New ties between the Alexander terrane and Wrangellia and implications for North America Cordilleran evolution

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ABSTRACT

Two large tectonic terranes, Alexander and Wrangellia, at the northwestern margin of North America, have long been considered exotic to each other and the rest of the northern Cordillera. Pennsylvanian plutons tie the two terranes together, but their seemingly dissimilar geological character led most workers to believe the two evolved separately before and after the Pennsylvanian. New chemical abrasion zircon U-Pb geochronology, whole-rock geochemistry, and other geological evidence from Paleozoic magmatic rocks in Yukon, Canada, suggest that the terranes evolved together by the late Paleozoic and that the Alexander terrane partially forms the basement to a portion of Wrangellia.

Large ca. 363 Ma gabbro complexes have non-arc geochemical signatures and intrude both terranes. Volcanic rocks near the base of northern Wrangellia are ca. 352 Ma and have back-arc to N-MORB geochemical signatures. At higher stratigraphic levels, Wrangellia contains abundant Mississippian to Pennsylvanian arc volcanic and volcaniclastic rocks (Skolai arc). Similar-aged arc/back-arc rocks are found in the southern part of Wrangellia (Sicker arc) and are interpreted as the southern extension of the Skolai arc.

We propose that the gabbros represent the initiation of extension through an arc located at the margin of the Alexander terrane (Skolai/Sicker arc system). Extension progressed enough to deposit basalts within a back-arc basin setting. Subduction reversal closed the basin and rejuvenated the arc in the Pennsylvanian. Collision of the arc with the Alexander terrane led to exhumation and deposition of conglomerates unconformably on top of the gabbros.

The evolution of the Alexander terrane and Wrangellia proposed here is broadly similar to the Late Devonian plate tectonic history along the northwestern Laurentian margin and is likely part of the same chain of arcs/back-arcs.

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INTRODUCTION

Western North America is characterized by the Cordilleran accretionary mountain belt that has seen episodic plate convergence since the early Paleozoic (Fig. 1; Colpron et al., 2007; Coney et al., 1980; Jones et al., 1977; Monger et al., 1982). The long-lived accretionary history of the northern Cordillera has resulted in a collage of terranes and overlap assemblages that seemingly have quite disparate geologic histories. Recent syntheses on terrane affinities has seen the collage transformed into a more coherent picture with geologic ties between terranes that were previously thought of as complete separate entities (cf. Colpron et al., 2007). This view of terranes adheres to the more traditional ideas of possible links between Laurentia and the accreted terranes with a few seemingly truly exotic pieces caught up in the collage (Coney et al., 1980; Jones et al., 1977; Rubin et al., 1990). Building upon these ideas, much of the current research in Cordilleran geology is focusing on those terranes that appear to show a more complex relationship with respect to Laurentia.

Wrangellia and the Alexander terrane are the two largest outboard terranes with characteristics that indicate a seemingly exotic nature with respect to the Laurentian margin (Fig. 1). The two terranes, along with smaller outboard terranes and the larger Peninsular terrane, comprise the Insular terranes and are separated from more inboard Intermontane terranes by Mesozoic and younger magmatic rocks and faults (Fig. 1). Current thinking indicates that the Insular terranes were amalgamated to the western margin of the Intermontane terranes as one tectonic entity by at least the Middle Jurassic (McClelland et al., 1992; van der Heyden, 1992).

Recent studies into the origin and tectonic history of the Alexander terrane have increased our knowledge significantly, suggesting early Paleozoic stratigraphic and tectonic linkages with the Timanide orogen of northeastern Baltica and Caledonian orogen of northern Laurussia (Bazard et al., 1995; Beranek et al., 2012; Beranek et al., 2013a, 2013b; Nelson et al., 2013). However, little is known about the relationship between the Alexander terrane and Wrangellia prior to accretion to the Laurentian margin. Gardner et al. (1988) showed that the two terranes were stitched together by a 309 Ma pluton, but only briefly speculated on the tectonic and stratigraphic significance of this relationship. This revelation was in direct contrast to earlier studies that suggested the two terranes were separate tectonic entities until their mutual accretion to the North American margin in the mid-Cretaceous. These studies, however, were based primarily on seemingly different Triassic stratigraphy present on each of the terranes (Jones et al., 1977).

We present new high-precision U-Pb zircon CA-TIMS (chemical abrasion isotope dilution thermal ionization mass spectrometry) ages and geochemical and stratigraphic data that indicate that Wrangellia and the Alexander terrane shared a tectonic setting and geologic history by at least the latest Devonian. The new data indicate that the Alexander terrane, at least in part, formed the basement to a portion of Wrangellia and thus, the two terranes must be thought of as one entity by the latter part of the Paleozoic when considering paleogeographic reconstructions.

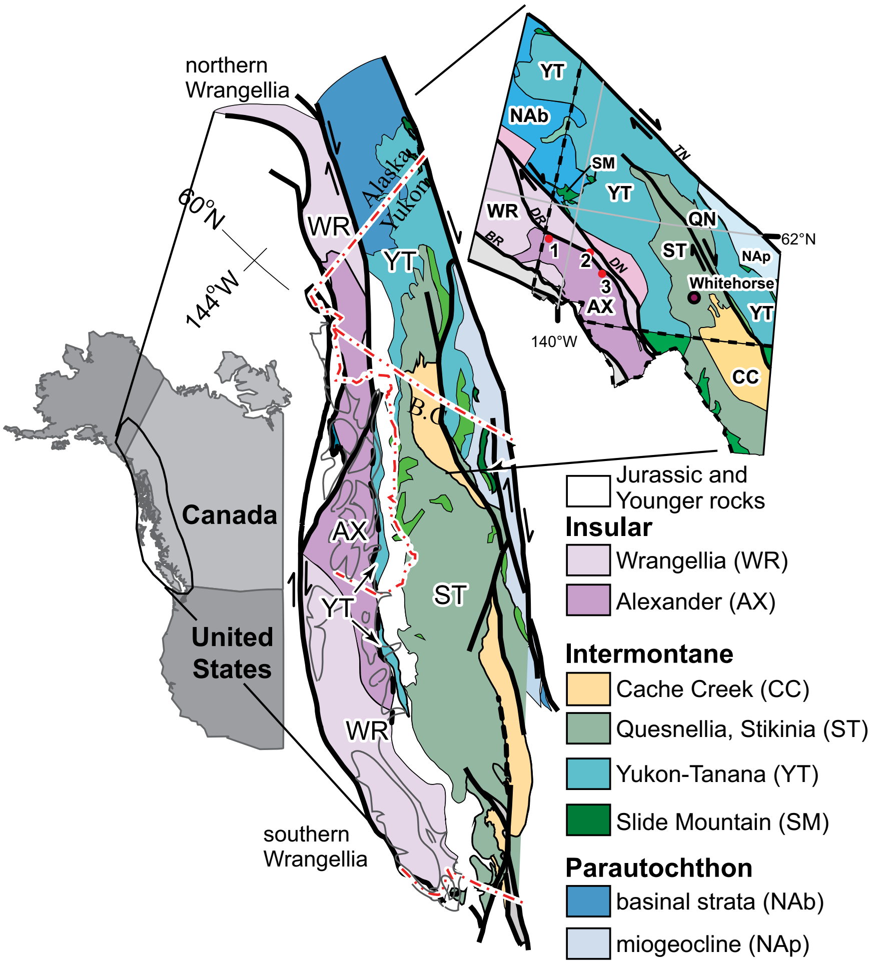

Figure 1. Tectonic assemblage map of a portion of the northern Cordillera (modified from Colpron and Nelson, 2009). Numbered red dots are locations for (1) Mount Constantine complex, (2) Steele Creek complex, and (3) Mount Vulcan complex. DR—Duke River fault; DN—Denali fault; BR—Border Ranges fault; TN—Tintina fault; NAb—North American basinal strata; NAp—North American platformal strata.

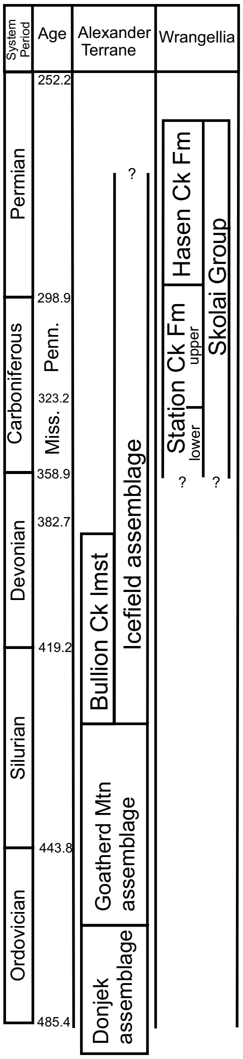

Figure 2. Generalized stratigraphy for the Alexander terrane and Wrangellia in southwest Yukon. Timescale based on Gradstein and Ogg (2012); lmst—limestone.

REGIONAL GEOLOGY

Wrangellia

Wrangellia encompasses rocks from eastern Alaska and Yukon (northern Wrangellia) to Vancouver Island and northwestern United States (southern Wrangellia; Fig. 1). It was first described as a terrane by Jones et al. (1977), primarily based upon a thick package of Triassic basalts that is ubiquitous to the whole terrane, but also the Paleozoic basement underlying the basalts.

Paleozoic rocks in southern Wrangellia are characterized by Devonian through Permian volcanic, volcaniclastic, siliciclastic, and carbonate rocks of the Sicker and Buttle Lake groups (Massey, 1995; Yorath et al., 1999). Recent studies on Vancouver Island have identified several episodes of arc and back-arc cycles beginning in the Late Devonian and continuing into the Early Permian (Ruks et al., 2009, 2010). Paleozoic rocks are unconformably overlain by Middle Triassic marine shale and a thick package of Upper Triassic mafic volcanic rocks and carbonate (Nixon and Orr, 2006).

Northern Wrangellia is characterized by a thick succession of Carboniferous volcanic and volcaniclastic rocks conformably overlain by Permian coarse- to fine-grained marine siliciclastic rocks and carbonates. These rocks comprise the Skolai Group with the volcanic member assigned to the Station Creek Formation and the sedimentary member to the Hasen Creek Formation (Fig. 2; Read and Monger, 1976; Smith and MacKevett, 1970). A thick succession of mafic flows, pillow basalt and hyaloclastite interbedded with chert and thin crystal tuffs are found at the base of the Station Creek Formation (Israel and Cobbett, 2008; Read and Monger, 1976). The Hasen Creek Formation in most places is found to gradationally overly the volcanic rocks of the Station Creek Formation. The Skolai Group is unconformably overlain by Middle Triassic marine sedimentary rocks and thick accumulations of Upper Triassic mafic volcanic rocks, carbonate and calcareous to carbonaceous turbidites.

Alexander Terrane

The Alexander terrane comprises much of coastal British Columbia and southeast Alaska and extends northwest through British Columbia, Yukon and southern Alaska (Fig. 1). It is a composite terrane divided into the Craig and Admiralty subterranes (Gehrels and Saleeby, 1987) that were likely amalgamated during the

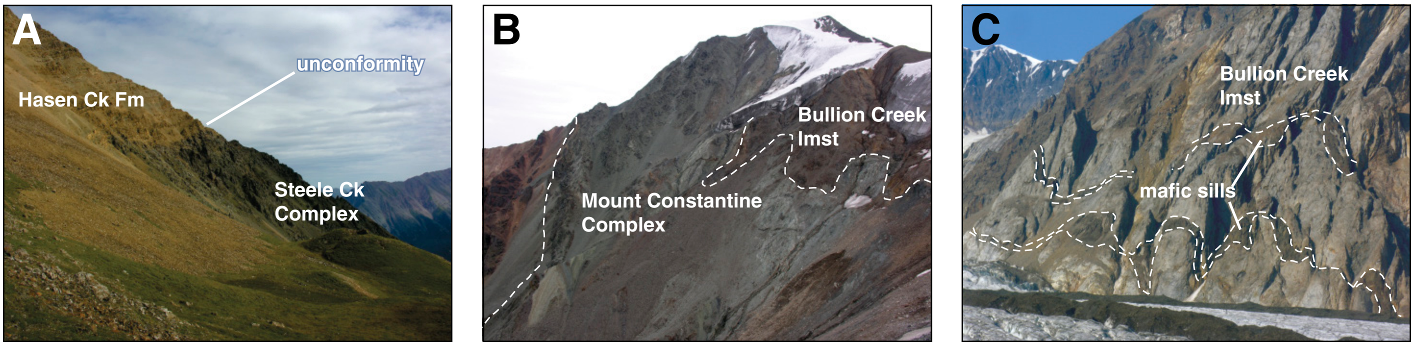

Figure 3. (A) Unconformable contact between Permian Hasen Creek Formation of Wrangellia and Devonian gabbro of the Steele Creek complex, southwest Yukon. (B) Intrusive relationship between Devonian gabbro of the Mount Constantine complex and Silurian to Devonian Bullion Creek limestone, Alexander terrane, southwest Yukon. (C) Mafic sills intruding Bullion Creek limestone, northwestern British Columbia.

late Paleozoic (Karl et al., 2010). The Craig subterrane underlies all of southwest Yukon and more than 90% of the rest of the Alexander terrane (Gehrels and Saleeby, 1987). In southeast Alaska, the Craig subterrane is composed of Neoproterozoic metamorphic rocks of the Wales Group overlain by Upper Cambrian to Lower Silurian mafic and felsic volcanic rocks, shale and limestone of the Descon Formation and Upper Silurian to Lower Devonian carbonate and red beds of the Heceta and Karheen formations, respectively (Beranek et al., 2012; Gehrels and Saleeby, 1987). The Craig subterrane in southwest Yukon and northwestern British Columbia is characterized by volcanic, carbonate, and siliciclastic rocks assigned to several informal assemblages, including the Cambrian to Ordovician Donjek assemblage, the Ordovician to Silurian Goatherd Mountain assemblage, the Devonian to Triassic Icefield assemblage, and the Silurian to Devonian Bullion Creek limestone (Fig. 2; Dodds and Campbell, 1992).

ALEXANDER-WRANGELLIA RELATIONSHIPS IN SOUTHWEST YUKON

In southwest Yukon, rocks in the Alexander terrane and Wrangellia are traditionally shown to be separated by the Duke River fault (Fig. 1). This fault has a protracted deformation history that includes oblique Early Cretaceous thrusting, possible latest Cretaceous to Paleocene strike-slip displacement and Miocene to present northeast directed thrusting (Cobbett, 2011). It is a young feature that is not representative of the original terrane boundary.

On the north side of the Duke River fault, Lower Permian conglomerates of the Hasen Creek Formation in Wrangellia overlie previously undated gabbro of the Steele Creek complex along a pronounced local unconformity (Fig. 3A; Read and Monger, 1976; Sharp, 1943). The unconformity can be tracked to the east for up to 20 km where it terminates against the Duke River fault. The unconformable relationship is unusual in that elsewhere in northern Wrangellia the contact between the Station Creek and the Hasen Creek formations is transitional from volcanic dominated to sedimentary dominated stratigraphy (Read and Monger, 1976; Smith and MacKevett, 1970).

In the Alexander terrane, on the south side of the Duke River fault, near the Alaska border, gabbros assigned to the previously undated Mount Constantine complex intruded Silurian to Devonian carbonate rocks of the Bullion Creek limestone (Figs. 1, 3B). Field observations show that this gabbro, although altered, is lithologically similar to the gabbro of the Steele Creek complex, north of the Duke River fault. Several other gabbro bodies, the largest near Mount Vulcan (Fig. 1), are interpreted as having intruded rocks assigned to the Alexander terrane.

Devonian and older rocks in the Alexander terrane, were intruded by swarms of mafic sills and dikes up to several meters thick. These sills are found throughout southwest Yukon and northwest British Columbia (Fig. 3C; Dodds and Campbell, 1992; Mihalynuk et al., 1993). The age of the dikes is unknown, but they are spatially associated with the gabbro bodies that intruded the Alexander terrane and have not been reported to have intruded rocks younger than Devonian.

GEOCHRONOLOGY

We used U-Pb zircon CA-TIMS geochronology to constrain the timing of gabbro intrusion and deposition of a felsic crystal tuff in the lower Station Creek Formation. One gabbro sample is from the Steele Creek complex in Wrangellia and another is from the Mount Constantine complex in the Alexander terrane near the Klutlan Glacier area. The tuff and the Steele Creek gabbro were analyzed at the Pacific Centre for Geochemical Isotopic Research at the University of British Columbia (PCIGR). The Mount Constantine gabbro was analyzed at the Isotope Geology Laboratory at Boise State University. Details of methods are given in the Data Repository[1]. Dates are weighted mean ^{206}Pb/^{238}U dates from 3 to 6 analyses of single zircon grains that are equivalent in age.

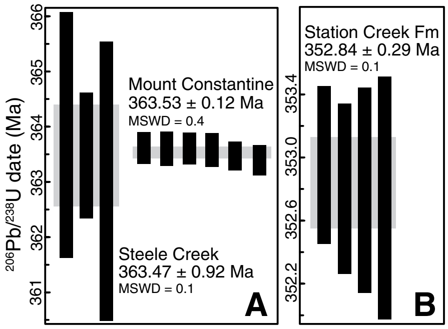

Figure 4. Ranked U-Pb zircon date plots for (A) Steele Creek complex and Mount Constantine complex, and (B) lower Station Creek Formation. Black error bars show 2σ errors on individual analyses. Grey boxes show 2σ errors on the weighted mean dates. MSWD—mean square of weighted deviates.

Gabbro from the Steele Creek complex in Wrangellia yielded a date of 363.47 ± 0.92 Ma (Fig. 4A; Table 1). Gabbro from the Mount Constantine complex in Alexander yielded a date of 363.53 ± 0.12 Ma (Fig. 4A; Table 2). Dates are identical and interpreted as igneous crystallization ages. A crystal-rich felsic tuff interbedded with pillowed mafic flows and chert from the lower Station Creek Formation yielded a date of 352.84 ± 0.30 Ma (Fig. 4B; Table 1), interpreted as the deposition age.

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[1] GSA Data Repository Item 2014196, geochronological methods and results, is available at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

TABLE 1. U-Pb ISOTOPIC DATA FOR THE STEELE CREEK COMPLEX AND THE STATION CREEK FORMATION

Sample (a)	Wt. (mg) (b)	Compositional parameters								Radiogenic isotope ratios								Isotopic ages					
		U (ppm) (c)	Th/U (d)	Pb (ppm) (c)	^{206}Pb* (×10^{-13} mol) (e)	mol% ^{206}Pb* (e)	Pb*/Pb$_c$ (e)	Pb$_c$ (pg) (e)	^{206}Pb/^{204}Pb (f)	^{208}Pb/^{206}Pb (g)	^{207}Pb/^{206}Pb (g)	% err (h)	^{207}Pb/^{235}U (g)	% err (h)	^{206}Pb/^{238}U (g)	% err (h)	corr. coef.	^{207}Pb/^{206}Pb (i)	± (h)	^{207}Pb/^{235}U (i)	± (h)	^{206}Pb/^{238}U (i)	± (h)
Steele Creek Complex																							
08-SI-179-1																							
A	0.005	23	1.215	2.0	0.2888	94.03%	6	1.51	310	0.389	0.055135	1.931	0.455174	2.072	0.059875	0.275	0.564	417.72	43.13	380.90	6.58	374.87	1.00
B	0.005	7	0.970	0.7	0.0905	86.17%	2	1.19	134	0.306	0.053942	6.037	0.431864	6.428	0.058066	0.630	0.651	368.61	136.01	364.50	19.69	363.85	2.23
C	0.005	9	0.813	0.8	0.1032	89.83%	3	0.96	182	0.257	0.054058	4.639	0.431755	4.954	0.057926	0.716	0.497	373.48	104.42	364.42	15.17	363.00	2.53
E	0.005	22	0.772	1.6	0.2641	95.68%	7	0.98	428	0.243	0.053779	2.010	0.430088	2.162	0.058002	0.321	0.531	361.79	45.33	363.24	6.60	363.47	1.14
Station Creek Formation																							
08SI-090-1																							
B	0.005	159	0.345	9.1	1.8636	99.31%	42	1.06	2681	0.108	0.053347	0.351	0.413774	0.429	0.056254	0.158	0.632	343.60	7.94	351.59	1.27	352.80	0.54
C	0.003	106	0.334	6.4	0.7435	97.86%	13	1.34	860	0.105	0.053453	0.573	0.414518	0.666	0.056244	0.225	0.553	348.06	12.96	352.12	1.98	352.74	0.77
D	0.004	142	0.309	8.3	1.3308	98.41%	18	1.77	1155	0.097	0.053543	0.455	0.415478	0.529	0.056279	0.147	0.608	351.88	10.28	352.81	1.58	352.95	0.50
E	0.003	119	0.278	7.1	0.8407	97.66%	12	1.66	785	0.088	0.053517	0.638	0.415078	0.721	0.056252	0.189	0.547	350.78	14.41	352.53	2.15	352.79	0.65

(a) A, B, etc. are labels for fractions composed of single zircon grains or fragments; all fractions annealed and chemically abraded after Mattinson (2005).
(b) Nominal fraction weights estimated from photomicrographic grain dimensions, adjusted for partial dissolution during chemical abrasion.
(c) Nominal U and total Pb concentrations subject to uncertainty in photomicrographic estimation of weight and partial dissolution during chemical abrasion.
(d) Model Th/U ratio calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{235}U age.
(e) Pb* and Pb$_c$ represent radiogenic and common Pb, respectively; mol % ^{206}Pb* with respect to radiogenic, blank and initial common Pb.
(f) Measured ratio corrected for spike and fractionation only. Daly analyses, based on analysis of NBS-982.
(g) Corrected for fractionation, spike, and common Pb; up to 3 pg of common Pb was assumed to be procedural blank: ^{206}Pb/^{204}Pb = 18.50 ± 1.0%; ^{207}Pb/^{204}Pb = 15.50 ± 1.0%; ^{208}Pb/^{204}Pb = 38.40 ± 1.0% (all uncertainties 1-sigma). Excess over blank was assigned to initial common Pb.
(h) Errors are 2-sigma, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(i) Calculations are based on the decay constants of Jaffey et al. (1971). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ages corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.
(j) Corrected for fractionation, spike, and blank Pb only.

TABLE 2. U-Pb ISOTOPIC DATA FOR THE MOUNT CONSTANTINE COMPLEX

Sample (a)	Compositional parameters						Radiogenic isotope ratios								Isotopic ages					
	Th/U (b)	^{206}Pb* (×10^{-13} mol) (c)	mol % ^{206}Pb* (c)	Pb*/Pb$_c$ (c)	Pb$_c$ (pg) (c)	^{206}Pb/^{204}Pb (d)	^{208}Pb/^{206}Pb (e)	^{207}Pb/^{206}Pb (e)	% err (f)	^{207}Pb/^{235}U (e)	% err (f)	^{206}Pb/^{238}U (e)	% err (f)	corr. coef.	^{207}Pb/^{206}Pb (g)	± (f)	^{207}Pb/^{235}U (g)	± (f)	^{206}Pb/^{238}U (g)	± (f)
10-SI-217-1																				
z1	0.388	0.4300	99.44%	52	0.20	3290	0.122	0.053764	0.309	0.430127	0.358	0.058024	0.082	0.670	361.18	6.97	363.27	1.09	363.59	0.29
z2	0.386	0.5681	99.63%	78	0.18	4900	0.122	0.053793	0.210	0.430098	0.260	0.057989	0.078	0.730	362.37	4.74	363.25	0.79	363.38	0.27
z3	0.385	0.5746	99.72%	105	0.13	6571	0.121	0.053739	0.220	0.429925	0.270	0.058024	0.088	0.680	360.11	4.96	363.12	0.82	363.60	0.31
z4	0.363	0.6105	99.72%	103	0.14	6519	0.114	0.053855	0.175	0.430693	0.227	0.058002	0.074	0.789	364.99	3.94	363.67	0.69	363.46	0.26
z5	0.436	0.5259	99.64%	83	0.16	5104	0.137	0.053762	0.264	0.430079	0.307	0.058020	0.088	0.600	361.07	5.96	363.23	0.94	363.57	0.31
z6	0.366	0.3765	99.45%	53	0.17	3334	0.115	0.053774	0.321	0.430220	0.369	0.058025	0.082	0.653	361.61	7.24	363.33	1.13	363.60	0.29

(a) z1, z2, etc. are labels for analyses composed of single zircon grains that were annealed and chemically abraded (Mattinson, 2005).
(b) Model Th/U ratio calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{235}U date.
(c) Pb* and Pb$_c$ are radiogenic and common Pb, respectively. mol % ^{206}Pb* is with respect to radiogenic and blank Pb.
(d) Measured ratio corrected for spike and fractionation only. Fractionation correction is 0.18 ± 0.03 (1 sigma) %/amu (atomic mass unit) for single-collector. Daly analyses, based on analysis of EARTHTIME ^{202}Pb-^{205}Pb tracer solution.
(e) Corrected for fractionation, spike, common Pb, and initial disequilibrium in ^{230}Th/^{238}U. Common Pb is assigned to procedural blank with composition of ^{206}Pb/^{204}Pb = 18.35 ± 1.50%; ^{207}Pb/^{204}Pb = 15.69 ± 0.75%; ^{208}Pb/^{204}Pb = 38.08 ± 1.00% (1 sigma). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.0 ± 0.3 (1 sigma).
(f) Errors are 2 sigma, propagated using algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(g) Calculations based on the decay constants of Jaffey et al. (1971). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb dates corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.0 ± 0.3 (1 sigma).

TABLE 3. MAJOR AND TRACE ELEMENT DATA FOR GABBROS AND SILLS INTRUDING ALEXANDER TERRANE AND BASALTS OF THE LOWER STATION CREEK FORMATION

Rock type:	Gabbro	Gabbro	Gabbro	Sill	Sill	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt
Unit:	Mount Constantine	Steele Creek	Mount Vulcan			Station Creek	Station Creek	Station Creek	Station Creek	Station Creek	Station Creek
Sample #:	10-SI-217-1	08-S1-179-1	10-SI-219-1	09VLB43	09VL12	08-S1-089-1	08-S1-096-1	08-S1-119-2	08-S1-178-1	08-S1-178-2	08-S1-179-1
SiO_2	44.61	47.11	44.26	45.43	47.22	48.66	48.06	48.54	51.96	45.3	47.11
Al_2O_3	21.68	18.38	14.28	15.38	15.5	16.19	14.7	14.32	13.07	13.32	18.38
Fe_2O_3(T)	4.67	6.54	17.2	9.72	9.43	10.01	12.44	12.19	8.68	15.41	6.54
MnO	0.092	0.11	0.263	0.146	0.146	0.141	0.193	0.173	0.118	0.158	0.11
MgO	10.51	10.38	5.45	7.82	7.74	8.62	7.11	6.44	7.75	4.56	10.38
CaO	12.06	10.95	7.48	13.9	11.98	10.1	12.84	10.62	12.53	9.49	10.95
Na_2O	1.27	2.28	3.41	1.59	2.86	2.7	2.07	3.61	2.12	3.63	2.28
K_2O	1.21	0.28	0.38	0.03	0.1	0.23	0.09	0.47	0.55	0.95	0.28
TiO_2	0.102	0.398	4.697	0.942	0.867	1.845	1.848	2.039	0.866	3.455	0.398
P_2O_5	0.02	0.03	0.02	0.08	0.07	0.21	0.17	0.22	0.2	0.24	0.03
LOI	4.44	2.96	2.05	4.57	3.32	2.23	0.82	1.72	2.35	3.03	2.96
Total	100.7	99.42	99.48	99.61	99.23	100.9	100.3	100.3	100.2	99.54	99.42
Sc	10	27	39	39	40	43	46	44	35	38	27
Be	<1	<1	<1	<1	<1	1	1	1	1	2	<1
V	43	119	260	295	264	337	363	362	269	383	119
Cr	530	290	<20	230	370	270	240	180	650	240	290
Co	37	40	48	41	38	39	41	50	37	42	40
Ni	320	150	30	100	110	<20	<20	<20	140	<20	150
Cu	40	20	20	80	80	30	60	100	80	500	20
Zn	50	<30	110	70	70	100	110	120	70	210	<30
Ga	11	12	19	13	15	17	17	15	13	17	12
Ge	1.4	0.9	1.5	1.4	1.6	1	1.1	1.1	1.9	1.4	0.9
As	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Rb	35	6	8	<1	<1	3	<1	7	10	17	6
Sr	303	222	161	303	147	174	132	287	120	93	222
Y	1.8	7.3	8.9	22.8	16.1	36.5	37.1	38.4	14.6	41.1	7.3
Zr	5	17	22	61	49	115	101	140	52	125	17
Nb	<0.2	0.7	2.9	2.9	2.8	5.2	3.8	7.4	12.1	15.5	0.7
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	2.5	<0.5	<0.5
In	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sn	<1	<1	<1	1	<1	1	1	1	<1	2	<1
Sb	1.3	3	0.5	<0.2	<0.2	2.9	<0.2	3.6	3.9	2.9	3
Cs	0.6	0.3	0.2	0.2	<0.1	0.1	<0.1	0.1	0.2	0.3	0.3
Ba	414	45	83	25	24	42	14	66	43	81	45
La	0.84	1.26	0.78	3.5	3.34	6.8	5.58	8.24	9.86	6.5	1.26
Ce	1.7	3.38	2.53	8.86	8.96	18	14	22.5	21.3	21.3	3.38
Pr	0.22	0.55	0.4	1.38	1.38	2.92	2.41	3.58	3.01	4.2	0.55
Nd	1.07	2.7	2.43	7.03	6.66	14	12.3	15.9	11.5	21	2.7
Sm	0.43	0.82	1.45	2.31	2.16	4.13	3.84	4.76	2.72	6.5	0.82
Eu	0.296	0.536	1.06	0.893	0.821	1.38	1.56	1.86	0.914	2.54	0.536
Gd	0.43	1.25	1.51	2.99	2.54	5.53	5.25	6.44	2.95	7.97	1.25
Tb	0.07	0.22	0.28	0.59	0.48	0.97	0.98	1.09	0.47	1.27	0.22
Dy	0.41	1.39	1.75	3.81	2.98	6.19	6.31	6.77	2.72	7.56	1.39
Ho	0.08	0.29	0.37	0.78	0.57	1.34	1.31	1.43	0.54	1.52	0.29
Er	0.23	0.86	1.02	2.28	1.63	4.15	3.92	4.28	1.57	4.35	0.86
Tm	0.034	0.125	0.153	0.343	0.248	0.628	0.572	0.623	0.232	0.608	0.125
Yb	0.25	0.78	0.98	2.27	1.59	3.99	3.53	3.85	1.49	3.59	0.78
Lu	0.045	0.117	0.147	0.357	0.239	0.584	0.52	0.561	0.229	0.514	0.117
Hf	0.3	0.5	0.7	1.4	1.2	3.1	2.7	3.8	1.5	3.6	0.5
Ta	<0.01	0.04	0.26	0.18	0.25	0.33	0.26	0.54	0.89	1.11	0.04
W	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	3.6	<0.5	<0.5	<0.5	<0.5
Tl	0.14	0.07	<0.05	<0.05	<0.05	<0.05	0.26	<0.05	<0.05	0.07	0.07
Pb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Bi	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Th	0.09	0.06	0.09	0.33	0.27	0.7	0.43	0.87	0.81	0.2	0.06
U	0.04	0.02	<0.01	0.27	0.06	0.51	0.32	0.52	0.18	0.08	0.02

GEOCHEMISTRY

Geochemical data were obtained from the two dated gabbros, one sample from the Mount Vulcan body, two samples of sills that intruded the Alexander terrane, and several of basalt from the lower Station Creek Formation to determine their composition and tectonic setting (Table 3). The basalts show primitive mantle-normalized trace element plots typical of back-arc basin basalt to N-MORB and E-MORB affinity (Fig. 5A). The sills and gabbro show non-arc like geochemical signatures (Fig. 5B). The sills are nearly identical with slightly depleted N-MORB characteristics and the Mount Vulcan gabbro is very slightly depleted similar to the sills. The Steele Creek gabbro is similar to the N-MORB characteristics of the Mount Vulcan gabbro, but shows elevated Ti, Eu, and Nb concentrations. The Mount Constantine gabbro has the most depleted values of all the gabbros (Fig. 5B). The pattern shows a non-arc affinity but with strongly depleted values for almost all elements.

DISCUSSION AND TECTONIC IMPLICATIONS

The U-Pb zircon and geochemical data provide the first evidence for a latest Devonian to Early Mississippian rifting event that affected the Alexander terrane and Wrangellia. We propose that this rifting was related to back-arc development along the margin of the Alexander terrane within the Skolai/Sicker arc system (Fig. 6A). A subduction zone would have been present at the margin of the Alexander terrane and extended beyond the terrane limits, into the oceanic realm, such that the Skolai portion of the arc was interacting with the Alexander terrane and the Sicker portion was not (Fig. 6A). In southern Wrangellia, arc activity during the Late Devonian to earliest Mississippian is well documented (Massey, 1995; Yorath et al., 1999). Extension of the arc-system began by the latest Devonian, likely due to slab rollback, and is manifested by the intrusion of non-arc gabbro complexes and voluminous sills and dykes at the margin of the Alexander terrane (Fig. 6A). The back-arc was fully developed by the Early Mississippian with deposition of the lower Station Creek Formation basalt and chert. The timing of back-arc development in northern Wrangellia corresponds with a similar tectonic setting in southern Wrangellia, documented by the presence of bimodal volcanic rocks and volcanogenic massive sulfide–style mineralization (Massey, 1995; Yorath, 1991) indicative of an arc under extension (cf. Piercey et al., 2004).

Collapse of the back-arc in northern Wrangellia in the latest Mississippian to latest Pennsylvanian was likely facilitated by a reversal of subduction polarity and accompanied by a resurgence of arc volcanic activity built primarily upon Wrangellia (Fig. 6B). Final closure of the back-arc led to the collision between Alexander and the arc system, clogging and subsequently shutting down subduction. We propose that the collision led to exhumation of the gabbro complexes along the margin of the Alexander terrane and the local deposition of conglomerates of the Hasen Creek Formation across the gabbro complexes and surrounding basement (Fig. 6B). Arc-related melts intruded across the Alexander-Wrangellia boundary, including the Barnard Glacier pluton (Dodds and Campbell, 1992; Gardner et al., 1988). Early Permian volcanic rocks are interbedded with the sedimentary rocks in both southwest Yukon and southeast Alaska, indicating that the arc in northern Wrangellia was slowly dying (Karl et al., 2010; Read and Monger, 1976). In southern Wrangellia, latest Mississippian to Early Permian volcanic and volcaniclastic rocks are interbedded with marine sedimentary rocks and capped by carbonates (Massey, 1995; Ruks et al., 2010), suggesting the Skolai/Sicker arc system also died out in the south by the Permian.

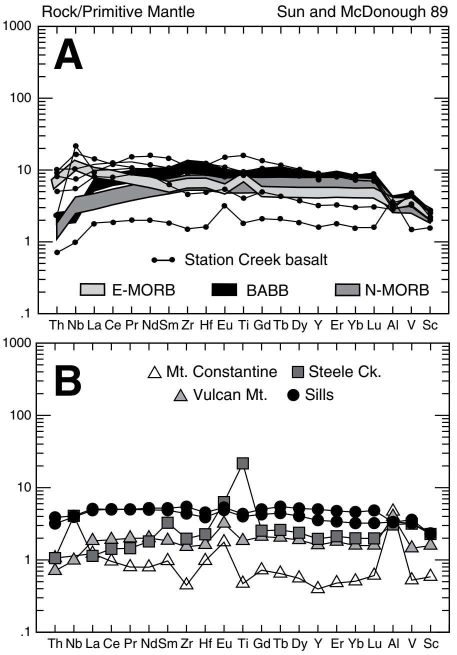

Figure 5. Primitive mantle normalized spider plots for (A) lower Station Creek Formation basalts, and (B) gabbro complexes and sills intruded into the Alexander terrane and Wrangellia. Values for back-arc basin basalts (BABB) from Ewart et al., (1994). Values for normal mid-ocean ridge basalt (N-MORB) and enriched mid-ocean ridge basalt (E-MORB) from Sun and McDonough (1989).

Wrangellia and the Alexander terrane relationships have broader implications for how tectonic terranes are perceived. Jones et al. (1977) defined Wrangellia largely on Triassic stratigraphy and thought the older portions of the terrane were separate from the Alexander terrane. Our data show a clear relationship between the two terranes, which were thought exotic to one another; they actually have ties that go back as far as their inception. This is a provocative idea that blurs the definition a terrane by showing that many of the observations of Jones et al. (1977) can actually be attributed to evolving tectonic processes rather than disparate geologic histories.

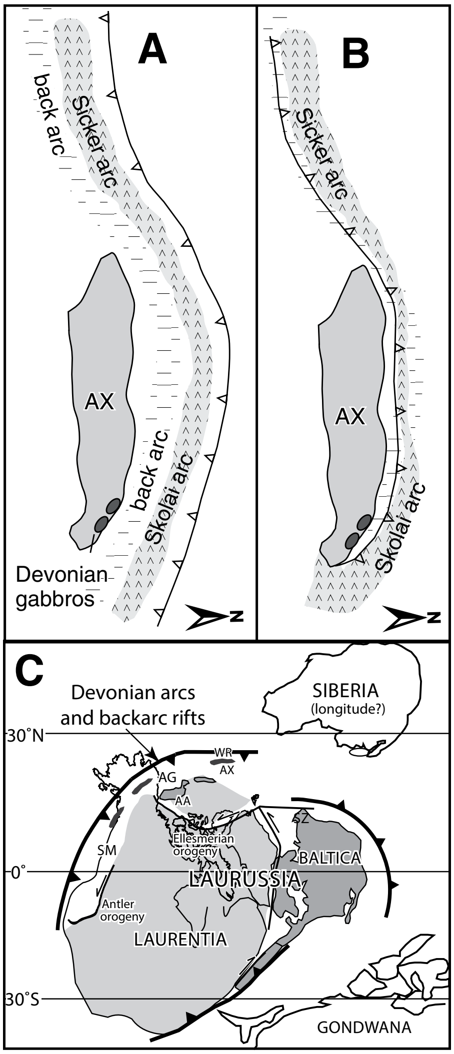

Figure 6. Diagram showing the relationships between the Alexander terrane and Wrangellia for (A) Late Devonian to Mississippian, and (B) late Mississippian to Early Permian. (C) Devono-Mississippian paleogeographic setting for the Alexander terrane and Wrangellia; North arrows indicate spatial reference for map in 6C. AA—Arctic Alaska, AG—Angayucham, AX—Alexander, SM—Slide Mountain, WR—Wrangellia.

CONCLUSION

Although the Alexander terrane and Wrangellia are seemingly exotic to Laurentia, we show they are not exotic from one another. From at least the late Devonian, the two can be considered as being tectonically and stratigraphically linked. Furthermore, the latest Devonian to Mississippian rifting is similar to other events recently identified along the Laurentian margin. The opening of the Slide Mountain basin in the Devonian to Mississippian involves the Intermontane terranes of the northern Cordillera, mainly the Yukon-Tanana and Stikine terranes (see Fig. 1 for terrane relationships), separating from the Laurentian margin (Colpron et al., 2007). Faunal and magmatic similarities between Wrangellia and the Stikine terrane existed in the late Paleozoic, suggesting that they were in close proximity (Belasky et al., 2002). It may be that the rifting observed within the Alexander terrane and Wrangellia is part of the system that opened the Slide Mountain–Angayucham ocean basin (Fig. 6C).

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