Wrangellia flood basalts in Alaska: A record of plume-lithosphere interaction in a Late Triassic accreted oceanic plateau

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[1] The Wrangellia flood basalts are part of one of the best exposed accreted oceanic plateaus on Earth. They provide important constraints on the construction of these vast submarine edifices and the source and temporal evolution of magmas for a plume head impinging beneath oceanic lithosphere. Wrangellia flood basalts (~ 231 – 225 Ma) extend ~ 450 km across southern Alaska (Wrangell Mountains and Alaska Range) where ~ 3.5 km of mostly subaerial flows are bounded by late Paleozoic arc volcanics and Late Triassic limestone. The vast majority of the flood basalts are light rare earth element (LREE) -enriched high-Ti basalt (1.6–2.4 wt % TiO_2) with uniform ocean island basalt (OIB) -type Pacific mantle isotopic compositions ($\epsilon_{\text{Hf}}(t) = +9.7$ to $+10.7$; $\epsilon_{\text{Nd}}(t) = +6.0$ to $+8.1$; $t = 230$ Ma). However, the lowest ~ 400 m of stratigraphy in the Alaska Range is LREE-depleted low-Ti basalt (0.4–1.2 wt % TiO_2) with pronounced negative high field strength element (HFSE) anomalies and Hf isotopic compositions ($\epsilon_{\text{Hf}}(t) = +13.7$ to $+18.4$) that are decoupled from Nd ($\epsilon_{\text{Nd}}(t) = +4.6$ to $+5.4$) and displaced well above the OIB mantle array ($\Delta\epsilon_{\text{Hf}} = +4$ to $+8$). The radiogenic Hf of the low-Ti basalts indicates involvement of a component that evolved with high Lu/Hf over time but not with a correspondingly high Sm/Nd. The radiogenic Hf and HFSE-depleted signature of the low-Ti basalts suggest pre-existing arc lithosphere was involved in the formation of flood basalts that erupted early in construction of part of the Wrangellia plateau in Alaska. Thermal and mechanical erosion of the base of the lithosphere by the impinging plume head may have led to melting of arc lithosphere or interaction of plume-derived melts and subduction-modified mantle. The high-Ti lavas dominate the main phase of construction of the plateau and were derived from a depleted mantle source distinct from the source of MORB and with compositional similarities to that of ocean islands (e.g., Hawaii) and plateaus (e.g., Ontong Java) in the Pacific Ocean.

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1. Introduction

[2] Oceanic plateaus and continental flood basalts (CFBs) represent transient large igneous provinces (LIPs) that are produced from the largest mantle melting events recorded on Earth. Oceanic plateaus and CFBs form from unusually high magmatic fluxes during emplacement over several million years or less [Saunders, 2005]. A longstanding controversy concerning the origin of magmas in many transient LIPs worldwide is whether they form by melting of the lithospheric mantle during any stage of LIP emplacement. CFBs have compositions that indicate involvement of subcontinental lithospheric mantle [e.g., Peate and Hawkesworth, 1996]. Compositional evidence of involvement of the lithospheric mantle in lavas erupted in oceanic plateaus, however, remains elusive. Although Ocean Drilling Program (ODP) and Deep Sea Drilling Program (DSDP) legs have drilled extant oceanic plateaus in the ocean basins, the vast majority of the stratigraphic sequence of oceanic plateaus remains generally unsampled and undescribed. Oceanic plateaus are enormous volcanic edifices (2–4 km high above the ocean floor) that are isolated from continents and form upon mid-ocean ridges, extinct arcs, detached or submerged continental fragments, or in intraplate settings [Coffin *et al.*, 2006]. The basalts that form oceanic plateaus have a better chance of avoiding interaction with continental lithosphere than basalts erupted along the margins or in the interiors of continents [Kerr and Mahoney, 2007].

[3] An enduring issue involving the geochemistry of flood basalt provinces has been the origin of high- and low-titanium basalts within the flood basalt stratigraphy [e.g., Arndt *et al.*, 1993]. Numerous LIPs have been found to possess two or more distinguishable groups of basalts based on titanium contents (e.g., Siberia [Wooden *et al.*, 1993]; Emeishan [Xu *et al.*, 2001]; Central Atlantic Magmatic Province [Nomade *et al.*, 2002]; Karoo [Cox *et al.*, 1967]; Ferrar [Hornig, 1993]; Paraná-Etendeka [Peate, 1997]; Deccan [Melluso *et al.*, 1995]; Ethiopia [Pik *et al.*, 1998]; Columbia River Basalts [Hooper and Hawkesworth, 1993]). In several of these provinces, the high- and low-titanium basalts are geographically distributed within the province, and in several provinces these lava types have a distinct stratigraphic distribution. However, all of these LIPs formed upon continental crust and involved interaction with metasomatized lithospheric mantle or continental crust during parts of their eruptive histories.

[4] The Wrangellia flood basalts in Alaska are remnants of an oceanic plateau that erupted in the eastern Panthalassic Ocean over <5 Ma in the Middle to Late Triassic, with accretion to western North America occurring in the Late Jurassic or Early Cretaceous [Jones *et al.*, 1977]. The Wrangellia flood basalts form thick successions of flood basalts bounded by marine sediments that extend over areas of Alaska, Yukon, and British Columbia (>2300 km in length). In south central Alaska, the flood basalt stratigraphy overlies late Paleozoic oceanic arc crust and marine sediments and is overlain by Late Triassic limestone. Most of the 3.5–4 km-thick sequence of flood basalts in Alaska erupted subaerially; however, in areas of Alaska there are pillowed and volcanoclastic basalts in the lower part of the volcanic stratigraphy.

[5] The Wrangellia oceanic plateau in Alaska is unusual as it is part of one of the only known LIPs that was constructed on the volcanic sequences of an older island arc. This raises the possibility that the erupted basalts contain a component from the subarc lithospheric mantle of this late Paleozoic arc. This is an intriguing hypothesis to test since both high- and low-titanium basalts have been recognized in the volcanic stratigraphy in Alaska as a result of this study, and thus may provide a direct comparison to CFBs built on older continental lithosphere.

[6] This study examines the volcanic stratigraphy, petrography, and geochemistry of flood basalts in the Wrangell Mountains and Alaska Range in south central Alaska and assesses the nature of the source and the origin of high- and low-titanium basalts in this part of the accreted Wrangellia oceanic plateau. A mantle plume origin was proposed for Wrangellia flood basalts by Richards *et al.* [1991] based on the large volume of flood basalts erupted in a short duration, the absence of evidence of rifting, and evidence of uplift prior to eruption of the flood basalts. The only previous modern analytical study of the Wrangellia flood basalts in Alaska involved major and trace element chemistry, and Sr, Nd, and Pb isotopic analyses, of nine basalts from the Wrangell Mountains [Lassiter *et al.*, 1995]. This present study is part of a larger research project on the origin and evolution of the Triassic Wrangellia flood basalts in Alaska, Yukon, and British Columbia [Greene *et al.*, 2008a, 2008b]. These areas (each ~400 km in length, for a total length of ~2300 km) have different volcanic stratigraphy, distinct geochemical characteristics (and similarities), and they overlie Paleo-

Figure 1. Simplified map of south-central Alaska showing the distribution of the Nikolai Formation (black), derived from the GIS-based digital map compilations of *Wilson et al.* [1998, 2005] and J. M. Schmidt (personal communication, 2006). The three main areas that were studied are outlined with boxes and indicated in the legend. The inset shows the extent of the Wrangellia flood basalts (green) in Alaska, Yukon, and British Columbia, with a red box indicating the map location. The red lines are faults and gray lines are glaciers.

zoic basement of different age and lithology. Exploring the internal stratigraphy and geochemistry of the accreted Wrangellia oceanic plateau provides constraints on the composition of less accessible examples in the ocean basins such as the Ontong Java and Kerguelen Plateaus.

2. Geologic Setting

2.1. Wrangellia in Alaska

[7] The Wrangellia Terrane, or Wrangellia, was defined by *Jones et al.* [1977] as a set of fault-bound crustal blocks with similar-aged flood basalts overlain by limestone along the margin of western North America (Figure 1). The Wrangellia flood basalts have been mapped as the Nikolai Formation in Alaska and Yukon where they directly overlie shale with Middle to Late Ladinian (~235–

232 Ma) *Daonella*. Wrangellia may have joined with parts of the Alexander Terrane, primarily in southeast Alaska, as early as the Late Pennsylvanian [*Gardner et al.*, 1988] and may have been in close proximity to the Peninsular Terrane of southern Alaska by the Late Triassic [*Rioux et al.*, 2007].

[8] Wrangellia extends ~450 km in an arcuate belt across southern Alaska in the Wrangell Mountains, Alaska Range, and Talkeetna Mountains (Figure 1). The northwest margin of Wrangellia is one of the most prominent geophysical features in south central Alaska and is exposed along the Talkeetna Suture Zone [*Glen et al.*, 2007]. The suture between Wrangellia and transitional crust to the northwest is well-defined geophysically [*Glen et al.*, 2007] and lies directly in the axis of the major orocline of southern Alaska, where structures curve from northwest- to northeast-trending [e.g., *Plafker*

Figure 2. Geologic map and stratigraphy of the Wrangell Mountains, Alaska (map location shown by box 1 in Figure 1). (a) Stratigraphic column depicts late Paleozoic to Jurassic units on the south side of the Wrangell Mountains, derived from *Smith and MacKevett* [1970] and *MacKevett* [1978]. (b) Simplified map showing the distribution of the Nikolai Formation (green) in the Wrangell Mountains, derived from the GIS-based digital map compilation of *Wilson et al.* [2005]. The four areas of field study are outlined with labeled boxes. The red lines are faults, gray lines are glaciers, and blue lines are rivers.

et al., 1994]. Wrangellia is bounded by the Denali Fault to the northeast and extends more than 300 km to the southeast in Yukon.

2.1.1. Wrangell Mountains

[9] Wrangellia stratigraphy is well-exposed in a northwest-trending belt extending ~100 km along the southern flank of the Wrangell Mountains in Wrangell-St. Elias National Park (Figure 2). The Nikolai Formation unconformably overlies the Skolai Group, which comprises Pennsylvanian to Early Permian volcanic arc sequences and marine sediments of the Station Creek and Hasen Creek Formations, respectively [*Smith and MacKevett*, 1970; Figure 2]. The Skolai Group is intruded by mafic and ultramafic intrusive bodies related to the Nikolai basalts. Exposures of the Nikolai basalts cover ~1057 km² in Wrangell-St. Elias National Park and are approximately 3.5–4 km in total thickness. Over 3.5 km of marine sedimentary rocks, ranging in age from Late Triassic to Late Jurassic, overlie the Nikolai Formation in the Wrangell Mountains [*MacKevett et al.*, 1997], and in turn are overlain by Cretaceous sedimentary

sequences and the Miocene to Holocene Wrangell volcanics [*MacKevett*, 1978; *Richter et al.*, 1990].

2.1.2. Eastern Alaska Range

[10] The Nikolai Formation in the eastern Alaska Range and small areas of the Talkeetna Mountains is exposed over ~666 km² and is 3.5–4 km thick in the Amphitheater and Clearwater Mountains (Figure 1). Volcanic and marine sedimentary sequences similar to the late Paleozoic successions in the Wrangell Mountains underlie the Nikolai basalts in the Alaska Range [*Nokleberg et al.*, 1994]. The most significant occurrence of plutonic rocks associated with the Nikolai basalts occurs in the Amphitheater Mountains within a broad synform. Sequences overlying the Nikolai basalts are poorly exposed in the Amphitheater Mountains but preserve interbedded volcanic and sedimentary horizons that give way to fine-grained marine sedimentary strata.

2.2. Age of the Nikolai Formation

[11] Biostratigraphy and geochronology provide bounds on the age and duration of emplacement of the Nikolai basalts. Fossil assemblages in finely

Figure 3. Photographs of the base of the Nikolai Formation in the Wrangell Mountains, Alaska. (a) Westward dipping Paleozoic arc volcanic rocks of the Station Creek Formation overlain by Early Permian shale and limestone (Phc-Hasen Creek Formation; Pgh-Golden Horn Limestone Lentil), isolated lenses of Middle Triassic “Daonella beds” (TRd), basalt flow-conglomerate with local pillows, and massive subaerial flows on the north side of Skolai Creek. Photograph by Ed MacKevett Jr. (b) Close-up photograph of area b in Figure 3a. (c) Close-up photograph of area c in Figure 3b showing basal flow-conglomerate with clasts of rounded cobbles of white limestone (<20 cm) derived from Golden Horn Limestone Lentil and red basalt (<40 cm) from Station Creek Formation. Pen (14 cm) in middle of photograph for scale.

laminated shale immediately beneath the Nikolai basalts in the Wrangell Mountains indicate a Middle to Late Ladinian age (~ 235 – 232 Ma) [Jones *et al.*, 1977; C. A. McRoberts, personal communication, 2007] and fossils in limestone disconformably overlying the Nikolai Formation are Late Carnian to Early Norian (~ 223 – 212 Ma) [Armstrong and MacKevett, 1977; Plafker *et al.*, 1989]. Five $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages for hornblende and biotite from intrusive rocks in the Amphitheater Mountains in the Alaska Range, which are interpreted to be comagmatic with Nikolai basalts, indicate for-

mation of these rocks at ~ 231 – 225 Ma [Bittenbender *et al.*, 2007; Schmidt and Rogers, 2007]. Three Nikolai basalt samples from the Wrangell Mountains yielded $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating ages of 228.3 ± 5.2 , 232.8 ± 11.5 , and 232.4 ± 11.9 Ma [Lassiter, 1995].

3. Volcanic Stratigraphy

[12] Field studies in Alaska focused in three general areas where parts of the entire flood basalt

Figure 4. Photograph of ~1000 m of continuous subaerial flood basalt stratigraphy at the top of the Nikolai Formation along Glacier Creek in the Wrangell Mountains, Alaska. The yellow line marks the contact between Nikolai basalts and the overlying Chitistone Limestone.

stratigraphy are well exposed: the southern flank of the Wrangell Mountains and the Amphitheater and Clearwater Mountains in the southern part of the eastern Alaska Range (Figure 1).

[13] In the Wrangell Mountains, four areas were examined and sampled: Skolai Creek, Glacier Creek, Hidden Lake Creek, and Nugget Creek (Figure 2). The volcanic stratigraphy in the Wrangell Mountains is predominantly subaerial flows with <100 m of submarine flows along the base. The base of the Nikolai Formation is exposed at Skolai Creek where basalt flow-conglomerate, pillow breccia, and minor pillow basalt unconformably overlie the Paleozoic Sicker Group (Figures 2 and 3). Middle to upper portions of the flood basalt stratigraphy are well exposed above Glacier Creek, where massive maroon- and green-colored flows form monotonous sequences with amygdaloidal-

rich horizons and no discernible erosional surfaces or sediments between flows (Figure 4). The top of the flood basalts are best exposed around Hidden Lake Creek where a sharp contact between Nikolai basalts and overlying Chitistone Limestone is mostly a smooth surface with minimal evidence of weathering [Armstrong and MacKevett, 1982] (Figure 5).

[14] In the Amphitheater Mountains, fieldwork was concentrated in five areas: Glacier Gap Lake, Landmark Gap Lake, Tangle Lakes (West), Sugarloaf Mountain, and Rainy Creek (Figure 6). The Amphitheater Mountains south of the Eureka Creek Fault form a broad synform consisting of flood basalts (3.5 km thick) with basal sill complexes and associated mafic and ultramafic rocks exposed along the outer margins. The lower ~500 m of volcanic stratigraphy are submarine

Figure 5. Photographs showing the top of the Nikolai Formation in the Wrangell Mountains, Alaska. (a) Chitistone Limestone overlying the Nikolai Formation above Hidden Creek in the Wrangell Mountains. Faulting has offset the contact. (b) Close-up photograph of uppermost Nikolai flow and base of the Chitistone Limestone from where Figure 5a was taken. (c) Cobbles <10 cm long along the contact between the Chitistone Limestone and Nikolai Formation. The oxidized cobbles are subangular, closely packed, aligned along their long axes, and are glomeroporphyritic basalt identical to the uppermost flows of the Nikolai Formation. Sledgehammer handle (4 cm wide) for scale. Thinly bedded siltstone also occurs along the contact.

flows and the stratigraphy above this is mostly massive subaerial flows (<15 m thick). The lowest part of ~1000 m of sills and submarine flows (e.g., Lower Tangle Lakes) consists of nonfossiliferous shale and siliceous argillite (<4 m thick) interbedded with massive mafic sills (2–30 m thick), in turn overlain by pillow basalt (Figure 7). Sills interbedded with thinly bedded basaltic sandstone and minor hyaloclastite also occur higher in the submarine stratigraphy (Figures 6 and 7).

[15] A small segment of Wrangellia in the northern part of the Amphitheater Mountains consists of a heterogeneous assemblage of mafic and ultramafic plutonic and volcanic rocks that forms a wedge between the Broxson Gulch Thrust and the Eureka Creek Fault (Figure 6). These units are distinct from those within the synform and therefore a suite

of eight samples, including several altered olivine-bearing picritic tuffs (Rainy Creek picrites), were collected for comparison to Nikolai basalts within the synform.

[16] In the Clearwater Mountains (~40 km west of the Amphitheater Mountains), the lower <400 m of the volcanic stratigraphy is submarine flows and the remainder of the stratigraphy is primarily subaerial flows (see Auxiliary Material).¹ The lowest flows are pillow basalt that directly overlie thin beds of shale and argillite (<3 m thick). Picritic pillow lavas have been found in the submarine stratigraphy. The upper parts of the volcanic stratigraphy contain subaerial flows (or

¹Auxiliary materials are available in the HTML. doi:10.1029/2008GC002092.

Figure 6. Simplified geologic map and stratigraphy of the Amphitheater Mountains, Alaska (map location shown by box 2 in Figure 1). (a) Stratigraphic column with sample lithologies and estimated vesicularity for flood basalts from the lower part of the volcanic stratigraphy, derived from three traverses marked by red lines in Figure 6b. Vesicularity estimated visually from thin-sections. (b) Generalized geology of the Nikolai Formation and related plutonic rocks in the Amphitheater Mountains. Five main field areas are outlined with numbered boxes (see legend). Map derived from *Nokleberg et al.* [1992] and the digital compilation of *Wilson et al.* [1998]. (c) Schematic cross-section of Amphitheater Mountains from A to A' in Figure 6b, adapted from *Nokleberg et al.* [1985].

sills) with columnar jointing, minor occurrences of tuff and volcanic breccia, and limestone and argillite lenses interbedded with flows are overlain by fine-grained sediments with diagnostic index fossils (bivalve *Halobia* and ammonoid *Tropites* [Smith, 1981]).

[17] A total of 111 samples of the Nikolai Formation and several Paleozoic, late Mesozoic, and Cenozoic volcanic and sedimentary rocks were collected for petrography and geochemical analysis. Fifty-three of these samples were selected for geochemistry based on the visual degree of alteration (see Auxiliary Material) and are grouped into high- and low-titanium basalts, sills, and picrites based on geochemistry. The sample preparation and analytical methods for whole-rock chemistry,

major elements, trace elements, and Sr, Nd, Hf, and Pb isotopes are described in Appendix A.

4. Whole-Rock Chemistry

4.1. Major and Trace Element Compositions

[18] The most noteworthy feature of the major element chemistry of the Nikolai Formation is two clearly distinguishable groups of high- and low-titanium basalt (Figure 8). The low-titanium basalts range from 0.4 to 1.2 wt % TiO_2 and the high-titanium basalts range from 1.6 to 2.4 wt % TiO_2 (Figure 8; Table 1). The high-titanium basalts have a limited range in MgO (5.7–7.9 wt % MgO, except for one plagioclase-rich flow with 4.8 wt %

Figure 7. Photographs of the base of the Nikolai Formation in the Amphitheater Mountains, east central Alaska Range, Alaska (from the Tangle Lakes (West) area shown in Figure 6). (a) Basal sills and sediments beneath submarine flows. Letters denote locations of other photographs. (b) Fissile shale (~4 m thick) and a mafic sill from the lowermost exposure of shale. (c) Pillow basalt with shale between pillows lying directly above shale similar to Figure 7b. (d) Pillow basalt (pillow tubes are <1 m diameter in cross-section) in the lowermost flow (13 m thick) in the Tangle section. Figure 7c is from the base of this flow. Sledgehammer (80 cm long) for scale. (e) Sequence of at least four massive sills (<8 m thick) interbedded with fine-grained tuff (<2 m thick). Tuff layers interbedded with sills contain plagioclase crystals (<0.5 mm), curvilinear shards, and local areas of volcanic breccia containing basaltic clasts with abundant small acicular plagioclase (<0.5 mm).

MgO) and SiO₂ (49.2–52.1 wt %), whereas the low-titanium basalts extend to higher MgO and have a significantly larger range in MgO (6.4–12.0 wt %) and SiO₂ (46.7–52.2 wt %). The low-

titanium basalts have noticeably higher Mg # (mean Mg # = 60) than the high-titanium basalts (mean Mg # = 50; Mg # = molar MgO/(MgO + FeO_T) × 100, where FeO_T refers to all Fe expressed

Figure 8. Whole-rock major element variation diagrams versus MgO for the Nikolai Formation in Alaska with fields for the Nikolai Formation in Yukon [Greene *et al.*, 2008a]. The boundary of the alkalic and tholeiitic fields is that of MacDonal and Katsura [1964]. Total iron expressed as FeO and oxides are plotted on an anhydrous, normalized basis. Note the clear distinction between the high- and low-titanium basalts in Figure 8b and the difference in alkali contents between the Nikolai basalts in Alaska and Yukon in Figure 8a. Fields for Nikolai basalts in Yukon are green for low-Ti basalts and red for high-Ti basalts.

as FeO). Nearly all of the Nikolai basalts in Alaska fall within the tholeiitic field in a total alkalis versus silica plot, with low-titanium basalts generally having lower total alkalis than the high-titanium basalts. The low-titanium basalts exhibit broadly decreasing trends of TiO_2 , FeO_T , and Na_2O with increasing MgO (Figure 8) and have higher loss-on-ignition (LOI; mean LOI = 2.7 ± 1.3 wt %) than the high-titanium basalts (mean LOI = 1.9 ± 1.5 wt %; Table 1). Low-titanium basalts with >8 wt % MgO have higher concentrations of Ni than the high-titanium basalts and the three picrite samples have noticeably higher Ni concentrations (525–620 ppm) than all basalts. Both the high- and

low-titanium basalts have a large range in CaO, which appears to be independent of MgO variation. A single Clearwater picrite (13.6 wt % MgO) and two Rainy Creek picrites (15.5–16.2 wt % MgO) have higher MgO with similar TiO_2 , FeO_T , and alkali contents to the low-titanium basalts, however, the Rainy Creek picrites have lower Al_2O_3 . The basal flow-conglomerate from the Wrangell Mountains has distinct major element chemistry compared to the other Nikolai basalts. Nikolai basalts in Alaska are lower in total alkalis than basalts from Yukon due to alkali metasomatism during alteration of the Yukon basalts [Greene *et al.*, 2008a].

Table 1 (Sample). Major Element and Trace Element Abundances in Whole-Rock Samples of Nikolai Basalts, Alaska^a [The full Table 1 is available in the HTML version of this article at <http://www.g-cubed.org>]

Sample	5707A3	5708A2	5710A2	5710A3	5712A2	5714A1	5714A3	5715A1 (1)	5715A1 (2)	5715A5
Group	HI-TI	HI-TI	HI-TI	HI-TI	HI-TI	HI-TI	HI-TI	HI-TI	HI-TI	LOW-TI
Area	WM	WM	WM	WM	WM	WM	WM	WM	WM	WM
Flow	FLO	FLO	FLO	FLO	FLO	FLO	FLO	FLO	FLO	FLO
UTM EW	6816521	6813830	6838676	6836850	6838178	6826371	6826390	6827794	6827794	6828050
UTM NS	430777	428595	356035	356266	353987	384783	384806	383399	383399	383641
<i>Unnormalized Major Element Oxides</i>										
SiO ₂	49.74	48.40	48.81	50.02	49.90	49.31	50.21	49.61	49.41	50.25
TiO ₂	1.96	2.36	2.4	1.95	1.89	1.66	1.6	1.69	1.68	1.14
Al ₂ O ₃	13.37	13.49	15.21	14.45	13.76	15.58	16.01	15.56	15.75	16.69
Fe ₂ O ₃ *	14.05	16.14	12.94	13.39	13.76	13.21	10.99	13	12.97	10.39
MnO	0.27	0.27	0.23	0.18	0.24	0.17	0.16	0.2	0.2	0.18
MgO	6.69	5.89	6.85	6.56	6.74	6.6	6.64	6.63	6.62	7.94
CaO	10.61	10.09	9.16	8.56	11.35	10.8	9.97	11.09	11.04	9.48
Na ₂ O	2.64	2.47	3.15	3.56	1.87	2.08	3.77	1.84	1.82	3.36
K ₂ O	0.29	0.61	0.58	1.03	0.22	0.42	0.28	0.2	0.2	0.67
P ₂ O ₅	0.16	0.23	0.21	0.18	0.16	0.15	0.14	0.15	0.14	0.09
Total	99.78	99.95	99.54	99.88	99.89	99.98	99.77	99.97	99.83	100.19
LOI	1.68	1.41	2.37	2.47	1.28	2.39	3.12	0.84	1.84	3.57
<i>Trace Elements</i>										
La		10.32			8.08			6.56	6.56	3.74
Ce		24.25			21.79			17.07	17.07	10.69
Pr		3.66			2.90			2.35	2.35	1.49
Nd		18.83			14.73			12.20	12.20	7.68
Sm		5.22			4.19			3.51	3.51	2.32
Eu		1.73			1.43			1.25	1.25	0.90
Gd		5.57			4.17			3.80	3.80	2.55
Tb		1.02			0.77			0.72	0.72	0.50
Dy		6.84			5.04			4.77	4.77	3.34
Ho		1.35			0.99			0.98	0.98	0.69
Er		4.02			2.85			2.86	2.86	1.98
Tm		0.51			0.33			0.36	0.36	0.25
Yb		3.58			2.37			2.59	2.59	1.77
Lu		0.53			0.36			0.40	0.40	0.28
Sc		44.06			42.52			41.17	41.17	38.50
V	362	411	349	337	346	329	276	354	352	249
Cr	165	62	167	119	133	156	282	165	167	460
Co		47			45			44	44	39
Ni	75	57	89	69	73	82	81	85	85	116
Cu		19			1067			126	126	64
Zn	121	176	126	108	113	109	88	110	111	68
Ga	19	20	21	19	19	19	17	20	19	15
Rb	3.4	9.7	6.1	15	2.2	5.2	2.6	1	1	8.5
Sr	237	162	263	481	184	334	394	184	184	437
Y	28.1	36.1	31.6	27.8	25.8	26.2	22.6	26	26.2	18.3
Zr	113	148	145	115	110	99	93	98	98	60
Nb	10.1	12.5	12.2	9.7	9.9	7.7	7.3	7.7	7.7	4.4
Cs		0.08			0.14			0.28	0.28	0.83
Ba	79	108	147	246	70	63	56	55	56	129
Hf		4.10			3.15			2.78	2.78	1.79
Ta		0.74			0.67			0.48	0.48	0.30
Pb		1.59			0.81			0.52	0.52	0.44
Th		0.98			0.72			0.64	0.64	0.34

^aMajor elements are measured in wt% oxide and trace elements are measured in ppm. Abbreviations for group are HI-TI, high-titanium; LOW-TI, low-titanium; RC, Rainy Creek; RCPIC, Rainy Creek picrite; CWPIC, Clearwater picrite. Abbreviations for flow are: FLO, massive flow; PIL, pillow basalt; FLO-BRE, flow-conglomerate-pillow breccia; SIL, sill; TUF, tuff. Abbreviations for area are: WM, Wrangell Mountains; TANGLE, Tangle Lakes; GLAC, Glacier Gap Lake; CLEAR, Clearwater Mountains; RAINY, Rainy Creek. Sample locations are given using the Universal Transverse Mercator (UTM) coordinate system (NAD83; zones 6 and 7). XRF analyses were performed at University of Massachusetts Ronald B. Gilmore XRF Laboratory. Fe₂O₃* is total iron expressed as Fe₂O₃. LOI is loss-on-ignition. Totals have not been resummed using the LOI value. Elements by XRF: Sc, V, Cr, Ni, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba. Elements by ICP-MS: REE, Co, Cu, Cs, Hf, Ta, Pb, Th, U.

Figure 9. Whole-rock REE and other incompatible-element concentrations for the Nikolai Formation in Alaska. (a, c, and e) Chondrite-normalized REE patterns for high-titanium basalts, low-titanium basalts, and picrites, respectively, from field areas in southern Alaska. (b, d, and f) Primitive mantle-normalized trace element patterns for high-titanium basalts, low-titanium basalts, and picrites, respectively. All normalization values are from *McDonough and Sun* [1995]. Depleted MORB average from *Salters and Stracke* [2004]. Note the clear distinction between LREE-enriched high-titanium basalt and mostly LREE-depleted low-titanium basalts. Trace element patterns for the basal flow-conglomerate and one Clearwater sample are not shown in Figure 9d for clarity.

[19] The low-titanium basalts are characterized by a range of flat and slightly light rare earth element (LREE) -depleted chondrite-normalized REE patterns (mean $\text{La}/\text{Sm}_{\text{CN}} = 0.8 \pm 0.5$, except one LREE-enriched sample) with flat, parallel heavy

REE (HREE) segments (mean $\text{Dy}/\text{Yb}_{\text{CN}} = 1.0 \pm 0.2$; Figure 9). The high-titanium basalts form a tight range of parallel LREE-enriched patterns (mean $\text{La}/\text{Yb}_{\text{CN}} = 2.3 \pm 0.9$) with higher REE abundances (mean $\text{Yb}_{\text{CN}} = 16.1 \pm 6.4$) than the

Figure 10. Whole-rock trace element concentration (in ppm) variations and ratios for the Nikolai Formation in Alaska (except Figure 10b is versus MgO in wt. %), with fields for the Nikolai Formation in Yukon. (a) Nb versus Zr. (b) Nb/La versus MgO. (c) Th versus Hf. (d) Sr versus Y/Nb (Yukon fields not shown). Note the clear distinction between the high- and low-titanium basalts in each of the plots. Fields for Nikolai basalts in Yukon are green for low-Ti basalts and red for high-Ti basalts.

low-titanium basalts (mean $Yb_{CN} = 11.0 \pm 2.2$; Figure 9). Several low-titanium basalts from the Amphitheater Mountains have positive Eu anomalies (Figure 9). Two high-titanium basalts from the Wrangell Mountains have patterns with flatter HREE segments. The basal flow-conglomerate from the Wrangell Mountains has a distinct LREE-enriched pattern ($La/Sm_{CN} = 2.7$) with a flat HREE segment ($Dy/Yb_{CN} = 1.2$). The Rainy Creek picrites are LREE-enriched ($La/Yb_{CN} = 2.8-3.1$) and the REE pattern of the Clearwater picrite is LREE-enriched ($La/Sm_{CN} = 1.9$) with a flat HREE segment ($Dy/Yb_{CN} = 1.0$).

[20] The low-titanium basalts have mostly parallel, primitive mantle-normalized trace element patterns with pronounced high field strength element (HFSE) depletions, especially for Nb, Ta, and Zr, relative to LILE and REE (Figure 9), and the HFSE (Nb and Zr) form linear trends in binary diagrams (Figure 10). The LILE segments of trace element patterns for low-titanium basalts are parallel and each of the patterns has a pronounced positive Sr anomaly, relative to Nd and Sm. The high-titanium basalts form a tight range of parallel, concave-downward extended trace element patterns with negative Pb anomalies, relative to Ce and Pr, and small negative K anomalies, relative to U and Nb

Figure 11. Whole-rock Sr, Nd, and Hf isotopic compositions for the Nikolai Formation in Alaska. (a) $^{176}\text{Hf}/^{177}\text{Hf}$ versus $^{176}\text{Lu}/^{177}\text{Hf}$. (b) $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{147}\text{Sm}/^{144}\text{Nd}$. (c) Initial ϵ_{Nd} versus $^{87}\text{Sr}/^{86}\text{Sr}$; age correction to 230 Ma. (d) Initial ϵ_{Hf} versus ϵ_{Nd} . (e) Initial ϵ_{Hf} versus $^{87}\text{Sr}/^{86}\text{Sr}$. Average 2σ error bars are shown in a corner of Figures 11a–11e.

(Figure 9). The LILE in the high-titanium basalts are slightly depleted relative to the HFSE and LREE. The Clearwater picrite is depleted in HFSE with a positive Sr anomaly, similar to the low-titanium basalts, whereas the Rainy Creek picrites have gently negative-sloping patterns with negative Sr anomalies (Figure 9).

4.2. Sr-Nd-Hf-Pb Isotopic Compositions

[21] The high- and low-titanium Wrangellia basalts in Alaska have distinct Hf and Sr isotope ratios (Figure 11). The low-titanium basalts have higher initial ϵ_{Hf} (+13.7 to +18.4) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70422–0.70554) than the high-titanium basalts (initial ϵ_{Hf} = +9.7 to +10.7, initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.70302–

0.70376), except for sample 5715A5, which has anomalous chemistry (age correction to 230 Ma; Figure 11; Tables 2 and 3). The low-titanium basalts have a narrower range in initial ϵ_{Nd} (+4.6 to +5.4) than the high-titanium basalts (initial ϵ_{Nd} = +6.0 to +8.1) and a wider range in initial ϵ_{Hf} , except for three low-titanium samples with higher initial ϵ_{Nd} (+7.0 to +7.6). The basal flow-conglomerate from the Wrangell Mountains has similar initial Sr, Nd, and Hf isotopic compositions to the high-titanium basalts. The Clearwater picrite lies between the high- and low-titanium basalts in initial ϵ_{Hf} and has the lowest initial ϵ_{Nd} and initial $^{87}\text{Sr}/^{86}\text{Sr}$ at the upper end of the range of all samples. The two Rainy Creek picrites have similar Sr, Nd, and Hf

Table 2. Sr and Nd Isotopic Geochemistry of Whole-Rock Samples of Nikolai Basalts, Alaska

Sample	Group ^a	Area ^b	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	2σ _m	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr _t	230 Ma	Sm (ppm)	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	2σ _m	ε _{Nd}	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd _t	230 Ma	ε _{Nd(t)}
5708A2	Hi-Ti	WM	9.7	162	0.703776	7	0.1733	0.70321	0.70321	5.22	18.83	0.513011	5	7.3	0.1677	0.51276	0.51276	8.1
5801A2	Hi-Ti	CL	1.7	225	0.703365	8	0.0219	0.70329	0.70329	5.55	21.10	0.512934	7	5.8	0.1592	0.51269	0.51269	6.9
5719A5	Hi-Ti	WM	5.9	200	0.703344	8	0.0854	0.70306	0.70306	4.45	16.26	0.512988	6	6.8	0.1653	0.51274	0.51274	7.7
5801A5	Hi-Ti	CL	5.9	187	0.703389	8	0.0913	0.70309	0.70309	4.25	15.51	0.512937	6	5.8	0.1659	0.51269	0.51269	6.7
5712A2	Hi-Ti	WM	2.2	184	0.703179	8	0.0346	0.70307	0.70307	4.19	14.73	0.512997	6	7.0	0.1720	0.51274	0.51274	7.7
5726A1	Hi-Ti	TA	2.1	239	0.703844	7	0.0254	0.70376	0.70376	4.07	14.35	0.512908	7	5.3	0.1713	0.51265	0.51265	6.0
5810A10	Hi-Ti	TA	2.6	231	0.703448	9	0.0326	0.70334	0.70334	3.95	13.98	0.512918	6	5.5	0.1707	0.51266	0.51266	6.2
5715A1	Hi-Ti	WM	1.0	184	0.703619	7	0.0157	0.70357	0.70357	3.51	12.20	0.513017	7	7.4	0.1738	0.51276	0.51276	8.1
5715A5	Low-Ti	WM	8.5	437	0.703602	8	0.0563	0.70342	0.70342	2.32	7.68	0.513030	5	7.6	0.1829	0.51275	0.51275	8.1
5802A5	Low-Ti	CL	3.0	252	0.704942	6	0.0345	0.70483	0.70483	2.19	6.68	0.513000	6	7.1	0.1980	0.51270	0.51270	7.0
5810A6	Low-Ti	TA	2.0	170	0.704704	7	0.0340	0.70459	0.70459	1.55	4.52	0.512924	6	5.6	0.2070	0.51261	0.51261	5.3
5810A1	Low-Ti	TA	0.9	151	0.704721	7	0.0172	0.70466	0.70466	1.26	3.31	0.512963	5	6.3	0.2303	0.51262	0.51262	5.4
5727A7	Low-Ti	TA	1.5	155	0.704865	9	0.0280	0.70477	0.70477	1.30	3.86	0.512906	7	5.2	0.2038	0.51260	0.51260	5.0
5802A2	Low-Ti	CL	2.1	303	0.705604	8	0.0201	0.70554	0.70554	1.31	4.04	0.512872	7	4.6	0.1959	0.51258	0.51258	4.6
5719A1	Basal	WM	25.4	158	0.705138	7	0.4652	0.70362	0.70362	4.26	20.65	0.512892	6	5.0	0.1248	0.51270	0.51270	7.1
5725A4	Sill (Hi-Ti)	TA	16.5	207	0.703775	8	0.2306	0.70302	0.70302	4.30	15.16	0.512916	7	5.4	0.1715	0.51266	0.51266	6.2
5727A2	Sill (Low-Ti)	TA	1.7	76	0.704532	8	0.0647	0.70432	0.70432	1.22	2.92	0.513098	6	9.0	0.2531	0.51272	0.51272	7.3
5727A3	Sill (Low-Ti)	TA	1.8	117	0.704872	8	0.0445	0.70473	0.70473	1.23	2.92	0.513115	8	9.3	0.2553	0.51273	0.51273	7.6
5727A6	Sill (Low-Ti)	TA	0.6	123	0.704857	10	0.0141	0.70481	0.70481	1.11	3.05	0.512930	7	5.7	0.2203	0.51260	0.51260	5.0
5727A6 (dup)	Sill (Low-Ti)	TA	0.6	123	0.704851	8	0.0141	0.70480	0.70480	1.13	3.09	0.512928	10	5.7	0.2202	0.51260	0.51260	5.0
5810A2	Sill (Low-Ti)	TA	0.8	141	0.704846	7	0.0164	0.70479	0.70479	1.16	3.21	0.512917	6	5.4	0.2187	0.51259	0.51259	4.8
5810A4	Sill (Low-Ti)	TA	0.4	198	0.704235	8	0.0058	0.70422	0.70422	1.96	6.12	0.512886	6	4.8	0.1937	0.51259	0.51259	4.9
5802A4	Pierite	CL	0.4	183	0.705530	9	0.0063	0.70551	0.70551	1.69	6.61	0.512746	6	2.1	0.1544	0.51251	0.51251	3.3
5808A2	Pierite	RC	6.1	127	0.704124	10	0.1395	0.70367	0.70367	2.69	9.85	0.512880	6	4.7	0.1649	0.51263	0.51263	5.7
5808A3	Pierite	RC	26.4	93	0.706307	9	0.8265	0.70360	0.70360	3.01	11.57	0.512811	6	3.4	0.1576	0.51257	0.51257	4.5

^a Hi-Ti, high-titanium basalt; Low-Ti, low-titanium basalt; Basal, basal flow-conglomerate.

^b Abbreviations for area are WM, Wrangell Mountains; TA, Tangle Lake; GG, Glacier Gap Lake; CL, Clearwater Mountains; RC, Rainy Creek. (dup) indicates complete chemistry duplicate. All trace-element and isotopic analyses were carried out at the PCIGR. The analytical methods are described in Appendix A.

Table 3. Hf Isotopic Compositions of Whole-Rock Samples of Nikolai Basalts, Alaska

Sample	Group ^a	Area ^b	Lu (ppm)	Hf (ppm)	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ _m	ε _{Hf}	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf _t 230 Ma	ε _{Hf(t)}
5708A2	Hi-Ti	WM	0.53	4.10	0.283016	5	8.6	0.0184	0.282935	11.0
5801A2	Hi-Ti	CL	0.38	4.03	0.282986	6	7.6	0.0134	0.282926	10.7
5719A5	Hi-Ti	WM	0.36	3.23	0.283009	6	8.4	0.0159	0.282939	11.1
5801A5	Hi-Ti	CL	0.36	3.17	0.283018	7	8.7	0.0161	0.282947	11.4
5712A2	Hi-Ti	WM	0.36	3.15	0.283003	6	8.2	0.0162	0.282931	10.8
5726A1	Hi-Ti	TA	0.27	2.66	0.282999	6	8.0	0.0146	0.282934	11.0
5810A10	Hi-Ti	TA	0.32	2.84	0.282988	6	7.6	0.0160	0.282917	10.3
5715A1	Hi-Ti	WM	0.40	2.78	0.283012	5	8.5	0.0202	0.282922	10.5
5715A5	Low-Ti	WM	0.28	1.79	0.283042	6	9.6	0.0223	0.282943	11.3
5802A5	Low-Ti	CL	0.33	1.51	0.283299	14	18.6	0.0309	0.283162	19.0
5810A6	Low-Ti	TA	0.33	0.88	0.283302	6	18.7	0.0537	0.283063	15.5
5810A1	Low-Ti	TA	0.27	0.66	0.283396	5	22.1	0.0581	0.283137	18.1
5727A7	Low-Ti	TA	0.33	0.70	0.283390	7	21.9	0.0670	0.283092	16.6
5802A2	Low-Ti	CL	0.39	0.78	0.283358	7	20.7	0.0717	0.283039	14.7
5719A1	Basal	WM	0.31	2.30	0.283008	6	8.3	0.0188	0.282924	10.6
5725A4	Sill (Hi-Ti)	TA	0.30	3.08	0.282991	5	7.7	0.0141	0.282928	10.7
5727A2	Sill (Low-Ti)	TA	0.27	0.80	0.283328	7	19.7	0.0489	0.283110	17.2
5727A3	Sill (Low-Ti)	TA	0.26	0.87	0.283331	9	19.8	0.0425	0.283142	18.3
5727A6	Sill (Low-Ti)	TA	0.24	0.57	0.283354	8	20.6	0.0602	0.283086	16.3
5810A2	Sill (Low-Ti)	TA	0.27	0.66	0.283374	6	21.3	0.0581	0.283115	17.4
5810A4	Sill (Low-Ti)	TA	0.32	0.96	0.283245	8	16.7	0.0481	0.283031	14.4
5802A4	Picrite	CL	0.27	1.05	0.283145	6	13.2	0.0365	0.282983	12.7
5808A2	Picrite	RC	0.22	1.71	0.283017	7	8.7	0.0184	0.282935	11.0
5808A3	Picrite	RC	0.25	1.88	0.282977	6	7.2	0.0189	0.282893	9.5

^a Hi-Ti, high-titanium basalt; Low-Ti, low-titanium basalt; Basal, basal flow-conglomerate.

^b Abbreviations for area are WM, Wrangell Mountains; TA, Tangle Lake; GG, Glacier Gap Lake; CL, Clearwater Mountains; RC, Rainy Creek. All trace-element and isotopic analyses were carried out at the PCIGR. The analytical methods are described in Appendix A.

isotope ratios to high-titanium basalts with slightly lower initial ε_{Nd} (Figure 11).

[22] The high- and low-titanium basalts have indistinguishable age-corrected Pb isotopic compositions, although the high-titanium basalts show a narrower range (Figure 12). The range of initial Pb isotopic compositions for low-titanium basalts is ²⁰⁶Pb/²⁰⁴Pb = 18.421–19.418, ²⁰⁷Pb/²⁰⁴Pb = 15.568–15.609, and ²⁰⁸Pb/²⁰⁴Pb = 37.962–38.481 and the high-titanium basalts have ²⁰⁶Pb/²⁰⁴Pb = 18.504–18.888, ²⁰⁷Pb/²⁰⁴Pb = 15.556–15.587, and ²⁰⁸Pb/²⁰⁴Pb = 38.008–38.451 (Figure 12; Table 4). The basal flow-conglomerate has a slightly lower initial Pb isotopic composition than the high- and low-titanium basalts. The Clearwater picrite has a lower initial Pb isotope ratio than the basalts and the Rainy Creek picrites have noticeably higher initial Pb isotope ratios than the basalts (Figure 12).

5. Alteration

[23] The Nikolai basalts generally preserve primary mineralogical, textural, and volcanological features and have retained most of their primary magmatic

composition. Secondary minerals have replaced variable, but generally small, proportions of primary minerals in the Nikolai Formation and the basalts contain zeolite to prehnite-pumpellyite facies alteration minerals (prehnite + pumpellyite + epidote + chlorite + quartz ± laumontite), primarily making up the amygdules [Stout, 1976; Smith, 1981; MacKevett *et al.*, 1997]. Many of the Nikolai basalts in the synform in the Amphitheater Mountains are exceptionally unaltered compared to flows in the Wrangell and Clearwater Mountains. Vesicles and interpillow voids in the Amphitheater Mountains commonly remain unfilled and secondary minerals are less common.

[24] Seventeen of the 21 low-titanium basalts have LOI greater than 2.5 wt % and greater than 8 wt % MgO, whereas only four high-titanium basalts have greater than 2.5 wt % LOI and all have less than 8 wt % MgO (Figure 13). Three of the four high-titanium basalts that lie within the alkalic field are plagioclase-rich, highly amygdaloidal, and were collected near a mineralized area at the top of the Nikolai Formation. Tight linear arrays are apparent on plots of HFSE and REE (not shown) indicating negligible affect of element mobility. Only a limited group of samples (5808A3, 5802A4, 5802A2,

Figure 12. Pb isotopic compositions of leached whole-rock samples by MC-ICP-MS for the Nikolai Formation in Alaska. Error bars are smaller than symbol size. (a) Measured $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$. (b) Initial $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$; age correction to 230 Ma. (c) Measured $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$. (d) Initial $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$.

5725A4, 5726A1) have LILE concentrations outside the narrow range of most high- and low-titanium basalts (Figure 9) and there is no correlation between LOI and LILE. All of the low-titanium basalts have positive Sr anomalies that are complemented with small positive Eu anomalies in most samples, and none of the high-titanium basalts have Sr anomalies (Figure 9), which indicates Sr concentrations probably represent primary values. U and Th show a linear relationship, whereas Pb and Th do not show a clear relationship (not shown), indicating some secondary mobility of Pb, especially in the low-titanium basalts.

[25] Initial Hf isotopic ratios, and to a lesser extent Sr and Pb isotopic compositions, are close to

magmatic compositions. Several of the more altered samples were not selected for isotopic analyses and leaching effectively removed most of the secondary alteration products [e.g., *Weis et al.*, 2006; *Nobre Silva et al.*, 2008]. Whole-rock Sm/Nd ratios and age-corrected Nd isotopes, however, may be affected by the leaching procedure in submarine rocks older than ~ 50 Ma [Thompson et al., 2008] and this may have caused a small degree of variation between Nd isotope ratios, especially for the low-titanium basalts (Figure 11). The Clearwater picrite (5802A4) was significantly affected by Pb loss and has less radiogenic age-corrected Pb isotopic ratios than the basalts (Figures 9 and 12). The correlation of LOI and $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{238}\text{U}/^{204}\text{Pb}$ in the low- and high-titanium basalts

Table 4. Pb Isotopic Compositions of Whole-Rock Samples of Nikolai Basalts, Alaska

Sample	Group ^a	Area ^b	U (ppm)	Th (ppm)	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	2σ _m	²⁰⁷ Pb/ ²⁰⁴ Pb	2σ _m	²⁰⁸ Pb/ ²⁰⁴ Pb	2σ _m	²³⁸ U/ ²⁰⁴ Pb	²³⁵ U/ ²⁰⁴ Pb	²³² Th/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁴ Pb _t	230 Ma	²⁰⁷ Pb/ ²⁰⁴ Pb _t	230 Ma	²⁰⁸ Pb/ ²⁰⁴ Pb _t	230 Ma
5708A2	Hi-Ti	WM	0.31	0.98	1.59	19.2557	0.0006	15.6040	0.0005	38.7613	0.0014	12.39	0.09	40.95	18.806	15.581	18.806	15.581	38.289	
5801A2	Hi-Ti	CL	0.36	1.24	1.01	19.4404	0.0008	15.6100	0.0007	39.0217	0.0019	23.11	0.17	82.17	18.601	15.567	18.601	15.567	38.074	
5719A5	Hi-Ti	WM	0.25	0.87	0.85	19.3198	0.0007	15.6023	0.0006	38.9183	0.0013	18.64	0.14	67.86	18.643	15.568	18.643	15.568	38.136	
5801A5	Hi-Ti	CL	0.24	0.84	0.72	19.6020	0.0008	15.6197	0.0007	39.1955	0.0019	21.58	0.16	78.29	18.818	15.580	18.818	15.580	38.293	
5712A2	Hi-Ti	WM	0.20	0.72	0.81	19.3834	0.0011	15.5974	0.0009	39.0093	0.0024	16.00	0.12	59.61	18.802	15.568	18.802	15.568	38.322	
5726A1	Hi-Ti	TA	0.23	0.86	0.95	19.4594	0.0008	15.6158	0.0007	39.1506	0.0018	15.73	0.11	60.68	18.888	15.587	18.888	15.587	38.451	
5810A10	Hi-Ti	TA	0.24	0.78	0.76	19.4551	0.0007	15.6141	0.0005	39.0577	0.0014	20.20	0.15	68.74	18.721	15.577	18.721	15.577	38.265	
5715A1	Hi-Ti	WM	0.19	0.64	0.52	19.3815	0.0009	15.6002	0.0008	38.9557	0.0021	24.15	0.18	82.22	18.504	15.556	18.504	15.556	38.008	
5715A5	Low-Ti	WM	0.09	0.34	0.44	19.2520	0.0008	15.5908	0.0007	38.8096	0.0027	13.88	0.10	51.33	18.748	15.565	18.748	15.565	38.218	
5802A5	Low-Ti	CL	0.11	0.34	0.50	19.1708	0.0012	15.6019	0.0011	38.6861	0.0024	14.80	0.11	45.79	18.633	15.575	18.633	15.575	38.158	
5810A6	Low-Ti	TA	0.12	0.28	0.63	19.0178	0.0007	15.5980	0.0006	38.5428	0.0017	11.84	0.09	29.87	18.588	15.576	18.588	15.576	38.198	
5810A1	Low-Ti	TA	0.04	0.09	0.23	19.0025	0.0008	15.5927	0.0007	38.4697	0.0018	11.64	0.08	24.48	18.580	15.571	18.580	15.571	38.188	
5727A7	Low-Ti	TA	0.10	0.29	1.21	19.1190	0.0007	15.6099	0.0005	38.6667	0.0014	5.54	0.04	16.07	18.918	15.600	18.918	15.600	38.481	
5802A2	Low-Ti	CL	0.20	0.56	0.21	21.6909	0.0009	15.7248	0.0009	40.5119	0.0025	62.57	0.45	185.21	19.418	15.609	19.418	15.609	38.376	
5719A1	Basal	WM	1.91	4.18	2.96	19.8855	0.0007	15.6160	0.0006	38.7767	0.0020	41.91	0.30	94.93	18.363	15.539	18.363	15.539	37.682	
5725A4	Sill (Hi-Ti)	TA	0.25	0.83	0.66	19.6092	0.0010	15.6258	0.0009	39.2093	0.0018	24.33	0.18	84.22	18.725	15.581	18.725	15.581	38.238	
5727A2	Sill (Low-Ti)	TA	0.07	0.17	0.55	18.8625	0.0008	15.6021	0.0007	38.4711	0.0019	8.05	0.06	20.11	18.570	15.587	18.570	15.587	38.239	
5727A3	Sill (Low-Ti)	TA	0.07	0.17	0.50	18.9004	0.0009	15.5998	0.0008	38.4641	0.0024	8.68	0.06	22.04	18.585	15.584	18.585	15.584	38.210	
5727A6	Sill (Low-Ti)	TA	0.03	0.07	0.20	18.9076	0.0007	15.5967	0.0006	38.4960	0.0017	8.37	0.06	22.36	18.603	15.581	18.603	15.581	38.238	
5727A6 (dup)	Sill (Low-Ti)	TA	0.03	0.07	0.18	18.9015	0.0005	15.5978	0.0005	38.4883	0.0014	9.40	0.07	25.99	18.560	15.581	18.560	15.581	38.189	
5810A2	Sill (Low-Ti)	TA	0.10	0.27	0.44	19.1968	0.0008	15.6089	0.0007	38.7776	0.0016	14.21	0.10	40.97	18.681	15.583	18.681	15.583	38.305	
5810A4	Sill (Low-Ti)	TA	0.09	0.30	0.26	19.2638	0.0008	15.6103	0.0007	38.8501	0.0018	23.20	0.17	77.04	18.421	15.568	18.421	15.568	37.962	
5802A4	Picrite	CL	0.32	0.89	0.13	23.7352	0.0018	15.8255	0.0013	42.3716	0.0043	168.73	1.22	491.95	17.606	15.514	17.606	15.514	36.699	
5808A2	Picrite	RC	0.26	0.70	0.76	21.2095	0.0014	15.7083	0.0012	40.5540	0.0030	23.59	0.17	64.96	20.353	15.665	20.353	15.665	39.805	
5808A3	Picrite	RC	0.38	1.06	0.65	21.7002	0.0009	15.7379	0.0008	40.5468	0.0024	39.32	0.29	114.80	20.272	15.665	20.272	15.665	39.223	

^a Hi-Ti, high-titanium basalt; Low-Ti, low-titanium basalt; Basal, basal flow-conglomerate.

^b Abbreviations for area are WM, Wrangell Mountains; TA, Tangle Lake; GG, Glacier Gap Lake; CL, Clearwater Mountains; RC, Rainy Creek. (dup) indicates complete chemistry duplicate. All trace-element and isotopic analyses were carried out at the PCIGR. The analytical methods are described in Appendix A.

Figure 13. Loss-on-ignition versus MgO and isotopic ratios for the Nikolai Formation in Alaska. (a) LOI versus MgO. (b) LOI versus measured $^{87}\text{Sr}/^{86}\text{Sr}$. (c) LOI versus measured $^{206}\text{Pb}/^{204}\text{Pb}$. (d) LOI versus measured $^{238}\text{U}/^{206}\text{Pb}$. The two insets show the expanded x axis for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$. Note the generally higher LOI and MgO for the low-titanium basalts. The differences in measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ within the suites of high- and low-titanium basalts are mostly not apparent after age correction.

is a primary feature that is not apparent with age correction (Figure 13). The rather small range of initial Pb and distinct initial Hf and Sr isotopic compositions for high- and low-titanium basalts reflects the isotopic compositions of the sources of Wrangellia flood basalts in Alaska.

6. Flood Basalt Chemostratigraphy

[26] Samples of the Nikolai Formation were collected traversing both upsection and downsection

through the volcanic stratigraphy. An estimate of the relative stratigraphic position of each sample was assigned, which was then used to determine the relationship between stratigraphic position and chemical composition. Figure 14 shows sample numbers, lithologies, relative stratigraphic height, and TiO_2 and MgO contents for Nikolai basalts from the three main areas of Alaska where field-work was undertaken (Figure 1). Each stratigraphic column is a combination of multiple traverses (separated by dashed lines in Figure 14). We are

Figure 14

confident in the relative position of each section of stratigraphy based on the continuous exposure and minimal disruption by faults in these areas. As the trace element and isotopic variations of the basalts generally correspond with variation in TiO_2 (Figures 8–11), only TiO_2 and MgO are shown in Figure 14.

[27] In the Clearwater and Amphitheater Mountains, there is a clear relationship between stratigraphic position and chemical composition of the flood basalts (Figure 14). The low-titanium basalts form the lowermost several hundred meters of flows (~ 10 – 15% of stratigraphy) and the high-titanium basalts form the majority of the flows (~ 85 – 90% of stratigraphy) above the lowest several hundred meters. More of the low-titanium basalts and sills were sampled, partly because the lower sections of volcanic stratigraphy were more easily accessible and partly because there are more interesting relationships with pre-Nikolai sediments and mafic sills and submarine units preserved lower in the stratigraphy. The transition from low- to high-titanium basalts does not appear to coincide with the transition from submarine to subaerial flows, but almost all of the low-titanium basalts that were sampled are submarine flows.

[28] In the Wrangell Mountains, there do not appear to be any low-titanium basalts, except for two anomalous samples (Figure 14). A single sample of the basal flow-conglomerate has a low titanium content ($0.67 \text{ wt } \%$), similar initial ϵ_{Hf} to the high-titanium basalts, and anomalous La/Yb_{CN} (6.4), Ba (1277 ppm), and Th (4.18 ppm ; Figures 8 and 9; Tables 1 and 3). Field observations and several other geochemical characteristics indicate the chemistry of this basal flow conglomerate is the result of considerable assimilation ($\sim 30 \text{ vol } \%$) of material derived from underlying Paleozoic sequences. The next sample upsection, $\sim 20 \text{ m}$ above the uppermost exposure of basal flow-conglomerate in the Wrangell Mountains, does not have visible assimilated material and is high-titanium basalt with normal chemistry. A single sample with a low titanium content ($1.14 \text{ wt } \%$ TiO_2 ; 5715A5) was collected from near the top of the stratigraphy in the Wrangell Mountains, but this sample has similar isotopic composition to the high-titanium basalts, atypical petrographic texture,

and is at the upper range of TiO_2 of low-titanium basalts.

7. Discussion

7.1. Source of Nikolai Basalts

[29] The Nikolai Formation in Alaska has two main lava types with distinct isotopic compositions. The high-titanium basalts in Alaska have depleted Hf and Nd isotopic compositions, although they are not as depleted as most Pacific and Indian mid-ocean ridge basalts (MORB), and overlap and are displaced just below the ocean island basalt (OIB) mantle array (Figure 15). The high-titanium basalts have similar initial Sr and Nd isotopic compositions to Ontong Java Plateau, Hawaii, and Caribbean Plateau basalts and similar initial ϵ_{Hf} to Ontong Java, with slightly lower initial ϵ_{Hf} than most Hawaii and Caribbean basalts (Figure 15). In contrast, the low-titanium basalts are displaced well above the OIB mantle array in a $\epsilon_{\text{Hf}}(t) - \epsilon_{\text{Nd}}(t)$ correlation diagram and have higher initial ϵ_{Hf} than age-corrected Pacific MORB at 230 Ma , with lower initial ϵ_{Nd} than age-corrected Pacific MORB by 3 epsilon units. The Hf isotopic compositions of the low-titanium basalts are 2 to 6 epsilon units higher than most samples from Ontong Java, which have comparable to slightly lower initial ϵ_{Nd} . Sr isotopic compositions for low-titanium basalts extend to significantly higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ than Ontong Java and Hawaii. Three low-titanium basalts with particularly high initial ϵ_{Nd} lie within a field for Indian MORB in $\epsilon_{\text{Hf}}(t) - \epsilon_{\text{Nd}}(t)$ space. Two Rainy Creek picrite samples lie close to the $\epsilon_{\text{Hf}}(t) - \epsilon_{\text{Nd}}(t)$ OIB mantle array with lower initial ϵ_{Nd} than the high-titanium basalts (Figure 15). The high- and low-titanium basalts have uniform initial Pb isotopic compositions that overlap the field for Caribbean basalts and have more radiogenic initial $^{207}\text{Pb}/^{204}\text{Pb}$ than Ontong Java, Hawaii, and a field for the East Pacific Rise (EPR; Figure 15). Pb isotopic compositions for the Wrangellia basalts form a linear trend in $^{208}\text{Pb} - ^{206}\text{Pb}$ space that intersects the field of Pacific MORB compositions and is slightly offset toward lower $^{208}\text{Pb}/^{204}\text{Pb}$ from Ontong Java and Hawaii. The Nikolai basalts have more radiogenic Pb isotopic compositions than MORB, Ontong

Figure 14. Chemostratigraphy of the Nikolai Formation in three areas of Alaska (Clearwater, Amphitheater, and Wrangell Mountains). Each column shows flow type, sample numbers, relative stratigraphic height, and TiO_2 and MgO contents (in $\text{wt } \%$). Dashed lines in each column separate individual traverses. Legend indicates flow type.

Figure 15. Comparison of age-corrected (230 Ma) Sr-Nd-Hf-Pb isotopic compositions for Nikolai basalts in Alaska to age-corrected OIB and MORB (except for Pb plots). (a) Initial ϵ_{Nd} versus $^{87}Sr/^{86}Sr$. (b) Measured and initial $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$. (c) Initial ϵ_{Hf} versus ϵ_{Nd} . (d) Measured and initial $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$. References for data sources are listed in Auxiliary Material (Text S2). Most of the compiled data was extracted from the GEOROC database (<http://georoc.mpch-mainz.gwdg.de/georoc/>). OIB array line from Vervoort *et al.* [1999]. EPR is East Pacific Rise. Dashed lines indicate Bulk Silicate Earth (BSE). Estimation of fields for age-corrected Pacific MORB and EPR at 230 Ma were made using parent-daughter concentrations (in ppm) from Salters and Stracke [2004] of Lu = 0.063, Hf = 0.202, Sm = 0.27, Nd = 0.71, Rb = 0.086, and Sr = 8.36.

Java, and OIB from Hawaii but are similar to basalts of the Caribbean Plateau.

[30] The initial Hf and Nd isotopic compositions of high-titanium basalts indicate a uniform plume-type Pacific mantle source derived from a long-term depleted source, distinct from the source of MORB. In contrast, the low-titanium basalts have initial Hf isotopic compositions that are clearly distinct from OIB and initial Nd isotopic compo-

sitions that are distinct from the Pacific MORB source at 230 Ma. The displacement of the low-titanium basalts well above the OIB array indicates involvement of a depleted component (mantle or crust), distinct from depleted MORB mantle, early in the formation of Nikolai basalts in Alaska. The origin of the isotopic and geochemical signature of the low-titanium basalts is the focus of subsequent discussion sections.

7.2. Lithospheric Involvement in Derivation of the Low-Titanium Basalts

[31] The stratigraphic relationship of the two contrasting lava types in the Nikolai Formation preserves a record of a shift in composition and provides a rare opportunity to evaluate the role of oceanic arc lithosphere in the formation of an oceanic plateau. Thus far, the low-titanium basalts have primarily been recognized in the lowermost part of the stratigraphy in the western part of Wrangellia in Alaska, where there is a substantial section of submarine flows (~500 m). The low-titanium basalts have the complete subduction-zone trace element signature; they have distinct negative-HFSE anomalies (Nb-Ta and Zr -Hf) and are enriched in LILE. The low-titanium basalts also have Hf-Sr-Nd isotopic compositions that are indicative of a component characterized by high Rb/Sr, low Sm/Nd, and high Lu/Hf; they have high initial ϵ_{Hf} and high initial $^{87}\text{Sr}/^{86}\text{Sr}$ compared to the high-titanium basalts. This compositional and stratigraphic evidence suggests involvement of the Paleozoic arc lithosphere in the generation of early erupted low-titanium basalts in the Wrangellia oceanic plateau of Alaska.

7.2.1. Nature of Underlying Paleozoic Arc Lithosphere

[32] The Paleozoic arc (320–285 Ma) and marine sedimentary sequences (Early Permian to Middle Triassic) exposed beneath the Nikolai basalts in Alaska are >2.5 km thick in areas [e.g., *Nokleberg et al.*, 1985]. Recent geophysical studies in southern Alaska by *Saltus et al.* [2007] indicate Wrangellia crust is at least 50 km thick between the Denali and Border Ranges Faults (Figure 1). The arc crust that the Wrangellia oceanic plateau was built upon may have been 20–30 km thick and presumably included a substantial subarc lithospheric mantle that was metasomatized during arc activity.

[33] In the Alaska Range, the Nikolai basalts are underlain, in decreasing order of depth, by the Paleozoic Tetelna Volcanics, the Slana Spur, and Eagle Creek Formations. Tetelna Volcanics (<1000 m) are andesitic and dacitic flows, tuffs interbedded with volcanoclastic rocks, and debris flow deposits; the Slana Spur Formation (~1400 m) is marine volcanoclastics, with lesser limestone and sandstone; and the Eagle Creek Formation (~900 m) is Permian argillite and limestone [Nokleberg *et al.*, 1985]. Numerous comagmatic intermediate to felsic plutonic rocks intrude Tetelna Volcanics and the Slana Spur Formation [Nokleberg

et al., 1994]. In the Wrangell Mountains, the Paleozoic sequences include the Station Creek Formation (~1200 m of mostly basaltic and andesitic flows and 800 m of volcanoclastic sequences) and the sedimentary Hasen Creek Formation (~500 m of chert, black shale, sandstone, bioclastic limestone, and conglomerate) [Smith and MacKevett, 1970; Figure 2]. The late Paleozoic arc sequences beneath the Nikolai basalts in Alaska predate eruption of the Nikolai basalts by ~55–90 Ma. They represent an extinct island arc assemblage that existed in the eastern Panthalassic Ocean in the late Paleozoic to Middle Triassic and formed the substrate upon which the Nikolai basalts were emplaced.

7.2.2. Implications of Trace Element and Isotopic Constraints

[34] The trace element and isotopic compositions of the early erupted low-titanium basalts are not typical of OIB and indicate involvement of a HFSE-depleted component that was different than the plume-type source of the high-titanium basalts. The arc lithosphere is a key suspect for derivation of the low-titanium basalts because (1) the geochemical and isotopic signature of the low-titanium basalts has very similar characteristics to rocks formed in subduction settings [e.g., *Kelemen et al.*, 2003]; (2) arc crust is exposed beneath the Nikolai basalts in Alaska; and (3) the low-titanium basalts only form ~10–15% of the lowest part of the volcanic stratigraphy.

[35] Figure 16 highlights differences in trace elements and isotopic compositions between the high- and low-titanium basalts. The high-titanium basalts form a concentrated cluster of points in each of the plots and show a remarkably small degree of variation, whereas the low-titanium basalts have a noticeably wider range of variation, which mostly does not overlap the range for the high-titanium basalts (Figure 16). The low-titanium basalts have low Nb/Th and Nb/La relative to primitive mantle, which is characteristic of subduction-related rocks [Pearce, 1982]. Except for three samples from the basal flow in the Amphitheater Mountains, which has pelagic sediment between pillow tubes derived from the directly underlying strata and has similar Nb/Th to the high-titanium basalts, the low-titanium basalts have similar Nb/Th and Nb/La to accreted arc crust from the Early Jurassic Talkietna arc exposed in southern Alaska ~50 km south of the Amphitheater Mountains [Greene *et al.*, 2006; Figure 16]. Low Nb/Th in arc magmas is

Figure 16. Trace element ratios and isotopic compositions of the Nikolai Formation in Alaska. (a) $^{176}\text{Lu}/^{177}\text{Hf}$ versus Nb/Th. (b) Initial ϵ_{Nd} versus Nb/Th. (c) Initial ϵ_{Hf} versus Nd/Zr. (d) Zr/Nb versus Y/Nb. (e) Initial ϵ_{Hf} versus Nb/La. (f) Initial ϵ_{Hf} versus Sr/Nd. Primitive mantle (PM) from McDonough and Sun [1995], depleted mantle (DM) from Salters and Stracke [2004]. Talkeetna arc lower crust compositions from Greene et al. [2006] and Talkeetna arc lavas from Clift et al. [2005]. Dashed circles outline samples 5727A2, 5727A3, and 5802A5.

commonly attributed to inheritance from subducted sediments [e.g., *Kelemen et al.*, 2003]. Low Nb/La may be related to a process whereby migration of REE into magma takes place, but mobilization of Nb is inhibited, such as by reaction between magmas and metasomatized peridotite [e.g., *Kelemen et al.*, 1990; *Kelemen et al.*, 1993]. The low-titanium basalts have high Sr/Nd and Nd/Zr relative to primitive mantle and the high-titanium basalts (Figure 16). Elevated Sr relative to REE may indicate addition of Sr to arc lithosphere through aqueous fluids, since Sr is more soluble than REE at high pressure [e.g., *Johnson and Plank*, 1999] or addition from Sr-enriched cumulates from gabbroic lower crust [e.g., *Kelemen et al.*, 2003]. The trace element patterns of the low-titanium basalts have sizable Sr peaks, and negative Nb-Ta and Zr-Hf anomalies, that closely resemble those of gabbroic rocks formed in the lower crust of island arcs (e.g., Early Jurassic Talkeetna arc [*Greene et al.*, 2006]).

[36] Figure 17 utilizes proxies described by *Pearce* [2008] for identifying lithospheric input (Th-Nb) and assessing depth of melting (Ti-Yb). For the Th-Nb proxy, all the high-titanium basalts lie within a diagonal MORB-OIB array parallel to a melting vector, whereas most of the low-titanium basalts are displaced above the array, oblique to the melting vector. The low-titanium basalts follow a trend for lavas that have a subduction component, or have interacted with continental crust, and they are consistent with a relatively small amount of assimilation ($F > 0.9$; F is melt fraction) combined with fractional crystallization (AFC) as shown by the modeling curve of *Pearce* [2008; Figure 17]. A Nb-Th-depleted component is indicated for the low-titanium basalts, which also have similar Nb-Th to Talkeetna arc lavas and lower crust. For the Ti-Yb proxy, high Ti/Yb ratios for high-titanium basalts indicate residual garnet from melting at high pressure, within the OIB melting array, whereas low-titanium basalts lie along a complementary mantle melt depletion trend, similar to compositions of Talkeetna arc lavas [*Pearce*, 2008].

[37] The geochemical and isotopic results for the low-titanium basalts from this study support the hypothesis for involvement of a component derived from subarc lithospheric mantle. *Lassiter et al.* [1995] suggested a minor role for the arc lithosphere in formation of the Nikolai basalts based on a suite of nine samples from the Wrangell Mountains in Alaska. They inferred that assimilation of low ϵ_{Nd} , low Nb/Th arc material may have

affected the composition of the Wrangellia basalts, but that mixing of MORB mantle with low ϵ_{Nd} arc material did not reproduce the trends in the Wrangellia basalts. Rather, *Lassiter et al.* [1995] suggested mixing of a plume-type source, with $\epsilon_{\text{Nd}} = +6$ to $+7$, with arc material with low Nb/Th could reproduce variations in the Wrangellia flood basalts. They noted that the absence of low Nb/La ratios in flood basalts from their data set suggests a restricted amount of lithospheric involvement. The lower FeO content for most of the low-titanium basalts also may reflect melting generated from refractory arc lithosphere [*Lassiter and DePaolo*, 1997].

[38] The low-titanium basalts may have developed an arc-type signature by melting of subduction-modified mantle, interaction of plume-derived melts with melts or material derived from the arc lithospheric, and/or reaction of magmas and metasomatized arc peridotite early in generation of the Nikolai basalts. All CFBs show compositional evidence of involvement of lithospheric mantle or continental crust in parts of their volcanic stratigraphy [e.g., *Saunders et al.*, 1992]. Several CFBs and volcanic rifted margins show a transition in the eruptive sequence from a lithospheric to a plume-derived signature (e.g., Siberia [*Wooden et al.*, 1993]; Parana [*Peate and Hawkesworth*, 1996]; North Atlantic Igneous Province [*Kerr*, 1994]; Ethiopia [*Pik et al.*, 1999]) and a number of influential studies have examined the role of plume-lithosphere interactions in the formation of flood basalt provinces [e.g., *Arndt and Christensen*, 1992; *Menzies*, 1992; *Saunders et al.*, 1992; *Turner et al.*, 1996; *Lassiter and DePaolo*, 1997]. *White and McKenzie* [1995] presented geochemical evidence for continental lithospheric contribution to flood basalts but indicated that the conduction of heat to the lithosphere from the plume is too slow to produce large volumes of magma in short time-spans. *Arndt and Christensen* [1992] found that $>96\%$ of melt in CFBs comes from the asthenosphere and only minor amounts of melt ($<5\%$) may originate in the lithosphere. Although there are conflicts with anhydrous melting models for the lithosphere, *Lassiter and DePaolo* [1997] found evidence for lithospheric mantle melting and typically these melts are more abundant during early phases of flood volcanism, as they usually represent a minor volume (10–20%) of the eruptive sequences (e.g., Siberia). *Pik et al.* [1999] proposed melting of a shallow-level, depleted source for low-titanium basalts from Ethiopia, with a strong, but variable, lithospheric contribution.

Figure 17. Th-Nb and Ti-Yb proxies of the Nikolai Formation in Alaska with data compilation and modeling results from *Pearce* [2008]. (a) Th/Yb versus Nb/Yb. MORB-OIB array and assimilation-fractional crystallization (AFC) model from *Pearce* [2008]. (b) TiO_2/Yb versus Nb/Yb. Talkeetna arc lower crust from *Greene et al.* [2006] and Talkeetna arc lavas from *Clift et al.* [2005]. Mariana arc data from *Pearce et al.* [2007] and *Woodhead et al.* [2001]. The low-titanium basalts indicate a depleted source and interaction with a subduction component combined with fractional crystallization, whereas the high-titanium basalts lie within an OIB array in Figure 17b, parallel to a melting vector that indicates higher pressure melting. See *Pearce* [2008] for parameters of polybaric melting and assimilation-fractional crystallization (AFC) modeling. Blue line in Figure 17a represents an AFC model following the modeling of *DePaolo* [1981]. Red line in Figure 17b illustrates a polybaric melting trend (with changing composition of pooled melt extracted from the mantle that undergoes decompression from the solidus to the pressure marked) for high and lower mantle potential temperatures, which corresponds to representative conditions for the generation of present-day MORB and OIB [*Pearce*, 2008].

[39] For certain conditions (e.g., lithospheric thickness, duration of heating, and temperature), modeling predicts that small volumes of lithosphere-derived basalts may be overlain by larger volumes of asthenospheric basalts [*Turner et al.*, 1996], as is the case for Wrangellia basalts in Alaska. *Turner et al.* [1996] concluded that the lithospheric mantle can contribute melt if it is less than 100 km thick and if the solidus is lowered from addition of volatiles at some time in the past. *Saunders et al.* [1992] suggested that, although conduction alone may not cause melting of the lithosphere, rifting, and decompression, the presence of hydrous phases in subcontinental lithospheric mantle [e.g., *Gallagher and Hawkesworth*, 1992], melt injection from the plume into the lithosphere, and thermal and mechanical erosion of the lithosphere may all facilitate melting. Numerical modeling of *d'Acremont et al.* [2003] involving plume head-lithosphere interaction and the formation of oceanic plateaus indicates thermal weakening may be less important than mechanical weakening at timescales of plume head flattening and related strain rates. *Farnetani and Richards*

[1994] found from numerical modeling, partly applied to Triassic Wrangellia stratigraphy that without extension, melting would likely be entirely sublithospheric; however, they note that they did not examine complexities of arc lithosphere and the presence of hydrous phases that would enhance melting. Although primary hydrous phases are not present in the low-titanium basalts, their origin may have involved melting of subarc lithospheric mantle prior to thinning of the lithosphere or from mechanical or thermal erosion of the base of the lithosphere.

7.2.3. Origin of Decoupled Hf and Nd Isotopes of Low-Titanium Basalts

[40] The initial Hf isotopic compositions of the low-titanium basalts indicate involvement of a component that evolved with high Lu/Hf over time but not corresponding high Sm/Nd. Parent isotopes ^{176}Lu and ^{147}Sm are more compatible during melting than their daughter isotopes ^{176}Hf and ^{143}Nd , respectively [*Salters and White*, 1998], and show a close coupling in the crust-mantle system; when plotting Hf versus Nd isotopes they

form the “terrestrial array” [e.g., *Vervoort and Blichert-Toft*, 1999; *van de Flierdt et al.*, 2004; Figure 18]. A range of processes has been proposed to decouple Hf and Nd isotopes. Depleted lithosphere (after MORB extraction) has high Lu/Hf and moderate Sm/Nd and can lead to decoupling [Salter and Zindler, 1995; Salter et al., 2006]. Processes that involve zircon or garnet, which result in larger fractionation of Lu/Hf than of Sm/Nd [e.g., *Patchett et al.*, 1984; *Vervoort et al.*, 2000], can drive Hf and Nd isotopic compositions from the terrestrial array. These processes may involve pelagic sediment, ancient melt extraction, or oceanic lithosphere modified by subduction [e.g., *Geldmacher et al.*, 2003]. The subarc mantle wedge can develop high Lu/Hf, compared to Sm/Nd, that will evolve over time to high $^{176}\text{Hf}/^{177}\text{Hf}$ relative to $^{143}\text{Nd}/^{144}\text{Nd}$ and displace compositions above the OIB array [e.g., *Barry et al.*, 2006].

[41] The low-titanium basalts have comparable initial ε_{Hf} to modern Pacific arcs (and Pacific MORB) with lower initial ε_{Nd} (Figure 18) and higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 15). The processes in the mantle wedge above a subduction zone can cause a more significant decrease in $^{143}\text{Nd}/^{144}\text{Nd}$ than $^{176}\text{Hf}/^{177}\text{Hf}$, which then evolve along a similar path to depleted compositions well above the mantle array [Kempton et al., 2002; Janney et al., 2005]. Along with high initial ε_{Hf} , high initial Sr isotope ratios of the low-titanium basalts indicate involvement of a component derived from an older source with high Rb/Sr, such as subarc lithospheric mantle. Elemental fractionation in the subarc mantle would lead to radiogenic $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ and less radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ [e.g., *Janney et al.*, 2005]; these are the characteristics of the low-titanium basalts.

[42] A binary mixing curve between average Pacific arc basalt composition and pelagic sediments, from ~1000 km east of the Tonga trench (DSDP site 595/596; J. D. Vervoort, personal communication, 2008), in a plot of initial ε_{Hf} versus ε_{Nd} suggests that involvement of a pelagic sediment component with high Lu/Hf could generate high initial Hf isotopic compositions similar to those of the low-titanium basalts (Figure 18). The bulk addition of a pelagic component (<3%) that underwent radiogenic ingrowth from high Lu/Hf could explain the displacement of low-titanium basalts above the OIB mantle array from a source more depleted than that of the high-titanium basalts. The pelagic sediment component is different than the local contamination of the basal pillowed flows in

the Alaska Range that contain sediment filling interpillow voids. Pelagic sediment has very high Pb contents compared to oceanic basalts, and would be expected to generate different Pb isotopic compositions in the low- and high-titanium basalts; however, the high- and low-titanium basalts have almost indistinguishable Pb isotopes. *Geldmacher et al.* [2003] suggested the high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ diagnostic of marine sediments may not be apparent in time periods of hundreds of millions of years if relatively high U and Pb, and high U/Pb ratio, in the sediment cause rapid in-growth of ^{206}Pb and very little in-growth of ^{207}Pb and ^{208}Pb (because of decay of ^{235}U early in Earth's history and the long half-life of ^{232}Th compared to ^{238}U). The trace element and isotope geochemistry of the low-titanium basalts is best explained by involvement of a subduction-modified mantle component, possibly including a pelagic sediment component, which may have evolved with high $^{176}\text{Hf}/^{177}\text{Hf}$ (and $^{87}\text{Sr}/^{86}\text{Sr}$) relative to $^{143}\text{Nd}/^{144}\text{Nd}$.

8. Conclusions

[43] The volcanic stratigraphy (3.5–4 km thick) of the Nikolai Formation forms an arcuate belt ~450 km long in the Wrangell Mountains and Alaska Range (Amphitheater and Clearwater Mountains) in southern Alaska. These sequences formed as part of an extensive oceanic plateau in the Middle to Late Triassic during a single, short-lived phase of volcanism lasting <5 Ma. The Nikolai Formation is bounded by marine sedimentary sequences and unconformably overlies late Paleozoic volcanic arc sequences. The volcanic stratigraphy is predominantly subaerial flows in Alaska but consists of ~500 m of submarine flows and basal sills intruding preexisting shale in the southern Alaska Range.

[44] The Nikolai Formation is composed of high- and low-titanium basalts that record a change in the source of magmas that constructed the Wrangellia oceanic plateau in Alaska. The low-titanium basalts form the lowest ~400 m of volcanic stratigraphy in the Alaska Range, and the remainder of the volcanic stratigraphy in the Alaska Range and all of the sampled stratigraphy in the Wrangell Mountains is high-titanium basalt. The geochemistry of erupted sequences of the Wrangellia oceanic plateau in Alaska allows for assessment of the different contributions from the preexisting lithospheric mantle and plume-type mantle. The high-titanium basalts were derived from a uniform plume-type Pacific

Figure 18. Global Hf-Nd isotope systematics with age-corrected data of the Nikolai Formation in Alaska. Data for terrestrial array are from *Vervoort and Blichert-Toft* [1999] and references therein. References for data sources for Pacific arcs, Fe-Mn crusts, eolian dust are listed in Auxiliary Material (Text S2). Pelagic sediment data from DSDP 595/596 provided courtesy of J. D. Vervoort (personal communication, 2008). The mixing curve shown is for mixing of pelagic sediment with arc basalt. Average pelagic sediment composition used for mixing curve is initial $\epsilon_{\text{Hf}} = +5.0 \pm 4.0$ and initial $\epsilon_{\text{Nd}} = -4.5 \pm 2.4$. Average arc basalt from average of *Pearce et al.* [2007] and *Woodhead et al.* [2001]. Pacific MORB from *Nowell et al.* [1998], *Salters and White* [1998], and *Chauvel and Blichert-Toft* [2001].

mantle source, with similar initial Hf and Nd isotopic ratios to Ontong Java. The low-titanium basalts involved a HFSE-depleted, high ϵ_{Hf} component that is distinct from OIB and MORB and was only involved during the early phase of this major melting event. There is no indication of a transitional lava type in Alaska and the high-titanium basalts do not indicate significant assimilation or interaction of lithospheric material.

[45] Whereas almost all CFBs, and at least one oceanic plateau (e.g., Kerguelen for its Cretaceous

part), record involvement of continental lithosphere, Wrangellia flood basalts in Alaska do not indicate involvement of low ϵ_{Nd} -low ϵ_{Hf} continental material. However, the low-titanium basalts have compositions that indicate melting and/or interaction with subduction-modified lithospheric mantle was involved in their formation. A large thermal anomaly may have initiated melting in the lithospheric mantle due to conduction of heat and possibly a lower liquidus temperature from volatiles in the older subarc lithospheric mantle. The

lithosphere may have been mechanically or thermally eroded, whereafter melting occurred mostly within the plume to produce the voluminous high-titanium basalts.

Appendix A: Sample Preparation and Analytical Methods

[46] The least altered samples of the Nikolai Formation were selected for geochemical analysis based on thorough petrographic inspection. Thirty-seven of 68 samples from the Alaska Range and 16 of 36 samples from the Wrangell Mountains were crushed (400 g) into pieces <2 mm in diameter in a Rocklabs hydraulic piston crusher between WC plates. The coarse crush was thoroughly mixed and 100 g was powdered in a planetary mill using agate jars and balls that were cleaned with quartz sand between samples.

A1. University of Massachusetts XRF Analytical Methods

[47] Fifty-three sample powders and six duplicate powders were analyzed at the Ronald B. Gilmore X-Ray Fluorescence Laboratory (XRF) at the University of Massachusetts. Major elements were measured on a fused La-bearing lithium borate glass disc using a Siemens MRS-400 spectrometer with a Rh X-ray tube operating at 2700 W. Trace element concentrations (Rb, Sr, Ba, Ce, Nb, Zr, Y, Pb, Zn, Ga, Ni, Cr, V) were measured on a separate powder pellet using a Philips PW2400 sequential spectrometer with a Rh X-ray tube. Loss on ignition (LOI) and ferrous iron measurements were made as described by *Rhodes and Vollinger* [2004]. Precision and accuracy estimates for the analytical data are described by *Rhodes* [1996] and *Rhodes and Vollinger* [2004]. Results for each sample are the average of two separate analyses. A total of four complete duplicates were analyzed for Alaska samples. Eighteen sample duplicate powders of Wrangellia flood basalts were also analyzed at Activation Laboratories and the results for most elements were within analytical error.

A2. PCIGR Trace Element and Isotopic Analytical Methods

[48] A subset of 24 samples was selected for high-precision trace element analysis and Sr, Nd, Pb, and Hf isotopic analysis at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia (UBC; Table 1). Samples were selected from the 53 samples ana-

lyzed by XRF, based on major and trace element chemistry, alteration (low LOI and petrographic alteration index), sample location, and stratigraphic position. Samples were prepared for trace element analysis at the PCIGR by the technique described by *Pretorius et al.* [2006] on unleached rock powders. Sample powders (~100 mg) were weighed in 7 mL screw-top Savillex[®] beakers and dissolved in 1 mL ~14N HNO₃ and 5 mL 48% HF on a hotplate for 48 h at 130°C with periodic ultrasonication. Samples were dried and redissolved in 6 mL 6N HCl on a hotplate for 24 h and then dried and redissolved in 1 mL concentrated HNO₃ for 24 h before final drying. Trace element abundances were measured with a Thermo Finnigan Element2 High Resolution-Inductively Coupled Plasma-Mass Spectrometer (HR-ICP-MS) following the procedures described by *Pretorius et al.* [2006] within 24 h of redissolution. High field strength elements (HFSE) and large ion lithophile elements (LILE) were measured in medium resolution mode at 2000X dilution using a PFA Teflon spray chamber washed with Aqua Regia for 3 min between samples. Rare earth elements (REE) were measured in high-resolution mode, and U and Pb were measured in low-resolution mode, at 2000X dilution using a glass spray chamber washed with 2% HNO₃ between samples. Total procedural blanks and reference materials (BCR-2, BHVO-2) were analyzed with the batch of samples. Indium was used as an internal standard in all samples and standard solutions. Background and standard solutions were analyzed after every five samples to detect memory effects and mass drift.

[49] Sample digestion for purification of Sr, Nd, Hf, and Pb for column chemistry involved weighing each sample powder. All samples were initially leached with 6N HCl and placed in an ultrasonic bath for 15 min. Samples were rinsed two times with 18 mega Ω -cm H₂O between each leaching step (15 total) until the supernatant was clear (following the technique of *Mahoney* [1987], modified by *Weis and Frey* [1991]). Samples were then dried on a hotplate for 24 h and weighed again. Sample solutions were then prepared by dissolving ~100–250 mg of the leached powder dissolved in 1 mL ~14N HNO₃ and 10 mL 48% HF on a hotplate for 48 h at 130°C with periodic ultrasonication. Samples were dried and redissolved in 6 mL 6N HCl on a hotplate for 24 h and then dried. Pb was separated using anion exchange columns and the discard was used for Sr, REE, and Hf separation. Nd was separated from the REE and Hf required two additional purification steps. Detailed

procedures for column chemistry for separating Sr, Nd, and Pb at the PCIGR are described by *Weis et al.* [2006] and Hf purification is described by *Weis et al.* [2007]. Sr and Nd isotope ratios were measured on a Thermo Finnigan Triton Thermal Ionization Mass Spectrometer (TIMS) in static mode with relay matrix rotation on a single Ta and double Re-Ta filament, respectively. Four to five filaments per barrel of 21 were occupied by standards (NIST SRM 987 for Sr and LaJolla for Nd) for each barrel where samples were run. Sample Sr and Nd isotopic compositions were corrected for mass fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Each sample was then normalized using the barrel average of the reference material relative to the values of $^{143}\text{Nd}/^{144}\text{Nd} = 0.511858$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.710248$ [*Weis et al.*, 2006]. During the period when the Alaska samples were analyzed, the La Jolla Nd standard gave an average value of 0.511853 ± 11 ($n = 8$) and NIST SRM 987 standard gave an average of 0.710253 ± 11 ($n = 9$; 2σ error is reported as times 10^6). $^{147}\text{Sm}/^{144}\text{Nd}$ ratio errors are approximately $\sim 1.5\%$, or ~ 0.006 . Leached powder of United States Geological Survey (USGS) reference material BHVO-2 was processed with the samples and yielded Sr and Nd isotopic ratios of 0.703473 ± 8 and 0.512980 ± 6 , respectively. These are in agreement with the published values of 0.703479 ± 20 and 0.512984 ± 11 , respectively [*Weis et al.*, 2006]. USGS reference material BCR-2 was processed with the samples and yielded Sr and Nd isotopic ratios of 0.705002 ± 9 and 0.512633 ± 7 , respectively, which are in agreement with the published values of 0.705013 ± 10 and 0.512637 ± 12 , respectively [*Weis et al.*, 2006].

[50] Pb and Hf isotopic compositions were analyzed by static multicollection on a Nu Plasma (Nu Instruments) Multiple Collector-Inductively Coupled Plasma-Mass Spectrometer (MC-ICP-MS). The detailed analytical procedure for Pb isotopic analyses on the Nu at the PCIGR is described by *Weis et al.* [2005]. The configuration for Pb analyses allows for collection of Pb, Tl, and Hg together. Tl and Hg are used to monitor instrumental mass discrimination and isobaric overlap, respectively. All sample solutions were analyzed with approximately the same Pb/Tl ratio (~ 4) as the reference material NIST SRM 981. To accomplish this, a small aliquot of each sample solution from the Pb columns was analyzed on the Ele-

ment2 to determine the precise amount of Pb available for analysis on the Nu Plasma. The SRM 981 standard was run after every two samples on the Nu Plasma. During the time samples were run, analyses of the SRM 981 Pb reference material gave values of $^{206}\text{Pb}/^{204}\text{Pb} = 16.9403 \pm 19$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4964 \pm 20$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7142 \pm 53$ ($n = 124$; 2σ error is reported as times 10^4); these values are in excellent agreement with reported TIMS triple-spike values of *Galer and Abouchami* [1998]. Results were further corrected by the sample-standard bracketing method or the ln-ln correction method described by *White et al.* [2000] and *Blichert-Toft et al.* [2003]. Leached powder of USGS reference material BHVO-2 yielded Pb isotopic ratios of $^{206}\text{Pb}/^{204}\text{Pb} = 18.6500 \pm 7$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.5294 \pm 7$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.2380 \pm 19$. These values are in agreement with leached residues of BHVO-2 from *Weis et al.* [2006].

[51] Hf isotopic compositions were analyzed following the procedures detailed by *Weis et al.* [2007]. The configuration for Hf analyses monitored Lu mass 175 and Yb mass 172 to allow for interference correction to masses 174 and 176. Hf isotopic ratios were normalized internally for mass fractionation to a $^{179}\text{Hf}/^{177}\text{Hf}$ ratio of 0.7325 using an exponential correction. Standards were run after every two samples and sample results were normalized to the ratio of the in-run daily average and a $^{176}\text{Hf}/^{177}\text{Hf}$ ratio for JMC-475 of 0.282160. During the course of analyses, the Hf standard JMC-475 gave an average value 0.282153 ± 3 ($n = 79$). USGS reference materials BCR-2 and BHVO-2 were processed with the samples and yielded Hf isotopic ratios of 0.282874 ± 5 and 0.283114 ± 6 , respectively. Published values for BCR-2 and BHVO-2 are 0.282871 ± 7 and 0.283104 ± 8 , respectively [*Weis et al.*, 2007].

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