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Atlin TGI Part III: Geology and Petrochemistry of Mafic Rocks Within the Northern Cache Creek Terrane and Tectonic Implications

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INTRODUCTION

The Cache Creek terrane is a belt of oceanic rocks that extend the length of the Cordillera in British Columbia, where they occupy a central position within the accreted terranes (Coney *et al*., 1980; Figure 1). Fossil fauna in this belt are uniquely exotic with respect to the remainder of the Canadian Cordillera as they are typical of the equatorial Tethyan realm, contrasting with coeval faunas in adjacent terranes that show closer linkages with ancestral North America (Monger and Ross, 1971; Orchard *et al*., 2001). Fossil data in the Atlin area suggest an age range from Mississippian through to Lower Jurassic for these rocks (Monger, 1975; Cordey *et al.*, 1991; Orchard, 1991). The bounding island arc terranes of Stikinia and Quesnellia, to the west and east respectively, may have developed in response to Palaeozoic through Mesozoic destruction of the Cache Creek ocean basin (Cordey *et al.*, 1987; Mihalynuk, 1999). Petrochemical analysis of the volcanic rocks of Cache Creek provides an opportunity to constrain the tectonic setting of the Cache Creek terrane throughout much of its early history. This terrane has played a pivotal role in the evolution of the Canadian Cordillera and improvements in understanding the Cache Creek terrane bear on the Cordillera as a whole.

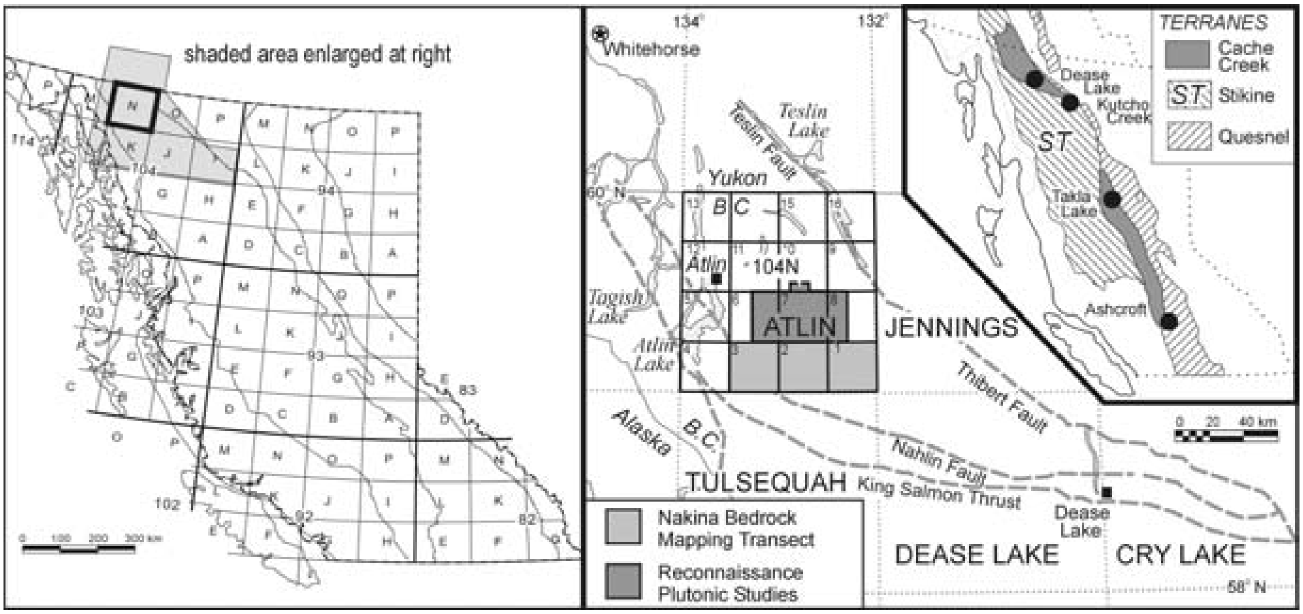

Figure 1. General location map of north-western British Columbia showing the Atlin Targeted Geoscience Initiative study area (1:250 000 sheet 104N), and the Nakina regional mapping project area (1:50 000 sheets 104N/1, 2, 3).

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PREVIOUS WORK

The existing regional geological context of the Nakina area of the Cache Creek terrane is based upon mapping conducted in the early to mid 1950s by Aitken (1959), prior to the origin of plate tectonic theory. Parts of the area were mapped by Monger (1975), who was the first to interpret the terrane as a dismembered ophiolite. Terry (1977) argued that the Nahlin Ultramafic body, the largest in the Canadian Cordillera, is part of a classical ophiolite. However, caution should be exercised in applying the term 'ophiolite' *sensu stricto*, as widespread exposures of pillow basalts and sheeted dykes of a pristine ophiolitic section are not known. In a more recent study, Ash (1994) drew similar conclusions from ultramafic rocks near Atlin and also demonstrated a MORB-chemistry for associated basalts.

Monger (1977) suggested that long-lived (Upper Mississippian–Upper Permian) carbonate-dominated successions in the Nakina region (the Horsefeed Formation) were founded on volcanic pediments and interpreted these as ancient seamounts or an oceanic plateau within the Cache Creek ocean basin. This concept is supported by geochemical analysis of Cache Creek rocks in central British Columbia, where Permian limestones are associated with basaltic rocks of ocean-island affinity (Ash and McDonald, 1993; Tardy *et al.*, 2001). However, this hypothesis remains untested within the Nakina area, where the age, petrogenesis and geologic setting of volcanic strata remain incompletely understood.

GEOLOGY OF NAKINA AREA

The Cache Creek Terrane is characterised by tectonically imbricated slices of chert, argillite, volcaniclastics, limestone and wacke, as well as ultramafics, gabbro and basalt. These lithologies represent two distinctive lithotectonic elements: Upper Triassic to early Jurassic, subduction-related accretionary complexes, and dismembered basement assemblages (Monger *et al.*, 1982; Gabrielse and Yorath, 1989; Coney, 1989; Ash, 1994) emplaced during the closure of the Cache Creek ocean basin in the Middle Jurassic (Thorstad and Gabrielse, 1986; Mihalynuk *et al.*, 1999). Mapping undertaken in the Nakina region (Figure 2) during the 2001 field season appears to support this concept (*see* Mihalynuk *et al.*, this issue).

The structural complexity of this region precludes substantial stratigraphic preservation. However, a number of distinct mafic igneous assemblages have been recognised. These include the magmatic "knockers" of the Nimbus ser-

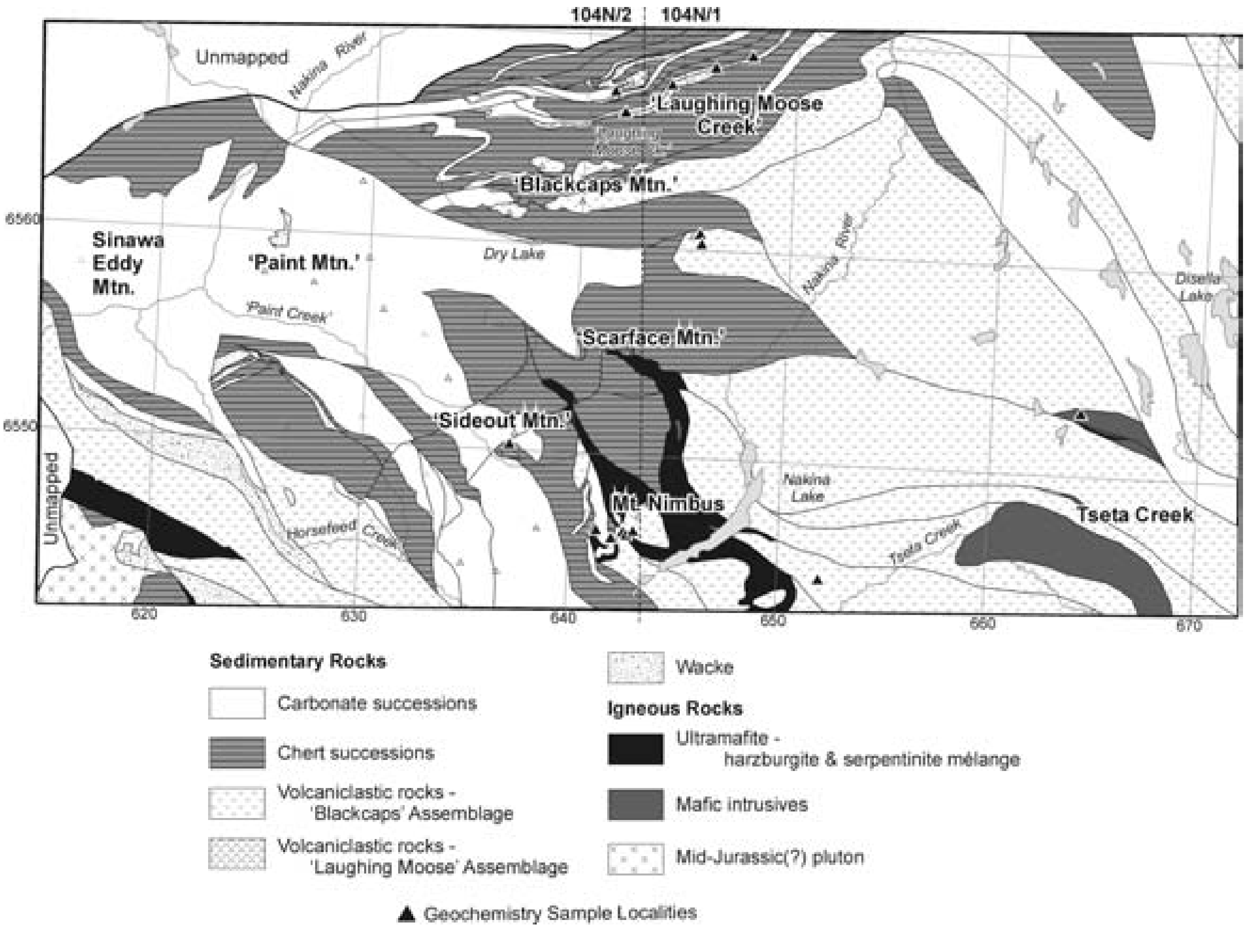

Figure 2. Generalized geologic map of the Nakina study area, NTS 104N/1 and 2 with a 10km UTM grid superimposed.

pentinite mélange; the mint-green tuffs of ‘Blackcaps’ Mountain; the coarse, augite-phyric breccia of ‘Laughing Moose’ Creek; as well as volcanic pediments to reef-forming carbonates. Mapping also revealed quartz-phyric felsic volcanic rocks (Mihalynuk *et al.*, this issue); their extent and nature is poorly defined and is not discussed further here.

NIMBUS MÉLANGE AND OTHER BASEMENT ROCKS

The Nimbus serpentinite mélange is exposed most extensively in the Mt. Nimbus region and extends eastward across Nakina Lake and north to the hills across ‘Paint’ Creek. The mélange belt has mafic volcanic rocks at its eastern margin, and to the west: chert, limestone and clastic sedimentary units. All bounding units display a layering that trends obliquely into the fault-bounded mélange belt. Blocks of mafic volcanics, up to 2 kilometres across, are surrounded by serpentinite within the mélange belt. Smaller, more lithologically varied blocks also occur within the mélange, enveloped in a scaly serpentinite matrix. These “knockers” are typically 1 to 50 metres across and include mafic volcanics, chert, harzburgite, limestone (rare), and plutonic rocks of gabbroic to granitic composition. The intrusive rocks are thought to be derived from the Cache Creek ocean basement or perhaps parts of a dismembered arc complex that was built atop such basement.

Southeast of Nakina Lake, the Nimbus mélange belt turns south and mafic volcanic rocks border it to the east and west. Farther east, in the Tseta Creek area, a transition to dominantly gabbroic rocks has been recognised. These gabbros display a broad range of grain size and degree of deformation. Some are intensely sheared while others are relatively undeformed. Similar textural variability is displayed by knockers within the Nimbus mélange.

`BLACKCAPS‘ TUFF

The ‘Blackcaps’ Tuff occurs within a series of thrust sheets with associated chert and limestone breccias. This unit is comprised mainly of mint-green, monomictic lapilli and ash tuff. Coarse lapilli tuff and tuff breccia is relatively uncommon, displaying a fragmental texture on weathered surfaces, with angular clasts up to 10 cm in size. These clasts are typically basaltic andesite with relict plagioclase and pyroxene phenocrysts. Locally the fine tuff is also pyroxene-phyric. Pyroxene crystals are generally fresh and euhedral, without obviously abraded surfaces. Disseminated pyrite, pyrhhotite and minor chalcopyrite, less than 1-2%, are common. The fine-grained matrix and plagioclase crystals have been subjected to alteration, principally the formation of prehnite, pumpellyite, white mica, clay minerals and calcite. However, protolith textures are everywhere apparent. Shear fabrics can be ubiquitous over entire mountainsides. As such, they are interpreted as produced during deposition/resedimentation; although, tectonic fabrics that are superimposed on the earlier depositional fabrics are common locally.

The base of the succession at ‘Blackcaps’ consists of chert. Radiolarian identification reveals an age of Carboniferous or Permian based upon the presence of the relatively poorly preserved fusulinid ***Latentifistulidae*** extracted from well-bedded grey chert along strike to the west (identified by F. Cordey, *see* Mihalynuk *et al*. this volume). The chert unit grades progressively upwards, through a transitional argillaceous chert unit, and into the ‘Blackcaps’ Tuff. The transitional unit is siliceous containing fine volcanic ash and occasional crystals that mark the onset of volcaniclastic deposition.

The ‘Blackcaps’ Tuff may attain a thickness of 500m, although a paucity of bedding and marker horizons makes it difficult to rule out structural repetition. Some chert bands, up to several metres thick, are useful local markers, but the dominance of the tuff appears to represent deposition rates that greatly exceed those of biogenic chert accumulation. High in the succession, a planar-bedded calcarenitic unit can be traced for several hundred metres and is interpreted as turbiditic in origin. Both the calcareous and chert units probably reflect periods of relative quiescence in volcanic activity. Upper contacts of the ‘Blackcaps’ Tuff are marked by a limestone breccia. As of yet, no fossil ages have been extracted from this unit.

‘LAUGHING MOOSE‘ AUGITE PORPHYRY BRECCIA

Basaltic breccia with coarse augite phenocrysts comprises a distinctive unit within the ‘Laughing Moose’ area, which lies just north of the ‘Blackcaps’ area. The Laughing Moose augite porphyry is a laterally extensive, monomictic matrix-supported breccia reaching up to 250m in thickness. The blocks are up to 1m across. It displays some variability, both flow-banding, presumably of pyroclastic origin, and coarse epiclastic sandstones containing well rounded clasts and crystals. Tuffs contain as much as 30% strikingly zoned euhedral augite crystals that are up to 1cm in diameter, and less abundant plagioclase phenocrysts. The groundmass is dominated by plagioclase and Fe-oxides. Some exposures illustrate syn-sedimentary deformation with microfaults offsetting graded beds. One isolated exposure of diorite is potentially co-magmatic, but contains a different phenocryst assemblage, predominantly hornblende and plagioclase.

The augite porphyry succession rests with angular unconformity on folded chert. Where observed, the base of the augite porphyry unit contains cm to dm-sized chert clasts.

In the upper part of this succession, the volcaniclastic sequence becomes more calcareous and eventually grades into limestones. No micro- or macrofossil data have yet been obtained from this limestone. The sequence is capped by carbonate granule conglomerates, tentatively interpreted as debris-flows.

TABLE 1
WHOLE ROCK MAJOR ELEMENTAL ABUNDANCES FOR MAFIC ROCKS IN THE NAKINA AREA

Sample	Assemblage	Easting	Northing	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Cr2O3	LOI	C	S	SUM
FDE01-14-12	'Laughing Moose' basalt	640750	6567060	44.64	2.97	11.06	11.44	-	0.13	10.3	11.07	2.33	0.98	0.47	0.074	4.4	0.64	<.01	99.96
FDE01-23-6	'Blackcaps' basalt	651840	6544708	53.61	0.65	13.66	8.63	-	0.14	6.96	9.37	3.54	0.12	0.06	0.04	3.2	0.11	0.02	99.99
FDE01-31-1A	Mt. Nimbus basanite	641345	6546812	39.21	4.54	13.33	12.22	-	0.17	6.93	9.55	1.87	1.88	2.07	0.011	7.6	0.71	<.01	99.52
FDE01-31-1B	Mt. Nimbus basanite	641345	6546812	38.51	4.96	14.25	12.91	-	0.16	7.27	8.17	1.29	2.34	2.49	0.017	6.8	0.28	0.01	99.31
FDE01-31-3	Mt. Nimbus basanite	641300	6546796	40.47	4.43	12.84	11.64	-	0.13	7.06	9	2.6	1.6	1.94	0.012	7.2	0.76	0.04	99.1
FDE01-31-4	Nimbus mélange basalt	641880	6546544	48.88	1.83	13.34	10.84	-	0.17	6.66	10.11	3.71	0.08	0.24	0.012	4	0.25	0.16	99.89
FDE01-31-6	Nimbus mélange gabbro	642538	6546533	46.58	0.21	19.48	5.42	-	0.1	7.45	13.2	2.25	0.52	<.01	0.017	4.8	<.01	<.01	100.1
FDE01-31-7	Nimbus mélange gabbro	642538	6546483	50.17	0.82	15.73	9.07	-	0.13	7.09	10.15	3.51	0.02	0.06	0.005	3.1	0.03	0.01	99.87
FDE01-31-10	Nimbus mélange basalt	642711	6546740	47.25	1.42	14.93	11.17	-	0.17	6.45	11.31	2.42	0.26	0.09	0.016	4.6	0.05	0.18	100.1
FDE01-31-12	Nimbus mélange tonalite	642536	6546483	77.23	0.12	12.93	0.23	-	<.01	0.32	1.17	5.4	1.46	<.01	0.008	0.9	0.09	<.01	99.79
JEN01-23-8	'Blackcaps' basalt	645368	6560715	48.67	1.32	15.34	10.48	-	0.16	6.17	11.16	1.53	0.26	0.16	0.013	4.7	0.01	0.02	99.98
JEN01-23-12	'Blackcaps' basalt	645419	6560010	48.24	1.33	15.38	10.49	-	0.14	6.56	11.41	2.2	0.32	0.08	0.019	3.9	0.04	0.11	100.1
JEN01-26-5A	Tseta Creek gabbro	665924	6551936	48.48	0.87	15.71	9.46	-	0.14	7.97	10.09	3.23	0.09	0.05	0.029	3.8	0.08	<.01	99.94
JEN01-27-6	'Blackcaps' basalt	644156	6567988	53.28	1.09	14.79	9.94	-	0.14	6.56	7.2	4.46	0.49	0.12	0.008	1.8	0.03	0.03	99.98
JEN01-32-1B	'Laughing Moose' basalt	646677	6568948	38.86	2.59	9.46	9.83	-	0.17	7.46	16.48	1.7	2.15	0.38	0.052	10	2.48	<.01	99.47
JEN01-32-8	'Laughing Moose' diorite	645724	6568619	52.65	1.79	16.46	8.38	-	0.11	5.06	5.74	4.19	0.96	0.41	0.002	3.9	0.33	0.13	99.71
MMI01-15-4	'Laughing Moose' basalt	641793	6566487	45.4	3.12	11.42	12.02	-	0.14	9.6	11.38	2.4	1.11	0.49	0.055	2.5	0.05	0.01	99.69
YME01-31-7C	'Sideout Mt.' trachyte	637065	6550442	70.47	0.93	12.39	4.82	-	0.04	1.01	1	6.11	0.54	0.09	<.001	2.2	0.11	0.18	99.87
N-MORB	global average[1]	-	-	50.4	1.36	15.2	1.3	8.14	0.18	8.96	11.4	2.3	0.09	0.14	-	-	-	-	99.47
E-MORB	global average[1]	-	-	51.2	1.69	16	9.4	-	0.16	6.9	11.5	2.74	0.43	0.15	-	-	-	-	100.17
OIB	global average[1]	-	-	49.2	2.57	12.8	-	11.4	0.17	10	10.8	2.12	0.51	0.25	-	-	-	-	99.82
IAT	Lau Basin[2]	-	-	56.76	1.39	14.58	-	11.5	0.22	3.74	7.66	3.37	0.52	0.16	-	-	-	-	99.92
RE: FDE01-31-7	Nimbus mélange gabbro			50.46	0.81	15.85	9.02	-	0.13	7.1	10.14	3.56	0.06	0.06	0.005	2.7	0.02	<.01	99.9
RE: JEN01-23-12	'Blackcaps' basalt	645419	6560010	47.99	1.32	15.28	10.46	-	0.14	6.55	11.37	2.19	0.33	0.13	0.018	4.2	0.05	0.07	100
% Difference	-	-	-	0.55	1	0.75	0.45	-	-	0.15	0.25	0.95	150	31.3	2.8	11.3	37.5	18.2	0.05
Std. SY4	-	-	-	49.9	0.29	20.69	6.21	2.86	0.108	0.54	8.05	7.1	1.66	0.13	-	4.56	-	-	102.14
RE: Std. SY4	-	-	-	49.84	0.3	20.93	6.24	-	0.1	0.51	8.22	6.79	1.58	0.07	<.001	5	1.1	0.03	99.63
% Difference	-	-	-	0.1	4.5	1.2	0.5	-	8	5.9	2.1	4.6	5.1	87.1	-	9.2	-	-	0.03

[1] Sun and McDonough (1989)

[2] Jenner *et al*. (1987)

VOLCANIC UNITS WITHIN CARBONATE

Isolated volcanic accumulations occur within carbonate units. At three localities, the volcanic rocks form the substrate of carbonate reefs. At another locality, glassy pillow lava flows occur within bioclastic limestone adjacent to the Nimbus mélange on the southwest flank of Mt. Nimbus. Here the volcanic rocks are highly fractured, as is the entire carbonate unit. Flows are brown-weathering, and pinkish maroon fresh, with pillows containing zones of elongate, calcite-filled vesicles and separated by interpillow hyaloclastite. Rounded to angular carbonate blocks comprise irregular interlayers within the volcanics; they are interpreted to be of olistostromal origin.

The most extensive framework reef constructed on an isolated accumulation of volcanics occurs on the southwest flank of 'Sideout Mountain', north of 'Paint Creek' (Monger, 1977; see also Mihalynuk *et al*., this issue). Here, Upper Mississippian reef/lagoonal carbonates were deposited on volcanic breccias. The breccia clasts are plagioclase-phyric (60-70%) and display a trachytic texture.

GEOCHEMISTRY

A representative suite of 18 intrusive and extrusive rocks from the Nakina area was analysed for major and trace element abundance in order to establish their composition and petrogenetic affiliation. Major oxides were determined by $LiBO_2$ fusion and ICP analysis and minor and trace element geochemistry was determined using ICP MS analysis, both at ACME Analytical Laboratories, Vancouver. These results are listed in Table 1, along with published data from volcanic rocks formed in various tectonic set-

Figure 3. Key to the symbols used in geochemical diagrams.

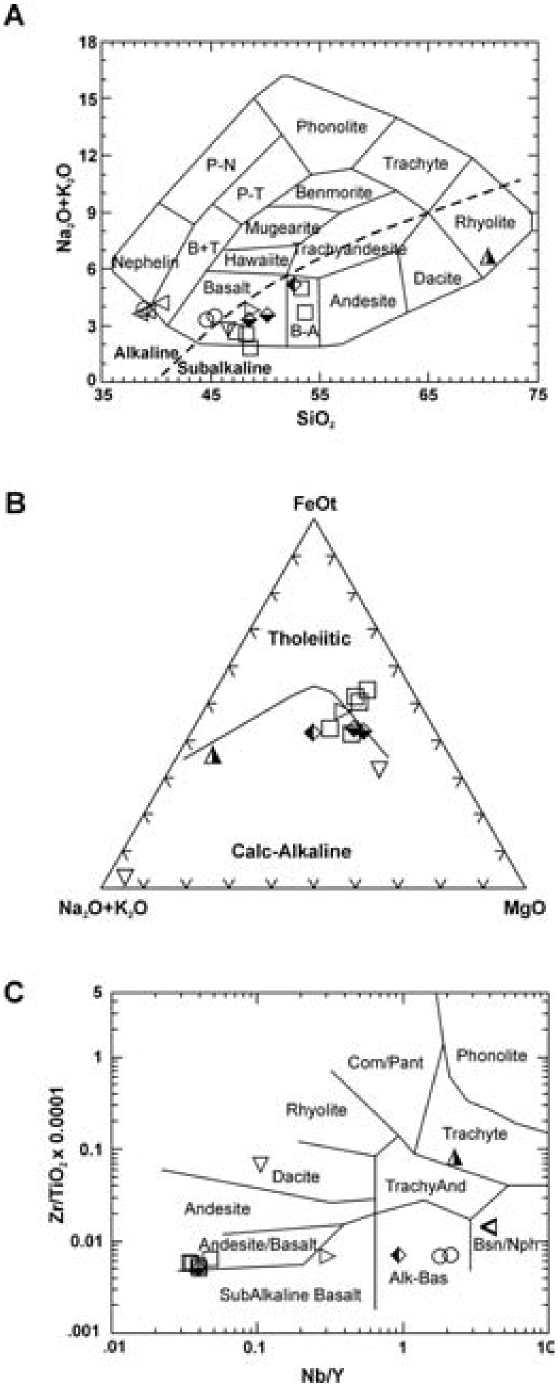

Figure 4. (a) Samples collected and analysed as part of this study are classified by using Na2O+K2O versus SiO2 (from Cox et al., 1979). This diagram also distinguishes between the fields for alkaline and subalkaline rocks (thick dashed line). Abbreviations: P-N – phonolite-nephelinite, P-T – phonolite-tephrite, B+T – basanite + tephrite, B-A – basaltic andesite. (b) The AFM (alkalis-FeOt-MgO) diagram of Irvine and Baragar (1971) can be used for subalkaline rocks to separate tholeiitic from calc-alkaline rocks. (c) Immobile trace element abundances are also used for classification (from Winchester and Floyd, 1977), particularly in altered volcanic rocks where elemental mobility is suspected. In this case little elemental mobility is shown - compare with (a). Abbreviations: Bsn/Nph – Basanite/Nephelinite; Com/Pant – Comendite/Pantellerite.

TABLE 2
WHOLE ROCK TRACE AND RARE EARTH ELEMENTAL ABUNDANCES FOR MAFIC ROCKS IN THE NAKINA AREA

Sample	Ba	Rb	Sr	Cs	Ga	Tl	Ta	Nb	Hf	Zr	Y	Th	U	Ni	Co	Sc	V	Cu	Pb	Zn	Bi
FDE01-14-12	341	31.5	165.1	1.1	18.4	0.1	2.8	50.5	5.3	207.5	23.5	4.7	0.9	105	47.7	35	234	84	<2	74	<.5
FDE01-23-6	11	1.1	66	<.1	13.3	0.1	<.1	0.8	1.2	42.6	16.8	0.1	0.1	36	34.3	35	205	66	<2	27	<.5
FDE01-31-1A	1113	52.7	985.6	31.7	24.6	0.2	9.2	162.1	14.5	659.1	41.8	16.4	3.1	81	41.5	20	215	24	7	138	<.5
FDE01-31-1B	1183	60	1082	29.8	23.3	0.2	9.7	172.7	15.9	687.9	44.7	15.9	2.6	86	43.7	21	224	27	6	177	<.5
FDE01-31-3	1464	38.3	1878	16.3	24.5	0.1	9.3	155.7	13.2	627.7	39.9	16.1	4.3	92	39	19	195	25	7	134	<.5
FDE01-31-4	69	1.5	152.9	0.5	17.9	0.1	0.2	9.2	2.8	127.3	30.2	0.6	0.4	32	39.2	43	264	77	<2	62	<.5
FDE01-31-6	20	5.7	173.5	0.7	14.3	0.2	<.1	<.5	<.5	6.5	6.6	<.1	<.1	85	28.2	28	97	30	<2	12	<.5
FDE01-31-7	12	<.5	146.2	<.1	13.9	0.1	<.1	0.7	1.1	41.3	18	<.1	<.1	29	37.4	38	225	5	<2	21	<.5
FDE01-31-10	23	2.4	105.5	<.1	18.3	0.2	<.1	1.2	2.4	80.3	33.8	0.1	<.1	48	44.5	38	304	81	<2	90	<.5
FDE01-31-12	94	17.9	150.8	0.2	8.7	0.2	<.1	2	3	82	19.1	1.9	0.5	11	0.5	3	<5	1	<2	1	<.5
JEN01-23-8	34	5.6	52.2	0.2	18.2	0.2	<.1	1.2	2	71.8	30.7	<.1	<.1	51	39.4	39	291	53	<2	68	<.5
JEN01-23-12	26	8.1	85.1	0.8	16.5	0.4	<.1	1.2	1.8	67.4	29.9	0.2	0.4	48	40.6	39	301	61	<2	67	<.5
JEN01-26-5A	24	1.1	101.3	<.1	14.5	0.3	<.1	<.5	1.3	37.2	20	0.2	<.1	60	41.6	41	259	70	<2	55	<.5
JEN01-27-6	735	7.1	145.8	0.1	14.4	1.1	<.1	0.9	1.7	63.5	26.1	0.2	<.1	23	33.6	37	293	14	<2	25	<.5
JEN01-32-1B	2792	52.6	445.2	3.4	14.5	0.6	2	38.5	4.4	176.5	21.5	3.5	0.6	121	39.1	33	264	94	<2	59	<.5
JEN01-32-8	473	17.1	611.2	1.4	21	0.9	0.6	17.8	3.1	125	19.1	2.4	1.2	49	27.1	14	136	22	2	89	<.5
MMI01-15-4	274	25.5	294.6	1.1	16.9	0.2	2.9	54.7	5	217.9	25.4	4.6	0.6	110	53.8	38	305	77	<2	71	<.5
YME01-31-7C	2401	14.8	516.2	0.5	25.6	0.2	9.5	182	16.5	756	80.9	12.5	2.6	5	12.7	6	26	5	4	38	<.5
N-MORB	6	0.6	90	0	-	-	-	2.3	2.1	74	28	0.12	0.05	177	50	40	262	-	-	-	-
E-MORB	57	5	155	0.1	-	-	-	8.3	2	73	22	0.6	0.18	-	-	-	-	-	1	-	-
OIB	350	31	660	0.4	-	-	-	48	7.8	280	29	4	1.02	-	-	-	-	-	3	-	-
IAT	102	8.2	169	0.2	-	-	0.1	1.1	2.3	79	34	0.41	0.18	25	-	32	350	-	-	114	-
RE: FDE01-31-7	12	<.5	153.4	<.1	16	0.2	<.1	0.6	1.5	41.9	18.4	0.2	<.1	60	36.4	38	238	5	<2	21	<.5
RE: JEN01-23-12	24	7.7	86	0.9	17.1	0.5	<.1	1.2	2	66.9	30.7	<.1	0.2	74	38.4	38	306	57	<2	62	<.5
% Difference	4.15	2.6	3	6.25	9.35	62.5	-	8.35	23.75	1.1	2.45	>100	25	13.23	4.2	1.3	3.75	3.5	-	4.05	-
Std. SY4	340	55	1191	1.5	35	-	0.9	13	10.6	517	119	1.4	0.8	9	2.8	1.1	8	7	10	93	-
RE: Std. SY4	335	56.6	1253	1.6	36.2	0.1	0.3	12.7	9.7	521.7	132.1	1.4	1	22	2.5	1	5	3	2	49	<.5
% Difference	1.5	2.9	5.2	6.7	3.4	-	200	2.4	9.3	0.9	11	-	25	144.4	12	10	60	133.3	400	89.8	-

tings. A key to the symbols used in the various plots is illustrated in Figure 3.

MAJOR AND TRACE ELEMENTS

Mafic rock samples from the Nakina area are both alkaline and subalkaline (Figure 4a). On the total alkalis versus silica (TAS) diagram of Cox *et al*. (1979), the 'Laughing Moose' augite porphyry breccia and carbonate-associated volcanics from Mt. Nimbus are classified as alkaline, whereas the rest of the samples are subalkaline. All of the samples reveal a basaltic to basaltic andesite composition, except for one sample representing an isolated volcanic accumulation in carbonate. Three of the representative intrusive rock samples were collected in the Mt. Nimbus area from blocks within the mélange. These include a medium grained, chloritised gabbro (FDE01-31-6); a green, vari-textured gabbro (FDE01-31-7), and a grey, recrystallised tonalite (FDE01-31-12). The other two intrusive samples are from the Tseta Creek gabbro (JEN0126-5A) and the 'Laughing Moose' diorite (JEN01-32-8). The 'Laughing Moose' diorite reveals a subalkaline chemistry and does not display any obvious similarities to its associated volcaniclastic rocks. The subalkaline rocks are plotted on an AFM diagram (Irvine and Baragar, 1971; Figure 4b). Most of these rocks appear to be calc-alkaline, although the 'Blackcaps' Tuff straddles the boundary.

Oxides in rocks, particularly alkalis, can move around during alteration and metamorphism (Smith and Smith, 1976). Petrographic analyses of samples considered in this study reveal varying degrees of alteration. The elevated LOI and C content of the Mt. Nimbus basanites is attributable to hydration of the glassy matrix and the presence of microscopic carbonate veinlets. High LOI content is also observed in one 'Laughing Moose' sample (JEN01-32-1B), and this is attributable to the presence of phyllosilicates and carbonate. However, compositional groupings based on major element profiles are consistent with those based on immobile trace element compositions, although classification may vary slightly. For example, rock classification based on the TAS diagram compares well with that based on the immobile element Zr/TiO_2 versus Nb/Y diagram (Figure 4c; Winchester and Floyd, 1977). The only major difference between these plots is that the porphyritic trachyte from 'Sideout Mountain' (YME01-31-7C) plots in the subalkaline field in major element classification of Figure 4a, but in the alkaline field in the trace element classification of Figure 4c. This sample is

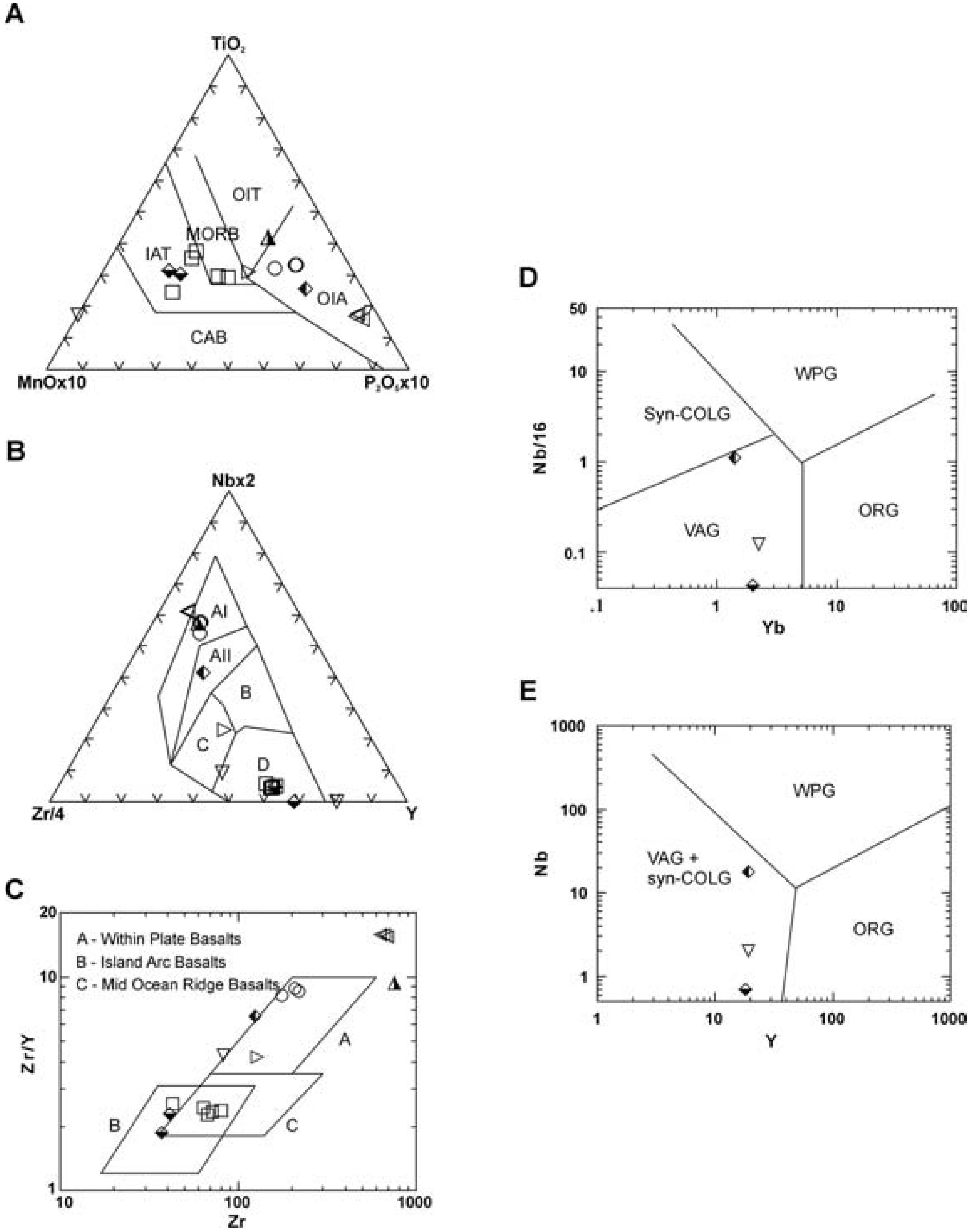

Figure 5. Trace element discriminant diagrams for rocks of basaltic composition following the methods of (a) Mullen (1983); (b) Meschede (1986) and Pearce and Norry (1979). Abbreviations when not given are: OIT – ocean island tholeiite; OIA – ocean island andesite; MORB – mid-ocean ridge basalt; IAT – island arc tholeiite; CAB – calc-alkaline basalt; AI – within-plate alkali basalts; AII – within-plate alkali basalts and within-plate tholeiites; B – E-type MORB; C – within-plate tholeiites and volcanic arc basalts; D – N-type MORB and volcanic arc basalts. Trace element discriminant diagrams for rocks of granitic composition are used in (d) and (e) (after method of Pearce *et al.*, 1984). Figure (d) is modified from the original, with Nb/16 used as a proxy for Ta. Abbreviations: syn-COLG – syn-collisional granites; VAG – volcanic arc granites; WPG – within plate granite; ORG – ocean ridge granite.

plagioclase-rich, and contains centimetre-sized alkali feldspar phenocrysts, which may skew the analyses due to their high Si and Na content (~65%), and very low Mg, Fe and Ca concentrations.

Major oxide and trace element distributions can also be used as indicators of the tectonic environment in which the sample was formed. Figure 5a shows tectonic discriminations based upon the TiO_2-MnO*10-P_2O_5*10 ternary plot of Mullen (1983). This plot indicates that the alkaline rocks, including the intrusive from the 'Laughing Moose' area, are of within-plate affinity. However, the tectonic affinity of the 'Blackcaps' Tuff is not entirely conclusive as it appears to straddle the island arc tholeiite (IAT) and mid-ocean ridge (MORB) fields. Although gabbroic rocks are not ideal for tectonic discrimination purposes, it is noted that these samples plot in the IAT field. The Nb*2-Zr/4-Y plot of Meschede (1986) (Figure 5b) further supports these basic observations.

A clearer picture is presented by Figure 5c, a Zr/Y versus Zr logarithmic discrimination plot of Pearce and Norry (1979). Yet again, a highly enriched within-plate source is suggested for the carbonate-associated volcanics and a within-plate setting also for the 'Laughing Moose' volcaniclastics. Gabbroic rocks plot in the island arc field and the 'Blackcaps' Tuff plots in the overlap between MORB and arc.

Further indication of a volcanic arc origin for the majority of the intrusive samples, is provided by the trace element diagrams of Pearce *et al.* (1984). Though these graphs were originally intended to show variations in tectonic origin of granitic rocks based on trace element versus SiO_2 values, the trend of the field division lines are well constrained at the low SiO_2 values, and we have extrapolated into lower SiO_2 values. Figure 5(d, e) illustrates that all of three intrusive rock samples lie within the volcanic arc field. Multi-element plots will now be utilised to probe the origin of these intrusive and volcanic rocks.

RARE EARTH ELEMENT (REE) AND MULTI-ELEMENT PLOTS

Primitive mantle normalised multi-element plots are used here to investigate the geochemical signature of these samples. The primitive mantle normalising values are those of Sun and McDonough (1989) and the element order is adopted from Jenner (1996). The Low Field Strength Element (LFSE) thorium is the only element used here that is acknowledged as being mobile during alteration.

In Figure 6a, samples from the 'Blackcaps' Tuff, the gabbroic body near Tseta Creek and from the basalt and gabbro within the Nimbus serpentinite mélange are plotted together with normal mid-ocean ridge basalt (N-MORB) and island-arc tholeiite (IAT) values. There is a striking consistency between all of the seven samples analysed, although some are slightly more enriched relative to others. All are characterised by a negative Nb anomaly, a characteristic signature of arc volcanic rocks (Jenner, 1996). However, this simple pattern is distorted by significant variability in the Th values. Apart from the negative Nb

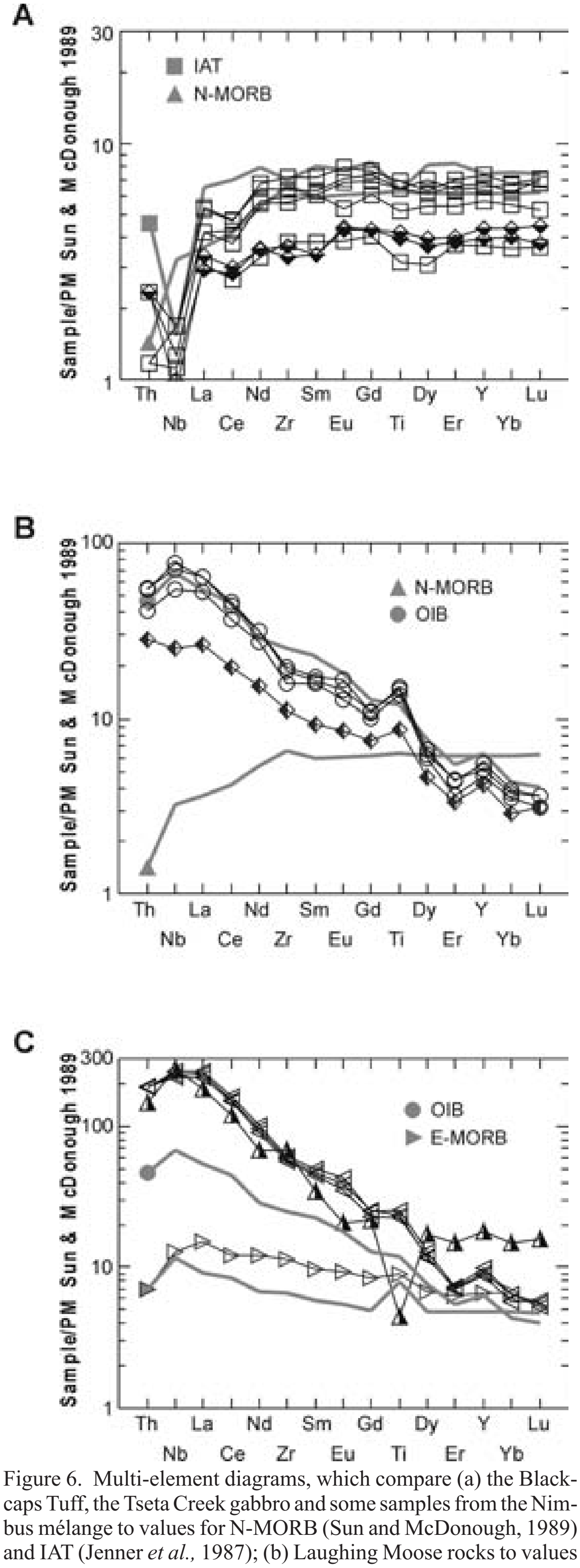

Figure 6. Multi-element diagrams, which compare (a) the Blackcaps Tuff, the Tseta Creek gabbro and some samples from the Nimbus mélange to values for N-MORB (Sun and McDonough, 1989) and IAT (Jenner *et al.,* 1987); (b) Laughing Moose rocks to values for N-MORB and OIB (Sun and McDonough, 1989), and (c) carbonate associated volcanics and one sample from Nimbus to values for OIB and E-MORB (Sun and McDonough, 1989).

anomaly, it is difficult to separate island-arc tholeiites from those volcanics of N-MORB affinity, as evidenced in the discrimination diagrams. However, the clastic nature of these volumetric deposits, and the presence of interbedded chert and bioclastic turbidites is consistent with an arc setting.

The 'Laughing Moose' augite porphyry displays enrichment in most of the incompatible elements relative to MORBs (Figure 6b). This humped pattern is characteristic of ocean-island basalts (OIB; Pearce, 1982, 1983), supporting interpretations drawn from discrimination diagrams. The intrusive rock sampled from this region (JEN01-32-8) appears to follow a similar trend, although it is relatively depleted in the light REEs, possibly reflecting its more evolved nature. This suggests that the diorite is comagmatic with the 'Laughing Moose' augite porphyry.

The final multi-element plot illustrated here (Figure 6c) displays the trends of the carbonate-associated basanite flows, as well as another sample from the Mt. Nimbus area (FDE01-31-4). The three samples of basanite are highly enriched in the incompatible elements, plotting at values three-times that of modern OIB. The solitary sample from 'Sideout Mountain' (YME01-31-7C) displays enrichment in both light and heavy REEs and a striking negative Ti anomaly. One possibility is that this enrichment in these samples may reflect a localised rifting event, tapping a very fertile mantle source. The final sample from Nimbus (FDE01-31-4) appears to reflect an enriched mid-ocean ridge (E-MORB) source, with a slight enrichment in LREE relative to N-MORB. This block, from near the margin of the mélange, had faint indications of calcite-filled vesicles and was thought to be a part of the pillowed basanite unit.

DISCUSSION

A rigorous evaluation of the Cache Creek terrane paleotectonic setting cannot be made based upon the limited data presented here. However, data obtained thus far from the Nakina region show it to be dominated by two different petrogenetic components; alkaline volcanic rocks of within-plate affinity, and primitive arc-related, subalkaline volcaniclastic rocks and intrusives.

First of all, there is a spatial association of alkali basalts of ocean-island affinity with the thick Horsefeed Formation platformal carbonate. Monger (1975) originally suggested that seamounts and/or oceanic plateaus in the Cache Creek ocean basin were the elevated oceanic basement on which the carbonate platforms were constructed, a contention supported by our data. Palaeontological and geochronological age-dating constrain the age of seamounts to older than the Permo-Carboniferous carbonate that caps them (Monger, 1975; see also Mihalynuk *et al.*, this volume). Secondly, the mafic volcanic rocks in the 'Blackcaps' area are of oceanic arc affinity, and share this characteristic with some of the intrusive rocks that have been analysed. This may explain the paucity of sheeted dykes and pillow basalts in the Nakina region while thick sequences of volcaniclastics are preserved.

These observations pose an interesting question. Although arc volcanics have been documented within the Cache Creek terrane (*e.g.* the Kutcho Formation - Thorstad and Gabrielse, 1986; Sitlika Assemblage - Schiarizza and Payie, 1997; Hall Lake and French Range volcanics - Mihalynuk and Cordey, 1997; Ashcroft - Childe *et al.*, 1997), is their volumetric importance in the Nakina area greater than was previously appreciated? Accretionary complexes of deep ocean sediments are often associated with oceanic arcs, and the incorporation of carbonate platforms, volcanic seamounts and MORB-type pillow basalts from the subducting oceanic crust has been documented at modern island arcs (*e.g.* Taira *et al.*, 1989; Bloomer *et al.*, 1995; Johnson *et al.*, 1990; Johnson *et al.*, 1991). Therefore, an accretionary prism/oceanic arc origin may provide a mechanism to explain the lithological diversity within the Nakina area.

CONCLUSIONS

A number of distinct mafic igneous assemblages are recognised in the dominantly volcaniclastic rocks of the Nakina area. These include the magmatic "knockers" of the Nimbus serpentinite mélange; the mint-green tuffs of 'Blackcaps' Mountain; the coarse, augite-phyric breccia of 'Laughing Moose' Creek; as well as volcanic pediments to reef-forming carbonates.

No N-MORBs have been identified based upon preliminary geochemical investigation of the Nakina area basalts, despite having been documented elsewhere in the terrane (*e.g.* Ash and MacDonald, 1993; Ash, 1994; Mihalynuk, 1999). Alkaline volcanic rocks of 'Sideout Mountain', Mt. Nimbus and 'Laughing Moose Creek' were most likely sourced in an ocean island/plateau environment, consistent with the early suggestions of Monger (1977).

Other mafic rocks in the region have textural and geochemical characteristics consistent with formation in an oceanic arc environment. Juxtaposition of basaltic crustal fragments with disparate petrogenesis has been documented in accretionary prisms worldwide. An accretionary prism/oceanic arc origin for much of the volcanic rocks of the Nakina area is supported by the geochemistry and geology of the area.

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REFERENCES CITED

Aitken, J.D., (1959): Atlin map-area, British Columbia; *Geological Survey of Canada,* Memoir 307, 89 pages.

Ash, C.H. (1994): Origin and tectonic setting of ophiolitic ultramafic and related rocks in the Atlin area, British Columbia (NTS 104N); *B.C. Ministry of Energy, Mines and Petroleum Resources,* Bulletin 94, 48 pages.

Ash, C.H. and Macdonald, R.W.J. (1993): Geology, mineralization and lithogeochemistry of the Stuart Lake area, central British Columbia (Parts of 93K/7, 8, 10 and 11); *in* Geological Fieldwork 1992, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1993-1, pages 69-86.

Bloomer, S.H., Taylor, B., MacLeod, C.J., Stern, R.J., Fryer, P., Hawkins, J.W. and Johnson, L. (1995): Early arc volcanism and the ophiolite problem: A perspective from drilling in the western Pacific; *in* Active Margins and Marginal Basins of the Western Pacific, Taylor, B. and Natland, J. (Editors), *American Geophysical Union*, Geophysical Monograph 88, pages 1-30.

Childe, F., Friedman, R.M., Mortensen, J.K. and Thompson, F.H. (1997): Evidence for early Triassic felsic volcanism in the Ashcroft (92I) map area, British Columbia; *in* Geological Fieldwork 1996, *B.C. Ministry of Employment and Investment*, Paper 1997-1, pages 117-123.

Coney, P.J. (1989): Structural aspects of suspect terranes and accretionary tectonics in western North America; *Journal of Structural Geology*, Volume 11, No. 112, pages 107-125.

Coney, P.J., Jones, D.L. and Monger, J.W.H. (1980): Cordilleran suspect terranes; *Nature*, Volume 288, pages 329-333.

Cordey, F., Gordey, S.P and Orchard, M.J. (1991): New biostratigraphic data from the northern Cache Creek terrane, Teslin map area, southern Yukon; *in* Current Research, Part E; *Geological Survey of Canada*, Paper 91-1E, pages 67-76.

Cordey, F., Mortimer, N., DeWeever, P. and Monger, J.W.H. (1987): Significance of Jurassic radiolarians from the Cache Creek terrane, British Columbia; *Geology*, Volume 15, pages 1151-1154.

Cox, K.G., Bell, J.D. and Pankhurst, R.J. (1979): The interpretation of igneous rocks; *George Allen and Unwin*, London, pages 450.

Gabrielse, H. and Yorath, C.J. (1989): Decade of North American Geology #4, The Cordilleran Orogen in Canada; *Geoscience Canada*, Volume 16, Number 2, pages 67-83.

Irvine, T.N. and Baragar, W.R.A. (1971): A guide to the chemical classification of the common volcanic rocks; *Canadian Journal of Earth Sciences*, Volume 8, pages 523-548.

Johnson, L.E. and Fryer, P. (1990): The first evidence for MORB-like lavas from the outer Mariana forearc: geochemistry, petrography and tectonic implications; *Earth and Planetary Science Letters*, Volume 100, pages 304-316.

Johnson, L.E., Fryer, P., Taylor, B., Silk, M., Jones, D.L., Sliter, W.V., Itaya, T. and Ishii, T. (1991): New evidence for crustal accretion in the outer Mariana fore arc: Cretaceous radiolarian cherts and mid-ocean ridge basalt-like lavas; *Geology*, Volume 19, pages 811-814.

Jenner, G.A. (1996): Trace element geochemistry of igneous rocks: geochemical nomenclature and analytical geochemistry; *in* Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration, Wyman, D.A. (Editor), *Geological Association of Canada,* Short Course Notes, Volume 12, pages 51-77.

Jenner, G.A., Cawood, P.A., Rautenschlein-M and White, W.M. (1987): Composition of back-arc basin volcanics, Valu Fa Ridge, Lau Basin: evidence for a slab-derived component in their mantle source; *Journal of Volcanology and Geothermal Research,* Volume 32, pages 209-222.

Meschede, M. (1986): A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram; *Chemical Geology*, Volume 56, pages 207-218.

Mihalynuk, M.G. (1999): Geology and mineral resources of the Tagish Lake area (NTS 104M/8, 9, 10E, 15 and 104N/12W) northwestern British Columbia; *B.C. Ministry of Energy, Mines and Petroleum Resources,* Bulletin 105, 217 pages.

Mihalynuk, M.G. and Cordey, F. (1997): Potential for Kutcho Creek volcanogenic massive sulphide mineralization in the northern Cache Creek terrane: A progress report; *in* Geological Fieldwork 1996, *B.C. Ministry of Employment and Investment*, Paper 1997-1, pages 157-170

Mihalynuk, M.G., Erdmer, P., Ghent, E.D., Archibald, D.A., Friedman, R.M., Cordey, F., Johannson, G.G. and Beanish, J. (1999): Age constraints for emplacement of the northern Cache Creek terrane and implications of blueshist metamorphism; in Geological Fieldwork 1998, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1999-1, pages 127-141.

Monger, J.W.H. (1975): Upper Paleozoic rocks of the Atlin terrane; *Geological Survey of Canada,* Paper 74-47, 63 pages.

Monger, J.W.H. (1977): Upper Paleozoic rocks of the northwestern British Columbia; *Geological Survey of Canada*, Paper 77-1A, pages 255-262.

Monger, J.W.H. and Ross, C.A. (1971): Distribution of fusulinaceans in the western Canadian Cordillera; *Canadian Journal of Earth Sciences*, Volume 8, pages 259-278.

Monger, J.W.H., Price, R.A. and Tempelman-Kluit, D.J. (1982): Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera; *Geology*, Volume 10, pages 70-75.

Mullen, E.D. (1983): $MnO_2/TiO_2/P_2O_5$: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis; *Earth and Planetary Science Letters*, Volume 62, pages 53-62.

Orchard, M.J. (1991): Conodonts, time and terranes: An overview of the biostratigraphic record in the western Canadian Cordillera; *in* Ordovician to Triassic conodont palaeontology of the Canadian Cordillera; Orchard, M.J. and McCracken, A.D., Editors; *Geological Survey of Canada*, Bulletin 417, pages 1-25.

Orchard, M.J., Struik, L.C., Rui, L., Bamber, E.W., Mamet, B., Sano, H. and Taylor, H. (2001): Palaeontological and biogeographical constraints on the Carboniferous to Jurassic Cache Creek terrane in central British Columbia; *Canadian Journal of Earth Sciences*, Volume 38(4), pages 551-578.

Pearce, J.A. (1982): Trace element characteristics of lavas from destructive plate boundaries; *in* Andesites, Thorpe, R.S. Editor; *John Wiley and Sons Inc.*, New York, pages 525-548.

Pearce, J.A. (1983): Role of the sub-continental lithosphere in magma genesis at active plate margins; *in* Continental basalts and mantle xenoliths, Hawkesworth, C.J. and Norry, M.J. (Editors), *Shiva Publishing Limited*, pages 230-249.

Pearce, J.A. and Norry, M.J. (1979): Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks; *Contributions to Mineralogy and Petrology*, Volume 69, pages 33-47.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks; *Journal of Petrology*, Volume 25, pages 956-983.

Schiarizza, P. and Payie, G. (1997): Geology of the Sitlika Assemblage in the Kenny Creek - Mount Olson area (93N/12, 13), central British Columbia; *in* Geological Fieldwork 1996, *B.C. Ministry of Employment and Investment*, Paper 1997-1, pages 79-100.

Smith, R.E. and Smith, S.E. (1976): Comments on the use of Ti, Zr, Y, Sr, K, P and Nb in classification of basalt; *Earth and Planetary Science Letters*, Volume 32, pages 114-120.

Sun, S.S. and McDonough, W.F. (1989): Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes; *in* Magmatism in the ocean basins, *Geological Society of London*, Special Publication 42, pages 313-345.

Taira, A., Tokuyama, H. and Soh, W. (1989): Accretion tectonics and evolution of Japan; *in* The evolution of the Pacific Ocean Margins, Ben-Avraham, Z. (Editor), *Oxford University Press,* New York, pages 100-123.

Tardy, M., Lapierre, H., Struik, L.C., Bosch, D. and Brunet, P. (2001): The influence of mantle plume in the genesis of Cache Creek oceanic igneous rocks: implications for the geodynamic evolution of the inner accreted terranes of the Canadian Cordillera; *Canadian Journal of Earth Sciences*, Volume 38, pages 515-534.

Terry, J. (1977): Geology of the Nahlin ultramafic body, Atlin and Tulsequah map-areas, northwestern British Columbia; *in* Current Research, *Geological Survey of Canada*, Paper 77-1A, pages 263-266.

Thorstad, L.E., and Gabrielse, H. (1986): The Upper Triassic Kutcho Formation, Cassiar Mountains, north-central British Columbia; *Geological Survey of Canada*, Paper 86-16, 53 pages.

Winchester, J.A. and Floyd, P.A. (1977): Geochemical discrimination of different magma series and their differentiation products using immobile elements; *Chemical Geology*, Volume 20, pages 325-343.