U-Pb zircon geochronology of Cretaceous arc magmatism in eastern Chukotka, northeast
Russia, with implications for Pacific plate subduction and the opening of the Amerasia Basin

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ABSTRACT

The tectonomagmatic evolution of eastern Chukotka, northeast Russia, is important for
refining the onset of Pacific plate subduction, understanding the development of the
Amerasia Basin, and constraining Arctic tectonic reconstructions. Field mapping and
strategic sample collection provide relative age constraints on subduction-related continental
arc magmatism in eastern Chukotka. Ion microprobe U-Pb zircon ages provide absolute

constraints and identify five magmatic episodes (c. 134, 122, 105, 94, and 85 Ma) separated by three periods of uplift and erosion (c. 122-105 Ma, 94-85 Ma, and post-85 Ma). Volcanic rocks in the region are more less contaminated than plutonic equivalents which record greater crustal assimilation. These data, combined with xenocrystic zircons, reflect ‘self-assimilation’ of a continental arc during its evolution. Proto-Pacific subduction initiated by c. 121 Ma and arc development occurred over c. 35-50 m.y. Crustal growth was simultaneous with regional exhumation and crustal thinning across the Bering Strait region. Ocean-continent subduction in eastern Chukotka ended at c. 85 Ma. The timing of events in the region is approximately synchronous with the inferred opening of the Amerasia Basin. Simultaneous arc magmatism, extension and development of the Amerasia Basin within a back-arc basin setting best explain these coeval tectonic events.

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39 KEYWORDS

40 Arctic, Chukotka, Cretaceous magmatism, subduction, U-Pb zircon

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42 Supplementary material includes SIMS U-Pb and geochemistry data tables, detailed
43 geological map and geochemical figures; see link xxxx.

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46 The tectonomagmatic evolution of eastern Chukotka, northeast Russia, constrains the onset of
47 northern Pacific plate subduction, the development of the Amerasia Basin, and Arctic
48 tectonic reconstructions. Although the tectonomagmatic evolution of some parts of the
49 adjacent Bering Strait region are well studied (e.g. Akinin and Calvert, 2002; Amato &
50 Miller, 2004; Amato et al., 2014), the history and nature of Cretaceous arc magmatism in

51 eastern Chukotka is poorly known. Limited geochronological data suggests that magmatism
52 across Chukotka was prolonged, spanning c. 120-80 Ma (Miller et al., 2002; 2009); this
53 partly overlaps the final phase of Amerasia Basin opening which is inferred to have occurred
54 at c. 131-127.5 Ma (Grantz et al., 2011) or as late as c. 110 Ma (Miller et al., *this volume*).
55 Thus Chukotka's magmatic history can be used to define the timing of tectonic events in the
56 region and bears on the question of when the Amerasia Basin opened, yet these details (e.g.-
57 geochronology, geochemistry, tectonic affinity) are only now being examined.

58

59 Chukotka, the East Siberian Shelf, Wrangel Island and Arctic Alaska, are collectively
60 referred to as the Arctic Alaska–Chukotka microcontinent (AACM; [Fig. 1](#)). The AACM is a
61 composite continental terrane of predominantly Neoproterozoic igneous and metamorphic
62 rocks overlain by early to late Palaeozoic carbonate rocks and a late Palaeozoic–Mesozoic
63 clastic cover sequence deformed during the Late Jurassic(?) to Early Cretaceous (Jones et al.,
64 1987; Kos'ko et al., 1993; Natal'in et al., 1999; Miller et al., 2006, 2010, *this volume*; Moore
65 et al., 1994; Strauss et al., 2013; Till et al., 2014). The southern boundary of the AACM is
66 the Angayucham terrane in Alaska and the South Anyui suture (SAS) in Chukotka which are
67 thought to represent the remains of a late Palaeozoic and Mesozoic ocean during the regional
68 shortening that produced the Brooks Range fold and thrust belt and the Chukotka foldbelt
69 (Seslavinskiy, 1979; Sokolov et al., 2002, 2009b; Moore et al., 1994). The Cretaceous
70 magmatic history of Chukotka discussed here largely post-dates this regional shortening and
71 is in part syn-extensional (Miller et al., 2002; 2009). Although the specifics are highly
72 debated (e.g. Pease, 2011; Amato et al., 2015; Miller et al., *this volume*), the AACM has been
73 inferred to have rifted from its conjugate margin along Arctic Canada, Greenland and the
74 Barents Shelf in the Mesozoic (Rowley & Lottes, 1988; Grantz et al., 1998, 2011; Lawver et
75 al., 2002; Gottlieb et al., 2014; Miller et al., 2010, *this volume*). This rift event is believed to

have caused the opening of the Amerasia Basin. The detailed study of magmatic rocks across the AACM can therefore provide further evidence for this history. Many studies have carefully documented the formation of deep-seated, syn-extensional metamorphic core complexes and gneiss domes associated with N-S (modern coordinates) crustal stretching across the Bering Strait in the Late Cretaceous (e.g. Akinin et al., 2009a and references therein), but few have focused on the igneous history recorded by the superb exposures of magmatic rocks in far eastern Chukotka described here.

Our investigation of Cretaceous igneous rocks in eastern Chukotka, based on several seasons of geological field mapping and systematic sampling in the Provideniya-Chaplino region (Fig. 1), defines fundamental cross-cutting and map relationships, and provides absolute age constraints from high-spatial resolution secondary ion-mass spectrometry (SIMS). These rocks were formed by subduction-related magmatism (Akinin & Miller, 2011; Rowe, 1998; Tikhomirov et al., 2012, 2016) and our new geochronology better constrains the initiation of palaeo-Pacific plate subduction in the region.

CRETACEOUS MAGMATISM OF EASTERN CHUKOTKA AND THE AACM

Uranium-lead (U-Pb) zircon age data from igneous rocks of eastern Chukotka provide a framework with which to understand the Cretaceous magmatic history of the AACM in the Russian Far East. Few older volcanic complexes (e.g. the c. 146 Ma Berlozhya 'Andean-style' arc to the west in Central Chukotka, Tikhomirov et al., 2008; the late Jurassic-early Cretaceous Pekulney island arc south of eastern Chukotka, Luchitskaya et al., 2005; the Upper Jurassic-Albian Uda-Murgal island arc further south, Sokolov et al., 2009a) are

101 recognized and are difficult to correlate regionally. Across Chukotka, abundant granitoids
102 yield U-Pb zircon ages of predominantly c. 120 - 100 Ma (Akinin et al., 2009b; Miller et al.,
103 2009; Luchitskaya et al., 2014), followed by an episode of uplift, erosion and the
104 development of a pronounced angular unconformity prior to eruption of the Okhotsk-
105 Chukotka volcano-plutonic belt (OCVB).

106
107 The OCVB is mostly 90 Ma, generally flat-lying, and is deposited unconformably across
108 older plutonic and metasedimentary rocks (Miller et al., 2009; Akinin and Miller, 2011). It is
109 a remarkable, 3000 km long continental magmatic arc dominated by volcanic rocks and their
110 hypabyssal equivalents (Akinin and Miller, 2011; Tikhomirov et al., 2012, 2016). Previously
111 older (Jurassic to early Cretaceous) volcanic complexes were erroneously grouped with
112 OCVB magmatism, but modern geochronology and geochemistry define the OCVB (*sensu*
113 *stricto*) as a mid- to late Cretaceous subduction-related, continental arc (Tikhomirov et al.,
114 2012, 2016). The Provideniya-Chaplino region of eastern Chukotka, with its extensive
115 Cretaceous volcanic and plutonic associations, provides a unique opportunity to study
116 tectonomagmatic events in the Bering Strait region and provides insight unavailable from
117 adjacent Chukotka and Alaska where very few volcanic rocks of pre-OCVB age have been
118 recognized. The progression of tectonomagmatic events in the Provideniya-Chaplino region
119 presented here and integrated with the temporal-spatial progression of magmatism across
120 Chukotka described above is critical for better understanding regional tectonic events.

123 **THE PROVIDENIYA-CHAPLINO REGION**

125 **Previous work and stratigraphic relationships**

The geology of the Provideniya-Chaplino area in eastern Chukotka was previously studied at a reconnaissance scale. Russian mapping expeditions produced the Provideniya 1:200 000 geological map (Borzakovsky, 1965) with explanatory notes (Borzakovsky et al., 1968; Kryukov and Plyasunov, 1987) that, when combined with older work (e.g. Shilo & Zagruzina, 1965), introduce the general geology and relative age relationships of the region. These studies showed the Provideniya-Chaplino region to include older rocks (sedimentary-metasedimentary units and high-grade metamorphic rocks such as schists, amphibolites and gneisses) overlain and intruded by relatively undeformed and unmetamorphosed volcanic and plutonic assemblages of felsic to intermediate composition.

Metamorphic rocks in the area were initially considered to be Proterozoic in age (e. g. Kryukov and Plyasunov, 1987), however a late Devonian Rb-Sr isochron from schists and amphibolites (Akinin, 1995) is interpreted to either date the time of metamorphism or to reflect an early Palaeozoic protolith age. These rocks are considered part of the Penkignei Series of the Senyavin uplift. They have been interpreted as a juxtaposed oceanic and shelf sedimentary assemblage regionally metamorphosed and deformed under amphibolite grade conditions (Akinin, 1995; Gans et al., 1995; Calvert, 1999). They were exhumed by 132-128 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages; Calvert, 1999). Lower grade rocks include limestones, phyllites and their metamorphosed counterparts (schists, marbles and calc-silicate rocks). Limestone on Ettygran Island contains Devonian fauna (Borzakovsky et al., 1968), thus on the 1:200,000 Russian geologic map other sedimentary and metasedimentary rocks of the region were also interpreted as being Devonian in age (Borzakovsky, 1965). However, they could be as young as the oldest cross-cutting granites (c. 135 Ma, this study) or the age of metamorphism (c. 130 Ma; Calvert, 1999).

In eastern Chukotka all igneous rocks that intruded and were deposited on metamorphic basement were assigned to the OCVB. These comprise several plutons and a volcanic section estimated to be 1-2 km thick (Borzakovsky et al., 1968) that is historically divided into three units, with a suggested unconformity between the middle and lower units (Borzakovsky et al., 1968):

- i) The upper Nunligran unit: Dacitic and andesitic lava flows.
- ii) The middle Leurvaam unit: Rhyolitic ash flow tuffs or ignimbrites, tuffs with spores of *Lygodium hirsutoide* L., *Gleichenia*, *Osmunda*.
- iii) The lower Etelkuyum unit: Altered andesitic to dacitic porphyry flows, their tuffs and lava breccia, and tuffaceous conglomerates at the base.

These units have been correlated across Chukotka (see Fig. 2 in Akinin & Miller, 2011) but, given our new data presented below, this correlation may need to be refined. Relative to Belyi's (1973) tripartite subdivision of the OCVB into 'lower andesites', mostly silicic rocks, and 'upper basalts', we note the absence of 'upper basalts' in the Provideniya-Chaplino region. Despite these ambiguities, there is general agreement that the magmatic rocks exposed in the Provideniya-Chaplino region are Cretaceous in age. K-Ar whole rock ages compiled from eastern Chukotka (GEOCRON 1.0 database; Akinin and Kotlyar, 1997) suggest that most OCVB magmatism here is between 100-80 Ma (Fig. 2). Early K-Ar whole rock ages for intrusive rocks include a 97 Ma age for hornblende granodiorite near Provideniya, a 94 Ma age for biotite granodiorite on Ettygran Island, and a 90 Ma age for the Rumilet granite (Borzakovsky et al., 1968). Biotite and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages between 93-84 Ma were obtained from plutonic rocks that intruded the metamorphic rocks on the margins of the Senyavin uplift (Calvert, 1999). Flora, K-Ar and Rb-Sr data from OCVB volcanic strata in the Provideniya-Chaplino region yield Cretaceous (Albian to Turonian) ages (Koren & Kotlyar, 2009). These ages are broadly consistent with our new, more detailed, data.

Local geology, field relationships, and unit descriptions

Our mapping provides a more detailed geologic understanding of the Provideniya-Chaplino region ([Fig. 3](#)) (also see [supplementary material Fig. S1](#)). We recognize and describe below sedimentary and metasedimentary units that are overlain and intruded by multiple Cretaceous igneous assemblages. Some of these rocks preserve fossils of Palaeozoic age and form the country rock to Cretaceous magmatism. Unconformities, fault contacts, and cross-cutting relationships are used to define the relative timing of units and events. The Cretaceous assemblages themselves include an older complex(es) of igneous rocks tilted and contact metamorphosed prior to the intrusion and eruption of younger igneous rocks that are inferred to correlate (Borzakovsky et al., 1968) with OCVB magmatism. Late normal faults cut the youngest units indicating syn- to post-OCVB extension, particularly in the eastern part of the study area. We retain the name Rumilet (after Borzakovsky et al., 1968) for the granite pluton found at Rumilet Bay. For other igneous associations we use informal names taken from nearby geographic features (e.g., Tkachen Bay pluton after Tkachen Bay) and towns (e.g., Providenya granodiorite) or lithology (Ignimbrite).

Metamorphic rocks. Palaeozoic metamorphic rocks (the Penkignei Series associated with the Senyavin uplift) are exposed in the northwestern-most part of the study area ([Fig. 3](#)) but were not studied herein. Their inferred equivalents in the central part of our study area occur as small (not visible at map scale), isolated fragments north of Tkachen Bay ([Figs. 3, 4a](#)).

Devonian limestones and phyllites and their metamorphosed counterparts (schists, marbles and calc-silicate rocks) are best exposed in the eastern part of the study area and on Ettygran Island ([Fig. 3](#)).

Valley pluton granitoids. Sparse exposures of previously unrecognized granitoids aligned NE-SW are restricted to the Tkachen valley and the south side of Tkachen Bay (Fig. 3). The contact with overlying rocks is unconformable and variably exposed, but these granitoids presumably intruded the older metamorphic rocks (Fig. 3). On the east side of Tkachen valley, Valley pluton granitoids give way over c. 10 m to limestone subcrop that is overlain by the steeply dipping Mt. Chaos complex, whereas south of Tkachen Bay the granitoid is brecciated and directly overlain Mt. Chaos complex rocks that entrain angular fragments of the granitoid (Fig. 4b). The Valley pluton granitoids are compositionally and texturally heterogeneous. They include i) a locally foliated medium- to fine-grained, hypidiomorphic saussuritized phase dominated by aligned feldspar (65%) and actinolite altering to chlorite (25%), with minor quartz (10%) and accessory oxides, titanite, and epidote, and ii) a foliated metafelsite (e.g., potassium feldspar-phenocrysts in a fine-grained groundmass) with accessory titanite and hematite. Localized brecciation and/or microfractures are also present. Magma-mingling textures are seen in outcrop and are evidence of the compositional heterogeneity of this unit. The rocks are characterized by a low-grade metamorphic assemblage of actinolite, epidote and chlorite.

Tkachen Bay pluton. According to the Russian geological map (Borzakovsky et al., 1968), the Tkachen Bay pluton is a semi-circular body surrounding the Chaplino complex and Rumilet Bay pluton between Tkachen and Abolasheva bays (Fig. 3). We studied exposures around Tkachen Bay. The pluton is typically medium- to coarse-grained and hypidiomorphic granular, with phenocrysts of hornblende (and rare quartz) up to 1 cm in size. Its composition varies from biotite hornblende quartz monzodiorite (15% quartz, 40-50% plagioclase, 15-25% potassium feldspar, and 20-30% mafic minerals with hornblende $\geq$ biotite) to biotite hornblende granodiorite, i.e.- more quartz-rich (20-25%), for example in exposures south of

New Chaplino. Fine-grained mafic enclaves of dioritic composition are locally present and have an average composition of <5% quartz, ~65% plagioclase, and ~35% hornblende. These enclaves show pronounced magma mingling textures with the surrounding pluton (Fig. 4c), suggesting that a mafic phase(s) not seen in the field was associated with Tkachen magmatism.

Mount Chaos complex. The Mt. Chaos complex is named for Mount Chaos which forms the steep slope of south Tkachen Bay (Fig. 3). It consists of steeply dipping, primary and reworked volcanic and volcanogenic rocks, with locally abundant intermingled hypabyssal equivalents that give way up section to massive sedimentary breccias. An unconformable contact is exposed at a single location (Location 8) between moderately SW-dipping Mt. Chaos rocks and underlying brecciated, hematized Valley pluton granitoids (Figs. 3, 4b). Hypabyssal rocks are mapped as distinct from volcanogenic rocks only north of Provideniya, adjacent to the Tkachen pluton (Fig. 3). The complex surrounds the Tkachen pluton to the south and east. It is intruded by the Provideniya pluton near the town of Provideniya. Volcanogenic rocks in the Mt. Chaos complex commonly display a distinctive maroon, red, purple, or blue-green color, while hypabyssal rocks are generally green. The rocks are all characterized by low-grade contact metamorphic assemblages (e.g., chlorite, actinolite, sericite, and epidote) and lack penetrative deformation.

At the base of the Mt. Chaos complex primary volcanic tuffs and pepperite occur. The tuffs are andesitic to dacitic in composition and include lithic crystal tuff, lapilli tuff, fine ash tuff, tuff breccia, and welded tuff. The tuffs contain a moderately to well-developed compaction foliation (welding) defined by flattened fiamme striking NNW with near vertical dips; bedding fines to the SSW, consistent with dip-direction. The tuff is composed of 10-30%

pumice fiamme, 10-20% plagioclase crystal fragments, and 5-15% fine grained volcanic lithics (some containing plagioclase phenocrysts) in a glassy ash matrix. Pepperite is abundant in east Tkachen Bay and contains flattened pumice, variable amounts of volcanogenic lithic fragments (aphyric or porphyritic with plagioclase $\pm$ hornblende phenocrysts), and crystals (plagioclase $\pm$ hornblende + potassium feldspar) (Fig. 4d).

The epiclastic component of the Mt. Chaos complex increases up-section and dominates exposures along south Tkachen Bay (Fig. 3) where volcanic breccia and conglomerate with subangular to subrounded (and locally well-rounded) cobble to boulder size (up to 1m) clasts are well-exposed. The tuffs and pepperites at the base of the complex grade into massively bedded subaerial breccias to the west, which in turn grade into clast-supported terrigenous avalanche-type deposits with meter-sized sub-angular/sub-rounded granitic boulders and interlayered red beds (Fig. 4e). These rocks are generally internally massive and poorly sorted, although bedding in fine to very coarse grained sandstone and siltstone can be well-defined locally on a scale that varies from fine laminations to 60 cm. These rocks are rich in angular plagioclase crystal fragments and altered volcanic lithic clasts. Most clasts are variably porphyritic (plagioclase $\pm$ hornblende) volcanic and hypabyssal lithics, but locally as much as 10% of the clasts are plutonic (Fig. 4e). The plutonic clasts appear similar in composition and texture to the Tkachen pluton, thus we infer they were derived from it and that the Mt. Chaos rocks post-date the Tkachen pluton.

Hypabyssal rocks of the Mt. Chaos complex are andesitic and include both massive rocks and compositionally similar intrusive breccia. The massive rocks and the intrusive breccia clasts both contain plagioclase or plagioclase + hornblende phenocrysts in a fine to medium grained, green crystalline groundmass.

278

279 *Provideniya pluton.* The Provideniya pluton is a fairly homogeneous, medium to coarse-
280 grained, equigranular biotite hornblende quartz monzonite found near the town of
281 Provideniya and on Ettygran island (**Fig. 3**). Its average composition is 5% quartz, 45%
282 plagioclase feldspar, 30% potassium feldspar, and 20-25% mafics, including hornblende and
283 biotite. Hornblende phenocrysts are found locally in some areas. Evidence that this pluton
284 intrudes rocks of the Mt. Chaos complex is based on the following observations: (1) The
285 pluton becomes finer grained as the contact with the Mt. Chaos complex is approached, and
286 (2) the pluton contains inclusions of fine-grained microdiorite with hornblende and
287 plagioclase phenocrysts that appear similar to Mt. Chaos hypabyssal rocks.

288

289 *Chaplino complex.* This complex comprises several units including a basal ignimbrite, tuffs
290 and volcanoclastic rocks, and hypabyssal rocks. The basal ignimbrite is only seen in a narrow
291 band on the north side of Tkachen Bay (**Fig. 3, Fig. 4f**) where it is unconformable on
292 metasedimentary rocks (presumably the Penkignei Series) at the base of the complex. The
293 younger tuffs and volcanoclastic rocks of the Chaplino complex (**Fig. 3**) overlie the ignimbrite
294 along a prominent angular unconformity. The ignimbrite is predominantly a dacitic ash flow
295 tuff with cognate inclusions and a strong welded fabric defined by flattened pumice fiamme
296 and flattened glass shards in the matrix. Pumice fiamme (15-30% of rock volume)
297 commonly have thickness to length ratios of up to 20:1. Crystal and lithic fragments are of
298 minor abundance and include plagioclase $\pm$ potassium feldspar (5%) and felsic volcanic
299 lithics (5-10%). Near Chaplino gabbro is exposed unconformably below the Mt. Chaos
300 complex and gabbroic xenoliths occur in the ignimbrite (not visible at map scale), but
301 xenoliths of the underlying metamorphic rocks are absent. The basal ignimbrite is not
302 metamorphosed and vapor-phase alteration and/or recrystallization of pumice occurs locally.

The unit is tilted and possibly folded, with variable dips of 17° to vertical, while dip-direction varies from NW to SW to SE.

The tuffs and volcanoclastic unit of this complex are best exposed around Rumilet Bay and SSW of Ettygran Island (**Fig. 3**). North of Tkachen Bay the tuffs and volcanoclastic rocks sit unconformably over the basal ignimbrite of the complex, and to the east are unconformable on the Mt. Chaos complex. These Chaplino complex rocks are up to 1100 m thick and gently (10-30°) dipping. The most abundant rocks of the Chaplino complex tuffs and volcanoclastic unit include dacitic tuff breccia, lapilli tuff, ash tuff, and welded ash flow tuff. Ash flow tuffs have a strong compaction fabric (welding), but compaction fabrics in the other tuffs are more variably developed. The tuff matrix is typically gray-green ash. Locally, the tuffs contain clasts of dacitic ignimbrite probably derived from erosion of the underlying basal ignimbrite. A densely welded dacitic vitrophyre (**Fig. 4g**) is notable and contains plagioclase ± potassium feldspar crystal fragments (5%), felsic lithic fragments (5-10%), fiamme (15%), and a glassy matrix (75%). Much less common in the Chaplino complex are reworked volcanoclastic deposits, including volcanic breccia and sandstone apparently sourced from the Chaplino complex itself. A biotite hornblende granodioritic lithic component is found locally in the Chaplino volcanic tuffs - rare clasts are foliated and possibly derived from the Valley pluton, the Tkachen pluton, or both.

Hypabyssal rocks of the Chaplino complex are well-exposed near the Rumilet pluton (**Fig. 3**). These fine-grained, medium to dark green rocks have a crystalline texture and typically contain phenocrysts of plagioclase, plagioclase + hornblende, or more rarely plagioclase + hornblende + potassium feldspar. The hypabyssal rocks are believed to be comagmatic and

broadly coeval with the adjacent tuffs and volcanoclastic rocks based on similar compositions and the presence of hypabyssal dykes cutting the volcanic rocks near their mutual contact.

Rumilet pluton. The main phase of the Rumilet pluton is a leucocratic biotite granite well exposed around Rumilet Bay (**Fig. 3**). It forms pinkish to orange, commonly miarolitic, outcrops and is inferred to be broadly coeval with the Rumilet volcanic and hypabyssal rocks described above. It is generally coarse-grained, composed of 25% quartz, 40% pink potassium feldspar, 30% plagioclase, and 5% biotite. Towards the southwest, the pluton becomes finer grained and more texturally complex, varying from very fine grained sugary aplite, to microgranite, to medium grained granite, and locally contains phenocrysts of potassium feldspar $\pm$ quartz $\pm$ plagioclase. Evidence for magma mixing/mingling between the pluton and the Rumilet hypabyssal rocks is common and observed at all scales, from large blocks of Rumilet hypabyssal rocks enclosed within the pluton, to 3 m enclaves to 2 mm micro-enclaves in hand sample (**Fig. 4h**), to disequilibrium phenocryst textures in thin-section. Locally enclaves of Rumilet hypabyssal rocks constitute nearly half of the pluton volume and show textural relations (chilled margins, irregular shapes with crenulated margins) indicating that the pluton intruded the hypabyssal rocks before they were fully crystallized. From these relationships it is clear that the Rumilet pluton is broadly comagmatic with, but slightly younger than, the Rumilet hypabyssal rocks.

West of Tkachen Bay the border phase of the Rumilet pluton cross-cuts the Tkachen Bay pluton (**Fig. 3**) and large blocks of the Tkachen pluton are locally engulfed in the Rumilet pluton. Buff colored NE-trending, subvertical dykes compositionally similar to the Rumilet pluton also intrude both Mt. Chaos and Tkachen rocks and are best seen west of Tkachen Bay

(Fig. 3). These dykes are leucocratic, with potassium feldspar $\pm$ quartz $\pm$ plagioclase and ~5% biotite.

Other relationships. The contact between the late Cretaceous magmatic rocks and the Tkachen pluton (Fig. 3) appears in places to have been a fault prior to final emplacement of the Rumilet pluton. Near the southwest contact, Chaplino hypabyssal rocks are marked by brittle fractures and alteration. In addition, Mt. Chaos rocks southwest of the contact dip steeply (near vertical) to the WSW, while Chaplino volcanogenic strata to the northeast of the contact dip gently to the NNW.

Samples

Eighteen samples from 15 locations representing the major units in the region were collected for U-Th-Pb SIMS zircon dating (Fig. 3). Samples included Valley pluton granitoids, the Tkachen Bay pluton, the Mt. Chaos complex, two granitic boulders from a Mt. Chaos complex breccia, the Provideniya pluton, the Chaplino complex, and samples of the Rumilet Bay pluton (Figs. 3, 4). Sample locations, sample numbers, lithologies, coordinates, and U-Pb crystallization ages are summarized in Table 1.

Valley granitoids. Three Valley pluton granitoids were collected. Two samples were collected at location 3 (Fig. 3), one a foliated, actinolite-bearing phase (VP05-017c) and another from a little deformed, more felsic phase (two feldspar + quartz; VP05-018). At location 8 (Fig. 3), the hematized and brecciated granitoid (sample VP05-013a) beneath the Mt. Chaos complex volcanogenic rocks (Fig. 4b) was sampled. The Valley granitoid samples represent the oldest igneous rocks in the study area.

376

377 *Tkachen Bay pluton.* Four samples (VP05-004, VP05-007a, ELMNC28.7a, P95-Q-36) of
378 this compositionally diverse pluton (**Fig. 4c**) were collected from the central part of the
379 study area at locations 5, 6, 9, and 14 (**Fig. 3**). The pluton exposed at location 6 (sample
380 VP05-004) is intruded by the fine-grained ‘micro’ granite dyke sampled at location 7
381 (sample VP05-006) (**Fig. 3**).

382

383 *Mt. Chaos complex.* Three samples of the Mt. Chaos complex were collected. One sample of
384 lithic-rich tuff (sample VP05-013b) from location 8 at Tkachen Bay (**Fig. 3**) is
385 unconformable with the underlying Valley granitoid (**Fig. 4b**). At location 10, two granitic
386 boulders were sampled (samples VP05-016b and VP05-016c; **Fig. 4e**) to confirm their
387 correlation with the Tkachen Bay pluton.

388

389 *Provideniya pluton.* A single sample of the Provideniya pluton was sampled. It represents
390 our western-most sample from near the town of Provideniya (location 15, sample P95-S-39).
391 This hornblende granodiorite intrudes the Mt. Chaos complex and is therefore expected to be
392 younger than the Mt. Chaos rocks.

393

394 *Chaplino complex.* Three samples of the Chaplino complex were collected. One sample of a
395 weakly crystalline, compositionally homogeneous cognate inclusion was collected from the
396 ignimbrite (sample P95-G-205, location 4; **Fig. 4f**) and provides the age of its host. Two
397 samples from the tuffs and volcaniclastic rocks of the Chaplino complex were collected;
398 these are among the youngest volcanic rocks in the region and field relationships indicate
399 that these are extrusive equivalents of the Rumilet pluton. Locations 1 and 2 are c. 8 km
400 apart and represent our most easterly samples of the Chaplino complex. Location 1 is from

the highest part of the section we sampled. The volcanogenic sediment sampled here (sample VP05-025a) is conformable with the volcanic rocks sampled at location 2. At location 2, a lavender crystal-rich tuff (sample VP05-020) represents the lowest part of this section and overlies limestone and phyllite of inferred Devonian age.

Rumilet pluton. The Rumilet Bay pluton represents the youngest magmatism in the region based on cross-cutting field relationships and three samples of the main miarolitic phase were collected (Fig. 4h). The northernmost sample is near Rumilet Bay (Location 11, sample VP05-030) (Fig. 3). Samples VP05-031a (Location 12) and P95-W-38 (Location 13) are proximal to each other and c. 2.5 km south of location 11 (Fig. 3). A potassium feldspar microgranite (location 7, sample VP05-006) intrudes the Tkachen pluton of location 6 (Fig. 3) and was collected as the cross-cutting relationship indicated it is a younger magmatic phase.

ANALYTICAL METHODS

The samples were crushed and milled. Zircon was separated using conventional water table, heavy liquid and magnetic techniques. Separated zircons and zircon standards were handpicked and mounted in epoxy resin and then polished to expose the interior of the grains. Textures of the polished zircons were studied using secondary electron microscopy (SEM) and cathodoluminescent (CL) imaging using a Hitachi SEM at the Swedish Museum of Natural History. U-Th-Pb geochronological data were obtained using the Cameca 1270 ion microprobe at the NORDSIM facility, Swedish Museum of Natural History (sample numbers beginning ‘VP’ and ‘ELM’) or the reverse geometry SIMS (SHRIMP-RG) at the

SUMAC facility, Stanford University (sample numbers beginning ‘P95’). The analytical spots are ca. 25 x 20 μm . The Pb/U ratio, elemental concentration and Th/U ratio calibration at the NORDSIM and SUMAC facilities were performed relative to international zircon standards 91500 (Wiedenbeck et al., 1995) and R33 (Black et al., 2004), respectively. The analytical methods follow that described by Whitehouse et al. (1999) and Whitehouse and Kamber (2005) for NORSIM data, or Williams (1998) for SUMAC data. A common lead correction, if needed, was performed using the measured ^{204}Pb signal and modern (i.e. - 0 Ma) Pb isotope composition of Stacey and Kramers (1975). Data reduction utilized Excel macros developed by M. J. Whitehouse at the Swedish Natural History Museum, Stockholm or the Squid software of Ludwig (2001). All U-Pb data were plotted using Isoplot (version 4.15; Ludwig, 2012). Inverse concordia diagrams are used for reporting concordia ages (Ludwig, 1998) which were calculated for the majority of samples. In some instances, however, the common Pb correction resulted in ‘over correction’, reflecting the difficulty associated with accurately determining lower- ^{204}Pb signals. In these cases, the weighted average of the so-called ^{207}Pb -corrected ages were used (e.g., the age projected to Concordia assuming a specific common lead composition) (Ludwig, 2003). A single sample uses the common-Pb intercept age, following the method described in Ludwig (2012). All errors are reported at 95% confidence unless stated otherwise.

ANALYTICAL RESULTS

The geochronological analyses are provided in supplementary data table S1. Representative CL images (Fig. 5) and U-Pb ages (Fig. 6) are presented by sample number. CL images show the presence of oscillatory growth zoning in all zircons analyzed (Fig. 5) and all

analyses have Th/U ratios predominantly between 0.4 and 1 ([Supplementary Table S1](#)).

These combined characteristics are consistent with a magmatic genesis for the zircons analyzed (Corfu et al., 2003; Belousova et al., 2002) and consequently all ages are considered to be crystallization ages.

Valley pluton granitoids. From field relationships, the oldest rocks in the region are represented by variably foliated granitoid samples VP05-017c and VP05-018, and the brecciated granitoid sample VP05-013c. The samples give ages of c. 131-136 Ma ([Fig. 6](#)). The more mafic (actinolite-bearing) sample VP05-017c gives a Concordia age of 135 ± 2 Ma (95% confidence, n=8). The more felsic sample VP05-018 gives a Concordia age of 131 ± 1 Ma (95% confidence, n=10). The brecciated granitoid sample VP05-13a gives a Concordia age of 136 ± 1 Ma (95% confidence, n=10).

Tkachen Bay pluton. The four samples representative of the older, undeformed plutonic suite yield consistent results ([Fig. 6](#)). Concordia ages are well defined at c. 122 Ma: sample VP05-004 (122 ± 2 , 95% confidence, n=9), sample VP05-007a (119 ± 2 , 95% confidence, n=7), sample ELMNC28.7a (120 ± 1 , 95% confidence, n=22), sample P95-Q-36 (121 ± 2 , 95% confidence 207-corrected age, n=11). Older ages (135 Ma in sample VP05-004, 132 Ma in sample ELMNC28.7a, 132 Ma in sample P95-Q-36) ([Fig. 6](#)) are interpreted as xenocrystic zircon.

Mt. Chaos complex. The sample representing the volcanogenic rocks (VP05-013b, [Fig. 6](#)) gives a Concordia age of 105 ± 1 Ma (95% confidence, n=7). Two granitic clasts from the Mt. Chaos conglomerate give slightly older, but similar, ages of c. 123 Ma, with sample VP05-016b yielding 124 ± 1 Ma (95% confidence, n=11) and sample VP05-016c giving 123

± 2 Ma (95% confidence, n=10). These three ages are consistent with field relationships inasmuch as the Mt. Chaos volcanogenic rocks sit unconformably on older granitic rocks with an age of 136 Ma, includes boulders and cobbles 123-124 Ma, and is intruded by the younger 94 Ma Provideniya plutonic rocks (see below).

Provideniya pluton. The granodiorite near Provideniya (sample P95-S-39) gives a 207-corrected age of 94 ± 2 Ma (95% confidence, n=12) (Fig. 6). This is consistent with field relationships as it intrudes the 105 Ma Mt. Chaos volcanogenic rocks.

Chaplino complex volcanics. The cognate inclusion from the basal ignimbrite (sample P95-G-205) has an age of 88 ± 1 Ma (95% confidence, n=6). This constrains the age of the ignimbrite and is consistent with field relationships that require it to be older than the overlying Chaplino complex hypabyssal and extrusive rocks (see below). It also contains zircon with ages of c. 110 and 92 Ma interpreted to be xenocrysts.

Two volcanoclastic samples (VP05-020, VP05-025a) representing the youngest Chaplino complex volcanic rocks in the region yield results in good agreement with each other (Fig. 6). Sample VP05-020 generates a Concordia age of 85 ± 1 Ma (95% confidence, n=10) and sample VP05-025a provides a common lead intercept age of 86 ± 2 Ma (95% confidence, n=9). Two older zircons with ages of c. 104 Ma (VP05-025a, Fig. 6) are interpreted as xenocrysts.

Rumilet Bay pluton. The three samples (VP05-030, VP05-031a, P95-W-38) known from field relations to be the youngest magmatic phase in the study area give nearly identical results (Fig. 6). Their weighted average 207-corrected ages (Ma) with 2σ errors are: 85 ± 2 (95% confidence, n=7), 85 ± 1 (95% confidence, n=11), and 85 ± 2 (95% confidence, n=12).

In addition, the microgranite (VP05-006) that intrudes the Tkachen pluton (VP05-004) gives a Concordia age of 85 ± 1 Ma (95% confidence, $n=8$) and is clearly related to this group.

DISCUSSION

Our new ages provide a detailed chronology of tectonomagmatic events in the Provideniya-Chaplino region of eastern Chukotka that span *c.* 55 m.y. This activity is punctuated by multiple unconformities, documenting episodes of uplift and erosion between discrete magmatic pulses (**Fig. 7**). Our refined understanding of the region's tectonomagmatic evolution allows us to place eastern Chukotka into a broader regional context associated with the AACM through comparison to equivalent age rocks in Russia, Alaska and Canada, and to integrate this evolution within a tectonic framework of Pacific plate subduction and the development of the Amerasia Basin.

Tectonomagmatic evolution of the Provideniya-Chaplino region

The oldest ages of *c.* 136-131 Ma are from the three Valley pluton samples that occur in the central part of the study area as small, localized outcrops (locations 3 and 8; **Fig. 3**). At location 8 Mt. Chaos volcanic rocks (dated to 105 Ma at one stratigraphic level) are exposed above an unconformity with the Valley pluton dated to 136 Ma. This relationship suggests that the Mt. Chaos complex is also unconformable on Palaeozoic metasedimentary rocks, as these are inferred to constitute the country rock of the Valley pluton granitoids. In addition, the Mt. Chaos volcanoclastic succession contains cobbles of the *c.* 121 Ma Tkachen pluton, therefore we infer that the contact between the Mt. Chaos complex and *c.* 121 Ma Tkachen pluton is also an unconformity and/or a fault (**Fig. 7**).

527

528 The above relationships establish a period of uplift and erosion post-dating intrusion of the *c.*
529 121 Ma Tkachen pluton and prior to eruption of the Mt. Chaos tuff at *c.* 105 Ma. This is
530 consistent with deposition of Mt. Chaos volcanoclastics that contain granite clasts presumably
531 derived from the Tkachen pluton. A second period of uplift and erosion followed tilting of
532 the 105 Ma Mt. Chaos complex to near vertical orientations prior to their intrusion by the *c.*
533 94 Ma Provideniya pluton. This second period of uplift and erosion affected all earlier units
534 which are unconformably overlain by extensive ash flow tuffs associated with the formation
535 of the Rumilet caldera; it therefore occurred between 94 and 85 Ma. All pre-85 Ma rocks
536 thus constitute the "basement" across which the Rumilet ash flow tuffs were deposited. A
537 third period of erosion followed the formation of the Rumilet caldera and intrusion of the
538 Rumilet pluton at 85 Ma, resulting in the present distribution of rock units in the region (Fig.
539 7).

540

541 **Arc magmatism in the Provideniya-Chaplino region**

542 We recompiled the major and trace element and isotopic data of Rowe (1998), correcting
543 known errors, reclassifying, and recalculating initial ratios of the samples on the basis of our
544 new mapping and revised magmatic chronology. The revised geochemical data is
545 summarized in **Table 2** and presented in detail (analytical methods, sample locations, etc.) as
546 Supplementary material (**Table S2, Figs. S1-S4**). The igneous rocks in the Provideniya-
547 Chaplino region (excluding two ultra-high-K outliers which are distinct from all other
548 samples; Supplementary **Figs. S1-2**) are medium- to high-K calc-alkaline subduction-related
549 arc magmas (**Table 2; Fig. 8**). All units, with the exception of the *c.* 133 Ma Valley pluton
550 samples that lack geochemical data, have typical arc geochemistry: enriched chondrite-
551 normalized light rare earth relative to heavy rare earth elements ($> 100\times$ chondrite), high Ce

concentrations (> 49 ppm), high chondrite-normalized large ion lithophile elements ($> 100\times$ chondrite), and notable depletions in Nb, Ti, and P (Table 2). There is no indication of garnet in their genesis (HREEs are unfractionated with NMORB-like to slightly depleted chondrite-normalized values). The only significant difference is associated with the miarolitic Rumilet Bay pluton which has pronounced negative Sr and Eu anomalies, and low Ba concentrations. The decoupled LREE and high field strength elements ($\text{Nb/Ta} = 4\text{-}8$) are consistent with typical arc signatures as seen in, for example, the modern-day Peruvian Andes (Fig. 8).

The integration of our new age data with the revised geochemical data of Rowe (1998) documents an arc that is becoming more differentiated over time: plutonic rocks evolve from dioritic to granodiorite to granite, and extrusive rocks evolve from basaltic-andesite to andesite. However, additional complexity involves both i) variable amounts of crustal assimilation associated with arc evolution through time, as well as ii) assimilation of diverse crustal sources (Fig. 8). The lack of a systematic relationship between the age of the units and their Nd and Sr isotopic signatures favors the former, while the incredible range in $^{87}\text{Sr}/^{86}\text{Sr}_i$ (up to 0.73366) associated with the Rumilet Bay pluton favors the later. These highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}_i$ values exceed what is expected from seawater alteration (<0.710 ; Hess et al., 1986). Numerous studies have argued for anatectic melting of the crust to generate high $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios (e.g., Hamet and Allegre, 1976; Downes & Duthou, 1988), even in arc settings (Goss et al., 2010). The Pb-isotopic values for these Provideniya-Chaplino samples (Table 2 and Supplementary Table S2) plot above the Northern Hemisphere Reference Line of Hart (1984) and indicate a crustal component. In agreement with Tikhomirov et al. (2016), the isotopic data (Pb and Sr in particular) combined with the i) decoupled LREE and HFSE elements, and ii) the sub-chondritic Nb/Ta, is more consistent with subduction-related partial melts from a hydrated depleted mantle wedge being variably

contaminated via assimilation/partial melting of a heterogeneous (sometimes Rb-rich)
continental crust during arc evolution.

Arc preservation in eastern Chukotka

In the Provideniya-Chaplino region continental arc magmatism began at *c.* 121 Ma. Arc
magmatism in the region lasted from *c.* 121- 85 Ma. The episodic magmatism of the
Provideniya-Chaplino region illustrates both the fortuitous preservation of units, as well as
the internal destruction of the arc. Tkachen plutonic activity at 119-123 Ma and Provideniya
plutonism at *c.* 94 Ma are well preserved, but extrusive equivalents of this age have not been
recognized in the area. On the other hand, intrusive equivalents of the *c.* 105 Ma Mt. Chaos
complex have not been recognized in the area. In addition, many of the units contain zircon
xenocrysts from the preceding magmatic episode (*c.* 133 Ma xenocrysts in *c.* 121 Ma
magmatism, *c.* 112 and 92 Ma xenocrysts in the 88 Ma ignimbrite, *c.* 104 Ma xenocrysts in
the 85 Ma magmas; [Fig. 6, Supplementary Table S1](#)), suggesting that the arc was
assimilating itself as it evolved. While there is no *a priori* reason to assume that all magmatic
activity has both intrusive and extrusive counterparts, given multiple and significant (85° of
tilt) periods of uplift/erosion, as well as the re-assimilation of magmatic products during arc
evolution, it seems unlikely that all elements of arc magmatism will be preserved. This
incomplete preservation of the geological record complicates our ability to make regional
correlations.

Regional correlations

Senyavin uplift. Pre-Cretaceous rocks in the Provideniya-Chaplino area are neither abundant
nor well-exposed, but elsewhere across Chukotka uplift, exhumation and deep erosion is
known to have occurred prior to eruption of OCVB-related arc magmas. In the nearby

Senyavin uplift ([Fig. 3](#)) protolith ages are not well constrained but a single U-Pb zircon age (conventional population, CA-TIMS) of *c.* 139 Ma defines the time of partial melting and leucogranite genesis associated with peak metamorphic conditions (A. Calvert, *pers. comm.*). The Valley pluton granitoids in the Provideniya-Chaplino region have similar ages (*c.* 136-131 Ma), are also presumed to intrude limestone of Devonian age, and were deformed, metamorphosed, and exhumed before *c.* 105 Ma (unconformity with Mt. Chaos units). Exhumation and cooling of the Senyavin uplift occurred by 132-128 Ma (Calvert, 1999) and was followed by deposition of OCVB volcanics. It is clear from our new data that subduction was initiated shortly after extension, as documented by *c.* 121 Ma Tkachen plutonism, and it seems likely that elevated heat flow associated with arc magmatism could have facilitated partial melting in the region (e.g., the Senyavin uplift). Geochemical and isotopic studies of the *c.* 135 Ma Valley plutonic rocks are needed to correlate these with similar aged rocks in the Senyavin uplift.

Koolen dome. North of the study area, rocks associated with the Koolen dome ([Fig. 1](#)) also have some characteristics in common with the Provideniya-Chaplino region. The Koolen dome includes metasedimentary rocks with numerous intrusions, most of them deformed, including orthogneiss and ultramafic rocks that range in age from *c.* 385-362 Ma (with some zircon crystals as old as *c.* 666-574 Ma; Amato et al., 2014), younger orthogneisses with ages at *c.* 108 Ma and 104 Ma, and undeformed cross-cutting pegmatites dated at *c.* 94 Ma (Bering Strait Geological Field Party, 1997; Natal'in et al., 1999). The older rocks reached sillimanite grade with concurrent partial melting at *c.* 108 Ma and apparently cooled to near surface temperatures in the latest Cretaceous when *c.* 84 Ma rhyolite was deposited over the exhumed dome (Akinin & Calvert, 2002).

Elemental and isotopic geochemistry for the Cretaceous plutonism in the Koolen region (KD in Fig. 1) indicates subduction-related arc signatures (Amato & Wright, 1997; Rowe, 1998). Isotopic data from both the orthogneiss ($\epsilon\text{Ndi} = -4.4$ to -7.7) and the younger plutonic rocks ($\epsilon\text{Ndi} = -5.2$ to -7.3) document significant crustal input (Fig. 8). In the Koolen area ≥ 94 Ma plutons are ductilely deformed (orthogneiss), whereas in the Provideniya-Chaplino region all post-133 Ma rocks record only tilting, brittle deformation, and contact metamorphism. We conclude that although the timing and genesis of magmatism across the Koolen and Provideniya-Chaplino regions is similar, the time of metamorphism and metamorphic grade are distinctly different. These apparently disparate metamorphic histories can be reconciled, however, if the Senyavin/Provideniya-Chaplino region represents shallower crustal levels than the Koolen dome region (e.g., Calvert, 1999). In fact, the ages, unconformities, and periods of erosion documented here for supracrustal rocks in the Provideniya-Chaplino region elucidate the tectonic setting of the deeper rocks in the metamorphic culminations and explain the source of heat for amphibolite facies metamorphism and partial melting of deeper crust. This is especially helpful in understanding the geology of adjacent Alaska, where no supracrustal rocks are exposed (see below).

Central Chukotka. Until now eastern Chukotka represented a geochronological data gap and correlations to other parts of the OCVB (*sensu-lato*) (e.g., Akinen & Miller, 2011; Tikhomirov et al., 2016) were speculative. Our new geochronology confirms that the latest magmatic activity in the Provideniya-Chaplino region occurred at 85 Ma, simultaneous with OCVB volcanism in central Chukotka and elsewhere (Akinen & Miller, 2011). Magmatic pulses of *c.* 105 Ma and *c.* 94 Ma are also in close agreement with known ages from the central OCVB and its correlatives further south (Akinen & Miller, 2011; Tikhomirov et al., 2012). However, in eastern Chukotka the *c.* 121-85 Ma magmatic rocks all have well-

defined continental arc geochemistry and imply that oceanic plate subduction beneath Chukotka was on-going throughout this period. On the other hand, in central Chukotka (Fig. 1) the c. 87 Ma OCVB is deposited unconformably on the Etchikun suite and documents an erosional hiatus, as well as a significant change in magma genesis from intraplate to subduction zone setting (Tikhomirov et al., 2016). On this basis Tikhomirov et al. (2016) suggested that the term OCVB should be restricted to rocks with subduction-zone geochemistry and post-dating the c. 107 Ma shoshonitic Etchikun suite. However, as highlighted in this study, subduction-related magmatism was ongoing throughout this period in eastern Chukotka and possibly elsewhere in the Russian Far East. We consider eastern Chukotka to document northward subduction of the ancestral Pacific plate from c. 121 Ma. Although the c. 107 Ma within-plate magmatism argues against subduction-related magmatism in central Chukotka, perhaps some far-field or back-arc stress links it to arc genesis occurring in eastern Chukotka at this time. It is difficult to correlate the tectonomagmatic events of the two regions given the lack geochronological and geochemical data from the intervening >500 km separating them.

Cretaceous magmatism across the AACM. Across the Bering Strait Cretaceous magmatism is preserved in the Kigluaik Mountains on the Seward Peninsula of Alaska (KM in [Fig. 1](#)). Field and geochronological evidence from the Kigluaik gneiss dome document pre-120 Ma blueschist to greenschist facies metamorphism prior to granitic (now orthogneiss) intrusion at c. 105 Ma; these rocks are overprinted by later coeval plutonism, metamorphism, and deformation at about 92 Ma (the age of the Kigluaik pluton) which is associated with the formation of the Kigluaik gneiss dome (Amato & Miller, 2004). Thus it is clear that magmatic activity in the Kigluaik gneiss dome overlaps and is coeval with magmatism in the Provideniya region; however, the Provideniya region provides a supracrustal view of tectonics

and magmatism, while the Seward Peninsula and Kigluaik gneiss dome represent a deeper level of exposure of the crust at this time (Akinin et al., 2009).

In addition, the widespread effects of Cretaceous magmatism from Chukotka to Alaska are well documented across Bering Strait (from Enmelen in Russia, across St. Lawrence Island to Nunivak and the Seward Peninsula of Alaska). Deep crustal xenoliths from Neogene basalts across this region yield only Cretaceous and younger ages, arguing for significant modification by, and crustal addition due to, Cretaceous magmatism in the Bering Strait region (Akinin et al., 2009). The deep crustal record of magmatism and metamorphism documented by Akinin et al. (2009) compares well with the history of supracrustal magmatism discussed here. SIMS U-Pb zircon ages from predominantly gneissic mafic xenoliths range from c. 138-60 Ma (N=125) with the main age peak at 80-90 Ma (Provideniya and Rumilet pluton ages) and a lesser peak at c. 70 Ma representing a southward jump in the locus of magmatism (Akinin et al., 2009) not recorded in the Provideniya region. Our new data documenting the supracrustal history of magmatism in the Provideniya region is consistent with the concept that the crust beneath this region was modified and significantly added to by a magmatic history spanning c. 35 Ma (c. 121-85 Ma).

Implications for Arctic tectonics

The timing and spatial distribution of ocean-continent subduction-related arc magmatism is crucial for understanding the convergent margin history of the Bering Strait region and the onset of Pacific plate subduction. Shortening in western Chukotka began in the middle Jurassic, lasted into the early Cretaceous, and may be related to collision between the AACM and Asia along the South Anyui Suture (see Miller et al., *this volume* and references therein) (**Fig. 1**). The Rauchua depression (near Pevek, Fig. 1) is filled by late Jurassic(?) through

early Cretaceous (Neocomian) syn-collisional deep water turbidites (Belyi et al., 1989). Intense folding of early Cretaceous strata within the South Anyui suture zone was followed by overprinting extensional fabrics at c. 110 Ma, indicating that shortening here ended between c. 133 – 110 Ma (Miller et al., 2009; Sokolov et al., 2002). This is consistent with within-plate magmatism occurring in central Chukotka at c. 107 Ma (Tikhomirov et al., 2012). On the other hand, in eastern Chukotka exhumation and cooling in the Senyavin uplift at c. 130 Ma (Calvert, 1999) was soon followed by subduction; arc magmatism was already underway by c. 121 Ma (this study) and confirms the onset of palaeo-Pacific plate subduction beneath North Asia by this time. While there is limited evidence for older arc-related magmatism preserved elsewhere in the AACM (see Amato et al., 2015 and Tikhomirov et al., 2016 and references therein), there is no consensus regarding the plate geometry associated with these Jura-Cretaceous arc-rocks (e.g., subduction of the South Anyui ocean or the palaeo-Pacific plate).

Our new data may also help to constrain models for the opening of the Amerasia Basin and the development of the Arctic Ocean, which are thought to have evolved during the Cretaceous Period. Others have convincingly argued that the broad belt of late Cretaceous plutons from Alaska to Canada is intimately linked to subduction of the ancestral Pacific plate beneath North America at this time (Rubin et al., 1995; Miller et al., *this volume* and references therein). Lower Cretaceous magmatism across the AACM (e.g., Provideniya-Chaplino, Senyavin uplift, Koolen dome, Kigluaik gneiss dome) documents the regional significance of arc activity at this time (e.g. Amato et al., 2003; Amato & Wright, 1997). In the Chukotka segment of the Uda-Murgal arc (CUM in [Fig. 1](#); Parfenov, 1984; Sokolov et al., 2009a) gabbro, diorite and granite of presumed Cretaceous age (c. 121 Ma whole-rock K-Ar age from sodic granite; Morozov, 2001) intruded and metamorphosed the accreted CUM.

This age agrees well with Cretaceous magmatic ages from the Provideniya-Chapline region presented here and the time of partial melting in the Senyavin uplift. The integration of our new age data with the published literature supports the initiation of palaeo-Pacific plate subduction northward beneath the AACM by Aptian time.

The creation of the Amerasia basin is widely thought to be the result of rifting and rotation of the AACM from a conjugate margin along Arctic Canada (modern-day coordinates) (e.g., Grantz, 2011 and references therein). For the Alaskan part of the AACM this link is firmly established from roughly mid-Jurassic time (e.g., sediment provenance studies, Gottlieb et al., 2014; stratigraphic correlations, Grantz & May, 1983, Embry, 1990, Houseknecht & Connors, 2016); rift-related unconformities, Grantz & May, 1983, Embry & Dixon, 1990, Houseknecht & Connors, 2016). The restoration of the Russian part of the AACM remains debated (e.g. Miller et al., 2006, 2010, 2011, *this volume*; Amato et al., 2009, 2015; Kuzmichev, 2009; Till, 2016). Nonetheless, thermochronological data from basement culminations across the Bering Strait region (e.g., Akinin & Calvert, 2002; Amato & Miller, 2004; Amato et al., 2014) indicate that magmatism and extension was an important influence on crustal evolution at this time (Miller et al., 2009). Across the AACM structures associated with subhorizontal shortening under lower greenschist facies conditions are intruded and thermally overprinted by voluminous c. 120-110 Ma granites (Miller et al., 2009). Our documentation of c. 121-85 Ma subduction-related magmatism in eastern Chukotka, combined with the regional history of crustal extension summarized above, agrees with previous suggestions for the southward migration of the Pacific subduction zone during trench roll-back (Amato & Wright, 1997; Rubin et al., 1995). This allows the Canada Basin to open in a back-arc-basin setting, permits extension

simultaneous with arc magmatism, and links the localization of magmatism to the migration of the arc. The lack of arc-related magmatism younger than 85 Ma across the region directly correlates to the significant migration of the subduction zone southward post-85 Ma, and which ultimately led to the modern-day configuration of the Aleutian arc (Akinin et al., 2009; Miller et al., *this volume*).

CONCLUSIONS

Subduction-related magmatism in the Provideniya-Chaplino region of eastern Chukotka spans at least c. 35 Ma (c. 121-85 Ma). This magmatism is punctuated and framed by multiple unconformities representing at least three episodes of uplift and erosion. Zircon xenocrysts, xenoliths, granitic debris in clastic avalanche-type deposits, and multiple unconformities define an arc that was uplifting, eroding, and partially cannibalizing itself as it evolved. The final stage of magmatism occurred at 85 Ma – there is no record of younger arc magmatism in the Provideniya-Chaplino region.

A significant part of the punctuated magmatic history documented here can be correlated across the Bering Strait, but in Alaska the upper-crustal successions are absent. Thus, AACM crystalline rocks record extended crust exhumed from shallow (Provideniya-Chaplino, Senyavin) to deeper (Koolen, Kigluaik) crustal levels. The timing of magmatism, extension, and uplift is relatively synchronous across the Chukotka and Seward Peninsula parts of the AACM when the initial crustal depth and geothermal gradient associated with arc magmatism is considered. The common structural and magmatic history of eastern Chukotka may have begun as early as c. 133 Ma, but certainly by c. 121 Ma palaeo-Pacific plate subduction

beneath North Asia-North America was initiated as indicated by Tkachen magmatism, by the age of the oldest volcanic rocks and plutons of Chukotka, and by the age of the oldest Cretaceous subduction-related plutonic/volcanic belts of Alaska and Canada (Rubin et al., 1995; Amato et al., 2003; Miller et al, *this volume*). This is consistent with the opening of the Amerasia Basin by a back-arc basin mechanism. Arc activity in the region ceased at c. 85 Ma (this study) when subduction migrated southward (modern coordinates) in latest Cretaceous-Palaeocene time (Akinin et al., 2009; Miller et al., *this volume*).

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TABLES

Table 1. Sample summary

Table 2. Summary of Provideniya-Chaplino arc geochemistry

Supplementary Table S1. U-Pb zircon geochronological data

Supplementary Table S2. Provideniya-Chaplino geochemical data

Supplementary Figures. Geochemical sample locations and associated plots.

FIGURE CAPTIONS

Figure 1. Regional setting of eastern Chukotka, Arctic Russia. A) The distribution of Cretaceous plutons (in red) from the Verkoyansk foldbelt in the west to Alaska in the east (after Miller et al., 2009). Note the spatial coincidence in the study area of the Cretaceous plutonic belts (red) and the OCVB (Okhotsk Chukotka Volcano-plutonic Belt, shown in stipple), and the lack of OCVB volcanic rocks in adjacent Alaska. A, Anadyr; AB, Angayucham belt; BRFB, Brooks Range Fold Belt; P, Pevek; NSI, New Siberian Islands; N, Nome; SAS, South Anyui Suture; WI, Wrangel Island. B) Simplified geology of the Bering Strait region (after Akinin et al., 2009). Important tectonic elements include the AACM (Arctic Alaska – Chukotka microplate) and the South Anyui-Angayucham suture. Location of the study area (Fig. 3) indicated by the square. BS, Berlozhya Suite; CC, Central Chukotka; CUM, Chukotka segment of the Uda-Murgal arc; EC, Eastern Chukotka; KD = Koolen dome; KM = Kigluaik Mountains; SU = Senyavin Uplift.

Figure 2. Phanerozoic K-Ar whole rock ages from the Okhotsk Chukotka Volcano-plutonic Belt (OCVB) of eastern Chukotka. OCVB magmatism in this area peaks between c. 100-80

Ma (dashed lines). Data summary from Quadrangle-2 in the Geochron 1.0 database of Akinin & Kotlyar (1997).

Figure 3. Geological map of the study area, Eastern Chukotka. Compilation based on mapping over several seasons by us (solid line), the Bering Strait Field Party (dashed line), and the Russian 1:200 000 geological map (Quadrangle 2-31-32, Borzakovsky, 1965) (remainder of the map).

Figure 4. Geological units. A) Calcsilicate metasedimentary rocks (small, low-lying outcrop NW of location 7). Hammer for scale (c. 40 cm long). B) Valley pluton granitoid in unconformable contact with overlying Mt. Chaos volcanogenic rocks (location 8). Note the hematized granitoid below the contact and angular granitoid clasts within the overlying Mt. Chaos complex. Scale bar below contact shows centimeters on left side. C) Tkachen Bay granodiorite with magma mingling textures (location 5). Field of view c. 25 cm across. D) Mt. Chaos complex pepperite (east of location 5). Pencil for scale. E) Mt. Chaos complex breccia dipping steeply to the west (west of location 10). Clasts up to 1 m across, hammer (circled) for scale c. 40 cm long. F) Chaplino complex basal ignimbrite (just west of Location 4). Pocket knife c. 8 cm long. G) Chaplino complex dacitic vitrophyre (small, low-lying outcrop at Location 11). Hammer c. 40 cm long. The vitrophyre contains numerous crustal xenoliths, including granitic fragments. H) Main phase of Rumilet pluton with mafic enclaves of different size (Location 12). Mirolitic cavities commonly present.

Figure 5. Zircon cathodoluminescence (CL) images representing the main age populations defined in Fig. 6. Scale bars are each 100 μm . White ellipse = the analytical spot which is c. 25 μm in the long dimension. Note the simple igneous oscillatory and sector zoning

associated with magmatic crystal growth.

Figure 6. U-Pb age data. Inverse concordia diagrams are used for reporting concordia ages (Ludwig, 1998) and ^{207}Pb -corrected ages are used to calculate weighted averages (Ludwig, 2003). One common-Pb intercept age (Ludwig, 2012) is also reported. All final age errors are reported at 95% confidence. MSWD, mean square of weighted deviates; c, concordance; e, equivalence. Concordia age shown by small, dark centroid ellipses; unfilled symbols excluded from the final age determination.

Figure 7. Summary of observed and inferred tectonomagmatic events in the Provedeniya-Chaplino region, eastern Chukotka. Although the contact relationship between the 94 Ma and 121 Ma granites was not seen, it is clear that the voluminous and regionally extensive Tkachen pluton must be intruded by the later Provideniya granodiorite.

Figure 8. A) Multi-element geochemistry from igneous suites in the Provedeniya-Chaplino region, eastern Chukotka. Note the difference of the Rumilet Bay pluton (lower Sr, Ba) from all other suites. Modern Peruvian arc andesites (PA) field shown for reference; the samples show strong compositional similarity to PA except for the latter's lower-K and more pronounced Ta-Nb, P and Ti anomalies. Normal mid-ocean ridge basalt (NMORB) normalization values from Sun & McDonough (1989). Reference field for PA extracted from GEMROCK database (restricted to frontal arc rocks of similar age, $\text{SiO}_2 = 55\text{--}56\text{ wt\%}$, $\text{MgO} < 4\text{ wt\%}$ and complete element analyses; $n = 84$). B) $\epsilon\text{Nd}(\text{i})$ versus $\epsilon\text{Sr}(\text{i})$ from eastern Chukotka. Initial ratios recalculated from Rowe (1998) (see supplementary material). Note i) the compositional distinction between all hypabyssal and plutonic samples, ii) the horizontal trend in $\epsilon\text{Sr}(\text{i})$ associated with the Rumilet pluton (grey arrow), and iii) the greater

1124 crustal influence in Koolen samples (grey arrow).

Table 1. *Sample summary*

Location ^a	Sample number	Sample classification	North Latitude	West Longitude	Age (this study)
1	VP05-025a	Chaplino complex volcaniclastic	64°32.977	172°31.169	86 ± 1 ^b
2	VP05-020	Chaplino complex volcanic tuff	64°32.915	172°40.191	85 ± 1 ^b
3	VP05-017c	Valley pluton granitoid	64°32.425	172°42.970	135 ± 2 ^b
	VP05-018	Valley pluton granitoid	64°32.257	172°42.755	131 ± 1 ^b
4	P95-G-205	Chaplino complex (cognate inclusion)	64°31.10	172°50.06	88 ± 1 ^c
5	VP05-007a	Tkachen Bay pluton	64°30.060	172°47.539	119 ± 2 ^b
6	VP05-004	Tkachen Bay pluton	64°28.682	172°52.851	122 ± 2 ^b
7	VP05-006	Rumilet pluton microgranite dike	64°28.602	172°53.863	85 ± 1 ^b
8	VP05-013a	Valley pluton granitoid	64°27.428	172°52.566	136 ± 1 ^b
	VP05-013b	Mt. Chaos complex tuff	64°27.428	172°52.566	105 ± 1 ^b
9	ELMNC28.7a	Tkachen Bay pluton	64°27.403	172°52.514	120 ± 1 ^b
10	VP05-016b	Mt. Chaos complex (granite clast)	64°26.619	172°57.785	124 ± 1 ^b
	VP05-016c	Mt. Chaos complex (granite clast)	64°26.619	172°57.785	123 ± 2 ^b
11	VP05-030	Rumilet Bay pluton	64°32.580	172°59.762	85 ± 2 ^b
12	VP05-031a	Rumilet Bay pluton	64°34.950	172°59.078	85 ± 1 ^b
13	P95-W-38	Rumilet Bay pluton	64°32.525	173°59.976	85 ± 1 ^c
14	P95-Q-36	Tkachen Bay pluton	64°29.154	173°03.460	121 ± 2 ^c
15	P95-S-39	Provideniya pluton	64°25.307	173°14.450	94 ± 2 ^c

Notes: a- Location numbers match those on figure 3; b- analyses from NORDSIM, errors at 95%;

c- analyses from SUMAC, errors at 2 σ .

Table 2. Summary of Provideniya-Chaplino arc geochemistry

Signature ¹	Tkachen Bay pluton (n=5)	Mount Chaos complex (n=2)	Provideniya pluton (n=2)	Chaplino complex (n=7)	Rumilet Bay pluton (n=6)
Age	c. 121 Ma	c. 105 Ma	c. 94 Ma	c. 85	c. 85
Rock types	diorite- granodiorite	basaltic andesite	granodiorite	andesite	granite
Series	med- to high-K calcalkaline	med-K calcalkaline	high-K calcalkaline	high-K calcalkaline	high-K calcalkaline
Ce	49-71	56-74	68-73	67-162	63-188
Nb/Ta	4-8	5-7	3-3.5	4-8	0.3-9
Zr/Nb	12-16	23-25	20-22	17-26	5-196
[La/Lu]_N²	4.61-8.05	4.83-6.27	13.9-18.9	6.20-10.1	2.47-9.32
[La/Sm]_N	3.19-4.62	2.30-2.46	5.05-6.17	2.71-4.30	1.26-3.70
[Sm/Lu]_N	1.40-1.95	2.10-5.54	2.75-3.06	1.94-2.45	1.86-2.50
Eu/Eu*³	0.71-0.91	0.90-0.95	0.86-0.93	0.56-0.94	0.01-0.14
⁸⁷Sr/⁸⁶Sr_i	0.70554	0.70508	0.70506	0.70533 to 0.70863	0.71513 to 0.73366
εNd_i	-0.00 to -0.54	+2.08 to +1.90	-0.61 to -0.80	+1.25 to -3.69	-0.51 to -2.53
²⁰⁶Pb/²⁰⁴Pb⁴	18.49-18.58	nd	18.46	nd	18.72
²⁰⁷Pb/²⁰⁴Pb	15.56-15.59	nd	15.56	nd	15.60
²⁰⁸Pb/²⁰⁴Pb	38.37-38.50	nd	38.34	nd	38.54

Notes: 1, data from Rowe (1998) but units reclassified according to our new mapping and geochronology. 2, normalized to chondrite values of McDonough & Sun (1995). 3, Eu/Eu* = (Eu_N/sq rt [Sm_N * Gd_N]). 4, from potassium feldspar. alk = alkaline, calc = calcalkaline, trans = transitional. Refer to supplementary table S1 for the complete major, trace, and isotopic dataset. nd, not determined.

A

B