Geochemistry and Petrography of Upper Hazelton Group Volcanics: VHMS-Favourable Stratigraphy in the Iskut River and Telegraph Creek Map Areas, Northwestern British Columbia

By T. Barresi[1] and J. Dostal[2]

KEYWORDS: Eskay Creek, Eskay Rift, Hazelton Group, geochemistry, petrochemistry, island arc, bimodal volcanism, VMS deposits, Targeted Geoscience Initiative II (TGI-II)

INTRODUCTION

In 2003, the British Columbia Geological Survey and the Geological Survey of Canada initiated a joint project to map lower Middle Jurassic, upper Hazelton Group rocks in the Telegraph Creek and Iskut River map areas of northwestern British Columbia. In this region, the upper Hazelton Group is host to the Eskay Creek volcanic-hosted massive sulphide (VHMS) deposit, as well as numerous showings, prospects and geochemical anomalies, making it one of the most highly prospective regions in British Columbia. The scope of the project includes regional and detailed mapping of the upper Hazelton Group as well as geochemical and geochronological studies. Funding is provided by the British Columbia Ministry of Energy and Mines, and by the Geological Survey of Canada's Targeted Geoscience Initiative II.

This paper is the first of a series that will present and interpret whole rock and mineral chemistry data from the study area. The purpose of studying these data is to better understand the igneous and tectonic processes that were dominant during the formation of the Eskay Creek VHMS deposit, and to determine the significance of similarities and variations in the geochemistry of Eskay Creek time-equivalent volcanic rocks along the length of the Eskay Rift. This study may lead to a better understanding of how whole rock geochemistry can be used as an exploration tool in finding VHMS style mineralization. The data presented in this article are whole rock geochemical analyses of 17 volcanic and related intrusive rocks that were collected during the 2003 field season from the area between More Creek and Kinaskan Lake, in the Telegraph Creek map area (Fig. 1). The focus of this study is on Lower to Middle Jurassic, upper Hazelton Group rocks, which in the study area are assigned to the Willow Ridge Complex (Alldrick *et al.*, 2004a; Alldrick *et al.*, 2004b).

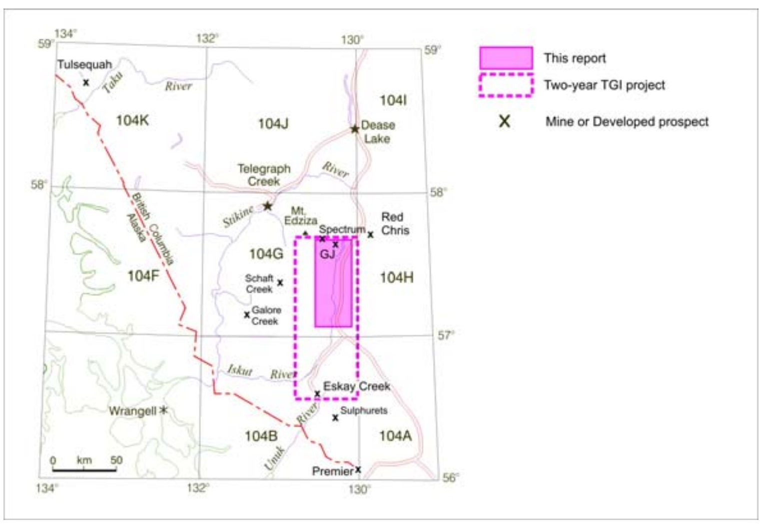

Figure 1. Project location map; modified from Logan *et al.* (2000)

1 – *Department of Earth Science, Dalhousie University, Halifax, NS, B3H 3J5 e-mail: TN425520@dal.ca*
2 – *Department of Geology, Saint Mary's University, Halifax, NS, B3H 3C3*

GEOLOGICAL SETTING

The Willow Ridge Complex (WRC) is located within the Stikine Terrane in northwestern British Columbia (Fig. 2). The Stikine Terrane, in the Iskut and Telegraph Creek map areas, is composed of three major pre-accretionary units and two younger, syn- and post-accretionary, units (Alldrick *et al.*, 2004a). The main stratigraphic components are: 1) the metavolcanic and metasedimentary Stikine Assemblage of Devonian to Permian age; 2) island-arc volcanic rocks of the Late Triassic Stuhini Group; 3) Early to Middle Jurassic island-arc volcanic and sedimentary rocks of the Hazelton Group; 4) the Middle Jurassic to Cretaceous Bowser Lake Group, which is a sedimentary overlap assemblage that overlies the eastern margin of the Stikine Terrane units; and 5) the upper Miocene to Holocene Mount Edziza Volcanic Complex.

The Willow Ridge Complex is defined by Alldrick *et al.* (2004a). It is considered to be a part of the Eskay Creek Facies of Anderson and Thorkelson (1990) and is interpreted to have been deposited in a subaqueous volcano-sedimentary environment, typical of rift settings (Alldrick *et al.*, 2004a). Alldrick *et al.* (2004a) describe the WRC as a "thick package of basalt lava flows and feeder dikes, minor interlayered dacite and rhyolite lava flows, breccias, feeder dikes and lava domes, and intercalated volcaniclastic sedimentary rocks". Alldrick *et al.* (2004a) interpret the volcanic rocks within the complex as a bimodal volcanic suite. The full thickness of the complex is uncertain, but on Table Mountain it is at least 4 km thick. The complex is divided into three units: a Lower Basalt Unit, a Middle Sedimentary Unit, and an Upper Basalt Unit, which unconformably overlie older, Stuhini Group or lower Hazelton Group volcanic breccias. All three WRC units have intercalated felsic flows and feeder dikes and sills. The Middle Sedimentary Unit is predominantly composed of clastic rocks but also contains bimodal volcanics, including a north-northwesterly trending line of felsic domes. The reader is referred to Alldrick *et al.* (2004a), Alldrick *et al.* (2004b), and Simpson and Nelson (2004) for detailed maps and descriptions of the geology in the study area.

PETROGRAPHY

The WRC consists of a bimodal, felsic and mafic igneous rock suite. Mafic rocks consist mainly of basalt and minor andesite; felsic rocks are rhyolite.

Mafic rock in the WRC is aphanitic and dark to olive green. Mafic intrusions include dikes and sills, and, on Willow Ridge, stocks assigned to the Three Sisters Plutonic Suite. Extrusive units include massive flows, pillowed flows and pillow breccia, hyaloclastite, and breccias of fluidly shaped clasts typical of fire fountain deposits (Simpson and Nelson, 2004). Basalts and andesites are commonly amygdaloidal and have characteristic white weathering variolites, a devitrification feature. Their primary mineralogy includes densely packed plagioclase laths and clinopyroxene phenocrysts in a devitrified glassy matrix. Amygdules are filled with chlorite and minor quartz and calcite. The primary mineralogy of basalts and andesites is well preserved with the exception of secondary calcite in the matrix and clinopyroxene phenocrysts that are in some cases replaced by chlorite and quartz. Secondary alteration accounts for between 5 and 25% of the modal mineralogy in mafic samples.

Felsic rock in the WRC is aphanitic, white to pale green, commonly spherulitic and rarely has small vesicles/amygdules that are elongated parallel to flow. High-level felsic intrusions include dikes, sills and cryptodomes; extrusive bodies occur as flows, breccias and domes. The rhyolites are generally aphyric, and rarely feldspar porphyritic with potassium feldspar and lesser plagioclase phenocrysts. The groundmass has undergone minor devitrification and is mainly composed of quartz and potassium feldspar. Accessory amounts of sphene are common; sample JN01-08 also contains zircon. The proportion of opaque minerals is low in most samples, but sample JN04-11 contains 14% opaque minerals. The samples have undergone varying degrees of alteration and contain secondary epidote, chlorite, calcite, quartz and white mica. Secondary alteration products account for between 5 and 15% of the modal mineralogy in rhyolite samples.

ANALYTICAL METHODOLOGY AND SAMPLING PROCEDURE

Seventeen samples for whole rock and trace element analysis were collected from surface exposures during regional mapping (Fig. 2; Alldrick *et al.* 2004a; Alldrick *et al.* 2004b). They were selected to represent the least altered instances of the full range of volcanic lithologies that occur commonly in the study area. Four samples (A03-14-7, A03-18-6, JN-07-01 and MS-03-07-02) represent the Triassic Stuhini Group and lower Hazelton Group. The remaining samples are upper Hazelton Group rocks of the Willow Ridge Complex. The data for all samples are presented in Table 1. For the analysis discussed in this paper, four samples are discarded. Sample A03-18-6 is discarded because it is a tuff. Samples A03-14-7 and MS-03-06-05 are discarded due to high degrees of alteration. Sample KS04-23B is discarded because it contains a high proportion of mafic xenocrysts. The remaining samples represent three lithologies: rhyolite, basalt and andesite.

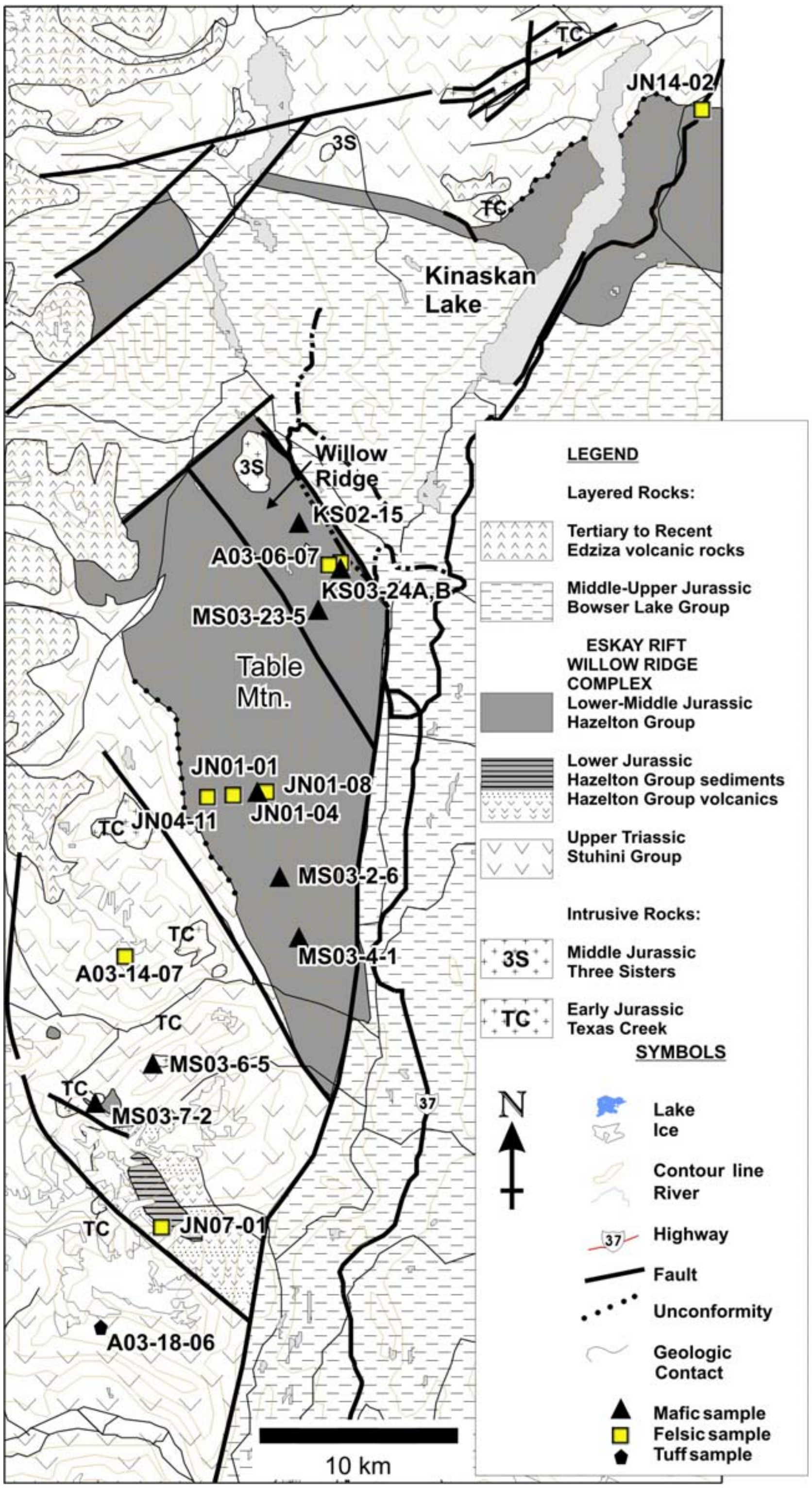

Figure 2. Geology map with sample locations; modified from Alldrick *et al.* (2004a).

TABLE 1. WHOLE ROCK GEOCHEMISTRY OF 17 SAMPLES FROM THE AREA BETWEEN MORE CREEK AND KINASKAN LAKE, IN THE TELEGRAPH CREEK MAP AREA

	WRC Rhyolite					WRC Mafic Rock						Triassic Rock		Discarded Samples			
	A03-06-07	JN01-01	JN01-08	JN04-11	JN14-02	JN01-04	KS02-15	KS03-24A	MS-03-23-05	MS-03-2-6	MS-03-04-01	JN07-01	MS-03-07-02	A03-14-07	A03-18-06	KS03-24B	MS-03-06-05
Northing	421260	416367	417267	415228	437134	417070	418813	421488	420457	419124	418694	412100	410866	409615	409310	421488	412705
Easting	6367558	6357233	6357929	6357218	6390500	6357677	6369407	6367159	6365319	6353741	6351346	6336122	6340927	6349481	6330150	6367159	6342981
SiO_2	82.58	76.48	81.94	69.01	69.87	46.11	47.09	51.77	56.7	61.77	53.91	83.9	52.93	96.58	64.9	71.02	55.34
TiO_2	0.1	0.15	0.23	0.5	0.18	1.51	0.98	1.94	1.73	1.15	1.36	0.12	0.87	0.05	0.94	0.68	0.68
Al_2O_3	8.27	11.84	7.73	12.68	14.06	13.02	16.09	13.64	14.89	13.55	15.06	7.46	18.23	0.87	12.93	13.34	16.38
Fe_2O_3	0.52	1.72	1.37	5.48	3.14	9.75	10.31	13.01	10.85	9.18	10.52	1.62	5.92	0.6	7.51	3.15	6.09
MnO	0.01	0.01	0.01	0.1	0.09	0.18	0.12	0.25	0.1	0.1	0.1	0.01	0.2	0.01	0.01	0.01	0.12
MgO	0.02	0.23	0.49	0.72	0.2	3.35	8.6	4.5	3.17	3.08	5.26	0.15	0.79	0.01	2.56	0.94	1.8
CaO	0.07	0.03	0.31	0.3	0.98	11.47	6.17	2.39	2.25	1.08	3.44	0.21	8.39	0.05	1.19	1	5.15
Na_2O	0.21	4.55	0.23	4.78	3.38	4.4	3.98	0.67	5.67	3.52	4.53	2.18	4.21	0.01	1.89	5.32	3.08
K_2O	6.96	3.07	5.46	1.12	5.19	0.64	0.62	6.03	0.02	2.42	1.13	2.75	1.99	0.18	2.68	2.22	3.83
P_2O_5	0.03	0.01	0.07	0.1	0.05	0.28	0.15	0.74	0.31	0.34	0.31	0.01	0.34	0.01	0.15	0.28	0.3
Ba	0.09	0.15	0.27	0.1	0.15	0.06	0.07	0.17	0.02	0.11	0.11	0.21	0.14	0.03	0.02	0.06	0.2
LOI	0.37	0.98	1.14	4.63	2	8.14	5.32	4.46	3.89	3.31	3.88	0.7	5.48	1.33	4.84	1.35	6.36
Total	99.23	99.22	99.25	99.52	99.29	98.91	99.5	99.57	99.6	99.61	99.61	99.32	99.49	99.73	99.62	99.37	99.33
V (ppm)	11	10	8	16	7	280	169	292	132	52	231	7	136	19	160	65	124
Y	14.55	48.05	31.73	51.76	32.08	35.52	18.47	40.79	39.04	31.04	43.53	42.67	22.63	4.34	19.92	30.98	18.82
Zr	99.19	365.48	216.59	352.68	308.44	147.48	68.5	157.27	189.8	186.33	222.51	253.57	135.22	17.10	163.88	178.48	140.75
Nb	5.00	21.03	11.50	21.88	17.94	13.53	6.17	9.01	14.95	15.08	15.1	20.53	12.34	3.72	10.05	9.19	13.8
La	19.79	26.97	14.15	23.23	32.48	10.96	4.25	15.38	18.35	13.23	15.37	7.68	18.65	6.00	13.81	20.12	16.3
Ce	37.28	53.69	26.26	46.59	60.97	24.58	10.62	31.83	37.28	31.18	33.33	17.29	35.62	13.36	28.78	42.07	30.42
Pr	3.50	6.65	3.53	5.92	7.18	3.48	1.69	4.50	5.06	4.50	4.50	2.44	4.53	1.43	4.34	5.37	3.80
Nd	11.42	27.65	14.46	25.04	27.20	16.36	8.79	20.71	22.54	20.57	20.08	11.22	19.38	5.44	18.90	22.03	16.05
Sm	1.84	6.41	3.17	6.06	5.30	4.39	2.52	5.39	5.47	5.30	5.15	3.57	4.33	0.70	4.54	4.74	3.58
Eu	0.14	1.05	0.58	1.63	0.89	1.40	0.90	1.47	1.33	1.23	1.43	0.67	1.43	0.11	1.24	0.96	0.98
Gd	1.51	6.96	3.87	7.34	5.25	5.66	3.18	6.87	6.63	6.02	6.50	4.93	4.50	0.53	4.63	4.98	3.62
Tb	0.30	1.30	0.73	1.32	0.89	0.98	0.54	1.16	1.10	1.01	1.13	1.04	0.69	0.10	0.72	0.85	0.56
Dy	2.28	8.83	5.20	9.01	5.82	6.49	3.54	7.54	7.04	6.38	7.66	7.26	4.30	0.71	4.43	5.55	3.50
Ho	0.57	1.96	1.19	2.03	1.29	1.41	0.76	1.63	1.50	1.29	1.67	1.63	0.89	0.16	0.87	1.22	0.73
Er	2.11	6.34	3.81	6.43	4.09	4.28	2.25	4.91	4.43	3.73	5.08	5.08	2.56	0.50	2.48	3.72	2.20
Tm	0.37	1.01	0.59	1	0.64	0.64	0.33	0.72	0.65	0.55	0.77	0.79	0.38	0.07	0.37	0.55	0.33
Yb	2.74	7.15	4.12	6.81	4.48	4.24	2.13	4.81	4.35	3.60	5.14	5.52	2.46	0.60	2.51	3.70	2.27
Lu	0.43	1.08	0.59	0.99	0.64	0.6	0.30	0.70	0.61	0.52	0.75	0.78	0.36	0.09	0.37	0.53	0.32
Hf	3.58	8.74	4.64	7.35	6.55	3.49	1.59	3.65	4.36	4.43	4.79	5.56	3.12	0.32	3.75	3.98	3.28
Ta	0.66	1.06	0.54	0.93	0.90	0.39	0.11	0.45	0.70	0.73	0.56	0.78	0.51	0.06	0.40	0.58	0.51
Th	13.77	6.07	3.93	6.41	11.43	1.60	0.25	2.26	3.23	3.56	3.30	4.51	3.61	0.42	1.75	5.46	5.75

Processing of samples included the removal of weathered surfaces by selective chip sampling. Samples were pulped in a chrome steel swing mill. The major oxides as well as Ba and V were determined by x-ray fluorescence (XRF) using a fused disc and Siemens spectrometer at Global Discovery Labs in Vancouver, British Columbia. Loss on ignition was determined by fusion at 1100°C. Trace element concentrations, including analyses of Y, Zr, Nb, Hf, Ta, Th and the rare earth elements (REE) were determined by inductively coupled plasma mass spectrometry (ICP-MS) at Memorial University of Newfoundland (rock powders were dissolved with Na_2O_2). The quality of analysis was monitored by simultaneous analysis of standard reference rocks. Major oxides and trace elements have been recalculated to anhydrous for all discussion in this paper. Table 1 contains the results of all original data, which are not recalculated to anhydrous compositions.

WHOLE ROCK GEOCHEMISTRY

WRC Rocks

Analysis of major oxides of metamorphosed and altered rocks, such as those from the WRC, poses difficulties because many major elements have a high degree of mobility. In particular, the hydrothermal alteration of feldspars and glass results in the loss of alkalis (Saeki and Date, 1980), and the formation of chlorite can affect Mg and Fe concentrations (Lentz, 1999). Other major elements, such as Al_2O_3 and TiO_2, are normally considered immobile. For this study an effort was made to collect samples exhibiting the least amount of alteration. However, petrography shows that many samples have been subject to significant alteration. As a result, the emphasis of this study is on trace element geochemistry utilizing mainly the REE and high field strength elements, which are considered to be immobile under low-grade alteration conditions (Whitford *et al.*, 1988; Lentz, 1999).

According to SiO_2 vs Zr/TiO_2 ratios, WRC rocks range, on an anhydrous basis, from basalts and andesites to dacites and rhyolites (Fig. 3). Two samples have very high contents of SiO_2 (83%), indicating that they were affected by secondary SiO_2 enrichment. In addition, petrography shows that secondary quartz is present in some mafic samples, which suggests that the rocks which plot as andesites may be silicified basalt. Because of this apparent SiO_2 mobility, classification of WRC rocks must be done using trace elements. According to Zr/TiO_2 vs Nb/Y ratios, the WRC volcanics are a bimodal rock suite, consisting of mafic rocks that range in composition from basalts to andesite-basalts, and felsic rocks that are all rhyolites (Fig. 4).

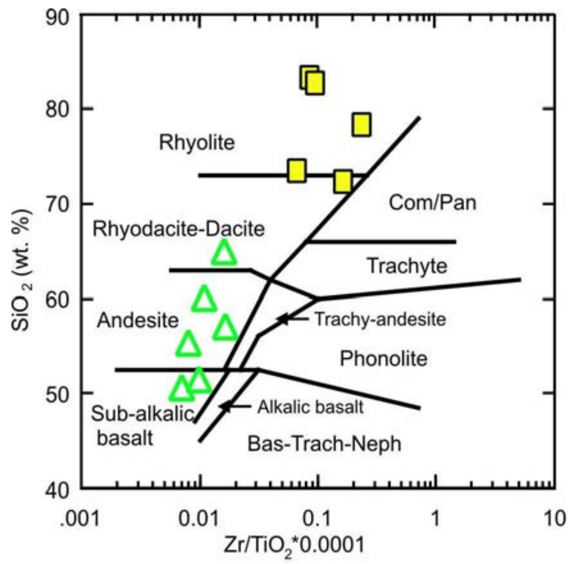

Figure 3. Classification of WRC volcanic rocks; squares = felsic samples, triangles = mafic samples; Com/Pan = comendite and pantellerite; Bas-Trach-Neph = basanite and trachyte and nephelinite; Winchester and Floyd (1977).

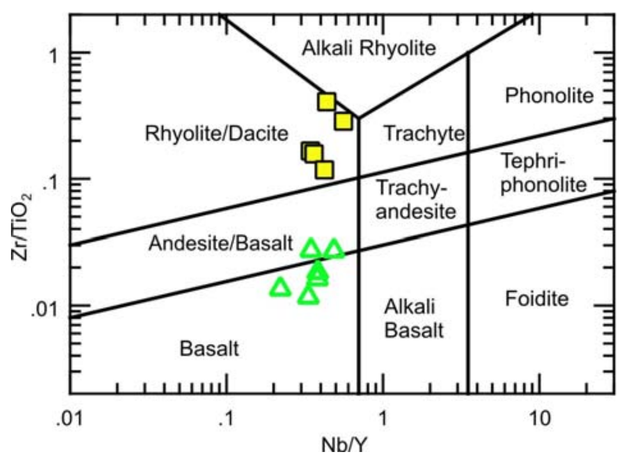

Figure 4. Classification of WRC volcanic rocks according to immobile elements; squares = felsic samples, triangles = mafic samples; Pearce (1996).

Both classification systems agree that the WRC rocks are sub-alkalic. A plot of TiO_2 vs Mg# (Mg# = $Mg/Mg+Fe_{tot}$) supports the bimodality of the suite, showing that the felsic and mafic rocks form two distinct populations (Fig. 5).

WRC Mafic Rocks

Mafic rocks of the Willow Ridge Complex are basalts and andesites (Fig. 4). According to their negative trend on a TiO_2 vs Mg# diagram (Fig. 5) and overall high TiO_2 values (1.3 – 2%), they have a

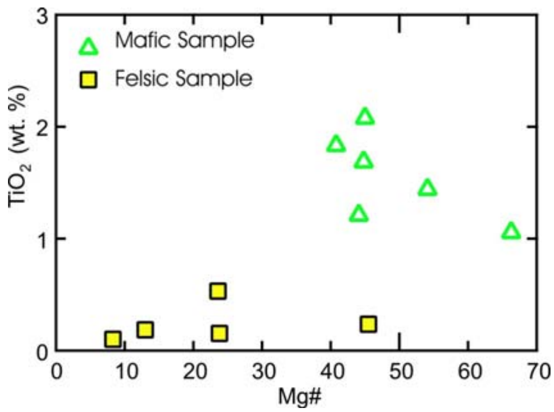

Figure 5. TiO_2 vs MG# (MG# = Mg/Mg+Fe_{tot}) plot of WRC mafic and felsic volcanic rocks; shows two unrelated populations; mafic samples have high TiO_2 concentrations and a negative slope.

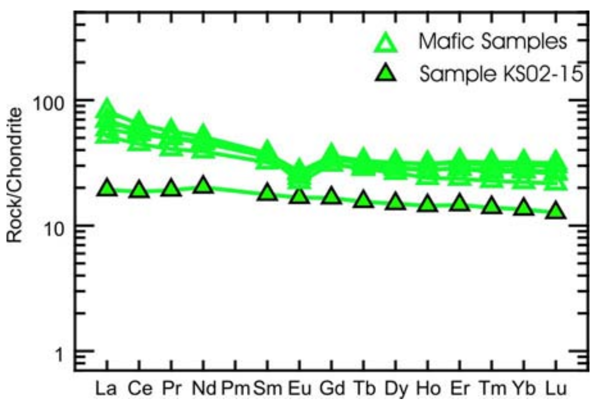

Figure 6. Chondrite normalized REE plot of WRC mafic rocks; Sun and McDonough (1989).

tholeiitic MORB affinity. Rare earth elements (REE) show a slight enrichment in light REE (LREE) (La_n/Sm_n = 1.83), flat heavy REE (HREE) (Gd_n/Yb_n = 1.19) and a small negative Eu anomaly (Fig. 6). Sample KS-02-15 has lower absolute abundance of REE and a nearly flat pattern (La_n/Yb_n = 1.43). Mantle normalized trace element abundance patterns for the mafic rocks show a slight enrichment of strongly incompatible elements, sloping from Th to Sm with a small but distinct negative Nb anomaly (Fig. 7). Sample KS02-15 has lower absolute abundances of incompatible elements than the other mafic samples, and it does not show a negative Nb anomaly. There are no significant systematic differences between the trace element characteristics of basalts and andesites.

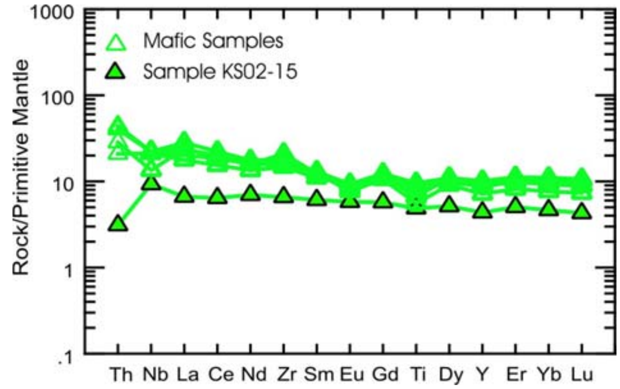

Figure 7. Primitive mantle normalized immobile element plot of WRC mafic rocks; Sun and McDonough (1989).

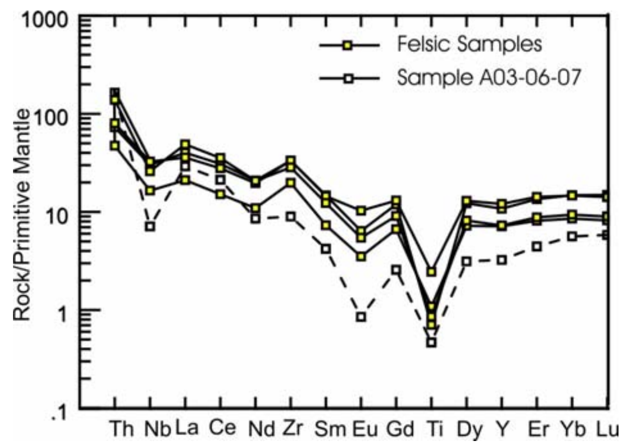

Figure 8. Chondrite normalized REE plot of WRC felsic rocks; Sun and McDonough (1989).

WRC Felsic Rocks

The very high concentrations of SiO_2 (between 72% and 83%) in the rhyolites suggest that at least some samples were affected by secondary silicification. The majority of felsic samples follow the same pattern on REE diagrams and show enrichment in LREE (La_n/Sm_n = 3.01), flat HREE (Gd_n/Yb_n = 0.86) and a slight negative Eu anomaly (Fig. 8). One sample (A03-06-07) has a very different, V-shaped, REE pattern. It has a moderately steep downward slope from La to Sm (La_n/Sm_n = 6.93), a shallow upward slope from Gd to Lu (Gd_n/Yb_n = 0.46) and a strong negative Eu anomaly. Mantle normalized trace element plots also distinguish sample A03-06-07 from the main felsic population (Fig. 9). The four felsic samples that plot together have a

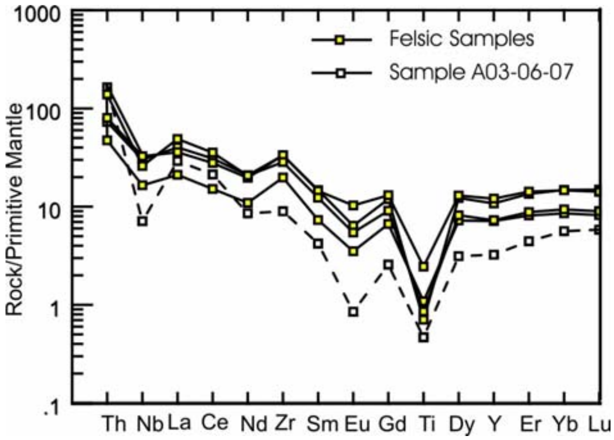

Figure 9. Primitive mantle normalized immobile element plot of WRC felsic rocks; Sun and McDonough (1989).

shallow downward slope up to Sm with mildly negative Nb, strongly negative Ti and weak positive Zr anomalies. Sample A03-06-07 has a lower absolute abundance of most incompatible elements, a steeper negative slope up to Sm and stronger negative Nb and Eu anomalies.

DISCUSSION

The volcanic rocks of the Willow Ridge Complex form a bimodal, sub-alkalic suite that is consistent with a rifting arc environment. Two sources are proposed for the mafic rocks within the complex. Sample KS02-15, which has a flat REE pattern and a positive Nb anomaly on a mantle normalized profile (Fig. 7), is typical of rift-related basalts generated from asthenospheric mantle. The remaining samples, which are relatively enriched in LREE and incompatible elements such as Th, and have a slight negative Nb anomaly, are derived from sub-arc lithospheric mantle.

Rhyolites in the WRC show a distinct grouping according to Zr/TiO_2 and Nb/Y ratios (Fig. 4). No intermediate or alkali rocks are represented. The absolute abundances of trace elements of rhyolites and basalts overlap (Fig. 10). This precludes the possibility that the rhyolites were derived from fractional crystallization of the basalts. Therefore they must have a different source than the WRC mafic rocks. The most obvious source of the rhyolites is melting of crustal rocks. Sample A03-06-07 has a very different trace element signature than most of the WRC rhyolites; this may be a result of the heterogeneous nature of the crust from which it is derived. A variety of explanations for similar V-shaped REE signatures in felsic rocks are described by Dostal and Chatterjee (1995).

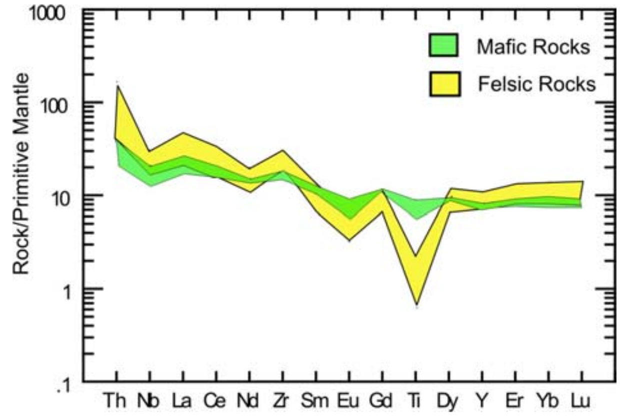

Figure 10. Primitive mantle normalized immobile element plot showing the overlap in element concentrations for WRC felsic and mafic rocks; Sun and McDonough (1989).

Field relations within the WRC and on a regional scale suggest that the upper Hazelton Group in the Telegraph Creek and Iskut River map areas is rift related. The geochemistry of the WRC is consistent with a rifting arc environment. Bimodal volcanism, as expressed in the WRC, is common of rift environments. The following is the most likely scenario that accounts for the range of volcanic rock compositions found within the WRC. Rift-related decompression melting of the asthenosphere produced mafic magmas represented by sample KS-02-15. However, the majority of the magma, which erupted during the period represented by the WRC, was derived from a sub-arc lithospheric mantle source. Heat derived from the mafic magmas caused partial melting within the crust. This generated felsic magmas, which have similar trace element abundances as the sub-arc mantle derived mafic rocks but different relative enrichment patterns, notably Nb and Ti depletions, which reflect their crustal source. Rift-related faulting allowed these magmas to erupt with minimal mixing, which accounts for the bimodality of the WRC volcanic suite.

Comparison of WRC and Eskay Creek Igneous Rocks

Volcanic rocks from the WRC and the Eskay Creek mine have similar chemical characteristics but there are also some subtle differences between them. Rhyolites at Eskay Creek are significantly enriched in the absolute abundances of REE with respect to basalts. This is similar to the relationship between the rhyolites of the WRC and the one asthenospherically derived mafic sample, but contrasts with the relationships seen between WRC rhyolites and the majority of basalts found in the complex. Significantly, Barrett and Sherlock (1996) indicate that the rhyolite and basalt magmas at Eskay Creek could be derived from different sources. They suggest that the rhyolites are derived from tholeiitic crustal rocks, and the basalts are derived from primitive mantle. This is also the most likely scenario for the genesis of the rhyolites, and the primitive basalt sample from the WRC. Barrett and Sherlock (1996) also agree that the eruption of primitive basalt at Eskay Creek might be due to rift-related deep faulting. Average element concentrations between Eskay Creek rhyolites and basalts are similar to WRC rhyolites and basalts but there are some differences. Barrett and Sherlock (1996) use approximate values of Zr, Y, Nb and $(La/Yb)_n$ to characterize Eskay rhyolites (Table 2). Willow Ridge Complex and Eskay Creek rhyolites have comparable $(La/Yb)_n$ ratios, but the absolute element concentrations are elevated in the WRC rhyolites. Barrett and Sherlock (1996) characterized Eskay Creek basalts by their range of immobile element concentrations. The ranges of element concentrations in WRC basalts have significant overlap with those of Eskay Creek basalts (Table 3).

Rhyolites from both Eskay Creek and from the WRC have incompatible element characteristics that are consistent with FIII type rhyolites of Lescher *et al.* (1986). These types of rhyolites are host to most of the Archean age VHMS deposits in the Superior Province as well as large tonnage VHMS deposits of other ages worldwide (*e.g.*, Kidd Creek, United Verde).

The bimodal volcanic suite of the WRC shows a marked departure from the volcanism in the lower part of the Hazelton Group. Early Jurassic rocks of the Hazelton Group have dominantly intermediate compositions with a calc-alkaline affinity (Marsden and Thorkelson, 1992). Macdonald *et al.* (1996) interpreted the Early Jurassic volcanic environment to be a partly emergent volcanic arc. The geochemical and field characteristics of the WRC both indicate that a shift occurred from an Early Jurassic arc-related environment to a rifting-arc environment during the Middle Jurassic.

CONCLUSIONS

Volcanic rocks from the Willow Ridge Complex are bimodal. Mafic rocks are rift-related tholeiites and all but the most primitive basalts were derived from the sub-arc lithospheric mantle. Rhyolites are derived from partial melting of a heterogeneous crust. The bimodality of the volcanics from the WRC, and the tholeiitic affinity of the mafic rocks, are consistent with field observations which suggest that the WRC represents a rift environment. Volcanic rocks from the WRC represent a shift from Early Jurassic arc formation to Middle Jurassic arc rifting, which has been observed elsewhere in the region, notably at Eskay Creek. Chemically the WRC volcanic rocks are very similar to those at Eskay Creek but there are some subtle differences in their geochemical signatures. Both WRC and Eskay Creek rhyolites have incompatible element characteristics that are consistent with FIII type rhyolites of Lescher *et al.* (1986). FIII type rhyolites are highly prospective and host most of the Archean VHMS deposits in the Superior province, and many other high tonnage deposits worldwide.

TABLE 2. COMPARISONS OF SELECTED IMMOBILE ELEMENTS IN RHYOLITES FROM ESKAY CREEK AND THE WRC

	Eskay Rhyolite	WRC Rhyolite
Zr	170 ppm	228 ppm
Y	55 ppm	37 ppm
Nb	30 ppm	16 ppm
$(La/Yb)_n$	2-4	2-5

TABLE 3 COMPARISONS OF SELECTED IMMOBILE ELEMENTS IN BASALTS FROM ESKAY CREEK AND THE WRC

	Eskay Basalt	WRC Basalt
TiO_2	1.3–2%	1.1–1.8%
Zr	60–90 ppm	73–235 ppm
Y	25–40 ppm	19–46 ppm
Nb	2–6 ppm	6–17 ppm

ACKNOWLEDGMENTS

We would like to thank Dani Alldrick, JoAnne Nelson, Martin Stewart and Kirstie Simpson for collecting the geochemical rock samples that are described in this article. We also thank JoAnne Nelson and Dani Alldrick for valuable discussions about upper Hazelton Group geology and for their constructive reviews of this article.

REFERENCES

Alldrick, D.J., Stewart, M.L., Nelson, J.L. and Simpson, K.A. (2004a): Tracking the Eskay Rift through northern British Columbia - geology and mineral occurrences of the Upper Iskut River area; *British Columbia Ministry of Energy and Mines*, Geological Fieldwork 2003, Paper 2004-1, pages 1-18.

Alldrick, D.J., Stewart, M.L., Nelson, J.L. and Simpson, K.A. (2004b): Geology of the More Creek - Kinaskan Lake area, northwestern British Columbia; *British Columbia Ministry of Energy and Mines*, Open File Map 2004-2, scale 1:50 000.

Barrett, T.J. and Sherlock, R.L. (1996): Geology, lithogeochemistry and volcanic setting of the Eskay Creek Au-Ag-Cu-Zn deposit, northwestern British Columbia; *Exploration and Mining Geology*, Volume 5, pages 339-368.

Dostal, J. and Chatterjee. A.K. (1995): Origin of topaz-bearing and related peraluminous granites of the Late Devonian Davis Lake pluton, Nova Scotia, Canada: Crystal versus fluid fractionation; *Chemical Geology*, Volume 123, pages 67-88.

Lentz, D.R. (1999): Petrology, geochemistry, and oxygen isotope interpretation of felsic volcanic and related rocks hosting the Brunswick 6 and 12 massive sulfide deposits (Brunswick belt), Bathurst mining camp, New Brunswick, Canada; *Economic Geology*, Volume 94, pages 57-86.

Lescher, C.M., Goodwin, A.M., Campbell, I.H. and Gorton, M.P. (1986): Trace-element geochemistry of ore-associated and barren, felsic metavolcanic rocks in the Superior Province, Canada; *Canadian Journal of Earth Science*, Volume 23, pages 222-237.

Logan, J.M., Drobe, J.R. and McClelland, W.C. (2000): Geology of the Forest Kerr - Mess Creek Area, Northwestern British Columbia (104B/10,15 & 104G/2 & 7W); *British Columbia Ministry of Energy and Mines*, Bulletin 104, 164 pages.

MacDonald, J.A., Lewis, P.D., Thompson, J.F.H., Nadaraju, G., Bartsch, R.D., Bridge, D.J., Rhys, D.A., Roth, T., Kaip, A., Godwin, C.I. and Sinclair, A.J. (1996): Metallogeny of an Early to Middle Jurassic arc, Iskut River area, northwestern British Columbia; *Economic Geology*, Volume 91, no 6, pages 1098-1114.

Marsden, H. and Thorkelson, D.J. (1992): Geology of the Hazelton volcanic belt in British Columbia: Implications for the Early to Middle Jurassic evolution of Stikinia; *Tectonics*, Volume 11, no 6, pages 1222-1287.

Pearce, J.A. (1996): A user's guide to basalt discrimination diagrams; *Geological Association of Canada*, Short Course Notes, Volume 12, pages 79-113.

Saeki, Y. and Date, J. (1980): Computer application to the alteration data of the footwall dacite lava at the Ezuri Kuroko Deposits, Akito Prefecture; *Mining Geology*, Volume 30, pages 241-250.

Simpson, K.A. and Nelson, J.L. (2004): Preliminary interpretations of mid-Jurassic volcanic and sedimentary facies in the East Telegraph Creek map area; *Geological Survey of Canada*, Current Research 2004-A1, 8 pages

Sun, S-S. and McDounough, W.F. (1989): Chemical and isotope systematics of oceanic basalts: Implications for mantle composition and processes; *Geological Society*, Special Publication 42, pages 313-345.

Whitford, D.J., Korsch, M.J., Porritt, P.M. and Craven, S.J. (1988): Rare-earth element mobility around the volcanogenic massive sulfide deposit at Que River, Tasmania, Australia; *Chemical Geology*, Volume 68, pages 105-199.

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.