

THE ORIGIN AND SETTING OF ANOMALOUS ARC MAGMATISM IN THE WRANGELL VOLCANIC BELT, SOUTHWEST YUKON

Thomas Skulski
Department of Geological Sciences,
McGill University
3450 University Street,
Montreal Quebec
H3A 2A7

SKULSKI, T., 1988. The origin and setting of anomalous arc magmatism in the Wrangell volcanic belt, southwest Yukon; in *Yukon Geology*, Vol. 2; Exploration and Geological Services Division, Yukon, Indian and Northern Affairs, Canada, p. 88 - 89

ABSTRACT

In the Wrangell Volcanic Belt (WVB) a northwesterly increase in volume of calc-alkaline versus transitional (sodic alkaline/calc-alkaline) magmatism is accompanied by a migration in the locus of magmatic activity. The space-time-composition relationships reflect oblique convergence between the North American and Pacific plates over the last 17.3 million years. Compositional-temporal trends are particularly well preserved in the four stages of volcanic stratigraphy in the St. Clare Creek field (17.3 - 6.5 Ma). Initially, alkaline olivine basalts, hawaiites and mugearites were erupted from small, isolated shield volcanoes in the axis of a continental molasse basin. The alkaline lavas were followed by an early stratovolcano stage of transitional trachybasalts and high-Fe basaltic trachyandesites, succeeded by basaltic trachyandesites, trachyandesites, trachytes, rhyolites and rare basaltic andesites. Widespread basaltic fissure eruptions dominated the third volcanic stage. The late stratovolcano stage consisted of renewed eruption of intermediate and felsic transitional lavas.

A systematic temporal-chemical relationship between early alkaline and younger transitional and calc-alkaline lavas in the St. Clare Group is illustrated by a decrease in FeO/MgO, Na+K/Si, Nb/Zr and Zr/Y, and an increase in Rb/Zr with increasing stratigraphic levels. Primitive basalts are non-primary and show variable degrees of fractionation between large ion lithophile (LILE) and high field strength element abundances.

A model is proposed in which the alkaline shield volcano and early stratovolcano stage magmas formed by progressive melting of a rising mantle diapir in response to local extension along the Duke River fault. Early Fe-rich magmas may have undergone clinopyroxene fractionation at high pressures, but most magmas appear to have differentiated in the near surface environment via fractional crystallization and local magma mixing. With the onset of Yakutat subduction, progressively larger amounts of slab-derived, LILE-enriched fluids metasomatised overlying peridotite, which in turn melted to form primitive, late-stratovolcano stage magmas.

RÉSUMÉ

Dans la zone volcanique de Wrangell (WVB), une augmentation, dans le sens nord-ouest, du volume de roches magmatiques calco-alkalines comparativement aux roches magmatiques transitionnelles (alkalines sodiques/calco-alkalines) a été accompagnée d'une migration du foyer d'activité magmatique. Les relations espace-temps-composition reflètent une convergence oblique des plaques nord-américaine et pacifique au cours des derniers 17,3 millions d'années. Les tendances du couple composition-temps sont particulièrement bien conservées dans les quatre étages stratigraphiques volcaniques du champ de St. Clare Creek (17,3-6,5 Ma). Initialement, des basaltes alcalins à olivine, des hawaiïtes et des mugéarites ont été émis au cours d'éruptions par de petits volcans isolés en bouclier dans l'axe d'un bassin molassique continental. Le dépôt des laves alcalines a été suivi d'une phase initiale d'émission par des stratovolcans, de trachybasaltes transitionnels et de trachyandésites basaltiques riches en Fe, auxquels ont succédé des trachyandésites basaltiques, des trachyandésites, des trachytes, des rhyolites et rarement, des andésites basaltiques. Des éruptions fissurales basaltiques étendues ont dominé la troisième phase volcanique. La phase stratovolcanique tardive s'est traduite par de nouvelles éruptions de laves transitionnelles, de caractère intermédiaire et felsique.

Dans le groupe de St. Clare, la relation systématique temps-composition chimique, qui existe entre les laves alcalines initiales et les laves plus récentes de caractère transitionnel et calco-alkalin, s'est traduite par une diminution des rapports FeO/MgO, Na + K/Si, Nb/Zr et Zr/Y et par une augmentation du rapport Rb/Zr à mesure que l'on remonte les niveaux stratigraphiques. Les basaltes primitifs sont non primaires, et montrent divers degrés de fractionnement entre les abondances des éléments lithophiles à ions de grande taille (LILE) et celles des éléments sidérophiles.

On propose un modèle dans lequel les magmas alcalins de volcans en bouclier et les magmas initiaux de l'étape stratovolcanique, se sont formés par fusion progressive d'un diapir ascendant du manteau, en réponse à une expansion locale de la croûte, le long de la faille de Duke River. Dans les magmas initiaux riches en Fe, a peut-être eu lieu une cristallisation fractionnée des clinopyroxènes sous des pressions élevées, mais il semble que la plupart des magmas se soient différenciés à proximité de la surface, par cristallisation fractionnée et mélange localisé des magmas. Avec le démarrage des processus de subduction de Yakutat, des quantités progressivement plus importantes de fluides dérivés de tranches de terrain et enrichis en éléments lithophiles, ont métasomatisé la péridotite sus-jacente, qui à son tour a fondu et formé des magmas primitifs d'étape strato-volcanique tardive.

INTRODUCTION

Magmas with sodic-alkaline affinity are a minor component of arc volcanism and are usually associated with specific Neogene tectonic settings. Examples of these settings include: lateral terminations of subduction zones undergoing hinge-faulting (e.g. Grenada, Lesser Antilles, DeLong et al., 1975); areas of subduction of fracture zones or other major linear features (e.g. Kanaga, Aleutians, DeLong et al., 1975) and intra-arc rifts (e.g. Penguin Island, South Shetlands, Weaver et al., 1979). Transitional magmas in these tectonic environments have been interpreted as mixtures of calc-alkaline (subduction-related) and sodic-alkaline (intra-plate) components (Pearce, 1982). However, such interpretation can be problematic since arc-terminating transform faults can be the sites of calc-alkaline, shoshonitic, boninitic or sodic-alkaline volcanism (Gill, 1982). Transitional magmatism may also postdate subduction by incorporating partial melts of peridotite metasomatised during a previous event (e.g., northern Azerbaijan, northwestern Iran, Riou et al., 1981).

The late Cenozoic Wrangell Volcanic Belt (WVB) in the northwestern Canadian Cordillera is an ideal study area for anomalous arc magmatism. The WVB occupies an area where late Cenozoic oblique convergence between the northeastern Pacific and North American plates has been accommodated both by transform fault movement and subduction of the Pacific plate beneath the North American continent. This study documents the occurrence and petrogenesis of sodic-alkaline, transitional and calc-alkaline volcanic rocks in the St. Clare Creek area of the WVB. A formal stratigraphy is proposed, and field, petrographic and chemical relationships are used to elucidate the volcanic and tectono-magmatic history of the lavas.

TECTONIC SETTING AND THE NATURE OF MAGMATISM WITHIN THE WVB

The 440 km long Wrangell Volcanic Belt includes a diverse group of volcanic rocks up to 2500 m thick, that range in age from 17.3 Ma to present. The Wrangell Volcanic Belt outcrops through parts of the Kluane and Icefield Ranges of the St. Elias Mountains in northwestern British Columbia and south-western Yukon, and Wrangell Mountains in southeastern Alaska (Fig. 1). In Alaska the WVB comprises mid-Tertiary to Recent Wrangell Lavas. These include mainly shield volcanoes covering older Tertiary lavas (Mendenhall, 1905; MacKevett, 1970; Deiniger, 1972; MacKevett, 1978; Richter et al., 1976; Richter et al., 1979) and Nye, 1983). Recent studies in the St. Elias Mountains (Souther and Stanciu, 1975; Skulski and Francis, 1986) extend the usage of the term "Wrangell Lava" (Mendenhall, 1905) to include all volcanic rocks in the WVB. The term "St. Clare Group" (Miller, 1967) is used in, and redefined by the present study. The St. Clare Group is mid to late Tertiary and comprises outliers along the Duke River Fault (DRF, Fig. 1).

The volcanic rocks in the St. Clare Group are chemically classified in this study on the basis of total alkali/silica ratios using the TAS diagram of Le Bas et al (1986). The rocks are grouped by petrographic and chemical characteristics into four magma types. The calc-alkaline type plots in the subalkaline field and has nearly constant Fe/Mg ratios and modal orthopyroxene. Transitional magmas (sodic alkaline/calc-alkaline) lie within the alkaline field, are hypersthene- and rarely nepheline-normative, show moderate Fe-enrichment, and contain modal olivine over a wide range in silica content. Alkaline magmas lie within the alkaline field contain normative nepheline and shows significant Fe-enrichment. The high-Fe transitional magma type is hypersthene- and rarely nepheline-normative and is characterized by high Ti, Fe, Na, K, P and incompatible trace elements abundances over a narrow range of silica contents.

On the basis of stratigraphy, structure (Souther and Stanciu, 1975), chemical composition and petrography, the St. Clare Group includes four distinctive volcanic fields; from southeast to northwest, the Stanley Creek, Lava Creek, Nines and St. Clare Creek fields (Fig. 1). The Nines and Stanley Creek fields are composed of transitional volcanic rocks. The St. Clare Creek field contains dominantly transitional volcanic rocks with minor calc-alkaline and sodic-alkaline

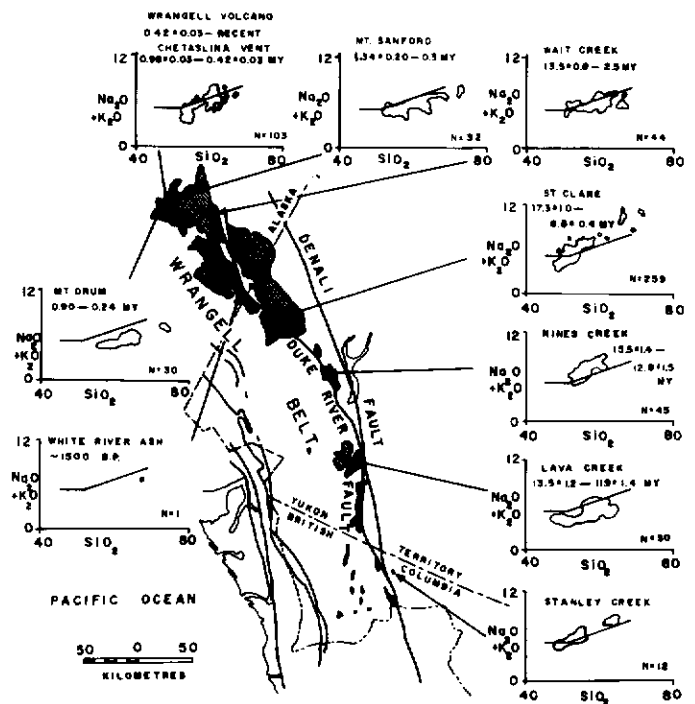


Figure 1. Outline of the Wrangell Volcanic Belt showing total alkali versus silica (TAS, wt%) variations for the various volcanic fields. Individual volcanoes are denoted by filled circles, the ruled pattern presents lavas and the black pattern sedimentary rocks. Chemical and K-Ar age data are from the following sources: Stanley, Lava, Nines and St. Clare areas, this study, Francis and Ludden unpublished, and Souther and Armstrong, writ. comm. (1987); Wait Creek area, Deiniger (1972); Mt. Sanford area, Richter and Smith (1976); Wrangell area, Nye (1983); Mt. Drum area, Richter et al. (1979); White River Ash, Lerbekmo (1969). The dividing line on the TAS diagram separates alkaline from subalkaline compositions (LeBas et al., 1986). Chemical analyses in this study were obtained by X-ray fluorescence spectrometry of whole rock samples. For further details on methodology, accuracy and precision see Eiche et al. (1987).

lavas. The Lava Creek field is composed of calc-alkaline volcanic rocks with lesser transitional and sodic-alkaline lavas. Post-volcanic deformation in the Stanley, Lava and Nines Creek fields is restricted to minor faulting and tilting. In the St. Clare Creek field, folding and faulting are intense in the central part of the field, which overlies the DRF (Souther and Stanciu, 1975 and Skulski and Francis, 1986). The volume and thickness of the St. Clare Group increases from the Stanley Creek field in the southeast to the St. Clare Creek field in the northwest. The ages of the youngest St. Clare Group rocks decrease from the Lava Creek field (11.9 +/- 1.4 Ma), through the Nines (12.8 +/- 1.5 Ma) and St. Clare Creek fields (6.5 +/- 0.4 Ma, minimum age) to the Recent Wrangell Lavas in Alaska (Souther and Armstrong writ. comm., 1987).

Prior to the onset of St. Clare Group volcanism (17.3 Ma in the St. Clare Creek field, Souther and Armstrong, writ. comm., 1987), continental molasse sediments of the Amphitheatre Formation were deposited in northwest-trending, fault-controlled, fluvial basins such as those along the DRF (Eisbacher and Hopkins, 1977). This dextral strike-slip fault juxtaposed Paleozoic rocks of the Alexander terrane in the south, against Permo-Triassic rocks of the Wrangellia terrane in the north during Late Mesozoic time (Campbell and Dodds, 1978). Displacement along the DRF continued into the early phases of St. Clare Group volcanism (Souther and Stanciu, 1975). The Cenozoic tectonic stress orientation in the southwest Yukon is dominated by north-trending principal, and east-trending minor stress axes (Eisbacher and Hopkins, 1977). This stress regime is consistent with the northerly strikes and steep dips (75°) of mafic dykes,

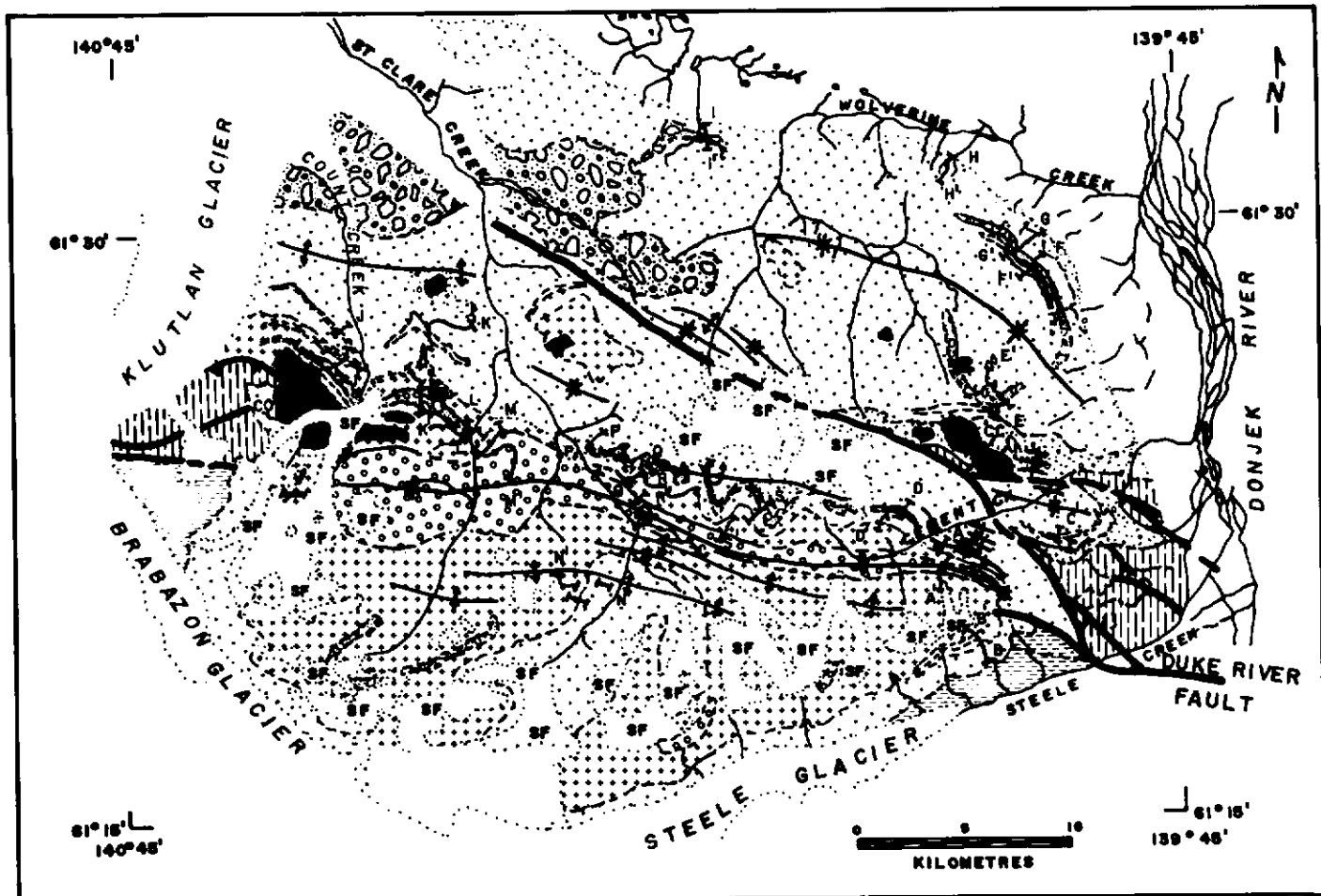
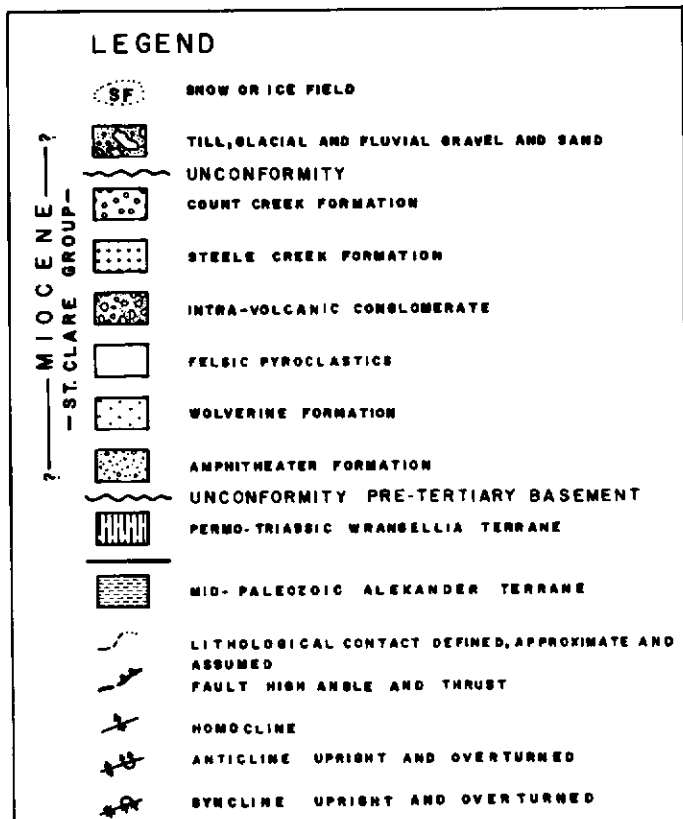


Figure 2. Generalized geological map of the St. Clare Creek field (CC = Cement Creek plug, CO = Count Creek plug). Based on data collected during this study and by Souther and Stanciu (1975).



and east-trending fold hinges in the St. Clare Creek field (Fig. 2). The youngest deformed lavas in the WVB are 1.6 Ma (White River valley, Denton and Armstrong, 1969).

Calc-alkaline volcanism in the WVB began about 13.5 Ma, over a 300 km strike length from Wait Creek (southeast Alaska) to the Lava Creek field (southwest Yukon). This volcanic activity appears to have been short-lived in the southeastern parts of the WVB (1.6 million years in the Lava Creek field) but has extended to the Recent in Alaska (Mendenhall, 1905). Calc-alkaline magmatism in the WVB is related to the north-dipping subduction of Pacific oceanic lithosphere at the leading-edge of the composite oceanic-continental Yakutat terrane (Lahr et al., 1983; Bruns, 1983; and Nye, 1983). Stephens et al. (1984) have described NNE-dipping Benioff Zone beneath southeastern Alaska.

FIELD RELATIONSHIPS IN THE ST. CLARE CREEK FIELD

Extrusive and Volcanoclastic Rocks

The extreme stratigraphic relief (up to 2650 m), large surface area (1400 km²), and spectrum of magma types of the St. Clare Creek field are well suited for an investigation of temporal magmatic variations. Previous geological descriptions of the area include Muller (1967), Souther and Stanciu (1975) and Skulski and Francis (1986). This paper subdivides the St. Clare Group, in the St. Clare Creek field, into the Wolverine, Steele Creek and Count Creek formations.

The Wolverine Formation includes a basal sequence of extrabasinal sediments, alkaline lavas, and plagioclase-phyric (15%, up to 1 cm) Fe-rich transitional lavas; and an upper sequence of transitional lavas and interbedded epiclastic and felsic pyroclastic rocks

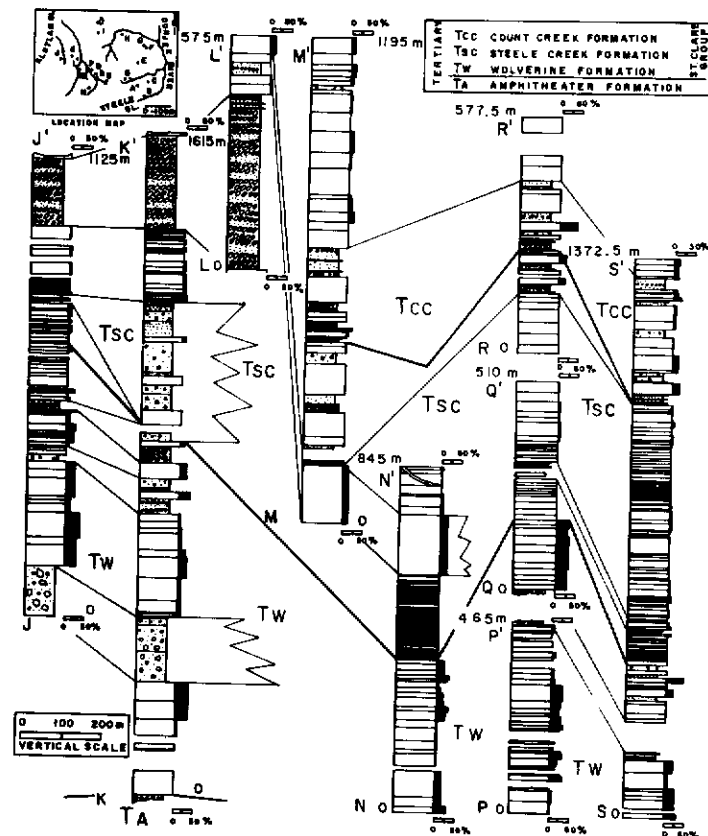
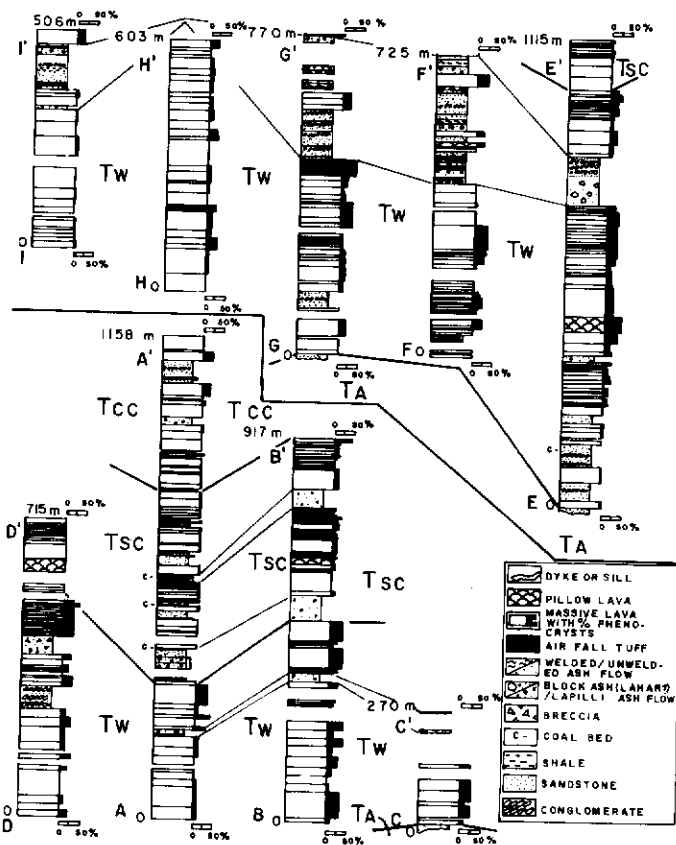


Figure 3. Stratigraphic sections of the St. Clare Creek field showing lithological types, phenocryst abundances, and stratigraphic markers and boundaries.



(locally welded trachytes, rhyolites and comendites). Calc-alkaline lavas occur near the top of the formation. The Wolverine Formation rests unconformably on Paleozoic rocks in the south, where it is relatively thin, and conformably on the Amphitheatre Formation in the central and northern parts of the field, where it attains maximum thickness (Figs. 3 and 4). The type section is 968 m thick (section E-E', Figs. 2, 3 and 4) and overlies the Amphitheatre Formation. The lower part consists of thin, massive, flint-like lava flows of aphyric hawallite, mugearite, and alkaline olivine basalt, interbedded with feldspathic sandstones, siltstones, conglomerates and thin lignite seams. The early lavas are overlain by closely-stacked, thin aa flows of basaltic trachyandesite, altered felsic pyroclastic rocks, and thin units of flow-banded rhyolite. Overlying porphyritic, Fe-rich basaltic trachyandesite lava flows are thick and pillowed near the base, and closely-stacked and thin near the top where they include trachyandesite flows. The top of the section consists of thin flows of basaltic andesite, basaltic trachyandesite and trachyandesite, and a thick, coarse-grained volcanoclastic deposit.

The Steele Creek Formation is characterized by a large proportion (90%) of basaltic lava flows either interbedded with basaltic trachyandesites, dacites and volcanoclastic rocks, or comprise thick successions of thin, individual lava flows (Figs. 3 and 4). The type section is 468 m thick (section A-A', Figs. 2, 3 and 4). Basal units consist of amygdaloidal (calcite) transitional basalts which have rusty-brown weathered surfaces and typically occur as thin, closely-stacked, pahoehoe flows. Stacks of 5-10 lava flows are interbedded with epiclastic sandstones, siltstones, conglomerates, thin lignite beds, and felsic pyroclastic flow- and fall-deposits.

The Count Creek Formation contains the youngest lavas in the St. Clare Group and is distinguished by thick flows of intermediate and evolved transitional lavas with low abundances (0-20%) of small (1 cm plagioclase) phenocrysts. The type section is 752 m thick (Section M-M', Figs. 2, 3 and 4). The lower part consists of cyclic epiclastic sandstones and conglomerates, with felsic tuffs (flow and fall) interbedded with basaltic trachyandesite and trachyandesite lava flows. The upper units consist of thick, basaltic trachyandesite, trachyandesite and trachyte lava flows, and a thin ash-flow bed near the top.

The relative volumes of rock types found in the St. Clare Creek field have been estimated assuming flat-lying stratigraphy and data from sections E-E' (Wolverine Fm.), M-M' (Count Creek Fm.), and Q-Q' and R-R' (Steele Creek Fm.). The volcanic pile consists of approximately 80% lavas and 20% volcanoclastic rocks. About 85% of the lavas are transitional, and 15% consist of equal proportions of alkaline and Fe-rich transitional types with less than 1% calc-alkaline lava. The transitional type consists of 30% basalts, 50% basaltic trachyandesites, 10% trachyandesites and 10% trachyte/rhyolite (excluding felsic pyroclastic and intrusive rocks).

Intrusive Rocks

The most prominent intrusive rocks in the St. Clare Creek field are large felsic plugs which outcrop in the east-central and west-central parts of the area (Fig. 2). The eastern intrusions comprise the polyphase, trachytic and rhyolitic Cement Creek plug (13.6 +/- 1.2 Ma, Souther and Armstrong writ. comm., 1987) and two smaller trachyte plugs. In the west, the Count Creek plug is an aplite of 6.5 +/- 0.4 Ma (minimum age, Souther and Armstrong, writ. comm., 1987). The roof of the Count Creek plug consists of brecciated and bleached volcanic rocks and aplite which are cut by east- and north-trending mafic dykes (up to 3 m wide). The oldest dykes are oxidized and carbonatized, whereas younger dykes have thick (30 cm) vitrophyric chilled margins. A small dyke-like intrusion immediately north of this roof zone is composed of porphyritic trachyte and contains numerous, partly resorbed xenoliths of volcanic rock. A small plug just east of St. Clare Creek is a porphyritic andesite. Basaltic sills and north-trending dykes are common in the ridges underlain by the Steele Creek Formation between the southeast and southwest forks of St. Clare Creek (Fig. 2). The sills are up to 6 m in width, have vitrophyric chilled margins, and contain vesicles and small calcite amygdules. A 3.7 km long, 150 m thick, composite gabbro, pyroxenite sill is exposed in the Cement Creek valley.

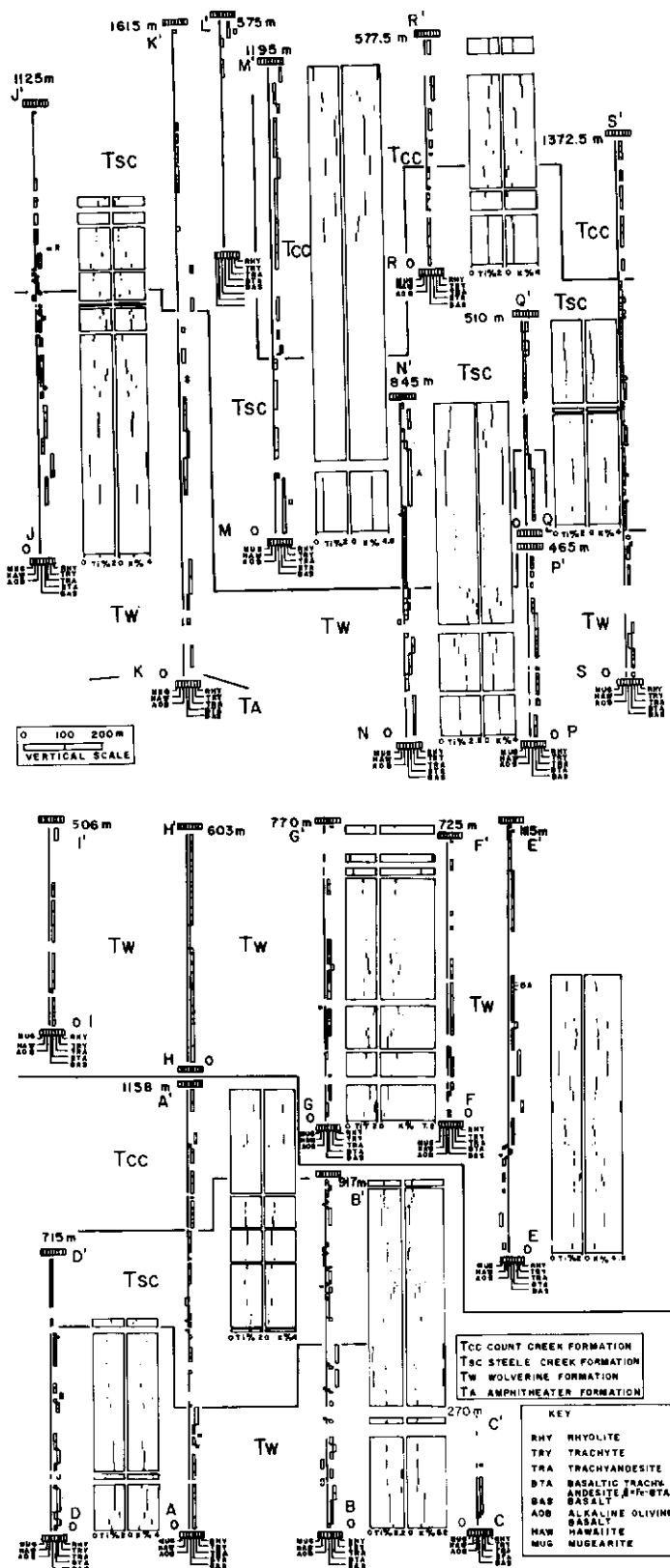


Figure 4. Chemical-stratigraphic sections showing rock types and Ti and K abundances in cation units. Calc-alkaline rocks are labelled as follows: BA = basaltic andesite, A = andesite, D = dacite; and R = rhyolite.

PETROGRAPHY OF THE LAVAS

Alteration of lava flows is minor and is characterized by subzeolite assemblages. Glass in basaltic rocks is replaced by clinopyroxene spherulites and/or carbonate. The alteration products of olivine

include aggregates of carbonate, goethite, hematite, celadonite or iddingsite. Incipient oxidation of titanomagnetite results in ilmenite ex-solution lamellae and in extreme cases causes replacement by hematite or goethite. Biotite and hornblende are commonly replaced by hematite. Plagioclase is rarely altered, but may be replaced by patchy carbonate or clay minerals. Clinopyroxene is unaltered in these rocks.

The alkaline magma type includes alkaline olivine basalts, hawaiites and mugearites. The alkaline olivine basalts are porphyritic to seriate rocks with phenocrysts of olivine (Fo 82-88), zoned plagioclase and titanomagnetite in a trachytic groundmass of plagioclase, olivine, an opaque phase and clinopyroxene (Figs. 3 and 4 for phenocryst abundance). Seriate varieties have a fine-grained ophitic texture with euhedral olivine and plagioclase chadacrysts in anhedral clinopyroxene oikocrysts. The hawaiites are porphyritic to seriate rocks with phenocrysts (trace - 15%) of olivine (Fo 71-79), plagioclase (An-30 up to 1.5 cm), titanomagnetite and ilmenite, and clinopyroxene (with hourglass twinning) in a trachytic groundmass of plagioclase, clinopyroxene, olivine and an opaque phase. Mugearites are typically aphyric, with microphenocrysts of olivine (Fo 53-55), plagioclase, titanomagnetite and ilmenite and minor amounts of hornblende and biotite, in a trachytic groundmass of plagioclase and an opaque phase. One sample of mugearite contains black melt schlieren with abundant fine-grained opaque minerals in the groundmass. The rock also contains resorbed orthoclase xenocrysts mantled by fine-grained reaction products.

The Fe-rich transitional magma type includes trachybasalts and Fe-rich basaltic trachyandesites. The trachybasalts are porphyritic (trace - 20%) with phenocrysts of olivine, plagioclase (up to 8 mm), titanomagnetite and clinopyroxene, in a trachytic groundmass of similar mineralogy. Clinopyroxene phenocrysts commonly exhibit corroded rims and occasional hourglass twinning. The Fe-rich basaltic trachyandesites contain phenocrysts (trace - 30%) of olivine, plagioclase (up to 1 cm), titanomagnetite and clinopyroxene, in a trachytic groundmass of similar composition. One sample of Fe-rich basaltic trachyandesite near the top of section E-E1 contains embayed clinopyroxene phenocrysts with resorbed cores of orthopyroxene.

The transitional magma type comprises basalts, basaltic trachyandesites, trachytes, rhyolites and comendites. Basalts are either porphyritic, seriate or equigranular. Porphyritic varieties contain phenocrysts of olivine (Fo 85-86), plagioclase (An 67-72) and occasionally titanomagnetite, in an intergranular to intersertal groundmass of olivine (Fo 62-75), plagioclase (An-55), clinopyroxene, an opaque phase and glass. A group of basalts at the base of section G-G¹ contain resorbed and zoned clinopyroxene phenocrysts rimmed by fine-grained reaction products (rarely olivine). Equigranular basalts contain euhedral olivine within subophitic plagioclase, clinopyroxene and magnetite. Basaltic trachyandesites contain phenocrysts (0-40%, generally high) of olivine (Fo 81-84), zoned plagioclase (An 58-73), titanomagnetite, and subrounded clinopyroxene (first appearance of clinopyroxene, Wo:En:F_s 38:52:9) in a trachytic groundmass of plagioclase (An 49-56), clinopyroxene (Wo:En:F_s 35:56:9), opaque phase, and occasional olivine (Fo 64) and glass.

Trachyandesites contain phenocrysts (trace - 40%) of olivine, plagioclase (An 32-51), titanomagnetite, clinopyroxene (Wo:En:F_s 35:49:16), and rarely olivine, ilmenite, hornblende and apatite. The phenocrysts are contained in a fine-grained trachytic groundmass of feldspar, an opaque phase and local clinopyroxene. Clinopyroxene phenocrysts are commonly subrounded to embayed and sometimes exhibit cores of resorbed orthopyroxene (Wo:En:F_s 2:72:30). Resorbed and sieve-textured plagioclase phenocrysts also occur in the orthopyroxene-bearing rocks. In the more evolved lavas, clinopyroxene is occasionally present as resorbed cores in hornblende. Trachytes, rhyolites and comendites usually occur as intrusions and pyroclastic deposits (comendites only outcrop in the latter form). These evolved rocks have highly variable mineralogy, and contain phenocrysts of olivine (rare in the most primitive trachytes), plagioclase (An 46 in trachyte, An:Ab:Or -11:81:8 in comendite), and occasional magnetite, clinopyroxene (in evolved trachyte, Wo:En:F_s 43:12:45), hornblende, biotite, anorthoclase (An:Ab:Or -4:82:13), apatite and zircon. Anorthoclase appears to be restricted

to sills and plugs, where it forms either phenocrysts or rims around plagioclase. The groundmass of more evolved rocks is trachytic and consists of feldspar microlites, fine-grained opaques, and quartz.

The calc-alkaline magma type includes basaltic andesites, andesites, dacites and rhyolites. The basaltic andesites contain phenocrysts of subrounded orthopyroxene, plagioclase and occasional olivine (rounded), magnetite and clinopyroxene, in a very fine-grained groundmass of clinopyroxene, an opaque phase and plagioclase. Andesites and dacites contain phenocrysts of orthopyroxene, plagioclase, titanomagnetite, hornblende and biotite in a fine trachytic groundmass of feldspar and an opaque mineral. Calc-alkaline rhyolites (including aplite) contain microphenocrysts of plagioclase and quartz in a very fine trachytic groundmass of feldspar microlites.

CHEMISTRY

The St Clare Creek field lavas comprise a chemical continuum between magmas of alkaline and calc-alkaline affinities, and exhibit systematic compositional variation with stratigraphic level. A concomitant decrease in slope in SiO_2 versus FeO/MgO (Fig. 5 in Skulski and Francis, 1986) and SiO_2 versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ compositional space (Figs. 1 and 5) progresses from early erupted alkaline lavas through high-Fe transitional, transitional and calc-alkaline type lavas. Petrographically similar transitional lavas in the Wolverine and Count Creek formations have overlapping chemical abundances in terms of Si-Mg-Fe-Na-K, although the former contain some Fe-, Na- and K-rich differentiates. Variations between the two formations of high field strength (HFSE) and large ion lithophile element (LILE) abundances are more pronounced. The St Clare Group is enriched in LILE relative to HFSE (Figs. 6 and 7), and Rb and Y increase and Nb decreases with stratigraphic height. These features are illustrated by average respective values of the ratios of Rb/Ba, Rb/Nb, Nb/Zr, Nb/Y and Zr/Y in the Wolverine Formation: alkaline 0.034, 0.79, 0.097, 0.75 and 7.74; high-Fe transitional 0.043, 0.98, 0.087, 0.59 and 6.86; transitional 0.052, 1.48, 0.076, 0.55 and 7.16; the Steele Creek Formation: 0.041, 0.91, 0.072, 0.41 and 5.67; and the Count Creek Formation: 0.70, 2.52, 0.062, 0.39 and 6.40, respectively.

Primitive Magmatic Compositions

The chemical differences between basaltic lava types are far less apparent than difference between more evolved lava types (Fig. 5). However, some of the least evolved rocks display chemical characteristics of significance to the derivation of the various magma compositions. The most primitive alkaline lava, from the base of section E-E' (Fig. 4, TS-15-85) is an olivine (Fo 82-88) phyric, plagioclase and titanomagnetite microphyric alkaline olivine basalt. Magma of this composition is probably non-primary since the $\text{Mg}\#$ ($\text{Mg}/\text{Mg} + \text{Fe}^{2+} = 0.60-0.64$ for $\text{XFe}^{3+} = 0.15$) and Ni abundances (98 ppm) are too low to be in equilibrium with upper mantle peridotite (cf. Frey et al., 1978). The presence of normally-zoned, olivine phenocrysts with core compositions as magnesian as Fo 88 indicates that a TS-15-85 magma may have been derived by olivine (+/- plagioclase and titanomagnetite) fractionation from potential primary magma with an $\text{Mg}\#$ of 0.68 (assuming $\text{XFe}^{3+} = 0$, cf. Roeder and Emslie, 1970).

The only other basalts with comparable and higher $\text{Mg}\#$ in the St Clare Creek field belong to the transitional series, of which the olivine (Fo 85-86) + plagioclase (An 67-72) phyric basalt (TS-101-85) is the best preserved and most magnesian example. However, a magma of TS-101-85 composition is probably also non-primary as suggested by a low Ni abundance (42 ppm). Trachybasalts are almost certainly non-primary and are likely to be released to more primitive magmas by olivine + plagioclase + magnetite + clinopyroxene fractionation. Least evolved calc-alkaline lavas are orthopyroxene, plagioclase and clinopyroxene phyric basaltic andesites (e.g. TS-192-85) with high Ni abundances (up to 492 ppm).

Evolved Compositions

The alkaline lavas at the base of section E-E' comprise a chemically distinctive magma group which spans the alkaline olivine

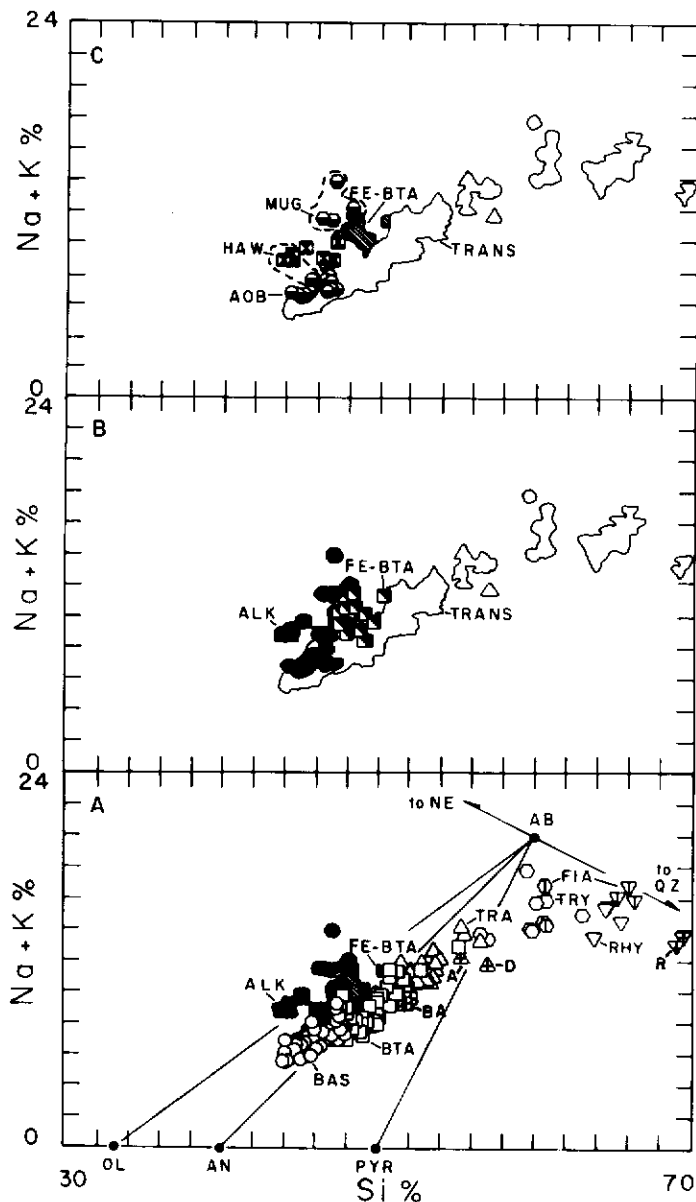


Figure 5. Total alkali versus silica diagram (cation units) showing the ideal positions of minerals: OL = olivine; AN = anorthite; PYR = pyroxene; AB = albite; QZ = quartz and NE = nepheline. Figure 5A illustrates the transitional (TRANS) and calc-alkaline magma types where: BAS = basalt; BTA = basaltic trachyandesite; TRA = trachyandesite; TRY = trachyte; RHY = rhyolite; FIA = fiamme; BA, A, D and R as in Figure 4; ALK = alkaline type; FE-BTA = Fe-rich transitional type. Figure 5B shows Fe-rich basaltic trachyandesites and trachybasalts. Figure 5C Alkaline magma type where: AOB = alkaline olivine basalt; HAW = hawaiite; MUG = mugearite. Dashed field encloses alkaline lavas from the base of section E-E' (Fig. 3 and 4).

basalt-hawaiite-mugearite compositions. These lavas are characterized by high Ti, Fe, Na, K, P and incompatible trace elements, and low Si abundances relative to other lavas (Figs. 4, 5, 7 and 8). Elsewhere in the St. Clare Creek field, (e.g., section J-J1) petrographically indistinguishable alkaline olivine basalt and transitional basalt lava flows have similar trace element abundances, and can only be discriminated by higher Ca contents in the former. The fractionation history of the alkaline lavas in section E-E' can be divided into alkaline olivine basalt-hawaiite and hawaiite-mugearite stages. The first stage is characterized by decreasing abundances of Si, Mg, Cr and Ni, near-constant Ca, V and Rb, and enrichment in all other elements as hawaiite is approached. The transition from hawaiite

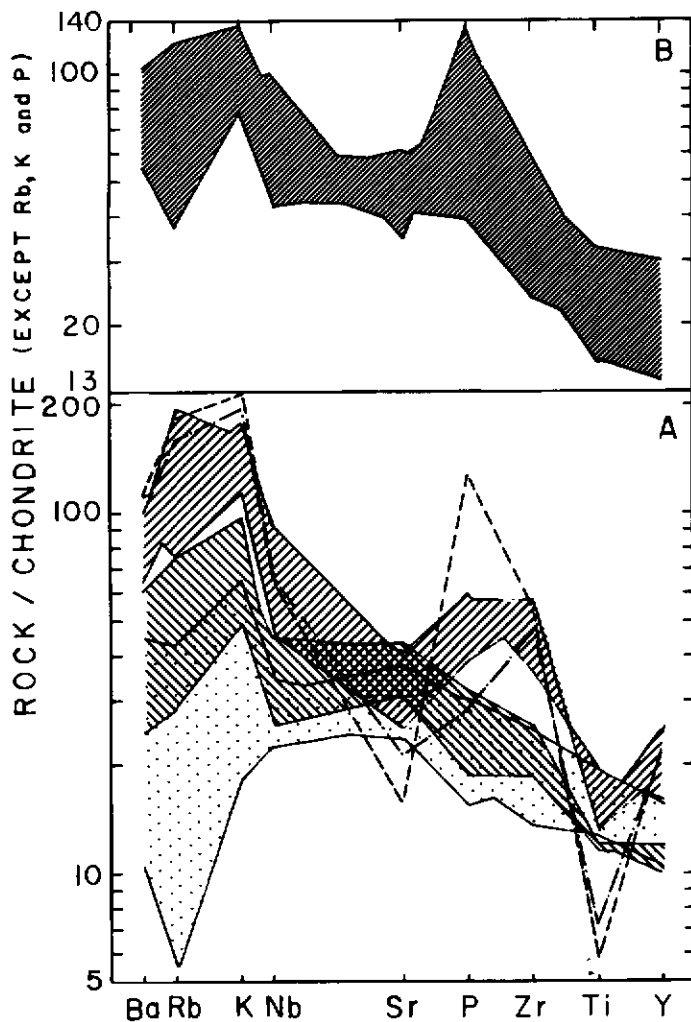


Figure 6. Chondrite-normalized trace element abundances of lavas. Normalization factors from Thompson (1983). Figure 6A illustrates transitional lavas and figure 6B the Fe-rich transitional lavas. In Figure 6A the dotted pattern = basalts (lower part of field is defined by TS-101-85, see text), NW-SE ruling = basaltic trachyandesites, NE-SW ruling = trachyandesites; dash-dot pattern = trachyte and dashed pattern = rhyolite.

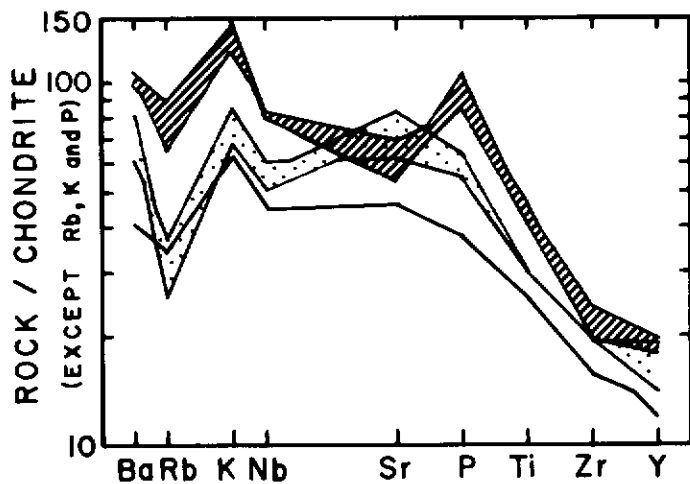


Figure 7. Chondrite-normalized trace element abundances for the alkaline lavas from the base of section E-E1. The single line is an alkaline olivine basalt (TS-15-85), the dotted pattern = hawaiites and the ruled pattern = mugearites.

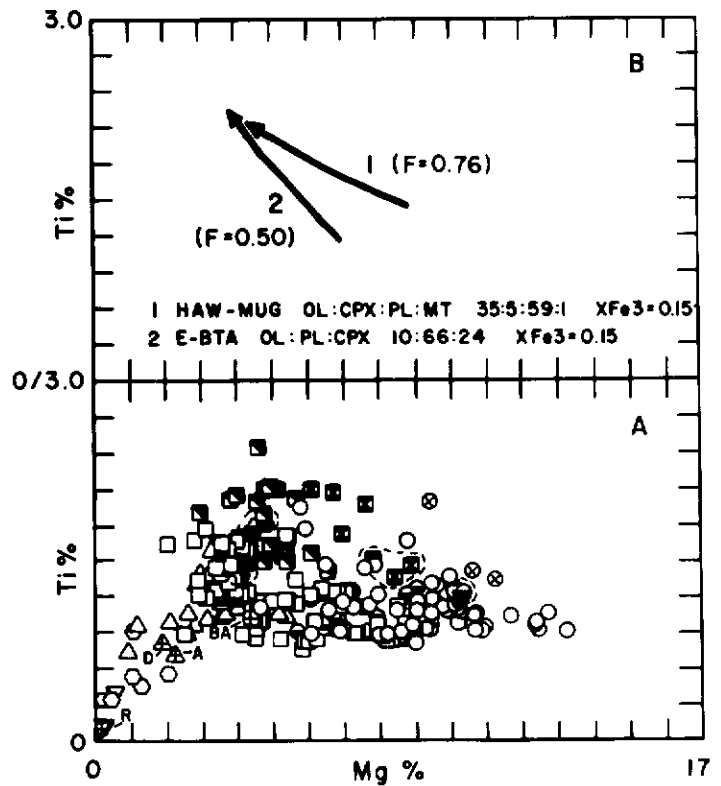


Figure 8. Ti versus Mg in cation units. Figure 8A utilizes the symbols as in Figure 5 with the addition of circles with an X which are clinopyroxene-phyric basalts from the base of section G-G'. Figure 8B shows the model fractional crystallization paths for (1) hawaiite to mugearite 76% fractionation, and (2) Fe-rich basaltic trachyandesites 50% fractionation. Proportions of phenocrysts removed are shown for olivine (OL), plagioclase (PL) and clinopyroxene (CPX). The algorithm calculates equilibrium compositions for olivine and plagioclase (at a fixed clinopyroxene composition) which are then removed in 0.1% fractionation steps from a starting liquid composition.

to mugearite is characterized by increasing Si, Na, K, P, Rb, Zr, Nb and Y and a decrease in Ca, Al and Sr. An initial rise in Ti and Fe contents is followed by a drop in these elements with further differentiation (Fig. 8a).

The high-Fe transitional magma type represents a hypersthene-normative intermediary between the transitional and alkaline magma types. These lavas have HFSE and LILE abundances that are similar to those in the alkaline rocks (Figs. 6 and 7). The lavas are characterized by a restricted range of Si variation (47.1 - 50.9%) over which there is -50% enrichment in incompatible trace element abundances with increasing differentiation. The aphyric lavas (<10% phenocrysts) contain increasing Fe, Ti, Na, K, P, and Si, and decreasing Al, Ca, Cr, Ni and Sr with progressive differentiation. Many high-Fe transitional lavas contain abundant (~10%) plagioclase phenocrysts, which is reflected by high Al, Ca and Sr and low Fe and Ti contents.

The transitional magma type encompasses a continuous range of evolved compositions that extend from basalt to rhyolite. In the St. Clare Creek field a magma composition of approximately 57-59% Si (Fig. 5) coincides with an abrupt change in eruptive style from flows to pyroclastic eruptives, and an increase in the relative volume of intrusive rocks. The nature and proportion of liquidus phases in the evolved lavas has strongly influenced the course of transitional magmatic evolution. The liquidus effects are superimposed on primary chemical differences between the various basaltic progenitors. The order of appearance of phenocryst phases and the corresponding Mg cation abundance of the lavas is olivine (►13.2% Mg), plagioclase (-13.2%), titanomagnetite (-9.5%), clinopyroxene (-7.7%), apatite (-3.0%), hornblende (-2.8%), biotite (-1.3%) and anorthoclase

(-0.5%). The basalt flows with resorbed clinopyroxene phenocrysts at the base of section G-G¹ (Fig. 4) contain 11.2 - 9.4% Mg and the highest Fe and Ti abundances (Fig. 8a) of all Mg-rich transitional basalts (>9% Mg). The appearance of titanomagnetite at high Mg abundances (-10.7%) also reflects the character of these basalts. Since titanomagnetite has a significant effect on Si abundances, variations in the initial appearance and separation of this phase may explain the overlap of Mg abundance (between 5 and 9%) of basalts and basaltic trachyandesites.

The early crystallization of olivine, plagioclase and titanomagnetite relative to clinopyroxene in the transitional lavas results in a decrease in the abundance of Mg, Fe, Ti, Cr and Ni, the buffering of Ca (and to a lesser extent Al) and an increase in the abundances of most other elements. The appearance of clinopyroxene on the liquidus causes an abrupt decrease in Ca, and an increase in Fe and Ti abundances (Fig. 8a). The increase in Fe and Ti abundances with the onset of clinopyroxene saturation in titanomagnetite-phyric basaltic trachyandesites suggests a physical control on the separation of titanomagnetite. The inflection at -3.5% Mg in Ti-Mg space (Fig. 8a) corresponds to an abrupt increase in Si, and the formation of Ti and Fe-poor trachyandesitic differentiates. Assuming Stokes Law behaviour, titanomagnetite crystals must attain a critical diameter at this inflection point, permitting physical separation. Intermediate compositions which do not have high Ti abundances at 3.5% Mg are invariably plagioclase-rich (>15%) and lie on a crystal-liquid mixing line.

DISCUSSION

Volcanic History of the St. Clare Creek Field

Four physical stages of volcanism in the St. Clare Creek field are: (1) alkaline shield volcano, (2) early-stratovolcano, (3) basaltic fissure, and (4) late-stratovolcano. These stages comprise the Wolverine (1 & 2) Steele (3) and Count Creek Formations, (4) respectively.

The alkaline shield stage initiated St. Clare volcanism (>17.3 Ma) with the formation of small volume (<1 km³, e.g., vicinity of section E-E¹), shield volcanoes composed of alkaline lavas in the lower part of the Wolverine Formations.

The early-stratovolcano stage or upper part of the Wolverine Formation marked the initiation of the main basin-filling phase by the formation of two major, central volcanoes. Vents were apparently centred over the Cement and Count Creek plugs as indicated by: the presence of large volume hypabyssal felsic intrusions, abundant dykes, local hydrothermal alteration (bleaching and weak argillic alteration), thickness of the Wolverine Formation, proximity of coarse pyroclastic rocks (sections E-E¹), central location relative to welded ashflow tuffs (section C-C¹, F-F¹ and G-G¹); and similarity in chemical composition of trachyte fiamme in sections F-F¹ and G-G¹ and the Cement Creek plug (Fig. 5). The early stratovolcano stage commenced by erupting high-Fe transitional lavas, followed by intermediate and evolved transitional lavas and local calc-alkaline basaltic andesites. Periodic erosion of the volcanic edifices and eruption of felsic pyroclastic rocks due to probable caldera collapse post-dated the high-Fe transitional lavas. Crosscutting relationships indicate that the Count Creek centre was the locus of volcanism from Wolverine time to possibly as late as 6.5 +/- 0.4 Ma (Souther and Armstrong, writ. comm., 1987). The age of the Cement Creek center, and the relative age of associated pyroclastic rocks bracket the age of early-stratovolcano activity between 17.3 +/- 1.0 and at least 13.6 +/- 1.2 Ma (Souther and Armstrong, writ. comm., 1987).

The Steele Formation represents eruption of a large volume of basaltic magma from north-trending fissures on the southern flanks of the Cement and Count Creek centers. The morphology of the flows suggest rapid eruption. This stage is estimated to have occurred between 13.6 +/- 1.3 and 9.9 +/- 0.4 Ma (data from Souther and Armstrong, writ. comm., 1987).

The late stratovolcano represented by the Count Creek Formation was largely centered around the Count Creek plug. The Count Creek Formation in the southeast part of the map area (Figs. 2 and 3; e.g., section A-A¹) is interbedded with distal epiclastic deposits, whereas more proximal deposits are found towards the west (e.g.,

sections M-M¹ and R-R¹). Distinctive pyroclastic-epiclastic cycles in the Count Creek Formation suggest that periods of erosion alternated with explosive volcanism. The late stratovolcano stage was characterized by the eruption of intermediate and evolved transitional lavas (post 9.9 +/- 0.4 Ma, data from Souther and Armstrong, writ. comm., 1987).

Magmatism in the St. Clare Creek Volcanic Field

Most volcanic samples from the St. Clare Creek field are of differentiated lavas. The continuous spectrum of magma compositions and the variability of compatible/incompatible element ratios suggest that the most important differentiation process was fractional crystallization. The majority of lavas appear to have fractionated in a near surface environment; the phenocryst assemblages are dominated by olivine, plagioclase, titanomagnetite and clinopyroxene. Resorbed clinopyroxene phenocrysts in some early-erupted, Fe-rich lavas may attest to a period of high pressure fractionation. Magma mixing may have been a locally important differentiation process as evidenced by orthopyroxene phenocrysts mantled by clinopyroxene with coexisting resorbed plagioclase and/or melt schlieren. The restricted stratigraphic occurrence of basalts suggest that their ability to erupt was a sensitive function of their buoyancy.

The applicability of fractional crystallization models in explaining the chemical compositions of differentiated alkaline and high-Fe transitional lavas in the St. Clare Creek field was assessed. The transition alkaline olivine basalt-hawaiite is characterized by decreasing silica contents that probably reflect pyroxene fractionation (Fig. 5c), however quantitative assessment of this process awaits additional mineralogical data. The hawaiite-mugearite stage requires (-26%) fractionation of olivine, clinopyroxene, plagioclase and titanomagnetite in the proportions 35:5:59:1 (Fig. 8b, assuming $X_{Fe^{3+}} = 0.15$). The enrichment of the incompatible elements K, P, Rb, Ba, Y, Zr and Nb over this transition is 32, 36, 43, 26, 27 and 28%, respectively. These higher degrees of fractionation for the LILE are somewhat problematic. It is unlikely that fractional crystallization alone can account for the chemical variation between hawaiites and mugearites. Local crustal contamination, as evidenced by orthoclase xenocrysts in mugearite, could explain the discrepancy between trace and major element fractionation models in the transition from hawaiite to mugearite.

The chemical compositions of high-Fe basaltic trachyandesites can be modelled by 50% fractional crystallization of olivine, plagioclase and clinopyroxene in the proportions 10:66:24 when $X_{Fe^{3+}} = 0.15$ (Fig. 8b). The indicated rise in Ti and constant Si abundances require that these melts did not fractionate titanomagnetite. The principal difference between the high-Fe transitional and transitional magma types is the enhanced role of clinopyroxene fractionation in the former.

It is possible to directly compare the whole rock compositions of least evolved alkaline and transitional basalts by correcting for the effects of fractional crystallization. The analysis is recalculated by adding olivine and plagioclase (in a ratio of 40:60, cf. Presnall et al., 1978) in small (0.2%) fractionation steps until the Mg abundance (14%) in the least evolved basalt is attained (cf. Eich et al., 1987). Although magmas of 14% Mg may not be primary, a minimum correction is required to attain this concentration. In addition, the effects of further olivine "back fractionation" do not change the relative incompatible element abundances. Fractionation-corrected alkaline magma is distinguished from transitional basalts by higher Ti, K, P, Sr, Zr, and Nb abundances. In the transitional lavas, key element ratios such as Na + K/Si (0.12 - 0.15), Na + K/Al (0.29 - 0.43), K/Na (0.06 - 0.16), Ti/P (4.76 - 7.75) and Zr/Y (4.43 - 6.35) overlap, or are close to, values for the alkaline magma (TS-15-85; 0.15, 0.41, 0.17, 3.93 and 6.74 respectively). These data are internally consistent since basalts with "alkaline-like" Na + K/Al ratios have similar elemental ratios. Thus there is a clear spectrum of basaltic magma compositions in the St. Clare Creek field.

The wide range of magmatic compositions may be related to one or more primary magmas. A single primary magma would need to account for both critically undersaturated basalts with high LILE/HFSE ratios (e.g., TS-15-85) and silica-saturated basalts with

low LILE/HFSE ratios (e.g., TS-101-85). Alkaline olivine basalt can be derived from a silica-saturated primary magma at high pressures (Presnall et al., 1978). However, both alkaline and lower pressure transitional differentiates would need to variably assimilate a LILE-enriched component to produce the observed trace element abundances. Typical mass and energy balance calculations require that the assimilant outweigh the contaminant (cf. Grove and Kinzler, 1986). However, large-scale crustal assimilation is unlikely to have been important in the St. Clare Creek field. The volume of LILE-enriched lavas outweighs the relatively LILE-depleted counterparts, and crustal xenoliths are rare. Sr^{87}/Sr^{86} data from a zoned pluton in the Nines Creek area also have typical mantle values (Downey et al., 1980). Therefore it is suggested that a spectrum of primary magma compositions were generated beneath the WVB.

Adiabatic melting of a rising mantle diapir could account for the chemical-temporal relationships between primitive lavas of the alkaline shield volcano, early stratovolcano and basaltic fissure stages. Both high pressure and CO_2/H_2O ratios favor the generation of alkaline magmas from upper mantle peridotite (Yoder and Tilley, 1962, Kushiro, 1972; Egger, 1974). Since volatile activities appear to have been relatively low during the alkaline shield volcano stage, pressure is probably the more important variable. The lack of pyroclastic activity, and the restricted occurrence of volatile bearing minerals in evolved compositions (mugearite) support this conclusion. Alkaline olivine basalt magma could be produced by approximately 10% melting a LILE-enriched spinel lherzolite at pressures of 12 kb (i.e. a result of Cretaceous subduction?; c.f. Frey et al., 1978). Progressive ascent and melting of a diapir could generate the required silica-saturated trachybasaltic and transitional basaltic magmas. Segregation of these magmas would progressively deplete the source region to the extent that low LILE/HFSE ratios could be produced in later basaltic derivatives.

Subduction-related metasomatism of the overlying, depleted mantle wedge by LILE-enriched fluids could produce a source region appropriate for the generation of calc-alkaline magmas. Lavas erupted during the late stratovolcano stage may be the precursors of "true" arc magmas. The suggested model predicts that alkaline shield volcano, earlystratovolcano and basaltic fissure magmas should be in isotopic equilibrium, and reflect minimal crustal contamination. Similarly, latestratovolcano stage magmatism should have a decoupled

alkaline and light rare earth element signature and have a distinctive isotopic signature.

A Tectonic Model of the Wrangell Volcanic Belt

The petrogenetic model proposed for the St. Clare Group implies that the alkaline shield volcano, earlystratovolcano and basaltic fissure stages reflect extension along the Duke River Fault, whereas the latestratovolcano stage reflects subduction and convergent tectonism. This suggestion is consistent with the 17.3 - 6.5 Ma of the St. Clare Creek field (Souther and Armstrong, writ. comm., 1987) and the onset of calc-alkaline magmatism in the WVB at - 13 Ma (Deininger, 1970). The Ti-Zr-Sr, Ti-Zr-Y and Ti/Y - Nb/Y abundances of St. Clare Creek basalts that precede the late stratovolcano stage overlap the compositional fields of arc and ocean floor basalts (cf. Pearce and Cann, 1973; Pearce, 1982). However, the St. Clare basalts have Nb/Ba ratios which approach the maximum values (Perfit et al., 1980) found in oceanic arcs and the Ti/V ratios are similar to those of ocean floor and within-plate basalts (Shervais, 1980). Thus the occurrence of alkaline and calc-alkaline magmatism in the WVB may reflect two contrasting styles of tectonic activity along the convergent plate margin; transcurrent fault motion and subduction.

ACKNOWLEDGEMENTS

Funding for this project was arranged through a contract with the Exploration and Geological Services Division, Northern Affairs Program, Yukon. Further funding was made available through NSERC grants to D. Francis and J. Ludden, and DNSR Summer Field Fellowships (McGill University). I thank J. Souther and R. Armstrong for generously providing unpublished K-Ar age determinations, and C. Nye for data from his thesis. However, I claim full responsibility for the interpretation of this data. I am grateful to A. Sasso and M. Diner for assistance in the field and T. Ahmedali and M. MacKinnon for consultation in laboratory work. This paper has benefited from a thoughtful, brutal yet brilliant review by J. Clark, and discussions with D. Francis, J. Ludden and my colleagues at McGill.

REFERENCES

- BRUNS, T.R., 1983. Model for the origin of the Yakutat block, an accreting terrane in the northern Gulf of Alaska; *Geology*, Vol. 11, p. 718-721.
- CAMPBELL, R.B. and DODDS, C.J., 1978. Operation St. Elias, Yukon Territory; *Geological Survey of Canada; Paper 78-1A*, p. 35-41.
- DEININGER, J.W., 1972. *Petrology of the Wrangell Volcanics near Nabesna, Alaska*; unpublished M.Sc. thesis, University of Alaska, 65 p.
- DELONG, S.E., HODGERS, F.N. and ARCULUS, R.J., 1975. Ultramafic and mafic inclusions, Kanaga Island, Alaska, and the occurrence of alkaline rocks in island arcs; *Journal of Geology*, Vol. 83, p. 721-737.
- DENTON, G.H. and ARMSTRONG, R.L., 1969. Miocene-Pliocene glaciations in southern Alaska; *American Journal of Science*, Vol. 267, p. 1121-1142.
- DOWNEY, M.E., ARMSTRONG, R.L. and PARRISH, R.R., 1980. K-Ar, Rb-Sr, and fission track geochronometry of the Bock's Brook Stock, Kluane Ranges, southwestern Yukon Territory; *Current Research, Part B, Geological Survey of Canada, Paper 80-1B*, p. 189-193.
- EGGLER, D.H., 1974. Effect of CO_2 on the melting of peridotite; *Carnegie Institution of Washington Yearbook*, Vol. 72, p. 457-467.
- EICH'E, G.E., FRANCIS, D.M. and LUDDEN, J.N., 1987. Primary alkaline magmas associated with the Quaternary Alligator Lake volcanic complex, Yukon Territory, Canada; *Contributions to Mineralogy and Petrology*, Vol. 95, p. 191-201.
- EISBACHER, G.H. and HOPKINS, S.L., 1977. Mid-Cenozoic paleogeomorphology and tectonic setting of the St. Elias Mountains, Yukon Territory; *Geological Survey of Canada, Paper 77-1B*, p. 319-335.

- FREY, F.A., GREEN, D.H. and ROY, S.D., 1978. Integrated models of basalt petrogenesis: A study of quartz tholeiites to olivine melilitites from southeastern Australia utilizing geochemical and experimental petrological data; *Journal of Petrology*, Vol. 19, p. 463-513.
- GILL, J.B., 1982. Mountain building and volcanism; in *Mountain Building Processes*, Academic Press, p. 13-17, (Hsu, K.J. ed.).
- GROVE, T.L. and KINZLER, R.J., 1986. Petrogenesis of andesites; *Annual Reviews of Earth and Planetary Sciences*, Vol. 14, p. 417-454.
- HART, S.R. and DAVIS, K.E., 1978. Nickel partitioning between olivine and silicate melt; *Earth and Planetary Science Letters*, Vol. 40, p. 203-219.
- KUSHIRO, I., 1972. Effect of water on the compositions of magmas formed at high pressures; *Journal of Petrology*, Vol. 13, p. 311-334.
- LAHR, J.C. and PLAFKER, G., 1980. Holocene Pacific-North American plate interaction in southern Alaska: implications for the Yakataga seismic gap; *Geology*, Vol. 8, p. 483-486.
- LE BAS, M.J., LE MAITRE, R.W., STRECKEISEN, A. and ZANETTIN, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram; *Journal of Petrology*, Vol. 27, p. 745-750.
- LERBEKMO, J.F. and CAMPBELL, F.A., 1969. Distribution, composition, and source of the White River ash, Yukon Territory; *Canadian Journal of Earth Sciences*, Vol. 6, p. 109-116.
- MACKEVETT, JR., E.M., 1970. Geology of the McCarthy B-4 quadrangle, Alaska; *United States Geological Survey, Bulletin 1333*, 31 p.
- MACKEVETT, JR., E.M., 1978. Geologic map of the McCarthy quadrangle, Alaska; *United States Geological Survey, Misc. Inv. map I-1032*, scale 1:250,000.
- MENDENHALL, W.C., 1905. Geology of the Copper River region, Alaska; *United States Geological Survey, Professional Paper 41*, p. 54-62.
- MULLER, J.E., 1967. Kluane Lake map-area, Yukon Territory (115 G, 115 F east half); *Geological Survey of Canada, Memoir 340*, 137 p.
- NYE, C.J., 1983. Petrology and geochemistry of Okmok and Wrangell volcanoes, Alaska; unpublished Ph.D. thesis, University of California Santa Cruz, 115 p.
- PEARCE, J.A. and CANN, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses; *Earth and Planetary Science Letters*, Vol. 19, p. 290-300.
- PEARCE, J.A., 1982. Trace element characteristics of lavas from destruction plate boundaries; in: *Andesites*, John Wiley and Sons, p. 525-548, (Thorpe, R.S., ed.).
- PERFIT, M.R., GUST, D.A., BENICE, A.E., ARCULUS, R.J. and TAYLOR, S.R., 1980. Chemical characteristics of island-arc basalts: implications for mantle sources; *Chemical Geology*, Vol. 30, p. 227-256.
- PRESNALL, D.C., DIXON, S.A., DIXON, J.R., O'DONNELL, T.H., BRENNER, N.L., SCHROCK, R.L. and DYEUS, D.W., 1978. Liquidus phase relations on the join diopside-forsterite-anorthite from 1 atm to 20 kbar: their bearing on the generation and crystallization of basaltic magma; *Contribution to Mineralogy and Petrology*, Vol. 66, p. 203-220.
- RICHTER, D.H. and SMITH, R.L., 1976. Geologic map of the Nabesna A-5 quadrangle, Alaska; *United States Geological Survey, Map GQ-1292*, scale 1:63,360.
- RICHTER, D.H., SMITH, R.L., YEHLE, L.A. and MILLER, T.P., 1979. Geologic map of the Gulkana A-2 quadrangle, Alaska; *United States Geological Survey, Map GQ-1520*, scale 1:63,360.
- RIOU, R., DUPUY, C. and DOSTAL, J., 1981. Geochemistry of coexisting alkaline and calc-alkaline volcanic rocks from northern Azerbaijan (N.W.) Iran; *Journal of Volcanology and Geothermal Research*, Vol. 11, p. 253-275.
- ROEDER, P.L. and EMSLIE, R.F., 1970. Olivine-liquid equilibrium; *Contributions to Mineralogy and Petrology*, Vol. 29, p. 275-289.
- SHERVAIS, J.W., 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas; *Earth and Planetary Science Letters*, Vol. 59, p. 101-118.
- SKULSKI, T. and FRANCIS, D., 1986. On the geology of the Tertiary Wrangell Lavas in the St. Clare Province, St. Elias Mountains, Yukon; in *Yukon Geology*, Vol. 1, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 161-170.

SOUTHER, J.G. and STANCIU, C., 1975. Operation Saint Elias, Yukon Territory: Tertiary volcanic rocks; *Geological Survey of Canada, Paper 75-1A*, p. 63-70.

STEPHENS, C.D., FOGLEMAN, K.A., LAHR, J.C. and PAGE, R.A., 1984. Wrangell Benioff zone, southern Alaska; *Geology*, Vol. 12, p. 373-376.

STOUT, J.H. and CHASE, C.G., 1980. Plate kinematics of the Denali fault system; *Canadian Journal of Earth Sciences*, Vol. 17, p. 1527-1537.

THOMPSON, R.N., 1983. Continental flood basalts...Arachnids rule OK?; in *Continental Basalts and Mantle Xenoliths*, Shiva Geology Series, p. 158-185, (Hawkesworth, C.J. and Norry, M.J., eds.).

WEAVER, S.D., SAUNDERS, A.D., PANKHURST, R.J. and TARNEY, J., 1979. A geochemical study of magmatism associated with the initial stages of back-arc spreading; *Contributions to Mineralogy and Petrology*, Vol. 68, p. 151-169.

YODER, H.S. Jr. and TILLEY, C.E., 1962. Origin of basaltic magmas: an experimental study of natural and synthetic rock systems; *Journal of Petrology*, Vol. 3, p. 342-532.