Paleozoic rocks of northern Chukotka Peninsula, Russian Far East: Implications for the tectonics of the Arctic region

Boris A. Natal'in,[1] Jeffrey M. Amato,[2] Jaime Toro,[3,4] and James E. Wright[5]

Abstract. Paleozoic rocks exposed across the northern flank of the mid-Cretaceous to Late Cretaceous Koolen metamorphic dome make up two structurally superimposed tectonic units: (1) weakly deformed Ordovician to Lower Devonian shallow marine carbonates of the Chegitun unit which formed on a stable shelf and (2) strongly deformed and metamorphosed Devonian to Lower Carboniferous phyllites, limestones, and andesite tuffs of the Tanatap unit. Trace element geochemistry, Nd isotopic data, and textural evidence suggest that the Tanatap tuffs are differentiated calc-alkaline volcanic rocks possibly derived from a magmatic arc. We interpret the associated sedimentary facies as indicative of deposition in a basinal setting, probably a back arc basin. Orthogneisses in the core of the Koolen dome yielded a Devonian (between ~369 and ~375 Ma) U-Pb zircon age which is similar to the ages of the Tanatap tuffs as well as granitic plutons formed within a Devonian active continental margin of northern Alaska. The stratigraphy of the Chegitun unit is similar to that of the Novosibirsk carbonate platform which overlies the Late Precambrian Bennett-Barrovia block. The basement of the block is exposed in Chukotka where ortogneiss in the Chegitun River valley yielded Late Proterozoic (~650 to 550 Ma) U-Pb ages. These two tectonic units form the shelf of the Chukchi and East Siberian Seas and may continue into northern Alaska as the Hammond subterrane. The deep-water Tanatap unit can be traced along the southern boundary of the Bennett-Barrovia block from the Novosibirsk Islands to northern Alaska. This basin was paired with a Devonian magmatic arc that existed farther to the south. The northern margin of the Bennett-Barrovia block collided with North America in the Late Silurian to Early Devonian. In Chukotka, during Middle to Late Carboniferous time the reconstructed Devonian arc-trench system at the southern edge of the Bennett-Barrovia block collided with an unknown continental object, fragments of which now occur to the south of the South Anyui suture. Triassic to Cretaceous deformation strongly modified the Paleozoic units. Our results provide new constraints on the geometry and Paleozoic history of the Chukotka-Arctic Alaska block, the essential element involved in the opening of the Canada basin.

[1] Department of Geology, Istanbul Technical University, Istanbul, Turkey.
[2] Department of Geological Sciences, New Mexico State University, Las Cruces.
[3] Department of Geological and Environmental Sciences, Stanford University, Stanford, California.
[4] Now at Department of Geology and Geography, West Virginia University, Morgantown.
[5] Department of Geology and Geophysics, Rice University, Houston, Texas.

Paper number 1999TC900044
0278-7407/99/1999TC900044$12.00

1. Introduction

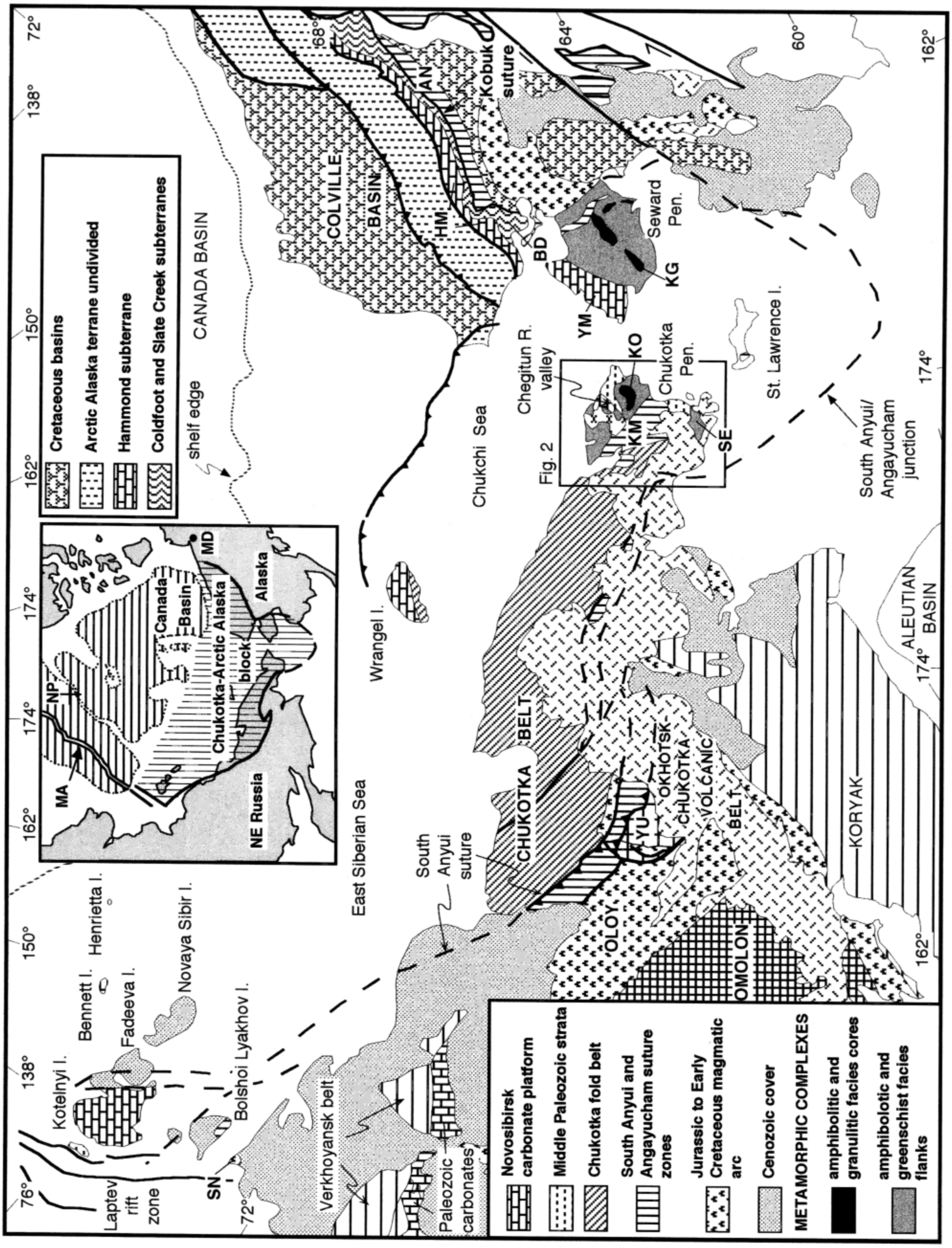
Interest in stratigraphic and tectonic correlations between the Russian Far East and Alaska recently has been revived as the result of collaboration between North American and Russian geologists. This paper presents the results of one such study from the Chegitun River valley, Russia, where field work was carried out to establish the stratigraphic, structural, and metamorphic relationships in the northern part of the Chukotka Peninsula (Figure 1). The Chegitun River region exposes an Ordovician to Lower Carboniferous carbonate and metacarbonate, shale, phyllite, and thin-bedded turbidite sequence with rare interbedded tuffs that were metamorphosed and deformed during the Cretaceous. This sequence is in fault contact with a mid-Cretaceous to Late Cretaceous high-grade metamorphic complex, the Koolen dome. The geology of the high-grade complex was discussed by the *Bering Strait Geological Field Party* (BSGFP) [1997].

Stratigraphic correlations between Paleozoic sequences in the Chegitun River region and similar successions in Chukotka, in the various islands of the Chukchi and East Siberian Seas, and in northern Alaska bear on an important unsolved problem for this region: the presence or absence of a large Precambrian block on which these lower Paleozoic carbonate platform deposits accumulated.

The Paleozoic framework of the region sheds light on the geometry and size of the Chukotka-Arctic Alaska microplate whose Early Cretaceous displacement is thought to be responsible for the opening of the Canada Basin (Figure 1) (see *Lawver et al.* [1990] for a review of the different models proposed for the opening of the Canada Basin). In this paper we investigate the correlation of Late Proterozioc and Paleozoic rocks of the Chegitun River valley with rocks of similar ages in the Siberian/northern Alaska sector of the Arctic region, the depositional setting of these strata, and the geochemistry and geochronology of Devonian magmatism on the Chukotka Peninsula. These data are then used to discuss the Paleozoic tectonic evolution of northeastern Russia and northern Alaska. We will address the Cretaceous thermal evolution and structural history of the Chegitun River valley metamorphic rocks in a later paper.

2. Tectonic Setting of the Study Area

Prior to the now widely accepted hypothesis of the counterclockwise rotation of the Chukotka-Arctic Alaska block for 60° about a pole at the McKenzie delta (Figure 1) [e.g., *Tailleur and Brosge*, 1970], the idea of a Hyperborean platform underlain by Precambrian basement in the central part of the Arctic Ocean was


Cretaceous basins
Arctic Alaska terrane undivided
Hammond subterrane
Coldfoot and Slate Creek subterranes
Novosibirsk carbonate platform
Middle Paleozoic strata
Chukotka fold belt
South Anyui and Angayucham suture zones
Jurassic to Early Cretaceous magmatic arc
Cenozoic cover
METAMORPHIC COMPLEXES
amphibolitic and granulitic facies cores
amphibolotic and greenschist facies flanks
NE Russia
Chukotka-Arctic Alaska block
Canada Basin
Alaska
MA
NP
MD
CANADA BASIN
shelf edge
COLVILLE BASIN
HM
AN
Kobuk suture
BD
Seward Pen.
KG
YM
KO
Chegitun R. valley
Chukotka Pen.
St. Lawrence I.
Fig. 2
KM
SE
Chukchi Sea
South Anyui/ Angayucham junction
Wrangel I.
ALEUTIAN BASIN
CHUKOTKA BELT
OKHOTSK-CHUKOTKA VOLCANIC BELT
YU
OLOY
OMOLON
KORYAK
East Siberian Sea
South Anyui suture
Henrietta I.
Bennett I.
Fadeeva I.
Novaya Sibir I.
Kotelnyi I.
Bolshoi Lyakhov I.
Laptev rift zone
SN
Verkhoyansk belt
Paleozoic carbonates
76°
72°
138°
150°
162°
174°
72°
64°
68°
60°

proposed by *Shatsky* [1935] to explain the sinuosity and disposition of fold belts (e.g., Chukotka fold belt, the Brooks Range) and high-grade metamorphic rocks in the Arctic region. *Eardley* [1948] referred to this Precambrian platform as "Ancient Arctica." American geologists proposed the existence of an area called "Barrovia Land" to provide a northern source region for Paleozoic and Mesozoic clastic rocks in northern Alaska [e.g., *Tailleur*, 1973]. However, if a rotational origin for the Chukotka-Arctic Alaska block about a pole in the McKenzie delta is assumed, the North American craton is a suitable source for these sediments. *Zonenshain et al.* [1990] defined a microcontinent, "Arctida," as one of several Precambrian cratons, such as the East European and Siberian cratons, which was later disrupted owing to the opening of the oceanic basins in the Arctic Ocean. *Şengör and Natal'in* [1996] supported the necessity of an old continental block but defined it with a shape and size different from that of Arctida. They named it after the Bennett massif which is located in the northwestern part of the East Siberian Sea [*Vinogradov et al.*, 1974] but noted that it may be contiguous with Precambrian crust in the northeastern part of the Chukchi Sea [*Grantz et al.*, 1990]. In this paper we use the term Bennett-Barrovia block for this Precambrian block. It should be stressed that the Bennett-Barrovia block is not the same as the Arctic Alaska terrane [*Newman et al.*, 1977; *Moore et al.*, 1994]. The latter is a younger tectonic element not assembled until Devonian time (see below).

The Chegitun River valley exposes carbonate and metacarbonate rocks which we correlate with the early to middle Paleozoic Novosibirsk carbonate platform. The Novosibirsk carbonate platform covers the Bennett-Barrovia block as defined by *Şengör and Natal'in* [1996]. This platform includes rocks exposed on the Novosibirsk (New Siberian) Islands of the East Siberian Sea, on Wrangel Island, and in several localities of northern Alaska including the Seward Peninsula and the western and central Brooks Range (YM and HM, Figure 1). The wide geographic distribution of rocks of similar age and composition, in addition to geophysical data, suggests that this early Paleozoic carbonate platform underlies the entire East Siberian shelf. On the basis of stratigraphic and fossil evidence, both *Dumoulin and Harris* [1994], for the Alaskan terranes, and Şengör and Natal'in, for the whole region, agree that these widely scattered pre-Middle-Devonian carbonate successions were part of a single carbonate platform, rather than disparate, far-traveled terranes as had been previously proposed [*Fujita and Cook*, 1990]. However, the Paleozoic tectonic history of this extensive platform has not been investigated in great detail.

The Paleozoic rocks of northern Chukotka Peninsula are in fault contact with the Koolen metamorphic dome (Figure 2) [*Natal'in*, 1979], one of several high-grade metamorphic complexes on the Chukotka and Seward Peninsulas [*Belyi*, 1964; *Drabkin*, 1970b; *Tilman*, 1973; *Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1977; *Natal'in*, 1979; *Amato et al.*, 1994]. These metamorphic complexes expose Late Proterozoic to Paleozoic igneous and sedimentary protoliths metamorphosed to upper amphibolite and locally granulite grade. The age of metamorphism was previously estimated to range from Archean [*Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1977] to Paleozoic [*Gnibidenko*, 1969; *Bunker et al.*, 1979] or with an additional episode in the Mesozoic [*Gelman*, 1973; *Natal'in*, 1979], but it is now known to have occurred during mid-Cretaceous time on both the Chukotka Peninsula [*BSGFP*, 1997] and on the Seward Peninsula [*Amato et al.*, 1994; *Amato and Wright*, 1998].

Paleozoic rocks and high-grade metamorphic complexes on the Chukotka Peninsula comprise part of a broader tectonic province in the Russian Far East and northern Alaska: the former Chukotka-Arctic Alaska microplate. The southern boundary of this ancient microplate is defined by the Neocomian South Anyui suture in northeast Russia and the Late Jurassic to Neocomian Kobuk suture in Alaska (Figure 1). For a review of the tectonics of northeast Asia, see the work of *Parfenov and Natal'in* [1985], *Zonenshain et al.* [1990], *Fujita and Cook* [1990], and *Şengör and Natal'in* [1996]. For a review of the tectonics of northern Alaska, see the work of *Moore et al.* [1994, 1997b].

3. Lithotectonic units of the Chegitun River Valley

From the southeast to the northwest, three principal fault-bounded lithotectonic units are exposed in the Chegitun River valley (Figure 3): (1) the High-Grade unit, which consists of upper amphibolite facies metamorphic rocks along the northern flank of the Koolen metamorphic dome; (2) the Tanatap unit, which consists of Devonian to Lower Carboniferous greenschist facies metasedimentary rocks; and (3) the Chegitun unit, which consists of virtually unmetamorphosed Ordovician through Lower Devonian shallow marine carbonate rocks. It was previously believed that the high-grade rocks represented the Precambrian depositional basement for the Paleozoic sedimentary rocks [*Belyi*, 1964; *Tilman*, 1973; *Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1977]. In this framework the Tanatap and Chegitun units were regarded as a continuous Paleozoic succession [*Nedomolkin*, 1977; *Oradovskaya and Obut*, 1977]. However, although the High-Grade unit does include Late Proterozoic protoliths, our research has shown that there is no evidence of a straightforward basement/cover relationship between the high-grade metamorphic rocks and the weakly metamorphosed sedimentary rocks that bear Paleozoic fossils. In addition, both the lithology and paleodepositional environment of the Tanatap unit are significantly different from those of the Chegitun unit and the inferred sedimentary protoliths for the high-grade metamorphic rocks. These differences in lithology and depositional environment allow us to define three fault-bounded lithotectonic units which have internal contacts that are truncated by the bounding faults. These units are described in sections 3.1-3.3 in order of decreasing metamorphic grade.

Figure 1. Principal tectonic units of northeastern Russia and northern Alaska [after *Natal'in*, 1981, 1984; *Moore et al.*, 1994, *Plafker and Berg*, 1994]). The inset shows the Chukotka-Arctic Alaska block. AN, Angayucham terrane; BD, Baird Group; HM, Hammond subterrane; KG, Kigluaik dome; KO, Koolen dome; KM, Kolyuchin-Mechigmen zone; MA, Arctic mid-ocean ridge; MD, McKenzie delta; NP, North Pole; PR, Primorsk Basin; SE, Senyavin Uplift; SN, Svaytoy Nos; YM, York terrane; YU, Paleozoic Yarakvaam and Aluchin blocks.

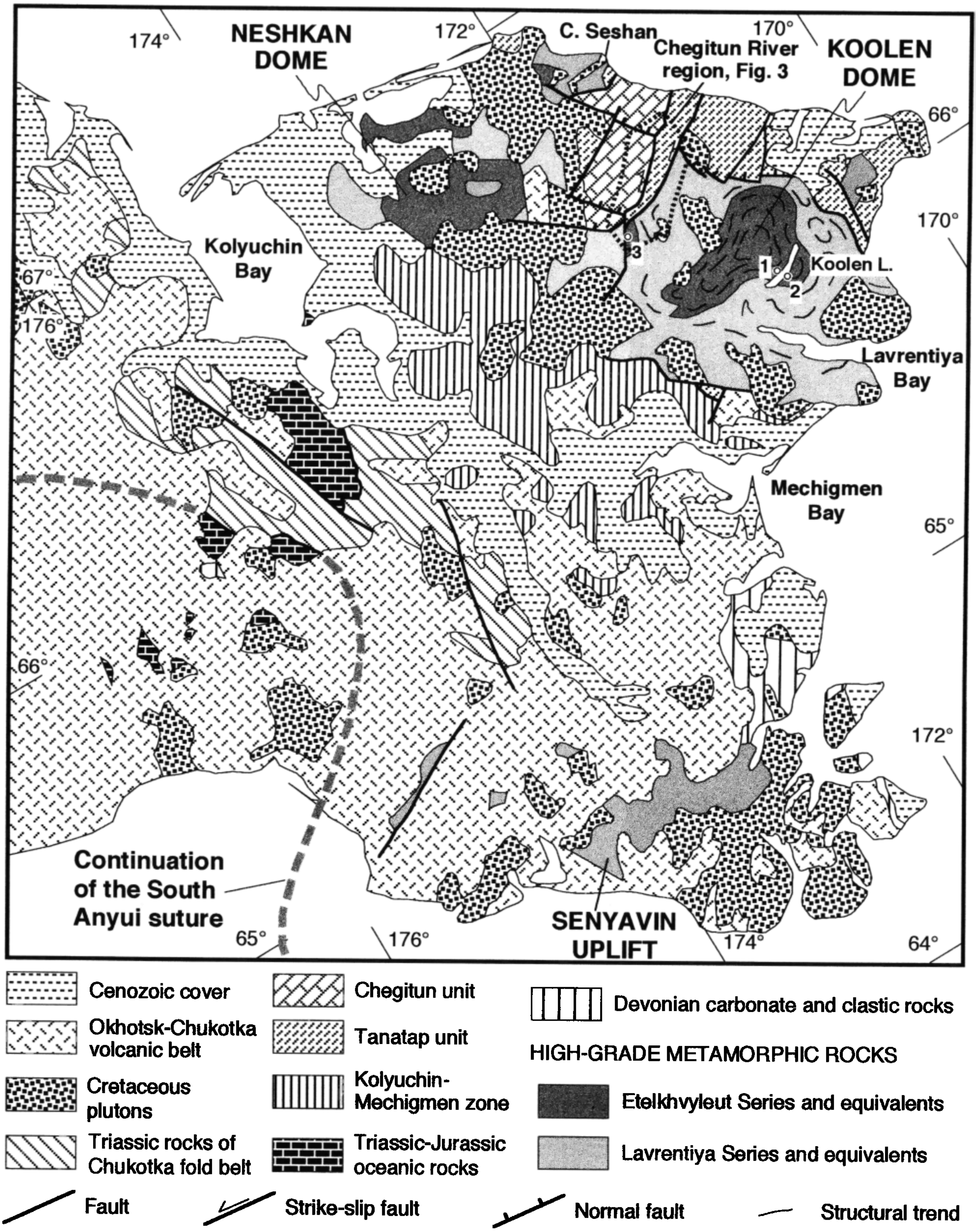


Figure 2. Geologic map of the Chukotka Peninsula modified after *Gorodinsky* [1980] showing the location of detailed geologic mapping in the Chegitun River valley area of Figure 3. The Etelkhvyleut Series is exposed in the core of the Koolen dome and the Lavrentiya Series represents flanks of the dome. Circles indicate locations of samples for U-Pb age determination: 1, M18-94K; 2, F45-94K; and 3, 95JT4a.

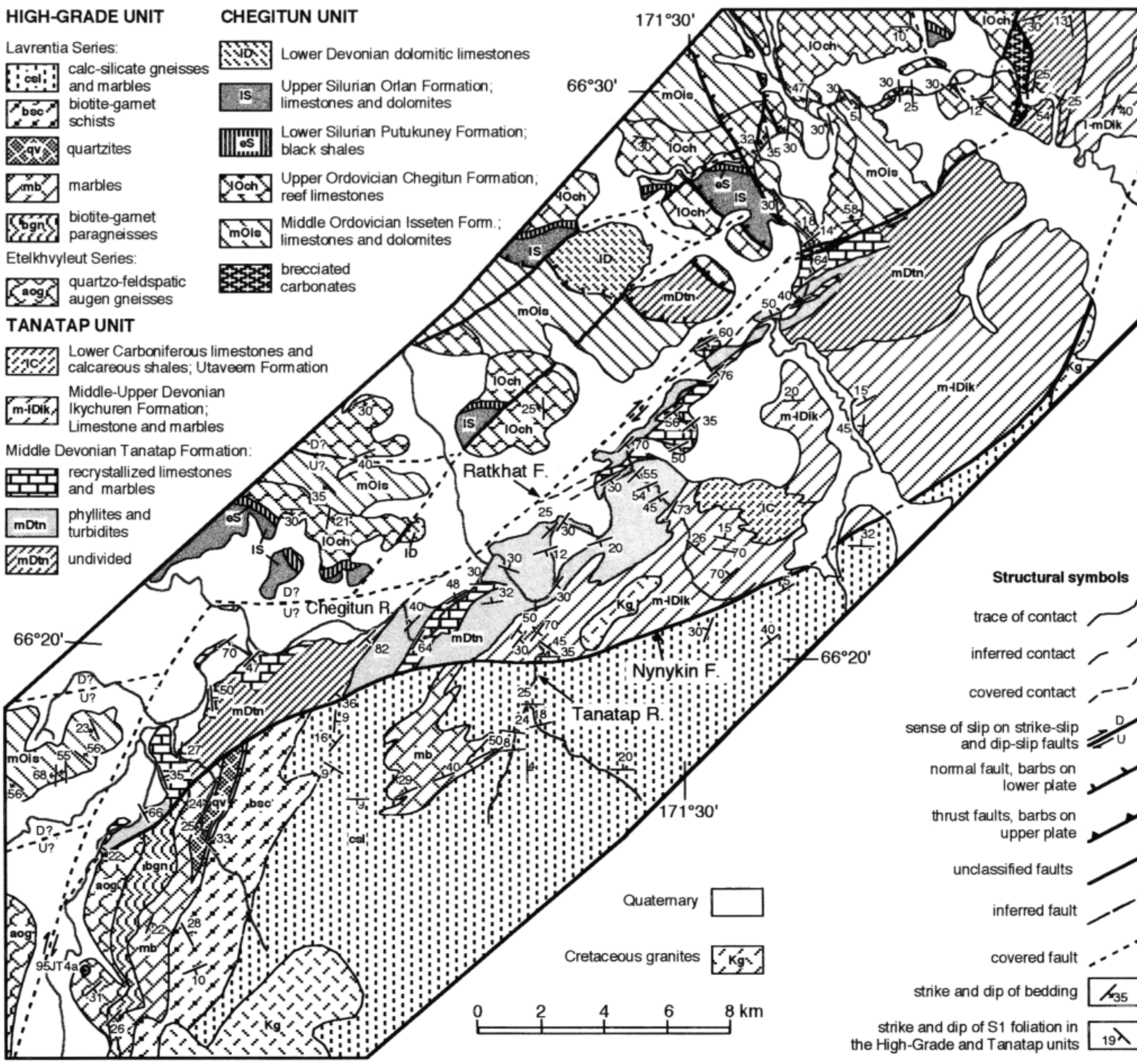


Figure 3. Geologic map of the Chegitun River valley.

3.1. High-Grade Unit

The high-grade metamorphic rocks in the Chegitun River valley are very similar to rocks in the core and southern flank of the Koolen dome that are exposed in the Koolen Lake region (Figure 2) [*Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1969, 1977; *Gelman*, 1973; *Natal'in*, 1979; *BSGFP*, 1997]. The Koolen metamorphic complex was divided into two major units by *Shuldiner and Nedomolkin* [1976]. A structurally lower succession of mostly orthogneiss is called the Etelkhvyleut Series, and a structurally higher, dominantly paragneiss, schist, and marble-bearing succession is called the Lavrentiya Series. In the Koolen Lake region, three types of rock assemblages have been observed in ascending order: (1) granitic orthogneisses of Cretaceous [*BSGFP*, 1997] and Devonian ages (see below) within both the Etelkhvyleut Series and the Lavrentiya Series; (2) thinly banded schists and quartzofeldspathic paragneisses that include lenses of ultramafic rocks, marbles, amphibolites, and rare quartzite (metachert?) [*BSGFP*, 1997], which together may represent accretionary prism material [*Şengör and Natal'in*, 1996]; and (3) marble and calc-silicate rocks that resemble the less metamorphosed lower to middle Paleozoic shallow marine sequence of the Novosibirsk carbonate platform as exposed on the Chukotka Peninsula [*Şengör and Natal'in*, 1996]. Mid-Cretaceous granites intrude the Koolen metamorphic complex [*Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1977; *BSGFP*, 1997] and the Tanatap unit in the Chegitun River area.

Along the Chegitun valley, in the southwestern part of the map area (Figure 3), biotite-bearing granitic augen gneisses interlayered with 3- to 30-m-thick horizons of coarse-grained white mar-

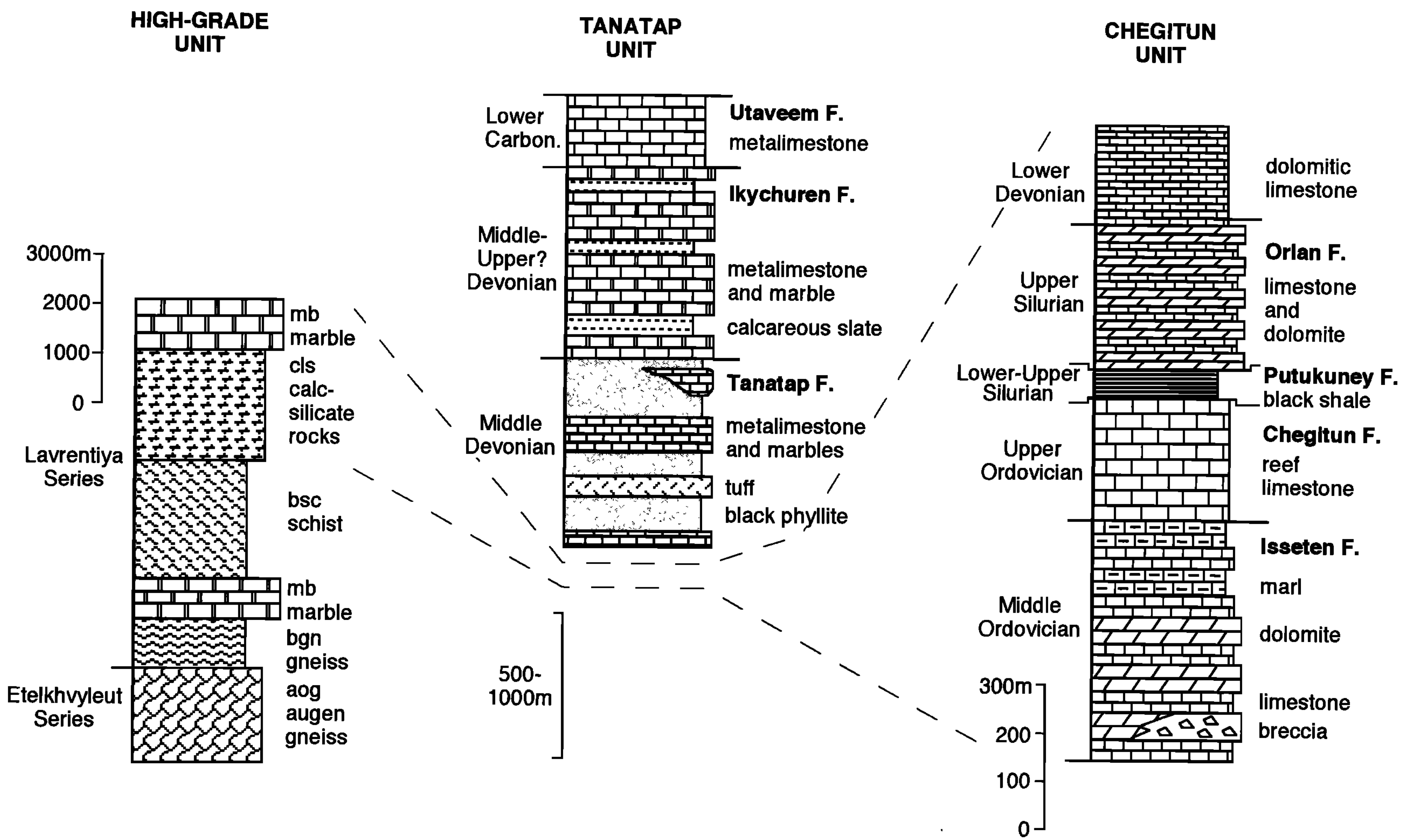


Figure 4. Stratigraphic columns of the tectonic units in the Chegitun River valley compiled taking into account data of *Oradovskaya and Obut* [1977] and *Nedomolkin* [1977].

ble constitute the lowest exposed structural unit (map unit "aog" in Figures 3 and 4). We carried out ion microprobe (super high resolution ion microprobe-reverse geometry (SHRIMP-RG)) U-Pb dating of zircon grains from this augen gneiss (sample 95JT4a) and obtained $^{206}Pb/^{238}U$ ages between ~650 and ~540 Ma (refer to Table 1 for analytical methods and to Figures 5a and 5b for data plots). This broad range of ages from a single sample is probably due to a combination of two effects: (1) the incorporation of somewhat older zircons by a latest Proterozoic granitic magma (inheritance) and (2) loss of radiogenic lead during younger metamorphic events. These two phenomena will conspire to spread the ages parallel to concordia (Figure 5a), making it impossible to assign a precise crystallization age to the protolith of the augen gneiss. In any case, these new data demonstrate the occurrence of Late Proterozoic granitic magmatism in Chukotka Peninsula.

A few lenses of plagioclase-bearing amphibolites, probably metagabbro, occur within the marbles. We correlate these rocks with the Etelkhvyleut Series of the Koolen Lake region [*Shuldiner and Nedomolkin*, 1976; *Nedomolkin*, 1969, 1977; *BSGFP*, 1997], but the augen gneisses and interlayered metasedimentary rocks of the Chegitun valley contain less pegmatite or other evidence for partial melting than equivalent units of the Koolen Lake region. The augen gneiss unit is overlain by a poorly exposed section of biotite gneisses containing subordinate horizons of augen gneisses (map unit "bgn"). Overlying rocks, from the structural base upward, include intercalated biotite gneisses, calc-silicate rocks, and marbles that grade upward to pure coarse-grained marbles (map unit "mb"). Muscovite-bearing garnet schists and quartzites form a lenticular body in the marbles in the upper part of the structural section (map unit "qv"). Biotite and garnet-bearing schists (map unit "bsc") overlie the marble unit. Peak metamorphism reached upper amphibolite facies in the deepest part of the structural section exposed in the Chegitun valley and in the core of the Koolen dome. This metamorphic event has been dated as occurring between 104 and 94 Ma in the Koolen Lake region [BSGFP, 1997].

In the Chegitun area, *Nedomolkin* [1969, 1977] assigned all rocks that lie structurally above the augen gneiss unit to the Lavrentiya Series. In general, we agree with this correlation, but the lithology and succession of the rocks in the Chegitun valley are different in detail from those of the Lavrentiya Series in the Koolen Lake region where thick quartzo-feldspatic paragneisses

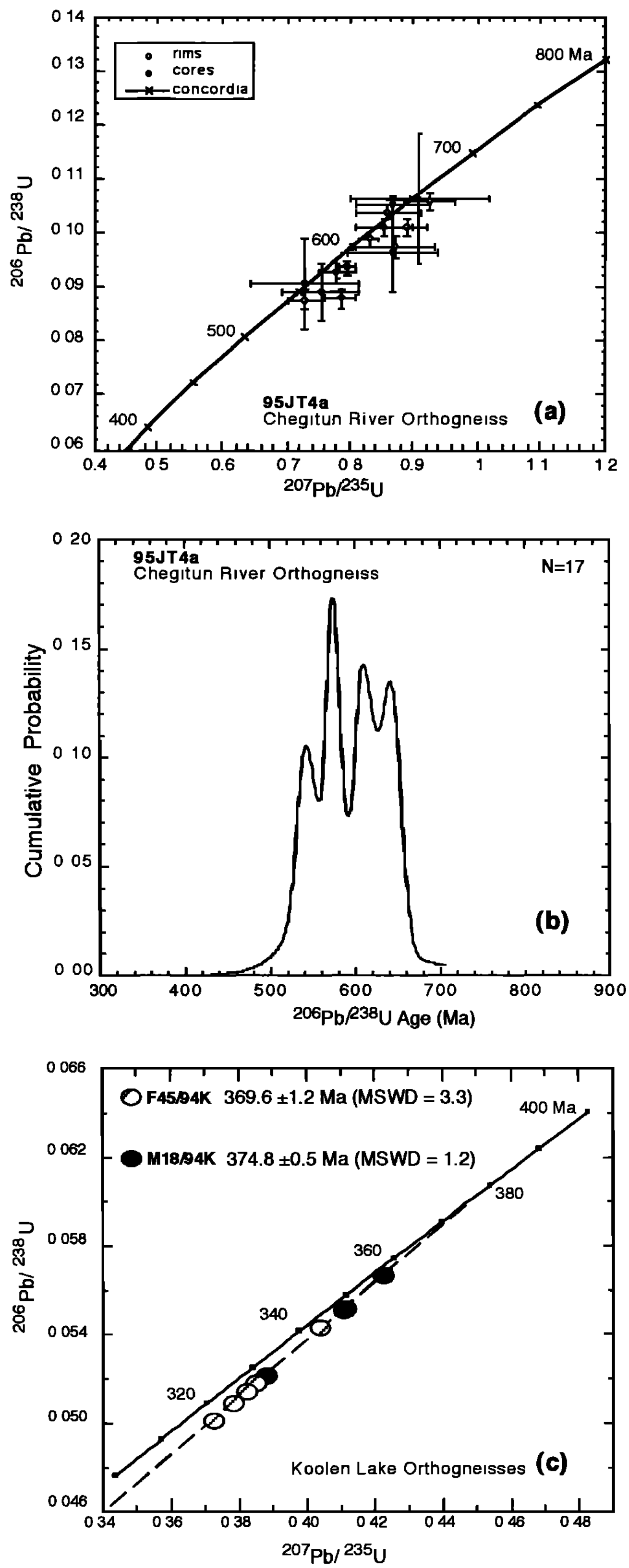


Figure 5. U-Pb concordia diagrams from the Koolen orthogneiss. (a) Concordia diagram of ion microprobe (super high resolution ion microprobe-reverse geometry (SHRIMP-RG)) data from sample 95JT4a of Late Proterozoic augen gneiss from the Chegitun valley. Each data point represents a single ~20 μm spot on a zircon crystal. The discordance and wide spread of ages is probably due to the combined effects of inheritance of older zircon and lead loss during Cretaceous high-grade metamorphism. (b) Cumulative probability diagram of $^{206}Pb/^{238}U$ ages of zircons from sample 95JT4a from the Chegitun valley. This histogram is calculated by taking the individual data points and assuming a Gaussian distribution of unit area with width proportional to the error. (c) U-Pb concordia diagrams from the Koolen orthogneiss, F45/94K and M18/94K. MSWD stands for mean standard weighted deviation, a measure of the goodness of fit of the chord. Both sets of analyses are discordant, but upper intercepts of 376 and 375 Ma agree within analytical error. These data show that the orthogneiss of the Etelkhvyleut Series is neither Precambrian nor Cretaceous as has been previously speculated. These Devonian ages are within the stratigraphic age limits of the Tanatap metatuff. See text and Table 3 for details.

Table 1. Ion Microprobe U-Pb Isotopic Data Etelvekhvyleut Series Orthogneiss, Sample 95JT4a, Chegitun Valley

	Concentrations			Isotopic Ratios						Apparent Ages, Ma					
Grain Spot	U, ppm	Th, ppm	^{204}Pb, ppb	$^{207}Pb/^{206}Pb$	Error, ±	$^{238}Pb/^{206}Pb$	Error, ±	$^{235}U/^{207}Pb$	Error, ±	$^{206}Pb/^{238}U$	Error, ±	$^{207}Pb/^{235}Pb$	Error, ±	$^{207}Pb/^{206}Pb$	Error, ±
6 Rim	52.1	25.3	0	0.0609	0.0009	10.12	0.12	1.21	0.02	607.6	7.2	613.1	9.3	633.8	31.1
7 Rim	60.9	26.7	1	0.0604	0.0018	11.42	0.23	1.37	0.05	541.1	10.4	556.1	16.1	618.2	64.2
7 Core	41.3	18.1	0	0.0648	0.0013	11.38	0.23	1.27	0.04	543.0	10.4	588.3	13.6	767.2	43.7
8 Rim	27.9	16.1	0	0.0638	0.0020	9.90	0.17	1.13	0.04	620.3	10.2	645.6	18	735.1	67.1
9 Rim	18.5	12.2	1	0.0599	0.0034	9.62	0.13	1.16	0.07	637.4	8.3	629.6	28.6	601.5	128.3
10 Rim	30.0	12.8	3	0.0584	0.0034	11.03	1.04	1.37	0.16	559.5	50.5	556.5	51.2	544.5	132.1
10 Core	103.6	27.0	4	0.0608	0.0020	10.76	0.14	1.28	0.05	573.0	7.1	585.4	16.6	633.7	72.9
11 Core	116.1	30.2	1	0.0617	0.0007	10.69	0.14	1.26	0.02	576.5	7.1	594.7	8.1	664.8	23.4
11 Rim	35.0	10.8	0	0.0620	0.0016	9.40	1.07	1.10	0.13	651.5	71.1	656.5	59.7	673.8	54.9
13 Rim	26.3	14.7	3	0.0648	0.0044	10.27	0.22	1.15	0.08	599.3	12.3	635.8	35.5	768.0	150.2
13 Core	54.1	31.5	2	0.0613	0.0029	9.90	0.16	1.17	0.06	620.1	9.9	626.7	24.3	650.4	103.3
14 Rim	35.3	26.0	1	0.0633	0.0025	9.44	0.14	1.08	0.05	649.2	9.2	664.7	21.6	717.5	85.9
14 Rim	45.0	33.4	2	0.0614	0.0030	11.22	0.64	1.32	0.11	550.4	30.1	571.0	35.2	653.8	107.5
15 Rim	40.1	28.2	1	0.0653	0.0013	10.39	0.79	1.15	0.09	592.1	43.3	633.8	39.1	785.5	43.4
16 Core	651.5	825.6	32	0.0607	0.0006	10.80	0.24	1.29	0.03	571.1	12.3	582.9	11.4	629.4	20.6
17 Rim	37.2	15.4	2	0.0597	0.0037	9.50	0.14	1.15	0.08	645.4	8.9	633.5	31.2	591.5	139.7

Analytical procedure was as follows: Zircons were obtained from the orthogneiss sample through standard heavy liquid and magnetic separation techniques. Zircons from the least magnetic fraction produced by a Frantz magnetic separator were mounted on epoxy without any hand-picking. The 95JT4a zircons are euhedral, translucent, light gold color with small dark inclusions. They are between 200 and 100 μm in length. The mount was polished to expose the mid-section of the grains. Cathodoluminescense images were used to characterize the zircon zoning and to identify the cores and rims. The zircons were then analyzed on the Stanford University/U.S. Geological Survey ion microprobe (super high resolution ion microprobe-reverse geometry (SHRIMP-RG)) using zircon AS57, with a known age of 1099 Ma, as a standard. The analytical techniques used are similar to those described by *Muir et al.* [1996]. The spot bore onto the zircon grains by the primary beam is ~ 25 μm in diameter. Therefore the spots analyzed are small enough relative to the size of the zircon grains to resolve the cores from the rims. The ion probe data were corrected for common Pb using the ^{204}Pb measured during the analysis and assuming a Pb isotopic composition according to the *Cumming and Richards* [1975] Pb evolution model. Overall, the U concentrations of 95JT4a zircons are low, leading to relatively large analytical errors for individual analyses.

separate the augen orthogneisses from the overlying marbles [see *BSGFP*, 1997].

A thick structural section of calc-silicate rocks and marble is exposed in the upper reaches of the Tanatap River (Figure 3). Individual horizons of foliated marble are internally homogeneous and often more then 10 m thick, suggesting that their protoliths were shallow water carbonate rocks. Lower-grade metamorphism may indicate that the calc-silicate rocks and marbles belong to the upper part of the structural section (Figure 4). This conclusion is supported by the correlation with the Koolen Lake region where marbles occur at the highest structural level [*BSGFP*, 1997].

The $^{40}Ar/^{39}Ar$ analyses indicate that the high-grade rocks near the Chegitun River cooled from 500°C to 350°C between 108 and 104 Ma [*Natal'in et al.*, 1997]. These cooling ages are slightly older than those (90-92 Ma) of the southern flank of the Koolen dome.

Sense of shear determined from stretching lineations is dominantly top-to-south, similar to the kinematics previously described for the southern flank of the dome [*BSGFP*, 1997]. Taking into consideration the structural relationships and lithologic similarity, the calc-silicate and carbonate units of the Lavrentiya Series are tentatively correlated with the Ordovician to Lower Devonian carbonate rocks of the Chegitun unit (see below), which are exposed to the northwest. Both of these units are interpreted to represent part of the Novosibirsk carbonate platform of *Şengör and Natal'in* [1996] (Figure 1).

Despite poor outcrops, the map pattern, together with structural data (B.A.Natal'in et al., manuscript in preparation, 1999) and the fact that internal contacts of the High-Grade unit are at an angle to the contact with the Tanatap unit, indicates that a fault (here named the Nynykin fault) separates the two tectonic units (Figure 3). The Nynykin fault cuts the mid-Cretaceous foliation in the high-grade rocks and is conjugate with north-west striking extensional faults and dikes. The dikes have been dated as Late Cretaceous [*Nedomolkin*, 1969]. On the other hand, the extensional structures have the same orientation as Tertiary extensional structures in the Hope Basin (Figure 1) [*Grantz et al.*, 1990]. Thus we infer the Late Cretaceous to Tertiary age of the Nynykin fault. Kinematic criteria indicate that the fault has a right-lateral sense of displacement.

3.2. Tanatap Unit

The Tanatap unit (Figure 3) consists of polydeformed greenschist facies rocks exposed along the Chegitun River from the southwestern corner of the map area to the Chukchi Sea coast. Similar rocks are also exposed along the northern flank of the Koolen dome (Figure 2) [*Nedomolkin*, 1969, 1977; *Natal'in*, 1979]. According to previous accounts and unpublished geologic maps, three stratigraphic units metamorphosed to lower greenschist facies have been recognized within the Tanatap unit (Figure 4) [*Drabkin*, 1970a; *Nedomolkin*, 1969, 1977; *Oradovskaya and Obut*, 1977; *Krasny and Putintsev*, 1984]: (1) the Tanatap Formation, consisting of graphitic phyllite, calcareous slate, limestone turbidites, and recrystallized limestone dated as early Middle Devonian (Eifelian) on the basis of extremely rare brachiopods and coral remnants; (2) the Ikychuren Formation, consisting of thinly bedded limestone and calcareous shale with rare late Middle Devonian (Givetian) corals and brachiopods; and (3) the Utaveem Formation, consisting of Lower Carboniferous gray to black fine-grained fossiliferous limestone, calcareous sandstone, and phyllite (Figures 3 and 4). *Drabkin* [1970a] and *Markov et al.* [1980] infer that Upper Devonian rocks are present in the Ikychuren Formation, although no Late Devonian fossils have been found so far in northern Chukotka.

In the Chegitun River region (Figure 3) the Tanatap unit is bounded by the Nynykin fault to the southeast and by what we call the Ratkhat fault in the northwest, which are both interpreted as right-lateral strike-slip faults (Figure 3). Rocks of the Tanatap unit possess an intricate structure produced by polyphase, inhomogenous deformation and greenschist facies metamorphism that resulted in formation of muscovite, chlorite, albite, and actinolite. Numerous isoclinal folds, shear zones, and faults make it impossible to reconstruct details of the initial stratigraphic succession. An unconformity was proposed to exist at the base of the Utaveem Formation [*Drabkin*, 1970a; *Nedomolkin*, 1969, 1977]. In our field area the Lower Carboniferous rocks indeed occupy the highest structural level (Figure 3); however, the lower contact of the Utaveem Formation is not exposed. Like the underlying Devonian rocks, the limestones of the Utaveem Formation display spaced anastomosing cleavage, and the calcareous phyllites have a penetrative foliation. This indicates that the Utaveem Formation was deformed and metamorphosed together with underlying Devonian rocks. If the unconformity does exist, it does not likely reflect a penetrative deformational event.

In general, graphitic phyllites and thinly bedded metacarbonates are the predominant lithologies of the Tanatap Formation. In zones of lower strain, sedimentary structures are locally well preserved. Turbidites consisting of Bouma C, D, and E intervals are commonly observed. In a few localities, flame structures and matrix-supported debris flow deposits several meters thick and rich in limestone pebbles were observed.

Metalimestone of the Tanatap and Ikychuren Formations is mainly thinly bedded and often interbedded with clear examples of carbonate turbidites. Medium- and thick-bedded metalimestone is rare. The metalimestone contains little terrigenous material and very few macrofossils. Both formations contain uniformly disseminated sulfides that, together with a high content of carbon in metapelitic rocks, are interpreted as evidence of an anoxic depositional environment. These sedimentological features suggest that they were deposited in a deep-water restricted marine basin.

In the Tanatap Formation we found 2- to 35-m-thick horizons of reddish and green andesite tuff containing abundant volcanic clasts (see below). Gray and dark gray metalimestone of the Lower Carboniferous Utaveem Formation is rich in macrofossils, mainly shallow marine corals [*Drabkin*, 1970a]. We recovered *Cavusgnathus unicornis, Cavusgnathus, and Bispathodus stabilis or Bispathodus utahensis conodonts* from this unit, thus corroborating a mid-Famennian to Meramecian age (latest Devonian to early late Mississippian) (A. Harris, written communication, 1997).

Middle to Upper (?) Devonian and Lower Carboniferous rocks are also exposed along the Chukchi sea coast to the southeast of the Chegitun River region (Figure 2). In that area, Devonian rocks that are similar to those of the Chegitun River valley are overlain by Lower Carboniferous (Visean) limestones that are

rich in shallow marine fossils. The limestones grade up into thin intercalated black phyllites and slates, sericitic and chloritic phyllite, and quartzo-feldspathic sandstones [*Drabkin*, 1970a]. Cleavage and schistosity developed at greenschist facies metamorphic conditions are reported from these rocks [*Drabkin*, 1970a; *Natal'in*, 1979]. Thus we assign these rocks to the Tanatap unit.

We infer that greenschist facies metasedimentary and metavolcanic rocks that are exposed to the northwest and north of the Chegitun unit, in the Seshan Cape region (Figure 2), are equivalent to those of the Tanatap unit. *Oradovskaya and Obut* [1977] distinguished there the Seshan Formation, which contains phyllites, rhyolites, and probably basaltic tuffs, and overlying, dark gray to black shale, phyllites, and limestones of the Ikoluvrun Formation. No fossils have been found in either of these formations. Their Cambrian-Early Ordovician age was inferred from their structural position beneath fossil-bearing Upper Ordovician rocks at Seshan Cape [*Oradovskaya and Obut*, 1977]. However, the lithological similarity of the Ikoluvrun Formation to the Tanatap Formation as well as strong deformation at the contact with the overlying Ordovician rocks [see *Oradovskaya and Obut*, 1977, Figure 7] allows the inference that there is a fault contact between the Ikoluvrun Formation and the Ordovician rocks. Thus an age determination based on structural position may not be valid. The lithologic and structural features, greenschist facies metamorphism and fault relationships with the Ordovician rocks of the Chegitun unit, as well as the presence of volcanic horizons in the Seshan Formation, indicate that the Seshan and Ikoluvrun Formations may also correlate with the Tanatap Formation.

Some researchers believe that the southern part of the Tanatap unit contains Riphean rocks. This belief is based on findings of oncolites [*Ivanov and Kryukov*, 1973] or acritarchs [*Gorodinsky*, 1980; *Krasny and Putintsev*, 1984], the location of which have not been specified. Within the area of supposedly Riphean rocks we observed rocks that are lithologically identical to rocks of the Tanatap Formation and in places containing remnants of crinoids. Thus we dispute the existence of the Riphean rocks in the Tanatap unit.

The $^{40}Ar/^{39}Ar$ dating of metamorphic white mica from the Tanatap unit has shown that the age of deformation and metamorphism in the Chegitun River valley is Early Cretaceous at 124 Ma [*Natal'in et al.*, 1997]. No traces of earlier deformational events have been detected by structural analysis.

3.3. Chegitun Unit

The Chegitun unit is represented by unstrained, fossil-rich, shallow marine Middle Ordovician to Lower Devonian limestone, dolomite, and minor shale (Figures 3 and 4). The base of the Chegitun unit is not exposed in the Chegitun River valley, but *Oradovskaya and Obut* [1977] assume that the unit rests upon the inferred Upper Cambrian to Lower Ordovician Seshan and Ikoluvrun Formations. These relationships have been disputed in section 3.2, in which the Seshan and Ikoluvrun Formations are correlated with the Middle Devonian Tanatap Formation.

At the base of the Chegitun unit lies the 430 - to 540-m-thick Isseten Formation (Figure 4), which consists of dark gray to gray pelitomorphic and bioclastic limestone (locally argillaceous), dolomite, marl, and rare sedimentary breccia with clasts of limestone, and dolomite. Marl is present in the upper part of the section and reflects the deepening of the basin over time. To the northwest of the Chegitun River, limestone breccia with a dolomite matrix is reported as the most abundant rock type within the lower part of the formation. The rocks contain Middle Ordovician corals (Late Llanvirnian to Llandeilo), graptolites, brachiopods, gastropods, and trilobites which are very similar to the faunal assemblages of the Siberian platform and Kolyma region [*Oradovskaya and Obut*, 1977]. A Middle Ordovician conodont assemblage was recovered from this unit, including *Protopanderodus* sp. indet., *Panderodus* sp. indet., *Acanthocodina (?)* sp. indet., *Acanthocordylodus* sp. indet., *Drepanoistodus* sp., and possibly *Erismodus* sp. (A. Harris, written communication, 1997). This Middle Ordovician conodont assemblage is characteristic of warm shallow water environments of the Siberian platform.

The Upper Ordovician Chegitun Formation (225-350 m) (Figure 4) conformably overlies the Isseten Formation and is represented by medium- to coarse-grained dark gray bioclastic and reefal limestone and rare dolomite. Dark, organic-rich silicified concretions are commonly present in reefal limestones. Bedding surfaces within this unit are wavy. Reefal limestones form lenses several meters thick. The rocks are generally rich in recrystallized pentamerids, corals, and gastropods of Ashgilian (Upper Ordovician) age which are similar to those of the Kolyma region [*Oradovskaya and Obut*, 1977]. *Oradovskaya and Obut* [1977] infer a disconformity at the base of the Chegitun Formation.

The Chegitun Formation is, in turn, conformably overlain by the Silurian Putukuney Formation (60-70 m) (Figure 4). The contact between formation is very sharp. The Putukuney Formation consists of black calcareous shale and dark, thinly bedded, flaggy argillaceous limestone which contains numerous graptolites indicating Late Llandoverian, Wenlockian, to Early Ludlovian age. Light gray to yellowish thick-bedded limestone and dolomite (300-315 m) of the Late Silurian (Upper Ludlow) Orlan Formation overlies the Putukuney Formation. Lacking fossil evidence, *Oradovskaya and Obut* [1977] determined the age of the Orlan Formation on the basis of its structural position between the Putukuney Formation and fossil-bearing Lower Devonian rocks. Silurian conodonts recovered from our samples of the Orlan Formation include *Ozarkodinus* sp. indet and *Walliserodus* sp. indet (A. Harris, written communication, 1997). At the top of the Chegitun unit are Lower Devonian (200-250 m) dolomitic limestones containing stromatoporoid corals [*Oradovskaya and Obut*, 1977; *Krasny and Putintsev*, 1984].

In contrast to the Tanatap unit, the internal structure of the Chegitun unit is very simple. There are northwest and north-south striking open folds, wavelength of which is of hundreds of meters to kilometer scale. These folds are oblique to the boundaries between the lithotectonic units and to the principal northeastern trends in the Tanatap units. Northwest striking normal faults and northeast striking steeply dipping strike-slip faults are superimposed on the above mentioned folds. Despite the simple map- and outcrop-scale structure and the lack of any penetrative metamorphic fabric, the conodonts recovered from rocks of the Chegitun unit have conodont alteration indexes (CAIs) ranging from 5 to 6 (A. Harris, written communication, 1997). These values correspond to paleotemperatures of 300°-435°C [*Rejebian et al.*, 1987]. We attribute this high CAIs to local heating of the Chegitun unit during emplacement of the mid-Cretaceous granitic intrusions that rim the Koolen and Neshkan metamorphic domes (Figure 2).

4. Devonian Magmatism on the Northern Chukotka Peninsula

The correlation of Paleozoic magmatic events between the Russian Far East and North America and the search for a tectonic framework that can help us to understand the disposition and origin of Paleozoic magmatic belts remain an outstanding problem. This is especially important in Chukotka where pre-Triassic rocks are generally buried by the Mesozoic sedimentary rocks of the Chukotka fold belt and by the mid-Cretaceous Okhotsk-Chukotka volcanic belt. Devonian volcanic and plutonic rocks of the Russian Far East have been correlated with similar rocks known from California to northern Alaska [e.g., *Tilman*, 1973; *Rubin et al.*, 1990]. We provide here new ages for Devonian orthogneisses from the core of the Koolen dome, and we report andesitic tuffs from the Tanatap unit of the Chegitun River valley. These Devonian magmatic rocks are the first recognized from the Chukotka Peninsula and provide an important link between the mid-Paleozoic tectonic history of Chukotka and northern Alaska.

4.1. The Etelkhvyleut Series Orthogneiss

The Etelkhvyleut orthogneiss of the Koolen dome (Figure 2) consists of metamorphosed and deformed biotite granodiorite and granite, in places exhibiting migmatization [*Shuldiner and Nedomolkin*, 1976]. Protolith ages for this unit were suspected to be Precambrian, but *BSGFP* [1997] considered the possibility that some of these orthogneisses were highly deformed and metamorphosed Paleozoic or Mesozoic plutonic rocks. U-Pb geochronology revealed that most of the orthogneisses are highly deformed Cretaceous granites related to the high-grade metamorphic event [*BSGFP*, 1997]. However, samples F45-94K and M18-94K yielded Devonian ages. These two samples are from a metaluminous biotite granitic orthogneiss (unit Egog) [see *BSGFP*, 1997, Figure 4]. SiO_2 is 60 wt % and 64 wt % in the two rocks, respectively, so the original composition was likely a granodiorite (Table 2). Accessory phases include sphene, zircon, and apatite.

We dated six fractions of zircon from each of two Etelkhvyleut Series orthogneisses along the north and southern sides of Koolen Lake (Table 3 and Figure 2). Because of the fairly limited spread in U-Pb dates and the complete agreement within analytical error of the $^{207}Pb^*/^{206}Pb^*$ dates from analyzed fractions of each sample we interpret the age of these samples to be the weighted mean of the $^{207}Pb^*/^{206}Pb^*$ dates. The six zircon fractions analyzed from sample F45-94K give an age of 369.6 ± 1.2 Ma (MSWD = 3.3) whereas the 5 zircon fractions from sample M18-94K give an age of 374.8 ± 0.5 Ma (MSWD = 1.2). These data establish a Devonian age for the Etelkhvyleut Series orthogneisses in this area. The initial Sr for these two samples is 0.706, and the ε_{Nd} is +0.2 (F45) and -0.3 (M18, Table 4).

4.2. The Tanatap Series Metatuff

At least four distinct horizons of alternating red and green andesite tuffs 2 - 35 m thick are present in the Tanatap Formation in the Chegitun River valley; whereas a thicker (340 m) body of volcanic rocks has been reported off Seshan Cape [*Oradovskaya and Obut*, 1977]. In places, these horizons contain altered clasts with relict porphyritic texture. The tuffs have been metamorphosed to greenschist facies, and the identifiable mineralogy is mainly white mica, calcite/dolomite, and chlorite. The layered fabric is similar to unmetamorphosed volcanoclastic rocks, al-

Table 2. Major and Trace Element Geochemistry for Devonian Igneous Rocks

	Koolen Lake Orthogneiss		Tanatap Metatuff	
	F45-94K	M18-94K	95JT-39	95JT-48
SiO_2†	60.37	64.02	57.27	58.91
Al_2O_3	17.39	16.27	20.03	20.02
TiO_2	1.04	0.89	1.05	1.06
FeO*	5.16	4.81	7.12	4.99
MnO	0.11	0.11	0.06	0.05
CaO	4.28	3.36	2.34	2.60
MgO	1.96	1.57	3.53	3.84
K_2O	3.57	4.45	4.42	3.48
Na_2O	4.43	3.88	0.44	1.08
P_2O_5	0.39	0.33	0.15	0.15
Sum	98.70	99.69	96.41	96.18
Ba‡	1271	1540	460	500
Rb	199.30	140.40	177.90	137.20
Th	58.20	18.38	11.19	12.18
Nb	8.52	16.97	17.37	18.28
Ta	2.56	2.69	1.17	1.25
Sr	360	536	172	479
Zr	460	339	162	188
Hf	9.79	7.40	4.58	5.20
Tb	0.88	1.10	1.08	1.06
Y	18.62	32.23	35.25	33.83
La		82.89	36.04	49.59
Ce		155.35	71.08	93.36
Pr		15.77	8.04	10.44
Nd		57.81	31.60	40.63
Sm		10.44	7.00	8.54
Eu		2.41	1.56	1.34
Gd		7.70	6.01	6.28
Tb		1.10	1.08	1.06
Dy		6.10	6.54	6.48
Ho		1.17	1.31	1.29
Er		3.03	3.71	3.71
Tm		0.45	0.51	0.53
Yb		2.67	3.20	3.40
Lu		0.43	0.49	0.53
Ni			68	63
Cr			118	126
Sc			15	13
V			184	184
Ga			27	31
Cu			1	487
Zn			33	37
Pb			1.6	1.3
U			3.5	3.5
Cs			6.9	6.3

† Major element data were collected by XRF.
* All Fe was calculated as FeO.
‡ Trace element data were collected by inductively coupled plasma mass spectrometry except for metatuff rare earth element (REE) data, which were collected by isotope dilution at the University of Wisconsin using a mixed REE spike.

Table 3. U-Pb Isotopic Data from Koolen Lake Orthogneiss

Sample†	U, ppm	$^{206}Pb^*$, ppm	Measured Ratios‡			Atomic Ratios			Apparent Ages,§ Ma		
			$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb^*}{^{238}U}$	$\frac{^{207}Pb^*}{^{235}U}$	$\frac{^{207}Pb^*}{^{206}Pb^*}$	$\frac{^{206}Pb^*}{^{238}U}$	$\frac{^{207}Pb^*}{^{235}U}$	$\frac{^{207}Pb^*}{^{206}Pb^*}$
F45/94K +100A	542.8	25.31	734	0.07390	0.22148	0.05428(27)	0.40417(230)	0.05400(15)	340.8	344.7	371.1 ±6.1
F45/94K +100	577.8	25.71	7692	0.05585	0.16927	0.05179(26)	0.38524(194)	0.05395(4)	325.5	330.9	369.0 ±1.5
F45/94K100-150A	680.8	32.24	9455	0.05555	0.19451	0.05512(28)	0.41085(206)	0.05401(3)	345.9	349.5	371.3 ±1.1
F45/94K 100-150	642.6	27.65	15385	0.05492	0.18732	0.05008(25)	0.37271(187)	0.05398(2)	315.0	321.7	369.9 ±1.1
F45/94K 150-210	699.7	30.90	21323	0.05464	0.19331	0.05141(26)	0.38243(192)	0.05395(2)	323.2	328.8	369.1 ±1.0
F45/94K 210-325	748.9	32.74	28634	0.05445	0.20330	0.05088(25)	0.37843(190)	0.05394(2)	319.9	325.9	368.5 ±1.0
M18/94K+100A	559.1	27.21	6550	0.05635	0.19370	0.05666(28)	0.42278(213)	0.05412(3)	355.3	358.0	376.0 ±1.4
M18/94K +100	576.2	27.27	5280	0.05685	0.18835	0.05509(28)	0.41078(207)	0.05408(4)	345.7	349.4	374.4 ±1.5
M18/94K 100-150	636.3	30.13	12686	0.05523	0.20365	0.05513(28)	0.41110(207)	0.05408(3)	345.9	349.7	374.5 ±1.1
M18/94K 150-210	712.3	31.88	22521	0.05473	0.21943	0.05210(26)	0.38850(195)	0.05408(2)	327.4	333.3	374.3 ±1.1
M18/94K 210-325	889.3	31.80	21323	0.05478	0.21213	0.04163(21)	0.31050(156)	0.05410(3)	262.9	274.6	375.1 ±1.1

† Value >100, <200, etc., refer to size fractions in mesh size. All analyzed zircon fractions consisted of the least magnetic crystals that could be fractionated on a Frantz magnetic separator. "A" refers to the fraction that was air abraded prior to dissolution. See *Wright and Fahan* [1988] and *Dilles and Wright* [1988] for details of the analytical procedure. The sample locations are F45/94K (65°55.7'-N, 171°7.32'-W) and M18/94K (65°57.12'-N, 171°57.12'-W).

* Radiogenic Pb is used, corrected for common Pb using the isotopic composition of $^{206}Pb/^{204}Pb = 18.6$ and $^{207}Pb/^{204}Pb = 15.6$.

‡ Isotopic compositions are corrected for mass fractionation of 0.11%. Sample dissolution and ion exchange chemistry are modified from *Krough* [1973].

§ Ages were calculated using the following constants: decay constants for ^{235}U and ^{238}U = 9.8485×10^{-10} yr^{-1} and 1.55125×10^{-10} yr^{-1} respectively; $^{238}U/^{235}U = 137.88$. Precessions on $^{206}Pb^*/^{238}U$ ratios are ~ 0.2 - 0.3% based on the replicate analysis of two "standard" zircon fractions. Accuracy of the $^{206}Pb^*/^{238}U$ dates, including uncertainties in spike calibration, are estimated to be of the order of 0.5%. The two-sigma uncertainties in the $^{207}Pb^*/^{206}Pb^*$ ages were calculated from the combined uncertainties in mass spectrometry and an assumed uncertainty of ± 0.1 in the $^{207}Pb/^{204}Pb$ ratio used for the common Pb correction [*Mattinson*, 1987].

Table 4. Rb-Sr and Sm-Nd Isotopic Data From Devonian Igneous Rocks

Sample	Age, Ma	Rb, ppm	Sr, ppm	Atomic Ratio $^{87}Rb/^{86}Sr$	Measured Ratio* $^{87}Rb/^{86}Sr$	Initial Ratio $^{87}Rb/^{86}Sr$	Sm, ppm	Nd, ppm	Atomic Ratio $^{147}Sm/^{144}Nd$	Measured Ratio† $^{143}Nd/^{144}Nd$	Initial Ratio $^{143}Nd/^{144}Nd$	ε_{Nd}‡
						Koolen Orthogneiss						
F45/94K	376	122.0	585.0	0.604	0.70938 (8)	0.70615	11.2	67.2	0.101	0.512411 (20)	0.512167	0.2
M18/94K	375	144.0	575.0	0.725	0.71007 (8)	0.70620	10.2	61.7	0.100	0.512383 (20)	0.512138	-0.3
						Tanatap Metatuff						
95JT-39	~380	172.0	153.2	3.25	0.71935 (7)	0.7018	6.6	28.1	0.142	0.512125 (20)	0.511781	-7.3
95JT-48	~380	134.6	448.1	0.870	0.71277 (7)	0.70806	8.0	35.6	0.135	0.512119 (20)	0.511791	-7.1

Koolen orthogneiss was analyzed at Rice University by J. Wright. Tanatap metatuff was analyzed at the University of Wisconsin, Madison, by J. M. Amato. Values used for chondritic uniform reservoir (CHUR) are $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$. Decay constants are the following: Sm, 6.54×10^{-2} yr^{-1}; Rb, 1.42×10^{-11} yr^{-1}. Rb, Sr, Sm, and Nd concentrations were determined by isotope dilution by the addition of a mixed spike prior to the sample dissolution. At Rice University, Nd was measured as Nd^+; at the University of Wisconsin, Nd was measured as NdO. Repeated analysis of NBS-987 yielded $^{87}Sr/^{86}Sr = 0.710247 \pm 10$ (Rice University, >80 analyses) and 0.710257 ± 18 (University of Wisconsin, 30 analyses). Repeated analysis of BCR-1 yielded $^{143}Nd/^{144}Nd = 0.512633 \pm 10$ (Rice University, >20 analyses) and 0.512630 ± 20 (University of Wisconsin, 4 analyses). Tanatap ages are assumed to be ~ 380 Ma on the basis of the orthogneiss ages and stratigraphic constraints (Middle Devonian: 377-386 Ma).

* Ratios are corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr = 0.1194$.

† All errors in measured isotopic ratios are at the 95% confidence limit. Ratios are corrected for mass fractionation by normalizing to $^{146}Nd/^{144}Nd = 0.72190$.

‡ $\varepsilon_{Nd}(T) = \{[^{143}Nd/^{144}Nd(T)_{sample}/^{143}Nd/^{144}Nd(T)_{CHUR}] - 1\} \times 10{,}000$.

though subsequent tectonic deformation may have contributed to the formation of the foliation.

Major element geochemistry on two of the volcanic samples indicates that the tuffs are calc-alkaline andesites (SiO_2 = 59-61 wt % anhydrous) significantly enriched in potassium (Table 1). Because of greenschist facies metamorphism, it is not known to what degree this potassium enrichment is the result of posteruptive metasomatic processes. Some notable aspects of the geochemistry include Cr concentrations of 118 and 126 ppm and Ni concentrations greater than 60 ppm. It is unclear what phases are responsible for these concentrations, which are elevated with respect to normal andesites [e.g., *Ewart*, 1982]. It is possible, however, that the whole rock SiO_2 concentration is elevated because of the inadvertent inclusion of felsic clasts in the whole rock analysis. If this is true, the tuffs may be of a more basaltic-andesite composition, for which such high Cr and Ni concentrations may be more characteristic. These rocks are enriched in the light rare earth elements (LREE) (Figure 6), with La/Lu ratios of 74-94 and a negative Eu anomaly.

Although we report Sr isotopic data for the tuffs (Table 2), the mobility of Rb during greenschist facies metamorphism may have affected the measured Sr ratios. Nd and the REE are less mobile during metamorphism, so we believe the Nd isotopic data is much more robust. Although the tuffs are foliated, there are no structural discontinuities or shear zones between the tuffs and the surrounding rocks of the Tanatap Formation from which rare findings of Middle Devonian fossils have been reported [*Nedomolkin*, 1969, 1977; *Oradovskaya and Obut*, 1977]. So if we assume an age for the tuffs similar to that for the orthogneisses (~375 Ma), the initial ε_{Nd} for both metatuff samples is about -7. This is significantly different from the values measured from the Koolen Lake orthogneiss and would seem to preclude a common source region. However, the tuffs could have interacted with significant amounts of older crustal material during their ascent and eruption. Alternatively, the isotopic analysis of the tuff could have been contaminated by the inclusion of crustal material of a different age or origin. These two possibilities could have the effect of decreasing the ε_{Nd}. The question of

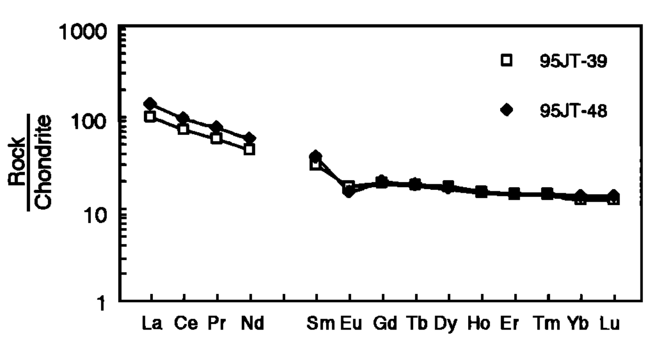


Figure 6. Rare earth element pattern from Tanatap metatuff. Light rare earth element enriched pattern with a negative Eu anomaly is commonly observed in continental arc volcanic rocks and may reflect derivation from an already fractionated source or a mixture of a primary magma with older, evolved crustal partial melts. Normalization factors are from *Anders and Ebihara* [1982].

whether or not the tuff and the orthogneiss are comagmatic is thus not resolvable using the isotopic data. We believe that the spatial relationships and the similar compositions point to a common origin for the orthogneiss and tuff.

Trace element geochemistry can be useful for identifying the tectonic setting of volcanic rocks, though large-ion lithophile elements such as Ba and Rb are to be avoided owing to both post-depositional alteration and the likelihood that the primary magma interacted with continental crust during its ascent. This crustal interaction may significantly alter the magmatic values and thus provide misleading information. High field strength elements and REE are less affected by alteration and metamorphism, and a comparison of the La/Th and La/Nb ratios with other orogenic andesite compositions indicates that the Tanatap tuffs overlap with high-K andesites from other areas [*Gill*, 1981].

Textural evidence, major and trace element chemistry, and Nd isotopic data all suggest that the Tanatap Series tuffs are differentiated calc-alkaline andesites possibly derived from a continental margin magmatic arc. The degree of metamorphism and alteration precludes a more rigorous assessment of the tectonic setting based on the tuffs alone. If we take into consideration the deep-water, anoxic, fine-grained nature and the lack of a terrigenous clastic component in the host rocks, it seems possible that these arc volcanic rocks were deposited in a back arc basin.

5. Paleozoic and Mesozoic Tectonic Units and Correlation of the Structures of Chukotka and Northern Alaska

The rocks exposed in the Chegitun River valley are an important element in Paleozoic tectonic reconstructions, because in many other areas of Chukotka and northern Alaska, Mesozoic magmatism, metamorphism, and deformation obscure earlier tectonic features. In addition, important tectonic elements may lie hidden within the broad continental shelves of the region. In this section we describe the important tectonic units of this region, attempt to correlate these features between Russia and Alaska, and propose a Paleozoic tectonic evolution for the region.

The major Paleozoic tectonic units of the Russian sector of the Chukotka-Arctic Alaska microplate are the following (Figure 7): (1) Precambrian crust which is inferred to underlie the Paleozoic and Mesozoic sedimentary cover (the Bennett-Barrovia block), (2) Ordovician to Devonian shelf carbonates and shales (the Novosibirsk carbonate platform) [*Şengör and Natal'in*, 1996], and (3) a middle Paleozoic arc-trench system stretching along the southern boundary of the Novosibirsk carbonate platform [*Natal'in et al.*, 1997]. Triassic-Early Jurassic passive continental margin deposits which now make up the Chukotka fold belt overlie these units and are bounded in the south by the Neocomian South Anyui suture [*Parfenov and Natal'in*, 1977, 1985; *Natal'in*, 1981, 1984].

In northern Alaska all Proterozoic to Early Cretaceous tectonic units located to the north of the Angayucham terrane (Figure 7) are assigned to the Arctic Alaska terrane [*Moore et al.*, 1994; *Plafker and Berg*, 1994]. The Seward Peninsula is generally correlated with the southern part of the Arctic Alaska terrane [*Moore et al.*, 1994; *Plafker and Berg*, 1994]. The Arctic Alaska terrane is unified by its Late Devonian through Jurassic passive margin stratigraphy (the Ellesmerian sequence). This sequence is predated by Middle (in places upper Lower Devonian) to Upper Devonian clastic rocks, shale, and mafic igneous rocks which formed in extensional environment and accumulated atop of strongly deformed basement [*Anderson et al.*, 1994; *Moore et al.*, 1994; 1997b]. *Grantz et al.* [1991] and *Moore et al.* [1994] suggest that pre-Middle-Devonian tectonic history of northern Alaska was a result of accretion of continental fragments of Siberian affinity to the continental margin of North America. Following this interpretation, the most significant pre-Middle-Devonian tectonic units are the following (Figure 7): (1) a fragment of the upper Proterozoic to lower Paleozoic passive continental margin rocks of the North American craton exposed in the Sadlerochit and Shublik mountains, northeastern Brooks Range; (2) lower Paleozoic rocks of oceanic and island arc affinity that are tectonically mixed with upper Proterozoic to lower Paleozoic passive continental margin deposits in the Franklinian fold belt (Figure 7) and which are exposed to the south of this fragment of the North American margin in the Romanzoff Mountains and in the Doonerak window of the Brooks Range and underlie part of the Colville Basin; (3) a complexly imbricated and metamorphosed assemblage of upper Proterozoic to Mississippian rocks mostly of continental affinity that make up the Hammond subterrane of the Brooks Range; and (4) Proterozoic to Mississippian (protolith age) schist, phyllite, metasandstone, and metacarbonate rocks with subordinate metaquartzite, metabasite, and felsic metavolcanic rocks of the Coldfoot subterrane. Units 3 and 4 and at least part of unit 2 have been considered as being of Siberian origin [*Grantz et al.*, 1991]. To the south of the Coldfoot subterrane there are quartzose phyllite, schist, slate, quartzite, minor metabasite, and chert of the Slate Creek subterrane which yield sparse Early and Middle Devonian and Mississippian fossils. The Hammond, Coldfoot, and Slate Creek subterranes were affected by intense deformation and blueschist to greenschist facies metamorphism during the Brookian orogeny in Late Jurassic to Early Cretaceous time.

The Late Jurassic to Early Cretaceous Kobuk suture, reactivated by mid-Cretaceous normal faulting [*Grantz et al.*, 1991], separates Arctic Alaska from the Angayucham terrane and, together with the South Anyui suture, defines the southern boundary of the Chukotka-Arctic Alaska block [*Parfenov and Natal'in*,

Figure 7. Tectonic map of the Siberian-Alaskan sector of Arctic. Abbreviations are as follows: AM, Alyarmaut Uplift; AN, Angayucham terrane; BD, Baird Mountains; BF, Barrow fault zone; BI, Belkov Island, BN, Belkovskyi-Nerpalakh Trough; DN, Doonerak window; HM, Hammond subterrane; HRT, Herald thrust; HT, Henrietta Island; KC, Kiber Cape; KG, Kigluaik dome; KI, Kotel'nyi Island; KM, Kolyuchin-Mechigmen zone; KO, Koolen dome; KU, Kuyul Uplift; NT, Nutesyn; PR, Primorsk Basin; RC, Rauchua Basin; RZ, Romanzof Mountains; SA, South Anyui suture zone; SE, Senyavin Uplift; SS, Shublik and Sadlerochit mountains; TP, Topolevka; YR, York Mountains; YU, Yarakvaam Uplift.

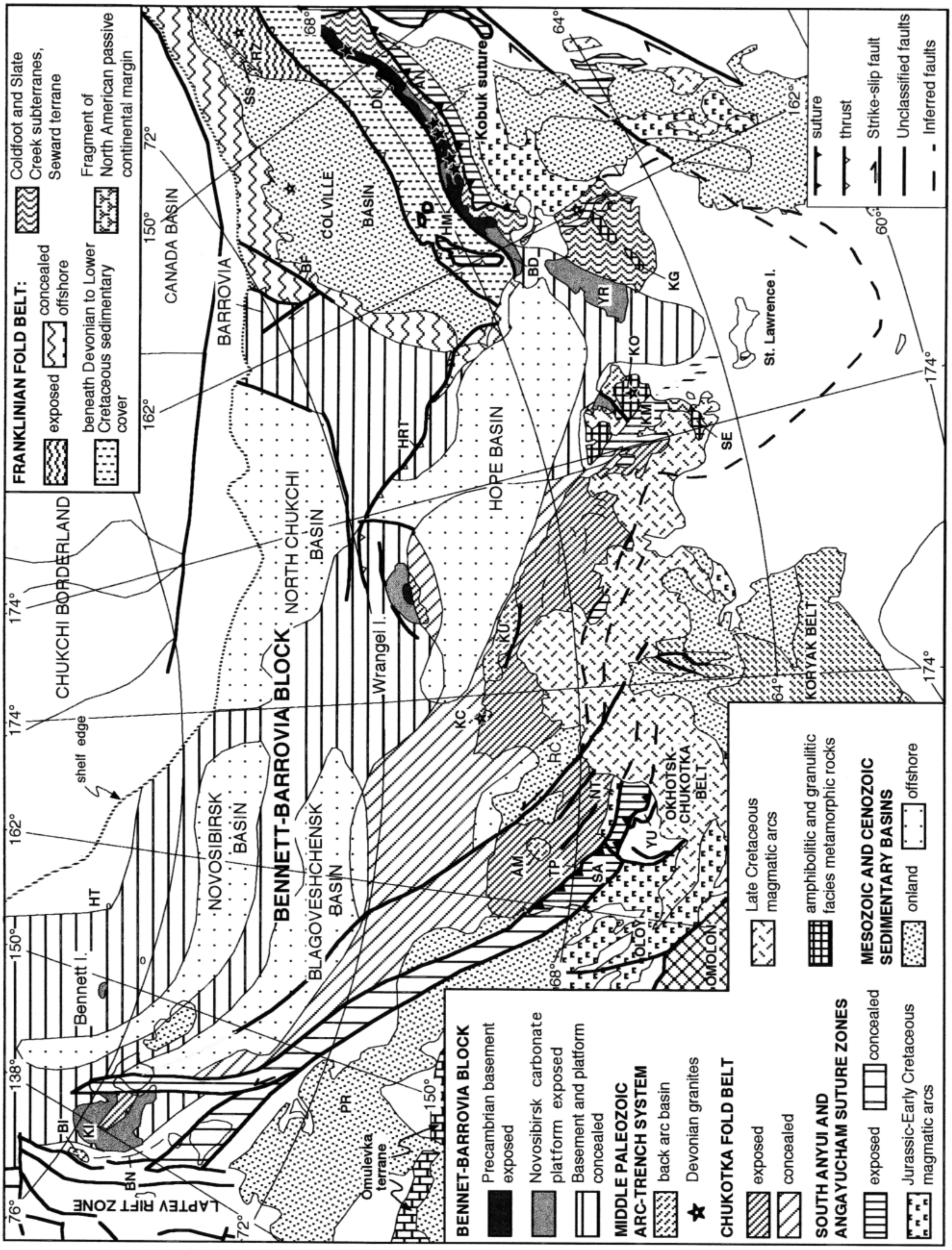

FRANKLINIAN FOLD BELT:
exposed
concealed offshore
beneath Devonian to Lower Cretaceous sedimentary cover
Coldfoot and Slate Creek subterranes, Seward terrane
Fragment of North American passive continental margin
BENNET-BARROVIA BLOCK
Precambrian basement exposed
Novosibirsk carbonate platform exposed
Basement and platform concealed
MIDDLE PALEOZOIC ARC-TRENCH SYSTEM
back arc basin
Devonian granites
CHUKOTKA FOLD BELT
exposed
concealed
SOUTH ANYUI AND ANGAYUCHAM SUTURE ZONES
exposed
concealed
Jurassic-Early Cretaceous magmatic arcs
Late Cretaceous magmatic arcs
amphibolitic and granulitic facies metamorphic rocks
MESOZOIC AND CENOZOIC SEDIMENTARY BASINS
onland
offshore
suture
thrust
Strike-slip fault
Unclassified faults
Inferred faults
CHUKCHI BORDERLAND
CANADA BASIN
BARROVIA
COLVILLE BASIN
Kobuk suture
NORTH CHUKCHI BASIN
HOPE BASIN
BENNETT-BARROVIA BLOCK
NOVOSIBIRSK BASIN
BLAGOVESHCHENSK BASIN
Wrangel I.
Bennett I.
St. Lawrence I.
LAPTEV RIFT ZONE
Omulevka terrane
OMOLON
OKHOTSK-CHUKOTKA BELT
KORYAK BELT
shelf edge

Figure 7.

1977, 1985; *Natal'in*, 1984, *Rowley and Lottes*, 1988]. In the sections 5.1-5.4 we discuss mainly the Russian sector of the region. Details of the geological structure of the Alaskan sector (the Arctic Alaska terrane) are given by *Moore et al.* [1994, 1997b] and *Grantz et al.* [1990].

5.1. Bennett-Barrovia Block

Two distinct tectonic hypotheses have been proposed for the evolution of this portion of the Arctic. In one, an intact Precambrian basement block forms the basement of the Novosibirsk Islands, Wrangel Island, the Chukchi and East Siberian Seas, and the Hammond subterrane in northern Alaska [e.g., *Zonenshain et al.*, 1990; *Şengör and Natal'in*, 1996]. In the other, this same region is an amalgamation of terranes that accreted to Asia or North America during Paleozoic-Mesozoic time and then rifted away during a subsequent event [*Fujita and Newberry*, 1982; *Fujita and Cook*, 1990]. We believe the "intact Precambrian basement block" hypothesis is valid for the following reasons: (1) The lower Paleozoic stratigraphy and lithology indicates a tectonically stable shallow marine environment that persisted throughout the area, from the Novosibirsk Islands to the Hammond subterrane in Alaska (see below), thus the different exposures are not likely to represent disparate terranes, but rather reflect deposition on a unified basement block; (2) faunal evidence places these exposures near each other and adjacent to Siberia during Paleozoic time [*Oradovskaya and Obut*, 1977; *Krasny and Putintsev*, 1984; *Moore et al.*, 1994]; and (3) low-amplitude, broad E-W or NW striking magnetic anomalies over most of the central and southern Chukchi and East Siberian Seas [*Vinogradov et al.*, 1974; see also *Fujita and Cook*, 1990] indicate an absence of sutures, which would be required in the terrane hypothesis.

The Bennett-Barrovia block underlies the shelf of the East Siberian and Chukchi Seas (Figure 7). The boundaries of the block and its main components can be inferred from (1) exposures of Paleozoic rocks, which reveal no evidence of extensive pre-Late Jurassic to Early Cretaceous deformation and thus formed in rather stable tectonic environment [*Kos'ko et al.*, 1993]; (2) disposition and geometry of the wide Mesozoic extensional basins (Figure 7); and (3) similarity of geophysical characteristics of the underlying basement [*Vinogradov et al.*, 1974, *Gramberg and Pogrebitzkiy*, 1984]. The boundaries and description of this block will be separately described for Russia, Alaska, and the Canadian Arctic islands.

5.1.1. Russia. The western boundary of the Bennett-Barrovia block coincides with the Laptev rift zone, which is a continuation of the Arctic mid-ocean ridge (Figure 9). *Zonenshain et al.* [1990] included the North Taimyr Peninsula and the Severnaya Zemlya Archipelago within their Arctida microcontinent, but both of these regions are characterized by a thick, strongly deformed succession of Riphean to Lower Ordovician flysch and rare red beds deposited on a passive continental margin. Such rocks are completely absent from the regions that we include in the Bennett-Barrovia block. In the Bennett Island region, in the East Siberian Sea (Figure 7), consolidated Precambrian crust underlying Paleozoic and Mesozoic sedimentary cover can be inferred from gravity and aeromagnetic anomalies [*Tkachenko and Egiazarov*, 1970; *Vinogradov et al.*, 1974; *Gramberg and Pogrebitzkiy*, 1984]. We infer that this basement is exposed in Wrangel Island where a Late Precambrian fold belt constitutes the basement for less deformed and less metamorphosed Silurian to Lower Devonian and younger rocks [*Kos'ko et al.*, 1993]. The fold belt consists of felsic to intermediate metavolcanic rocks, slate, schist, quartzite, and conglomerate, intruded by mafic sills and dikes as well as by small bodies of granite yielding a U-Pb age of 699 Ma [*Cecile et al.*, 1991b]. The discovery of Late Proterozoic protolith ages in the Etelkhvyleut orthogneiss in the Chegitun River valley indicates that a Late Proterozoic granitic magmatic belt extends to Chukotka.

In the eastern Chukchi Sea (Barrovia in Figure 7), another fragment of Precambrian crust covered by undeformed Upper Proterozoic to Cambrian [*Grantz et al.*, 1990] or lower Paleozoic [*Sherwood*, 1994] carbonate rocks can be inferred from seismic reflection profiling. Dips of foreset beds in overlying Paleozoic clastic rocks indicate that the source area for them was to the northwest (in the internal part of the Bennett-Barrovia block).

In the Chukotka sector the northern boundary of the Bennett-Barrovia block is masked by deep Cretaceous to Cenozoic basins which stretch along the shelf edge. On the basis of geophysical data, *Vinogradov et al.* [1974] defined the Henrietta fold belt to the northeast of Bennett Island (Figures 7 and 9). The only exposure of the belt in Henrietta Island is represented by sandstone, tuffaceous sandstone, shale, conglomerate with numerous lavas, sill, and dikes of basalt, andesite, and diabase. Conglomerate contains pebbles of granite, greenschist, and gneiss. A Paleozoic age is evidenced from recrystallized, presumably Carboniferous, foraminifera and K-Ar ages of volcanic rocks of 450-310 Ma [*Vinogradov et al.*, 1975]. The Ordovician age of volcanic rocks has been confirmed by recent $^{40}Ar/^{39}Ar$ dating (A. Kaplan, oral communication, 1998). The rocks of the Henrietta Island are markedly different from the Paleozoic cover of the Bennett-Barrovia block and have previously been interpreted as an independent terrane [*Fujita and Cook*, 1990]. We infer here that Ordovician basalt to andesite volcanic rocks of the Henrietta belt may indicate a magmatic arc along the northern side of the Bennett-Barrovia block

5.1.2. Canadian Arctic Islands. The lower Paleozoic rocks of Henrietta Island may represent a link to Arctic Canada, where the exotic Pearya terrane (PE in Figure 9) provides a record of a Middle Ordovician collision of a Precambrian block with an Early to Middle Ordovician island arc [*Trettin*, 1991]. After their collision a new Middle Ordovician to Silurian arc of southern polarity [*Klaper*, 1992; *Bjørnerud and Bradley*, 1994] was constructed above the suture within the Pearya terrane [*Trettin*, 1991]. Another arc (CM in Figure 9) was active in the area between the Pearya terrane and the passive continental margin of North America during the Ordovician and Silurian. This arc also had southern polarity, as is indicated by the vergence of the Clements Markham fold belt [*Trettin*, 1991; *Klaper*, 1992].

Trettin [1991] correlated pre-Middle-Ordovician rocks of the Pearya terrane with the Caledonides of the northern Atlantic. He inferred that the collision of Pearya with the Clements Markham arc happened before the Late Silurian in a sinistral transpressional environment. In turn, the Clements Markham arc collided with the passive continental margin of Arctic Canada in the Late Silurian to Early Devonian. Structural studies revealed no evidence of sinistral regime of these collisions [*Klaper*, 1992]. Consequently, we infer that the Pearya terrane and Clements Markham arc were at least in the position between Bennett-Barrovia and Arctic Canada and thus relevant to the Bennett-Barrovia block evolution.

5.1.3. Alaska. Proterozoic rocks have been found in two structurally imbricated units in the western part of the Hammond subterrane in northern Alaska [*Moore et al.*, 1994]. The lower unit consists of metacarbonate rocks with subordinate siliciclastic and metavolcanic rocks. The upper unit is made up of metasedimentary rocks and metabasites. The rocks of the upper unit are intruded by granitic rocks yielding a U-Pb age of 750 Ma. The amphibolitic facies metamorphism that affected these rocks occurred at about 655-594 Ma [*Moore et al.*, 1994]. These rocks are very different from a more or less continuous succession of Proterozoic to lower Paleozoic carbonate rocks of the North American continental margin that are exposed in the Sadlerochit Mountains in the northeastern Brooks Range.

Granitoids yielding a 705 Ma U-Pb age also have been reported as intruding metasedimentary and metavolcanic rocks in the Coldfoot terrane [*Moore et al.*, 1994]. In addition, Nd and Sr isotopic data from younger magmatic rocks, as well as Proterozoic inherited zircons found in the Devonian orthogneisses, suggest that these magmatic rocks were in part derived from Proterozoic crust [*Dillon et al.*, 1987; *Nelson et al.*, 1993; *Toro*, 1998]. In Alaska, these rocks form the most probable basement for the Paleozoic Baird Group carbonate rocks [*Nelson et al.*, 1993; *Moore et al.*, 1994]. The timing of Late Proterozoic granitoid magmatism in the Brooks Range is similar to a magmatic event recorded in rocks found on Wrangel Island [*Kos'ko et al.*, 1993] and Chukotka. Late Proterozoic orthogneisses also have been reported from the Seward Peninsula [*Till and Dumoulin*, 1994; *Amato and Wright*, 1998].

In Alaska, Cambrian to Silurian rocks of island arc and oceanic origin are exposed between the Hammond subterrane and the fragment of the North America continental margin in the northeastern Brooks Range (the Franklinian belt in Figure 7) [*Grantz et al.*, 1991; *Moore et al.*, 1994]. These rocks mark an ocean which was closed at the end of the Silurian to Early Devonian, as it is evidenced by a sharp unconformity at the base of the Middle Devonian rocks [*Anderson et al.*, 1994]. The suture between the Bennett-Barrovia block and North America is inferred to be located at the northern boundary of the island arc and oceanic rocks [*Grantz et al.*, 1991]. This conclusion is supported by Cambrian fossils of Siberian type found in the island arc rocks [*Dutro et al.*, 1984] and by their position near the boundary with the Hammond subterrane.

5.2. Novosibirsk Carbonate Platform

The early to middle Paleozoic Novosibirsk carbonate platform was defined by *Şengör and Natal'in* [1996] as cover deposits of the Bennett-Barrovia block. The platform includes mainly shelf and lagoonal carbonate rocks that are exposed in both Russia and Alaska (Figures 7 and 8).

5.2.1. Russia. Ordovician to Lower Devonian shallow marine and lagoonal carbonate rocks and shales have been described from Kotel'nyi Island within the Novosibirsk Archipelago [*Tkachenko and Egiazarov*, 1970; *Volnov*, 1975; *Kos'ko*, 1977; *Kos'ko et al.*, 1990]. On Kotel'nyi Island the oldest rocks are Lower to Middle Ordovician, but farther to the north, on Bennett Island, shale and siltstone are interbedded with rare limestone containing Middle Cambrian trilobites. These rocks are unconformably (?) overlain by Lower to Middle Ordovician shale, siltstone, and quartzose sandstone [*Tkachenko and Egiazarov*, 1970; *Kos'ko et al.*, 1990]. Thin beds of limestone and the presence of quartzose sandstones in the Ordovician rocks on Bennett Island may be interpreted as evidence of facies changes from an area of carbonate deposition in Kotel'nyi Island toward an uplifted area in the north [*Kos'ko*, 1994]. Starting in the Early Silurian, two depositional zones existed in Kotel'nyi Island [*Kos'ko*, 1977; *Kos'ko et al.*, 1990]. In the northwestern zone, shallow marine and lagoonal carbonate accumulated while in the southwestern zone fine-grained limestone was deposited with deep-water shale, siltstone, and siliceous shale. Middle Devonian limestone, debris flow deposits, and conglomerate conformably or unconformably overlie the older rocks of both zones and mark another tectonic cycle [*Kos'ko et al.*, 1990].

Silurian to Lower Devonian shallow marine carbonates and clastic rocks on Wrangel Island which formed in stable shelf, shallow marine environments [*Kos'ko et al.*, 1993] can also be assigned to the Novosibirsk platform. The unconformably lying on the Proterozoic rocks the Lower to Upper Devonian unit (the oldest fauna is Givetian) consists of conglomerates and sandstones. Silurian to Lower Devonian sandstones consist predominantly of quartz and feldspar and are compositionally similar to the Ordovician sandstones in the Bennett Island. Conglomerate and sandstone of the Lower to Upper Devonian unit, in contrast, are lithic and include fragments of volcanic, volcanoclastic, and granitic rocks derived from the underlying basement [*Kos'ko et al.*, 1993].

5.2.2. Alaska. A characteristic succession of lower to middle Paleozoic shallow marine carbonate rocks is found in the York Mountains of the Seward Peninsula [*Till and Dumoulin*, 1994], in the Baird Mountains of the western Brooks Range, and in several localities in the central and eastern Brooks Range within the Hammond subterrane [*Dumoulin and Harris*, 1994; *Moore et al.*, 1994] (Figures 7 and 8). In the York Mountains the succession starts with Arenigian deepening-upward subtidal to supratidal limestones which are overlain by shallowing-upward Lower Llanvirnian shales and thin-bedded limestones [*Dumoulin and Harris*, 1994]. Rocks of this age are missing on Chukotka Peninsula but exist on the Kotel'nyi Island [*Kos'ko*, 1977]. The Upper Llanvirnian to Lower Llandeilian black limestone of the York Mountains correlates well with the Isseten Formation of Chukotka. The overlying Upper Ordovician bioclastic fossiliferous limestones are similar to the Chegitun Formation of the Chukotka Peninsula. Lower Upper Ordovician rocks are not documented or missing in both regions. Silurian (Ludlovian) dolostone of the York Mountains may be correlated with the dolomites of the Orlan Formation of Chukotka. *Till and Dumoulin* [1994] reported that in addition to carbonate rocks the Silurian section of the York Mountains includes mudstone and that Middle Silurian fossils have been documented from this section. These rocks may be equivalent to the Putukuney Formation shales of the Chegitun River area.

In the Baird Mountains there are two fault-bounded carbonate sequences. The west central sequence consists of Lower Ordovician to Devonian shallow to deeper water platformal carbonate rocks, and its stratigraphy is very similar to that of the York Mountains on the Seward Peninsula [*Dumoulin and Harris*, 1994] and the Chegitun unit on the Chukotka Peninsula (Figure 8). The Lower to Middle Ordovician and Upper Silurian rocks are represented by limestone and dolomite, and the Upper Ordovician consists of limestone. The northeastern sequence of the Baird Mountains consists of Lower to Middle Ordovician shale and chert which grade up into inner shelf metalimestone

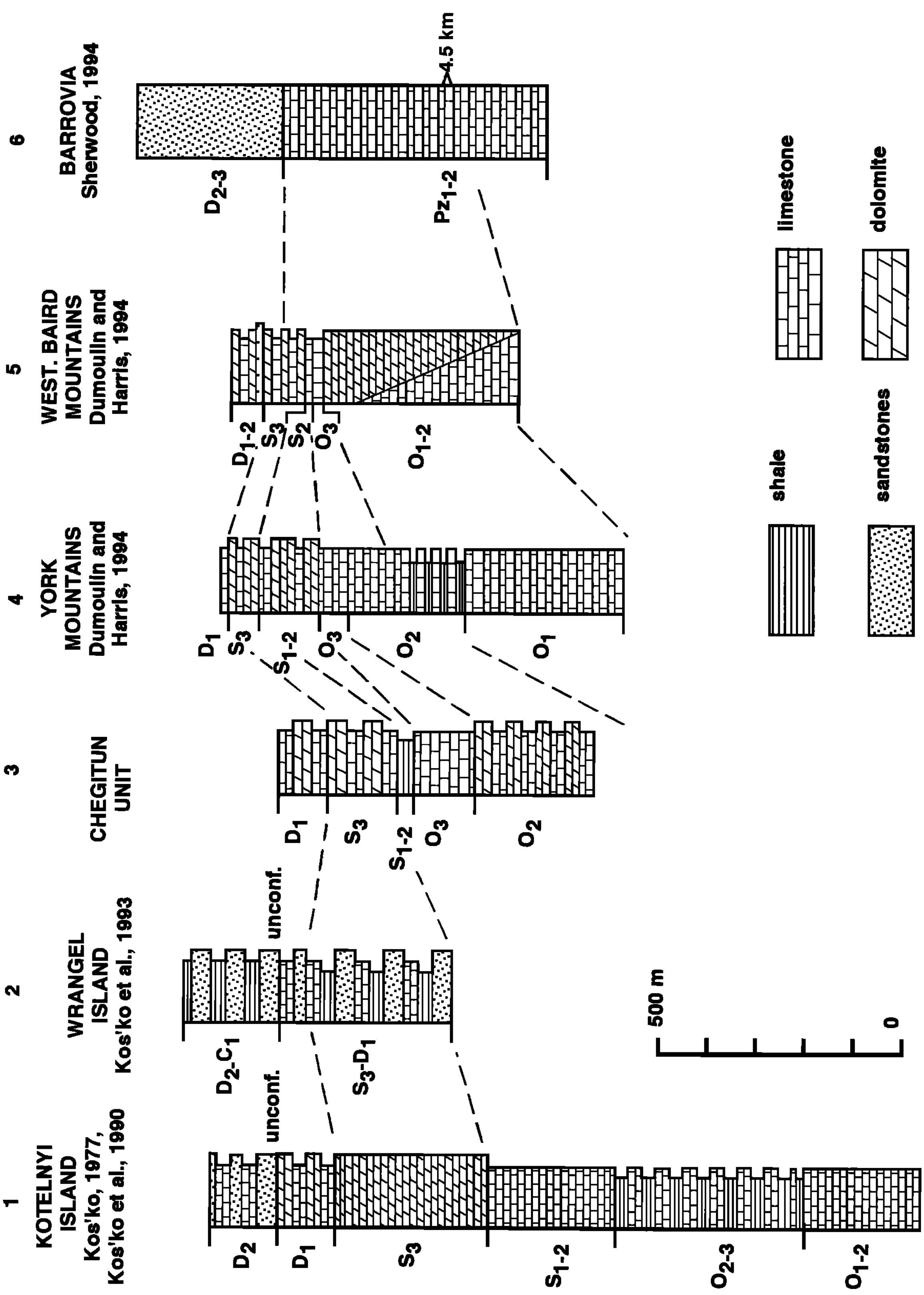


Figure 8. Stratigraphic correlation of lower and middle Paleozoic rocks of the Novosibirsk carbonate platform.

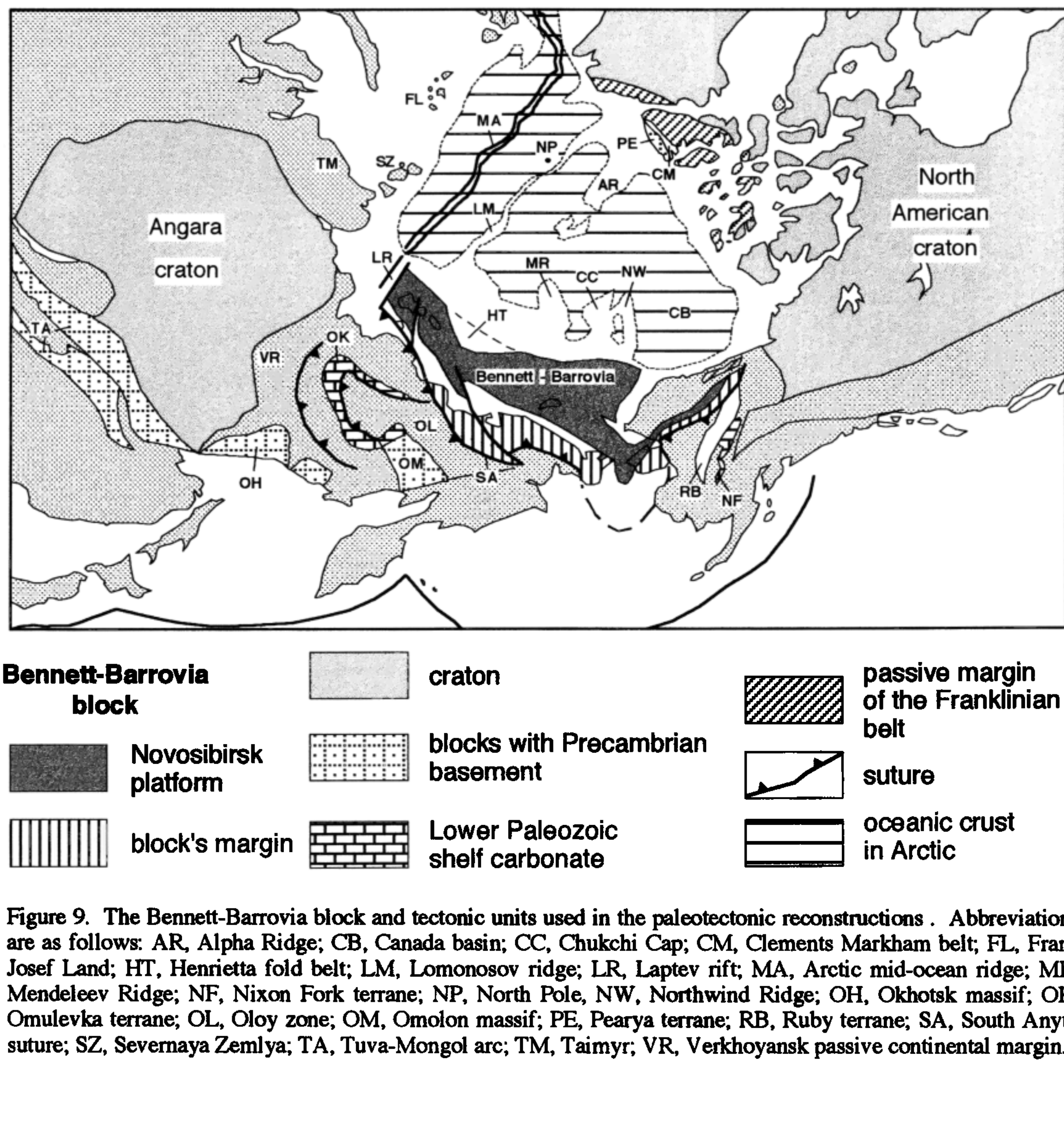


Figure 9. The Bennett-Barrovia block and tectonic units used in the paleotectonic reconstructions. Abbreviations are as follows: AR, Alpha Ridge; CB, Canada basin; CC, Chukchi Cap; CM, Clements Markham belt; FL, Franz Josef Land; HT, Henrietta fold belt; LM, Lomonosov ridge; LR, Laptev rift; MA, Arctic mid-ocean ridge; MR, Mendeleev Ridge; NF, Nixon Fork terrane; NP, North Pole, NW, Northwind Ridge; OH, Okhotsk massif; OK, Omulevka terrane; OL, Oloy zone; OM, Omolon massif; PE, Pearya terrane; RB, Ruby terrane; SA, South Anyui suture; SZ, Severnaya Zemlya; TA, Tuva-Mongol arc; TM, Taimyr; VR, Verkhoyansk passive continental margin.

[*Dumoulin and Harris*, 1994]. This change of facies is different than that of the previously described regions. The upper Upper Ordovician to Lower Devonian carbonate rocks are represented by shallow marine facies. The Middle to Upper Cambrian metal-imestone have been described from this region. *Dumoulin and Harris* [1994] report that the Cambrian and the Ordovician to Lower Devonian rocks of the eastern Baird Mountains are similar to the rocks of the Snowden Mountain in the eastern part of the Hammond terrane.

Lower Paleozoic fauna from rocks of the Novosibirsk platform reveal a similarity with the Siberian fauna [*Tkachenko and Egiazarov*, 1970; *Oradovskaya and Obut*, 1977; *Krasny and Putintsev*, 1984; *Moore et al.*, 1994; *Till and Dumoulin*, 1994]. *Oradovskaya and Obut* [1997] emphasized a similarity of Chukotkan and Alaskan (Kuskokwim and Yukon-Porcupine regions (NF in Figure 9) and Seward Peninsula) Middle Ordovician brachiopods, Late Ordovician corrals, and Silurian graptolites. *Rozman* [1977] determined the Kolyma-Alaska region (Novosibirsk Islands, Chukotka and Seward Peninsula, Kuskokwim, and Yukon-Porcupine regions) as a unique one in northern Asia and North America for the Late Ordovician brachiopods. *Dumoulin and Harris* [1994, p.56] noted that "both 'Siberian' and 'North American' faunal affinities occur at different times and in different fossil groups within all of the (meta)carbonate successions" in northern Alaska making it likely that the Novosibirsk platform formed in a position between Siberia and North America.

In the northeastern corner of the Chukchi Sea (Barrovia in Figure 7), seismic reflection profiling revealed two [*Grantz et al.*, 1990] or three [*Sherwood*, 1994] subhorizontal pre-Mississippian seismostratigraphic units. There is a controversy in the age determination of these units. *Grantz et al.* [1990] infer, on the basis of seismic velocities and the character of the reflectors, that the lower unit is made up of Precambrian or Cambrian carbonate rocks and that the upper unit consists of Ordovician to Silurian clastic rocks. In contrast, *Sherwood* [1994] infers a Proterozoic (?) to Middle Devonian age for the carbonate unit and a Middle to Late Devonian age for the clastic rocks in which he recognized two units separated by a low-angle thrust. Both authors agree that the NW striking Barrow fault (BF in Figure 7) separates

these units from strongly deformed and slightly metamorphosed Ordovician to Silurian argillite, phyllite, slate, chert, and graywacke in the basement of the Colville basin. Regardless of the age determination, both interpretations corroborate the idea of the Novosibirsk carbonate platform as the sedimentary cover of the Bennett-Barrovia block.

We consider the regions listed above in Russia, Seward Peninsula, and northern Alaska as part of the continuous Bennett-Barrovia block covered by the Novosibirsk carbonate platform (Figure 9). The original size of this block could have been much larger, as other exposures of similar rocks may also be a part of these tectonic units. For example, in Alaska the Nixon Fork terrane (Figure 9) consists of the Ordovician to Lower Devonian shallow marine carbonate, calcareous turbidite, and shale. Fossils from these rocks indicate a link to Siberia [*Dumoulin et al.*, 1998], and thus this terrane could also be a part of the Novosibirsk platform.

5.3. Middle Paleozoic Arc-Trench System

5.3.1. Magmatic arc. Devonian and lower Mississippian volcanic and plutonic rocks are found throughout the North American Cordillera, from California to northern Alaska [*Rubin et al.*, 1990]. These magmatic rocks and related basinal strata have been interpreted as remnants of an arc system developed near the edge of the Proterozoic craton on continental crust, transitional crust, or oceanic crust [*Dusel-Bacon and Aleinikoff*, 1985; *Dillon et al.*, 1987; *Rubin et al.*, 1990; *Plafker and Berg*, 1994]. Devonian plutonic rocks from both northern Alaska and Russia are briefly described here.

In northern and central Alaska, Devonian granites are widely scattered through the Hammond and Coldfoot subterranes (recently, parts of the Hammond subterrane where granites are exposed were assigned to the Coldfoot subterrane [*Moore et al.*, 1997a]) and on the Seward Peninsula [*Till and Dumoulin*, 1994; *Miller*, 1994] (Figure 7). A few granitic bodies of uncertain origin are known from the North Slope subterrane [*Moore et al.*, 1994]. Felsic to intermediate volcanic rocks in the eastern part of the Hammond terrane (Nutirwik Creek unit) yield the Early to Middle Devonian U-Pb zircon ages [*Moore et al.*, 1997b]. Middle Frasnian conodonts have been collected from the upper part of their section. Petrologic features of these rocks indicate a subduction-related origin of the rocks. Their age partly overlaps the age of the extension-related igneous rocks of the Hammond subterrane. Early to Middle Devonian granitoids (now orthogneiss) vary in composition from diorite to granite [*Moore et al.*, 1994]. They yield U-Pb ages of 398-383 Ma and reveal a subduction-related signature although mixing of some other magma type with partial melts from preexisting subduction-related rocks is possible [*Moore et al.*, 1997b]. Younger granitic rocks in the Coldfoot terrane are Late Devonian (discordant U-Pb zircon age is 366 Ma) [*Moore et al.*, 1994]. Their major element and isotopic composition indicates that these granites incorporated large components of continental crust [*Nelson et al.*, 1993]. Euhedral detrital zircons from quartzites in the Coldfoot subterrane varying in age from 370 to 360 Ma may have various igneous sources, and granite plutons are considered among the possible ones [*Moore et al.*, 1997a]. Orthogneiss on the Seward Peninsula yields a 381 Ma U-Pb zircon age [*Till and Dumoulin*, 1994].

In Chukotka the knowledge of the distribution of Devonian plutonic and volcanic rocks is limited by the scarcity of exposures of Paleozoic rocks and the lack of high-quality U-Pb geochronology. We have described the Devonian plutons in the core of the Koolen dome and the Devonian tuffs in the Tanatap unit. In the Cape Kiber area (KC in Figure 7), biotite granites intrude clastic rocks that are similar to the rocks bearing Middle Devonian fossils in the central and eastern parts of the uplift. Clasts of the same granites appear in the Lower Carboniferous conglomerate exposed nearby [*Cecile et al.*, 1991a]. A Rb-Sr whole rock age of the granites has been determined as 439 Ma (Early Silurian) with an initial Sr ratio of 0.7042 [*Tibilov et al.*, 1986]. Subsequent studies of the Cape Kiber granite [*Cecile et al.*, 1991a] questioned the Silurian age and recently a U-Pb zircon age has been determined at 360 Ma [L. Lane, personal communication, 1998]. Composition of the granite including REE data indicates that the granite is subduction-related. Small fault-bounded blocks of tuffs and lavas ranging in composition from basalt to dacite containing lenses of limestone with Lower Carboniferous (Visean) corals are exposed at the northern margin of the South Anyui suture (TP in Figure 7) [*Natal'in*, 1984].

We agree with the many authors [e.g., *Dusel-Bacon and Aleinikoff*, 1985; *Rubin et al.*, 1990; *Plafker and Berg*, 1994] who proposed that a Devonian, or in places Devonian to Early Carboniferous, active continental margin existed along the Proterozoic craton of North America and Alaska, and we suggest that this arc system can be extended into northeastern Russia. Some geologists believe that in Alaska the magmatic arc was active only during the Early to Middle Devonian and that it was succeeded in the Middle to Late Devonian by extension that led to the formation of the passive continental margin [*Moore et al.*, 1994, 1997b]. However, the ages of the subduction- and extension-related igneous rocks in the Hammond and Coldfoot subterranes overlap. If euhedral zircons of 370-360 Ma did have granitic sources [*Moore et al.*, 1997a], granitic intrusions and eruption of enriched MORB-type basalts in the same tectonic zone (rift/passive continental margin tectonic setting according to *Moore et al.* [1997a]) seems unlikely. Thus we infer that extension in northern Alaska could be a result of the back arc basin formation related to the Devonian arc. In Chukotka the magmatic arc stretches along the southern margin of the Bennett-Barrovia block. In Alaska the Coldfoot subterrane, in which the majority of the Devonian granites are exposed, is to the south of the Hammond subterrane, and one possible restoration of Mesozoic thrusting places it in the same position [*Moore et al.*, 1997b].

5.3.2. Back arc basin. In the Novosibirsk Islands the rocks of the Novosibirsk carbonate platform are bounded in the south by the Belkovskyi-Nerpalakh Trough (BN in Figure 7). The trough is filled with thick (8900 m) Upper Devonian to Lower Carboniferous limestone, shale, sandstone, and conglomerate that in the Devonian part of the sequence contain dikes and sills of low-potassium gabbro [*Tkachenko and Egiazarov*, 1970; *Vinogradov et al.*, 1974; *Volnov*, 1975]. The mafic intrusions are here interpreted as evidence for an extensional origin of the Belkovskyi-Nerpalakh Trough. The subsidence of the southern margin of the Novosibirsk platform began in the Silurian as evidenced from facies changes of shallow marine Lower Silurian carbonate rocks in the central and northern part of Kotel'nyi Island to the deep-water shales and limestones in the southwest-

ern part of the island [*Kos'ko*, 1977]. Underlying Ordovician rocks do not reveal such changes. The Middle Devonian rocks include debris flow deposits and limestone conglomerate and breccia with local unconformities at the base of these rocks [*Kos'ko et al.*, 1990] that may also indicate tectonic activity related to the formation of the Belkovskyi-Nerpalakh Trough. In spite of the large distance from the Novosibirsk Islands, the Chegitun and the Tanatap units on the Chukotka Peninsula reveal similar ages, composition of rocks, and timing of events.

In the Alyarmaut uplift (AM in Figure 7), metaclastic rocks of amphibolite to greenschist facies are presumably of Devonian age, because they are conformably overlain by Lower Carboniferous metalimestones and black phyllites [*Tilman*, 1973]. These rocks contain actinolite schists [*Markov et al.*, 1980] formed from volcanic(?) rocks. In the Kuyul Uplift (KU in Figure 7), Lower to Middle Devonian rocks up to 1300 m thick are represented by siltstone and shale with minor limestone. Upper Devonian rocks (1200 m) consist of arkose and quartz sandstone [*Rogozov and Vasilyeva*, 1968]. Unconformably overlying these rocks are Lower Carboniferous (2500 m) arkose sandstone, black shale with abundant sulfides, siliceous and calcareous shale, dolomite, limestone, and conglomerate [*Markov et al.*, 1980]. These rocks are twice as thick as coeval rocks on Wrangel Island [*Kos'ko et al.*, 1993]. Exposures of Devonian to Lower Carboniferous rocks in the Alyarmaut and Kuyul uplifts in central and western Chukotka [*Drabkin*, 1970a; *Krasny and Putintsev*, 1984] are in an intermediate position between the Novosibirsk Island and Chukotka Peninsula and argue for former continuity between the Devonian Belkovskyi-Nerpalakh Trough and Tanatap basins.

In Alaska the tectonic equivalent of these basins may be an extensional basin filled with the Givetian(?) (late Middle Devonian) to Early Frasnian (early Upper Devonian) Beaucoup Formation and associated metasedimentary and metavolcanic rocks within the Hammond subterrane (Deitrich River phyllite in the eastern part of the subterrane) [*Moore et al.*, 1994, 1997b]. These rocks are intruded by sills, dikes, and stocks of metadiabase and gabbro. Composition and elemental abundance patterns of igneous rocks are similar to mafic magmatism in an extensional environment through lithosphere with a previous history of subduction magmatism [*Moore et al.*, 1997b]. Detailed studies in the eastern part of the Hammond subterrane have shown that the extension-related rocks occur as a series of thrust-bounded sheets emplaced from the south during the Brookian orogeny [*Moore et al.*, 1997a].

5.3.3. Fore arc region. It is not easy to discern a forearc region for the reconstructed middle Paleozoic magmatic arc in Chukotka and Alaska. All structures to the south of the arc were strongly reworked by Triassic rifting in Chukotka and by Jurassic-Early Cretaceous thrusting and mid-Cretaceous extensional deformation both in Chukotka and in Alaska. Amphibolite and ultramafic rocks have been reported in metamorphic rocks of the Senyavin Uplift of the Chukotka Peninsula (SE in Figure 7) [*Akinin*, 1995; *Calvert and Gans*, 1996]. The Rb-Sr isochron age of these rocks is 365 Ma [*Akinin*, 1995], but it is unclear whether this age reflects the protolith age or a subsequent metamorphic event. Devonian fossils have been found in the weakly metamorphosed limestone and shale of the Senyavin uplift [*Egiazarov and Dundo*, 1985], but their relationship with the ultramafic rocks occurring within the Senyavin metamorphic complex is uncertain. Ultramafic rocks also exist in the lower part of the Lavrentiya Series in the Koolen Lake region. From these data we infer that middle Paleozoic accretionary prism material is present in the metamorphic complexes of the Chukotka Peninsula [*Şengör and Natal'in*, 1996]. Lenticular bodies of Devonian or older mafic and ultramafic rocks of oceanic origin (metavolcanic rocks of NMORB and EMORB type) and a melange in the Coldfoot subterrane in northern Alaska [*Moore et al.*, 1997b] suggest that a part or all of the Coldfoot subterrane may have once composed a middle Paleozoic accretionary prism which was in front of the Devonian arc.

5.4. Chukotka Fold Belt

The Chukotka fold belt (Figures 1 and 7) is a zone of Triassic to Lower Jurassic passive continental margin deposits (Middle Triassic rocks are not confirmed paleontologically) deformed before the mid-Cretaceous during closure of the South Anyui suture [*Natal'in*, 1981, 1984; *Parfenov and Natal'in*, 1977, 1985; *Zonenshain et al.*, 1990]. Thick (5.5 km) Triassic to Lower Jurassic turbidites unconformably overlie the Devonian to Middle Carboniferous rocks exposed in the Kuyul and Alyarmaut uplifts [*Sadovsky*, 1965; *Tilman*, 1973; *Drabkin*, 1970a]. Upper Carboniferous and Permian rocks are almost completely absent. Numerous sills and dikes of gabbro and diabase and sparse lava flows occur among Lower to Middle(?) Triassic rocks. These magmatic rocks indicate a rifting event that can also be recognized along the northern boundary of the Siberian craton, within the Siberian craton itself, in Franz Josef Land, and in the Severnaya Zemlya Archipelago in the Arctic Ocean [*Gramberg and Pogrebitzkiy*, 1984; *Milanovsky*, 1987; *Zonenshain et al.*, 1990]. In the east the Chukotka fold belt terminates at the Kolyuchin-Mechigmen zone of the Chukotka Peninsula (Figures 2 and 7). In the west it narrows toward the Novosibirsk Islands (Figure 7) where Triassic argillite, sandstone, limestone, and basalt (in Lower Triassic part of the section) and Lower Jurassic mudstone, siltstone, and sandstone have been reported [*Tkachenko and Egiazarov;* 1970, *Kos'ko et al.*, 1990]. The Nutesyn zone (Figure 7), consisting of the Middle Jurassic to Neocomian basalt to dacite of island arc affinity, tuff, volcanoclastic sandstone, conglomerate, and shale, rests unconformably atop of the Triassic rocks at the southern margin of the central part of the Chukotka belt but does not continue to the west [*Natal'in*, 1981, 1984]. Similar volcanic rocks exist in the Late Jurassic to Early Cretaceous Rauchua Basin (Figure 7) and in small basins along the southern margin of the eastern part of the Chukotka belt. All these data allow the reconstruction of a Late Jurassic-Early Cretaceous magmatic arc along the southern margin of the eastern part of the Chukotka belt [*Natal'in*, 1981, 1984].

To our knowledge, an equivalent of this early Mesozoic turbidite (plus gabbro) succession of the Chukotka belt does not exist in northern Alaska. There the Carboniferous to Lower Cretaceous Ellesmerian sequence is continuous, and the thickness of Triassic rocks does not exceed 200 m [*Moore et al.*, 1994].

In Chukotka, Triassic rifting led to the formation of a passive continental margin along the southern side of the Bennett-Barrovia block and the opening of the South Anyui ocean. From the location of the middle Paleozoic arc-related rocks at the very boundary of the South-Anyui suture zone (TP in Figure 7) and the location where there is an apparent absence of arc/forearc tec-

tonic zones in the Novosibirsk Islands sector (a back arc extensional basin exists there), we suggest that this rifting was oblique to the Paleozoic structures of the Bennett-Barrovia block and the middle Paleozoic arc-trench system and thus fragments of the arc-trench system could have been rifted away. In the present-day structure they may be presented on the opposite side of the South Anyui suture. Indeed, to the south of the suture within the Oloy zone (Figure 7), numerous fault-bounded fragments of Devonian to Middle Carboniferous arc-related magmatic rocks, Paleozoic ophiolite, and flysch occur among Mesozoic volcanic rocks [*Natal'in*, 1984; *Zonenshain et al.*, 1990]. Their Paleozoic fauna assemblages are similar to Siberian and Chukotkan fauna assemblages [*Krasny and Putintsev*, 1984] which fits a hypothesis of a local origin of these blocks. To the north of the Omulevka terrane, in the basement of the Primorsk Cenozoic basin (PR in Figure 7), continental blocks, island arc complexes, and ophiolites are inferred from geophysical data [*Litinsky and Raevsky*, 1977; *Spector et al.*, 1981]. The Chukotka passive continental margin collided with Siberia at the end of Neocomian time along the South Anyui suture [*Parfenov and Natal'in*, 1977; *Natal'in*, 1981, 1984; *Seslavinsky*, 1980].

6. Summary of the Paleozoic Tectonic History of Northeastern Russia and Northern Alaska

The Paleozoic tectonic evolution of the Late Proterozoic Bennett-Barrovia block in some respects resembles the tectonic evolution of the Arctida microcontinent outlined by *Zonenshain et al.* [1990]. They proposed that in the early Paleozoic, Arctida was separated from the Siberian craton. This is supported by the existence of a pre-Ordovician unconformity and Ordovician felsic volcanic rocks in the Severnaya Zemlya Archipelago [*Milanovsky*, 1987]. Alternatively, *Şengör and Natal'in* [1996] infer a Vendian (latest Precambrian) age of separation by linking it to the main rifting event between the Russian and Angara cratons.

Figure 10 shows the Late Ordovician position of the Bennett-Barrovia block with respect to the Angara craton, the North American craton, and the tectonic units of northeastern Russia. The shape of the Bennett-Barrovia block is corrected by restoration of Mesozoic left-lateral strike-slip faults in the Chukotka belt [*Sutygin and Tibilov*, 1969; *Parfenov and Natal'in*, 1985] and by unbending the Bering Strait orocline [*Patton and Tailleur*, 1977].

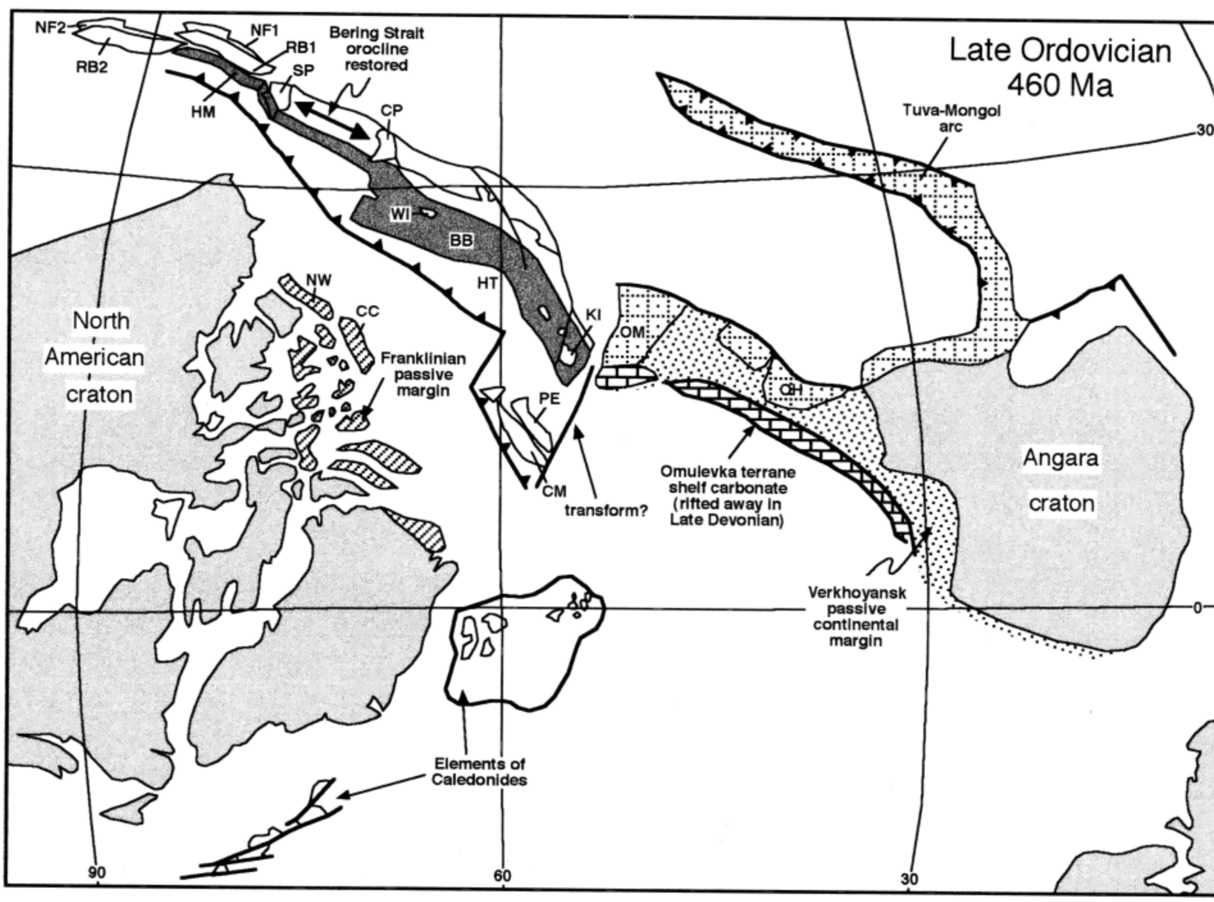


Figure 10. Late Ordovician paleotectonic reconstruction of the Bennett-Barrovia block. The positions of major continents are after *Lawver et al.* [1990]. The reconstruction of the Tuva-Mongol arc, Okhotsk, Omolon, and Omulevka terrane is after *Şengör and Natal'in* [1996]. Abbreviations are the same as those in Figure 9. Positions of the Chukchi Cap and Northwind Ridge are after *Grantz et al.* [1998]. BB - Bennett-Barrovia; CP - Chukotka Peninsula; WI -Wrangel Island.

There are no paleomagnetic data to constrain the position of the Bennett-Barrovia block. Our inference about its location is based on the following reasons.

1. Facies indicate that lower Paleozoic rocks of the block accumulated in a warm climate, and fossil assemblages are similar with the Omulevka terrane, Siberia, and North America.

2. The Omulevka terrane is characterized by Ordovician to Lower Carboniferous reefal limestone, shale, sandstone, and minor gypsum [*Zonenshain et al.,* 1990]. Thus it is reasonable to place the Bennett-Barrovia block either in front of the Omulevka terrane or as a continuation along strike. We have chosen the latter because it makes a simpler subsequent tectonic evolution (see below).

3. The Omulevka terrane was rifted away from the Verkhoyansk passive margin in the Late Devonian [*Parfenov and Natal'in,* 1985; *Zonenshain et al.,* 1990]. If we infer that the Bennett-Barrovia and Omulevka blocks were close to each other during the early Paleozoic and the beginning of the middle Paleozoic, the line of the rifting of the Omulevka terrane would be on the continuation of the Devonian extensional basin of the Bennett-Barrovia block.

4. The lower Paleozoic carbonate rocks of the Bennett-Barrovia block are similar to platformal carbonate successions within the Central Composite terrane, including the Ruby and Nixon Fork terranes [*Plafker and Berg,* 1994; *Moore et al.,* 1997a], which contains both Siberian and North American fossils [*Dumoulin et al.,* 1998]. Therefore we keep the western part (Ordovician paleocoordinates) of the Bennett-Barrovia block closer to North America.

The Ruby and Nixon Fork terranes could have two possible positions: (1) to the north of the Hammond and Coldfoot subterranes (NF1 and RB1 in Figure 10), from which these subterranes could be rifted away during the opening of the Angayucham ocean [*Patton et al.,* 1994, and references therein] or (2) on the continuation of the Hammond and Coldfoot terranes (NF2 and RB2 in Figure 10); from which these terranes could be strike-slipped along the dextral Proto-Tintina fault [*Grantz et al.,* 1991].

In the Late Silurian to Early Devonian the Bennett-Barrovia block collided with North America (Figures 11a and 11b). This collision led to the Ellesmerian orogeny of northern Alaska and the Canadian Arctic Islands. In Arctic Canada, episodes of compressional deformation related to the collision have been recorded until the Early Carboniferous [*Trettin,* 1991]. In northern Alaska, compressional deformation terminated by the Middle Devonian, and then it was followed by extensional deformation and the accumulation of clastic rocks [*Anderson et al.,* 1994; *Moore at al.,* 1994, 1997b]. However, in places (western Baird Mountains), shelf carbonate deposits persist from Silurian until Middle Devonian [*Dumoulin and Harris,* 1994]. Thus a part of the Bennett-Barrovia block in northern Alaska was not affected by the extensional deformation. Traces of the Ellesmerian orogeny may be detected on Wrangel Island by an unconformity at the base of the Middle to Upper Devonian unit and the drastic change in the composition of clasts in sandstones and conglomerates [*Kos'ko et al.,* 1993]. On Kotel'nyi Island, stable shelf sedimentation was succeeded, in places unconformably, by coarse-grained clastic rocks in the Middle Devonian [*Kos'ko et al.,* 1990]. No unconformities have been reported for Devonian sections of Chukotka [*Rogozov and Vasilyeva,* 1968; *Drabkin,* 1970a; *Markov et al.,* 1980; *Nedomolkin,* 1977]. All of this may be interpreted as evidence that the effect of the Ellesmerian orogeny in the Chukotkan part of the Bennett-Barrovia block diminished away from the zone of Ellesmerian collision.

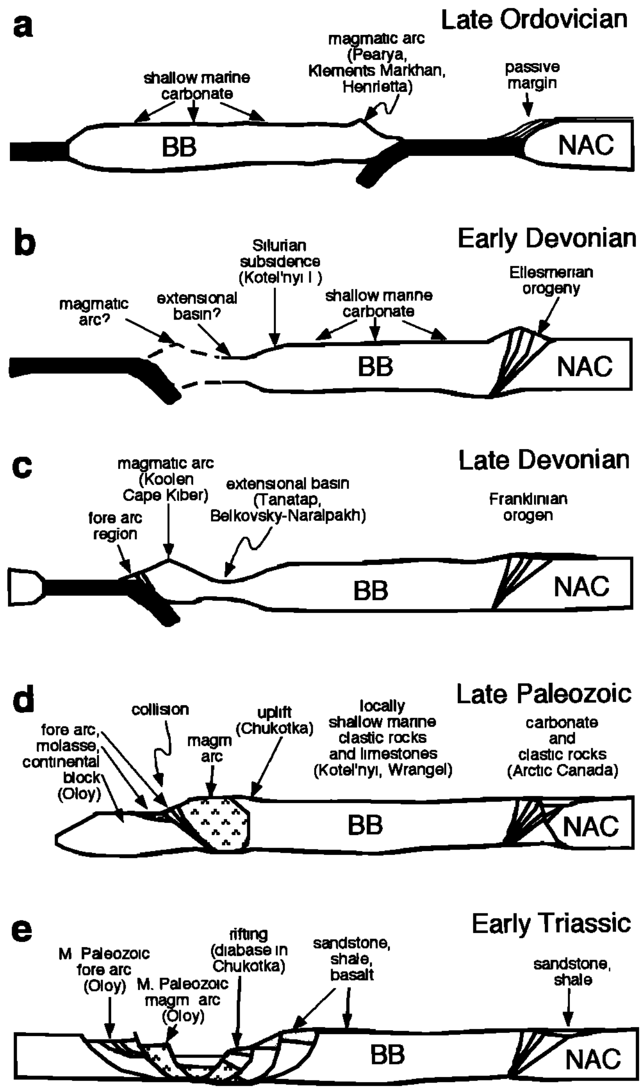


Figure 11. Tectonic evolution of Chukotkan sector of the Bennett-Barrovia block: (a) The Bennett-Barrovia block is separated by an ocean from North America. The early Paleozoic subduction beneath the Bennett-Barrovia block created magmatic arcs (Canadian Arctic Islands, Henrietta belt, northern Alaska). (b) The collision of the Bennett-Barrovia block and North America led to the Elesmerian orogeny in Alaska and the Canadian Arctic Islands. The arc-trench system originated along the southern (present-day coordinates) margin of the Bennett-Barrovia block. (c) The Devonian to Early Carboniferous evolution of the arc-trench system. (d) The collision of an uknown continental object and the Bennett-Barrovia block. (e) The Early Triassic rifting and the origination of the South-Anyui ocean. Slivers of the middle Paleozoic arc-trench system and the continental object were rifted away. See text for discussion. BB, Bennett-Barrovia; NAC, North American craton.

After collision of the Bennett-Barrovia block with North America, the middle Paleozoic arc-trench system and the exten-

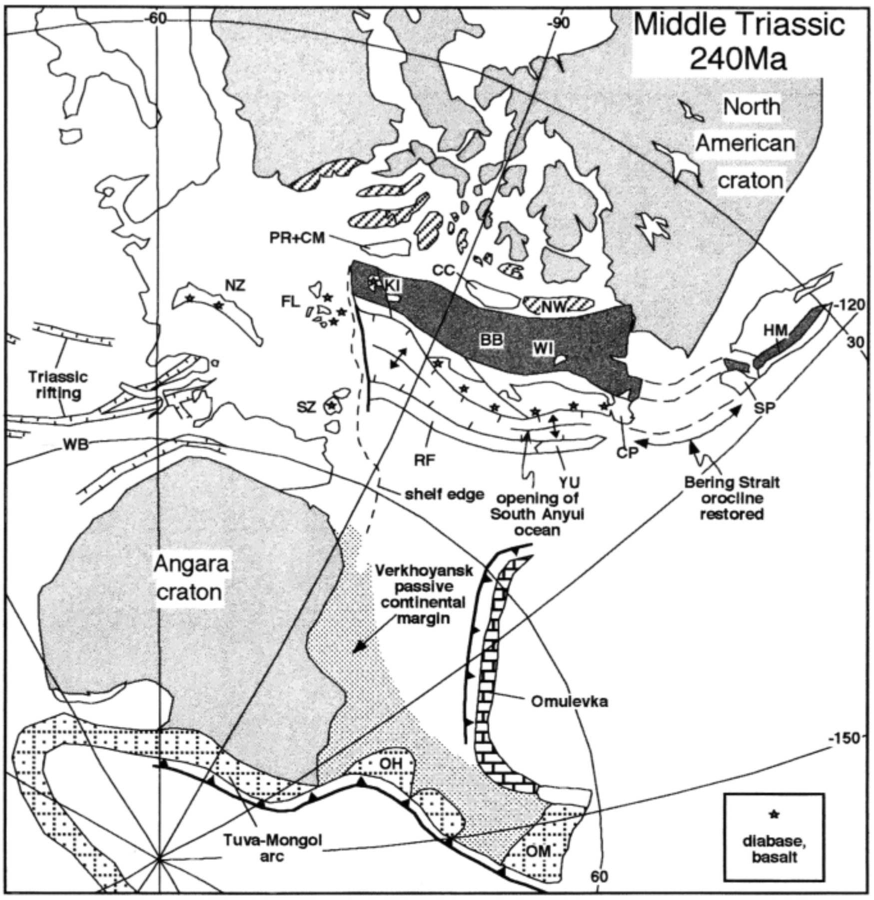


Figure 12. Early Triassic paleotectonic reconstruction of the Bennett-Barrovia block. The positions of major continents after *Lawver et al.* [1990]. The reconstruction of the Tuva-Mongol arc, Okhotsk, Omolon, and Omulevka terrane is after *Şengör and Natal'in* [1996]. Triassic rift zones in the Western Siberian basin (WB) are after *Zonenshain et al.* [1990]. HM, Hammond and Coldfoot subterranes; KI, Kotel'nyi Island; RF, rifted fragments of the fore-arc region of the middle Paleozoic arc-trench system of the Bennett-Barrovia block and unknown continental block collided with it; SP, Seward Peninsula. See Figures 9 and 10 for other abbreviations.

sional basin were established along the opposite side the Bennett-Barrovia block (Figure 11c). The overlap of ages of the magmatic arc and the extensional basin allow the inference that the extensional basin formed as a back arc basin.

In Alaska, arc magmatism started in the Early Devonian. In Chukotka, dated granitic plutons are Late Devonian and Early Carboniferous, but the extensional (back arc) basin is Eifelian (Middle Devonian) or older. In the Kuyul Uplift the stratigraphic succession of the extensional basin includes the Lower Devonian clastic rocks. The Belkovskyi-Nerpalakh Trough (Figure 11c) formed in the early Late Devonian (Frasnian). Visean andesites near the contact of the Chukotka fold belt and South Anyui suture (TP in Figure 7) and Lower Carboniferous clastic rocks and turbidites in the Belkovskyi-Nerpalakh Trough and Tanatap basin suggest that the arc-trench system was still active during the Early Carboniferous.

In Arctic Alaska, Devonian magmatism and extensional basin formation ended with the establishment of a passive margin which lasted from the Late Devonian to the Early Cretaceous. In turn, this passive margin sedimentation ended with the closure of the Angayucham ocean and the onset of the Brookian orogeny. However, the sudden appearance of the enigmatic Nuka Land [*Moore et al.*, 1994] during the Early/Middle Carboniferous in the very southern part of the margin does not fit a model of the stable development of the passive margin facing the Angayucham ocean. In contrast, in the Chukotka segment of the southern margin of the Bennett-Barrovia block, an unknown continental object collided with the magmatic arc in the Middle to Late Carboniferous (Figure 11d).

The following lines of evidence can be used to show that the evolution of the active continental margin at the southern boundary of the Bennett-Barrovia block in Chukotka ended in the Middle to Late Carboniferous time: (1) There are no Middle Carboniferous to Permian rocks in the Chukotka fold belt except presumably Permian shale, coaly shale, and sandstone [*Drabkin*, 1970a] which indicate the existence there of an uplifted area for ~70 Ma. (2) There is an unconformity at the base of the Middle Carboniferous clastic rocks, including conglomerate and limestone breccia and sparse felsic lavas, on Kotel'nyi Island [*Vinogradov et al.*, 1974; *Kos'ko et al.*, 1990]. (3) There is an unconformity at the base of the 200 m thick Permian marine shale predominant section on Kotel'nyi Island and ~150 km to the

south on the Bolshoy Lyakhovsky Island (Figure 7); Permian rocks are 1200 m thick and represented by sandstones with coal seams and phyllite [*Kos'ko et al.*, 1990; *Fujita and Cook*, 1990]. Thus the late Paleozoic uplift and formation of continental basins followed the middle Paleozoic active margin development along the southern edge of the Bennett-Barrovia block. The process that was responsible for these events is not well understood, but the collision of a continental mass is a viable hypothesis.

The object which deformed the Devonian arc is inferred to have been removed, together with slivers of the forearc region, during Early-Middle Triassic rifting (Figures 11e and 12). This rifting could have transferred both the continental mass in question and the forearc region of the Devonian active continental margin to the Asian side of the South Anyui suture. Immediately to the south of the suture within the Yarakvaam Uplift (YU, Figure 7), Devonian and Lower Carboniferous andesites and rhyolites are intruded by granite and diorite and unconformably overlain by Upper Carboniferous shallow marine and terrestrial tuffaceous sandstone and conglomerate [*Markov et al.*, 1980; *Natal'in*, 1984]. The first unit may be considered as a rifted fragment of the middle Paleozoic active margin of the Bennett-Barrovia. We interpret the late Paleozoic granites and molasse deposits of the second unit as evidence for the collision. Farther to the south, there are fragments of Paleozoic oceanic rocks, island arc volcanic rocks, and ophiolites which may belong to the aforementioned continental mass and its margin.

Triassic rifting led to the formation of the South Anyui ocean and the Triassic to Early Jurassic passive continental margin of the Bennett-Barrovia block (Figure 12). Note that this zone of rifting lies on the continuation of rifts in the basement of the Western Siberia Basin [e.g., *Zonenshain et al.*, 1990]. Triassic diabase and gabbro in Severnaya Zemlya, Franz Josef Land, and Novaya Zemlya show a link between these two regions. During the Late Jurassic, fragments rifted from the margin of the Bennett-Barrovia block (RF in Figure 12) collided with the Omulevka terrane, leading to the oroclinal bending of the Omulevka terrane [*Şengör and Natal'in*, 1996].

7. Conclusions

The Paleozoic Chegitun and Tanatap units from the study area formed in different tectonic settings. Both units were strongly deformed in the Mesozoic, and their relations with the larger tectonic units and history were reconstructed on the basis of sedimentological and stratigraphic data and regional correlation. The Ordovician to Lower Devonian shallow marine carbonates of the Chegitun unit belong to the Novosibirsk carbonate platform that covers the Precambrian basement of the Bennett-Barrovia block [*Şengör and Natal'in*, 1996]. This unit underlies the Chukchi shelf and the East Siberian Sea and continues into northern Alaska as the Hammond subterrane. The Devonian to Lower Carboniferous deep-water sedimentary rocks of the Tanatap unit formed in an extensional basin most likely behind a Devonian magmatic arc. After being separated from Siberia in the Vendian or in the early Paleozoic, the Bennett-Barrovia block collided with North America during Late Silurian to Early Devonian time and caused the Ellesmerian orogeny. Devonian granites in northeastern Brooks Range and near the Barrow Arch may be related to this collision. In the late Paleozoic an unknown continental object collided with the southern side of the Chukotkan Bennett-Barrovia block. Triassic rifting truncated the southern portion of the Bennett-Barrovia block. In the Mesozoic this block evolved as a part of the Chukotka-Arctic Alaska microplate.

Similarity of Paleozoic stratigraphy and timing of events in the vast area between the Novosibirsk Islands and the Hammond subterrane in Alaska defines the unity of this tectonic province and imposes constraints on the geometry and shape of the Chukotka-Arctic Alaska block. Several models for the opening of the Canada Basin have been proposed [see *Lawver and Scotese*, 1990]. *Fujita and Newberry* [1982] were the first to notice that the Chukotka-Arctic Alaska block is too long to fit against the margin of the Canadian Arctic Islands as is assumed in the rotational model. To solve this space problem, they diminished the size of the Chukotkan sector of the block, placing the western boundary of the Chukotka-Arctic Alaska block across the Chukotka fold belt. The same solution of the problem is typical for all rotational models of the Chukotka-Arctic Alaska block [*Tailleur and Brosge*, 1970; *Newman et al.*, 1977; *Rowley and Lottes*, 1988; *Grantz et al.*, 1990]. The basis of such a solution lies either in the lack of adequate knowledge of the geology of northeastern Russia or in the inference that the South Anyui suture abruptly changes in strike to N-S beyond its last exposure in western Chukotka [e.g., *Rowley and Lottes*, 1988]. Magnetic anomalies which mark the suture and the continuation of the Jurassic to Early Cretaceous magmatic arc which is paired with the suture and stretches to the Svaytoy Nos Cape area (SN in Figure 1), do not allow this last solution [*Natal'in*, 1981, 1984; *Parfenov and Natal'in*, 1985; *Zonenshain et al.*, 1990]. Our correlation of the Paleozoic structures corroborates the real dimensions of the Chukotka-Arctic Alaska block and shows that the rotational model still has a significant space problem.

Acknowledgments. The work was funded by the Continental Dynamics Division of the National Science Foundation, International Division of the National Science Foundation, as part of award EAR-93170087-005 to E. Miller and S. Klemperer, and EAR-9316573 to J. E. Wright, as well as TÜBİTAK-İTÜ joint research unit GloTec. Amato acknowledges the support of the Albert and Alice Weeks Foundation at the U. of Wisconsin and C. Johnson for the use of his laboratory. We are grateful to E. Miller, S. Akinin, A. Calvert, L. Gahagan, K. Fujita, M. Gelman, A. Grantz, A. Kaplan, L. Lane, L. Lawver, and L. Popeko for discussions of different aspects of the geology of Alaska and Chukotka. E. Miller and C. Şengör read the first version of the paper and their constructive remarks improved the final version. The paper was considerably improved owing to comments and suggestions of A. B. Till, T. E. Moore, and W. K. Wallace. We are also grateful to many people from the towns of Lavrentiya and Provideniya who helped us during the fieldwork.

References

Akinin, V. V., Metaultramafites of the crystalline basement of the Chukchi Peninsula, in *1994 Proceedings: International Conference on Arctic Margins*, edited by K.V. Simakov and D. K. Thurston, pp. 214-219, N. East. Inst. of Sci. Res., Magadan, 1995.

Amato, J. M., and J. E. Wright, Geochronologic investigations of magmatism and metamorphism within the Kigluaik Mountains gneiss dome, Seward Peninsula, Alaska, in *Short Notes on Alaskan Geology 1997*, edited by J. G. Clough and F. Larson, Alaska Div. Geol. Geophys. Surv., Prof. Rep. *118*, 1-21, 1998.

Amato, J. M., J. E. Wright, P. B. Gans, and E. L. Miller, Magmatically induced metamorphism and deformation in the Kigluaik gneiss dome, Seward Peninsula, Alaska, *Tectonics*, *13*, 515-527, 1994.

Anderson, A. V., W. K. Wallace, and C. G Mull, Depositional record of a major tectonic transition in northern Alaska: Middle Devonian to Mississippian

rift-basin margin deposits, upper Kongakut River region, eastern Brooks Range, Alaska, in *International Conference on Arctic Margins Proccedings*, edited by D. K. Thurston, and K. Fujita, pp. 71-76, Miner. Manag. Serv., Anchorage, Alaska, 1994.

Anders, E., and M. Ebihara, Solar-system abundances of the elements, *Geochim. et Cosmochim. Acta, 46*, 2363-2380, 1982.

Barron, E. J., Ancient climates: investigation with climate models, *Rep. Prog. Phys., 47*, 1563-1599, 1984.

Belyi, V. F., K voprosy o zhestkoy strukture Vostochnoy Chukotki i Alyaski (On a problem of the rigid structure in eastern Chukotka and Alaska), in *Materialy po Geologii i Poleznym Iskopaemym Severo-Vostoka SSSR, 17*, pp. 40-48, Magadan, 1964.

Bering Strait Geological Field Party (BSGFP), Koolen metamorphic complex, NE Russia: Implications for the tectonic evolution of the Bering Strait region, *Tectonics, 16*, 713-729, 1997.

Bjørnerud, M. G., and D. C. Bradley, Silurian foredeep and accretionary prism in Northern Ellesmere Island: Implication for the nature of the Ellesmerian orogeny, in *International Conference on Arctic Margins Proccedings*, edited by D. K. Thurston, and K. Fujita, pp. 129-134, Miner. Manag. Serv., Anchorage, Alaska, 1994.

Bunker, C. M., C. E. Hedge, and C. L. Sainsbury, Radioelement concentrations and preliminary radiometric ages of rocks of the Kigluaik Mountains, Seward Peninsula, Alaska, *U.S. Geol. Surv. Prof. Pap., 1129-C*, 11 pp., 1979.

Calvert, A. T., and P. B. Gans, Jurassic(?) kyanite-grade metamorphism and earliest Cretaceous exhumation of the Senyavin complex, Chukchi Peninsula, NE Russia, *EoS Trans. AGU, 77*, (46), Fall Meet. Suppl., F767, 1996.

Cecile, M. P., Y. M. Buchkov, O. N. Vinogradova, M. E. Gorodinsky, M. K. Kos'ko, and L. S. Lane, Rezultaty polevykh rabot Sovetsko-Kanadskoy gruppy na Severo-Vostoke SSSR letom 1989 goda (Results of field works of the Soviet-Canadian group in northeastern USSR in summer 1989), in *Geologiya Skladchatogo Obramleniya Ameraziyskogo Subbasseyna*, pp. 15-21, NPO Sevmorgeologiya, VNIIOkeangeologiya, St. Petersburg, 1991a.

Cecile, M. P., J. C. Harrison, M. K. Kos'ko, and R. Parrish, Precambrian U-Pb ages of igneous rocks, Wrangel Island Complex, Wrangel Island, U.S.S.R., *Can. J. Earth Sci., 28*, 1340-1348, 1991b.

Cumming, G. L., and J. R. Richards, Ore lead isotope ratios in a continuously changing Earth, *Earth Planet.Sci. Lett., 28*, 155-171, 1975.

Dilles, J. H., and J. E. Wright, The chronology of early Mesozoic arc magmatism in the Yerington District of western Nevada and its regional implications, *Geol. Soc. Am. Bull., 100*, 644-652, 1988.

Dillon, J. T., G. R. Tilton, J., Decker, and M. J. Kelly, Resource implications of magmatic and metamorphic ages for Devonian igneous rocks in the Brooks Range: in *Alaskan North Slope Geology, Field Trip Guideb.* vol. 50, edited by I. L. Tailleur, and P. Weimer, pp. 713-723, Pac. Sec., Soc. of Econ. Paleontol. and Mineral., Bakersfield, Calif., 1987.

Drabkin, I. E. (Ed), Geologiya SSSR (Geology of the USSR. Vol. XXX) Severovostok SSSR: Geologicheskoe opisanie (Northeastern USSR: Geological Description.), book 1, 548 pp., Nedra, Moscow, 1970a.

Drabkin, I. E. (Ed), Geologiya SSSR (Geology of the USSR. Vol. XXX) Severovostok SSSR: Geologicheskoe opisanie (Northeastern USSR: Geological Description.), book 2, 548 pp., Nedra, Moscow, 1970b.

Dumoulin, J. S., and A. G. Harris, Depositional framework and regional correlation of Pre-Carboniferous metacarbonate rocks of the Snowden Mountain area, central Brooks Range, northern Alaska, *U.S. Geol. Surv. Prof. Pap., 1545*, 73 pp., 1994.

Dumoulin, J. S., D. C. Bradley, A. G. Harris, and J. E.Repetski, Sedimentology, conodont biostratigraphy, and subsidence history of the Nixon Fork terrane, Medfra quadrangle, Alaska, paper presented at III International Conference on Arctic Margins, Deutsche Forschungsgemeinschaft (DFG), Celle, Germany, 12-16, Oct. 1998.

Dusel-Bacon, C., and J. N. Aleinikoff, Petrology and tectonic significance of augen gneiss from a belt of Mississippian granitoids in the Yukon-Tanana terrane, east-central Alaska, *Geol. Soc. Am. Bull., 96*, 411-425, 1985.

Dutro, J. T., Jr., A. R. Palmer, J. E. Repetski, and W. P. Brosgé, Middle Cambrian fossils from the Doonerak anticlinorium. central Brooks Range, Alaska, *J. Paleontol., 58*, 1364-1371, 1984.

Eardley, A. J., Ancient Arctica, *J. Geol., 56*, 409-436, 1948.

Egiazarov, B. K., and O. P. Dundo, (Eds.), *Geologıya Beringova Morya i Prilegayuschikh Kontinentalnykh Okrain (Geology of the Bering Sea and Adjacent Continent Margins)*, 127 pp., Nedra, Leningrad, 1985.

Ewart, A., The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: With special reference to the andesitic-basaltic compositional range, in *Andesites: Orogenic Andesites and Related Rocks*, edited by R. S. Thorpe, pp. 26-87, John Wiley, New York, 1982.

Fujita, K., and D.B. Cook, The Arctic continental margin of eastern Siberia, in *Geology of North America*, v. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 289-304, Geol. Soc. of Am., Boulder, Colo., 1990.

Fujita, K., and J.T. Newberry, Tectonic evolution of northeastern Siberia and adjacent regions, *Tectonophysics, 89*, 337-357, 1982.

Gelman, M. L., Osnovnye osobennosti posleproterozoyskogo metamorphizma na severo-vostoke SSSR (Main feature of the post-Proterozoic metamorphism in northeastern USSR), in *Metamorficheskie Kompleksy Vostoka SSSR*, pp. 161-180, DVNT, Vladivostok, 1973.

Gill, J. B., *Orogenic Andesites and Plate Tectonics*, Springer-Verlag, New York, 1981.

Gnibidenko, G. S., *Metamorphicheskie Kompleksy v Structurakh Severo-Zapadnogo Sektora Tikhookeanskogo Poyasa (Metamorphic Complexes in Structures of the Northwestern Sector of the Circum-Pacific Belt)*, 135 pp., Nauka, Moscow, 1969.

Gorodinsky, M. E. (Ed.), Geologicheskaya karta severovostoka SSSR (Geological map of northeastern USSR), scale 1:1,500,000, 9 Sheets, Minist. Geol. SSSR, Leningrad, Russia, 1980.

Gramberg, I. S., and Y. E. Pogrebitzkiy, (Eds), *Morya sovetskoy Arktiki (Seas of the Soviet Arctic)*, v. 9, 280 pp., Nedra, Leningrad, Russia, 1984.

Grantz, A., S. D. May, and P. E. Hart , Geology of Arctic continental margin of Alaska, in *Geology of North America*, v. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 257-288, Geol. Soc. of Am., Boulder, Colo., 1990.

Grantz, A., T. E. Moore, and S. M. Roeske, Continent-ocean transect A-3: Gulf of Alaska to Arctic Ocean, *Geol. Soc. Am. Centen Continent/Ocean Transect, 15*, 72 pp., 1991.

Grantz, A., D. L. Clark, R. L. Phillips, and S. P. Srivastava, Phanerozoic stratigraphy of Northwind Ridge, magnetic anomalies in the Canada basin, and geometry and timing of rifting in the Amerasia basin, Arctic Ocean, *Geol. Soc. Am. Bull., 100*, 801-820, 1998.

Ivanov, O. N., and Y. V. Kryukov, Dokembriy vostochnogo sektora Sovietskoy Arktiki, *Geol. Geofiz. 9*, 50-59, 1973.

Klaper, E. M., The Paleozoic tectonic evolution of the northern edge of North America: A structural study of northern Ellesmere Island, Canadian Arctic Archipelago, *Tectonics, 11*, 854-870, 1992.

Kos'ko, M. K., Struktumo-formatsionnaya zonalnost ordovik-srednedevonskogo karbonatnogo kompleksa ovov Anzhu (Structural and formation zonation of the Ordovician to Middle Devonian carbonate complex of the Anzhu islands), in *Tektonika Arktiki: Skladchatyy Fundament Shelfovykh Sedimentatsionnykh Basseynov*, edited by Y. E. Pogrebitskiy and M. K. Kos'ko, pp. 55-85, Nauchno-Issled. Inst. Geol. Arktiki, Leningrad, Russia, 1977.

Kos'ko, M. L., Major tectonic interpretation and constraints for the East Siberian Seas, Northeastern Russia, in *International Conference on Arctic Margins Proccedings*, edited by D. K. Thurston, and K. Fujita, pp. 195-200, Miner. Manag. Serv., Anchorage, Alaska, 1994.

Kos'ko, M. K., B. G. Lopatin, and V. G. Ganelin, Major geological features of the islands of the East Siberian and Chukchi seas and northern cost of Chukotka, *Mari. Geol., 93*, 349-367, 1990.

Kos'ko, M. K., M. P. Cecile, J. C. Harrison, V. G. Ganelin, N. V. Khandoshko, and B. G. Lopatin, Geology of Wrangel Island, between Chukchi and East Siberian seas, northeastern Russia, *Bull. Geol. Surv. Can., 461*, 101 pp., 1993.

Krasny, L. I., and V. K. Putintsev (Eds.), *Vostok SSSR. Tom 8 (Eastern part of the USSR, vol.8)*, 560 pp., Nedra, Leningrad, Russia, 1984.

Krough, T. E., A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations, *Geochim. Cosmochim. Acta, 37*, 485-494, 1973.

Lawver, L. A., C. R. Scotese, A review of tectonic models for the evolution of the Canada Basin, in *Geology of North America*, v. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 593-618, Geol. Soc. of Am., Boulder, Colo., 1990.

Lawver, L. A., R. D. Müller, S. P. Srivastava, and W. Roest, The opening of the Arctic Ocean, in *Geologic History of the Polar Oceans: Arctic Versus Antarctic*, edited by U. Bleil and J. Thiede, pp. 29-62, Kluwer Academic Publishers, Netherlands., 1990.

Litinsky, V. A., and S. S. Raevsky, Struktura fundamenta Primorskoy nizmennosti i prilegayuschey territorii i akvatorii po geofizicheskim dannym (Geophysical data on structure of the basement of the Primrosk lowland id neighboring areas), in *Tektonika Arktiki: Skladchatyi Fundament Sedimentatzionnykh Bassejnov*, edited by Y. E. Pogrebitzkiy and M. K. Kos'ko, pp. 98-121, Nauchno-Issled. Inst. Geol. Arktiki, Leningrad, Russia, 1977.

Markov, M. S., Y. M. Pushcharovsky, S. M. Tilman, V. S. Fedorovsky, and N. A. Shilo, *Tektonika Kontinentalnykh Okrain Severo-Zapada Tikhogo Okeana (Tectonics of the Continental Margins of the North-West Pacific)*, 285 pp., Nauka, Moscow, 1980.

Mattinson, J. M., U-Pb ages of zircon: A basic examination of error propagation, *Chem. Geol., 66*, 151-162, 1987.

Milanovsky, E. E., *Geologiya SSSR, chast 1, Vvedenie: Drevnie Platformy i Meetaplatformennye Oblasti (Geology of the USSR, Part 1, Introduction: Ancient Platforms and Metaplatform Regions)*, 415 pp, Izdatelstvo Moskovskogo Univ., Moscow, 1987.

Miller, T. P., Pre-Cenozoic plutonic rocks in mainland Alaska, in *The Geology of North America*, vol. G1, *The Geology of Alaska*, edited by G. Plafker and H. C. Berg, pp. 535-554, Geol. Soc. of Am., Boulder, Colo., 1994.

Moore, T. E., W. K. Wallace, K. J. Bird, S. M. Karl, C. G. Mull, and J. T. Dillon, Geology of northern Alaska, in *The Geology of North America*, vol. G1, *The Geology of Alaska*, edited by G. Plafker and H. C. Berg, pp. 535-554, Geol. Soc. of Am., Boulder, Colo., 1994.

Moore, T. E., J. N. Aleinikoff, and A. G. Harris, Stratigraphic and structural implications of conodont and detrital zircon U-Pb ages from the metamorphic rocks of the Coldfoot terrane, Brooks Range, Alaska, *J. Geophys. Res., 102*, 20,797-20,820, 1997a.

Moore, T. E., W. K. Wallace, C. G. Mull, K. E. Adams, G. Plafker, and W. J. Nokleberg, Crustal implications of bedrock geology along the Trans-Alaska Crustal Transect in the Brooks Range, northern Alaska, *J. Geophys. Res., 102*, 20,645-20,684, 1997b.

Muir, R. J., T.R. Ireland, S. D. Weaver, and J. D. Bradshaw, Ion microprobe dating of Paleozoic granitoids: Devonian magmatism in New Zealand and correlations with Australia and Antarctica, *Chem. Geol., 127*, 191-210, 1996.

Natal'in, B. A., Tektonicheskaya priroda metamorphicheskogo kompleksa Chukotskogo poluostrova (Tectonic nature of the metamorphic complex in Chukotka Peninsula). *Geol. Geof., 6*, 31-38, 1979.

Natal'in, B. A., Mezozoyskie aktivnye kontinentalnye

okrainy v Yuzhno-Anyuiskoy skladchatoy sisteme (Mesozoic active continental margins in the South Anyui fold belt), in *Drevnie zony Benioffa*, edited by G. M. Vlasov, pp. 78-109, Dalnevostochnyi Nauchnyi Tsentr Akademii Nauk SSSR, Vladivostok, Russia, 1981.

Natal'in, B. A., *Rannemezozoiskie Skladchatye Sistemy Severnoy Chasti Tikhookeanskogo Obramleniya (Early Mesozoic Folded Belts in the North Part of the Pacific Rim)*, Nauka, Moscow, 135 pp., 1984.

Natal'in, B. A., J. Toro, and J. Amato, Paleozoic rocks of northern Chukotka Peninsula, their structural history and relevance to the Mesozoic tectonic evolution of the Arctic, *EoS Trans. AGU, 78(46)*, Fall Meet. Suppl., F665, 1997.

Nedomolkin, V. F., Chegitun, in Gosudarstvennaya Geologicheskaya Karta SSSR (The state geological map of the USSR), scale 1:200,000, sheet Q-2-VII,VII,IX), Minist. Geol., Leningrad, Russia, 1969.

Nedomolkin, V. F., Geologiya Eskimosskogo sredinnogo massiva (Geology of the Eskimos median massif). avtorferat kandidatskoy dissertatsii, 16 pp., Far East Sci. Center Acad. Sci. USSR, Vladivostok, 1977.

Nelson, B. K., S. W. Nelson, and A. B. Till, Nd- and Sr-isotope evidence for Proterozoic and Paleozoic crustal evolution in the Brooks Range, northern Alaska, *J. Geol., 101*, 435-450, 1993.

Newman, G. W., C. G. Mull, and N. D. Watkins, Northern Alaska paleomagnetism, plate rotation, and tectonics, in *The Relationship of Plate Tectonics to Alaskan Geology and Resources: Proceedings of the Sixth Alaska Geological Society Symposium*, edited by A. Sisson, pp. C1-C7, Alaska Geol. Soc., Anchorage, 1977.

Oradovskaya, M. M., and A. M. Obut, Stratigrafiya, korrelyatsiya i paleogeografiya ordovikskikh i siluriyskikh otlozheniy na Chukotskom poluostrove (Stratigraphy, correlation, and paleogeography of the Ordovician and Silurian strata in Chukotka Peninsula), in *Stratigrafiya i Fauna Ordovika i Silura Chukotskogo Poluostrova*, edited by A. M. Obut, pp. 4-42, Nauka, Novosibirsk, Russia, 1977.

Parfenov, L.M., and B.A. Natal'in, Tektonicheskaya evolyutsiya Dalnego Vostoka v mezozoe i kainozoe (Tectonic evolution of north-eastern Asia in the Mesozoic and Cenozoic). *Dok. Acad. Nauk SSSR, 235*, (5), 1132-1135, 1977.

Parfenov, L. M., and B. A. Natal'in, Mesozoic accretion and collision tectonics of northeastern Asia, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, vol. 1, edited by D. G. Howell, pp. 363-373, Circum-Pac. Counc. for Energy and Miner. Resour., Houston, Tex., 1985.

Patton, W. W., Jr., and I. L. Tailleur, Evidence in the Bering Strait region for differential movement between North America and Eurasia, *Geol. Soc. Am. Bull ., 88*, 1298-1304, 1977.

Patton, W. W., Jr., S. E. Box, E. J. Moll-Stalcup, and Miller, T. P., Geology of west-central Alaska, in *The Geology of North America*, vol. G1, *The Geology of Alaska*, edited by G. Plafker and H. C. Berg, pp. 153-204, Geol. Soc. of Am., Boulder, Colo., 1994.

Plafker, G., and H. C. Berg, Overview of the geology and tectonic evolution of Alaska, in *The Geology of North America*, vol. G1, *The Geology of Alaska*, edited by G. Plafker and H. C. Berg, pp. 989-1022, Geol. Soc. of Am., Boulder, Colo., 1994.

Rejebian, V. A., A. G. Harris, and J. S. Huebner, Conodont color and textural alteration: An index to regional metamorphism, contact metamorphism, and hydrothermal alteration, *Geol. Soc. Am. Bull., 99* 471-479, 1987.

Rogozov, U. G., and N. M. Vasilyeva, Devonskie otlozheniya poberezhya proliva Longa (Devonian rocks of the De Long Strait coast), *Uch. Zap. Naucho-Issled. Inst. Geol. Arktiki, Leningrad, 13*, 51-157, 1968.

Rowley, D. B., and A. L. Lottes, Plate-kinematic reconstructions of the North Atlantic and Arctic: Late Cretaceous to present, *Tectonophysics, 155*, 73-120, 1988.

Rozman, K. S., *Biostratigrafiya i Zoogeografiya Verkhnego Ordovika Severnoy Azii i Severnoy Ameriki (po brakhiopodam) (Stratigraphy and biogeography of the Upper Ordovician of northern Asia and North America (brachiopods))*, 169 pp., Nauka, Moscow, 1977.

Rubin, C. M., M. M. Miller, and G. M. Smith, Tectonic development of Cordilleran mid-Paleozoic volcano-plutonic complexes: Evidence for convergent margin tectonism, *Spec. Pap.Geol. Soc. Am.*, 255, 1-16, 1990.

Sadovsky, A. I., Istoriya geologicheskogo razvitiya i tektonicheskoe stroenie Anyuyskogo megasinkliniriya (Geological history and tectonic structure of the Anyui anticlinorium). *Sov. Geol., 3* , 59-73, 1965.

Şengör, A. M. C., and B. A. Natal'in, Palaeotectonics of Asia: fragments of a synthesis, in *The Tectonic Evolution of Asia*, edited by A. Yin and M. Harrison, pp. 486-640, Cambridge Univ. Press, New York, 1996.

Seslavinsky, K. B., Yuzhno-Anyuyskaya sutura (South-Anyui suture), *Dokl. Akad. Nauk SSSR, 249* (5), 1181-1185, 1980.

Shatsky, N. S., O tektonike Arktiki (On tectonics of Arctic), in *Geologiya i Poleznye Iskopaemye Severa SSSR*, Trudy pervoy geologo-razvedochnoy konferentsii Glavsevmorputi, vol. 1, pp. 3-28, Geologiya, Leningrad, Russia, 1935.

Sherwood, K. W., Stratigraphy, structure, and origin of the Franklinian, Northeast Chukchi Basin, Arctic Alaska plate, in *International Conference on Arctic Margins Proccedings*, edited by D. K. Thurston, and K. Fujita, pp. 245-250, Miner. Manag. Serv., Anchorage, Alaska, 1994.

Shuldiner, V. I., and V. F. Nedomolkin, Kristallicheskiy fundament Eskimosskogo massiva (Crystalline basement of the Eskimos massif), *Sov. Geol., 10*, 38-47, 1976.

Spector, V. B., A. M. Andrusenko, E. A. Dudko, and N. F. Kareva, Prodolzhenie Yuzhno-Anyuiskoy sutury v Primorskoy nizmennosti (Continuation of the South Anyui suture in the Primorsk lowland), *Dokl. Akad. Nauk SSSR, 260* (6), 1447-1450, 1981.

Sutygin, G. N., and I. V. Tibilov, Glubinnye sdvigi Tzentralnoy Chukotki i nekotorye voprosy metallogenii (Deep-seated strike-slip faults in central Chukotka and problems of metallogeny), in *Mezozoyskiy Tektogenez*, pp. 100-101, Sov. Tek. Sibiri i Dal. Vostoka, Magadan, Russia, 1969.

Tailleur, I. L., Probable rift origin of Canada Basin, Arctic Ocean, in *Arctic Geology*, edited by M. G. Pitcher, *AAPG Mem., 19*, 252-258, 1973.

Tailleur I. L., and W. P. Brosge, Tectonic history of Alaska, in *Proceedings of the Geological Seminar on the North Slope of Alaska*, edited by W. L. Adkison and W. P. Brosge, E1-E19, AAPG, Los Angeles, 1970.

Tibilov, I. B., A. P. Milov, and I. A. Davydov, O proyavlenii domezozoyskogo granitoidnogo magmatizma na Chukotke (On the appearance of the pre-Mesozoic granitoid magmatism in Chukotka), *Tikhookean. Geol., 4*, 95-98, 1986.

Till, A. B., and J. A. Dumoulin, Geology of Seward Peninsula and Saint Lawrence Island, in *The Geology of North America*, vol. G1, *The Geology of Alaska*, edited by G. Plafker and H. C. Berg, pp. 141-152, Geol. Soc. of Am., Boulder, Colo., 1994.

Tilman, S. M., *Sravnitelnaya Tektonika Mesozoid Severa Tikhookeanskogo Koltsa (Comparative tectonics of the Mesozoides of the Northern Part of the Pacific Rim)*, 326 pp., Nauka, Novosibirsk, Russia, 1973.

Tkachenko, B. V., and Egiazarov, B. X. (Eds), *Geologiya SSSR Ostrova Sovetskoy Arktiki: Geologicheskoe opisanie (Geology of the USSR)*, vol. XXVI, *(Islands of the Soviet Arctic: Geological descriptions)*, 547 pp., Nedra, Moscow, 1970.

Toro, J., Structure and thermochronology of the metamorphic core of the central Brooks Range, Alaska, Ph.D. thesis, 200 pp., Stanford Univ., Stanford, Calif., 1998.

Trettin, H. P., The Proterozoic to Late Silurian record of Pearya, in *The Geology of North America*, vol. E,*Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland*, edited by H. P. Trettin, pp. 241-259, Geol. Soc. of Am., Boulder, Colo., 1991.

Vinogradov, V. A., G. I. Gaponenko, I. M. Rusakov, and V. N. Shimarayev, *Tektonika Vostochno-Arkticheskogo Shelfa SSSR (Tectonics of the eastern part of the Arctic shelf of the USSR)*, 144 pp., Nedra, Leningrad, Russia, 1974.

Vinogradov, V. A., G. I. Kameneva, and G. P. Yavshits, O Giperboreyskoy platforme v svete novyh dannyh o geologicheskom stroenii o-va Genrietty (On the Hyperborean Platform in light of new data on the geologic structure of Henrietta Island), *Tektoni. Arktiki, 1*, 21-25, 1975.

Volnov, D. A., Istoriya geologicheskogo razvitiya Novosibirskikh ostrovov (History of the geological evolution of the Novosibirsk Islands), in Geologia i Poleznye Iskopaemye Novosibirskikh Ostrovov i Ostrova Vrangeya, edited by D. A.. Volnov and V. L. Ivanov, pp. 61-71, Nauchno-Issled. Inst. Geol. Arktiki, Leningrad, Russia, 1975.

Wright, J. E., and M. R. Fahan, An expanded view of Jurassic orogenesis in the western United States Cordillera: Middle Jurassic (pre-Nevadan) regional metamorphism and thrust faulting within an active arc environment, Klamath Mountains, California, *Geol. Soc. Am. Bull., 100*, 859-876, 1988.

Zonenshain, L. P., M. I. Kuzmin, and L. M. Natapov, *Geology of the USSR: A plate tectonic synthesis*, 242 pp., *AGU Geodynamic Series, 21*, 1990.

J. M. Amato, Department of Geological Sciences/3AB, New Mexico State University, P.O. Box 30001, Las Cruces, NM 88003. (amato@nmsu.edu)

B. A. Natal'in, Istanbul Technical University, İ.T.Ü. Maden Fakültesi, Genel Jeoloji ABD, Ayazaga 80626, Istanbul, Turkey. (natalin@itu.edu.tr)

J. Toro, Department of Geology and Geography, West Virginia University, Morgantown, WV 26506-6300. (toro@geo.wvu.edu)

J. E. Wright, Department of Geology and Geophysics, Rice University, MS-126, Houston, TX 77005. (jwright@owlnet.rice.edu)

(Received March 18, 1999;
revised June 28, 1999;
accepted July 21, 1999)