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TECTONO-MAGMATIC EVOLUTION OF THE 1.9-Ga GREAT BEAR MAGMATIC ZONE, WOPMAY OROGEN, NORTHWESTERN CANADA*

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Abstract

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The 1875-1840-Ma Great Bear magmatic zone is a 100-km wide by at least 900-km-long belt of predominantly subgreenschist facies volcanic and plutonic rocks that unconformably overlie and intrude an older sialic basement complex. The basement complex comprises older arc and back-arc rocks metamorphosed and deformed during the Calderian orogeny, 5-15 Ma before the onset of Great Bear magmatism. The Great Bear magmatic zone contains the products of two magmatic episodes, separated temporally by an oblique folding event caused by dextral transpression of the zone: (1) a 1875-1860-Ma pre-folding suite of mainly calc-alkaline rocks ranging continuously in composition from basalt to rhyolite, cut by allied biotite-hornblende-bearing epizonal plutons; and (2) a 1.85-1.84-Ga post-folding suite of discordant, epizonal, biotite syenogranitic plutons, associated dikes, and hornblende-diorites, quartz diorites, and monzodiorites. The pre-folding suite of volcanic and plutonic rocks is interpreted as a continental magmatic arc generated by eastward subduction of oceanic lithosphere. Cessation of arc magmatism and subsequent dextral transpression may have resulted from ridge subduction and resultant change in relative plate motion. Increased heat flux due to ridge subduction coupled with crustal thickening during transpression may have caused crustal melting as evidenced by the late syenogranite suite. Final closure of the western ocean by collision with a substantial continental fragment, now forming the neoautochthonous basement of the northern Canadian Cordillera, is manifested by a major swarm of transcurrent faults found throughout the Great Bear zone and the Wopmay orogen.

Although there is probably no single evolutionary template for magmatism at convergent plate margins, the main Andean phase of magmatism, exemplified by the pre-folding Great Bear magmatic suite, evolves as larger quantities of subduction-related mafic magma rise into and heat the crust. This results in magmas that are more homogeneous, siliceous, and explosive with time, ultimately leading to overturn and fractionation of the continental crust.

Introduction

The spatial association of magmatic arcs and subduction zones was first recognized by Daly (1933, p. 263) and later became a cornerstone in the theory of plate tectonics and in concepts of crustal growth. Although the tectonic setting of magmatic arcs is one of convergence at the scale of the plates, seismological and geological studies show that deformation localized by arcs is complex, characterized by evolving systems

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of extensional, transcurrent and compressional strains (Dewey, 1980). How arc deformation influences the magmatic processes and their products has not been well described and is, therefore, poorly understood.

In the northwest corner of the Canadian Shield is an early Proterozoic Cordilleran-type plate margin (Hoffman, 1973, 1980a, 1984; Hoffman and McGlynn, 1977; Hildebrand, 1981, 1982, 1984a,b) in which the interaction of deformation and magmatism over a period of about 100 Ma, from 1.94 to about 1.83 Ga, is remarkably well preserved and has been studied in some detail. A comprehensive U-Pb zircon dating program (Bowring and Van Schmus, 1982, in press) founded on 15 years of geological mapping permits the resolution of tectono-magmatic events on the order of 5 Ma, allowing direct comparisons with well-studied Cenozoic magmatic arcs. The purpose of this paper is to outline the tectono-magmatic evolution of the plate margin, and to describe in some detail one component of it, the Great Bear magmatic zone, which was active for a period of about 30 Ma, and includes two distinct phases of magmatism.

Regional geology

The Great Bear magmatic zone occupies most of the western exposed part of the Wopmay orogen, an early Proterozoic north-trending orogen that developed on the western side of the Archean Slave craton between 2.1 and 1.8 Ga (Hoffman, 1973, 1980a). The orogen is divided into three major tectonic elements parallel to the trend of the belt itself. From east to west they are the Calderian accretionary wedge, the Great Bear magmatic zone, and the Hottah terrane (Fig. 1). Each of the 3 tectonic elements contains at least two distinct major magmatic assemblages that together form a magmatic continuum of about 100-Ma duration.

The westernmost zone, the Hottah terrane (Fig. 1), contains the oldest magmatic suite in the Wopmay orogen. The terrane comprises mostly amphibolite facies, sedimentary and intermediate volcanic rocks cut by calc-alkaline biotite-hornblende-bearing plutons (1914–1902 Ma). The volcanic rocks and the plutons are interpreted as a continental magmatic arc originally located on the western edge of the Slave craton (Hildebrand and Roots, 1985). The Hottah terrane is believed to extend eastward as the basement for much of the Great Bear magmatic zone (McGlynn, 1979; Hildebrand et al., 1983).

At about 1900 Ma, arc magmatism apparently shut-down and a bimodal suite of submarine volcanic rocks (Easton, 1981, 1982; Reichenbach, 1985b, 1986) erupted through and onto block-faulted, subsided and sediment-veneered continental crust (Hoffman and Pelletier, 1982). This tectono-magmatic phase was rather short-lived, lasting between 5 and 10 Ma, and is interpreted to represent magmatism related to intra-arc extension that culminated in the development of a marginal basin, which lay to the east of the Hottah arc (Hildebrand and Roots, 1985; Reichenbach, 1985b, 1986, in press). Whether the basin was everywhere floored by stretched continental crust or evolved into an oceanic back-arc basin is unknown, but as it widened, a 2-km-thick west-facing continental margin prism comprising siliciclastic and carbonate rocks developed above the volcanic sequence, lapping well east onto the Archean basement of the Slave craton (Hoffman, 1972, 1973; Grotzinger and Hoffman, 1983; Grotzinger, 1986).

Within 5–10 Ma of its formation, the volcano-sedimentary basin fill was shortened and simultaneously intruded by a diverse suite of peraluminous to metaluminous plutons (1896–1878 Ma), collectively termed the Hepburn intrusive suite (Lalonde, 1984). The shortening culminated in the detachment and thin-skinned eastward thrusting of the imbricated basinal rocks to form the Calderian accretionary wedge (Tirrul, 1983; Hoffman et al., in press) and Hepburn plutons were transported and emplaced onto the nonstretched western margin of the Slave craton. Inverted

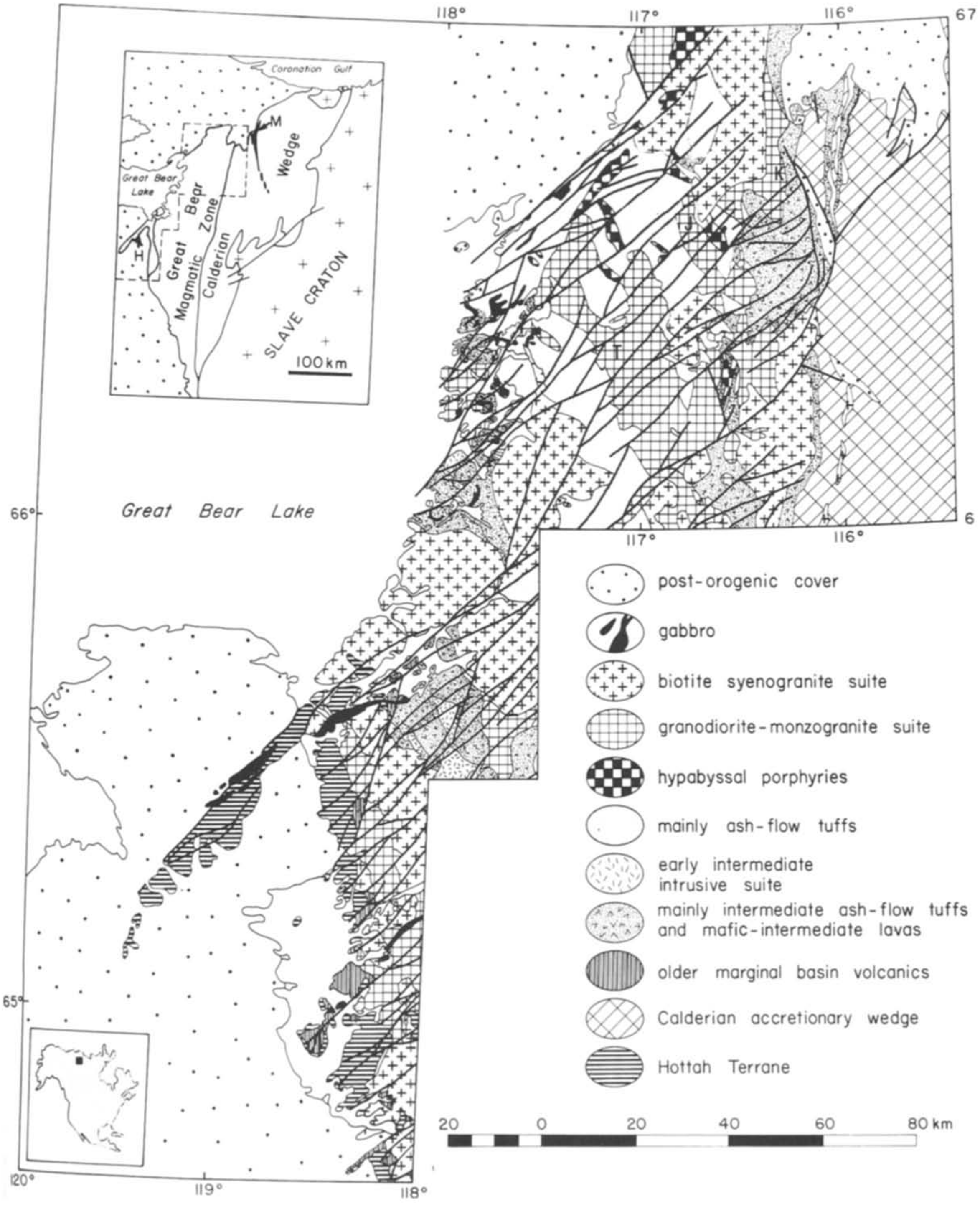

Fig. 1. Generalized geological map of the northern and western parts of the Great Bear magmatic zone showing the distribution of major rock units. This figure is based on geological mapping by the authors over the period 1973 to the present. Although virtually all of the zone has been mapped in reconnaissance fashion, this figure shows only our more detailed work in recent years. Inset maps show the location of Wopmay orogen and its tectonic subdivisions. *M* = Muskox intrusion; *H* = Hottah terrane; *T* = Torrie pluton, *J* = Jacier pluton, *K* = Kamut pluton.

metamorphic isograds, that cut obliquely across the basal décollement, resulted as hot plutons of the Hepburn intrusive suite, were placed over the colder autochthon (St-Onge et al., 1984; St-Onge, in press).

The Great Bear magmatic zone contains the two youngest magmatic suites exposed in the orogen. The zone is an approximately 100-km-wide belt of mainly volcanic and plutonic rocks (1878–1843 Ma) that outcrop over a strike length of 450 km (Fig. 1) and cover the contact between the Calderian accretionary wedge and the Hottah terrane. The zone continues beneath a thin veneer of flat-lying Paleozoic cover rocks in the south, and gently-dipping Proterozoic cover in the north, where it can be traced for an additional 400–500 km on the basis of a strong positive magnetic anomaly (Coles et al., 1976). This interpretation is supported in the south by granitoid and volcanic rocks recovered from drill holes (Williams, 1981) on the magnetic high and in the north by the Great Bear outliers.

There was at least one major period of deformation during Great Bear magmatism, post-dating all of the volcanic rocks and separating the plutons into two suites (Hoffman and McGlynn, 1977). The deformation produced macroscopic folds which plunge gently about northwest-trending axes, oblique to the trend of the zone as a whole, except adjacent to the margins of the zone where they trend north (Hoffman and McGlynn, 1977). Because the folds generally trend oblique to the zone and are en-echelon, Hoffman (1980a) and Hildebrand (1981) argued that they are dextral transpressional features related to oblique plate convergence (Fitch, 1972).

All rocks of the Great Bear zone are cut by a system of northeast-trending dextral transcurrent faults (used in the sense of Freund, 1974), most steeply dipping to vertical with up to several kilometers of strike-slip displacement. The faults are but one domain of a much larger regional set of conjugate transcurrent faults found throughout Wopmay orogen (Hoffman, 1980a,b, 1984). They reflect east–west shortening and north–south extension approximately plane strain on a regional scale (Tirrul, 1984).

Thus, the overall tectonic-magmatic development of Wopmay orogen is presently considered to represent stages in an evolving Cordilleran-type plate margin developed above an east-dipping subduction zone as follows:

(1) establishment of the Hottah magmatic arc on the western margin of the Slave craton by at least 1914 Ma;

(2) extension within the arc leading to formation of a marginal sea (1900–1890 Ma) behind the arc in which a sedimentary succession accumulated;

(3) shortening of the basin and concurrent emplacement of the Hepburn intrusive suite (1896–1878 Ma);

(4) inception (1878 Ma) and growth of the Great Bear magmatic zone upon the closed marginal basin;

(5) oblique folding of the Great Bear zone between about 1860 and 1850 Ma;

(6) emplacement of syn- to post-folding syenogranites (1858–1843 Ma); and

(7) regional transcurrent faulting at some time between 1843 and 1810 Ma.

Great Bear magmatic zone

All of the volcanic rocks and many of the plutons in the Great Bear magmatic zone are folded. While at first this might appear disadvantageous, it is actually beneficial because unrivaled sections, up to 10 km thick, through the upper crust are exposed on fold limbs. This, along with a general lack of metamorphism and penetrative strain, makes study of the area rewarding in terms of understanding the three dimensional configuration and overall evolution of an early Proterozoic magmatic belt, both of which may have direct application to younger, flat-lying magmatic terranes.

Volcanic rocks

The stratigraphy of the Great Bear magmatic zone is complex in detail but basically consists of volcano-sedimentary sequences on both the eastern and western margins and a younger dominantly volcanic sequence in the central part of the zone. Therefore, the overall structure of the zone is interpreted to be synclinal.

The oldest rocks of the western Great Bear magmatic zone unconformably overlie pillow basalts of the earlier marginal basin on a surface of considerable relief and comprise a heterogeneous amalgamation of subaerial volcanic and sedimentary rocks. This sequence is exposed only along the western margin of the zone in two belts, separated by younger granites and transcurrent faults (Hoffman et al., 1976). Although the facies are very complex, the group has been studied in some detail and it compreses mainly intermediate ash-flow tuff, erupted from large calderas, and lavas of intermediate composition, occurring as post-collapse caldera-fill and forming large stratovolcanoes (Hildebrand, 1981, 1983, 1984a,b, 1985).

The rocks along the eastern margin of the Great Bear zone are similar to those along the western margin but differ in that the ash-flow tuffs are mainly outflow facies rather than intracauldron facies: the tuffs and lavas flowed out over rather broad alluvial plains. The sequence is also characterized by thick sections of lacustrine mudstone intruded by porphyritic intrusions. The rocks along this side of the zone unconformably overlie deformed rocks of the Calderian accretionary wedge and were originally considered (Hoffman and McGlynn, 1977; Hoffman, 1978) to overlie Great Bear volcanics in the central part of the zone; however, recent detailed mapping casts doubt on this relationship and they are here considered to be of similar age to rocks along the western side of the zone. This is consistent with volcanic and sedimentary facies which suggest that the volcanic front was located along the western side of the zone and that the broad expanses of outflow facies tuff and alluvial braidplains represent material deposited behind the main volcanic front.

The youngest supracrustal rocks in the Great Bear magmatic zone occur throughout the central part of the zone. They disconformably overlie the caldera-stratovolcano sequences in the west but occur only in tectonic contact with older rocks in the eastern part of the zone. They are mainly intermediate ash-flow tuffs of great thickness intercalated with andesitic lava flows (Hoffman and McGlynn, 1977) cut by swarms of intermediate composition porphyritic sills. Sections in the central zone differ considerably from the older sequences to the east or west in that there are, for the most part, few sedimentary rocks intercalated with the volcanic rocks. Even though most of the central belt has not been mapped in detail, the great thicknesses, dense welding, and high crystal content of many of the ash-flow sheets suggest that the region contains abundant coalesced and superimposed caldera complexes.

Metamorphism

All of the volcanic rocks are metamorphosed or altered to some degree but the style and intensity vary tremendously. Although the metamorphism and alteration have not been studied in great detail, various types have been recognized in the field, under the microscope, and by chemical analysis. For example many formerly glassy lavas and tuffs lost or gained constituents, especially the alkali and alkaline earth metals, during hydration and devitrification. Other volcanic rocks were altered by hot acidic water and the most altered or metamorphosed rocks of this type occur adjacent to intrusive bodies such as those of the early intermediate intrusive suite (Hildebrand, 1986). Those rocks are intensely Na_2O metasomatized with nearly complete loss of all elements that could not be accommodated in the albite crystal lattice.

As is typical of most young continental volcanic fields, K_2O metasomatism occurs locally. This type of alteration is characterized by a dramatic increase in K_2O, typically to 8–10%, with concommitant loss of Na_2O to values less than 1% (Hildebrand, 1981). Chapin and Lindley (1986) and Sheppard and Gude (1968) relate such changes to destruction of glass by relatively low-temperature, saline-dominated brines in evaporitic basins.

Although there is abundant evidence for local water–rock interaction, there is little evidence for regional metamorphism. Virtually all volcanic textures, including delicate vitroclastic textures, are well-preserved. In many areas, mudstones are still red, a qualitative measure of lack of metamorphism confirmed by study of illite crystallinity elsewhere in the Wopmay orogen (Lucas, 1984).

Rocks selected for chemical analysis span the entire range from samples with fresh pyroxenes to completely recrystallized albitites. The extremely altered rocks were analyzed in order to understand the various chemical changes that took place so that chemical mobility in less altered rocks could be realistically evaluated. In the most altered rocks, affected by high-temperature highly acidic fluids, even the so-called "immobile elements" were mobile (Hildebrand, 1986). Nevertheless, the least altered samples define linear arrays on variation diagrams which are similar to magmatic trends elsewhere.

Plutonic rocks

Plutonic rocks of the zone are divided on the basis of age relations, composition, and structure in a pre-folding supersuite (1875–1860 Ma) that is temporally and compositionally related to volcanic rocks; and a post-folding suite (1858–1843 Ma) with associated north to northeast-trending granitoid dikes but no known eruptive equivalents. The pre-folding supersuite is informally subdivided into 2 suites: "the early intermediate intrusive suite" and the younger "granodiorite-monzogranite suite".

Early intermediate intrusive suite

This suite of plutons is temporally, spatially, and compositionally associated with andesite stratovolcanoes along the western part of the magmatic zone. The plutons are mainly medium-grained sheets and laccoliths, 5–25 km in diameter and 1–2 km thick, of monzonite, monzodiorite, and diorite with razor-sharp external contacts. They intruded 2–3 km beneath the surface, are compositionally heterogeneous, metasomatically altered, had plagioclase as the first liquidus phase, and have kilometer-wide alteration haloes comprising an inner albite zone, a central magnetite-apatite-actinolite zone, and an outer pyritic zone (Tirrul, 1976; Hildebrand, 1984a, 1986). Most are seriate-textured with subhedral-euhedral hornblende and biotite. Border phases may contain serpentinized orthopyroxene and relict clinopyroxene. In general, there are few, if any, xenoliths in the plutons and room for the bodies was probably created by lifting, or doming, of the roof rocks. At least two plutons of this suite were unroofed during subsequent ash-flow volcanism (Hoffman et al., 1976; Hildebrand, 1981, 1984a).

Granodiorite-monzogranite suite

The granodiorite-monzogranite suite is the major pre-folding plutonic suite in the Great Bear magmatic zone. Most plutons of this suite trend northwest, parallel to the regional fold axes (Fig. 1). This, along with the spatial orientation of compositional zoning in individual plutons, suggests that the suite is folded. In general, most large plutons of this suite post-date, or are possibly coeval with, the thick central accumulations of ash-flow tuff. There are, however, several bodies that are temporally and spatially related to calderas of the slightly older western caldera-stratovolcano complexes.

In general, this suite of epizonal plutons has narrow thermal aureoles ranging in grade up to hornblende hornfels facies. Contacts with their wall rocks are commonly flat and semi-concordant, suggesting that many of the plutons are sheet-like in overall form. However, in at least two cases plutons of this suite have dome-

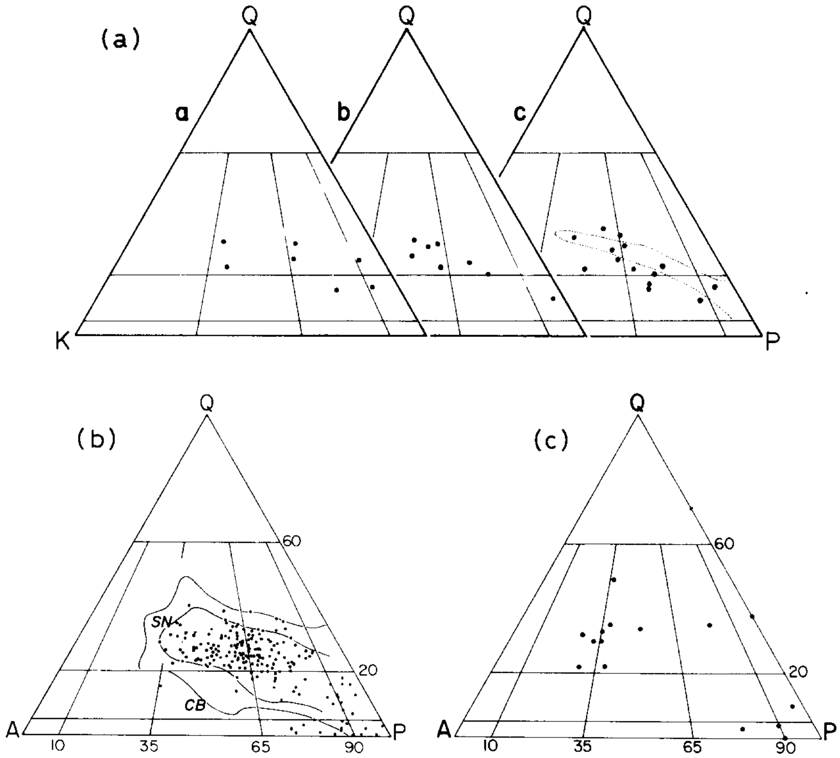

Fig. 2. a. Modal analyses of three intrusive complexes (*a* = Kamut pluton, *b* = Jacier pluton, *c* = Torrie pluton; see Fig. 1 for locations) in the northern Great Bear magmatic zone compared to the modal variation in the Tuolumne Intrusive Series (field outlined by dots), Sierra Nevada batholith (Bateman and Chappell, 1979). Classification triangles after Streckheisen (1976). b. Modal analyses of pre-folding, calc-alkaline plutons of the Great Bear magmatic zone compared to the fields for plutons from the Sierra Nevada (SN) compiled from Bateman et al. (1963) and the Coastal batholith of Peru (CB), compiled from Cobbing et al. (1981) and Atherton and Sanderson (1985). The modes are also similar to, but slightly less quartz-rich overall than those of Cretaceous arc granites in Japan (see Yamada and Katada, 1970) but the line encompassing the Japanese modal analyses has been left out of this diagram for clarity. c. Modal analyses of the post-folding suite of plutons.

shaped roofs where they intrude the cores of caldera complexes and are interpreted as resurgent plutons (Hildebrand, 1984a,b).

Most commonly, members of this suite are large medium-grained, but variable, bodies of seriate-textured granodiorite and monzogranite; syenogranite and quartz diorite are less abundant. They typically contain 5–25% subhedral to euhedral biotite and hornblende, with hornblende mostly predominant. Anhedral quartz and potassium feldspar fill interstices between plagioclase and the ferromagnesian minerals. Several plutons contain 3–4% clinopyroxene rimmed by hornblende. Apatite and zircon are the most abundant accessory minerals.

Individual plutons of this suite are composite bodies and typically have internal modal variations nearly as great as those of the suite as a whole (Fig. 2). In some cases the gradations between phases occur over a few tens of centimeters, and several rock types may occur on the same outcrop. In others the gradations take place over tens of meters.

Post-folding syenogranite suite

The plutons of the post-folding suite are mainly biotite syenogranites and are the largest and most uniform intrusive bodies in the Great Bear magmatic zone. Whereas the contacts of the monzogranite-granodiorite plutons parallel the northwest-trending fold axes, plutons of the

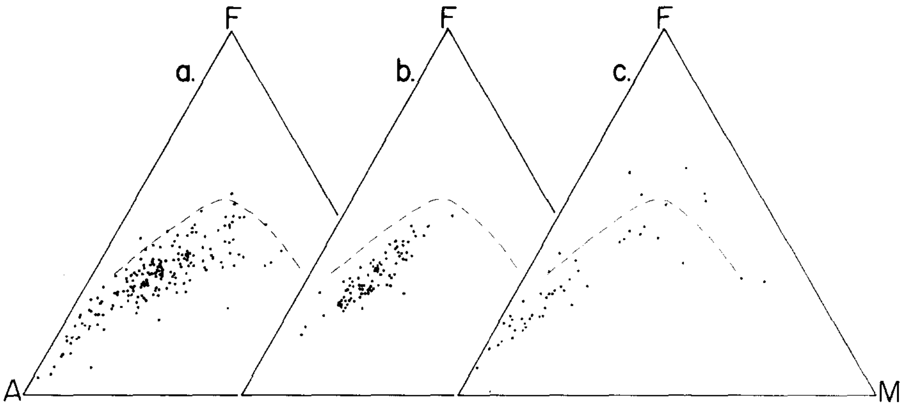

Fig. 3. a. AFM diagram for volcanic rocks of the Great Bear magmatic zone. Dots represent individual analyses from the main volcanic sequences. Dividing line between calc-alkaline and tholeiitic fields is from Irvine and Barager (1971). b. AFM diagram for pre-folding plutonic rocks of the Great Bear zone. c. AFM diagram for post-folding plutonic rocks. The data in this and subsequent chemical plots are normalized to 100% on an volatile free basis and are from Hildebrand (1982, unpublished information) and Bowring (unpublished information).

post-folding suite have external contacts that are completely discordant with respect to folds in the volcanic rocks. In at least two cases, granites of this suite have been shown to be large tabular-shaped bodies with flat floors.

Generally, members of this suite are strongly porphyritic, containing subhedral to euhedral potassium feldspar phenocrysts up to 4 cm long and subhedral crystals of plagioclase up to 1.5 cm in a fine- to medium-grained matrix of anhedral quartz, feldspar, and tiny flakes of biotite. Euhedral to subhedral prisms of hornblende are locally present but are mostly less common than biotite.

Associated in both time and space with the post-folding suite of granites are swarms of siliceous dikes. The dikes generally trend north to north-northeast and are up to 20 or 30 m wide. They are similar in bulk composition to the granites (Hildebrand, 1982) and consist of variable proportions of hornblende, biotite, quartz, and feldspar phenocrysts in a generally cryptocrystalline matrix.

In the eastern part of the magmatic zone, small ovoid to linear bodies of hornblende-quartz diorite, diorite, and monzodiorite intrude, and are intruded by, the syenogranites. They are heterogeneous bodies that contain mostly euhedral hornblende, subhedral plagioclase with subordinate amounts of euhedral sphene, in a fine-grained groundmass of quartz and feldspar. They constitute much less than 1% of the total area covered by the syenogranites; are therefore volumetrically insignificant, but demonstrate that intermediate magmatism was active after folding of the Great Bear zone.

Chemistry

Chemical analyses of rocks from the Great Bear magmatic zone (Tables 1 and 2) indicate that the vast majority of magmatism in the zone was calc-alkaline (Fig. 3). Overall, the volcanic rocks form a continuous suite ranging in composition from basalt to rhyolite, with the bulk of analyzed samples of intermediate silica content (Fig. 4). They typically have less than 1% TiO_2 (Table 1). A comparison of major oxide content with values for other arcs, as compiled by Ewart (1979, 1982), indicates that the magmatic rocks of the zone are best classified as a high-K suite, similar in most oxide contents to the Andes and the Cenozoic arcs of western North America (Fig. 5).

Rare earth element (REE) analyses of both volcanic and plutonic rocks show that they are

TABLE 1

Representative analyses of volcanic rocks, Great Bear magmatic zone

Sample no:	Lavas						Ash-flow tuffs				
	C-81-76	S-80-78	H-80-7	H-80-89	H-80-12	J-79-128	P-80-59	J-80-4	R-80-109	H-79-129	H-79-137
SiO_2	49.6	48.0	54.6	53.9	56.8	55.8	63.2	63.7	66.6	67.5	72.3
TiO_2	1.00	0.74	0.61	0.87	0.70	0.80	0.53	0.55	0.59	0.29	0.22
Al_2O_3	17.7	19.6	18.7	14.7	15.2	15.6	15.7	15.9	16.4	13.7	12.2
Fe_2O_3*	9.46	9.64	5.70	7.57	8.55	8.02	5.52	5.38	4.51	3.91	3.49
MnO	0.13	0.18	0.15	0.17	0.19	0.27	0.17	0.10	0.08	0.22	0.09
MgO	5.79	4.99	2.58	6.32	3.92	5.54	2.18	2.33	1.15	2.26	0.76
CaO	5.55	9.34	6.54	6.37	5.37	6.28	4.08	3.65	3.01	0.93	0.60
Na_2O	2.80	2.10	4.13	2.00	2.61	2.78	3.39	3.20	2.89	3.02	2.41
K_2O	2.78	3.02	3.73	4.08	3.53	2.92	3.63	3.80	4.66	4.83	5.91
P_2O_5	0.33	0.27	0.31	0.26	0.17	0.19	0.12	0.17	0.18	—	0.04
LOI	3.38	2.76	1.70	2.33	1.68	1.44	1.80	1.17	1.08	2.38	1.66
Total	99.00	100.6	98.75	98.57	98.79	99.64	100.32	99.95	101.2	99.04	99.69
Nb	7	3	9	10	10	8	11	10	14	17	21
Zr	142	76	133	157	151	126	132	145	208	151	298
Y	23	20	25	26	27	26	32	30	34	34	64
Sr	399	435	430	578	343	357	364	376	272	176	96
U	2	6	0	8	11	4	5	3	8	5	5
Rb	74	137	108	109	124	102	133	148	149	183	230
Th	0	4	3	12	4	3	11	12	16	24	24
Pb	9	20	12	21	23	13	37	31	32	7	6
Ga	21	21	17	19	18	20	—	23	23	7	6
Zn	100	111	86	129	105	186	141	111	69	277	98
Cu	0	73	0	191	0	0	28	0	9	19	15
Ni	14	18	11	89	14	34	—	4	4	11	—
Cr	4	7	27	226	49	150	0	7	0	16	—
V	204	183	151	170	167	178	318	84	48	63	239
Ba	648	743	779	1372	1049	845	683	795	1256	851	1009

Samples analyzed by AA, ICP, and XRF at Memorial University of Newfoundland and the Geological Survey of Canada; 0 = not detected; — = not analyzed.

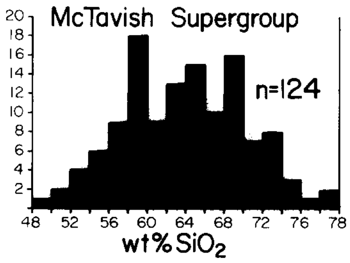

Fig. 4. Histogram of silica content in volcanic rocks of the Great Bear magmatic zone illustrating its dominantly intermediate nature.

enriched in light REE and have high overall abundances (Hildebrand, 1981, 1982). A few mafic andesites have less evolved flat REE patterns with abundances of REE around 10–20 times chondrite. Mass balance calculations (Hildebrand, 1982) show that it is possible to generate the more evolved REE patterns found in the high-silica andesites and the intermediate tuffs from the low-silica andesites by fractionation of plagioclase, clinopyroxene, and orthopyroxene. However, such solutions are not unique because various combinations of fractionation and assimilation yield the same results. Virtually all the high-silica andesites have REE abundances and patterns that are similar to the dacitic and rhyodacitic ash-flow tuffs, suggesting that the tuffs and lavas represent different magma batches. In terms of major and trace elements it appears impossible to derive the ash-flow tuffs from the andesites by fractionation using combinations of the observed phenocryst phases.

TABLE 2

Representative analyses of plutonic rocks, Great Bear magmatic zone

Sample no:	Early intermediate intrusive suite				Granodiorite-monzogranite suite				Post-folding suite		
	J-79-62	H-79-40	C-79-12	C-79-14	H-78-351	J-80-94	HY-57-74	HY-28-74	H-80-58	P-80-36	HY-105-73
SiO_2	60.5	65.5	53.6	50.8	65.4	65.5	58.0	68.4	65.9	73.7	51.9
TiO_2	0.59	0.34	0.51	0.72	0.30	0.55	0.65	0.39	0.57	0.34	1.43
Al_2O_3	14.1	15.9	20.6	18.9	14.6	14.4	15.0	14.6	13.6	12.7	17.5
Fe_2O_3*	6.49	4.12	5.98	7.75	3.19	4.37	7.11	3.35	5.90	2.21	10.1
MnO	0.36	0.04	0.10	0.22	0.08	0.06	0.21	0.07	0.44	0.03	0.21
MgO	3.33	1.51	2.24	2.54	1.88	1.76	3.37	1.26	1.39	0.35	4.29
CaO	4.76	3.71	5.49	5.14	3.08	3.30	5.29	2.19	1.31	1.34	5.19
Na_2O	2.45	3.25	4.18	3.21	3.33	2.96	3.07	3.06	2.52	2.61	1.99
K_2O	4.15	4.03	3.51	3.72	3.90	4.41	3.71	4.25	5.10	5.63	4.17
P_2O_3	0.14	0.10	0.26	0.55	0.06	0.10	0.22	0.10	0.14	0.08	0.32
LOI	2.88	0.64	2.81	2.81	3.98	1.40	3.00	1.80	1.45	0.92	3.50
Total	99.69	99.14	99.28	98.36	99.80	98.80	99.63	99.47	98.32	99.61	100.6
Nb	13	12	3	8	12	11	11	12	27	22	13
Zr	185	187	64	89	138	147	150	190	340	211	160
Y	25	36	15	24	27	27	15	19	77	74	46
Sr	264	280	642	579	208	214	320	320	134	84	360
U	4	5	0	0	5	3	0	0	8	14	0
Rb	160	142	110	113	139	196	120	170	211	307	130
Th	15	17	9	1	22	15	0	19	30	43	0
Pb	62	20	5	21	6	22	31	24	64	41	23
Ga	—	13	19	21	14	—	—	—	19	—	—
Zn	125	29	77	170	84	48	170	77	311	43	150
Cu	63	22	4	38	0	16	28	18	5	11	20
Ni	—	13	22	4	19	—	61	35	2	—	47
Cr	94	14	22	10	22	0	87	46	0	0	36
V	113	59	104	212	66	268	190	48	40	11	230
Ba	834	973	935	1158	537	518	1200	890	1448	518	720

Samples analyzed by AA, ICP, and XRF at Memorial University of Newfoundland and the Geological Survey of Canada; 0 = not detected; — = not analyzed.

Virtually all pre-folding plutonic rocks of the zone are I-type (Chappell and White, 1974) and calc-alkaline (Fig. 3b). It is not only the entire suite which defines a classic calc-alkaline trend, and smooth trends on variation diagrams, but each individual compositionally zoned plutonic complex does so as well (Fig. 6). This suggests that each complex represents an individual batch of magma that underwent subsequent fractionation to produce the observed trends as envisioned for the Sierra Nevada batholith (Presnall and Bateman, 1973). Within the pre-folding suite there is a general trend toward more siliceous compositions with time; the early intermediate suite having a lower mean silica content than the granodiorite-monzogranite suite (Fig. 7a,b).

The post-folding syenogranite suite is also calc-alkaline (Fig. 3c) and I-type but is somewhat bimodal (Fig. 7c), containing mainly syenogranites and lesser quantities of intermediate rocks. Individual plutons of this suite, although very large, are more siliceous than either of the pre-folding suites and display less variation in composition. Most members of this suite are slightly corundum normative. The intermediate plutons of the post-folding suite are both calc-alkaline and tholeiitic (Fig. 3c).

The Great Bear magmatic zone as a volcano-plutonic arc

The process of subduction leads to a strongly linear, or arcuate chain of magmatism in all Cenozoic arcs, whether continental or oceanic

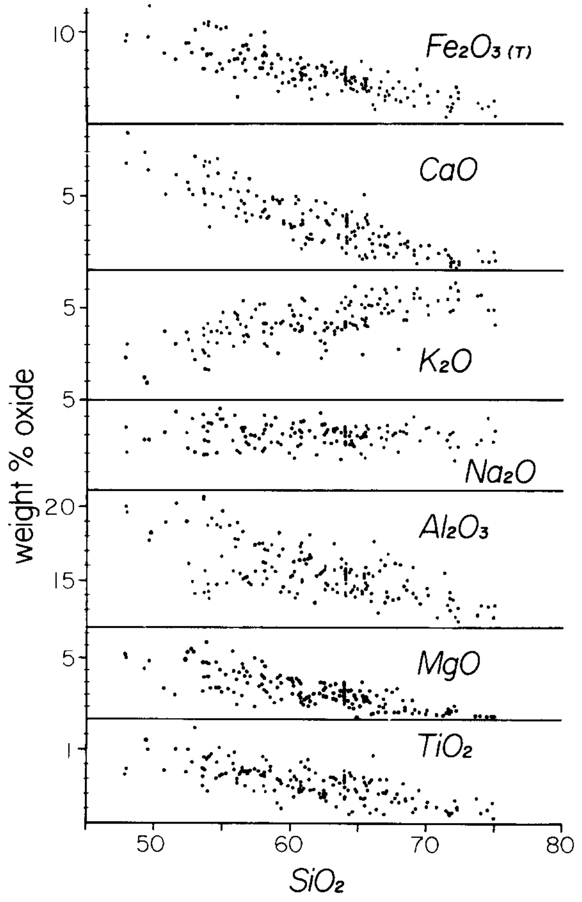

Fig. 5. Harker diagrams for least altered volcanic rocks in the Great Bear magmatic zone.

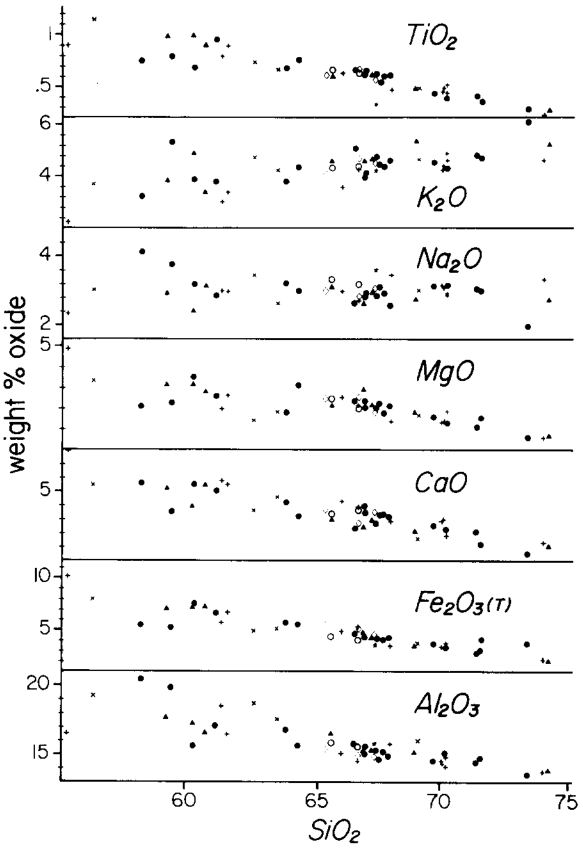

Fig. 6. Harker diagrams for pre-folding granodiorite - monzogranite suite. Dots = Torrie pluton; + = Jacier pluton; triangles = Kamut pluton; other symbols = other individual plutons. Note that several plutons have chemical variations as large as the entire suite.

and most young arcs developed upon continental crust, such as the Alaskan Peninsula (Burk, 1965), Japan (Aramaki and Ui, 1982), Sumatra (van Bemmelen, 1949; Verstappen, 1973), the Sierra Nevada batholith (Bateman, 1981, 1983), and the Coastal batholith of Peru (Cobbing et al., 1981; Pitcher, 1985), are about 100 km wide at any one time. The Great Bear magmatic zone is such a belt, its length being at least 900 km and its width 100 km. Furthermore, it exactly parallels the ancient continental margin as defined by sedimentary facies, a feature of all young arcs built on continental crust.

The regional geological and tectonic setting appears to be similar to several Cenozoic arcs in that the Great Bear magmatic zone sits upon a collapsed marginal basin (Hildebrand and Roots, 1985; Reichenbach, 1985b, 1986b, in press; Hildebrand et al., 1986). Many continental arcs, such as the Coastal batholith of Peru (Cobbing et al., 1981; Atherton et al., 1983, 1985) and the Sierra Nevada batholith (Davis et al., 1978; Saleeby, 1981), straddle a closed marginal basin or a suture between an accreted terrane and continent. This may be the norm rather than the exception because subduction tends to step outboard of the accreted block following collision and physically the Benioff Zone must dip toward the continent if subduction is to continue long enough for the slab to reach sufficient depths for arc volcanism to ensue.

The synclinal structure of the Great Bear

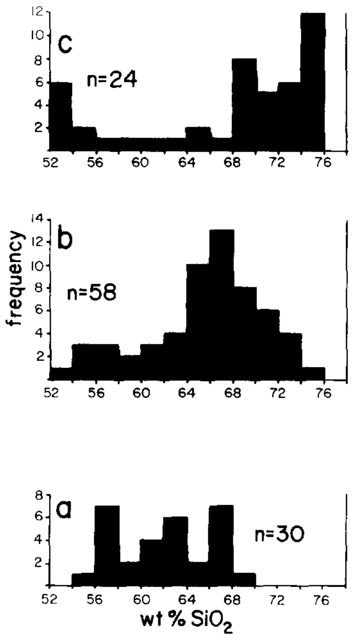

Fig. 7. Histograms showing the silica variation in the three main plutonic suites of the Great Bear magmatic zone. a. Early intermediate intrusive suite; the two peaks at either end result from more analyses of 2 plutons studied in detail. b. Monzogranite-granodiorite suite; c. Post-folding syenogranites and quartz diorites.

magmatic zone, with the oldest rocks on both margins and the youngest in the core, is common in younger continental arcs. We have elsewhere (Hildebrand and Bowring, 1984) hypothesized that such synclinal basins in arcs develop when the mass of basaltic andesite emplaced in the lower crust equals the mass of vitric ash transported out of the immediate region by high level winds. Irrespective of their origin, such synclinal structures with very thick sections of supracrustal rocks occur in many young continental arcs, such as the Mesozoic–Paleogene arc of Chile (Zeil, 1979; Levi and Aguirre, 1981; Åberg et al., 1984), the coastal lowlands of Hokkaido, Japan (Oide, 1968), Kamchatka (Erlich, 1968, 1979), and the Sierra Nevada batholith (Bateman, 1968; Fiske and Tobisch, 1978; Busby-Spera, 1984).

The overall chemical composition of the suite is comparable to Cenozoic continental magmatic arcs. The volcanic rocks of the Great Bear magmatic zone range continuously in composition from basalt to rhyolite (Figs. 4 and 5), thus forming a typical basalt-andesite-dacite-rhyolite association. The suite is calc-alkaline and all of the rocks have very low TiO_2, a feature common to arc rocks (Ewart, 1979, 1982; Green, 1980). REE analyses from the volcanic rocks have the light-REE-enrichment patterns and high overall abundances typical of continental magmatic arcs such as the Andes (Thorpe et al., 1976, 1979; Atherton et al., 1979), Sardinia (Dupuy et al., 1979), and the San Juan volcanic field (Zielinski and Lipman, 1976).

Modal compositions of the pre-folding plutonic suites are virtually identical to classic examples of Cordilleran batholiths such as the Coastal batholith of Peru and the Sierra Nevada batholith of California (Fig. 2).

The general magmatic evolution of the zone is similar to other continental arcs in that magmatism progressed with time from intermediate stratovolcanoes and calderas to dominantly ash-flow volcanism followed by intrusion of large granodioritic-monzogranitic plutons. For example, a similar progression of arc magmatism is known from the Cretaceous arc of Japan (Ichikawa et al., 1968).

Although any one of the above is not in itself compelling evidence, when taken together they overwhelmingly support the idea that the pre-folding rocks of the Great Bear magmatic zone represent an arc. Furthermore, if ancient arcs were generated by the same processes as those of today then the Great Bear arc provides evidence for the subduction of oceanic lithosphere during the early Proterozoic. In this case, the subduction must have been easterly directed because any ocean or marginal basin between the Hottah terrane and the Slave craton had already closed during the Calderian Orogeny.

Cessation of arc magmatism, origin of the syenogranites and closure of the western ocean

Arc magmatism in the Great Bear magmatic zone stopped at about 1.860 Ga (Bowring and

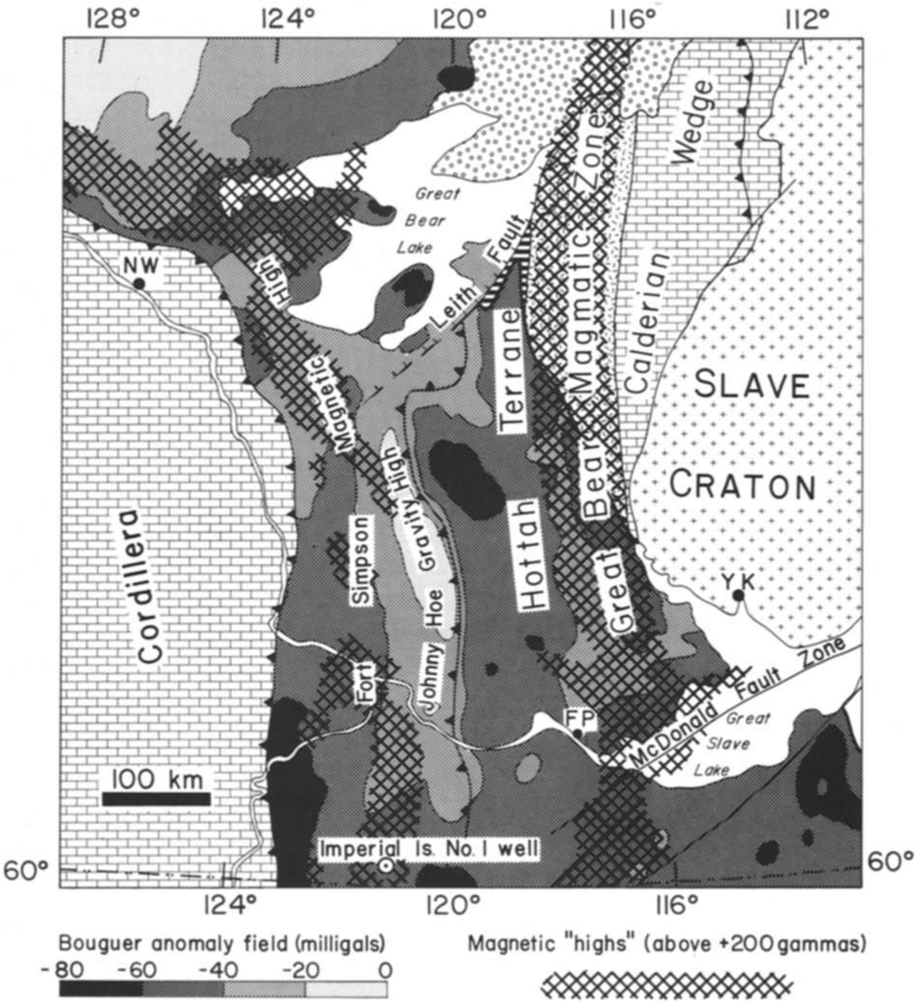

Fig. 8. Diagram showing the prominent gravity and magnetic anomalies beneath the thin Paleozoic sedimentary cover west of the Canadian Shield. See text for discussion. *NW* = Norman Wells, *FP* = Fort Providence, *YK* = Yellowknife.

Van Schmus, 1982; in press) and the arc rocks were folded about axes that are oblique to the overall trend of the zone (Hoffman and McGlynn, 1977). Emplacement of large, discordant, epizonal granites and small bodies of quartz diorite followed between about 1858 and 1843 Ma (Bowring and Van Schmus, 1982, in press). After intrusion of the post-folding plutons, but probably prior to 1.81 Ga (Hoffman, 1980a; Hoffman et al., in press), the entire magmatic zone and the rest of Wopmay orogen was broken by a swarm of transcurrent faults. The following tectonic model, based on geological, geophysical and geochronological evidence, is proposed to account for the cessation of Great Bear magmatism, the oblique folding, the post-folding plutons, and the transcurrent faults.

About 100–150 km west of the Great Bear magmatic zone, beneath thin Paleozoic platform cover, are paired gravity anomalies, high to the west, which lie between to linear magnetic highs 200 km apart (Fig. 8). The eastern magnetic high represents the Great Bear zone and the other, termed the Fort Simpson magnetic high, is interpreted to represent an arc on

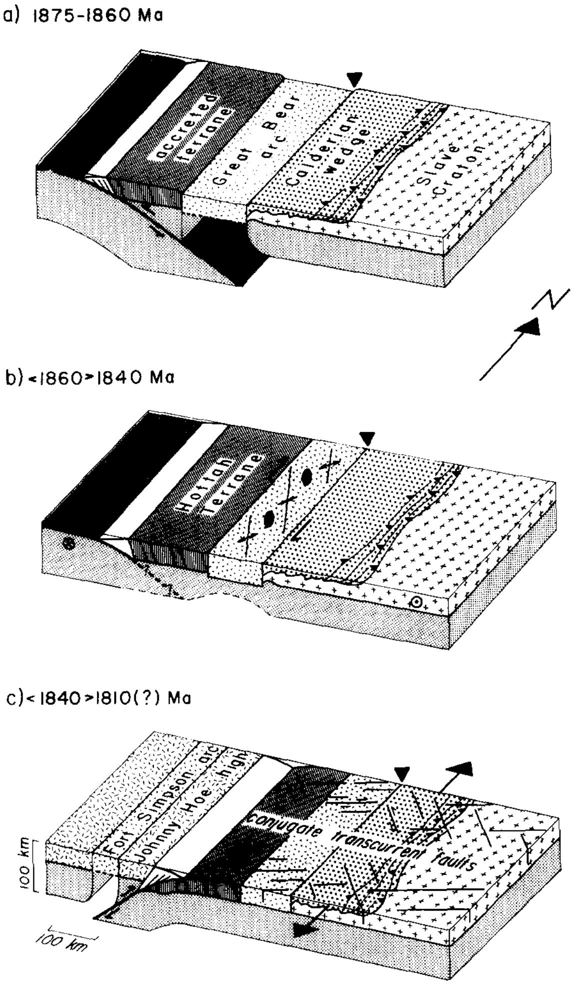

Fig. 9. Cartoon illustrating the overall magmatic and tectonic evolution of the Great Bear magmatic zone: a. Eastward-directed subduction of oceanic crust leads to arc magmatism in the suture zone between an older accreted terrane (Hottah Terrane), believed to represent the west side of a marginal basin in which volcanic and sedimentary rocks of the Calderian wedge were deposited, and the Slave craton between about 1875 and 1860 Ma. b. Ridge subduction leads to a change in relative plate motions and the Great Bear magmatic zone is folded during transpression. c. A collision between the western margin of the amalgamated Hottah-Slave continent and an unnamed arc-bearing continental block to the west, along a suture located at the eastern margin of the Johnny Hoe gravity high, generates the conjugate transcurrent faults throughout the northwestern Canadian Shield.

the opposite side of the ocean that lay to the west of the Great Bear arc (Hoffman et al., 1982). We theorize that arc volcanism in the Great Bear zone shut-down due to subduction of a spreading, or aseismic, ridge located in the ocean that lay between the Great Bear and Fort Simpson arc (Fig. 9a). Cessation of arc magmatism resulting from subduction of a ridge is a common feature in Mesozoic–Cenozoic arc terranes. For example, arc volcanism stopped in Japan during the Late Jurassic as the ridge between the Farallon and Izanagi-Kula plates was subducted beneath Asia (Maruyama and Seno, 1985); in California as the East Pacific rise was subducted beneath North America (Atwater, 1970; Dickinson and Snyder, 1979); in South America during the ongoing subduction of the Chile rise (Forsythe and Nelson, 1985) and the Nazca Ridge (Vogt et al., 1976) into the Peru-Chile trench; and again in Japan about 48 Ma ago following subduction of the ridge between the Pacific plate and the Kula plate (Taira, 1981, 1985; Ozawa et al., 1985; Maruyama and Seno, 1985). Arc magmatism may also be shut-down by the subduction of other high-standing topographic features such as remnant arcs, as is presently the case where the Palau-Kyushu ridge is being consumed by the Nankai trough (Kelleher and McCann, 1977).

Following cessation of arc magmatism the entire Great Bear magmatic zone was folded in an en-echelon fashion oblique to the trend of the zone as a whole (Fig. 9b). This suggests that the relative plate motions between the two plates were different following ridge subduction than before, much in the same way as relative plate motions in western North America changed after subduction of the East Pacific rise (Atwater, 1970; Atwater and Molnar, 1973). The oblique, en-echelon nature of the folds indicates that in the case of the Great Bear magmatic zone such plate interactions were transpressive; that is, the entire arc was dextrally wrenched. Although there is a major strike-slip fault near the eastern margin of the zone along which considerable movement took place, most, if not all, of the movement pre-dates Great Bear magmatism (Hoffman and McGlynn, 1977; King et al., 1983) and it can-not be a major wrench fault responsible for the folding as is common elsewhere (Fitch, 1972; Wilcox et al., 1973). We suggest that such a fault is not necessary for the generation of the folds because the lithosphere beneath the arc was probably "softened" and thinned to such a degree by mafic magmas rising through, interacting with, and melting it that it behaved in a much more plastic manner relative to the cooler, more rigid internal zone of the Wopmay orogen to the east or the fore-arc region to the west (Dewey, 1980).

Shortly after folding, the suite of syenogranite plutons was emplaced at very high structural levels. That they post-date folding is clear from their discordant relationships to the folded rocks and sheet-like form. However, the overall stress regime just prior to, or during, their emplacement may still have been transpressive because the porphyritic dike swarms associated with the suite have a north-northeast trend, compatible with dextral transpression. The syenogranites are clearly of crustal derivation and owe their origin to widespread anatexis of the lower crust, perhaps caused by the thermal effects of ridge subduction coupled with those of crustal thickening due to folding. The plutons are closely comparable in composition, temporal relationship to arc magmatism, texture, and mineralogy to the "big-feldspar granites" of the Coastal batholith (Pitcher, 1978) and the "leucoadamellites" of the New England batholith (Shaw and Flood, 1981) but the origin of the Phanerozoic examples is unresolved at present.

The youngest syenogranite plutons of the Great Bear magmatic zone and the rest of the Wopmay orogen are sliced and broken by a regional set of conjugate transcurrent faults. Tirrul (1984) has shown that the faults probably resulted from regional east–west shortening. The faults are similar to swarms of transcurrent faults in other orogenic belts related to distal collisions (Freund, 1970; Molnar and Tapponnier, 1977; Tirrul et al., 1983). We concur with Hoffman et al. (1982) that the paired gravity anomalies, located beneath the thin Paleozoic cover to the west of the Hottah terrane, may represent the site of a suture between the western margin of the Hottah terrane and an arc-bearing microcontinent or continent. The polarity of the gravity anomalies — high to the west, low to the east — suggests that the leading edge of the Hottah terrane was subducted beneath the eastern margin of the postulated continental block represented by the Johnny Hoe gravity high (Fig. 9c). The Fort Simpson magnetic high, located just west of the gravity high, can then be interpreted as due to magnetite-rich arc plutons on the upper plate. The maximum age of such an arc is unconstrained but the minimum age should be no younger than the age of the transcurrent faulting, about 1.81 Ga (Hoffman, 1980a), if the transcurrent faulting is related to the closure of the ocean west of the Hottah terrane. A sample of biotite-hornblende granodiorite, recovered from an oil well (Imperial Island No. 1 — see Fig. 8 for location) that penetrated basement on the magnetic high, has yielded a U-Pb zircon age of 1.86 Ga, consistent with the model presented here both in rock type and age. Thus, the timing of events in the Great Bear magmatic zone and the geophysical data are explained by eastward subduction of oceanic lithosphere, ridge subduction, consequent dextral transpression of the zone, and ultimate collision due to west-dipping subduction beneath another continental block. The extent of the Fort Simpson magnetic high (Fig. 8) suggests that the hypothesized collided continent might underlie much of the northern Canadian Cordillera.

Discussion

We consider that the overall evolution of the Great Bear magmatic zone represents only about 30 Ma in the life of a continental magmatic arc located at a convergent plate boundary active for at least 100 Ma (Hildebrand et al., 1986). Based on Cenozoic magmato-tectonic interactions, changes in magma composition are interpreted to reflect changes in the stress regime. For example, when magmatism is of the "classical" Andean-type the stress regime is essentially neutral. When an arc terrane is extended, a bimodal suite dominated by basalt results and a intra-arc, or marginal, basin may form. Alternatively, when an arc is compressed a somewhat bimodal suite, dominated by silicic melts similar to the post-folding suite of the Great Bear magmatic zone, may be typical.

Although there is probably no overall pattern of magmatism at convergent plate margins because the magmatism responds to a variety of stresses which themselves may vary in a non-systematic fashion, it is possible for individual phases of magmatism related to specific stress regimes to have a typical or common evolutionary path. For example, our data for the main Andean phase of magmatism in the Great Bear magmatic zone suggest that it became more homogeneous, more explosive, and more siliceous with time. Plutonism became progressively more important, at least in the upper 10 km of crust we are able to observe, and pre-folding magmatism culminated in the emplacement of batholithic masses at very high crustal levels.

The evolution of magmatism during the Andean phase can be explained if we consider that the rise and emplacement of mafic magmas into continental crust generates intermediate to siliceous melts by crustal fusion, assimilation, and mixing (Presnall and Bateman, 1973; Eichelberger and Gooley, 1977; Hildreth, 1981). Thus, during the earliest stages of arc development magmatism is generally intermediate to siliceous in composition and relatively small volume without large plutonic equivalents because the crust is not hot enough for large volumes of crustal melt to be generated by the crystallization of basaltic magma. With increasing time and continued influx of mafic magma into the lower crust, the temperature of the region is elevated and larger quantities of crustal melts are generated, eventually leading to greater volumes of magma that rise diapirically toward the surface. Some of the diapirs erupt to form caldera complexes and stratovolcanoes and others invade previously erupted volcanic rocks much in the manner envisioned by Hamilton and Myers (1967). Protracted intrusion by subduction-related basalt eventually raises the temperature of the lower crust to such a degree that volumes of magma on the order of hundreds of thousands of cubic kilometers begin to rise toward the surface. That is, the lower, or middle, crust rises diapirically to create the extensive ash-flow fields and related batholithic masses that characterize Andean-type continental arcs. Such "crustal overturning" coupled with the influx of mafic magma results in chemical and isotopic fractionation of the continental crust.

Conclusions

Detailed study of the Great Bear magmatic zone reveals that it is a linear belt of volcanic and plutonic rocks that contains the products of two distinct magmatic episodes separated by a period of oblique folding: a major calc-alkaline suite of volcanic and plutonic rocks developed upon a continental margin and a suite of biotite syenogranites and subordinate intermediate bodies. The calc-alkaline suite is a typical Andean-type volcanoplutonic arc and probably developed in a relatively neutral tectonic regime although located at a convergent plate margin. Calc-alkaline magmatism lasted for 15–20 Ma before it stopped and the arc folded. The somewhat bimodal post-folding suite is related to a transpressional stress regime and it may owe its origins to the combination of high heat flow during ridge subduction and crustal thickening due to transpression.

The Andean phase of magmatism in the Great Bear zone became progressively more siliceous, explosive, and homogeneous with time. The observed secular trends result from the protracted rise of mafic magmas into the crust, and their crystallization, a process that increases the ambient temperature of the crust such that successive batches of mafic magma can generate increasingly larger quantities of crustal melts.

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