

ORGANIC GEOCHEMISTRY OF LATE TRIASSIC TO EARLY JURASSIC SEDIMENTARY ROCKS IN NORTHERN VANCOUVER ISLAND

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ABSTRACT

Regional mapping in northern Vancouver Island has recognized the presence near the Triassic-Jurassic boundary of an organic-rich horizon up to 50 m thick. Detailed sampling of a section exposed in road cuts overlooking Neroutsos Inlet was undertaken to determine the thermal maturity and organic geochemistry of this horizon. Thermal maturity of these rocks, based on Ro reflectance analysis, indicates that the section is at or near the upper limit of the dry gas preservation zone, and results from Rock-Eval pyrolysis show residual organic carbon contents as high as 34%, with an average of approximately 6%. Very little or no generative capacity is present in these rocks due to the high thermal maturity, and, based on Rock-Eval results no information can be obtained concerning the original type of organic material present. Sampling of a horizon within this section at or near the Triassic-Jurassic boundary was carried out in an attempt to obtain from a Re-Os isochron a more accurate absolute age of this boundary; preliminary analysis suggests several of these samples will have high enough Re levels for this procedure and that further sampling is warranted.

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INTRODUCTION

Regional mapping in northern Vancouver Island has delineated an organic-rich sequence of latest Triassic to earliest Jurassic age at the base of the Bonanza Group (Nixon and Orr 2007). This package of sedimentary and lesser volcanic rocks is time-equivalent to parts of the Kunga Group, which contains one of several hydrocarbon source beds within the Queen Charlotte Basin. In order to assess the organic richness of these sediments and the hydrocarbon generation potential of this horizon, a series of samples were taken across the unit and analyzed via a Rock-Eval 6 pyrolysis apparatus at the Geological Survey of Canada laboratories in Calgary, Alberta.

In addition, regional mapping in northern Vancouver Island has led to a refinement of the Early Mesozoic stratigraphic framework (Nixon and Orr 2007). In particular, geochronological data from the sequence containing these organic-rich sediments has increased the resolution of the absolute age of the Triassic-Jurassic boundary (Nixon et al. 2000). Bonanza Group organic-rich shales straddle

this boundary; a horizon very close to the Triassic-Jurassic boundary was sampled in hopes of further refining the age of this boundary through use of the Re-Os geochronometer (see Creaser et al. 2002; Selby and Creaser 2005).

This paper presents Rock-Eval pyrolysis and vitrinite reflectance data for samples taken within these organic-rich sediments. A description and location of samples taken towards a Re-Os isochron are also shown, together with major, minor, and trace element data for these samples.

The study area is located on the west shore of Neroutsos Inlet, approximately 5 km northwest of Port Alice (Figure 1). Access from Port Alice is afforded by a series of logging roads that lead south from the town and around the southern end of the inlet.

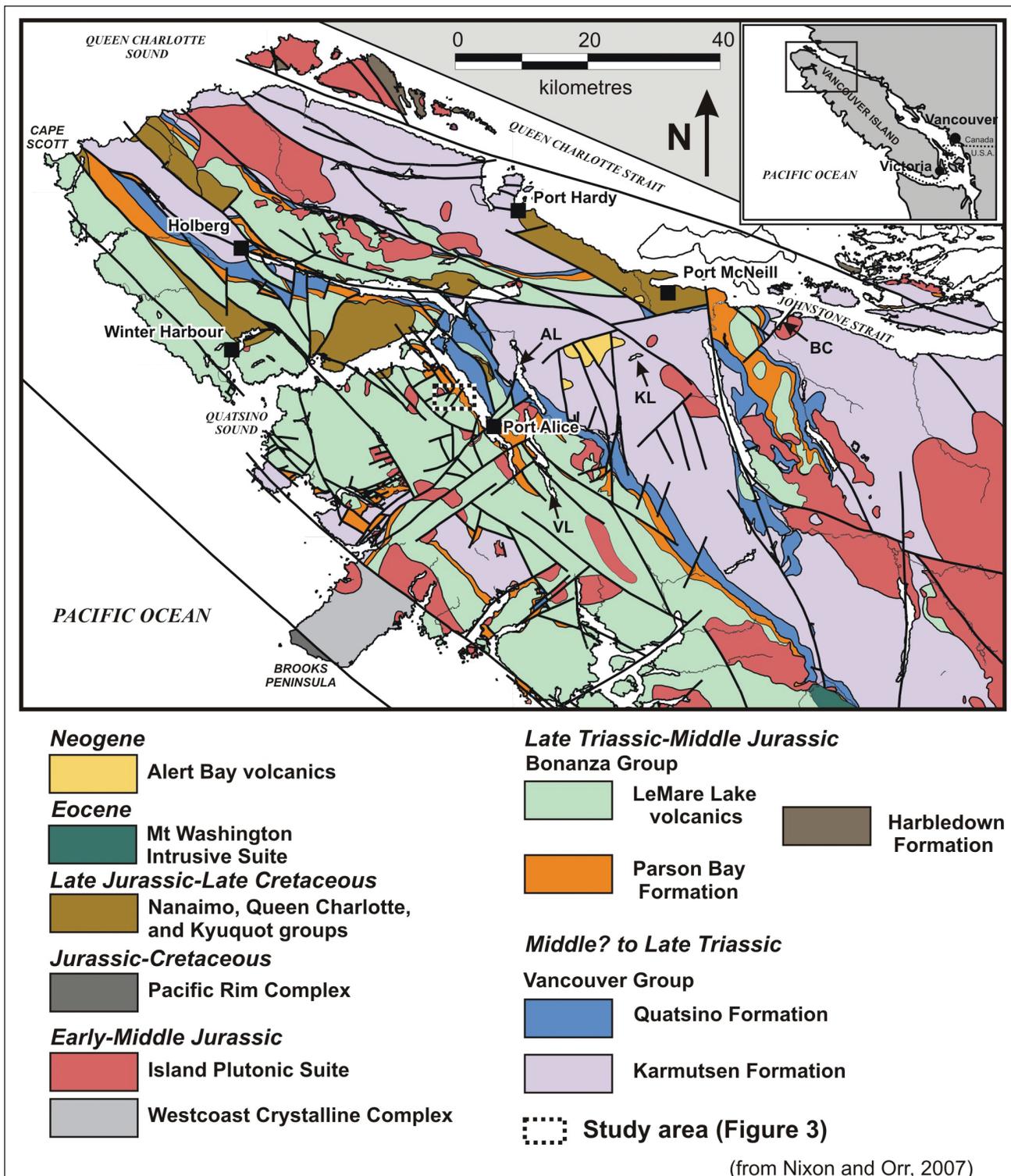


Figure 1: Regional geology of northern Vancouver Island (after Massey et al., 2005). AL, Alice Lake; BC, Beaver Cove; KL, Keogh Lake; VL, Victoria Lake.

REGIONAL GEOLOGY

Late Paleozoic to Early Mesozoic rocks on Vancouver Island belong to Wrangellia, a tectonostratigraphic terrane that encompasses the southern Coast area and the Queen Charlotte Islands and underlies the Queen Charlotte Basin (Figure 1; Wheeler and McFeely 1991). These rocks began amalgamating with the northern Alexander Terrane in Pennsylvanian times, forming the Insular Belt, which was then juxtaposed against Coast and Intermontane belt rocks to the west either as early as the Middle Jurassic (van der Heyden 1991; Monger and Journey 1994) or as late as the mid-Cretaceous (Monger et al. 1982).

In the study area, bedrock stratigraphy is dominated by Late Triassic to Early Jurassic volcanic and sedimentary rocks of the Vancouver and Bonanza Groups. Although not exposed in the area, Devonian to Early Permian island-arc volcanic and sedimentary rocks of the Sicker and Buttle Lake Groups form the basement of Wrangellia (Massey 1995a, b, c). Nixon and Orr (2007) provide a revision of the Early Mesozoic stratigraphy for northern Vancouver Island, which is adhered to in this report.

The structural history of northern Vancouver Island and the Queen Charlotte Basin is complex and includes Jurassic to Cretaceous contractional or transpressional tectonics followed by Tertiary extension. A major angular unconformity separates Bonanza Group rocks from succeeding Jura-Cretaceous sequences.

LOCAL GEOLOGY

In northern Vancouver Island, Vancouver Group rocks are represented by Mid(?) to Late Triassic flood basalts of the Karmutsen Formation and succeeding massive to well bedded micritic and bioclastic limestone of the Quatsino Formation (Figure 2). These are followed by Latest Triassic (Norian to Rhaetian) rocks of the marine Parson Bay Formation, an intermixed package of intermediate, aphanitic to augite-plagioclase phyric lava flows and volcanoclastic rocks together with impure limestone, siltstone, mudstone, shale, and epiclastic rocks. The uppermost part of the Parson Bay Formation contains a thin, pale grey, locally coralline limestone provisionally correlated with the Sutton limestone of the Lake Cowichan area, southern Vancouver Island. These rocks give way to Early to Middle Jurassic subaerial basaltic to rhyolitic flows, related volcanoclastics, and minor marine clastics and limestone of the LeMare Lake volcanics. Bonanza Group rocks, particularly the LeMare Lake volcanics, represent an island arc sequence.

The transition between the Parson Bay Formation and LeMare Lake volcanics is represented by an interbedded sequence of volcanoclastic and sedimentary rocks together with minor volcanic rocks. This unit straddles the Triassic-Jurassic boundary and is informally referred to as the

‘volcanoclastic-sedimentary unit’ (Nixon and Orr 2007). The sequence is dominated by thickly bedded to laminated epiclastic rocks. Volcanoclastics and minor massive flows are similar to those within the LeMare Lake volcanics. This package is cut by numerous dikes and sills, which are feeders to overlying LeMare Lake volcanics. The base of this epiclastic succession occurs where carbonate rocks of the Parson Bay Formation are the dominant lithology. The upper contact is marked by the first occurrence of massive volcanic flows and breccias of the LeMare Lake volcanics.

Epiclastic rocks are dominated by dark grey to grey-green lithic and feldspathic wacke, dark grey siltstone, mudstone, and shale. These all can be calcareous and associated with dark, impure limestone. The central 30 to 50 m of this unit is characterized by interbedded dark grey to rusty weathering, dark grey to black, blocky siltstone and fissile, dark grey to black, locally carbonaceous shale. Sections of dark grey to black, fetid limestone up to 3.5 m thick are found in the lower part of the sequence.

The upper 3 m of the interval is composed of rusty weathering, slightly fetid, dark grey to black, fissile shale to blocky siltstone containing calcareous (and fossiliferous) nodules up to 50 cm in size and located along a horizon several metres from the top of the section. Identification of pelecypod fauna within the nodules indicates that this sequence is Early Jurassic (Hettangian) in age and likely within a few tens of metres above the Triassic-Jurassic boundary. Six samples were taken along a horizon in the centre of the section for the purposes of obtaining a Re-Os radiometric age and more accurately determining the absolute age of the Triassic-Jurassic boundary.

SAMPLING

Twenty samples of dark grey siltstone and limestone were obtained for Rock-Eval analysis from parts of the Parson Bay Formation and through the volcanoclastic-sedimentary unit at the transition between the Parson Bay and LeMare Lake units (Table 1). The bulk of the sampling was within the sedimentary-dominated portion of the volcanoclastic-sedimentary unit (Figure 3). In the central part of this sedimentary interval, a section some 8 m thick was sampled every 0.5 m at station 6, with the upper 3.5 m consisting of limestone to silty limestone. Sample FF07-6-1 occurs at the base of the section. The sample interval at map station 7 was across 3 m of section with samples taken approximately every 0.5 m. Samples at map station 8 (FF07-11) were taken every 1 m across a 3 m section, with sample 11-1 originating from the base of the section. In addition, 6 samples of Jurassic siltstone were taken at the top of the volcanoclastic-sedimentary unit (same locality as FF07-11) in hopes of obtaining an absolute age via a Re-Os isochron. Several analyses of thermal maturity were acquired through reflectance determinations on organic

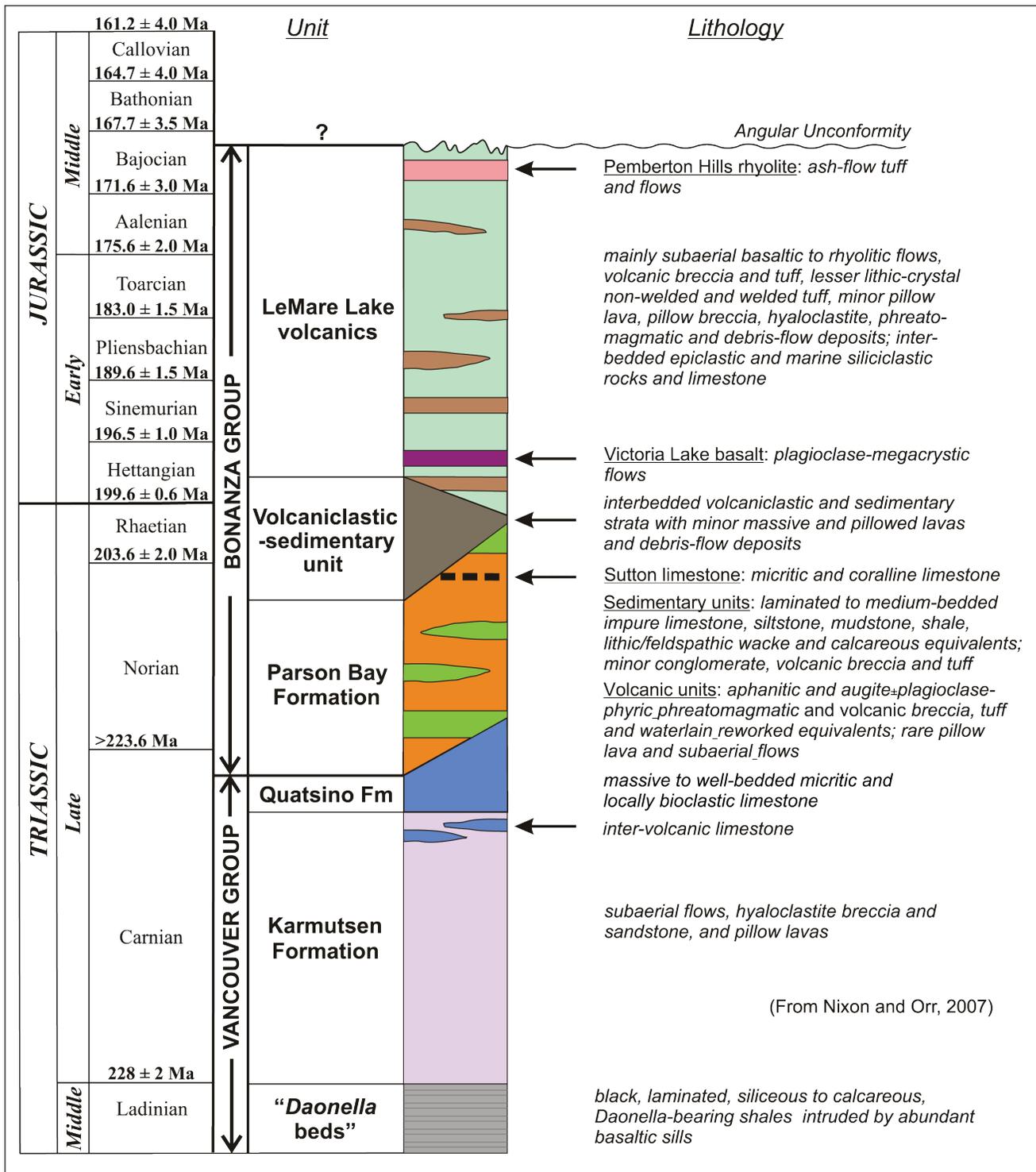


Figure 2: Schematic stratigraphy of northern Vancouver Island taken from Nixon and Orr (2007). The geological time scale is that of Gradstein et al. (2004), except for the Carnian-Norian Stage boundary, which is taken from Furin et al. (2006).

TABLE 1: ROCK-EVAL PYROLYSIS RESULTS FOR SAMPLES OF SILTSTONE, SHALE, AND CARBONATE COLLECTED WITHIN THE VOLCANICLASTIC-SEDIMENTARY UNIT AND PARSONS BAY FORMATION. NUMBERS IN THE "MAP UNIT" COLUMN CORRELATE WITH SAMPLE LOCALITIES (PLOTTED IN FIGURE 3).

Sample	Map		Easting	Northing	Mass	TOC(%)	S1	S2	S3	PI	S2/S3	PC(%)	Tmax	HI	OI
	Unit	Unit													
FF07-1	1	Parson Bay Fm.	603313	5589437	70.0	0.18	0.01	0.09	0.12	0.11	0.75	0.02	426	50	67
FF07-2	2	Parson Bay Fm.	603352	5589027	70.2	0.34	0.01	0.05	0.41	0.11	0.12	0.02	383	15	121
FF07-3	3	Sutton Lmst?	603174	5588607	70.1	0.21	0.01	0.06	0.08	0.14	0.75	0.01	386	29	38
FF07-4	4	Sutton Lmst?	603063	5588723	70.8	0.86	0.01	0.02	0.37	0.18	0.05	0.01	411	2	43
FF07-5A	5	Volc. Sed. Unit	602737	5588821	10.8	34.81	0.04	0.20	10.36	0.16	0.02	0.37	522	1	30
FF07-6-1	6	Volc. Sed. Unit	602670	5588918	20.2	7.41	0.02	0.03	1.38	0.37	0.02	0.05	342	0	19
FF07-6-2	6	Volc. Sed. Unit	602670	5588918	20.4	3.99	0.02	0.05	0.65	0.34	0.08	0.03	353	1	16
FF07-6-3	6	Volc. Sed. Unit	602670	5588918	20.5	4.95	0.01	0.01	0.46	0.66	0.02	0.02	302	0	9
FF07-6-4	6	Volc. Sed. Unit	602670	5588918	20.8	14.77	0.02	0.02	1.03	0.49	0.02	0.04	304	0	7
FF07-6-5	6	Volc. Sed. Unit	602670	5588918	20.8	4.16	0.01	0.02	1.28	0.41	0.02	0.05	330	0	31
FF07-6-6	6	Volc. Sed. Unit	602670	5588918	70.1	1.47	0.01	0.01	0.30	0.30	0.03	0.01	337	1	20
FF07-6-7	6	Volc. Sed. Unit	602670	5588918	70.1	1.76	0.00	0.01	0.39	0.40	0.03	0.01	336	1	22
FF07-6-8	6	Volc. Sed. Unit	602670	5588918	70.4	1.64	0.00	0.01	1.01	0.29	0.01	0.03	531	1	62
FF07-7	7	Volc. Sed. Unit	602600	5588877	70.0	4.15	0.01	0.01	0.15	0.49	0.07	0.01	324	0	4
FF07-8	7	Volc. Sed. Unit	602600	5588891	20.8	6.99	0.02	0.04	0.20	0.32	0.20	0.01	315	1	3
FF07-9	7	Volc. Sed. Unit	602603	5588882	50.4	16.45	0.01	0.04	0.35	0.27	0.11	0.02	309	0	2
FF07-10	7	Volc. Sed. Unit	602600	5588893	50.1	1.75	0.01	0.02	0.09	0.34	0.22	0.01	408	1	5
FF07-11-1	8	Volc. Sed. Unit	602430	5589259	50.9	4.46	0.03	0.03	0.13	0.52	0.23	0.01	368	1	3
FF07-11-2	8	Volc. Sed. Unit	602430	5589259	51.0	2.34	0.01	0.01	0.22	0.60	0.05	0.01	311	0	9
FF07-11-3	8	Volc. Sed. Unit	602430	5589259	50.5	4.37	0.01	0.03	1.94	0.32	0.02	0.07	329	1	44
7GNX-39-10-4	8	Volc. Sed. Unit	602430	5589259	50.7	3.03	0.01	0.03	0.28	0.28	0.11	0.01	295	1	9
7GNX-39-10-5	8	Volc. Sed. Unit	602430	5589259	50.3	3.37	0.01	0.01	0.40	0.30	0.03	0.01	334	0	12
7GNX-39-10-6	8	Volc. Sed. Unit	602430	5589259	50.9	4.25	0.01	0.03	0.21	0.31	0.14	0.01	489	1	5
7GNX-39-10-7	8	Volc. Sed. Unit	602430	5589259	69.9	2.83	0.01	0.01	0.15	0.35	0.07	0.01	550	0	5
7GNX-39-10-8	8	Volc. Sed. Unit	602430	5589259	70.6	2.70	0.01	0.02	0.16	0.25	0.13	0.01	327	1	6
7GNX-39-10-9	8	Volc. Sed. Unit	602465	5589234	50.3	2.52	0.00	0.01	0.11	0.41	0.09	0.01	339	0	4

Mass = mg; TOC = Total Organic Carbon, weight per cent; S1, S2 = mg hydrocarbons (HC)/g rock; S3 = mg CO₂/g rock;

PI = Production Index = S1/(S1+S2); PC = Pyrolyzable Carbon(weight per cent) = ((0.83*(S1+S2))+(S3*.273)+((S3CO+(S3*CO/2))*0.4286))/10

Tmax = °C; HI = Hydrogen Index = (100*S2)/TOC; OI = Oxygen Index = (100*S3)/TOC

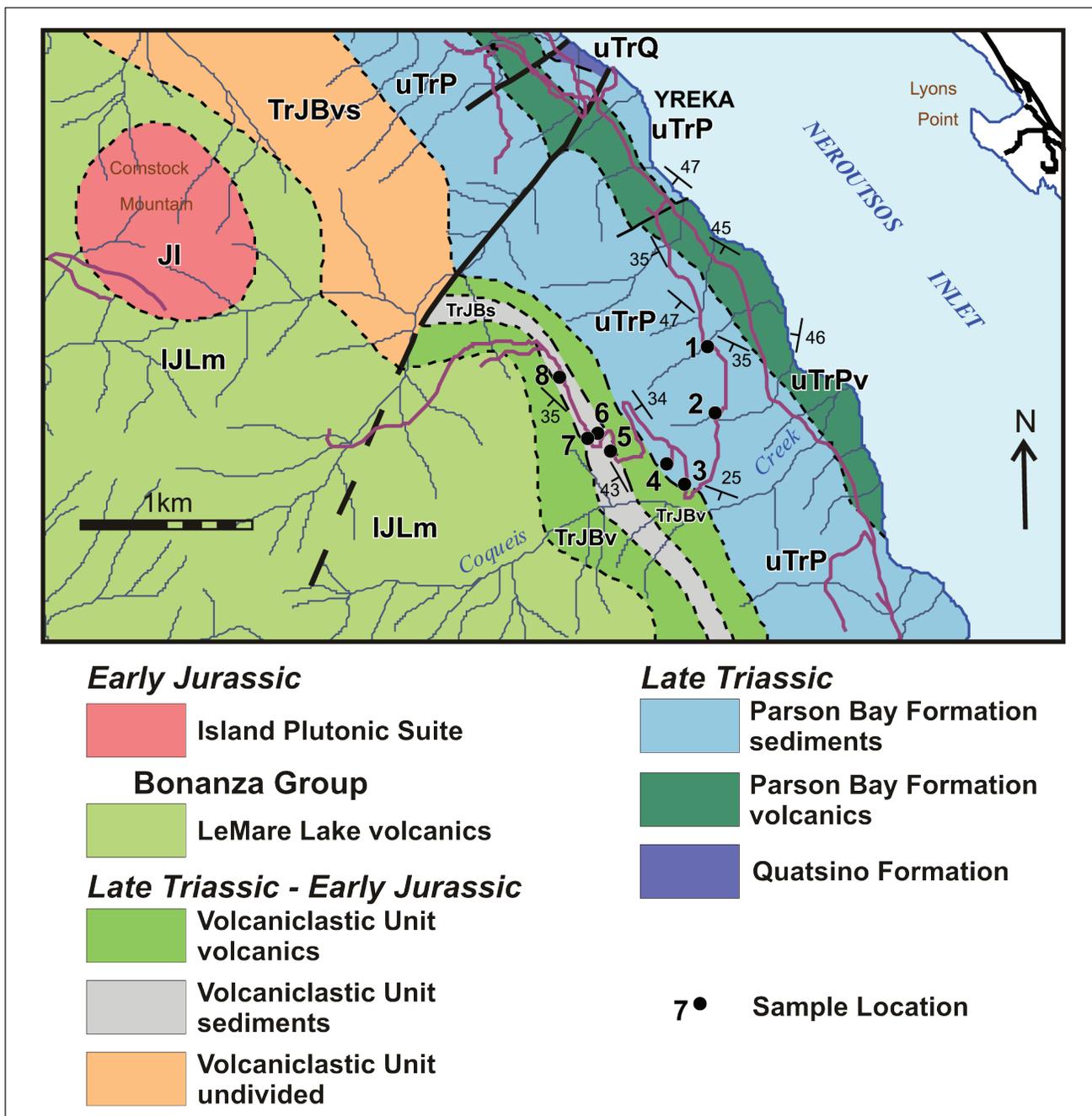


Figure 3: Detailed geological map of the study area showing location of sample sites. Sample locations correspond to “Map Unit” column in Table 1. Geological description of units can be found in Nixon et al. (2006).

matter (Table 2). In addition, 6 samples obtained for Re-Os geochronometry were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) to determine if specific elemental concentrations were high enough to warrant proceeding further with this radiometric dating technique (Table 3).

RESULTS AND DISCUSSION

Organic Geochemistry

Thermal maturity levels, based on reflectance data from 2 samples, indicate the section reached or exceeded the dry gas preservation zone (%Ro equivalent 3.33 and 4.21; Table 2, Figure 4). High thermal maturity levels may be related to the abundant number of mafic to intermediate sills and dykes that cut the volcaniclastic-sedimentary unit

TABLE 2: RO EQUIVALENT VALUES FROM ORGANIC MATERIAL FOUND WITHIN SELECT SAMPLES OF THE VOLCANICLASTIC-SEDIMENTARY UNIT. SAMPLE LOCALITIES CAN BE SEEN IN FIGURE 3.

Sample	Easting	Northing	OT ¹	%R _{oR}	SD	N	%R _o max	%R _o equiv ²	%R _o min	SD	COMMENTS
FF07-5b	602737	5588821	21	5.73	0.30	29		3.94			Mainly pyrobitumen showing signs of oxidation. Some are very fine to fine grain anisotropic pyrobitumen.
			21,30	4.75	0.19	8		3.33			Some are oxidized and some are min %Ro of anisotropic bitumen matrix. See organic type 33 %R _o .
			21,30	6.63	0.11	14		4.50			
			33				5.7		4.70		
FF07-6-9	602670	5588918	30, 33	4.91	0.44	39	5.45		4.64	0.19	Mostly very to fine grain pyrobitumen (organic type 33) and granular pyrobitumen (organic type 30) within carbonate fractures and pores.
			21	6.17	0.16	3		4.21			

OT = organic type; SD = standard deviation; N = number of analysis

¹Grint and March (1981), White (1976); ²0.618*%R_{oR} + 0.4; Jacob (1989)

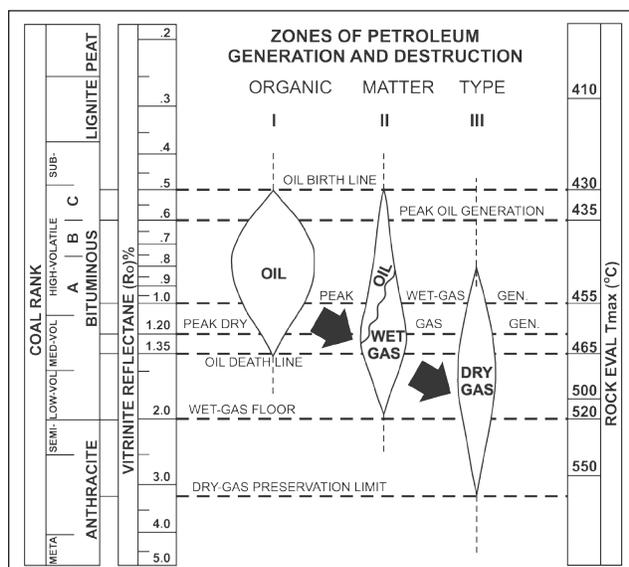


Figure 4: Zones of hydrocarbon generation and destruction with respect to coal rank, vitrinite reflectance, and Tmax values from Rock-Eval pyrolysis. Modified from Leckie et al. (1988) and Dow (1977).

and were most likely feeders to LeMare Lake volcanism. In addition, Jurassic volcanism and plutonism was likely accompanied by elevated heat flows.

Organic carbon levels for these rocks are generally over 2%, with some samples returning concentrations as high as 35%. The high organic carbon levels in these later samples suggest coaly material, although petrographic work indicates it is mostly pyrobitumen (Table 2; figures 5 and 6). The high thermal maturities in these samples, together with S₂ and HI values (Table 1), also indicate that much of the hydrocarbons have been expelled and suggest that initial organic carbon levels were significantly higher. Consequently, based on pyrolysis results, very little can be

deduced about the original nature of the organic material. Characterization of this organic material could be achieved by further petrographic work.

Correlations of this stratigraphy with strata along northernmost parts of Vancouver Island and the Queen Charlotte Basin suggest this organic-rich horizon is most likely time-equivalent to parts of the Kunga and Maude Groups. These latter 2 units have organic-rich horizons containing Type II kerogens that were sources of oils found within the Queen Charlotte Basin (see Bustin 1997; Vellutini and Bustin 1991; Hamilton 1989). If this correlation is correct, the carbonaceous shales and siltstones of the volcanoclastic-sedimentary unit may have produced significant quantities of oil early in the thermal history of this area.

Re-Os Geochronometry

The ability to use the Re-Os geochronometer depends on high enough levels of these elements for accurate analysis. The reducing environment represented by these black shales would have facilitated the incorporation of various elements, such as Re, from the sea water during their deposition. Creaser et al. (2002) indicate that Re and Os levels within organic-rich shales are up to 2 orders of magnitude higher than average continental crustal rocks. As such, a first step in determining the suitability of the Re-Os geochronometer in a sedimentary sequence is to establish if sea water conditions were reducing during sediment deposition. An indirect means of establishing this is an analysis of total organic carbon (TOC) content. Typically, TOC contents of 2% or higher result from preservation of organic material in reducing environments. Direct measurement of Re through ICP-MS analysis is suspect due to the volatile nature of this element during sample preparation and analysis; as such, its relative abundance is determined by measuring the levels

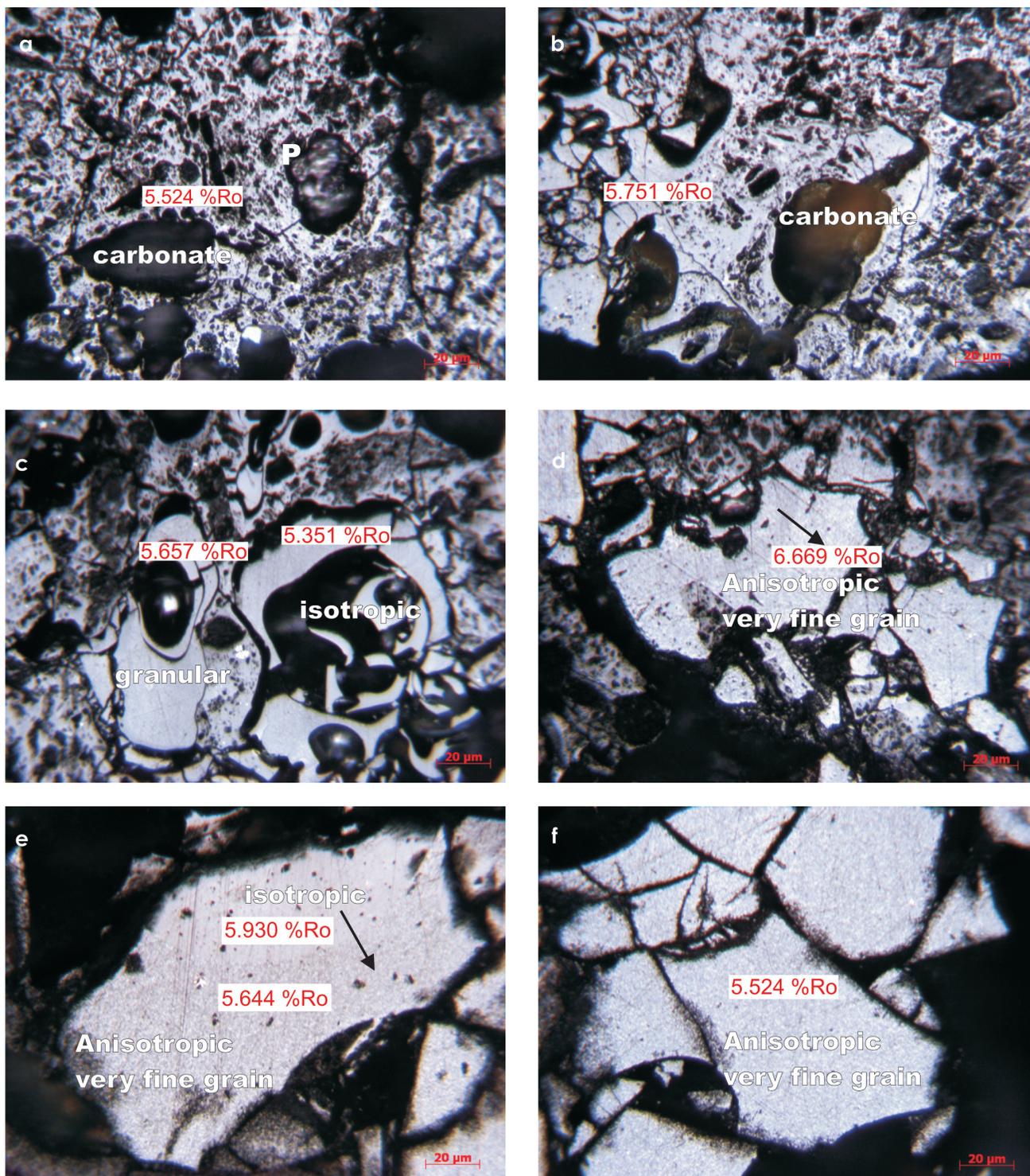


Figure 5: The high percentage of organic carbon in this sample is from bitumen/pyrobitumen consisting of; (a and c) networks of partially oxidized isotropic solid pyrobitumen; (c and d) very fine grain anisotropic pyrobitumen, and (e and f) large matrix of both isotropic and anisotropic and fine grained pyrobitumen. P – pyrobitumen.

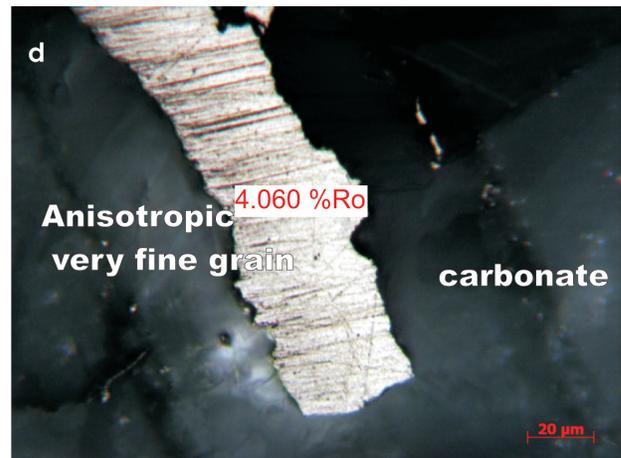
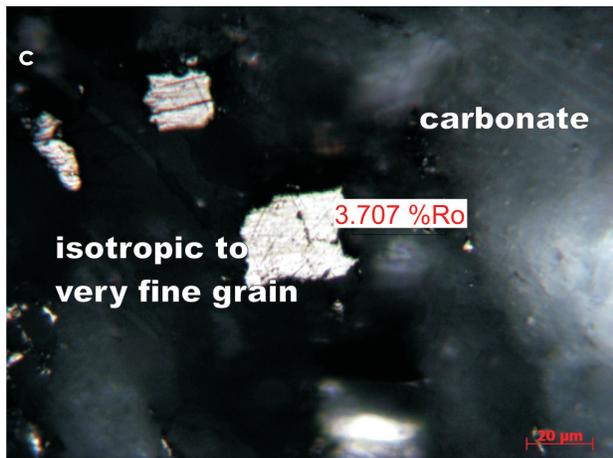
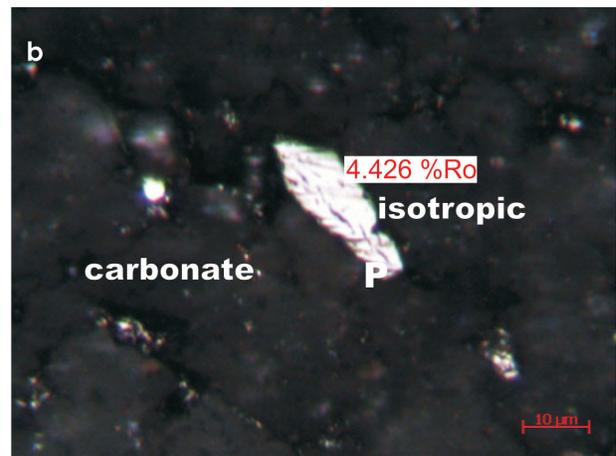
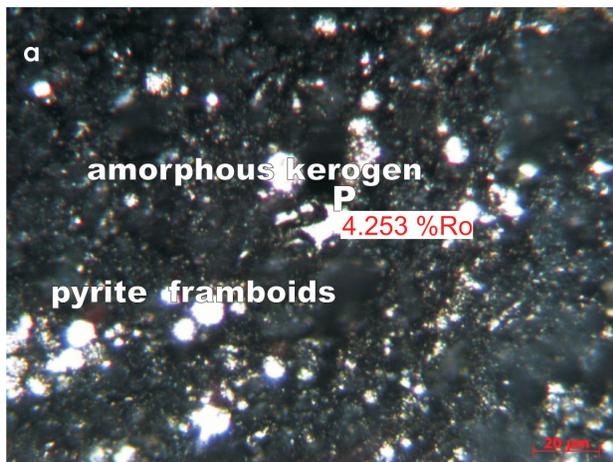


Figure 6: Mainly brecciated amorphous kerogen within carbonate matrix (a). Isotropic pyrobitumen (b) to anisotropic very fine grain pyrobitumen (c and d) migrated into the pores and fractures of the carbonate matrix. P – pyrobitumen.

of other elements (Mo, V, Cr, Cd, U) that are incorporated into the sediment in levels proportional to Re. On average, Mo concentrations are 1000 times those of Re (R. Creaser, personal communication 2008).

Whole rock geochemistry of the 6 samples near the top of the sequence is shown in Table 3. The concentrations of Mo within the 6 samples indicates that only 4 samples (07GNX-39-10-4, 5, 6, 9) have levels high enough to suggest corresponding Re concentrations suitable for Re-Os geochronometry (R. Creaser, personal communication 2008). These samples are currently being analyzed and further samples will be acquired along this horizon to better constrain the isochron and obtain a more precise age.

CONCLUSIONS

- In northern Vancouver Island, an organic-rich sequence of Late Triassic to Early Jurassic age and up to 50 m thick is present within the upper part of the volcanoclastic-sedimentary unit, transitional between the Parsons Bay Formation and LeMare Lake volcanics of the Bonanza Group.
- Organic carbon contents within this horizon are up to 34% and average approximately 6%.
- Thermal maturity, based on Ro analysis of organic matter, suggests the sequence is at or above the upper limit of the dry gas preservation zone.
- Preliminary analysis of 6 samples collected for Re-Os geochronometry to better constrain the absolute age of the Triassic-Jurassic boundary suggests that several of these will be suitable for delineating an isochron and that further sampling and analysis is justified.

TABLE 3: SELECT MAJOR, MINOR, AND TRACE ELEMENT CONCENTRATIONS WITHIN SAMPLES COLLECTED FOR RE-OS GEOCHRONOLOGY.*

Element		07GNX- 07GNX- 07GNX- 07GNX- 07GNX- 07GNX-											
		39-10-4		39-10-5		39-10-6		39-10-7		39-10-8		39-10-9	
		VSU	VSU	VSU	VSU	VSU	VSU	VSU	VSU	VSU	VSU	VSU	VSU
			Siltstone	Limestone									
	Det.	602430N	602430N	602430N	602430N	602430N	602430N	602430N	602430N	602465N			
	limit	5589259E	5589259E	5589259E	5589259E	5589259E	5589259E	5589259E	5589259E	5589234E			
P	%	0.001	0.014	0.027	0.013	0.04	0.036	0.018					
Ti	%	0.01	0.21	0.28	0.28	0.45	0.42	0.23					
S	%	0.01	2.86	4.6	3.75	4.68	5.31	3.59					
Fe	%	0.01	3.09	5.01	4.58	5.51	4.79	2.95					
Na	%	0.001	1.49	1.88	1.51	2.16	1.96	1.24					
Mg	%	0.01	0.68	0.49	0.31	0.74	0.8	0.25					
Al	%	0.01	5.5	7.56	6.83	> 10.0	9.94	4.77					
K	%	0.01	0.9	1.49	1.44	2.82	2.23	0.88					
Ca	%	0.01	0.62	4.93	0.15	0.54	3.78	5.46					
Mn	ppm	1	277	496	218	357	434	398					
Cu	ppm	0.2	21.8	28	33.9	28.1	24.1	19					
Pb	ppm	0.5	5.4	2.9	3.4	4	3.5	2.5					
Zn	ppm	0.2	60	76.6	29.2	40	69.3	53.7					
Ag	ppm	0.05	< 0.05	0.05	0.05	< 0.05	< 0.05	< 0.05					
Mo	ppm	0.1	13.9	30.3	23.4	7.1	6.7	17					
Ni	ppm	0.5	11.8	20.9	17.9	13.1	14.6	12.8					
Cd	ppm	0.1	0.3	0.6	0.3	0.2	0.6	0.5					
V	ppm	1	41	91	85	151	133	46					
Cr	ppm	0.5	22.7	37.4	33.3	59.1	41.4	18.4					
Ba	ppm	1	88	70	24	26	49	98					
Li	ppm	0.5	9.7	6.9	4.7	9	8.4	3.6					
B	ppm	1	24	5	5	7	4	3					
Hf	ppm	0.1	1.5	2	2.1	2	1.8	1.4					
Cs	ppm	0.05	0.8	1.1	1.5	2.2	1.8	0.7					
Co	ppm	0.1	4.9	11.3	6.4	7.3	10.6	5.7					
Eu	ppm	0.05	0.6	1	0.5	0.9	1	0.6					
Bi	ppm	0.02	0.15	0.39	0.13	0.12	0.12	0.1					
Se	ppm	0.1	1.6	2.4	1.9	3.1	1.8	1.6					
Ga	ppm	0.1	6.7	10.1	8.4	16.9	14.5	6.2					
As	ppm	0.1	8.4	12.7	12.8	8.9	7.2	7.6					
Rb	ppm	0.2	27.2	38.6	41.7	76.8	64.1	22.7					
Y	ppm	0.1	13.6	24.5	12	24	23.3	14.6					
Sr	ppm	0.2	286	381	178	426	461	511					
Zr	ppm	1	31	52	54	54	48	34					
Nb	ppm	0.1	1	2	1.2	3.4	2.6	1.4					
Er	ppm	0.1	1.7	2.9	1.5	3	2.8	1.9					
Be	ppm	0.1	0.4	0.6	0.5	0.7	0.7	0.4					
Ho	ppm	0.1	0.6	1	0.5	1	1	0.6					
In	ppm	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1					
Sn	ppm	1	< 1	1	1	1	< 1	< 1					
Sb	ppm	0.1	1.1	1.2	1.3	0.6	0.8	0.7					
Te	ppm	0.1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	< 0.1					
La	ppm	0.1	5	9.6	4.6	8.7	10.9	6.9					
Ce	ppm	0.1	10.6	18.3	10.9	19.6	22.1	13.3					
Pr	ppm	0.1	1.8	3.1	1.7	3.4	3.6	2.1					
Nd	ppm	0.1	8.3	14.9	7.7	15.5	16.4	9.8					
Sm	ppm	0.1	2	3.4	1.7	3.5	3.6	2.2					
Gd	ppm	0.1	2.5	4.4	2.1	4.4	4.6	2.7					
Tb	ppm	0.1	0.4	0.6	0.3	0.7	0.6	0.4					
Dy	ppm	0.1	2.1	3.7	1.9	3.8	3.7	2.3					
Ge	ppm	0.1	0.1	0.1	0.1	0.1	0.1	0.1					
Tm	ppm	0.1	0.2	0.4	0.2	0.4	0.4	0.3					
Yb	ppm	0.1	1.6	2.7	1.5	2.9	2.6	1.8					
Lu	ppm	0.1	0.2	0.4	0.2	0.4	0.4	0.3					
Ta	ppm	0.1	< 0.1	0.1	0.1	0.2	0.2	0.1					
W	ppm	0.1	1	1	0.8	0.9	0.6	0.4					
Re	ppm	0.001	0.029	0.05	0.042	0.022	0.022	0.033					
Tl	ppm	0.05	0.34	0.59	0.75	0.58	0.48	0.34					
Th	ppm	0.1	1.1	1.2	1.7	1.9	1.8	1					
U	ppm	0.1	3.7	6.9	5.8	4.5	3.9	2.5					

VSU = Volcanic Sedimentary Unit
 All samples steel milled at ACTLABS, Ancaster, Ontario.
 All samples digested by HF-HClO4-HNO3-HCl
 P, Ti and S determined by inductively coupled plasma emission spectrometry
 All other elements determined by inductively coupled plasma mass spectrometry
 % - per cent; ppm - parts per million

**These analyses were determined by inductively coupled plasma mass and emission spectrometry at Activation Laboratories in Ontario. Sample locations shown in Figure 3.*

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