Preliminary O-S isotopic compositions of Cretaceous granitoids in the Cassiar Platform and Selwyn Basin, Yukon and Northwest Territories

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ABSTRACT

A regional stable isotopic study of Cretaceous granitoids (109-90 Ma) emplaced into miogeoclinal Cassiar Platform and Selwyn Basin rocks was undertaken to provide new insights into the origin of several plutonic suites (Cassiar, Hyland, Tay River, Tungsten, Mayo and Tombstone). All of the intrusions have high positive $\delta^{18}O$ (+8.4 to +16.9‰). There is very little systematic variation in $\delta^{18}O$, indicating that the majority of the plutons assimilated significant amounts of, or were entirely derived from, crustal rocks. $\delta^{34}S$ typically ranges from +2.0 to +11‰ for all of the plutonic suites. This is consistent with derivation of the majority of sulphur from seawater sulphate, with some component of mantle or sedimentary (sulphide) sulphur evident in samples with the lowest $\delta^{34}S$. Future work, including comparison of these data with radiogenic isotopic data, will better define the specific roles that the crust and the mantle played in the petrogenesis of Cretaceous magmatism.

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INTRODUCTION

Stable sulphur (S) and oxygen (O) isotopic compositions of granitoids can provide constraints on the magma source as well as extent and nature of crustal contaminants (e.g., Taylor and Sheppard, 1986). These stable isotope systems can be both more sensitive to crustal contamination and better indicators of magma generating processes than are radiogenic isotopic systems (Pb-Pb, Nd-Sm and Sr-Rb), therefore the stable isotopic compositions can provide more specific evidence for the nature and composition of source regions and contaminants (particularly crustal).

A regional sulfur and oxygen isotope study of intrusive rocks was undertaken in order to provide new insights into the origin of Cretaceous felsic magmatism in the northern Cordillera. Several plutonic suites have been characterized throughout the Selwyn Basin and Cassiar Platform regions in south central to eastern Yukon and the southwesternmost Northwest Territories (Fig. 1). Most of these suites are interpreted to be entirely derived from partial melting of underlying miogeoclinal metasedimentary rocks of predominantly North American affinity, however some uncertainty remains as to the presence and amount of a mantle component that may have interacted with the intrusions (Mortensen *et al.*, 2000; Hart *et al.*, 2004a,b; Heffernan, 2004). We herein present a comprehensive S and O stable isotope dataset to determine what role melts sourced from the mantle may have had on the genesis of the different plutonic suites, which components of the crust may have contributed sulphur to the melts, and what clues into the underlying basement could be determined from the isotopic composition of the intrusions.

CRETACEOUS MAGMATISM IN THE CASSIAR PLATFORM AND SELWYN BASIN

Cretaceous intrusions emplaced into the Cassiar Platform and Selwyn Basin have been interpreted to be a result of collisional to post-collisional back-arc magmatism related to ongoing subduction along the western margin of North

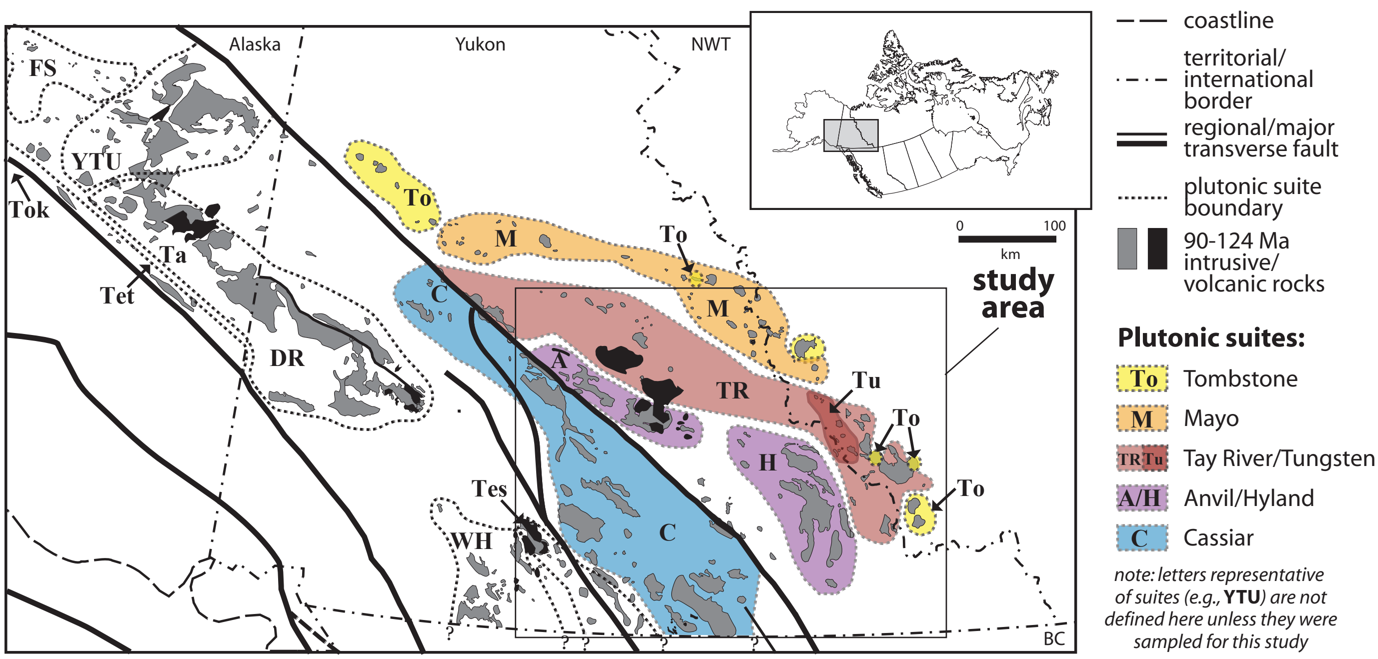

Figure 1. *Location map (inset) and distribution map of Cretaceous igneous rocks emplaced into the autochthonous North American margin and Intermontane terranes in the northern Cordillera. The plutons are subdivided into the suites: Tok-Tet = Tok-Tetlin, FS = Fairbanks-Salcha, YTU = Yukon-Tanana Uplands, Ta-DR = Tanacross-Dawson Range, WH = Whitehorse, Tes = Teslin, C = Cassiar, TR = Tay River, A = Anvil, H = Hyland, Tu = Tungsten, To = Tombstone and M = Mayo. The study area is indicated by the box, and plutonic suites of interest are shaded. Intrusion polygons and regional structures are modified from Gordey and Makepeace (1999) and Nelson and Colpron (2007); outlines of plutonic suites are adapted from Mortensen et al. (2000), Hart et al. (2004a,b) and Rasmussen et al. (2007).*

America. This aerially extensive magmatism (Fig. 1) is attributed to partial melting of the crust with late-enriched, mantle-derived melts contaminating the youngest plutonic suite(s). Based on geochronological, geochemical and radiogenic isotope similarities, there are two main groups of plutonic suites in the study area that are discussed here: (1) Cassiar, Hyland/Anvil and Tay River; and, (2) Tungsten, Mayo and Tombstone.

The Cassiar (approximately 115-99 Ma), Hyland/Anvil (109-95 Ma) and Tay River (99-96 Ma) suites comprise several belts in which many of the intrusions form large composite batholiths, and with the exception of the Cassiar suite (emplaced primarily into the Cassiar Platform), these plutonic suites are located northeast of the Tintina fault in rocks of the Selwyn Basin (Fig. 1). This aluminous and sub-alkalic magmatism consists primarily of biotite ± hornblende or muscovite-bearing quartz monzodiorite, granodiorite and monzogranite with associated mafic enclaves and local felsic volcanism. This voluminous magmatism is interpreted to have formed in response to arc-continent collision to the west, either through partial melting of over-thickened continental crust driven by regional compression (Woodsworth *et al.*, 1991), decompression melting during orogenic collapse (Hart *et al.*, 2004a,b; Mair *et al.*, 2006), or decompression melting during movement along deep transpressional structures (Gabrielse *et al.*, 2006). Most of the larger intrusions are emplaced into, or near to, thick Proterozoic rift-related sedimentary packages largely eroded from crystalline Precambrian Shield (*e.g.,* Boghossian *et al.*, 1996; Garzione *et al.*, 1997; Patchett *et al.*, 1999) with thin overlying Paleozoic metasedimentary miogeoclinal (Cassiar Platform and Selwyn Basin) rocks (*e.g.,* Cook *et al.*, 2004). Regardless of their exact petrogenesis, Cassiar, Hyland/Anvil and Tay River plutonic suites should have stable isotopic compositions consistent with derivation from the rift-related and miogeoclinal crustal rocks that are inferred to underlie much of the North American miogeocline (Cook *et al.*, 2004; Clowes *et al.*, 2005; Evenchick *et al.*, 2005).

The Tungsten (98-94 Ma), Mayo (96-93 Ma) and Tombstone (93-90 Ma) suites emplaced into the Selwyn Basin in central to eastern Yukon and southwestern Northwest Territories are the youngest and most inboard mid-Cretaceous magmatic rocks (Figs. 1, 2). These intrusions typically form very small to medium-sized circular plutons (*e.g.,* <1 km to 10 km in diameter), lack the large batholiths that are characteristic of the older plutonic suites described above, and are frequently associated with mafic dykes. The Tungsten suite typically comprises subalkalic and peraluminous biotite ± muscovite ± garnet monzogranitic to leucogranitic plugs, and is interpreted on the basis of mineralogy, geochemistry, and radiogenic isotopic data to have been derived entirely by crustal melting (Woodsworth *et al.*, 1991; Gordey and Anderson, 1993; Hart *et al.*, 2004a,b; Mair *et al.*, 2006). Similar to the Tungsten suite, sub-alkalic biotite ± hornblende ± clinopyroxene quartz monzonite to quartz monzodiorite to monzogranite Mayo suite intrusions also appear to have been primarily derived from partial melting of middle to upper crustal rocks, but there is also evidence for minor enriched-mantle melt contamination of these bodies (Hart *et al.*, 2004a,b). Weakly to strongly alkalic biotite ± hornblende ± clinopyroxene monzonite to monzogranite Tombstone Suite plutons, in contrast, include abundant intermediate and minor mafic components (*e.g.,* enclaves, dykes) and have mineralogical, geochemical and radiogenic isotopic features that indicate at least some melt was derived from melting of an enriched or lithospheric mantle source (Mortensen *et al.*, 2000; Hart *et al.*, 2004a,b). These later plutonic suites are typically exposed in the Paleozoic miogeoclinal rocks overlying Proterozoic rift-related packages, and are interpreted to have been emplaced in a tensional post-collisional tectonic regime (Mair *et al.*, 2006).

Despite previous work on the origin of Cretaceous magmatism in the northern Cordillera, there are still many unknowns with respect to the nature and the source of the intrusions and associated mineralization. For example: what is the nature of the underlying crust, and which part(s) of it are undergoing partial melting? How much of a mantle melt component is present in each plutonic suite, and have any of the older plutonic suites interacted with mantle-derived melts? From where do the intrusions obtain their sulphur? Although these uncertainties are in part due to the felsic composition of most of the intrusions, much of the confusion regarding the origin of Cretaceous magmatism results from contradictory evidence. This stable isotope study aims to provide new insights into the petrogenesis of the Cretaceous plutonic suites emplaced into North American miogeoclinal rocks by addressing the questions above.

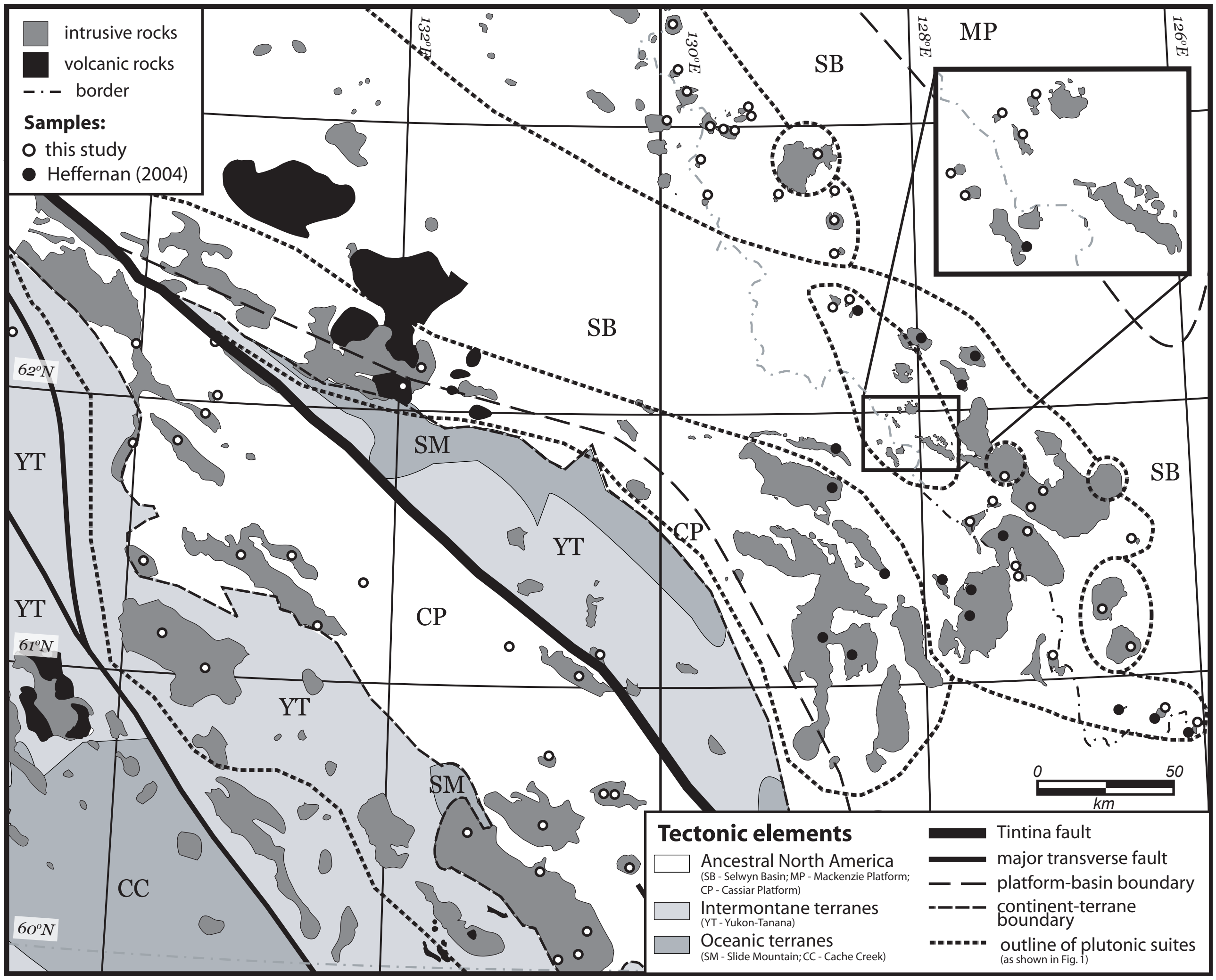

Figure 2. *Detailed map of terranes and mid-Cretaceous intrusive and extrusive rocks exposed in the study area. Locations of samples collected for this study and from Heffernan (2004) are denoted by open and solid dots respectively. Plutonic suites of interest are outlined with a dashed line; refer to Figure 1 for the plutonic suite names. Map is modified from Gordey and Makepeace (1999) and Nelson and Colpron (2007).*

STABLE ISOTOPE STUDY

Analyzing oxygen isotopic compositions ($\delta^{18}O$) allows us to distinguish between rocks that were derived solely from mantle material and rocks that were derived from, or heavily contaminated by, crustal material. Because oxygen is present in large quantities in virtually all rocks, it is relatively difficult to alter the primary $\delta^{18}O$ signature of a melt without significant assimilation of material of a distinctly different isotopic signature. Mantle-derived rocks have $\delta^{18}O$ of ~6.0 ± 0.5‰ (Kyser, 1986), whereas most sedimentary rocks have higher values (*e.g.*, >8‰; Taylor and Sheppard, 1986). Oxygen isotopic values from plutons that are greater than 8-9.0‰ would therefore indicate a significant crustal component to the melt. In contrast, hydrothermal water-rock interaction with meteoric waters (which have low $\delta^{18}O$) will act to lower the $\delta^{18}O$ signature of the rock. In many (but not all) cases, water-rock interaction is evident petrographically, thus samples for this study were selected to discriminate against hydrothermally altered rocks.

Sulfur isotopic compositions ($\delta^{34}S$) are particularly useful for detecting even small contributions of differing types of contaminants to a melt. Due to the relatively low concentrations of sulfur in igneous rocks, particularly in felsic magmas, it takes very little assimilation of a sulphur-bearing material (*e.g.,* pyritic shale, evaporates or stratiform barite) to alter $\delta^{34}S$ in a magma body. This makes sulphur a particularly sensitive tool for detecting not only the presence of contamination, but even different types of crustal contamination. However, this sensitivity may also complicate the interpretation of $\delta^{34}S$ data. Mantle-derived sulfur typically has a narrow and consistent range of $\delta^{34}S$ (0 ± 0.3‰), whereas sedimentary sulfur has a very large range of $\delta^{34}S$ (-40 to +40‰). Goodfellow (2007) reports values for sedimentary sulfur (from syngenetic pyrite and barite) for the northern Cordillera that are typically >10‰.

ANALYTICAL METHODS

Eighty-seven representative samples with pre-existing radiogenic, geochemical and geochronological data of approximately 65 intrusive bodies in the Yukon and Northwest Territories were analyzed for sulfur and oxygen isotopic compositions. Eighteen of these samples were provided by S. Heffernan from samples used for an MSc thesis at UBC (Heffernan, 2004). Prior to crushing, hand samples were examined and sample material containing quartz ± sulphide-bearing veins or fractures were avoided to the best of our ability. However, minor hydrothermal alteration and its effects on the stable isotope systematics, although minimized, cannot be completely dismissed for all samples.

Oxygen

Quartz grains were handpicked from a light fraction of crushed and coarsely ground whole rock material that was processed on a Wilfley table. Quartz grain samples weighing approximately 1000 µg were sealed into tin cups; oxygen isotopes in quartz were analyzed using the high-temperature carbon reduction technique in which silicate oxygen is liberated by reaction with graphitic carbon to produce CO (Arehart and Poulson, 2006). The resultant CO is then introduced to the mass spectrometer in continuous-flow mode for isotopic analysis. Ten percent of the samples underwent duplicate analysis in order to monitor repeatability. Replicate analyses of standards NCSU, NBS-28 and ARQ indicated a precision of ±0.2‰, and $\delta^{18}O$ is reported relative to an NBS-28 value of +9.6‰. Data are presented in Table 1.

Table 1. *Oxygen isotope data. Samples appended with "r" are replicate analyses and samples appended with "d" are duplicate analyses.*

Sample ID	Pluton Name	Plutonic Suite	Weight (mg) / no. samples	$\delta^{13}C$	Raw $\delta^{18}O$	Corrected $\delta^{18}O$ / raw $\delta^{18}O$ st.dev.	Stretch corr	Reported $\delta^{18}O$
KR-05-198	Hole-in-the-Wall	Tombstone	987	20.91	21.35	14.49	2.79	14.0
KR-05-62	Mt. Christie	Tombstone	1023	21.28	22.04	14.31	2.61	13.9
KR-05-62_d	Mt. Christie	Tombstone	992	21.40	22.36	14.63	2.93	14.1
KR-05-97b	O'Grady	Tombstone	1030	21.46	22.80	15.07	3.37	14.5
CL-06-33	Dechen'La	Tombstone	992	20.88	20.72	13.32	1.62	13.0
CL-06-33_d	Dechen'La	Tombstone	1028	21.06	22.32	14.92	3.22	14.4
CL-06-34	Natla	Tombstone	1012	20.69	22.44	15.04	3.34	14.5
SH-99-011	Big Charlie	Tombstone	969	21.26	23.66	17.00	5.30	16.1
98-HAS-14	McLeod	Tombstone	998	20.20	19.71	12.10	0.40	12.0
KR-05-113	S. Nahanni	Mayo	1031	21.64	23.16	15.43	3.73	14.8
KR-05-130	C. Nahanni	Mayo	980	21.68	22.97	15.24	3.54	14.6
KR-05-136	N. Nahanni	Mayo	982	21.07	22.08	14.35	2.65	13.9
KR-05-68	Mt. Wilson	Mayo	990	21.44	23.54	15.81	4.11	15.1
CL-06-35	Logan	Mayo	1013	20.43	21.36	13.96	2.26	13.6
CL-06-36	Mt. Christie	Mayo	1022	20.85	21.59	13.86	2.16	13.5
CL-06-37	Christie Pass	Mayo	1021	21.18	22.52	14.79	3.09	14.3
CL-06-38	Ross River	Mayo	980	20.52	20.83	13.10	1.40	12.9
CL-06-39	Keele River	Mayo	979	20.62	21.49	13.76	2.06	13.4
CL-06-39_d	Keele River	Mayo	972	21.52	23.43	15.70	4.00	15.0
CL-06-40	Mile 222	Mayo	1025	21.60	22.83	15.10	3.40	14.5
KR-05-110	Cac	Tungsten	992	22.19	23.98	16.25	4.55	15.5

Table 1. *continued.*

Sample ID	Pluton Name	Plutonic Suite	Weight (mg) / no. samples	δ 13C	Raw δ 18O	Corrected δ 18O / raw δ 18O st.dev.	Stretch corr	Reported δ 18O
KR-05-143	Rifle Range	Tungsten	1029	22.02	23.64	15.91	4.21	15.2
KR-05-148	Circular Stock	Tungsten	1019	21.83	22.63	14.90	3.20	14.3
KR-05-175	Lened	Tungsten	982	21.04	21.17	14.10	2.40	13.7
KR-05-175_d	Lened	Tungsten	997	20.75	20.48	13.46	1.76	13.2
KR-05-208	Little Hyland	Tungsten	990	20.47	20.28	13.46	1.76	13.2
KR-05-210	Nahanni Range Rd.	Tungsten	1028	20.57	20.14	13.36	1.66	13.1
KR-05-215	Mine Stock	Tungsten	1009	20.45	20.69	13.95	2.25	13.6
KR-05-215_d	Mine Stock	Tungsten	1020	20.66	21.30	14.60	2.90	14.1
KR-05-32	Ivo	Tungsten	995	22.51	24.60	16.87	5.17	16.0
SH-99-016	Tuna	Tungsten	974	20.44	20.54	12.93	1.23	12.7
98-Z-C-028	Rudi	Tungsten	1028	20.60	21.37	13.81	2.11	13.4
98-Z-C-028_d	Rudi	Tungsten	973	20.81	21.50	13.95	2.25	13.6
KR-05-08	Powers	Tay River	1021	23.05	25.01	17.28	5.58	16.3
KR-05-10	Jorgensen	Tay River	1039	22.90	22.05	15.23	3.53	14.6
KR-05-164	Hole-in-the-Wall	Tay River	1006	21.97	24.25	16.52	4.82	15.7
KR-05-191	Coal River	Tay River	1028	22.54	23.48	16.50	4.80	15.7
KR-05-194	Coal River	Tay River	1003	21.02	21.29	14.35	2.65	13.9
KR-05-196	Coal River	Tay River	981	20.51	18.60	11.70	0.00	11.7
KR-05-22	Roy	Tay River	1001	21.67	21.94	14.21	2.51	13.8
KR-05-26	Fish	Tay River	1048	23.05	24.69	17.95	6.25	16.9
KR-05-43	Park	Tay River	1003	21.68	21.27	13.54	1.84	13.2
SH-99-001	Shannon Creek	Tay River	982	20.49	19.18	12.52	0.82	12.4
SH-99-006	Coal River	Tay River	1023	20.66	18.32	11.70	0.00	11.7
SH-99-008	Coal River	Tay River	983	20.56	18.45	10.79	-0.91	10.9
SH-99-009	Coal River	Tay River	999	21.92	22.41	14.76	3.06	14.2
SH-99-013	Caesar Lakes	Tay River	1020	20.41	19.28	11.64	-0.06	11.7
SH-99-013_d	Caesar Lakes	Tay River	1004	20.55	19.38	11.76	0.06	11.7
98-HAS-02	Mt. Appler	Tay River	994	20.41	21.88	14.29	2.59	13.8
98-HAS-03	Faille	Tay River	987	20.85	21.14	13.94	2.24	13.6
98-HAS-06	Mulhulland	Tay River	994	20.87	20.70	13.57	1.87	13.3
98-HAS-07	Jorgensen	Tay River	978	20.70	19.32	12.28	0.58	12.2
98-HAS-07_d	Jorgensen	Tay River	1010	20.53	18.69	11.72	0.02	11.7
98-HAS-12	Patterson	Tay River	997	20.35	18.85	11.25	-0.45	11.3
98-HAS-12_d	Patterson	Tay River	1012	21.00	20.15	13.25	1.55	13.0
98-Z-12	Powers	Tay River	998	21.32	18.67	11.10	-0.60	11.2
SH-005	Mt. Billings	Hyland/Anvil	1005	20.39	15.18	7.75	-3.95	8.4
SH-011E	Mt. Billings	Hyland/Anvil	1011	20.65	19.18	11.90	0.20	11.9
SH-029	Tyers Pass	Hyland/Anvil	977	20.62	17.33	9.97	-1.73	10.3
SH-070	Anderson	Hyland/Anvil	991	20.79	20.88	13.37	1.67	13.1
07M-150	Carolyn/Orchay	Hyland/Anvil	1016	20.71	18.87	11.14	-0.56	11.2
07M-151	volcanic	South Fork	978	21.60	21.99	14.26	2.56	13.8
KR-07-01	Dycer Creek	Cassiar	977	21.00	21.10	13.37	1.67	13.1
KR-07-02	Quiet Lake	Cassiar	1013	21.44	22.68	14.95	3.25	14.4
KR-07-03	Quiet Lake	Cassiar	995	21.25	21.66	13.93	2.23	13.5
KR-07-04	Nisutlin	Cassiar	1027	22.03	23.93	16.20	4.50	15.4
KR-07-05	Nisutlin	Cassiar	1002	21.90	24.29	16.56	4.86	15.7

Table 1. *continued.*

Sample ID	Pluton Name	Plutonic Suite	Weight (mg) / no. samples	δ ^{13}C	Raw δ ^{18}O	Corrected δ ^{18}O / raw δ ^{18}O st.dev.	Stretch corr	Reported δ ^{18}O
KR-07-06	Nisutlin	Cassiar	986	21.21	21.19	13.46	1.76	13.2
KR-07-07	“Young”	Cassiar	985	22.00	23.94	16.21	4.51	15.4
KR-07-08	unnamed	Cassiar	1003	20.75	20.02	12.29	0.59	12.2
KR-07-09	Fox Mountain	Cassiar	1010	21.12	21.63	13.90	2.20	13.5
KR-07-10	Big Salmon	Cassiar	1000	20.45	19.55	11.82	0.12	11.8
KR-07-10_d	Big Salmon	Cassiar	984	20.41	19.81	12.08	0.38	12.0
KR-07-11	Glenlyon	Cassiar	985	21.01	23.07	15.34	3.64	14.7
KR-07-12	unnamed	Cassiar	995	21.01	22.19	14.46	2.76	14.0
KR-07-14	“Black Lake”	Cassiar	990	20.50	20.39	12.66	0.96	12.5
KR-07-15	Meister Lake	Cassiar	991	20.59	19.30	11.57	-0.13	11.6
07M-152	Battle Creek	Cassiar	1021	21.33	22.56	14.83	3.13	14.3
07M-153	Glenlyon	Cassiar	994	20.31	19.55	11.82	0.12	11.8
KR-07-16	Cassiar	Cassiar	998	20.42	20.02	12.29	0.59	12.2
KR-07-17	Cassiar	Cassiar	1005	19.84	19.14	11.41	-0.29	11.5
KR-07-18	Cassiar	Cassiar	987	20.40	20.88	13.15	1.45	12.9
KR-07-19	Marker Lake	Cassiar	1020	20.80	21.09	13.36	1.66	13.1
KR-07-20	Cabin Creek	Cassiar	1009	20.56	20.34	12.61	0.91	12.5
KR-07-21	Cabin Creek	Cassiar	998	20.84	19.84	12.11	0.41	12.0
KR-07-22	Cassiar	Cassiar	997	21.59	20.56	12.83	1.13	12.6
KR-07-23	Gravel Creek	Cassiar	1014	22.58	25.18	17.45	5.75	16.5
KR-07-24	Cassiar	Cassiar	1005	21.34	22.43	14.70	3.00	14.2
KR-07-13	“Square Lake”	unknown	1006	20.12	22.14	14.41	2.71	13.9
07M-154	Cornolio	unknown	971	20.62	20.36	12.63	0.93	12.5
07M-154_d	Cornolio	unknown	1011	21.42	22.20	14.47	2.77	14.0

Sulfur

Sulfur was extracted from whole rock powder using the Kiba method (Sasaki *et al.*, 1979) and ultimately precipitated as Ag_2S; approximately 10% of the samples underwent a duplicate sulphide extraction. About 380 µg of silver sulphide was weighed into a tin cup with V_2O_5 (to aid oxidation), sealed, and then combusted in a high-temperature elemental analyzer oven to produce SO_2, which was then introduced to the mass spectrometer in continuous-flow mode. Approximately 30% of the samples, including half of the duplicated samples, also underwent replicate analysis in order to monitor repeatability in the unknown samples. GSL (sphalerite) and MIC (marcasite) standards of known isotopic composition were used to correct for the presence of $^{32}S^{16}O^{18}O$ (which has the same isotopic weight as $^{34}SO^{16}O^{16}$) and for machine drift. Typical analytical precision for these analyses is ±0.3‰ or better, and data are reported relative to the Vienna Canyon Diablo Troilite (VCDT) standard. Data are presented in Table 2.

Table 2. *Sulphur isotope data with calculated wt% sulphur. Italicized data are minimum estimates only due to either loss of material during sulphur extraction (wt% S), or a lack of sufficient sample material to obtain a peak height >1. Samples appended with “r” are replicate analyses and samples appended with “d” are duplicate analyses.*

Sample ID	Pluton Name	Plutonic Suite	Calc. S (wt%)	Peak Height (nA)	δ$^{34}S_{VCDT}$ (‰)
KR-05-198	Hole-in-the-Wall	Tombstone	0.0018	2.07	2.92
KR-05-62	Mt. Christie	Tombstone	0.0244	2.87	9.27
KR-05-97	O’Grady	Tombstone	*0.0061*	2.24	8.40
KR-05-97b_r	O’Grady	Tombstone	*0.0061*	3.38	8.45
CL-06-33	Dechen’La	Tombstone	0.0033	1.97	8.79
CL-06-34	Natla	Tombstone	0.0026	2.37	11.24
SH-99-011	Big Charlie	Tombstone	0.0012	2.91	4.93
SH-99-011_r	Big Charlie	Tombstone	0.0012	2.69	5.35
98-HAS-14	McLeod	Tombstone	0.0008	3.14	5.85

***Table 2.** continued.*

Sample ID	Pluton Name	Plutonic Suite	Calc. S (wt%)	Peak Height (nA)	$\delta^{34}S_{VCDT}$ (‰)
KR-05-113	S. Nahanni	Mayo	0.0029	2.57	13.30
KR-05-130	C. Nahanni	Mayo	0.0050	2.32	11.02
KR-05-136	N. Nahanni	Mayo	0.0195	2.57	11.04
KR-05-68	Mt. Wilson	Mayo	*0.0156*	2.57	7.42
KR-05-68_d	Mt. Wilson	Mayo	0.0237	2.66	7.85
KR-05-76	Pelly River	Mayo	0.0024	2.36	6.27
KR-05-77	Pelly-mafic dyke	Mayo	0.0251	2.40	7.77
KR-05-77_r	Pelly-mafic dyke	Mayo	0.0251	2.28	7.77
CL-06-35	Logan	Mayo	0.0028	1.75	12.57
CL-06-36	Mt. Christie	Mayo	0.0048	1.94	9.93
CL-06-37	Christie Pass	Mayo	*0.0241*	2.85	10.00
CL-06-37_d	Christie Pass	Mayo	0.0361	2.12	9.91
CL-06-37_dr	Christie Pass	Mayo	0.0361	2.13	9.90
CL-06-38	Ross River	Mayo	0.0057	1.61	11.00
CL-06-38_r	Ross River	Mayo	0.0057	1.58	10.91
CL-06-39	Keele River	Mayo	0.0062	1.12	8.16
CL-06-40	Mile 222	Mayo	0.0028	2.31	10.40
KR-05-110	Cac	Tungsten	0.0046	2.86	10.54
KR-05-110_r	Cac	Tungsten	0.0046	2.72	10.53
KR-05-143	Rifle Range	Tungsten	0.0035	2.13	7.29
KR-05-143_r	Rifle Range	Tungsten	0.0033	2.40	7.36
KR-05-143_d	Rifle Range	Tungsten	0.0033	2.45	7.35
KR-05-148	Circular Stock	Tungsten	0.0108	2.56	8.68
KR-05-175	Lened	Tungsten	0.0026	2.32	9.47
KR-05-207	East Tuna	Tungsten	0.0029	2.24	9.14
KR-05-208	Little Hyland	Tungsten	0.0012	1.89	9.02
KR-05-210	Nahanni Range Rd.	Tungsten	0.0007	2.09	9.75
KR-05-212	Cantung-felsic dyke	Tungsten	0.5447	2.51	8.62
KR-05-213	Cantung-mafic dyke	Tungsten	0.1042	3.34	4.56
KR-05-213_r	Cantung-mafic dyke	Tungsten	0.1042	3.80	4.60
KR-05-213_r	Cantung-mafic dyke	Tungsten	0.1042	1.86	3.97
KR-05-215	Mine Stock	Tungsten	0.0024	2.39	6.54
KR-05-215_r	Mine Stock	Tungsten	0.0024	2.31	6.53
KR-05-32	Ivo	Tungsten	0.0015	2.11	4.59
KR-05-32_r	Ivo	Tungsten	0.0015	2.25	4.58
SH-99-016	Tuna	Tungsten	*0.0027*	2.80	4.46
98-Z-C-028	Rudi	Tungsten	0.0006	*0.66*	*6.82*
KR-05-08	Powers	Tay River	0.0921	2.59	7.39
KR-05-08_r	Powers	Tay River	0.0921	2.54	7.30
KR-05-10	Jorgensen	Tay River	0.0120	2.31	4.23
KR-05-157	Roy-mafic dyke	Tay River	0.1504	3.73	11.13
KR-05-157_r	Roy-mafic dyke	Tay River	0.1504	1.75	10.97
KR-05-164	Hole-in-the-Wall	Tay River	0.0049	2.46	9.91
KR-05-191	Coal River	Tay River	0.0047	2.17	8.08
KR-05-194	Coal River	Tay River	0.0014	2.36	6.73
KR-05-196	Coal River	Tay River	0.0020	2.53	8.32
KR-05-22	Roy	Tay River	0.0050	2.06	5.38
KR-05-26	Fish	Tay River	0.0039	2.35	3.93
KR-05-43	Park	Tay River	0.0051	2.65	3.94
SH-99-001	Shannon Creek	Tay River	0.0007	*0.87*	*3.94*
SH-99-006	Coal River	Tay River	0.0025	2.83	5.08
SH-99-006_r	Coal River	Tay River	0.0025	3.03	5.14
SH-99-008	Coal River	Tay River	0.0010	2.93	5.78
SH-99-009	Coal River	Tay River	0.0061	3.58	7.50
SH-99-013	Caesar Lakes	Tay River	*0.0017*	nd	nd
SH-99-013	Caesar Lakes	Tay River	nd	nd	nd
98-HAS-02	Mt. Appler	Tay River	0.0005	1.60	8.25
98-HAS-03	Faille	Tay River	0.0020	3.45	4.46
98-HAS-03_r	Faille	Tay River	0.0020	3.31	4.46
98-HAS-06	Mulhulland	Tay River	0.0011	3.01	7.41
98-HAS-07	Jorgensen	Tay River	0.0008	2.15	2.41
98-HAS-12	Patterson	Tay River	*0.0058*	3.42	9.21
98-HAS-12_r	Patterson	Tay River	*0.0058*	3.72	9.28
98-HAS-12_d	Patterson	Tay River	*0.0113*	1.48	9.30
98-HAS-12_dr	Patterson	Tay River	*0.0113*	3.10	9.58
98-Z-12	Powers	Tay River	0.0661	3.84	12.75
98-Z-12_r	Powers	Tay River	0.0661	2.05	12.36
SH-005	Mt. Billings	Hyland/Anvil	0.0010	2.56	8.51
SH-99-022	Mt Billings	Hyland/Anvil	*0.0049*	3.22	3.17
SH-011E	Mt. Billings	Hyland/Anvil	0.0132	3.37	13.57
SH-011E_r	Mt. Billings	Hyland/Anvil	0.0132	2.10	13.40
SH-029	Tyers Pass	Hyland/Anvil	0.0014	3.02	6.12

Table 2. *continued.*

Sample ID	Pluton Name	Plutonic Suite	Calc. S (wt%)	Peak Height (nA)	$\delta^{34}S_{VCDT}$ (‰)
SH-029_r	Tyers Pass	Hyland/ Anvil	0.0014	3.07	6.05
SH-070	Anderson	Hyland/ Anvil	*0.0242*	4.69	nd
SH-071_r	Anderson	Hyland/ Anvil	*0.0242*	1.96	9.41
07M-150	Carolyn/ Orchay	Hyland/ Anvil	0.0010	1.70	8.86
07M-151	volcanic	South Fork	0.0031	2.15	10.24
KR-07-01	Dycer Creek	Cassiar	0.0016	3.06	7.31
KR-07-02	Quiet Lake	Cassiar	0.0010	*0.53*	*9.04*
KR-07-03	Quiet Lake	Cassiar	0.0003	*0.19*	*4.39*
KR-07-04	Nisutlin	Cassiar	0.0003	*0.41*	*3.37*
KR-07-05	Nisutlin	Cassiar	0.0010	*0.63*	*10.12*
KR-07-06	Nisutlin	Cassiar	0.0019	3.41	8.08
KR-07-07	"Young"	Cassiar	0.0062	3.40	8.68
KR-07-08	unnamed	Cassiar	0.0061	3.01	8.02
KR-07-08_d	unnamed	Cassiar	0.0063	2.97	8.02
KR-07-08_dr	unnamed	Cassiar	0.0063	2.84	8.02
KR-07-09	Fox Mountain	Cassiar	0.0013	2.69	9.63
KR-07-10	Big Salmon	Cassiar	0.0020	3.02	7.92
KR-07-10_r	Big Salmon	Cassiar	0.0020	2.85	7.96
KR-07-11	Glenlyon	Cassiar	0.0003	*0.73*	*7.44*
KR-07-12	unnamed	Cassiar	0.0007	*0.54*	*8.37*
KR-07-14	"Black Lake"	Cassiar	0.0011	2.75	10.23
KR-07-15	Meister Lake	Cassiar	0.0002	nd	nd
07M-152	Battle Creek	Cassiar	0.0066	2.89	9.31
07M-152_r	Battle Creek	Cassiar	0.0066	2.53	9.30
07M-153	Glenlyon	Cassiar	0.0036	2.14	9.08
KR-07-16	Cassiar	Cassiar	0.0005	2.82	4.45
KR-07-17	Cassiar	Cassiar	0.0012	3.17	8.00
KR-07-18	Cassiar	Cassiar	0.0009	2.04	8.35
KR-07-19	Marker Lake	Cassiar	*0.0100*	3.39	2.06
KR-07-19_d	Marker Lake	Cassiar	0.0113	3.06	2.03
KR-07-20	Cabin Creek	Cassiar	0.0008	2.98	5.14
KR-07-21	Cabin Creek	Cassiar	0.0011	2.68	6.00
KR-07-22	Cassiar	Cassiar	0.0035	3.58	8.58
KR-07-23	Gravel Creek	Cassiar	0.0004	*0.23*	*5.70*
KR-07-24	Cassiar	Cassiar	0.0012	2.72	3.86
KR-07-24_r	Cassiar	Cassiar	0.0012	2.95	3.84
KR-07-13	"Square Lake"	unkn	0.0004	*0.93*	*0.78*
07M-154	Cornolio	unkn	0.0008	1.29	3.46

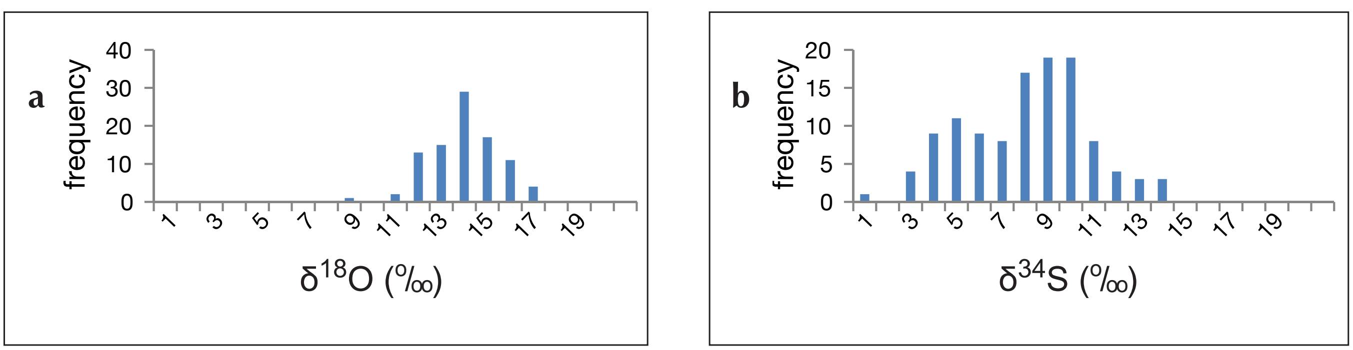

Figure 3. *(a) Frequency plot for all $\delta^{18}O$ values. (b) Frequency plot for all $\delta^{34}S$ values.*

RESULTS

Oxygen

All of the intrusions analyzed have a normal distribution of high positive $\delta^{18}O$, ranging from +8.4 to +16.9‰ (Table 1; Fig. 3a). There is very little systematic variation in the $\delta^{18}O$ across the study area, indicating that the majority of the rocks in the region were derived from, or significantly contaminated by, crustal materials (Fig. 4a). There is, however, a small group of lower $\delta^{18}O$ (+8.4 to +11.9‰) in the southeastern part of the study area, or the 'southeastern block'. Plutonic suites with the smallest range in $\delta^{18}O$ on the data summary plotted in Figure 5a (*e.g.,* Tombstone, Mayo and Tungsten) were sampled from smaller geographic areas, therefore the increasing range of $\delta^{18}O$ from Tombstone to Tay River suite intrusions may be due more to regional variations in the basement, rather than intra-plutonic suite variation.

Sulfur

Throughout the study area, $\delta^{34}S$ ranges from +2.1‰ to +13.6‰ and contains two sub-populations (Table 1; Fig. 3b), although the majority of the intrusions have $\delta^{34}S$ values ranging from +6 to +10‰, which is suggestive of the influence of seawater sulphate. There is also a significant population of lower $\delta^{34}S$ ranging from +3‰ to +6‰ that is primarily concentrated in the southeast block (Fig. 4b); many of these isotopically 'lighter' sulphur samples correlate with lower $\delta^{18}O$. Furthermore, the highest $\delta^{34}S$ values appear to be concentrated in the northeastern part of the study area ('northeastern block') and are predominantly associated with small Mayo suite intrusions (Fig. 4b). From the data summary plot, it appears that from younger to older rocks (*i.e.*, Mayo through to Tay River suites), there is a general decrease in $\delta^{34}S$ (Fig. 5b).

DISCUSSION

SOURCE OF MELT

As most $\delta^{18}O$ isotopic compositions are well above +10‰, it is clear that all of the plutonic suites were derived, in significant portion, from crustal melts, or have assimilated a significant amount of crustal material. This effect is still evident in the Tombstone suite, which is interpreted to have at least some enriched mantle-derived component (*e.g.,* Hart *et al.*, 2004a,b). The generally lower $\delta^{18}O$ observed in the southeastern block may be reflecting either less input of middle to upper crustal material into the melt versus lower crustal rocks (of unknown composition), or melting of crustal material with slightly lower $\delta^{18}O$ due to compositional variations in the basement. Although globally most granitoids do not have $\delta^{18}O$ >14‰ in quartz even after extensive interaction

a

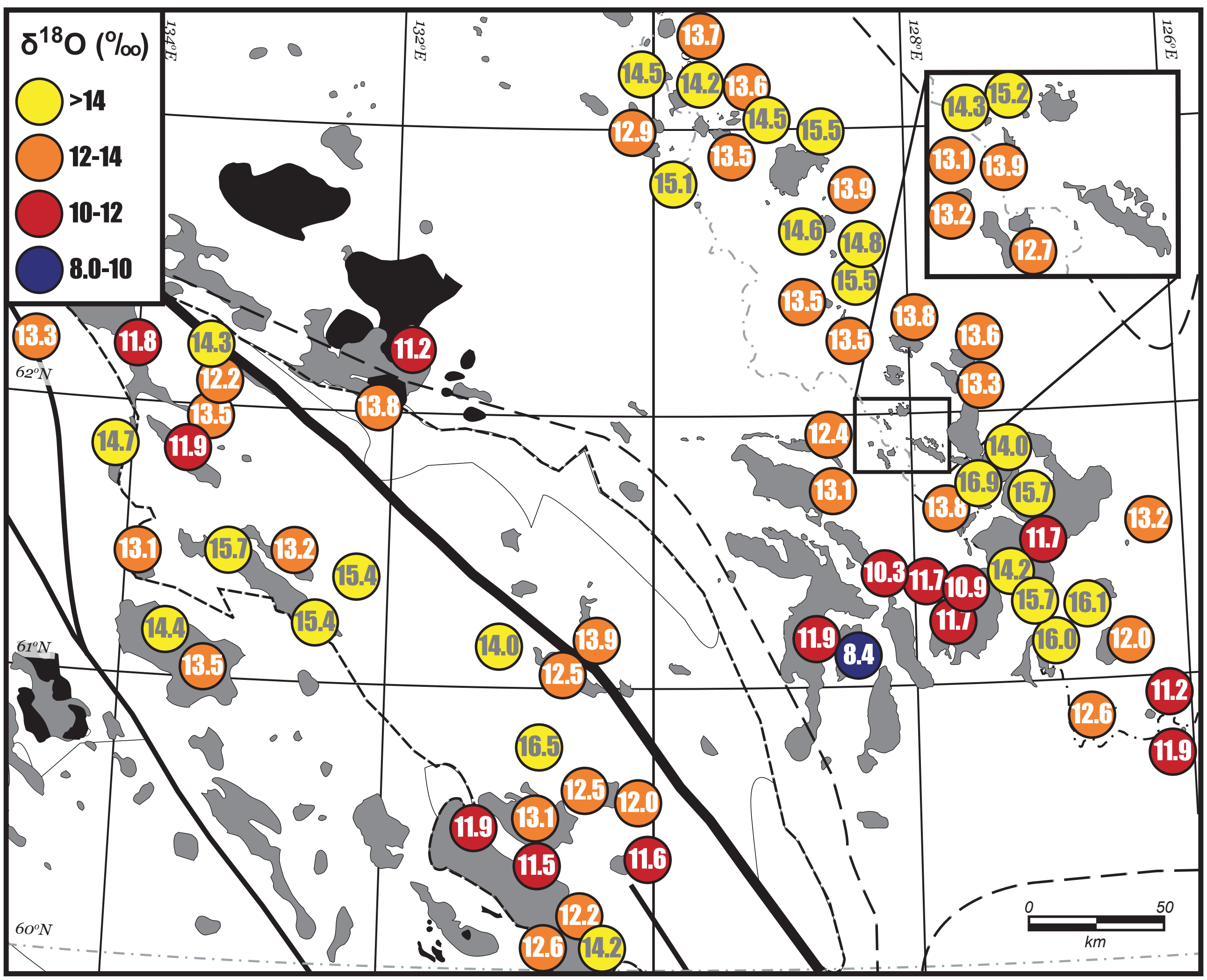

Figure 4. (a) *Spatial distribution of δ^{18}O isotopic compositions. Line work as in Figures 1 and 2.*

with the crust, many intrusions that were sampled for this study returned values of +14‰ to +16.9‰, which is probably indicative of primarily partial melting of pelitic rocks, or in some cases, incorporation of significant sedimentary material along plutonic margins (*e.g.,* Taylor and Sheppard, 1986).

For the most part, $\delta^{34}S$ is greater than +6‰, particularly in the northeastern block in association with Mayo suite intrusions, and is generally typical of incorporation of seawater sulphate (*e.g.,* evaporate lithologies), such as the Gypsum Formation of the Proterozoic Little Dal Group ($\delta^{34}S$ = +13.9‰ to +17.6‰; Turner, 2009). There is, however, a second significant population of +3‰ to +6‰. These 'lighter' $\delta^{34}S$ values are predominantly from samples located in the southeastern block of the study area and could be a result of lesser amounts of the seawater sulphur contaminant, but contamination from either mantle-derived, or sedimentary-derived (sulphide) sulphur is possible. Interestingly, this southeastern block is also correlative with particularly low εNd values (K.L. Rasmussen, unpublished data, 2009), which suggests that either the basement underlying the southeastern block may be isotopically more juvenile, or that mantle-derived material has been incorporated into all plutonic suites in this area. The general decrease in $\delta^{34}S$ with increasing age (Fig. 5b) might indicate decreasing interaction with crustal material in general in the older plutonic suites, or perhaps some input from mantle-derived melts; this is contrary to current models of mid-Cretaceous magmatism in the region where geochemistry, mineralogy and radiogenic isotopic compositions indicate that the younger intrusions are more likely to have

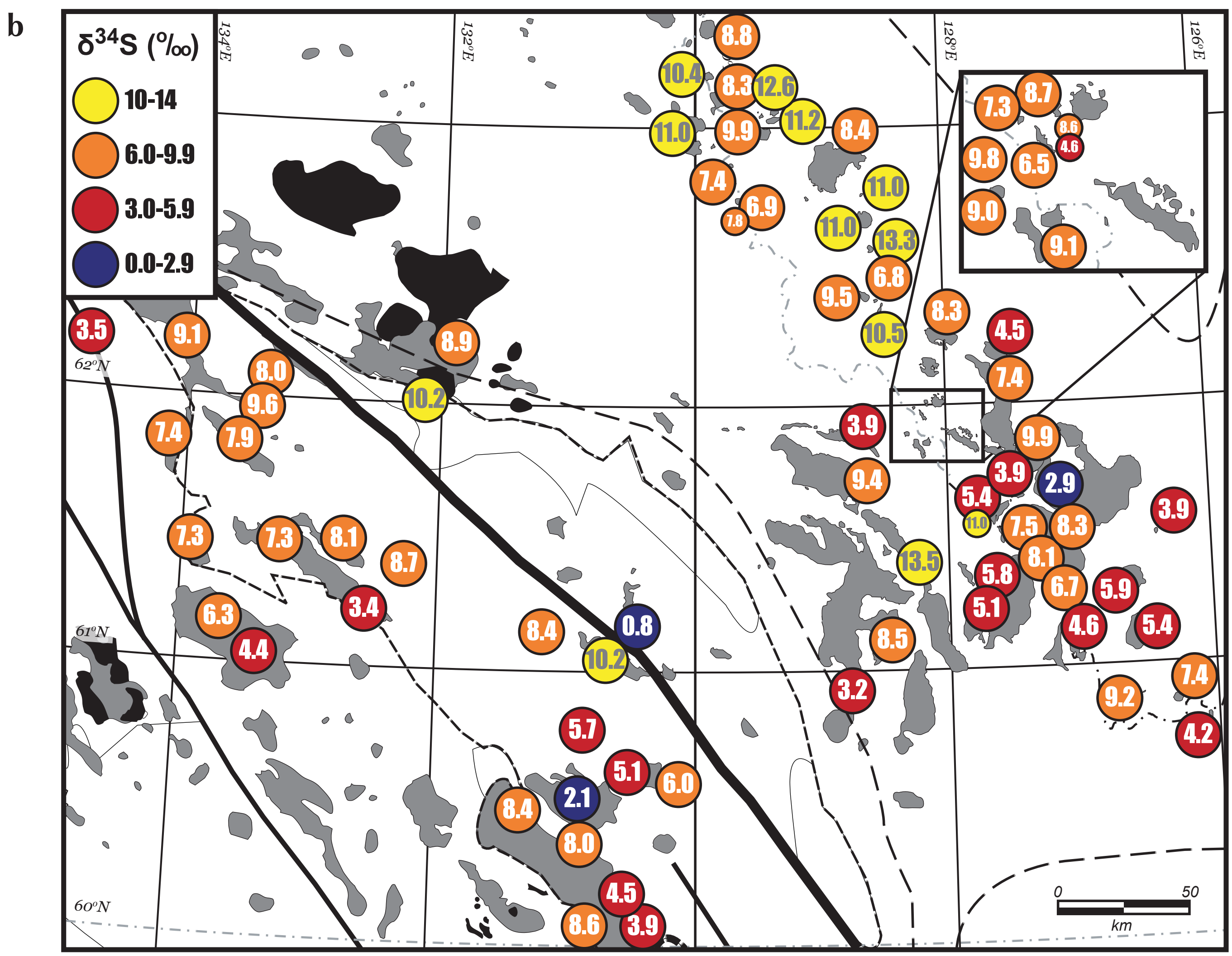

Figure 4. (b) *Spatial distribution of $\delta^{34}S$ isotopic compositions. Line work as in Figures 1 and 2.*

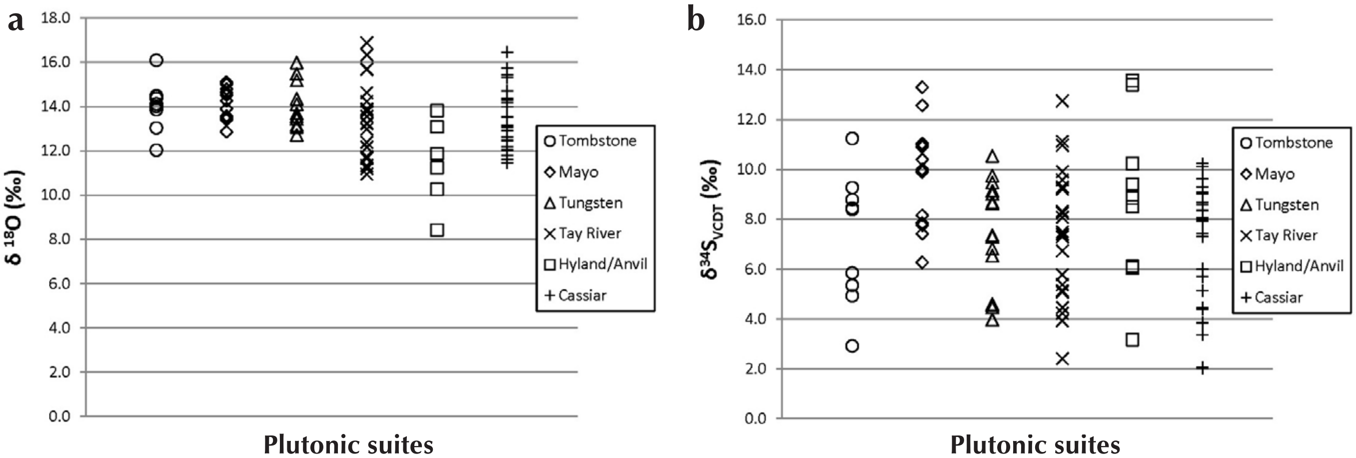

Figure 5. *Summary plots of all stable isotopic data, subdivided by plutonic suite:* ***(a)*** $\delta^{18}O$; ***(b)*** $\delta^{34}S$.

incorporated some mantle-derived material (*e.g.,* Hart *et al.*, 2004a,b). Further work such as comparison of $\delta^{34}S$ with radiogenic isotopic data (*e.g.,* Sm-Nd, Rb-Sr) is required to resolve the uncertainties of granite melt sources.

REGIONAL VARIATIONS AND IMPLICATIONS FOR THE NATURE OF THE BASEMENT

The Cassiar plutonic suite was emplaced southwest of the Tintina fault and largely within the Cassiar Platform: an offshelf carbonate platform that was deposited from at least the latest Proterozoic through to the Devonian (*e.g.,* Cecile and Morrow, 1997). After restoration of 400-430 km of primarily Cenozoic dextral offset along the Tintina fault (Gabrielse *et al.*, 2006), the Cassiar plutonic suite is essentially the coeval and along-strike southern equivalent of magmatism in the Selwyn Basin. The Cassiar Platform was deposited originally as a marginal plateau along an upper plate margin, or a continental rifted margin with a sub-crustal detachment (related to mid- to late Proterozoic rifting; Hansen *et al.*, 1993; Cecile *et al.*, 1997). Conversely, the magmatism examined northeast of the Tintina fault in the Selwyn Basin has been interpreted by the same authors to have been emplaced within a lower plate margin, or a continental rifted margin with a shallow crustal detachment overlain by highly rotated normal fault blocks. This geometry of the rifted margin has been used to explain the difference in width of mid-Cretaceous magmatism in the Selwyn Basin, as much as 250 km relative to magmatism in the Cassiar Platform, which was emplaced over a much narrower region (~100 km).

Overall, there are no significant variations in the stable isotope compositions between intrusions emplaced into the Selwyn Basin of the lower plate rifted margin (*e.g.,* northeast of the Tintina fault) and those emplaced into the Cassiar Platform of the upper plate rifted margin (*e.g.,* southwest of the Tintina fault). This suggests that the composition of the middle to upper crust, from which the granitic melts were likely derived, is reasonably homogenous for ~1700 km along the length of the ancient continental margin. However, intrusions in the southern part of the Selwyn Basin do have somewhat lower $\delta^{34}S$ and $\delta^{18}O$. Although pyritiferous shales may be responsible for lower $\delta^{34}S$, these would be expected to lead to higher $\delta^{18}O$ compositions. Therefore, the combination of sulphur and oxygen isotopic data are suggestive of the incorporation of melts that are not derived from a middle to upper crustal source. The correlation of these lighter stable isotopic values with more juvenile εNd values for this region (K.L. Rasmussen, unpublished data, 2009) further supports this inference for a second distinct melt source, such as the underlying mantle, or an unknown basement component (*e.g.,* mafic/ultramafic lower crust). Cretaceous movement along deep transverse structures related to Proterozoic rifting is a possible mechanism that may have allowed for the ascension of such deeper melts.

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