 spectrometers; bd—below detection limits; blanks—not analyzed. *All Fe was calculated as Fe$_2$O$_3$. $^\dagger$Loss on ignition (LOI) determined by weight loss after heating at 1000 °C for 20 min.
Four samples from Triassic sedimentary rocks were analyzed for U-Pb ages (Fig. 9A). Sample 02An-34 is a siltstone with slatey cleavage previously mapped as Late Triassic–Carnian in age (Dovgal, 1964). The sample is a poorly sorted, slatey siltstone with angular quartz fragments and detrital muscovite. Our geochronology data (Table 5; Tables DR2 and DR3 [see footnote 1]) revealed that one Triassic grain at 246 Ma (Middle Triassic) and a relative probability distribution curve with a main peak at 266 Ma (Fig. 9B), encompassing ages from 290 to 258 Ma, several Paleozoic peaks including a prominent Silurian peak, and the tallest Precambrian peak at 1890 Ma. When combined with the data from Miller et al. (2006) from a sample at the same locality (adding their data [n = 62 after applying our discordance and uncertainty filters] for a total n = 152), there is a total of four Triassic grains are present, and these provide a maximum depositional age of 248 ± 11 Ma (Fig. 9B). When combined with the data from Miller et al. (2006) from a sample at the same locality (adding their data [n = 62 after applying our discordance and uncertainty filters] for a total n = 152), these peaks are at 381 Ma (Devonian), 442 Ma (Silurian), and 535 Ma (Cambrian). Other prominent ages are 17 Proterozoic ages and two in the late Archean.

Sample 02An-32 was collected from a Late Triassic unit. It is a siltstone with less cleavage than the previous two samples (Fig. 9A). Although the data set is small (n = 43), sufficient numbers of young zircons (n = 6) were analyzed for a maximum depositional age of 244 ± 3 Ma.

Sample 02An-33 was collected from a unit previously mapped as Lower Cretaceous in the upper Ustieva Valley. It is a fine-grained Middle Triassic and a relative probability distribution curve with a main peak at 266 Ma (Fig. 9B), encompassing ages from 290 to 258 Ma, several Paleozoic peaks including a prominent Silurian peak, and the tallest Precambrian peak at 1890 Ma. When combined with the data from Miller et al. (2006) from a sample at the same locality (adding their data [n = 62 after applying our discordance and uncertainty filters] for a total n = 152), there is a total of four Triassic grains are present, and these provide a maximum depositional age of 248 ± 11 Ma (Fig. 9B). When combined with the data from Miller et al. (2006) from a sample at the same locality (adding their data [n = 62 after applying our discordance and uncertainty filters] for a total n = 152), these peaks are at 381 Ma (Devonian), 442 Ma (Silurian), and 535 Ma (Cambrian). Other prominent ages are 17 Proterozoic ages and two in the late Archean.

The final Triassic sample (02An-10) was collected from a unit previously mapped as Lower Cretaceous in the upper Ustieva Valley. It is a fine-grained
Figure 6. U-Pb zircon dates for intrusive rocks. (A) Weighted mean age for syenite sample Z321. (B) Weighted mean age for syenite sample Z336. (C) Tera-Wasserburg concordia plot for both syenite samples, Z321 in red, Z336 in blue. (D) Tera-Wasserburg concordia plot for dike sample 02An-05 with inset showing weighted mean plot. Dashed ellipses represent zircons likely affected by Pb loss. (E) Tera-Wasserburg concordia plot for dike sample 02An-11 with inset showing weighted mean plot; unfilled bar in weighted mean plot was not used to calculate the age. MSWD – means square of weighted deviates.
sandstone with quartz, plagioclase, microcrystalline chert clasts, and muscovite. It has a maximum depositional age of 216 Ma (Late Triassic) and a main peak at 307 Ma (late Carboniferous), encompassing ages from 315 to 290 Ma (Fig. 9A). Other peaks are at 360 Ma (Late Devonian), and 429 Ma (Silurian). Out of all of the analyses (n = 102), there were 28 Proterozoic ages and one Archean age at 2.58 Ga (Fig. 9A). Because of the lack of Jurassic zircons and the similarity in the relative probability plot to the other Triassic samples, we interpret this rock as having been deposited in Late Triassic time.

Together, our new detrital zircon data combined with those of Miller et al. (2006) (Table 5; Fig. 10) indicate that Triassic rocks have maximum depositional ages ranging from 248 ± 11 Ma to 216 ± 11 Ma, consistent with published paleontological ages for these units (Carnian to Norian). The relatively large uncertainties arise from the scant number of Triassic zircons in each sample. Out of 528 analyses, only 35 are Triassic or within error of the Permian-Triassic boundary, with a peak at 247 Ma. The main peaks in the entire data set are at 298 Ma (Early Permian, 33% of the zircons), 440 Ma (Early Silurian, 29%), 808 Ma (Neoproterozoic, 10%), 1.15 Ga (Mesoproterozoic, 5%), and 1.85 Ga (Paleoproterozoic, 19%), and a few 2.22 Ga to 3.23 Ga ages (Paleoproterozoic to Archean, 5%). The Pre cambrian-aged zircons from all of the Triassic samples, when plotted together (Fig. 11), show a wide range of ages, including grains younger than 1700 Ma.

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Note: Analyses conducted by sensitive high-resolution ion microprobe (SHRIMP) at the Stanford/U.S. Geological Survey facility.

*Common Pb component (%) of total 206Pb, determined using measured 204Pb.

TABLE 3. COMPLETE IGNEOUS U/Pb ZIRCON SHRIMP DATA

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### TABLE 4. RECALCULATED POINT-COUNT DATA

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<td>59</td>
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</tr>
<tr>
<td>Middle–Late Triassic (Chukotka)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02An-10 (Medium-grained sandstone)</td>
<td>77</td>
<td>7</td>
<td>16</td>
<td>62</td>
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<tr>
<td>02An-32 (Fine-grained sandstone)</td>
<td>75</td>
<td>9</td>
<td>16</td>
<td>59</td>
</tr>
<tr>
<td>02An-33a (Fine-grained sandstone)</td>
<td>67</td>
<td>6</td>
<td>27</td>
<td>59</td>
</tr>
<tr>
<td>02An-34 (Fine-grained sandstone)</td>
<td>73</td>
<td>5</td>
<td>22</td>
<td>70</td>
</tr>
</tbody>
</table>

### TABLE 5. MAXIMUM DEPOSITIONAL AGES OF SOUTH ANYUI SANDSTONES

<table>
<thead>
<tr>
<th>Sample Locality</th>
<th>Maximum depositional age (±2σ Ma)</th>
<th>MSWD</th>
<th>N (mean)</th>
<th>Youngest zircon (Ma)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Age (previous)</td>
<td>Age (revised)</td>
<td>N (total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chukotka: Mid–Late Triassic</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>02An-34/ELMCH2.6 Bilibino</td>
<td>T3</td>
<td>T2</td>
<td>152</td>
<td>248 ± 11</td>
<td>1.3</td>
</tr>
<tr>
<td>02An-33/ELMCH3.1b Keperveem</td>
<td>T3</td>
<td>T2</td>
<td>135</td>
<td>244 ± 3</td>
<td>1.4</td>
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<tr>
<td>02An-32 Upper Uyamkanda</td>
<td>T3</td>
<td>T3</td>
<td>49</td>
<td>225 ± 36</td>
<td>9.7</td>
</tr>
<tr>
<td>02An-10 Upper Ustieva</td>
<td>K1</td>
<td>T2</td>
<td>132</td>
<td>216 ± 11</td>
<td>3.7</td>
</tr>
<tr>
<td>Oloy: Mid-Jurassic</td>
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<td></td>
<td></td>
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<tr>
<td>02An-18 Upper Orlovka</td>
<td>J2</td>
<td>J3</td>
<td>85</td>
<td>164 ± 1</td>
<td>1.0</td>
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<td>South Anyui suture zone: Late Jurassic</td>
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<tr>
<td>02An-01 Upper Ustieva</td>
<td>J2–J3</td>
<td>J3</td>
<td>93</td>
<td>156 ± 3</td>
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<td>J3</td>
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<td>154 ± 9</td>
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<td>J3</td>
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<td>02An-31/GB9986 Upper Uyamkanda</td>
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<td>K1</td>
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<tr>
<td>South Anyui suture zone: Mid-Cretaceous</td>
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<tr>
<td>02An-02 Upper Ustieva</td>
<td>K1</td>
<td>K1</td>
<td>92</td>
<td>124 ± 3</td>
<td>2.0</td>
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</tbody>
</table>

Note: MSWD—mean square of weighted deviates. T2—Middle Triassic; T3—Late Triassic; J2—Middle Jurassic; J3—Late Jurassic; K1—Early Cretaceous.
Figure 7. Photomicrographs of Triassic–Cretaceous strata from the South Anyui suture zone (note that photos to the left are in plane-polarized light [PPL] while photos to the right are in polarized light; scale bar is in the lower right corner of each plane-polarized light photo). (A) Middle–Late Triassic rocks of the Chukotka margin: Monocrystalline quartz (Qm) together with lithic metamorphic (Lm) and lithic sedimentary (Ls) fragments are the main constituents of Triassic strata; also present is polycrystalline quartz (Qp) and chert (C); (B) Jurassic strata of the Oloy arc: strata consist primarily of plagioclase (P) and lithic volcanic fragments (Lv) with subordinate amounts of monocrystalline quartz (Qm); Also present is augite (Ag). (C) Late Jurassic South Anyui suture zone (SAZ) strata: Monocrystalline quartz (Qm) along with subordinate occurrences of plagioclase (P), polycrystalline quartz (Qp), lithic volcanic (Lv), lithic sedimentary (Ls), and lithic metamorphic fragments (Lm) are the primary constituents of these strata. (D) Mid-Cretaceous SAZ strata: these consist primarily of lithic volcanic fragments (Lv) with subordinate amounts of monocrystalline quartz (Qm), chert (C), plagioclase (P), serpentine (Sp), and augite (Ag).
Oloy Arc Strata (Middle Jurassic)

Several samples were collected from the region south of the South Anyui suture zone previously mapped as being from the Alazeya-Oloy fold belt, consisting of volcanic arc and volcanogenic sandstone related to the Oloy arc (e.g., Sokolov et al., 2009). These Middle Jurassic strata contain elevated abundances of lithic fragments (Fig. 7B), with subordinate amounts of feldspar and quartz (Q 16%, F 19%, L 65%; Fig. 8). The total quartz composition consists primarily of chert (C) and monocrystalline quartz (Qm), with rare polycrystalline quartz (Qp). Feldspar grains are common, with plagioclase (P) being the dominant component (Qm 27%, P 70%, K 3%; Fig. 8). Lithic fragments consist primarily of volcanic types (Lv), with lithic sedimentary (Ls) and metamorphic (Lm) fragments making up a relatively smaller overall proportion (Lv 76%, Lm 10%, Ls 14%; Fig. 8). A majority of lithic volcanic fragments (>75%)...
are characterized by lathwork volcanic textures (Fig. 7B). Lithic metamorphic components consist primarily of serpentinite, metachert, and metavolcanic fragments. Lithic sedimentary fragments consist primarily of siltstone and sandstone.

One sample was dated from the Oloy arc unit. Sample 02An-18 is from a J2-J3 map unit along the Orlovka River that lies in fault contact with Permian igneous rocks. It is a quartz-poor volcanic litharenite dominated by intermediate volcanic (andesite) clasts. Unlike our other samples, there are no pre-Jurassic ages. The ages (n = 85; Fig. 9B) form a cluster of three partly overlapping age distributions on a relative probability distribution diagram: one at 164 Ma, a second one at 171 Ma, and a smaller peak at 183 Ma. The maximum depositional age is 164 ± 1 Ma, calculated from the 32 youngest zircons. The age range of the individual analyses is 200–159 Ma.

South Anyui Suture Zone Strata

Late Jurassic–Early Cretaceous

This group of samples was collected from the region previously mapped as the South Anyui suture zone (e.g., Sokolov et al., 2002). The Late Jurassic strata may also include rocks deposited in the earliest Cretaceous. They have elevated occurrences of quartz (Fig. 7C), with subordinate occurrences of volcanic fragments and rare occurrences of feldspar (Q 60%, F 19%, L 21%; Fig. 8). The total quartz composition consists primarily of monocrystalline quartz (Qm), with subordinate polycrystalline quartz (Qp) and chert (C; Fig. 8). Feldspar is dominated by plagioclase (P) grains, whereas potassium feldspar (K) is rare (Qm 70%, P 27%, K 3%; Fig. 8). Lithic fragments consist primarily of lithic volcanic (Lv) and sedimentary (Ls) grains, with lithic metamorphic fragments (Lm) making up a relatively smaller overall percentage (Lv 48%, Lm 19%, Ls 33%; Fig. 8). Lithic volcanic fragments are characterized almost entirely by fine-grained volcanic groundmass. Lithic metamorphic components are characterized primarily by phyllite and schist fragments with lesser quartzite and gneiss fragments. Lithic sedimentary fragments consist primarily of mudstone and sandstone grains.

Two samples from units mapped as Jurassic were dated, and three were from a unit previously mapped as Triassic, but all yielded Jurassic maximum depositional ages (Fig. 9B).

Sample 02An-01 is a fine-grained sandstone from a Middle to Late Jurassic unit (J2-J3) that overlies Triassic sedimentary rocks in the Ustieva River, a tributary of the upper Orlovka River. It has abundant quartz and plagioclase along with volcanic lithic and chert clasts. Sample 02An-01 has a maximum depositional age of 156 ± 3 Ma (Late Jurassic, based on a total n = 77; peak ranges from ca. 165 to 145 Ma; Fig. 9B). Prominent peaks are at 282 Ma and 247 Ma (Fig. 10). There are no ages between ca. 500 Ma and 1.75 Ga (Fig. 9A), and the main Precambrian peaks are at 1.86 Ga and 2.67 Ga.
Figure 9 (continued).
Sample 02An-12 is a fine-grained black siltstone with trace fossils on the bedding plane that appear to be Planolites. Although this sample was previously mapped as Late Triassic (T3k, Carnian), the youngest zircon is 150 Ma, and five zircons are Jurassic in age, yielding a maximum depositional age of 154 ± 9 Ma (Fig. 9B). The main peak of the \( n = 66 \) data set is at 265 Ma (Permian, with a range from 275 to 255 Ma), a Triassic peak is present, and other prominent peaks are at 609 Ma, 1.07 Ga, and 1.92 Ga (Fig. 9A). Nine grains are Archean, with the oldest at 2.83 Ga.

Sample 02An-04 was collected from a unit also mapped as Late Triassic (Carnian) west of the Ustieva River (Dovgal, 1964). It is a fine-grained sandstone with quartz, plagioclase, and volcanic lithic fragments. Sample 02An-04 was analyzed multiple times. Although in the original data set \( (n = 55) \), there were three Cretaceous zircons, the youngest peak \( (n = 5) \) yields a maximum depositional age of 150 Ma (Late Jurassic, with an age range from 163 to 147 Ma; Figs. 9A and 9B). Redating this sample \( (n = 66) \) did not yield any zircons younger than 150 Ma. Other peaks are at 265 Ma, 291 Ma, and 485 Ma. Proterozoic peaks are at 1.91 Ga and 1.74 Ga (Fig. 9B). A prominent Archean peak is at 2.7 Ga.

Sample 02An-31 is from the same locality as sample 9986 of Bondarenko et al. (2003). It is a fine-grained lithic sandstone with abundant angular quartz, plagioclase grains, and volcanic lithic clasts. This unit was originally mapped as \( T_1n \) (Triassic; Norian) but was remapped as Upper Jurassic–Lower Cretaceous turbidites by Bondarenko et al. (2003). Sample 02An-31 has a maximum depositional age, based on 68 detrital zircon U-Pb ages, of 147 Ma, or latest Jurassic, with the peak including ages from 154 to 135 Ma (Figs. 9A and 9B). Other peaks are at 164 Ma, 236 Ma, several Paleozoic peaks, a prominent Proterozoic peak at 1.92 Ma, and an Archean peak at 2.73 Ga (Fig. 9A).

Together, the samples all have maximum depositional ages close to the Jurassic-Cretaceous boundary, but the actual depositional age could be younger than the maximum depositional age (i.e., in Early Cretaceous time). Samples 02An-01, 02An-04, 02An-12, and 02An-31 all have Late Jurassic maximum depositional ages ranging from 156 ± 3 Ma to 147 ± 2 Ma. The main peaks in the combined data set (Fig. 10) are Late Jurassic (154 Ma), Middle Permian (266 Ma), middle Paleoproterozoic (1.92 Ga), and Neoarchean (2.67 Ga). There are also minor peaks at 488 Ma and 1.74 Ga. There are few zircons (4 out of 266) between the 500 Ma and 1.70 Ga range (Fig. 11).
Mid-Cretaceous

Cretaceous strata of the South Anyui suture zone contain elevated abundances of lithic fragments (Fig. 7D), with subordinate amounts of feldspar and quartz (Q 19%, F 9%, L 72%; Fig. 8). The total quartz composition consists primarily of monocrystalline quartz (Qm) and relatively lower occurrence of polycrystalline quartz (Qp) and chert (C). Feldspar grains are mostly plagioclase (P), with no occurrences of potassium feldspar (Qm 59%, P 41%, K 0%; Fig. 8). Lithic fragments consist primarily of volcanic types (Lv), with lithic metamorphic (Lm) and lithic sedimentary fragments (La) making up a relatively smaller overall occurrence (Lv 64%, Lm 27%, La 9%; Fig. 8). A majority of lithic volcanic fragments (>75%) are characterized by lathwork volcanic textures (Fig. 7D). Lithic metamorphic components consist primarily of serpentinite and metavolcanic fragments, with fewer occurrences of phyllite, schist, quartzite, and metachert. Lithic sedimentary fragments consist primarily of sandstone and mudstone.

Sample 02An-02 is a lithic sandstone dominated by mafic-intermediate volcanic clasts from a unit previously mapped as Lower Cretaceous (Valanginian: Cr-v) located south of the Jurassic arc rocks. Based on dating of 74 zircons (Fig. 9A), it has a maximum depositional age of 124 ± 3 Ma (Aptian; Fig. 9B). The main peak from the analyses at 124 Ma is the youngest peak and ranges from 132 to 114 Ma, and other peaks are at 150 Ma and 247 Ma. There is a gap between 650 Ma and 1.85 Ga. The main Precambrian peak is at 1.93 Ga (Fig. 11).

Summary of Mesozoic Sedimentary Provenance Trends

Compositional data from Mesozoic strata from along the South Anyui suture zone indicate some variations in provenance between each of the four stratigraphic units (Fig. 8). The relative abundance of quartz and lithic fragments is similar in Middle–Late Triassic strata of the Chukotka margin (Q 73%, F 7%, L 20%) and Late Jurassic strata of the South Anyui suture (Q 60%, F 19%, L 21%), but these samples are in sharp contrast to Middle Jurassic strata of the Oloy arc (Q 16%, F 19%, L 65%) and Mid-Cretaceous strata (Q 19%, F 9%, L 72%). It is also noteworthy that the relative abundance of lithic volcanic fragments is much lower in Middle–Late Triassic strata (Lv 16%) than in the Late Jurassic (Lv 48%) and Middle Jurassic strata (Lv 76%). Lithic metamorphic fragments in Middle–Late Triassic and Late Jurassic strata consist exclusively of phyllite, schist, quartzite, and gneiss, whereas Middle Jurassic strata primarily contain serpentinite, metachert, and metavolcanic fragments.

The compositional differences from these strata suggest sediment contributions from at least two distinct source areas. A comparison of our compositional data with provenance fields of Dickinson et al. (1983) shows that Middle–Late Triassic Chukotka strata plot with sandstone derived from quartz-rich, recycled orogen source areas, whereas Middle Jurassic Oloy arc strata plot with sandstone that was derived primarily from arc sources (transition to undissected; Fig. 8). Late Jurassic South Anyui suture zone strata overlap with sandstone that plots in mixed recycled orogen and arc sources (Fig. 8), but they are clearly distinguished from the Middle–Late Triassic strata by their higher content of lithic volcanic fragments. Mid-Cretaceous strata of the South Anyui suture zone plot with sandstone that overlaps primarily with arc source areas (transition to undissected; Fig. 8).

Structural Geology Results

Structural analysis of the South Anyui suture zone is challenging because of locally intense deformation and the poor outcrop conditions typical of Arctic regions that escaped Pleistocene glaciations, as is the case in Chukotka, where most outcrops are tundra-covered piles of frost-heaved rock. The faults postulated to separate the major units from each other are not exposed and generally run through wide valleys with no outcrop. Their presence on geological maps is inferred based on changes in lithology, and, as such, detailed information about kinematics on these structures are not available. In this section, we describe our structural observations from north to south across the South Anyui suture zone.

The northernmost part of the area (Fig. 4) is dominated by a thick section of Triassic turbidites in the Chukotka fold belt. They are generally metamorphosed to lower-greenschist grade, so that shale units have well-developed, and typically steeply dipping, slatey cleavage, whereas sandstone units preserve primary bedding (Tuchkova et al., 2009). These are intruded by numerous granitoid plutons of Albian–Aptian age that have been attributed to a postcollisional extensional phase (Miller et al., 2009). Intensity of shortening strain generally increases to the south, toward the South Anyui suture, and it is manifest by stronger cleavage development and tighter folding.

Our northernmost detailed structural observations are from Late Jurassic and Early Cretaceous rocks in the South Anyui suture zone along the northern Uyamkanda and Ustieva River valleys (sample localities 1–10 and 31–32; Fig. 4). In these areas, bedding is predominantly steeply dipping, with an average fold axis of 110°/03, approximately parallel to the margins of the South Anyui suture zone (Fig. 12A). Cleavage is steeply south-dipping, suggesting shortening perpendicular to the suture with a slight component of north-vergent tectonic transport at the surface (Fig. 12A). The Mid-Cretaceous plutonic rocks do not appear to have been involved in the deformation, and thus this shortening predates 117–109 Ma (e.g., Miller et al., 2009).

Farther south along the Orlovka and Bolskoi Anyui Rivers (Fig. 4), there is a separate structural domain in the Oloy terrane where bedding dips more gently, and cleavage, on average, dips to the north (Fig. 12B). It is clear from the cleavage orientations and fold geometries that the predominant vergence in this area is to the south. The scatter in the cleavage and bedding data may be the result of a superimposed folding event about a SW-trending fold axis. This axis is not parallel to the regional trend of structures, defined by the unit contacts in the central Orlovka River region, but it may have been affected by a late-stage component of right-lateral strike-slip deformation.
In a major geophysical effort, the 2DV deep geotransect (Fig. 13) was acquired by the Federal State Unitary Enterprise of the Siberian Science Research Institute of Geology, Geophysics, and Mineral Resources across northeastern Russia from Magadan to the Arctic coast, near Pevek (Figs. 3, 4, and 13). Between kilometers 1505 and 1570, the line crosses the South Anyui suture zone almost orthogonal to the structural grain, thus offering an excellent view of the large-scale structure. From kilometer 1570 to 1705, it traverses the Chukotka fold belt, but, because of a bend in the line, it does so obliquely to the trend of the main structures.

Most of this part of the 2DV line (Fig. 13) is characterized by strong reflectivity in the lower crust, a relatively transparent middle crust, and variable imaging in the upper crust, depending on location. The reflection Moho is visible at ~50 km depth at the southern end, under the Oloy terrane, shallowing to ~42 km under Chukotka. The Moho is relatively deep (~46 km) directly south of the South Anyui suture zone and is accompanied by a panel of strong north-dipping reflections at 45–60 km that may represent a fragment of a subducted slab.

The most remarkable aspect of the seismic line (Fig. 13) is that the entire South Anyui suture zone, and even some of the area to the south, has strong north-dipping reflections that we interpret as a system of major south-vergent thrust faults. North-dipping reflections project to the surface starting at about kilometer 1475 in rocks that have been previously mapped as part of the Yarakvaam terrane (Sokolov et al., 2002), which is associated with the Oloy arc and includes the Aluchin ophiolite complex. However, it appears that at least from the structural point of view, this panel of rocks, including the Aluchin complex, belongs to the South Anyui accretionary system. Thus, it appears that the Aluchin complex did not originate within the SAZ, but it was likely faulted away from the lower plate (i.e., the Kolyma-Omolon–Oloy–Yarakvaam terranes) and incorporated into the upper plate (i.e., SAZ and Chukotka).

The bounding fault on the southwest side of the Yarakvaam terrane strikes to the northwest (Figs. 4 and 5) and can be traced on the seismic line to ~20 km depth, where it is lost in the low-reflectivity middle crust. At ~15 km depth, there is a clear truncation of flat reflectors to the south. The fault that bounds the southern edge of the South Anyui suture zone, which we will call the Angarka fault (Fig. 4), is particularly clearly imaged at kilometer 1505 (Fig. 13). In its upper 8 km, it has a ramp with an apparent dip of 35°N on the seismic line. Its true dip should be ~50°NW, because the fault is cut by the
Figure 13. (A) Interpreted and (B) uninterpreted seismic-reflection data from the 2DV seismic line that passes through the South Anyui suture zone. The location of the line is shown on Figures 1, 3, and 4. Along the top of the line, we show the geological units exposed at the surface (Fig. 4). Main structural vergence is to the south in the South Anyui suture zone, based on dominance of north-dipping reflectors. The line is shown with a vertical exaggeration of 4:3. For a high-resolution version of this figure, please visit http://dx.doi.org/10.1130/GES01165.S2 or the full-text article on www.gsapubs.org.
seismic line at an oblique angle (Fig. 4). At a depth of 8–10 km, the Angarka fault flattens along a detachment but has a second ramp that continues to perhaps 35 km depth under Chukotka. In spite of the tight folding observed at the surface, gently north-dipping reflections underlie much of the South Anyui suture zone, indicating that the shallow folds are detached. We interpret a second major fault bounding the block that contains the Nutesyn arc rocks (Fig. 4), but this structure is not evident in the seismic data. Instead, the upper crust of this part of the South Anyui suture zone is relatively transparent, which is not surprising given the tight folding observed at the surface. The fault that separates the Triassic turbidites of the Chukotka microcontinent from the South Anyui suture zone rocks is not well imaged either. Gently north-dipping reflectors in the upper 10 km of the crust are observed in the Chukotka block, at least as far north as kilometer 1630, where the line takes a sharp bend to the east, along the Maly Anyui River. This is evidence that north-vergent structures, like those of the South Anyui suture zone, also exist along the southern Chukotka fold belt. The northern end of the line lacks continuous reflectors in the upper crust but has several prominent domal structures at 15–20 km depth. We are not sure how to interpret them. They could be thrust-cored antiforms, or perhaps igneous-metamorphic domes related to the numerous Mid-Cretaceous granitic plutons that are found in this area. Alternatively, they could be diffractions from underlying dense structures. The lower crust, below the downdip continuation of the Angarka fault, is strongly reflective and has folds with 30 km wavelengths that are out of phase with the domal structures observed above them. We interpret this as further evidence that the upper crust and lower crust of Chukotka are structurally detached from each other.

If this interpretation is correct, rocks of the South Anyui suture zone and the Yarakvaam terrane form a wedge ~100 km wide and a maximum of ~20 km thick, which underthrusts Chukotka down to ~25 km depth. The rest of the lower crust, down to the Moho, is likely Oloy arc material, and the true Chukotka crust is relatively thin (between 35 km and 0) along its southern margin.

**DISCUSSION**

**Tectonic Model**

Constraints on the Mesozoic evolution of the South Anyui suture zone include the depositional ages of sedimentary rocks, source rock ages, provenance trends, structural patterns, the position of ophiolitic and arc rocks, and data obtained from the deep crustal 2DV seismic-reflection line (Fig. 13). We combine these data to create a tectonic model (Figs. 14A–14D).

The 2DV deep crustal seismic data suggest that the Chukotka block was thrust over the terranes that lie to the south (Fig. 13). The predominant vergence of the orogen is top-to-the-south, as shown by the north dip of the seismic reflections across the South Anyui suture zone and into Chukotka. This vergence is consistent with our structural observations close to the southern boundary of the South Anyui suture zone. This geometry is best explained if the Triassic South Anyui Ocean (Fig. 14D) was subducted with final closure of the suture taking place over a north-dipping subduction zone (Fig. 14C); therefore, a double-dipping subduction system must have existed in Late Jurassic time (Fig. 14C) to produce the Oloy arc on the Kolyma-Omolon side and Nutesyn arc on the Chukotka side. Sokolov et al. (2002), Nokleberg et al. (2000), and Shephard et al. (2013) all indicated opposite-dipping subduction zones on either side of the South Anyui Ocean.

We agree with previous workers that the Oloy arc is likely a continental margin arc, based on its composition and location, but there are uncertainties regarding the age, polarity, and exact setting of the Nutesyn arc. Natal’ in (1984) and Sokolov et al. (2002) suggested that the Nutesyn arc was built directly on Chukotka basement as a continental arc resulting from north-dipping subduction. The exposed volcanic rocks in our study area are basaltic andesite in composition and do not contain any zircon. This is more consistent with an island-arc origin, and the lack of any xenocrystic zircon also argues against the arc magmas passing up through Chukotka crust. If it were an island arc, there must have been a back-arc oceanic basin adjacent to Chukotka. Along the 2DV seismic line, the Moho lies consistently at ~45 km depth under Chukotka, but subtracting the underthrusted accreted material leaves a relatively thin southern margin of Chukotka prior to the closure of the South Anyui suture, more typical of a passive continental margin than of an active one.

The final closure of the South Anyui suture zone in Early Cretaceous time (Fig. 14B) was likely preceded by a collision between the Nutesyn arc and the Chukotka margin. During this collision, the back-arc basin was closed. Then, the Oloy arc and Kolyma-Omolon blocks were accreted, resulting in the preservation of some of the ultramafic rocks in the South Anyui suture zone. We recognize that some of these mafic-ultramafic rocks may instead represent island-arc basement, but, given their Carboniferous to Triassic radiometric ages, they would predate both the Nutesyn and Oloy arcs.

Because the packages of north-dipping reflectors in the seismic line sole out under the middle crust of Chukotka (Fig. 13), we suggest that the South Anyui suture zone is actually a relatively low-angle south-vergent thrust system. This is contrary to previous studies that concluded that the South Anyui suture zone rocks overthrust Chukotka, based on field observations of these poorly exposed and complexly deformed rocks (Sokolov et al., 2002, 2009). In a marine seismic-reflection profile of the East Siberian Shelf, located east of the New Siberian Islands and north of the South Anyui suture zone (Fig. 1), Franke et al. (2008) recognized sets of south-dipping reflectors at 6–10 s TWT, which they interpreted as part of a north-vergent thrust wedge associated with closure of the South Anyui suture. This interpretation is consistent with ours: The structures observed in the 2DV line are the retrowedge of the collision zone, while the structures imaged by Franke et al. (2008) are the prowedge. The structures imaged by Franke et al. (2008) are along strike of north-vergent structures observed on land in the northern part of the Chukotka fold belt (Fig. 14; Katkov et al., 2005; Miller and Verzhbitsky, 2009).
The exact timing of final South Anyui suture zone closure is constrained only broadly. Early Cretaceous sedimentary rocks are deformed within the suture zone, but the main structures are overlapped by relatively undeformed Albian–Cenomanian deposits of the Okhotsk-Chukotka volcanic belt (Fig. 3). Structures of the Chukotka fold belt, north of the South Anyui suture zone, are cut by postkinematic plutons that range in age from 117 to 119 Ma (Miller et al., 2009). Two intrusions that we dated within the South Anyui suture zone, at 110 Ma and 101 Ma, likely belong to this category (Fig. 14A).

Previous workers (Sokolov et al., 2002) have emphasized the role of strike-slip deformation during the late stages of the South Anyui suture zone. This interpretation is entirely possible given the oblique plate motions involved in the closure, but our data do not address this question.

Depositional Ages and Provenance

A comparison between the detrital zircon ages of precollisional Triassic strata of the Chukotka continental margin and Jurassic–Cretaceous syncollisional and postcollisional strata reveals a significant change in the provenance record (Figs. 9 and 10). This is not surprising in light of the compositional data discussed here. The Triassic rocks have a broad distribution of Paleozoic zircons with peaks characteristic of the Uralian (late Paleozoic) and Timanian (late Neoproterozoic) orogens of Siberia and Baltica (Fig. 15). They also have a lower, but significant, number of Neoproterozoic zircons with ages that are common in the Barents region of Baltica, but not in Siberia as strictly defined. In contrast, the Jurassic–Cretaceous sandstone is distinguished by a major Triassic peak that overlaps with the age of Siberian Trap magmatism, and there
Figure 15. Relative probability curves for areas in the Arctic region showing the time spans of significant orogenic events as gray bars. SASZ—South Anyui suture zone.
is a remarkable lack of zircons in the 550–1700 Ma range. We suggest that this gap in the detrital zircon record is one of the fingerprints of Siberian provenance. Therefore, closure of the South Anyui suture zone brought about a shift from provenance from the west along the axis of Chukotka to provenance from the south or southwest. We explore these provenance trends in more detail in the following, compare our data to published data sets from adjacent Arctic regions (Fig. 15), and indicate on paleogeographic maps the likely sources for the sediment in the South Anyui suture zone region (Figs. 16–18).

**Chukotka Triassic Passive-Margin Strata**

Miller et al. (2006) suggested that the 247 Ma zircon peak in detrital zircon ages from Triassic rocks in Chukotka is related to silicic magmatism associated with the Siberian Trap basalts or to silicic stocks on the Taimyr Peninsula. Subsequently, it has become apparent that the gabbro sills that are abundant in the Lower Triassic strata of Chukotka are also coeval with the Siberian Traps (Ledneva et al., 2011). In addition, Ivanov et al. (2013) noted the presence of coeval granitic magmatism in Siberia ca. 250 Ma and extending to Late Triassic time. Therefore, the Siberian Triassic large igneous province may have encompassed Chukotka and provided local sources for zircons of this age (Fig. 16). The 298 Ma peak coincides with the main period of magmatism in the Uralian-Taymyr orogen, which formed during the late Paleozoic collision of Siberia and Baltica (Bea et al., 2002). This peak is dominant in Triassic sandstone from the Taimyr Peninsula (Zhang et al., 2015) and even in the zircon record of modern river sands from drainages on the east flank of the Urals (Safonova et al., 2010). Devonian zircons, which form a secondary peak in the Triassic sandstone of Chukotka, could have been derived either from proximal sources, Devonian plutons exposed along the north coast of Chukotka (Kos’ko et al., 1993; Amato et al., 2014), or more distally from the Urals.
Animation 1. Arctic plate model from 180 Ma to Present, shown holding North America fixed, created by J. Toro in GPlates by modifying the global model of Seton et al. (2012). The yellow star tracks the location of the Iceland hotspot. Yellow lines are the mid-ocean ridges relevant to the Arctic and some shelf edges. Magnetic anomalies and subduction zones are shown as lines of the color of the plate to which they are attached in the model. Color key: Dark Blue—Kamchatka, Rocky Mountains, Canadian Arctic Islands; Dark Green—Laurentia, Central Ellesmere, South Anyui zone; Dark Grey—Eurasia, Yukon-Tanana, Chukchi Cap; Light Blue—Lower Yukon, Svalbard, Western Europe, Sakhalin; Light Green—Brooks Range; Orange—Pribilofs, North Slope, Seward Peninsula, Baffin Island, Peninsular terrane, Alexander terrane; Pink—Greenland, Lomonosov Ridge, Western Ellesmere, Northwind Ridge; Red—Kolyma-Omolon terrane, Kokukuk arc; Yellow—Chukotka, Eastern Ellesmere. Some of the light grey area are continental shelves. To view the animation, click above in the PDF, or visit http://dx.doi.org/10.1130/GES01165.03 or the full-text article on www.gsapubs.org.
The 440 Ma peak, which is the second most prominent one in the Triassic sandstone, is made up of zircons ranging from 404 to 662 Ma, and it includes several secondary peaks (Fig. 9). This range of ages corresponds to early Paleoproterozoic magmatism in the Uralian and the Caledonian orogens (Fig. 15) and to the late Neoproterozoic Timanian orogen of northeastern Baltic and the Barents Shelf (Gee and Pease, 2004). The Caledonian-age peak is more prominent in the Triassic of Chukotka than in samples from the Taimyr Peninsula, indicating a more significant input of detritus from the Barents Shelf region (Fig. 15). Late Neoproterozoic zircons are important because magmatism of this age is rare in Laurentia. For example, Timanian-age zircons are almost absent in samples from the Sverdrup Basin of the Canadian Arctic (Fig. 15; Omma et al., 2011) and are only a minor component of the detrital record from Svalbard (Pózer Bue and Andresen, 2013). Late Neoproterozoic zircons are important because zircons of this age are common in the Grenville orogen of Laurentia and Baltic (Rainbird et al., 1992; Mosher, 1998; Tollo et al., 2004; Li et al., 2007; Gasser and Andresen, 2013; Pózer Bue and Andresen, 2013), Severnaya Zemlya (Lorenz et al., 2008), and Novaya Zemlya (Lorenz et al., 2013) but are rare in Siberia and are absent from our Late Jurassic samples from the South Anyui suture zone (Fig. 15).

The last major peak is a broad one at 1850 Ma, composed of zircons ranging from 1354 to 2143 Ma. Such a long time span likely represents multiple magmatic events. Zircons in this range are common in the detrital records of northern Baltic (Fig. 15; Pózer Bue and Andresen, 2013), Siberia (Prokopiev et al., 2008), and in the Trans-Hudson orogen of Laurentia (Voice et al., 2011). Therefore, it is not a particularly diagnostic provenance signature.

In summary, we suggest that the zircon populations in the Triassic rocks were derived from a combination of Siberian, Baltic, and perhaps Laurentian sources. The Uralian-Taimyr orogen provides the best match (Fig. 15), but there was also a contribution from a Grenville-age source that could have been in Laurentia, or in the Barents region, as was suggested by Lorenz et al. (2013). Our conclusions are consistent with the interpretation of Miller et al. (2006) for Triassic deposits in northern Chukotka (Fig. 15).

One of the important differences between the detrital zircon ages in our Triassic and Late Jurassic samples is that the combined Late Jurassic samples have few grains between 500 Ma and 1740 Ma. Out of 550 analyses, only nine zircon grains fall in this range (Figs. 8B and 10). Three of those grains are at ca. 650 Ma, and all of the others are isolated single grains that do not form a peak. Siberian basement ages are typically either 2100–1850 Ma or >2300 Ma (Frost et al., 1998). The main Paleoproterozoic peak in Triassic rocks is at 1850 Ma, whereas in Late Jurassic rocks, it is at 1920 Ma. The older Paleoproterozoic peaks are at 2485 Ma in Triassic rocks and 2690 Ma in the Late Jurassic rocks (Fig. 11). These Paleoproterozoic peaks are sufficiently different in Triassic and Late Jurassic samples to conclude that they do not represent the same source region.

**Oloy Arc Strata**

The detrital zircon age pattern of sample 02An-18 contrasts with the rest of our data set in that it yielded only Jurassic 206Pb/238U ages (Fig. 10). This sample was collected south of the South Anyui suture zone in rocks that are considered to be part of the Yarvakam terrane overlapped by volcanic and volcanioclastic rocks of the Oloy arc (e.g., Parfenov et al., 1993; Nokleberg et al., 1994). The narrow range of detrital zircon ages in the Jurassic sandstone, combined with evidence for volcanic clasts, strongly suggests a local provenance for this sandstone from the Oloy arc region, and that significant magmatism in the Oloy arc spanned the period 190–160 Ma.
**South Anyui Suture Zone Strata (Late Jurassic–Early Cretaceous)**

We interpret the youngest peak in the Late Jurassic sandstone (154 Ma) as the product of the Late Jurassic Nutesyn arc (Natal’in, 1984), which developed close to the Chukotka margin prior to closure of the South Anyui suture (Nokleberg et al., 2000; Shephard et al., 2013). If this is correct, this peak on the age distribution provides a good estimate of the age of Nutesyn arc magmatism. Alternative, more distal, sources for these Late Jurassic zircons are the extensive Main plutonic belt and Uyandina-Yasachnaya arc of the western Kolyma-Omolon block, which developed prior to its collision with the Verkhoyansk margin of Siberia (Fig. 1; Akinin et al., 2009).

There is a significant group of Permian–Triassic zircons in the Late Jurassic sandstone of the South Anyui suture zone, which may have been sourced either directly from the Siberian Traps large igneous province, or indirectly by recycling of the Triassic rocks of Chukotka. If recycling of the Triassic were a significant source, we would expect to see some contribution of early Paleozoic and Neoproterozoic grains, but these are either not prominent, or are entirely absent from Late Jurassic sandstone. Instead, the age gap in the zircon ages between 500 and 1700 Ma is characteristic of Mesozoic sedimentary rocks from the Verkhoyansk margin of Siberia (Prokopiev et al., 2008) and along the western edge of the Kolyma-Omolon block (Harris et al., 2013) and in the Jurassic of the Indigirka River, in the Moma Basin (Fig. 15). This leads us to believe that a southern source from the Kolyma-Omolon block is likely for the South Anyui Late Jurassic sandstone. These rocks were deposited when the Jurassic arcs were active and thus probably before the collision between the Kolyma-Omolon and Chukotka blocks, and this collision would have shut off arc magmatism. However, the two blocks may have been relatively close to each other before the collision, and thus either block could have been a sediment source for the sandstone. The Omolon block has Precambrian sources with ages similar to the main peaks in this unit, namely 3.2 Ga (minor), 2.6 Ga, and 2.0–1.8 Ga (Akinin and Zhulanova, 2019). Thus, a Kolyma-Omolon source for the Late Jurassic–Early Cretaceous strata is possible.

**South Anyui Suture Zone Strata (Early Cretaceous)**

Sample (02An-02), with a Mid-Cretaceous maximum depositional age of 124 ± 3 Ma, defined by six zircons (8% of the sample), has a similar relative probability age spectrum as the samples with Late Jurassic maximum depositional ages, although with only 74 zircon ages in this sample, it is difficult to evaluate the significance of small peaks present in the larger Late Jurassic data set (Fig. 10). Aside from the Cretaceous ages, they have nearly identical peaks to the Late Jurassic samples at 164 Ma, 247 Ma, and 267 Ma. The Jurassic samples, though, have 45 grains with ages between 300 and 500 Ma (~10%), and these ages are lacking in the Cretaceous sample. It appears that from Triassic to Cretaceous time, the sources contributing early Paleozoic zircon, which we attributed to the Uralian and Caledonian orogens, were progressively cut off from Chukotka. On the other hand, the Cretaceous sample has three grains at 517 Ma to 651 Ma, a time period that is not represented in the Jurassic samples, but both the Cretaceous and Jurassic samples share broad peaks typical of Siberian basement at ca. 1.92 Ga and 2.5–2.7 Ga. We suggest that by Mid-Cretaceous time, the collision of Chukotka with the Kolyma-Omolon block was complete, and subsequent precursors to the Okhotsk-Chukotka volcanic belt (120 Ma Tytlyvleem unit; Akinin and Miller, 2011) could have contributed the Aptian or later sandstone unit represented by sample 02An-02.

It is also worth mentioning that the Jurassic–Cretaceous detrital zircon signature of the South Anyui suture zone sandstone is remarkably similar to that of Late Jurassic sandstone from the Indigirka River, in the Moma Basin, located 1000 km west within the Kolyma-Omolon terrane (Fig. 15), to that of Jurassic–Cretaceous sandstone of the Rauch foreland basin on the north side of the Chukotka fold belt, and to the Stolbovoskaya Formation of the New Siberian Islands (Miller et al., 2008). Thus, it appears that the Jurassic–Cretaceous depositional system associated with the South Anyui–Chukotka orogen was extensive. In contrast, the provenance signature for Early Cretaceous sandstone from the foreland basin associated with the Brooks Range orogen of Alaska has greater similarity with the Triassic of Chukotka and is inferred to have been sourced by recycling of Triassic deposits uplifted in the Chukotka fold belt (Moore et al., 2015).

**Summary of Provenance**

During the earliest stage of Middle–Late Triassic basin development on Chukotka, strata were most likely derived from quartz-rich, recycled orogen sources from the Uralian-Taimyr region, with a contribution from the Siberian Trap large igneous province and a Grenville-age source, likely on what today is the Barents Shelf (Fig. 15). By Jurassic time, oceanic arc source areas to the south of Chukotka were being exhumed and were contributing arc detritus as well as serpentinite and chert/metachert. The Late Jurassic–Early Cretaceous Period marked a transition in which detrital contributions most likely involved both recycled orogen sources of the emerging South Anyui–Chukotka convergent orogen and Jurassic arc components. The detrital zircon spectra are typical of Jurassic–Cretaceous deposits in the Kolyma-Omolon and Verkhoyansk areas. Strata of this age likely record exhumation and synorogenic sedimentation associated with arc-continent collision along the southern margin of Chukotka. Mid-Cretaceous sedimentation likely records regional exhumation across the South Anyui suture zone, resulting in a combination of arc, oceanic, and continental sources.

**Paleogeographic Reconstructions**

We have created an animated plate model for the Mesozoic–Cenozoic evolution of the Arctic using GPlates software and incorporating the ideas outlined herein together with further data from the Arctic region. The maps shown in
Figures 16–18 are stills from Animation 1. The new Arctic plate model was built on the global model of Seton et al. (2012). Some of the goals of our model were to solve the space problem associated with restoring Chukotka and Arctic Alaska to their pre-Cretaceous positions, allow for accretion of arcs along the current southern margins of both blocks, achieve a kinematically viable opening of the Amerasia Basin by rifting, and honor the available geological and geophysical data. We treated the Kolyma-Omolon block in a manner similar to that proposed by Nokleberg et al. (2000).

The provenance signatures place Chukotka in the Triassic adjacent to the Taimyr Peninsula (Fig. 16). At that time, southern Chukotka was blanketed by a geophysical data. We treated the Kolyma-Omolon block in a manner similar to ing of the Amerasia Basin by rifting, and honor the available geological and current southern margins of both blocks, achieve a kinematically viable open-

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Our detrital zircon data from Oloy volcanogenic sandstone provide evidence for volcanism along the southern margin of the South Anyui Ocean through the Jurassic. Early Cretaceous (144 Ma and 136 Ma) monzonites and a quartz syenite porphyry, collected west of the Aluchin complex, which intruded rocks attributed to the Oloy arc, might be related to the latest stages of the Oloy arc magmatism, the age range of which is not well constrained. In our tectonic model (Figs. 16 and 17), the closure of the South Anyui Ocean is primarily driven by the accretion of the Kolyma-Omolon block, including the arc terranes that surrounded it, to the Siberia and Chukotka margin. This is in contrast to most other models (Zonenshain et al., 1990; Nokleberg et al., 2000; Lawver et al., 2002; Shephard et al., 2013), which use the opening of the Amerasian Basin to drive the closure of the South Anyui Ocean.

The South Anyui suture zone has long been assumed to be the western extension of the Angayucham suture in Alaska (e.g., Churkin and Trexler, 1981; Nokleberg et al., 2000; Amato et al., 2004). However, the seismic data (Fig. 13) indicate that the closure of the South Anyui Ocean and collision between Chukotka and the Kolyma-Omolon blocks to the south were south vergent, likely above a north-dipping subduction zone on the Chukotka side, whereas the closure of the Angayucham Ocean in Alaska was north vergent above a south-dipping subduction zone. This raises questions about not only the correlation between the Angayucham terrane and the South Anyui suture zone, but also between the Koyukuk arc of Alaska and the Nutesyn arc of Russia. Furthermore, in our model, we also challenge the assumption that Arctic Alaska and Chukotka had a shared history throughout the Mesozoic. We believe that it is only in Early Cretaceous time, during the opening of the Amerasia Basin, that Arctic Alaska came in contact with Chukotka (Fig. 18). As Arctic Alaska rifted away from the Canadian Arctic margin and rotated in a counterclockwise direction, the present-day northern margin of Chukotka was reactivated as a dextral transform. Discussion of the details of Amerasia Basin opening are beyond the scope of the present paper, but they can be seen in Animation 1. The proximity of Arctic Alaska to Chukotka starting in the Early Cretaceous is required by the detrital zircon provenance signature of Colville Basin sandstone, which is clearly derived from the west and has strong similarities to the Triassic of Chukotka (Moore et al., 2015).

CONCLUSIONS

The South Anyui suture zone exposes multiple mafic/ultramafic complexes within a zone of accretion separating the Kolyma-Omolon block and the associated Oloy arc from the Chukotka block and associated Nutesyn arc. The mafic/ultramafic complexes may represent island-arc basement or oceanic crust from the South Anyui Ocean. This ocean basin initiated as early as the late Paleozoic, based on dates from subduction-related island-arc ultramafic rocks (Ganelin et al., 2013; Sokolov et al., 2015), and prior to 164 Ma, based on U-Pb ages of zircons from Jurassic arcs that indicate subduction of oceanic lithosphere was occurring. The collision formed the Chukotka and Oloy-Ala-
We used U-Pb ages of detrital zircons from Mesozoic sandstone to help constrain the main phases of deposition in the South Anyui suture zone. These include four groups: (1) quartz-rich, passive continental margin Triassic sandstone of Chukotka with sparse Triassic zircons yielding maximum depositional ages ranging from 240 to 212 Ma; (2) volcanogenic sandstone likely derived only from the Oloy arc with a narrow zircon age range with peaks at 164 Ma, 171 Ma, and 184 Ma; (3) sandstone within the South Anyui suture zone with Late Jurassic maximum depositional ages and abundant volcanic lithic fragments; and (4) potentially post- or syncollisional sandstone with maximum depositional ages of 124 Ma. The Triassic rocks have provenance signatures that link them to the Uralian-Taimyr orogen and the Barents Shelf, whereas the Late Jurassic and Cretaceous sandstone has characteristic signatures of the Siberian Verkhoyansk margin or the Kolyma-Okmoklom block.

Point-count compositional data indicate that Triassic sedimentary rocks are much more quartz-rich compared to Jurassic-Cretaceous sandstone (73% vs. 16%) and have more lith metamorphic and sedimentary fragments. The metamorphic lithic fragments are dominantly quartzite phyllite, schist, and gneiss. This is consistent with the Triassic sedimentary rocks having a recycled orogen source. The Late Jurassic–Early Cretaceous strata have dominantly arc sources mixed with a recycled orogen source. The youngest unit dated, the <124 Ma late Early Cretaceous sandstone, has a dominantly arc source. The metamorphic fragments in the Jurassic and Cretaceous units include serpentinite, metachert, and metatamafic clasts.

Structural analysis indicates bedding in Jurassic and Cretaceous rocks near the South Anyui suture zone is folded about a gently plunging axis trending ESE (110°), approximately parallel to the trend of the suture. Cleavage dips steeply to the south, indicating shortening perpendicular to the suture with a component of north vergence, but farther south in the South Anyui suture zone, the primary vergence is to the south. Scattered in structural data may be related to postcollisional, dextral strike-slip deformation, consistent with the model of Sokolov et al. (2002) to explain the trends of mafic/ultramafic complexes that are not parallel to the suture.

We have interpreted a portion of the 2D seismic-reflection line that runs through the South Anyui suture zone in the field area (Surov et al., 2007; Goryachev et al., 2008) to establish the crustal-scale architecture of the system and use it to support a new tectonic model. We infer that the Kolyma-Okmoklom-OLob block was subducted beneath the Chukotka block during the collision that formed the South Anyui suture zone, in agreement with the interpretation of Goryachev et al. (2008). In this model, the South Anyui zone consists mainly of deformed sedimentary rocks with minor volumes of exposed mafic/ultramafic complexes that relate to either arc basement (of the Oloy and/or Nutesyn arcs) or oceanic crust from the South Anyui Ocean. Prior to the collision, the South Anyui Ocean had subduction zones on both sides, creating the Oloy arc adjacent to the Okmoklom block and the Nutesyn arc offshore of the Chukotka margin. The south vergence of the South Anyui suture zone is the opposite of the Brooks Range fold-thrust belt, and thus the South Anyui suture zone should not be directly correlated to the Angayucham suture of Alaska. In addition, we propose that Chukotka may have been a separate block from Arctic Alaska until the opening of the Canada Basin and counterclockwise rotation of Alaska in Early Cretaceous time.

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