The Early Tertiary Sifton Range volcanic complex, southwestern Yukon

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ABSTRACT

The early Tertiary magmatic episode in the northern Canadian Cordillera is linked to the restructuring of the Kula-North American plate system from orthogonal to oblique convergence. Resultant volcanism was widespread, and remnant successions outcrop along the eastern margin of the Coast Plutonic Complex (CPC). The Sifton Range volcanic complex of southwestern Yukon is a member of the Paleogene Sloko-Skukum Group, and comprises a 900-m thick, shallow-dipping, volcanic succession dominated by intermediate to evolved lava and pyroclastic rocks deposited in a northwesterly trending half-graben. Locally, the volcanic sequence is intruded by alkali-feldspar granites of the CPC's Nisling Plutonic Suite dated at 57.5 Ma. Felsite sills radiate from the main intrusive body, and together with numerous basaltic to dacitic dykes traverse the volcanic package. Both the felsic volcanic rocks and epizonal granitoids exhibit anomalous enrichments in large-ion lithophile elements indicating crustal contributions during the late-stage petrogenesis of the complex. In addition, the Sifton Range intrusive rocks exhibit modal mineralogy reflective of lower ambient pressures relative to the compositionally similar Annie Ned granites along the Alaska Highway between Stony Creek and Mendenhall, 20 km south of the complex. The amount of post-Eocene uplift (ca. 30 m/Ma) that exposed the contact between the intrusive and corresponding volcanic rocks is constrained by the presence of a calc-silicate bed at an elevation of 1830 m within the upper volcanic stratigraphy.

RÉSUMÉ

Le changement d'orientation des plaques Kula-Nord américaine, passant d'un système orthogonal à oblique, est responsable de l'épisode magmatique du début du Tertiaire dans le nord de la Cordillère canadienne. Cet épisode est associé à du volcanisme largement étendu, et les successions volcaniques préservées affleurent tout au long de la bordure Est du Domaine Côtier Plutonique (DCP). Le complexe magmatique de Sifton Range situé dans le sud-ouest du Yukon constitue le centre volcanique du groupe Sloko-Skukum du Paléogène. Les dépôts volcaniques du Sifton Range sont situés dans un hémi-graben d'orientation Nord-Ouest et forment une succession de 900 m d'épaisseur faiblement inclinée. La succession est dominée par des laves et des dépôts pyroclastiques de compositions intermédiaires à évoluées. La section volcanique est recoupée par des granites à feldspath alcalin appartenant à l'intrusion Nisling du DCP (57.5 Ma). Des sills felsiques se propagent du centre intrusif principal et, tout comme plusieurs dykes basaltiques et dacitiques, coupent les dépôts volcaniques. Les similitudes géochimiques entre la succession volcanique felsique et les granitoïdes epizonaux sont interprétées comme le résultat d'un système magmatique riche en silice remplie périodiquement. Les roches intrusives du Sifton Range sont caractérisées par une minéralogie modale indiquant de basses pression ambiantes par rapport aux granites Annie Ned de composition similaire, exposées le long de l'autoroute d'Alaska entre Stony Creek et Mendenhall à 20 km au sud du complexe. La quantité de soulèvement post-Eocène (ca 30 m/Ma) qui a exposé le contact entre les roches intrusives et les roches volcaniques associées est contrainte par la présence d'un lit de marbre à 1830 m d'altitude à l'intérieur de la stratigraphie volcanique supérieure.

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INTRODUCTION

Despite numerous studies of continental calc-alkaline volcanic sequences and subduction-related granitoid plutons, few studies have addressed the relationships between the two. This lacuna is partly a problem of exposure because where intrusive rocks outcrop, the associated volcanic suite is commonly lost to erosion, whereas preserved volcanic remnants tend to conceal their intrusive component. However, in the Sifton Ranges of the eastern Coast Plutonic Complex (CPC) of southwestern Yukon, an uplifted batholith is in direct contact with its contemporaneous volcanic equivalents, thus representing an exceptional natural setting for such an integrated study (Fig. 1). This paper reports the initial results of a study of the Sifton Range volcanic complex (SRVC), located at 61°00' N 136°10' W, 75 km northwest of Whitehorse, Yukon (Fig. 2).

Regional mapping by Kindle (1953), Tempelman-Kluit (1974) and Wheeler and McFeely (1991) had variously assigned the Sifton volcanic package to the Triassic Mush Lake Group, the compositionally similar Mount Nansen felsic volcanics, and the Upper Cretaceous Carmacks Group, respectively. Following a reconnaissance survey by D. Francis and C. Hart in 1995, the calc-alkaline character of the complex was established, and equivalence to the Sloko-Skukum volcanics was proposed.

Here we report the results of detailed geological mapping and sampling conducted within the Sifton Range complex, and along a traverse across the Annie Ned pluton that outcrops by the side of the Alaska Highway between

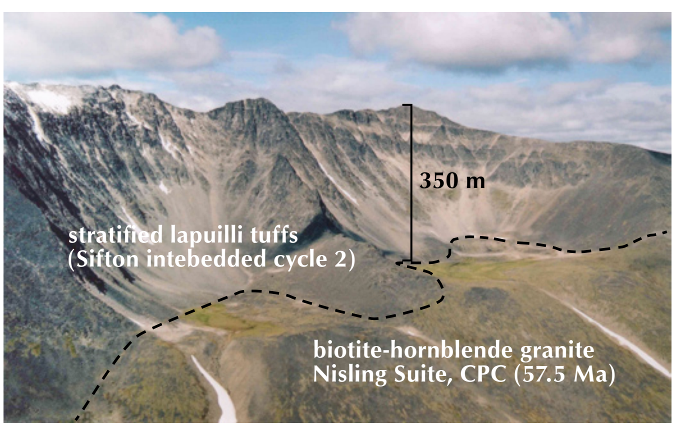


Figure 1. *Granite of the Nisling Plutonic Suite forms the base of two cirques in the western Sifton Ranges (location in Figure 2). The intruded coeval volcanic sequence consists of gently-dipping lapilli tuffs and volcanic breccias.*

Stony Creek and Mendenhall (southeastern corner of Aishihik (115H), and northeastern corner of Dezadeash (115A) map areas). The 2002 and 2003 field seasons involved documentation of volcanic stratigraphy and collection of over 150 specimens for the purpose of petrographic, geochemical and geochronological analyses.

GEOLOGICAL FRAMEWORK

With an axial length of 1800 km, the Coast Plutonic Complex (CPC) is the largest exposed continental-margin batholith in the world. It is a complex accumulation of orthogneisses, migmatites and I-type plutons intruded along the western margin of the Intermontane Superterrane during Mesozoic and early Cenozoic times (Armstrong, 1988). The final phase of widespread plutonism within the CPC of the northern Canadian Cordillera occurred during the Early Tertiary (62 to 48 Ma). This magmatic episode is linked to a change in the motion of the Kula plate relative to the North American plate, from dominantly orthogonal to oblique subduction (Engebretson et al., 1985; Gabrielse et al., 1992). Contemporaneous uplift (ca. 5 to 30 km) and erosion exposed the plutons to increasing depths westward across the CPC, and resulted in a transition from the tonalites of Skagway (Alaska) through the central granodiorites of Summit Lake and Clifton (British Columbia), into subcircular alaskites and rhyolite stocks to the east (Barker, 1986).

Simultaneously with the plutonism, volcanic activity was pervasive, and remnant volcanic sequences outcrop along the length of the western Intermontane (Fig. 2). In southern Yukon, major Eocene volcanic complexes occur at Sekulmun Lake, Mount Skukum and Bennett Lake, and are all assigned to the Skukum Group (Wheeler, 1961), while in northern British Columbia, equivalent Eocene volcanic rocks occur south of Atlin Lake and are referred to as the Sloko Group (Aitken, 1959; Figure 2). Collectively, this episode of calc-alkaline volcanism is referred to as the Sloko epoch (Hart, 1995).

SIFTON RANGE VOLCANIC COMPLEX

Together with the Miners Range to the east and the Ruby Range to the west, the Sifton Range marks a physiographic transition from the high peaks of the Coast Mountains to the flat Kluane Plateau further north. At an average elevation of 1700 m, it is an area of rugged topography with numerous cliff-faces exceeding 300 m in height. Approximately three-quarters of the outcrops are above tree line, while the lowermost stratigraphy is discontinuously exposed along stream banks and bluffs. The principal structural feature of the Sifton Range volcanic complex (SRVC) is a west-northwesterly trending half-graben that resulted in a 10 km-long, linear juxtaposition of the Early Tertiary volcanic rocks with the Paleozoic basement southwest of the complex (Fig. 3). Large-scale normal and rotational (block) faulting locally created over 100-m offsets between corresponding volcanic units. The bulk of the SRVC is underlain by green, biotite-muscovite-quartz-feldspar schists, and felsic, chlorite-biotite orthogneisses assigned to pre-400-million-year-old Nisling Assemblage of the Yukon-Tanana Terrane (Tempelman-Kluit, 1974). The Early Jurassic Aishihik Suite granodiorites, and the Late Triassic, augite-phyric Povoas basalts comprise the basement below its western and easternmost sections, respectively.

The Sifton Range complex exhibits a striking complementary relationship between its volcanic and plutonic components. The volcanic rocks span a continuum from basaltic andesite to rhyolite, with the bulk of compositions being classified as dacites (Fig. 4). A decrease in abundance of more SiO_2-rich compositions is matched by simultaneous emergence of evolved pyroclastic rocks and granitic plutonism.

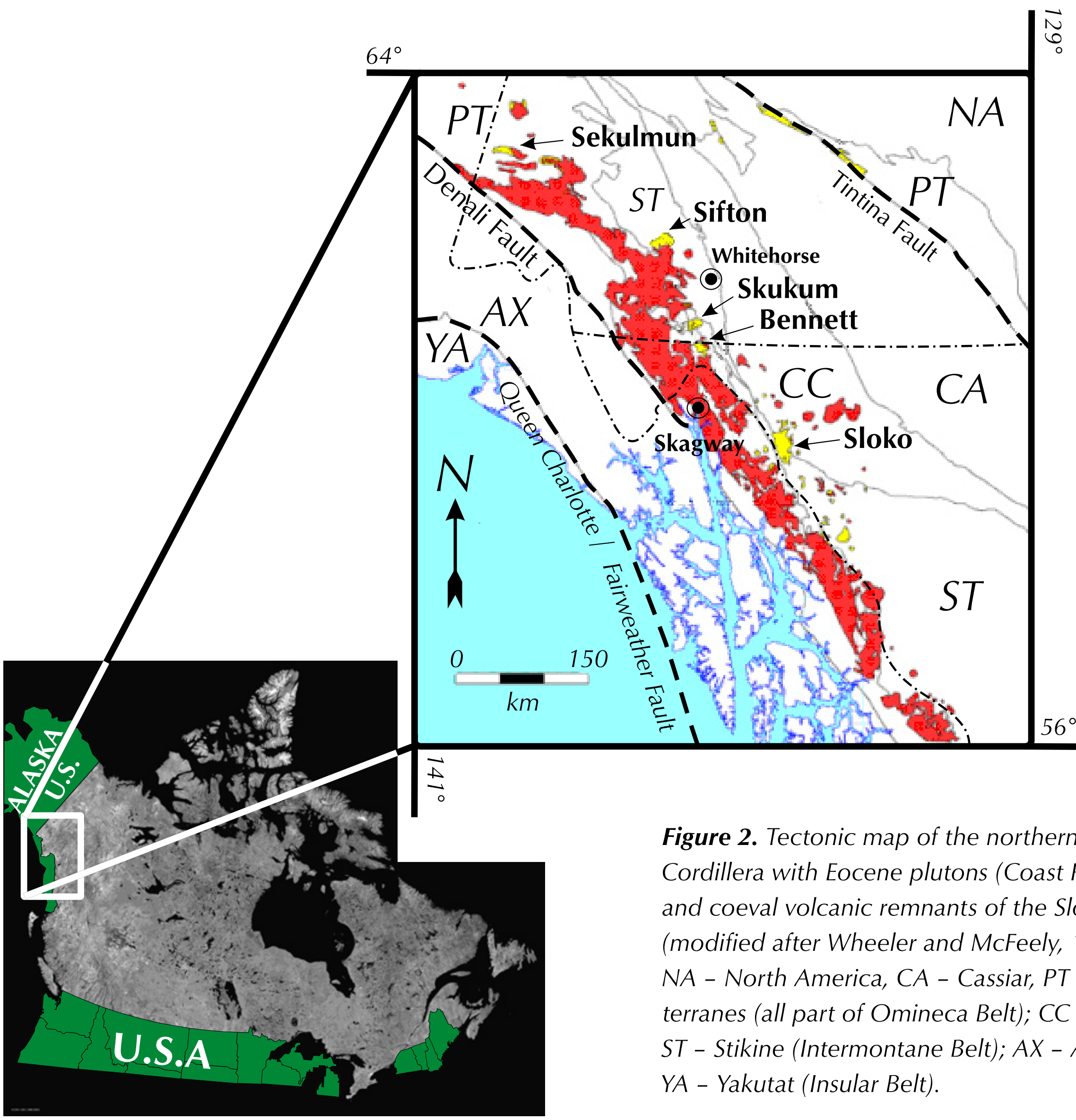


Figure 2. *Tectonic map of the northern Canadian Cordillera with Eocene plutons (Coast Plutonic Complex), and coeval volcanic remnants of the Sloko-Skukum Group (modified after Wheeler and McFeely, 1991). Terranes: NA – North America, CA – Cassiar, PT – pericratonic terranes (all part of Omineca Belt); CC – Cache Creek, ST – Stikine (Intermontane Belt); AX – Alexander and YA – Yakutat (Insular Belt).*

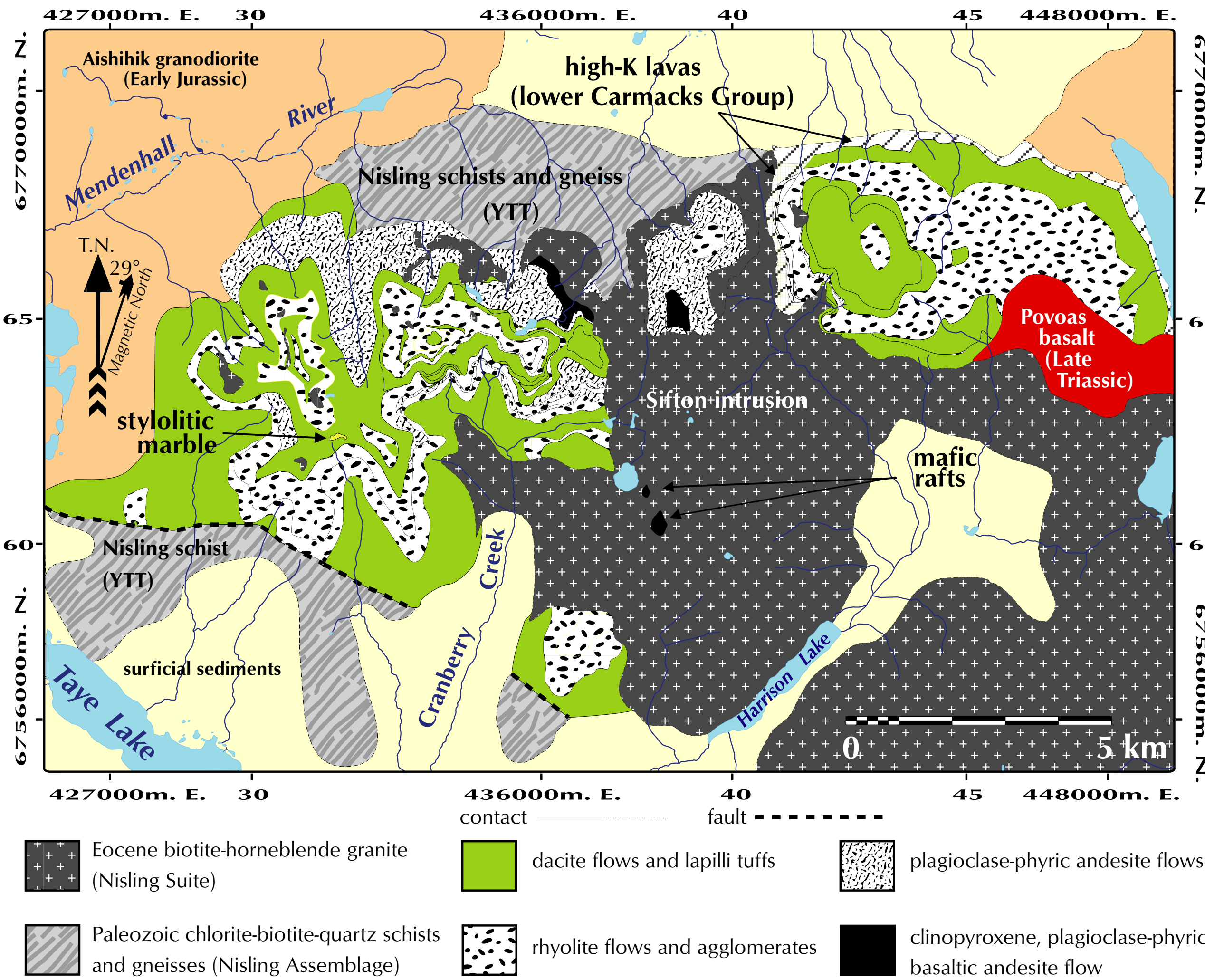


Figure 3. *Geological map of the Sifton Range volcanic complex, Yukon. The previously unrecognized shoshonitic lava rocks (lower Carmacks Group) underlie the northeastern part of the complex. Marble bed and mafic rafts exaggerated 30 times.*

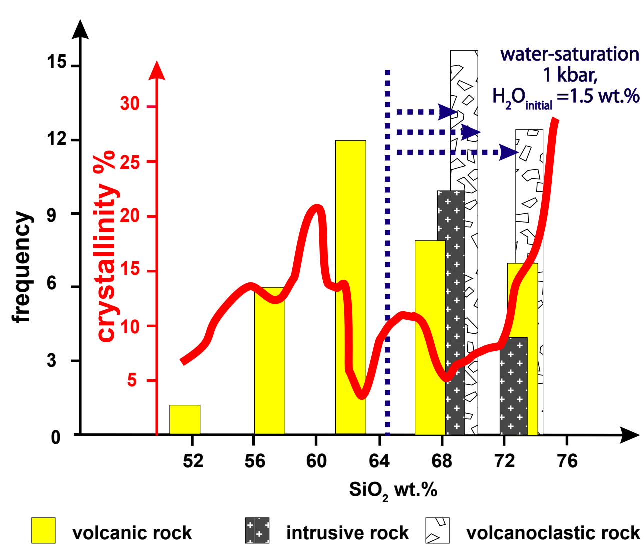


Figure 4. *Volumetric distribution of the Sifton volcanic rocks and measured lava phenocrysts as functions of the silica content. The distribution of erupted volcanic rock compositions varies as a function of magma viscosity (i.e., crystallinity), and roughly mirrors abundance of phenocrysts in the Sifton lava rocks. Fractional crystallization, modeled at the initial concentration of 1.5 wt. % and pressures of 1 kbar, predicts H_2O saturation at 65 wt. % SiO_2 – preceding the onset of rhyolitic pyroclastic rocks.*

VOLCANIC ROCKS

The Sifton lava and pyroclastic rocks comprise 40% of the Sifton complex by area (95 km^2), totaling 65 km^3 of preserved volcanic material. A central granitic plug separates the volcanic pile into larger, dominantly felsic segments to the east and west, while the relatively primitive lavas are exposed in the middle of the complex. The volcanic strata are gently inclined to the southwest (5-10°), however, the bedding attitudes change locally in the central part of the complex where the rocks dip to the northwest and northeast, away from the intruding granitoid stock. Overall, the Sifton volcanic rocks have experienced low-grade, post-depositional alteration characterized by zeolite and sub-greenschist mineralogies. Augite and hornblende phenocrysts have been replaced mostly by chlorite; plagioclase is saussuritized and partially replaced by secondary epidote, quartz and calcite. The phenocrysts and matrix mineralogies tend to be entirely obliterated along the margins of the pluton, and the rocks are locally hornfelsed.

The volcanic rocks were subdivided into lava flows, pyroclastic 'cooling units', and packages of polymictic breccias (agglomerates). Pyroclastic rocks of variable fragment size and crystallinity comprise 60% of the eruptive units. Three distinct volcanic sequences are recognized, from bottom to top: a) 1st Interbedded Unit, b) Middle Sequence, and c) 2nd Interbedded Unit (Fig. 5). The 1st Interbedded unit constitutes the lowermost 300 m of volcanic stratigraphy exposed on the southern and easternmost flanks of the complex. Due to restricted exposure, the true base of this unit is unknown. This sequence consists of thick (up to 20 m), massive, glassy, high-SiO_2 rhyolitic flows interstratified with dacitic and rhyolitic lapilli tuffs and breccias. Pyroclastic units are characterized by the following: homogeneous clast-size distributions (2 to 5 cm large lapilli fragments; volcanic bombs and breccia fragments, 10 to 20 cm in diameter), matrix-supported character, and monotonous chemical composition throughout the bed thickness. Coarser-grained volcanoclastic rocks near the base of the unit contain abundant fragments of the schist basement. A distinct sequence of high-potassium, shoshonitic lavas has been identified within the dataset in the lower part of the easterly volcanic succession (Fig. 3). These blue-weathering, exceptionally feldspar–phyric lavas may represent previously unrecognized outcrops of Lower Carmacks volcanics (Fig. 6), and as such, would contrast markedly with the less potassic character of the Carmacks-age volcanic rocks of the Miners Range just to the east.

The lavas of the Middle Sequence appear to represent a transition from explosive volcanism of the underlying 1st Interbedded cycle to more effusive volcanic activity. The sequence is 200 m thick and discontinuously exposed in the central, and the lowermost stratigraphy of the western part of the complex. It is composed of a succession of 5- to 10-m-thick, blue-weathering, sparsely plagioclase-phyric andesite flows overlain by dark grey augite- and plagioclase-phyric basaltic andesites, and the uppermost matrix-supported andesitic lapilli tuffs.

The 2nd Interbedded Unit consists of intermediate to felsic lava and pyroclastic rocks topping the volcanic column. It is the thickest stratigraphic subdivision, comprising over 550 m in stratigraphy in the western part of the complex. Overall, the unit is characterized by terraced outcrops formed by the presence of alternating resistant lava flows and recessive lapilli tuffs. The bottom 50 m of the sequence are dominated by 3- to 5-m-thick, high-SiO_2 rhyolite flows, with thin interbeds of green-weathering, epiclastic sandstone, and finely laminated ash tuffs (Fig. 7a). The overlying 150 m consists of columnar-jointed, porphyritic dacite and rhyolite flows that grade upward into dacitic volcanoclastic cooling units. The volcanoclastic rocks display lateral gradation from highly heterolithic volcanic breccias along the eastern and westernmost margins of the complex to thick lapilli tuffs, and variably welded ignimbrite sheets in the centre. Volcanic fragments spatially change from peripheral rhyolitic and andesitic volcanic bombs up to 50 cm in diameter (Fig. 7b, 7c) to central, 10-cm-long chloritized, eutaxitic fiammes, and angular lapilli fragments. In contrast to the compositionally homogeneous fragmental rocks of the 1st Interbedded Unit, the upper pyroclastic rocks exhibit zoning on a scale of individual cooling units, starting from coarse-grained, dominantly rhyolitic bottoms to matrix-dominated, dacitic tops. Thin rhyolite flows occur interstratified with breccias and lapilli tuffs within the uppermost 180 m of this sequence. A 4 m-thick, horizontal bed of white-weathering, coarsely crystalline dolomitic marble occurs 200 m below the top of the 2nd Interbedded Unit. This calc-silicate unit is characterized by prominent 1- to 3-mm-thick, sub-horizontal, wavy stylolites, anhedral dolomite crystals imbedded in calcite matrix, and the presence of sparse garnet and clinopyroxene.

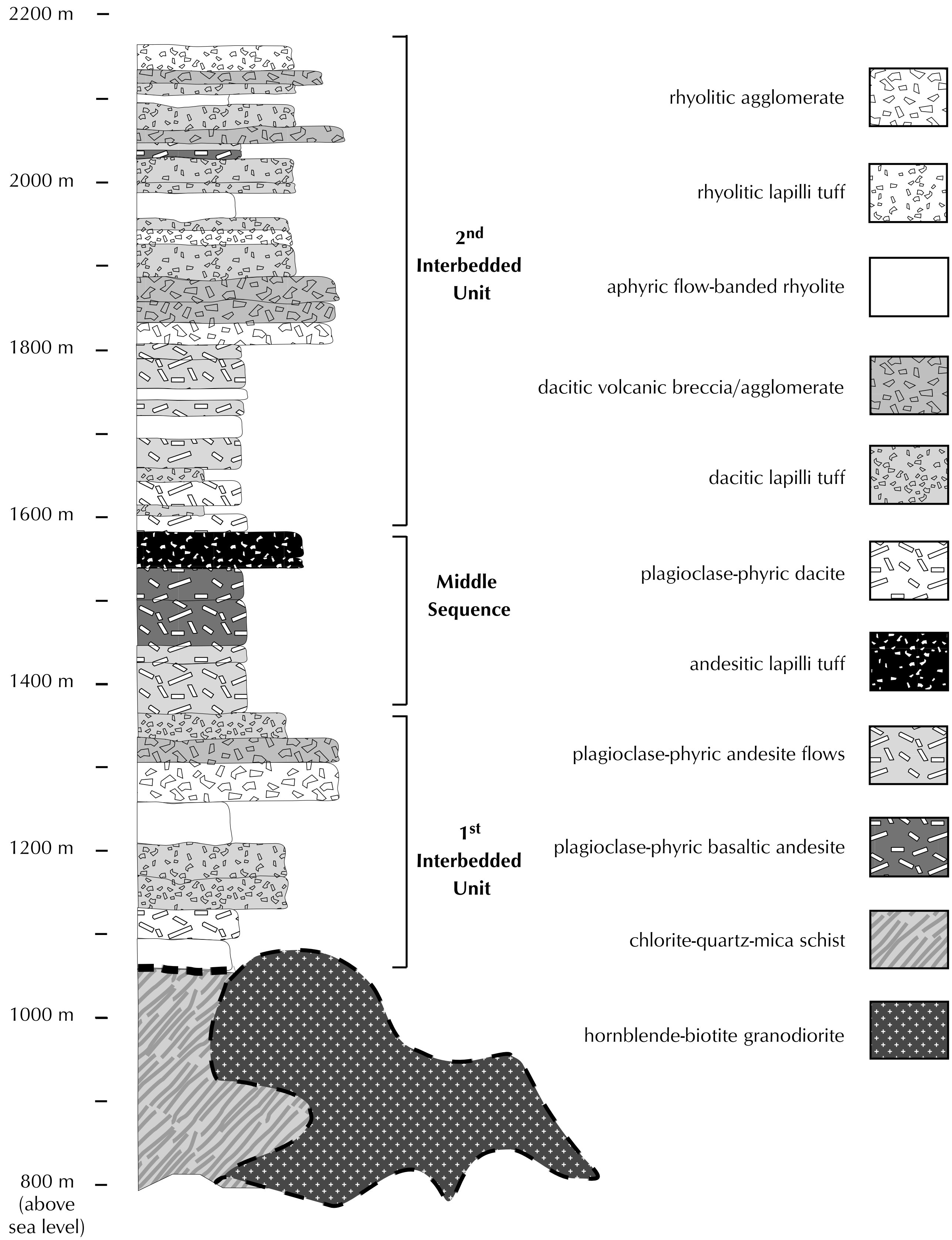


Figure 5. *Stratigraphy of the Sifton Range volcanic complex.*

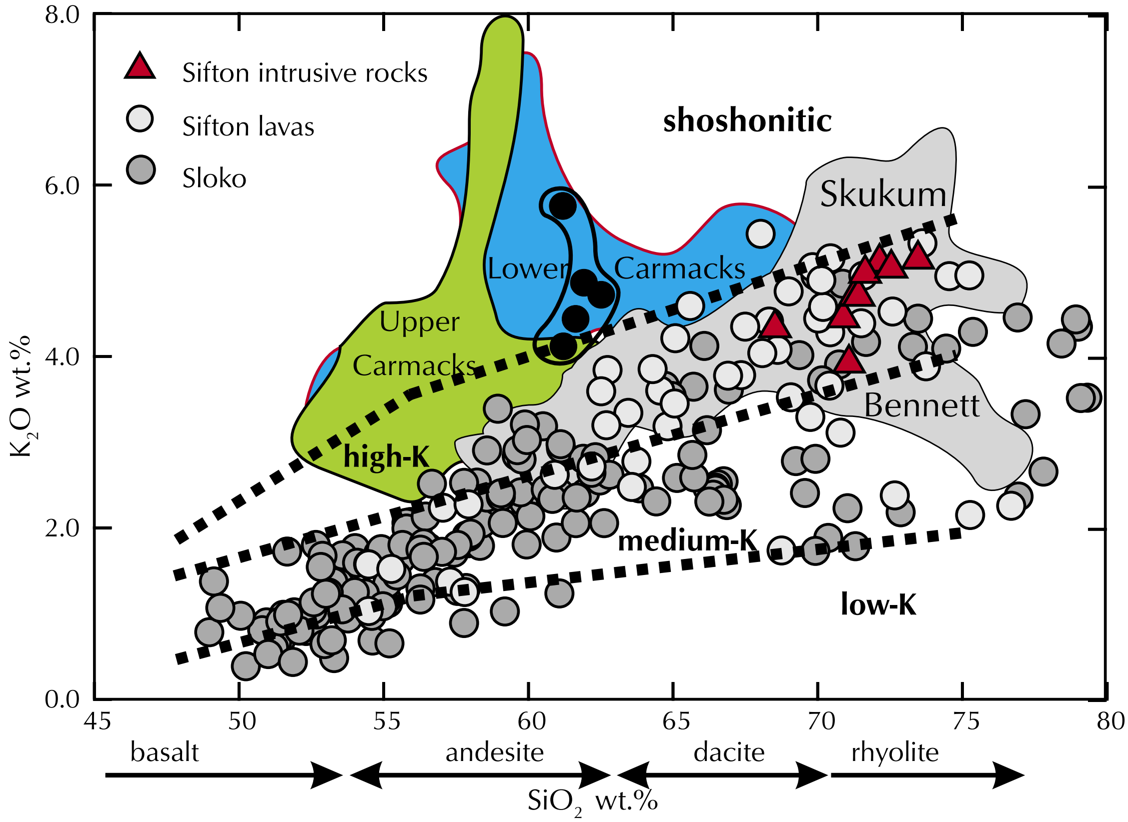


Figure 6. *The Eocene magmatism of the northern Canadian Cordillera spans all four arc volcanic rock classification series of Tatsumi and Eggins, 1995 (modified after Gill, 1981). The Sifton shoshonites (black circles) are representative of the relatively more evolved Lower rather than Upper Carmacks Group.*

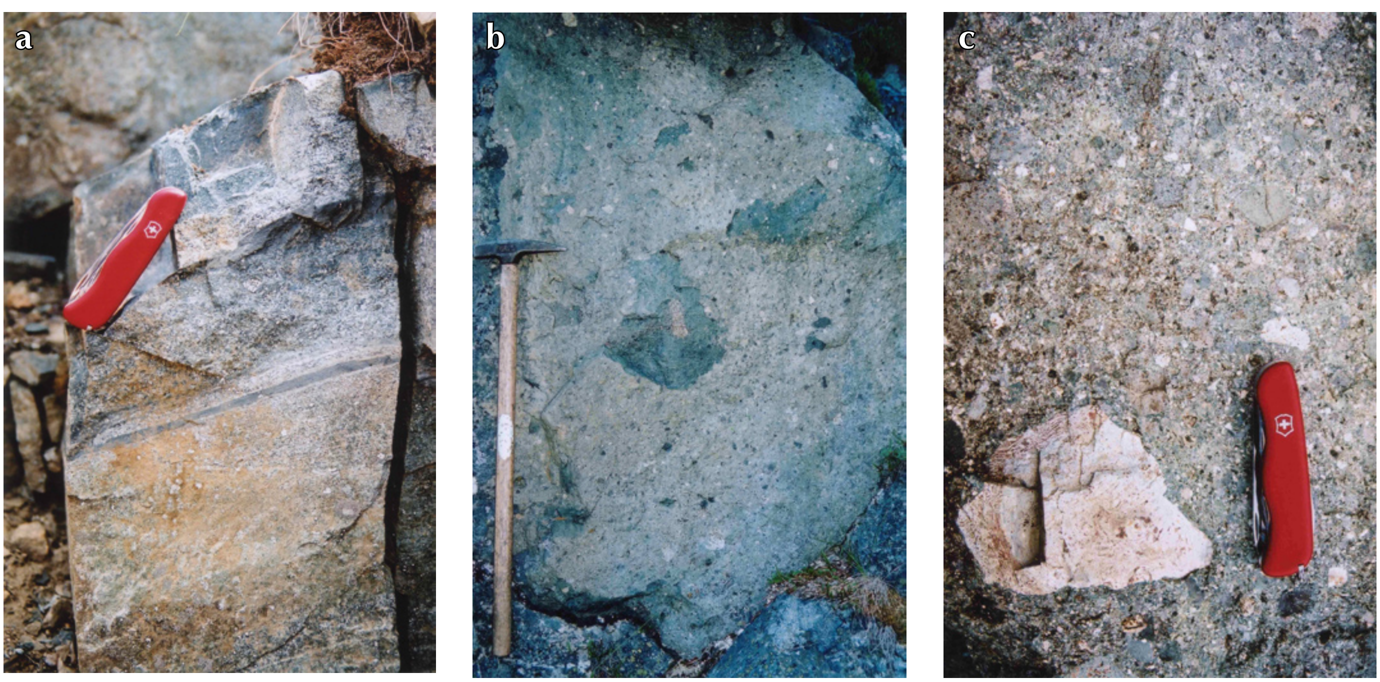


Figure 7. (a) *A 0.5-m-thick layer of finely laminated ash tuff and epiclastic rocks (base of the 2nd Interbedded cycle);* ***(b)*** *a 30-cm-long angular andesitic volcanic bomb within a dacitic agglomerate;* ***(c)*** *a 10-cm-long fragment of flow-banded rhyolite incorporated into rhyodacitic lapilli tuff matrix.*

INTRUSIVE ROCKS

The Sifton Range volcanic complex (SRVC) is cored by the monotonous, medium-grained, granite stock containing sparse alkali feldspar megacrysts, and 5 to 10% biotite and hornblende by mode. The granite is characterized by two compositionally distinct feldspars (An_{36-50} and Or_{77-79}) exhibiting minor exsolution textures. The pluton is massive, lacking the structural fabric common in older (Mesozoic) intrusive rocks of the CPC (Rusmore, 1991). A sample collected from the centre of the complex, 300 m below the contact with the SRVC yielded a U-Pb (zircon) age of 57.5 ± 0.2 Ma (J.K. Mortensen, pers. comm., 2003). Two isolated, subangular mafic rafts, 3 and 8 m in diameter are found incorporated within the granitic stock (Fig. 3). These mafic enclaves are composed almost entirely of coarse-grained hornblende with traces of interstitial magnetite and pyrrhotite.

Dykes and sills are widespread throughout the SRVC, and exhibit a dominantly bimodal character. Clinopyroxene- and plagioclase-bearing mafic dykes, 1 to 3 m in thickness indiscriminately intersect the volcanic units, but are conspicuously absent in the underlying granite. Felsic dykes tend to be associated with epizonal granites, and a dense pattern of quartz- and feldspar-porphyritic rhyolite dykes radiates from the shallow intrusion in the western section of the complex.

The Sifton intrusive rocks locally mark the northernmost extent of the Early Tertiary Nisling Range Plutonic Suite — a northwest-trending Coast Plutonic Complex batholith that extends for 230 km from Whitehorse to the northern limit of Kluane Lake. In order to supplement the Sifton granite, and compare proximal, yet different plutonic phases, we conducted systematic sampling of the Nisling intrusive rocks along the Alaska Highway between Stony Creek (UTM: E447212, N6741594) and Mendenhall (UTM: E450592, N6744473, Zone: 8, NAD 27), 20 km south of the Sifton Range. This section of the Nisling Plutonic Suite is referred to as the Annie Ned pluton, and exhibits a composite, multiphase emplacement history (Hart, 1997). Early biotite quartz monzonites and diorites are intermingled with late leucocratic biotite granites and granodiorites. The plutonic rocks are commonly cut by north-trending basaltic and andesitic dykes up to 5 m in thickness. Numerous late-stage aplite dykes and localized clusters of coarsely crystalline gabbroic enclaves are also present.

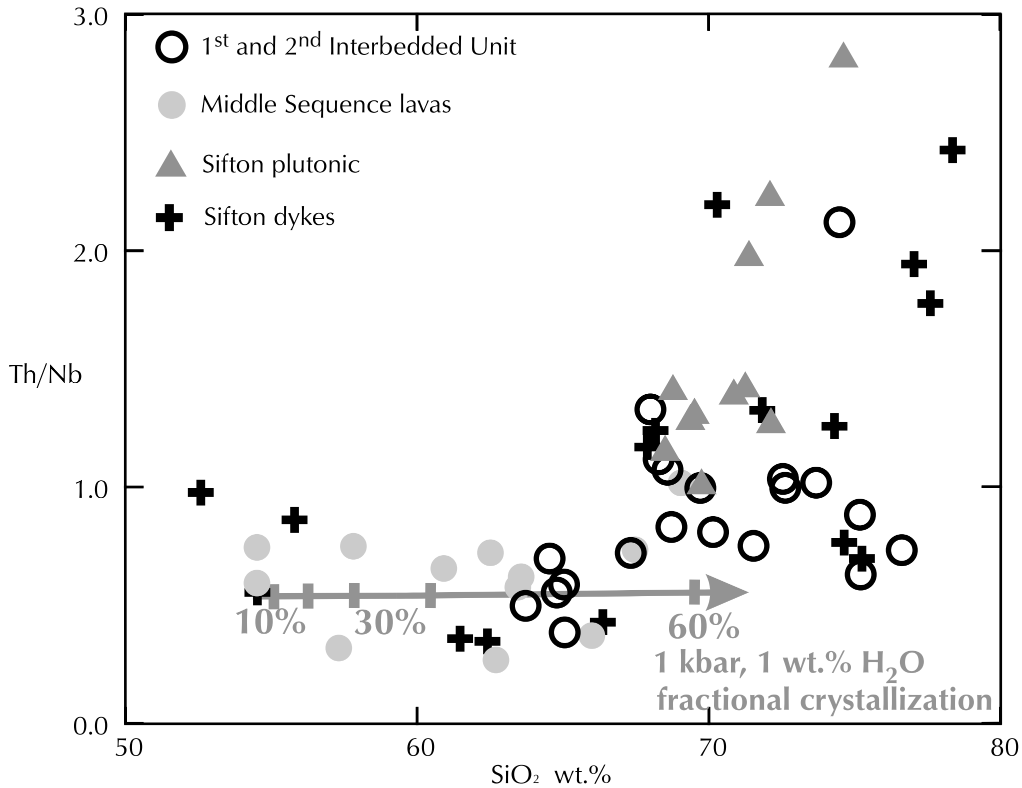
GEOCHEMISTRY

The Sifton volcanic suite exhibits a predominantly high-K, calc-alkaline fractionation trend (Fig. 6). The SRVC displays trace-element patterns characteristic of subduction-zone magmatism. The rocks are depleted in high field strength elements (HFSE: Ti, P and Nb), prominently enriched in thorium and uranium (Th, U) and the large ion lithophile elements potassium, rubidium and barium (LILE: K, Rb and Ba), with positive lead anomalies relative to the primitive mantle composition. The evolution of the relatively primitive Sifton lavas (< 66 wt. % SiO_2) can be modeled by a two-step fractional crystallization of plagioclase + clinopyroxene + orthopyroxene + iron-titanium (Fe-Ti) oxides at upper crustal (1 kbar), damp (1.5 wt. % H_2O) conditions. The more evolved volcanic rocks (SiO_2 >66 wt. %) and corresponding intrusive rocks are characterized by an anomalous rise in highly incompatible LILE (Ba, K), and HFSE (Th, Nb) that cannot be accounted for by up to 60 wt. % crystallization of a basaltic precursor (Fig. 8).

Although similar in terms of the major and trace-element chemistry (e.g., SiO_2 = 69-74 wt. %, LILE enrichment, moderate europium (Eu) anomalies), the Sifton rhyolites cluster near the low-pressure, water-saturated minimum of Tuttle and Bowen (1958), whereas the Sifton plutonic rocks are clearly two-feldspar (subsolvus) granites, requiring a minimum of 2.5 kbar of partial H_2O pressure. This pressure discrepancy may reflect different depths of crystal fractionation and/or different water contents.

Compared to the Annie Ned granitoids along the Alaska Highway, the Sifton Range granite is relatively enriched in the incompatible HFS elements (Th, Nb), and exhibits normative proportions of quartz, albite and orthoclase (Table 1) that reflect lower ambient pressures of ca. 3.0 kbars. The elevated rubidium-strontium (Rb-Sr) ratios with decreasing Ba concentrations of the Sifton plutonic rocks as compared to the Annie Ned granitoids can be explained by fractionation of potassium feldspar — a megacrystic phase readily observed in the Sifton Range. However, neither of the two plutonic localities exhibit trace-element (Ba, Sr, Rb) trends that are compatible with the extensive, late-stage fractional crystallization of the quartz-plagioclase-orthoclase assemblage — a trend clearly observed in the Early Tertiary alaskites of the Yukon Crystalline Terrane (Lynch et al., 1983).

Figure 8. *HFSE-SiO_2 plot displaying anomalous increase in Th relative to the equivalently incompatible high field strength element Nb for the SRVC rhyodacites, rhyolites and granites. Arrow indicates modeled HFSE ratios after 60 % fractionation by weight of a basaltic precursor (MgO = 6.62 wt. %) under closed-system conditions.*



INTERPRETATION

Extension by large-scale, normal (block) faulting appears to have imposed the primary structural control on deposition and preservation of the Sifton Range volcanic complex (SRVC). The linear juxtaposition of the southwest-dipping volcanic sequence with the Paleozoic basement rocks, and the dominant attitude of dykes (north-northwest) are complementary with the principal stress directions of a northwest-southeast transtensional regime. Local variability in dip attitudes, especially in the central part of the complex, is attributed to the post-depositional modification related to both, the Nisling Suite plutonism and prominent block faulting. The extent of erosion within the complex can be constrained by inspection of pressure-dissolution features found within the marble bed near the top of the 2nd Interbedded Unit (Fig. 3). If attributed solely to lithostatic pressure, the thickness of stylolites (1 to 3 mm) indicates a minimum of 600 m of overburden (Eric Mountjoy, pers. comm., 2003), and therefore at least 400 m of missing volcanic stratigraphy. Furthermore, if the marble unit was formed in a marine environment, its current position at 1830 m suggests a rate of apparent uplift along the northeastern margins of the Coast Plutonic Complex (CPC) of approximately 32 m/Ma since the Eocene.

Compared to the coeval evolved volcanism of the Mt. Skukum and Bennett Lake complexes on the one hand, and relatively primitive volcanic rocks of the Sloko Lake on the other, the SRVC constitutes a compositionally intermediate volcanic suite. The Sifton volcanic rocks cross boundaries between orogenic magma series defined on the basis of K_2O content (Fig. 6), and exhibit anomalous enrichment in the incompatible elements (Th, Rb, K), indicating an open-system petrogenesis. Compositional stratification and transition between effusive and explosive units of the SRVC are interpreted in terms of a dynamic interaction between a shallow (ca. 3 km) magma chamber undergoing fractional crystallization with increasing water content, and a granitoid crustal component. According to this scenario, the evolution of the Sifton volcanism commenced by initial eruption of crustally derived, LILE-enriched, high-SiO_2 rhyolites and pyroclastic rocks of the 1st Interbedded Unit, followed by effusive eruption of the Middle Sequence (basaltic) andesite and andesite lavas tapping deeper portions of the magma chamber. Continuing crystal fractionation and assimilation within the magma

Table 1a. *XRF, LA-ICP-MS[1] analyses and normative mineralogies for representative diorites, quartz monzonites and granites of the Annie Ned pluton (Nisling Plutonic Suite); major elements and normative phases shown in wt. % , trace elements in ppm.*

Locality: Alaska Highway transect (Annie Ned pluton - Nisling Plutonic Suite)							
Major elements (wt. %)							
Sample	SF-21	SF-29	SF-32	SF-33	SF-35	SF-44	SF-49
SiO_2	69.87	68.67	68.52	68.63	67.97	73.89	71.69
TiO_2	0.24	0.26	0.32	0.25	0.35	0.25	0.29
Al_2O_3	15.49	15.96	16.01	16.44	16.25	13.6	14.47
Fe_2O_3	3.08	3.15	2.81	2.31	3.1	1.86	2.28
MnO	0.06	0.09	0.1	0.07	0.09	0.04	0.04
MgO	0.05	0.04	0.77	0.19	0.77	0.34	0.41
CaO	1.54	1.78	2.69	2.47	2.67	1.49	1.79
Na_2O	5.06	5.39	4.57	4.53	4.48	3.44	3.53
K_2O	3.95	4.27	3.56	4.2	3.89	4.54	4.59
P_2O_5	0.05	0.05	0.12	0.1	0.14	0.06	0.08
LOI	0.2	0.26	0.37	0.52	0.37	0.27	0.25
Total	99.59	99.92	99.84	99.71	100.08	99.78	99.42
Trace elements (ppm)							
Rb	77	94	121	122	118	87	80
Zr	337	307	144	132	150	172	208
V	6	5	31	22	36	8	15
Co	3	7	13	9	6	6	7
Pb	16	18	15	15	13	17	17
Zn	27	60	27	3	12	3	0
Nb	0	6	10	9	10	4	1
Sr	216	222	316	335	339	344	487
Ba	3352	3590	1285	1711	1779	3471	5971
Ni	1	1	1	3	1	5	3
Cu	10	9	25	4	7	8	8
Cr	17	20	10	8	14	16	14
Ga	20	20	17	15	16	15	15
Y	20	28	21	19	21	12	10
Th	8	8	14	9	14	12	11
U	5	5	5	5	5	5	4
Normative mineralogy (phase wt. %)							
quartz	20.44	15.97	20.47	19.81	19.00	31.96	27.98
orthoclase	23.48	25.32	21.17	25.03	23.08	26.93	27.30
albite	43.09	45.78	38.92	38.68	38.08	29.23	30.08
anorthite	7.94	6.77	12.74	12.16	12.79	7.85	9.79
clinopyroxene	0.16	2.28	0.23	0.00	0.05	0.00	0.00
orthopyroxene	3.34	2.29	4.74	2.89	5.09	2.67	3.28
magnetite	0.90	0.92	0.82	0.68	0.91	0.54	0.67
ilmenite	0.46	0.50	0.61	0.48	0.67	0.48	0.56
apatite	0.11	0.11	0.26	0.22	0.31	0.13	0.18
zircon	0.07	0.06	0.03	0.03	0.03	0.03	0.04

[1]LA-ICP-MS: laser-ablation induced coupled plasma spectrometry

Table 1b. *XRF, LA-ICP-MS analyses and normative mineralogies for representative granites of the Sifton Range intrusion (Nisling Plutonic Suite); major elements and normative phases shown in wt. % , trace elements in ppm.*

Locality: Sifton Range Intrusion (Nisling Plutonic Suite)								
Major elements (wt. %)								
Sample	SF-60	SF-61	SF-62	SF-63	SF-64	SF-98	SF-116	SF-265
SiO_2	69.74	69.85	70.64	70.51	69.72	69.79	66.11	69.70
TiO_2	0.36	0.36	0.34	0.30	0.36	0.39	0.48	0.30
Al_2O_3	14.57	14.60	14.39	14.63	14.54	15.01	15.43	15.27
Fe_2O_3	2.60	2.64	2.37	2.30	2.53	2.66	3.21	2.69
MnO	0.12	0.08	0.06	0.11	0.07	0.11	0.09	0.09
MgO	0.71	0.71	0.64	0.08	0.64	0.66	0.93	0.72
CaO	1.74	1.68	1.41	1.00	1.57	1.96	2.21	2.42
Na_2O	4.03	3.93	3.71	4.42	3.63	4.13	4.48	4.04
K_2O	4.63	4.62	5.02	4.96	4.86	4.40	4.20	3.86
P_2O_5	0.10	0.10	0.09	0.08	0.10	0.13	0.17	0.11
LOI	1.38	1.13	1.17	1.19	1.57	0.60	2.60	0.47
Total	99.98	99.70	99.84	99.58	99.59	99.84	99.91	99.66
Trace elements (ppm)								
Rb	129	149	169	139	168	154	119	131
Zr	223	225	215	244	239	206	223	138
V	27	35	32	22	32	29	38	34
Co	4	8	3	2	10	3	5	5
Pb	16	16	16	10	16	16	14	16
Zn	37	27	13	29	10	17	28	0
Nb	11	9	9	10	7	9	9	8
Sr	213	230	242	175	271	299	337	297
Ba	2299	2370	2227	2722	2737	2183	2213	1356
Ni	13	3	4	2	3	1	0	7
Cu	44	5	9	9	10	7	27	0
Cr	15	21	19	9	21	11	19	23
Ga	17	17	17	16	16	16	17	16
Y	28	25	23	31	25	23	24	18
Th	15	17	20	13	23	12	11	13
U	5	5	5	5	5	5	5	5
Normative mineralogy (phase wt. %)								
quartz	23.10	23.87	25.22	22.82	25.09	22.87	17.36	24.30
orthoclase	27.76	27.70	30.06	29.79	29.30	26.21	25.53	23.01
albite	34.61	33.76	31.83	38.02	31.35	35.24	39.01	34.50
anorthite	8.11	8.36	7.03	5.13	7.94	9.49	9.86	11.77
clinopyroxene	0.45	0.00	0.00	0.00	0.00	0.00	0.70	0.00
orthopyroxene	4.24	4.44	3.94	2.61	4.14	4.32	5.19	4.62
magnetite	0.77	0.78	0.70	0.68	0.75	0.78	0.96	0.79
ilmenite	0.70	0.70	0.66	0.58	0.70	0.75	0.95	0.57
apatite	0.22	0.22	0.20	0.18	0.22	0.29	0.39	0.24
zircon	0.05	0.05	0.04	0.05	0.05	0.04	0.05	0.03

chamber resulted in appearance of siliceous, water-saturated melts that gave rise to the second cycle of explosive activity. Each eruptive episode began explosively with deposition of pyroclastic material (agglomerates and tuffs), and concluded with effusive outpouring of progressively more primitive lavas — a process that resulted in the localized 'inverse' zoning presumably reflecting the compsitional stratification of the magma reservoir.

The gradation from pyroclastic deposits through aphyric felsite into fine-grained, and finally medium-grained intrusive rocks described by Souther (1971) suggests a cogenetic relationship between the Early Tertiary volcanism and plutonism of the northern Canadian Cordillera. We interpret the Sifton Range plutonism as being linked to the increase in crystallinity of a magmatic 'mush' present in the shallow magma chamber, and ultimately related to rheological thresholds imposed by the build-up and subsequent release of magmatic water (i.e., degassing). Elevated water concentrations suppressed the rapid onset of plagioclase crystallization (Spulber et al., 1983), and postponed attainment of critical crystallinity until the magma reached the composition of dacite. At this point, the simultaneous saturation in water and appearance of exsolved gas bubbles resulted in elevated magma viscosities (Manga et al., 1998) ultimately leading to ponding of high-SiO_2 melt as granitic plutonism, or explosive eruption of pyroclastics rather than flows.

Similar to the overlying felsic volcanic rocks, the Sifton granites display enrichments of incompatible elements (Ba, Rb and Th) relative to HFSE (Nb, Zr, Ti) that cannot be entirely explained by closed-system crystal fractionation, and require a contribution of crustally derived magmas (Fig. 8). However, the low Sr-isotopic signature of the Eocene Nisling Plutonic Suite ($0.7045 < (^{87}Sr/^{86}Sr)i < 0.705$; Hart, 1995) suggests that the crustal components involved in the genesis of the Sifton granite were also isotopically juvenile. This excludes a possibility of any large-scale anatexis of the Precambrian schist basement, which by late Mesozoic time mostly exceeded $(^{87}Sr/^{86}Sr)i$ of 0.710 (Barker et al., 1986).

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