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Tectonic evolution of the Brooks Range ophiolite, northern Alaska

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Abstract

Analysis of internal structures of the Brooks Range ophiolite at the three largest and well-exposed klippen reveals a NE–SW structural grain that may parallel the original axis of magmatism of a slow spreading marginal ocean basin. Sub-parallel directions of lattice fabrics in olivine of mantle peridotite and shape fabrics in pyroxene and plagioclase of layered gabbro indicate that asthenospheric and magmatic flow was closely coupled. These structures, including the petrologic moho, mostly dip steeply to the NW and SE, with slightly oblique flow lineations. Sedimentary and volcanic cover deposits also dip SE. The few exposures found of sheeted dike complexes generally strike parallel, but dip orthogonal to both the petrologic moho and cover deposits. These structural features are locally disturbed by syn- and post-magmatic normal faults emblematic of slow-spreading ridge processes. However, the consistent geometry of structures over a distance of 200 km demonstrates not only that the magmatic system was organized in a similar manner to an oceanic ridge, but that there was little to no rotation of individual klippe during tectonic emplacement.

Ductile fabrics related to tectonic emplacement yield top-to-the NNW sense of shear indicators. The basal thrust and accompanying serpentinized shear zone is mostly flat-lying and truncates the steeply dipping ductile fabric of the ophiolite. This relationship and paleomagnetic data from the igneous sequence suggest that flow fabrics were most likely moderately inclined at the time the ophiolite formed. Similar relationships are found at diapiric centers along oceanic ridges and in other ophiolite bodies.

Keywords: Ophiolites; Brooks Range; Alaska; Structure

1. Introduction

Ophiolites provide a unique opportunity to understand the structure of oceanic lithosphere and the processes of ocean basin construction and demise. Geometrical relations between sedimentary and volcanic cover sequences, sheeted dikes, magmatic layering, and the mantle/crust transition zone can indicate the general orientation and character of the magmatic system that formed the ophiolite (Ave Lallemant, 1976; Juteau et al., 1977; Nicolas and Violette, 1982). Kinematic indicators from ductile fabrics formed at various temperatures can reveal the flow pattern of asthenosphere and magmas. The degree of syn- and post-magmatic extension provides evidence for slow- versus fast-spreading (Dilek et al., 1998). Shear fabrics along the structural base of an ophiolite provide clues about its tectonic emplacement history. Many of these structural features are found throughout the Brooks Range ophiolite of northern Alaska, yet few are documented.

This paper presents a synthesis of new data collected from the Brooks Range ophiolite during a series

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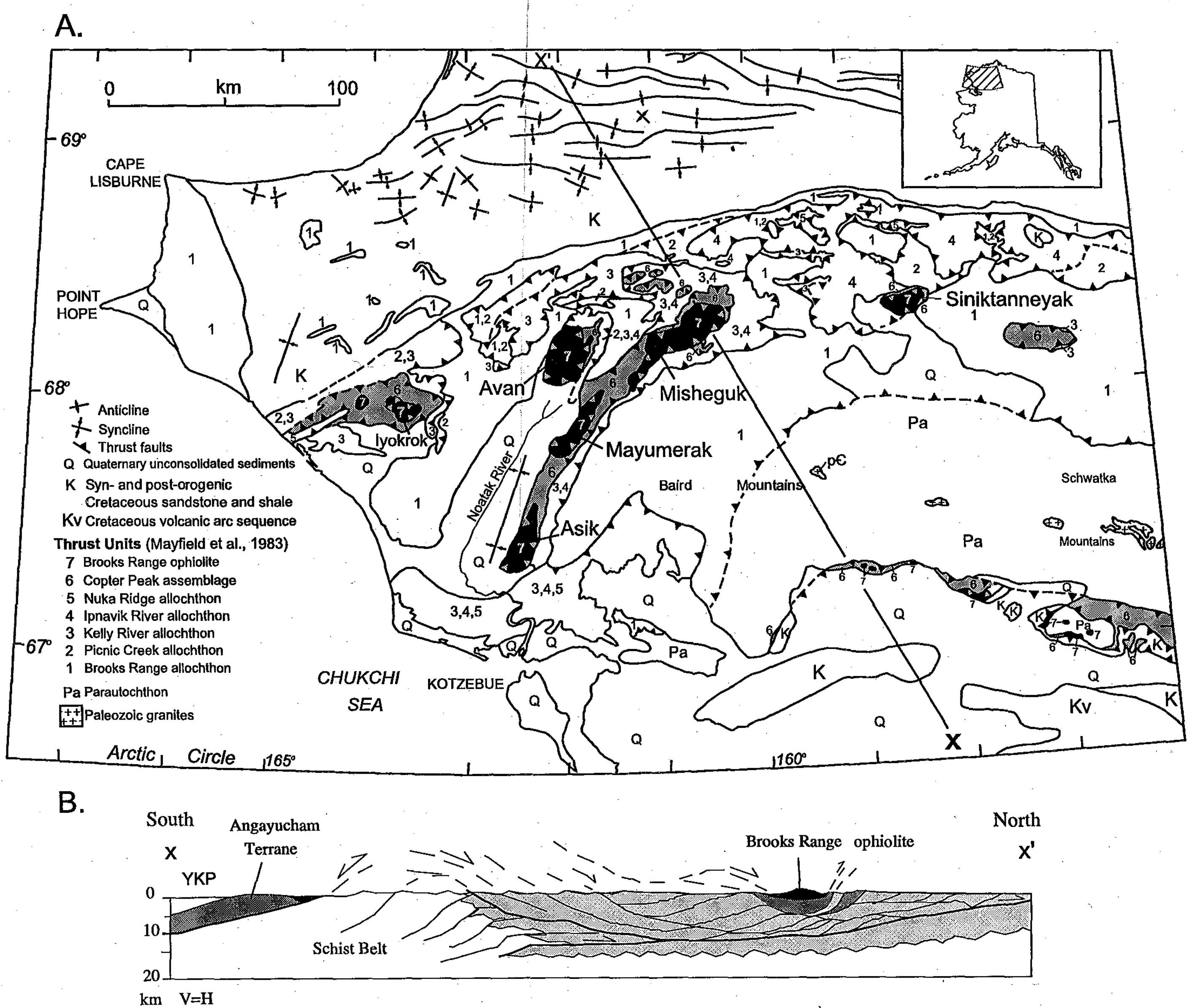

A.
0 km 100
69°
68°
67°
CAPE LISBURNE
POINT HOPE
Avan
Iyokrok
Misheguk
Mayumerak
Asik
Siniktanneyak
Noatak River
Baird Mountains
Schwatka Mountains
CHUKCHI SEA
KOTZEBUE
Arctic Circle
165°
160°
X'
X
Anticline
Syncline
Thrust faults
Q Quaternary unconsolidated sediments
K Syn- and post-orogenic Cretaceous sandstone and shale
Kv Cretaceous volcanic arc sequence
Thrust Units (Mayfield et al., 1983)
7 Brooks Range ophiolite
6 Copter Peak assemblage
5 Nuka Ridge allochthon
4 Ipnavik River allochthon
3 Kelly River allochthon
2 Picnic Creek allochthon
1 Brooks Range allochthon
Pa Parautochthon
Paleozoic granites
B.
South
North
X
X'
Angayucham Terrane
YKP
Brooks Range ophiolite
Schist Belt
0
10
20
km V=H

of mostly reconnaissance-scale field studies of the internal structure, age and composition of the three largest ophiolite klippen imbedded in the Brooks Range fold and thrust belt (Fig. 1). These new data provide a way to relate the tectonic evolution of the Brooks Range ophiolite with other ophiolites of similar age, structure and composition found throughout the Circum-Pacific region. The structural analysis focuses mostly on how the geometry of magmatic flow fabrics and lithological layering at each ophiolite body relate to one another and to newly discovered sheeted dikes and cover deposits. The paper also places the Brooks Range ophiolite into a spreading ridge reference frame and the geological setting of the Jurassic Brooks Range arc-continent collision.

2. Geological overview of the Brooks Range

The Brooks Range of northern Alaska is the northern- and western-most expression of the North American Cordilleran fold and thrust belt. Its stratigraphic record preserves a long interval of passive continental margin development that persisted from at least the Carboniferous until Middle Jurassic arc-continent collision (Churkin et al., 1979; Dutro, 1981; Mull, 1982; Box, 1985; Patton and Box, 1989). The tectonic setting of the collision is emblematic of decoupled, Tethyan-type orogenic systems (Burchfiel and Davis, 1975). These orogens are characterized by simultaneous extension and shortening, where marginal basins open behind an active collisional fold–thrust belt. Fragments of the oceanic basins are commonly incorporated into the orogenic wedge as passive roof thrusts under which shortened units of a passive continental margin are successively stacked (Harris, 1992).

General descriptions of the western Brooks Range, where the ophiolite klippen reside, were first published by Martin (1970), Tailleur (1970), and Mayfield et al. (1983). Their reconstructions of the Devonian to Jurassic thrust assemblage shows that it is regionally arranged with more distal units above more proximal ones, with the ophiolite at the top of the stack. Locally, out-of-sequence faults disrupt this order. The thrust assemblage as a whole records greater than 400 km of total shortening beneath and in front of the ophiolite nappe (Mull, 1982; Mayfield et al., 1983; Oldow et al., 1987).

A similar tectonic scenario to the Brooks Range is inferred for most of the Jurassic Cordillera of western North America (Moores, 1970; Burchfiel and Davis, 1975; Schweickert and Cowan, 1975; Saleeby, 1982). However, much of the Cordillera has been repeatedly modified and obscured by post-Sevier orogenic pulses, whereas the western Brooks Range has been mostly shielded from these events.

3. The Brooks Range ophiolite

The Brooks Range ophiolite consists of six klippen-like massifs (Fig. 1) of similar composition, internal organization, structure, and age. The individual massifs most likely represent eroded remnants of what was initially an extensive roof thrust more than 350 km in length, 50 km in width, and several km thick. Although most of the upper-crustal cover units have been eroded away, a complete, relatively undeformed succession of ophiolite units is preserved in synforms in the core of the fold and thrust belt.

The three most complete massifs, Avan, Misheguk and Siniktanneyak, are the focus of this study (Figs. 2 and 3). Each of these bodies offers nearly comprehensive exposure of the structural base of the Brooks Range ophiolite, the overlying mantle sequence, transition zone with the crust, and thick sections of layered and massive gabbro (Fig. 4). High-level intrusives are found at Misheguk and Siniktanneyak. Sheeted dikes, pillow basalt and sedimentary cover units are preserved at Siniktanneyak. Studies of the tectonomagmatic affinity (Harris, 1995), age (Boak et al., 1987; Harris, 1992; Wirth and Bird, 1992), and emplacement kinematics (Harris, 1998) of the Brooks

Fig. 1. Lithotectonic units of the western Brooks Range (modified from Mayfield et al., 1983). (A) Map of the various thrust units, including the Brooks Range ophiolite (black) and Copter Peak assemblage (gray). Notice the westward change in strike of the fold and thrust belt from E–W to NE–SW. (B) Schematic cross section showing structural position of the Brooks Range ophiolite nappe (black); Copter Peak assemblage/ Angayucham Terrane (dark grey); pre Mississippian basement (white); sedimentary cover sequences (light grey). The ophiolite nappe is preserved in a synform of the fold and thrust belt. YKP = Yukon–Koyukuk Province (Cretaceous arc complex).

Range ophiolite present an emerging understanding of its tectonic evolution and significance. The results of these studies are summarized here.

3.1. Composition

The Brooks Range ophiolite consists of the following sequence of units in ascending order, with the correlative map symbol used in Figs. 2 and 3: (1) metamorphic sole (ms), (2) tectonized peridotite (tp), (3) emplacement-related granitic intrusives (gre), (4) transitional ultramafic cumulates (tum), (5) layered gabbro (lg), (6) massive gabbro (mg), (7) high-level intermediate intrusives (hi), (8) ultramafic/mafic late-stage intrusions (uml), and (9) diabase dikes (dd), pillow basalt (pb), and sedimentary deposits. Each nappe generally displays a consistent, steeply dipping, NNE-trending internal structure dominated by large dunite-rich pods locally up to 4 km thick (Fig. 3). These bodies are commonly transitional into layered gabbro up to 2 km thick. Many of the contacts between ophiolitic units are extensional faults that juxtapose hanging walls of upper crustal material against footwalls of mantle and lower crustal units. The petrochemistry of the ophiolite sequence (Harris, 1995) indicates that it is transitional between ocean-ridge basalt (ORB)- and arc-type affinities, which is a common characteristic of ophiolites originating above a subduction zone (e.g. Stern and Bloomer, 1992; Taylor et al., 1992).

3.1.1. Mantle sequence

The mantle sequence consists of sparse tectonized harzburgite and lherzolite and thick (2–4 km) dunite

a

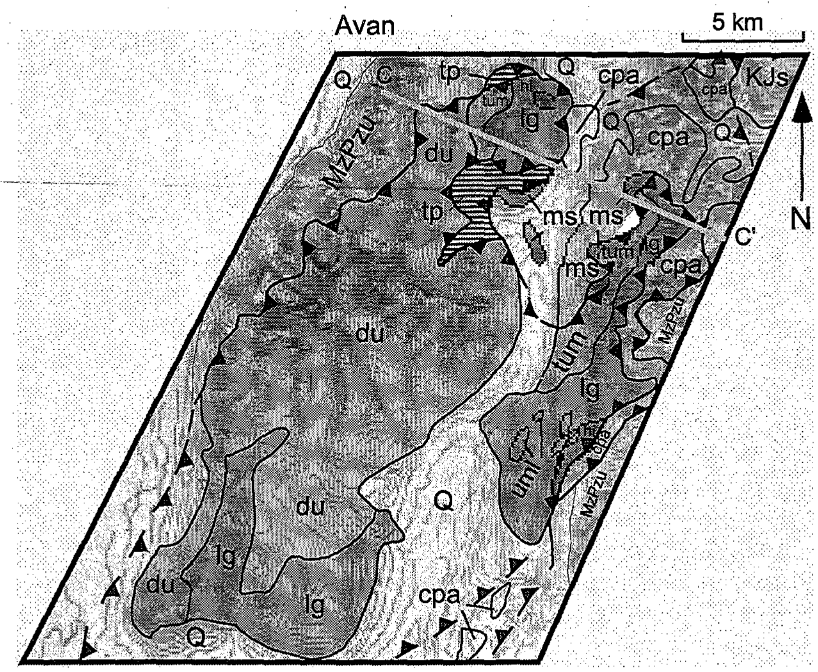
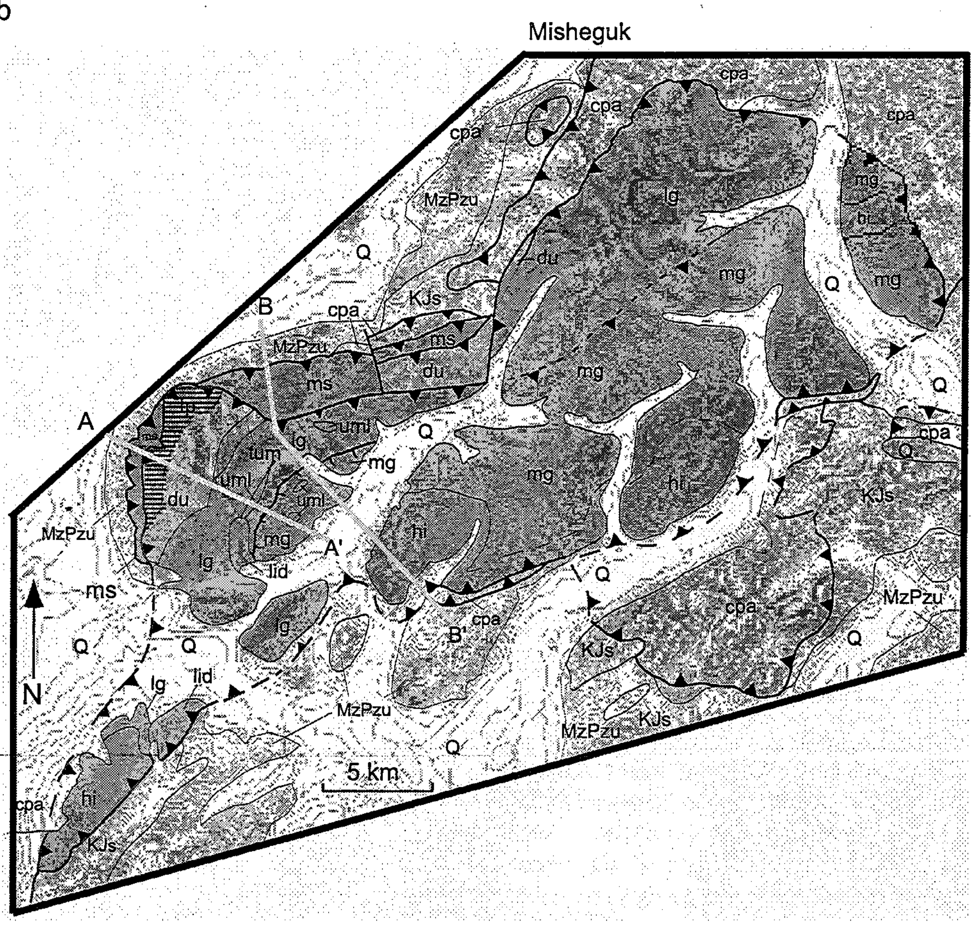


Fig. 2. Reconnaissance geologic maps of the Avan, Misheguk and Sinaktanneyak ophiolite bodies of the Brooks Range ophiolite. Description of units (in ascending order): MzPzu—Mesozoic/Paleozoic undifferentiated, cpa—Copter Peak assemblage, ms—metamorphic sole, tp—tectonized peridotite, du—dunite, tum—transitional ultramafic cumulates, lg—layered gabbro, wh—wehrlite, mg—massive gabbro, hi—high-level intermediate intrusives, uml—ultramafic/mafic late-stage intrusions, dd—diabase dikes, pb—pillow basalt, KJs—Cretaceous/Jurassic synorogenic units, Q—Quaternary units. Credit Note: Compiled from Ellersieck et al., 1982; Frank and Zimmerman, 1982; Nelson and Nelson, 1982; Harris, 1995, 1998; Bickerstaff, 1994; and unpublished maps from R.A. Harris, J.Y. Foley, and T.D. Light, 1986–1992. Base maps from Delorme. This figure can be viewed in colour in the web version of the article.

b



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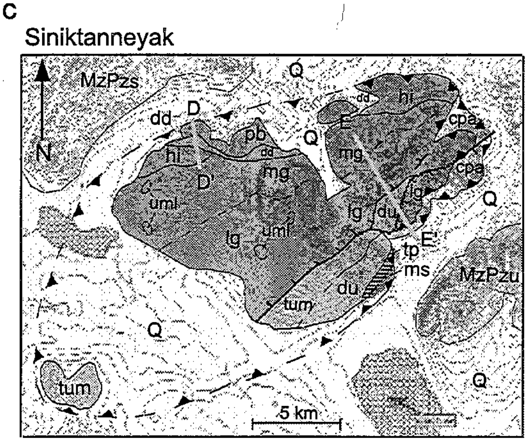


Fig. 2 (*continued*).

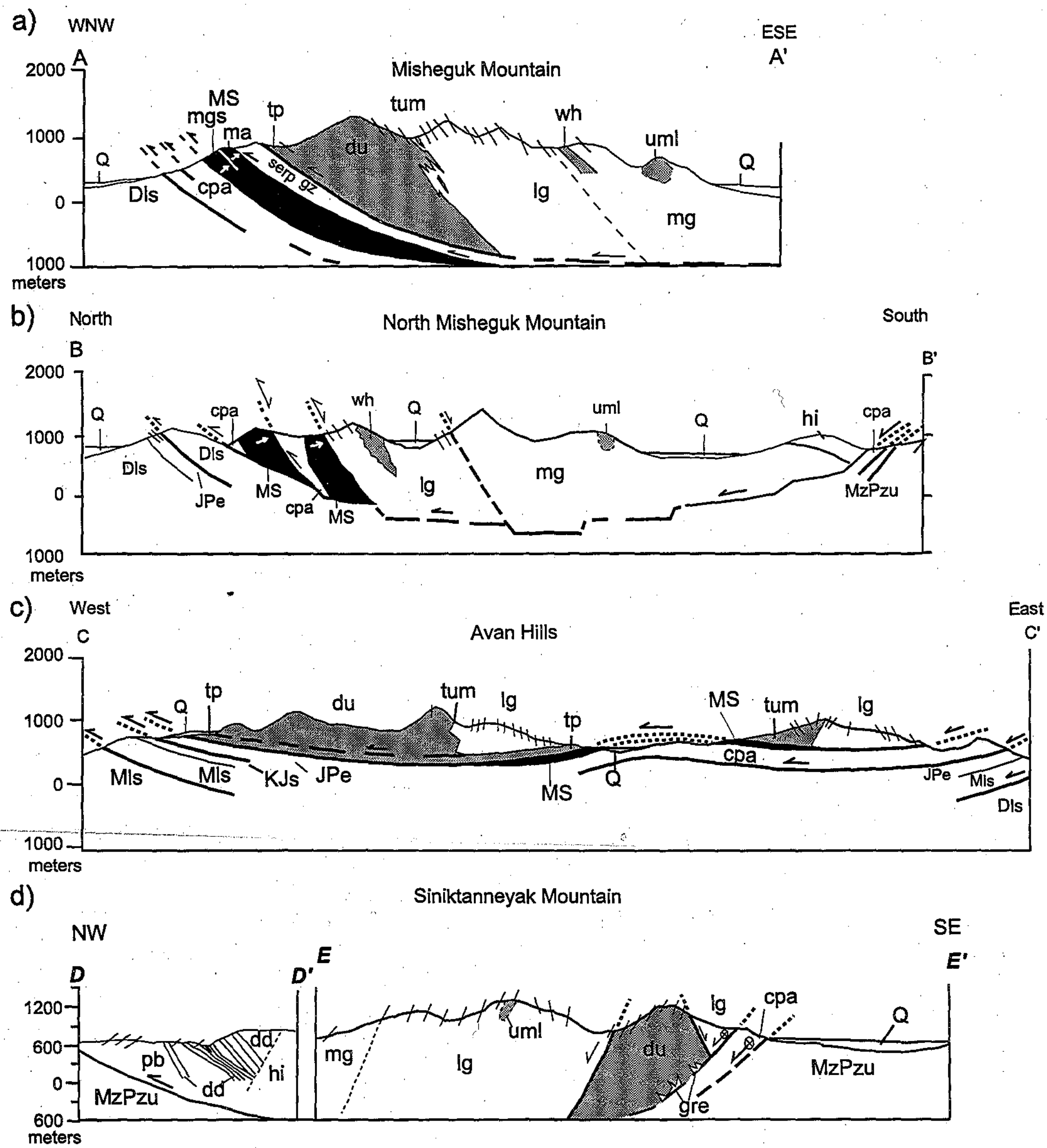


Fig. 3. Cross-sections of the Brooks Range ophiolite. Lines of section and description of units are given in Fig. 2. Notice the flat-lying nature and exposure of the emplacement thrust at Avan, and the different facing direction of the Siniktanneyak body. The truncation of steeply dipping internal layering of the ophiolite bodies by emplacement faults and serpentinite and metamorphic soles precludes that these layers are steep because of post-emplacement folding. Units not included in Fig. 2: Dls—Devonian limestone, Mls—Mississippian limestone, JPe—Jurassic to Pennsylvanian Etivluk Group, mgs—greenschist facies metamorphic sole, ma—amphibolite facies metamorphic sole, gre—emplacement-related granitic intrusives.

bodies (Figs. 2–4). The mineral and whole-rock chemistry of the mantle sequence yield intermediate abundances of magmaphile elements, Mg-rich olivine, Al-poor orthopyroxene, Ti-poor clinopyroxene (cpx), and Cr-rich spinel. These characteristics are typical of intermediate to high amounts (>20%) of melt extraction consistent with a supra-subduction zone setting (Pearce et al., 1984).

Intruded into the mantle sequence are a series of small (< 10 m thick), wedge-shaped, two mica granitoid bodies that extend up from mylonites of the metamorphic sole. Many of the dikes have mylonitic fabrics as well, which indicates that they were most likely generated by partial melting of footwall rocks during thrust emplacement. These intrusions have been found at the structural base of each of the ophiolite bodies (Harris, 1998).

3.1.2. Crustal sequence

Cumulate sequences of the upper-most mantle and lower crust are clinopyroxene-dominant. The most common crystallization sequence is olivine–cpx–plagioclase, which yields the rock sequence dunite–wehrlite–olivine gabbro. Cumulate layers of the mantle/crust transition zone grade into a more cyclic and gabbro-dominant layered series up to 4 km thick (Fig. 3). The thickness of layers and grain size decreases upward and grade into a zone of variegated textures separating layered and massive gabbros. Cumulate textures and structures are poorly preserved. A strong foliation, defined by planar preferred orientation of plagioclase, indicates disruption of cumulate crystallization textures by contemporaneous or later magmatic and/or tectonic processes.

The layered gabbro series and ultramafic intrusives of the Brooks Range ophiolite are dominated by clinopyroxene, which is partially depleted in TiO_2 relative to clinopyroxene in ORB-type cumulates. The cumulate crystallization sequence and notable lack of opx is characteristic of intermediate-type ophiolite complexes (i.e. Ishiwatari, 1985). These ophiolites are more evolved than most ORB-type sequences, but not as much as an arc complex. For example, co-existing calcic plagioclase (An_{87}) and moderately Fe-rich olivine (Fo_{77}) in gabbros at Misheguk (Harris, 1995) and Siniktanneyak (Bickerstaff et al., 1993) are more akin to oceanic island arc tholeiite cumulate sequences than those associated with ORB (Beard, 1986).

A zone of variegated textures ranging from altered microgabbro to pegmatite facies is commonly found near the top of the layered gabbro series. Veins filled mostly with prehnite and locally clinozoisite crosscut secondary mineral phases. The zone of variegated textures marks a sharp boundary between layered and massive gabbro. It also represents the maximum depth of hydrothermal metamorphism and secondary mineral stability. Alteration products include assemblages of chlorite + actinolite + albite + epidote. Lack of preferred orientations and incomplete reactions of secondary minerals, and the limited depth of water/rock interaction are all characteristics of sea-floor metamorphism under static, greenschist and lower amphibolite facies conditions. The grade of metamorphism decreases from the base of the zone of secondary mineral stability upward through high-level intrusives and cover sequences (Bickerstaff et al., 1993). High-level intrusives commonly crosscut and alter layered and variegated gabbro assemblages, mostly lack penetrative magmatic flow fabric, and are very altered. Intrusive contacts are mostly sharp, indicating that the host gabbro had cooled significantly before intrusion of high-level leucocratic bodies.

3.1.3. Cover sequence

Mafic dikes, pillow lavas, and sedimentary material of the cover sequence, are scarce throughout the Brooks Range ophiolite and associated ophiolitic rocks of northern Alaska (Patton et al., 1977). A continuous section from massive gabbro and high-level intrusives into a complete cover sequence is found at Siniktanneyak (Bickerstaff et al., 1993). This section, which is unbroken by major faults, includes a cover sequence of pillow basalt, broken pillow breccia and sheet flows that is depositionally overlain by water-lain, bedded tuff. The tuff is finely bedded with alternating green and black layers between 2 and 12 mm thick that dip 25° to the NW. Abundant extensional growth faults and soft sediment collapse structures offset the tuff layers.

A similar cover sequence section is also reported from Maiyumerak (Fig. 1), although the relation of this sequence to the rest of the ophiolite is not exposed (Wirth, 1991; Wirth et al., 1994). Both of these sections consist of sheeted dikes and pillow basalt with a lower greenschist facies metamorphic overprint characteristic of sea floor alteration. Analysis of trace and rare-earth elements shows a consistent affinity for 'Island Arc Tholeiite' and 'Arc Volcanic' fields of various basalt discrimination diagrams (Bickerstaff et al., 1993).

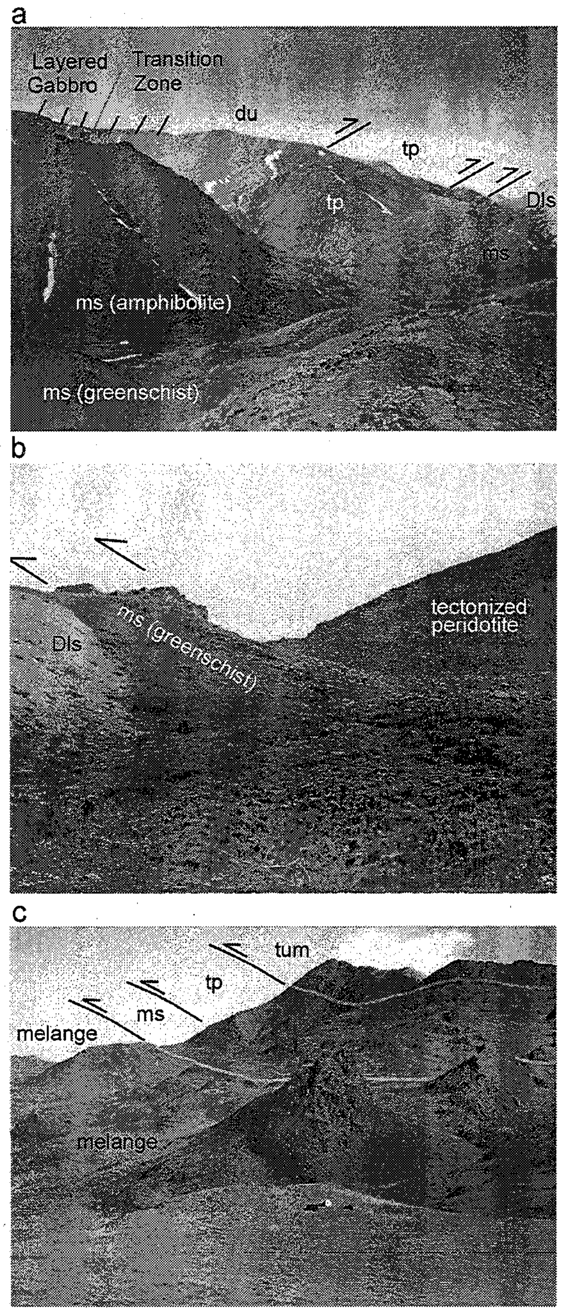
The composition and alteration of the Brooks Range ophiolite cover sequences contrast sharply with the basalt–chert–limestone assemblage (Copter Peak assemblage) that structurally underlies the Brooks Range ophiolite (Harris, 1998; Harris et al., 2003). The Copter Peak assemblage (cpa, Figs. 2–4) consists mostly of basaltic rocks with intercalated chert layers that yield Pennsylvanian to Upper Triassic radiolaria, and carbonate units of Devonian age(?). The basalt is commonly alkalic with trace-element characteristics of "within plate basalts" (Moore, 1987; Harris, 1992, 1998; Wirth et al., 1994). These data show that the Brooks Range ophiolite and CPA were derived from different magmatic lineages and preclude the possibility that they could be co-magmatic as suggested first by Roeder and Mull (1978) and more recently by Saltus et al. (2001). A similar relationship between ophiolites and structurally underlying continental rift assemblages is found associated with most Tethyan-type ophiolites (Dilek et al., 1999), such as in Oman where the Semail Ophiolite structurally overlies the older and chemically distinct Haybi volcanics (e.g. Lippard et al., 1986).

3.1.4. Late-stage intrusives

Throughout the Brooks Range ophiolite are found intrusions of wehrlite–gabbro bodies into the upper crustal part of the ophiolite sequence. These occur as sills and pods (10–100 m in thickness) that intrude the layered series, high-level gabbro, and diorite (Figs. 2 and 3). These rocks are chemically and petrologically indistinguishable from mafic and ultramafic rocks of adjacent dunite transition zones, which may be their source. The intrusion of these bodies into high levels of the crustal sequence may have involved late stage magmatic processes associated with compactional stresses (Nicolas and Rabinowicz, 1984), or shortening during tectonic emplacement (Reuber, 1988).

3.1.5. Summary

The composition of the Brooks Range ophiolite is akin to that of the Zambales ophiolite of the Philippines, and the Oman and Vourinos ophiolites of the Tethyan belt (Harris, 1992). Each of these ophiolites defines an intermediate compositional type that is transitional between ORB- and Arc-types (Ishiwatari, 1985). Transitional-type ophiolites are considered by Pearce et al. (1984) to represent tholeiitic magmas derived from partial melts of a moderately depleted mantle. Most modern analogs of this type of oceanic lithosphere are found in marginal and intra-arc ocean basins that formed



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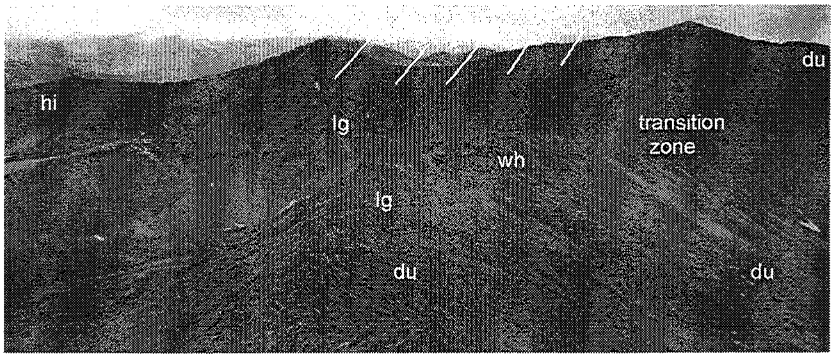

Fig. 4. Photographs of the Brooks Range ophiolite. (a) Looking SW from the northern edge of Misheguk (near 'B' in Fig. 2). Black lines trace the orientation of mafic and ultramafic cumulate layers. In the foreground is the thickest section of the sub-ophiolite metamorphic rocks found throughout the Brooks Range ophiolite. The metamorphic grade increases toward the basal thrust of the ophiolite. (b) Looking NE at the structural base of Misheguk from near 'A' in Fig. 2b. Structural stripping has removed most of the units seen in (a). Tectonized peridotite (tp) is juxtaposed with a thin sheet of greenschist facies metamorphic sole and Devonian limestone (Dls). (c) Looking NE from near 'B' in Fig. 2b at the structural base of the Misheguk ophiolite body. Structural stack of thrust sheets include (from top to bottom) (1) dunite and tectonized peridotite of the mantle sequence; (2) metamorphic sole that increases in metamorphic grade upward toward basal thrust of the ophiolite; (3) mélange with building-sized blocks of basalt, chert and limestone, mostly derived from the Copter Peak assemblage (CPA) that are encased in scaly clay matrix mostly derived from Pennsylvanian to Triassic distal continental margin units of the Etivluk Group. The large block in the foreground (near tents) is alkalic pillow basalt. (d) Looking SW from the top of Misheguk Mountain (highest peak in far left of (a)) at the mantle/crust transition zone. White lines are traces of inclined layered gabbro (lg) layers of the lower crustal sequence. The transition zone is composed of inter-fingers of dunite (du), wehrlite (wh) and gabbro (lg). The transition zone is over 300 m thick in this location. Misheguk Mountain is the highest peak near the boundary between layered gabbro (lg) and high-level intrusives (hi). The ridge on the horizon is around 2 km in length. This figure can be viewed in colour in the web version of the article.

above subduction zones (i.e. Stern and Bloomer, 1992).

3.2. Age relations

The Jurassic age of the Brooks Range ophiolite was first established by conventional K/Ar analysis of amphibole, which yielded a wide age range from 147 ± 5 to 202 ± 6 Ma (Fig. 5). Boak et al. (1987) interpreted the young amphibole ages (147–156 Ma) as reset during obduction-related metamorphism. The older ages (161–202 Ma) were interpreted as either from slow cooling or a composite terrane of ophiolite fragments of various ages.

^{40}Ar/^{39}Ar age analysis of hornblende from gabbro and plagiogranite at both Asik (Harding et al., 1985) and Misheguk (Fig. 6, Table 1) yield eight plateau ages that cluster between 163 and 169 ± 2–4 Ma. A zircon U/Pb age of 170 ± 3 Ma from plagiogranite that intrudes gabbro at Siniktanneyak also falls within this range (Moore et al., 1993). These ages are mostly concordant with those reported from igneous boulders and cobbles found in Late Jurassic to Early Cretaceous mélange and clastic sedimentary rocks of the Brooks Range (Mayfield et al., 1978). The lack of any other possible igneous source material for this detritus suggests that it was most likely sourced from the erosion of Brooks Range ophiolite cover sequences. A striking age similarity also exists between the Brooks Range ophiolite and igneous material from the Koyukuk Terrane and associated ophiolites south of the Brooks Range (Loney and Himmelberg, 1989), including those throughout other parts of the Cordillera and Tethys (Harris, 2004).

3.3. Tectonic emplacement

Structural field relations, petrological and geochemical studies, and radiometric age analysis of metamorphic rocks at the base of the Brooks Range ophiolite provide a record of the time, tectonic setting, and initial conditions of ophiolite emplace-

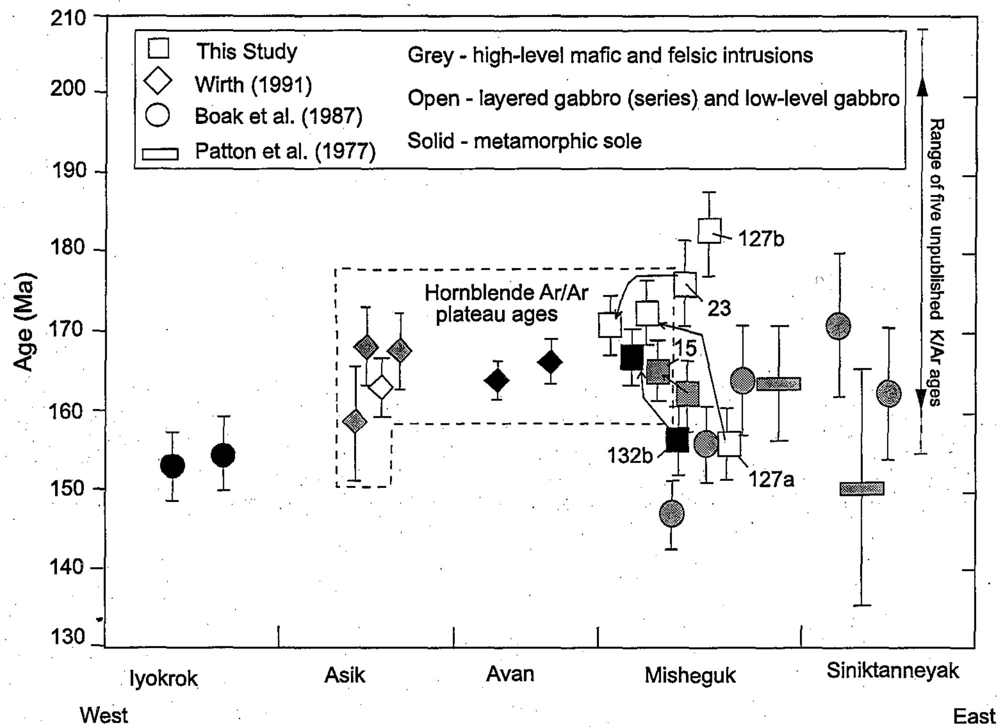

Fig. 5. Hornblende K/Ar and $^{40}Ar/^{39}Ar$ plateau age data from various ophiolite bodies of the Brooks Range ophiolite (modified from Boak et al., 1987). $^{40}Ar/^{39}Ar$ analysis reduces significantly the apparent age range of ophiolite formation (arrows point to $^{40}Ar/^{39}Ar$ age of same mineral separate used for K/Ar age analyses). Hornblende $^{40}Ar/^{39}Ar$ plateau ages from layered gabbro (open symbols) cluster around 163–169 ± 5 Ma, which is nearly contemporaneous with hornblende $^{40}Ar/^{39}Ar$ plateau cooling ages of the metamorphic sole (solid symbols). High-level leucocratic and intermediate intrusives (striped symbols) generally yield younger ages than the layered gabbro series. Mineral separations and K/Ar analyses of amphibole were conducted at the Geophysical Institute of the University of Alaska under the direction of D.L. Turner; the same lab used for the study of Boak et al. (1987). Splits from amphibole separates used for K/Ar analyses were also used for the $^{40}Ar/^{39}Ar$ method at the University of Leeds geochronology laboratory under the direction of D.C. Rex.

ment during the Middle Jurassic western Brookian orogeny (Harris, 1998). The metamorphic sole of the Misheguk, Siniktanneyak, and Avan Hills ophiolite bodies is transitional with, and geochemically similar to basalt, chert, limestone, and psammitic material mostly of the Copter Peak assemblage. Dynamothermal metamorphism of these rocks produced garnet bearing amphibolite and quartz–mica schists that decrease in metamorphic grade and ductile strain intensity structurally downward (Harris, 1998). These high-grade rocks are separated by thin, fault-bounded intervals from underlying greenschist facies and unmetamorphosed basalt and sedimentary rocks. Localization of strain at the base of the ophiolite during emplacement produced mylonitic fabrics in the metamorphic sole that document syn-kinematic crystal growth at high flow stress and strain rates. Kinematic indicators show mostly top-to-NW sense of shear at the base of the ophiolite. Minimum temperature estimates, from garnet–biotite and garnet–amphibole geothermometric studies range from 500 to 560 °C at around 5 kb (Harris, 1998). These conditions are similar to closing temperatures estimated for Ar retention in hornblende near the base of the ophiolite that yield $^{40}Ar/^{39}Ar$ ages of 164–169 Ma (Harris, 1998). The near concordance of this age with that of ophiolite crystallization limits the time between crystallization and tectonic emplacement of the Brooks Range ophiolite. Compositional similarities between the metamorphic sole and continental margin material also imply close spatial and tem-

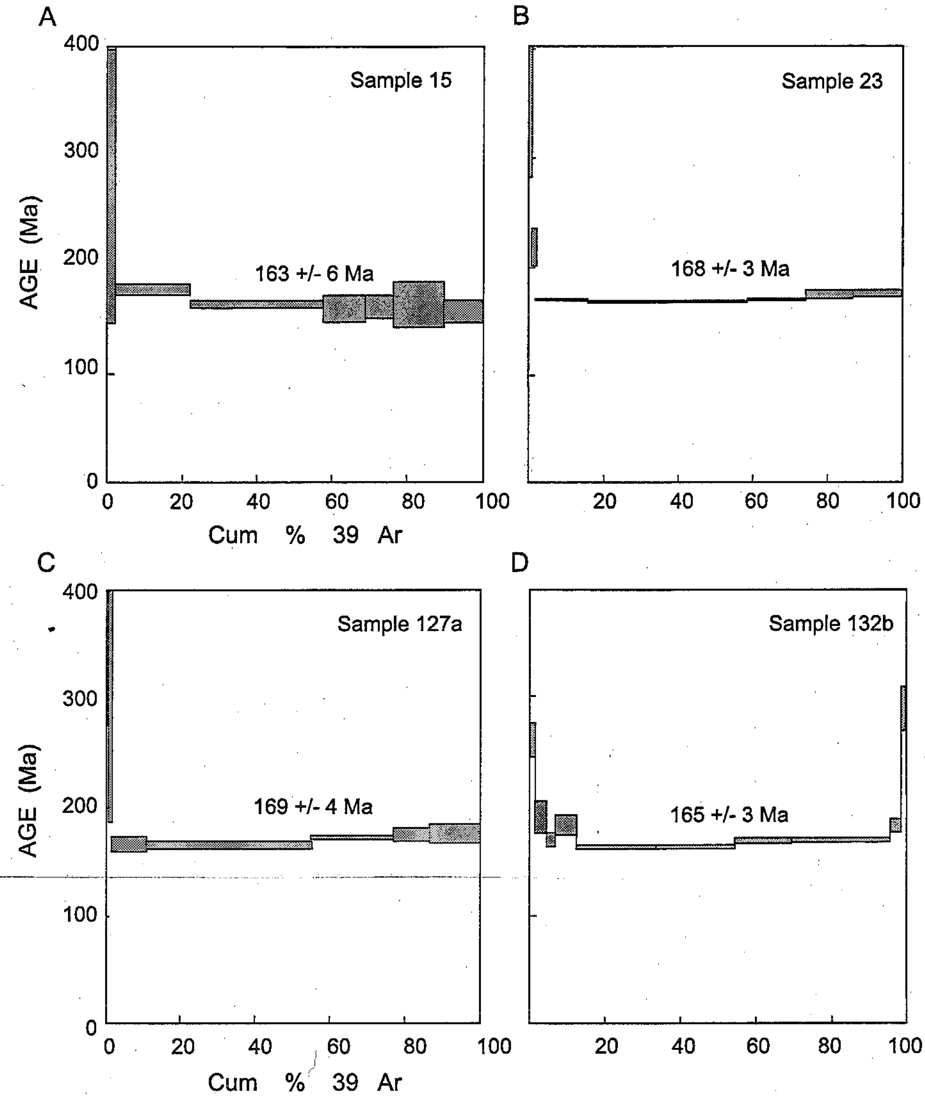

Fig. 6. $^{40}Ar/^{39}Ar$ age spectra for samples from the transition between the layered gabbro series and high-level intrusions at Misheguk. The layered gabbro series (Sample 127B, Fig. 5) in this area is host to younger leucogabbro and diorite intrusions (samples 127A and 23, respectively), and in places is metamorphosed to lower amphibolite facies (Sample 15). Amphibole separates are mostly primary magmatic phases, except for sample 15, which is mostly a secondary or low-temperature primary phase. Incremental-release age spectra show some evidence of excess argon at low-temperature steps, but no evidence for argon loss or resetting as suggested by Boak et al. (1987). Sample 132b is from the metamorphic sole at Misheguk (Harris, 1998).

poral ties between the ophiolite and the Brookian orogen prior to emplacement (Harris, 1992).

Lenses of mélange commonly structurally underlie the metamorphic sole and Copter Peak assemblage at the base of the Brooks Range ophiolite (Fig. 4c). Commonly included as part of the Okpikruak Formation (Crane, 1987), this mélange consists of abundant greywacke and remobilized marine shale with blocks of mafic igneous rocks, chert, carbonate, and other units of Devonian to Triassic age mostly derived from broken formations of the Copter Peak assemblage and Etivluk Group. The varicolored matrix clay that

Table 1
Radiometric age analyses of hornblende from the Brooks Range ophiolite and its metamorphic sole

Sample number	Rock type	Rock unit	K^2O (wt.%)	$^{40}ArRAD/^{40}K \times 10e-3$	$\%^{40}ArRAD$	K/Ar age (Ma)	Integrated values (Ar/Ar) $^{40/39}K$	Ar/Ar age (Ma)	Ar/Ar plateau age (Ma)
15	metagabbro	high-level gabbro	0.145	9.808	51.09	161.37 ± 4.84	33.881	168.53 ± 5.43	163 ± 6
23	diorite	high-level intrusives	0.602	10.747	47.05	176.1 ± 5.28	34.171	172.71 ± 1.23	168 ± 3
127A	leucogabbro	layered gabbro series	0.161	9.49	60.52	156.37 ± 4.69	34.133	171.96 ± 5.44	169 ± 4
132B	garnet amphibolite	metamorphic sole	0.377	8.884	47.05	156.84 ± 4.71	35.053	170.64 ± 1.0	165 ± 35

incases most blocks yields Late Jurassic (Tithonian) to Early Cretaceous (Valanginian) fauna.

4. Internal structure of the Brooks Range ophiolite

Three genres of ductile fabrics are found throughout the Brooks Range ophiolite. These include two early high temperature textures formed by preferred orientations of crystal lattices and shape, which are overprinted by a third lower temperature porphyroclastic fabric near the basal detachment of the ophiolite. The earlier high temperature fabrics relate to the construction of the Brooks Range ophiolite, while the later porphyroclastic fabric relates to ophiolite emplacement and incorporation into the Brooks Range fold and thrust belt.

4.1. Lattice fabric

Lattice fabrics are generally found near the base of the ultramafic section of the Brooks Range ophiolite and weaken upward through a poorly differentiated zone near where impregnated dunite and cumulate structures (locally graded and cross-bedded) become more prevalent. These fabrics are characterized by nearly equant olivine grains that were polygonized into sub-grains with a common extinction angle and unimodal grain size (around 3–4 mm). The equigranular, lattice preferred orientations of the grains are evidence of high degrees of recovery from strong plastic shear strains in the asthenosphere at around 1000–1200 °C (Nicolas and Poirer, 1976).

4.2. Shape fabric

The mantle/crust transition zone and layered gabbro series of the Brooks Range ophiolite have well defined compositional laminations and foliations (Sm) with lineations (Lm) of anisometric mineral grains (plagioclase hornblende and pyroxene). Preferred orientations are of mineral shapes, not lattices, which is evidence of viscous (magmatic) flow. Evidence of crystal plastic strain and other effects of solid-state deformation are mostly lacking. These shape or flow fabrics (Sm) dominantly strike NE–SW and dip 60–90°SE and NW (Fig. 7). The outcrop-scale fabrics generally parallel the orientation of the crust/mantle transition zone (petrological Moho) at each ophiolite body. This zone dips steeply to the SE at Misheguk (Fig. 4) and Avan Hills, and steeply to the NW at Siniktanneyak (Fig. 3). The difference in dip direction between Siniktanneyak and the other ophiolite bodies of the Brooks Range ophiolite is consistent with its opposite facing-direction. Whether the facing-direction is a primary or secondary feature of the Brooks Range ophiolite is problematic.

Meso-scale folds are inferred from structural measurements of each body (Fig. 7), where poles to compositional layers (Sm) define great circles with low to moderate angle *p*-axes. The axial planes of the folds parallel the regional foliation direction. This foliation has a uniform or progressively changing pattern for distances of over 150 km, which implies that it records a single, regional-scale event.

Flow lineations (Lm) consistently plunge east at a moderate angle in the foliation plane (Fig. 7). Rake angles are generally >60°. The mean trend of lineations are 54°ESE at Misheguk; 56° east at Avan

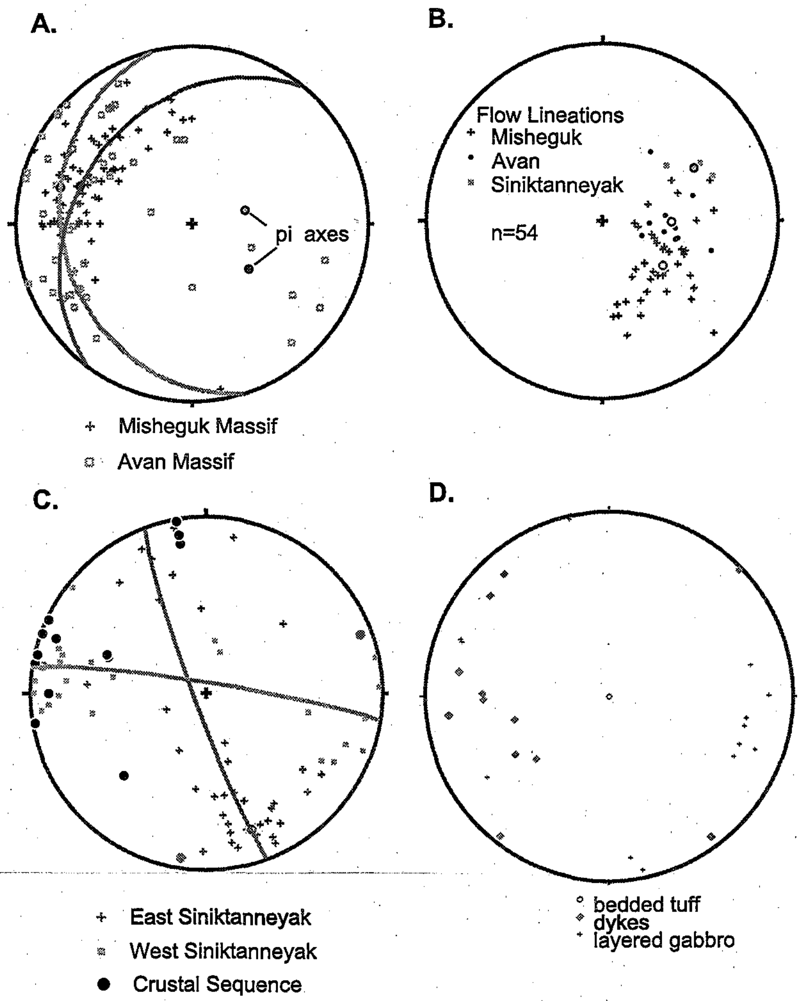

Fig. 7. Lower hemisphere equal-area stereographs of structural features of the Brooks Range ophiolite. (A) Poles to magmatic flow foliation from Avan (blue) and Misheguk (red). Mean directions are shown as filled circles intersected by pi-girdles. (B) Lineation directions of magmatic flow of the Brooks Range ophiolite. Mean directions for each ophiolite body are large circles of corresponding color. These directions indicate a general eastward magmatic flow direction. (C) Poles to magmatic flow foliation at Siniktanneyak. Two different domains are shown that correspond to the eastern and western parts of the ophiolite body. Mean directions are filled circles intersected by pi-girdles. Pi-poles are filled circles normal to each pi-girdle. (D) Poles to structurally contiguous bedded tuff, dykes, and layered gabbro of the northern Siniktanneyak ophiolite body. Data has been rotated about the strike (NE–SW) and dip angle (25° NW) of the bedded tuff layers. This figure can be viewed in colour in the web version of the article.

Hills, and, 39°ENE at Siniktanneyak, which are similar to the *p*-axes of poles to foliation planes (Fig. 7). Relative to meso-scale folds, lineations indicate that the flow direction is in the $\sigma 2-\sigma 3$ plane. These results indicate that compositional layers were most likely transposed into the direction of laminar magmatic flow at the time of ophiolite cooling.

Other indications of large, syn-magmatic flow strains within the lower crustal section of the Brooks Range ophiolite include: (1) transformation of modal compositional layers (cumulate) to isomodal layers, (2) transposition of dikes that cross cut layering, impregnations, and chromite seams and pods into the plane of laminar flow, and (3) layer modification by boudinage. Many cross-cutting dikes and cumulate structures have a consistent flow lineation pattern regardless of their orientation, which indicates high strains persisted to some degree into the solid state.

At Siniktanneyak the pattern of flow foliation diverges from west to east (Fig. 7C). The general pattern throughout the massif overlaps with that of Avan and Misheguk, but is evidence of either a more complex flow regime or solid-state deformational history.

4.3. Mantle diapirism

The consistent pattern and internal relations of flow fabrics observed in the exposed Brooks Range ophiolite is similar in many ways to that predicted by Nicolas et al. (1988) for models of mantle diapirism at spreading ridges. One of the most significant similarities between the Brooks Range ophiolite and other ophiolites interpreted in a diapiric reference frame is the structure of the mantle/crust transition zone or paleo-moho region and associated magmatic layering. Detailed studies of these features at the Oman ophiolite (Ceuleneer, 1986; Juteau et al., 1988; Nicolas et al., 1988; Reuber, 1988) document that the mostly flat-lying paleo-moho and magmatic layers are abruptly modified at regularly spaced intervals by mantle diapirism. The diapirs cause abrupt changes in structure and composition, such as inflation and steepening of the transition from mantle to crust over a broad impregnated zone of thick dunite and out-of-sequence wehrlitic intrusions. The transition is characterized by contorted layers, large-scale folds, chromite enrichment, and near vertical foliation and lineation patterns consistent with diapiric disruption of earlier cumulate fabrics. Similar relations are also documented in the ophiolites at Canyon Mountain, Oregon (Ave Lallemant, 1976); Troodos, Cyprus (Malpas et al., 1987), Acoje massif of Zambales (Violette, 1980), Lewis Hills massif of Newfoundland (Girardeau and Nicolas, 1981), and Tiebaghi massif in New Caledonia (Moutte, 1979).

Progressive change in the internal structure and character of the paleo-moho along strike in these ophiolites argues against unique oceanic environments or emplacement-related deformation as explanations for the steep orientation, thickening, and out-of-sequence wehrlitic intrusions of the diapiric zones (Nicolas and Violette, 1982).

The absolute thickness of the mantle/crust transition zone in Oman abruptly increases by orders of magnitude in the dunite-rich zones interpreted as mantle diapirs. In less than 6 km of lateral distance, ultramafic rocks progressively increase in thickness from 20 m to 3 km (Reuber, 1988). The abrupt change in thickness of the ophiolite succession is also reflected in variations of structural thickness of individual ophiolite nappes, with thick nappes corresponding to diapiric zones. The shear zone at the base of these nappes is "spoon-shaped", which Reuber (1988) interprets as a function of lithospheric mantle weakening near the paleo -1000 °C isotherm.

Many of these characteristics interpreted as relicts of diapirism are found in the Brooks Range ophiolite. Mantle/crust transition zones in the Brooks Range ophiolite increase in thickness towards the thickest parts of the ophiolite nappes at Misheguk, Avan and Siniktanneyak. At Misheguk, the thickness of dunite in the transition zone ranges from 3 km to a few hundred meters over a few km along strike (Fig. 2). Compositional layers, including the mantle/crust transition, become steeper and thicker from SW to NE along strike at Avan (Fig. 2). Late-stage wehrlitic intrusions are common adjacent to the thick zones of transitional dunite at each of the ophiolite bodies. Basal shear planes of the Brooks Range ophiolite nappes are typically "spoon-shaped" with dunite bodies occupying the base of the spoon troughs. Where the transition zone between mantle and crust is exposed, it is near vertical.

It is likely that the thick dunite-rich bodies of the Brooks Range ophiolite represent erosional remnants of only the thickest parts of what was originally a much more laterally continuous ophiolite nappe. Analogous to Oman, the dunite bodies may correspond to the structurally thickest part of the originally contiguous ophiolite nappe. If this was the case, then the thinner sections of the Brooks Range ophiolite connecting the six remaining massifs of the Brooks Range ophiolite have already completely eroded away, leaving only the diapirically thickened parts. Similar relationships are documented adjacent to the Bay of Islands massif where thin ophiolite sections, such as Table Mountain, are much more eroded (Dunsworth et al., 1986).

Another similarity between what is observed in the Brooks Range ophiolite and the ophiolite of Oman is the size and spacing of thick ophiolite sections. In Oman, diapiric zones associated with anomalously thick mantle/crust transition zones are around 5–10 km in width and spaced between 30 and 50 km apart (Nicolas et al., 1988). These dimensions are very similar to the width and spacing of the Brooks Range ophiolite massifs, assuming they represent remnants of anomalously thick magmatic centers (Fig. 1).

Paleomagnetic analysis of the steeply dipping compositional layers at Misheguk shows that the angle between magmatic layers near the petrologic Moho and the paleomagnetic inclination of these layers is 50–63° (Harris et al., 1993). Layers in high-level gabbros that are disrupted by later intrusions display a greater variation. Assuming that the characteristic magnetization is primary, and that the primary inclination was around 80°, magmatic layers and the Moho had initial dips from 17–40°. These layers now dip 40–70°SE, which is consistent with the 30° of eastward tilt measured in dikes and layered sedimentary units found in cover sequences to the south.

4.4. Porphyroclastic fabric

Near the structural base of the Brooks Range ophiolite a porphryoclastic fabric is superimposed onto the high temperature lattice and shape fabrics. Porphyroclastic fabrics are distinguished by incomplete grain size reduction at high enough stresses and low enough temperatures to prevent much recovery from crystal–plastic strain (Ceuleneer et al., 1988). Temperatures of around 850–900 °C are estimated by Mercier and Nicolas (1975). This implies that the base of the Brooks Range ophiolite was near thermal equilibrium with the metamorphic sole, where temperatures were as high as 600–700 °C (Harris, 1998). High stresses along this contact are documented by piezometric studies of quartz sub-grains in mylonite in the metamorphic sole that predict flow stresses of at least 150–200 MPa and rapid strain rates of 10^{-10} s^{-1} to 10^{-9} s^{-1} (Harris, 1998).

The most characteristic feature of porphryoclastic fabrics in the Brooks Range ophiolite is a bimodal grain-size distribution of millimeter-sized porphryoclasts of orthopyroxene and clinopyroxene floating in a host of serpentinized olivine grains (Fig. 8). The olivine is commonly reduced to a fine-grained recrystallized matrix. Porphryoclasts are commonly elongate with a dense substructure. Matrix subgrains commonly display a wavy extinction (Fig. 8) most likely produced by numerous free dislocations. In places where the basal thrust cuts through gabbro, porphryoclastic fabrics are composed of strained plagioclase and pyroxene grains in a matrix of recrystallized sub-grains. The localization of porphryoclastic fabrics along the structural base of the Brooks Range ophiolite is clear evidence of the association of these structures with its early emplacement history.

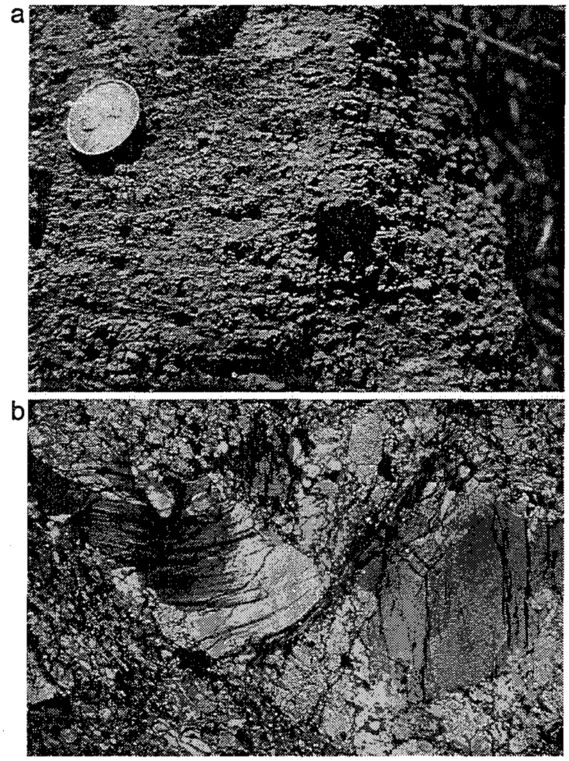

Fig. 8. Photographs of porphyroclastic fabric in outcrop (a) and thin-section (b). Thin section is a 2 mm field of view. See text for description. This figure can be viewed in colour in the web version of the article.

The strike direction of porphyroclastic foliation and shear planes, and the trend and plunge of lineations associated with stretched porphryoclasts, are sub-parallel to the strike of the emplacement fault, which commonly parallels the trend and plunge of grooves scribed on fault planes (Harris, 1998). These structures, and the emplacement fault, where it is not folded, consistently dip gently to the SE. Similar styles and orientations of porphyroclastic fabrics are also well developed below the emplacement fault in sub-ophiolite metamorphic rocks, which show top-to-the-NW sense of shear (Harris, 1998). The kinematic pattern of porphryoclastic fabrics link ophiolite emplacement to the structure of the western Brooks Range fold and thrust belt.

4.5. Serpentinite sole

A 'rind' of serpentinization along the structural base of the Brooks Range ophiolite mantle sequence is well expressed at the Misheguk, Avan, and Siniktanneyak ophiolite bodies. This feature consists of a highly altered (70–90% serpentine), nearly flat basal surface that grades upward into less serpentinized mantle and crust away from the basal shear zone of the Brooks Range ophiolite over a distance of several decimeters (Fig. 4). The top of the serpentinized zone is marked by a distinct color change from orange, highly serpentinized peridotite to brown to dark-blue mostly peridotite with less than 20% serpentine. The shallow-dipping serpentinite zone crosscuts the steeply dipping ductile fabric and compositional layering of the mantle sequence and the transition zone, and is sub-parallel to the basal shear zone and metamorphic sole (Fig. 3). Since serpentinization is considered an in situ, pre-emplacement process for most ophiolites (e.g. Coleman, 1984) the structural relations of the serpentinite sole of the Brooks Range ophiolite support evidence presented above for a primary, steep internal layering, and may also indicate that the emplacement fault used this initial weakness in the ophiolite section.

4.6. Internal faulting

Internal faults and gentle folds associated with thrust emplacement modify the early structural fabric of the Brooks Range ophiolite. At least two different phases of extension are found that pre- and post-date shortening from thrust emplacement. The earliest phase of extension was syn-magmatic as evidenced by intrusion of hornblende-rich, K-feldspar bearing pegmatite dikes along some normal faults. Other normal faults, most likely of the same phase, show evidence of increased amounts of hydrothermal alteration. These faults juxtapose upper level gabbro with mantle sequence at both Misheguk and Siniktanneyak (Fig. 2).

A later phase of extension is associated with a persistent set of minor high-angle shear fractures and normal and oblique slip faults that offset the basal thrust of the Brooks Range ophiolite. These faults are interpreted as hanging-wall drop faults and other types of accommodation structures associated with thrusting and post-contractional relaxation. Similar structural relations are well documented in the Tyrolean Alps (Engelen, 1963) and Timor (Harris, 1998) where thick sheets of carbonate are offset by vertical faults that form as over-pressured shale is extruded from beneath. This process may also be the cause of local steepening of the basal thrust of the Brooks Range ophiolite near the edges of some nappes.

Thrust duplication of the ophiolite sequence is rare and mostly restricted to local repetition of the mantle sequence and metamorphic sole near its structural base. Faults beneath the ophiolite commonly disrupt the basal shear zone, metamorphic sole, and the stacking order of underlying thrust assemblages. Well-exposed examples of these faults are found at the structural base of the northern Avan massif (Fig. 2) and southwestern Misheguk massif (Fig. 2). In both cases these faults juxtapose non-tectonized ultramafic rocks of the Brooks Range ophiolite with undeformed shallow-water carbonate sequences of the Ellesmerian continental platform (Fig. 4). The intervening slope and rise sequences that commonly structurally underlie the ophiolite and the basal emplacement shear zone are structurally omitted in these regions.

4.7. Folding of the Brooks Range ophiolite nappe

Klippe of the Brooks Range ophiolite are preserved in synforms created by Early Tertiary refolding of the Jurassic western Brooks Range fold and thrusts belt (Fig. 1). The later long-wavelength Tertiary folds are widely distributed throughout the Brooks Range (O'Sullivan et al., 1997). This deformation event transformed the Brooks Range into a regional west-plunging antiform that preserves the higher structural levels in the western part of the range that have been stripped by erosion from much of the rest of the Range. This includes the striping of most of the ophiolite.

The axes of folds are oriented nearly E–W at Siniktanneyak and NNE–SSW at Misheguk, Avan and Asik (Fig. 1). Most secondary folds have wavelengths of around 20–30 km and warp the entire stack of pre-existing thrust sheets that make up the western Brooks Range allochthon belt of Mayfield et al. (1983). The overall pattern indicates multiple phases of shortening that are generally north-directed for the Range as a whole, but curve at the western edge of the Range.

The earliest indications of NNW-directed shortening are found in sense of shear indicators at the base of the Brooks Range ophiolite (Harris, 1998). These include mylonitic fabrics in the metamorphic sole at Misheguk and Avan with top-to-the-NW rotational shear, gentle S and SE dipping thrust fault planes, and asymmetric folds in underlying continental margin units with axial-planes and back-limbs dipping gently to the SSE. These structures indicate that the Brooks Range ophiolite at Misheguk was thrust mostly to the NNW over a stack of continental margin thrust sheets that were subsequently refolded in a similar direction.

The pattern of poles to foliation in the metamorphic sole of the Brooks Range ophiolite (Harris, 1998) is nearly identical to that of magmatic flow fabrics at Misheguk and Avan. These similarities indicate a general parallelism between the axis of magmatism and the Ellesmerian continental margin, and the affects of transposition of early, high temperature fabrics associated with construction of the Brooks Range ophiolite by later deformational events. The relative contribution of each deformation phase to the observed structural pattern is not known. However, the degree of similarity between structures within the Brooks Range ophiolite with those of structurally underlying units, suggests caution in interpreting the structure of ophiolites as purely a reflection of spreading ridge processes.

4.8. The Asik and Maiyumerak massifs

The Asik and Maiyumerak mafic and ultramafic bodies protrude up through Quaternary deposits that may obscure a much larger nappe of the Brooks Range ophiolite at depth. Petrochemical studies of basalt and sheeted dike units at Maiyumerak indicate that they most likely form the volcanic, upper part of the Brooks Range ophiolite (Wirth, 1991; Karl, 1992). These units may be contiguous with a west-facing mantle and lower crustal ophiolite sequence exposed at Asik.

The ophiolite nappe forms the steeply dipping SE flank of large, asymmetric synform occupied by the Noatak River drainage (Fig. 1). The likelihood that a large part of the nappe is buried beneath Quaternary deposits is supported by potential field data (Saltus et al., 2001). Gravity data suggest that the nappe may be as much as 8 km thick, although unknown thicknesses of mafic units of the Copter Peak assemblage probably lie beneath the ultramafic rocks and would complicate interpretations of the geophysical data at depth.

5. Structural restoration

The consistent orientation of internal structural features of the Brooks Range ophiolite, limited structural disruption and the preservation of a complete intact ophiolite sequence at Siniktanneyak provides a way to partially reconstruct the initial position of the spreading ridge that may have formed the ophiolite and how it was incorporated into the Brooks Range orogenic wedge. Models relating magma chamber structure to the structure of ophiolites (i.e. Greenbaum, 1972; Casey and Karson, 1981) vary considerably. For example, models based on studies of the Semail ophiolite predict opposing dip directions of layered gabbro. Smewing (1981) predict that cumulate layers dip toward the ridge axis, while Nicolas et al. (1988) predict the opposite. Only the structure of cover sequences and the crust/mantle transition relative to the ridge are consistent between models. The deposition planes in sedimentary and volcanic cover sequences and the normal to the strike direction of sheeted dikes are used here to reconstruct paleo-horizontal. The strike length of sheeted dikes and the mantle/crust transition zone are used to relate ophiolite structure to spreading ridge strike.

5.1. Dikes and cover sequences

Sheeted dikes in the Brooks Range ophiolite are documented at the Maiyumerak (Wirth et al., 1994) and Siniktanneyak (Bickerstaff et al., 1993) ophiolite bodies. At Maiyumerak sheeted dikes strike around 030° and dip 65–75°NW. Sedimentary and volcanic flow layering associated with the dikes have the same strike, but dip around 30°SE, which is nearly orthogonal as predicted by most spreading ridge models. Although contact relations between these dikes and underlying crustal and mantle sequences are not found at Maiyumerak, they are sub-parallel to magmatic flow fabrics and the mantle/crust transition measured at the nearby Misheguk and Avan ophiolite bodies (Fig. 7).

Dike swarms and some dike sheets at Siniktanneyak strike generally NNE–SSW. These dikes intrude pillow basalt with depositionally overlying bedded tuffs that strike NE–SW and dip 25°NW. These structural relations support the interpretation that the bedded tuffs are most likely part of the ophiolite sequence and provide a way to restore the other structural features of the Siniktanneyak massif to ancient horizontal (Fig. 7). Most of the layered gabbro in structural continuity (no faults between units) with the cover sequences restore to a NE–SW strike and steep dip to the E. The similar strike, but opposite facing direction of Siniktanneyak may indicate that it is a segment of an opposing side of a ridge or diapir (Fig. 9).

Differences in the orientation of structures from one ophiolite body to another may document minor amounts or rotation within and between each body during incorporation into the western Brooks Range fold and thrust belt or may reflect variation in original spreading ridge structure (Fig. 9). Although the thickness and competence of the ophiolite nappes would prevent much folding, there is some evidence of folding about a generally E–W axis, which may explain the similarity between pi-girdles of magmatic flow foliations (Fig. 7), and foliations of the metamorphic sole and bedding planes in underlying sedimentary units (Harris, 1998). This folding event is

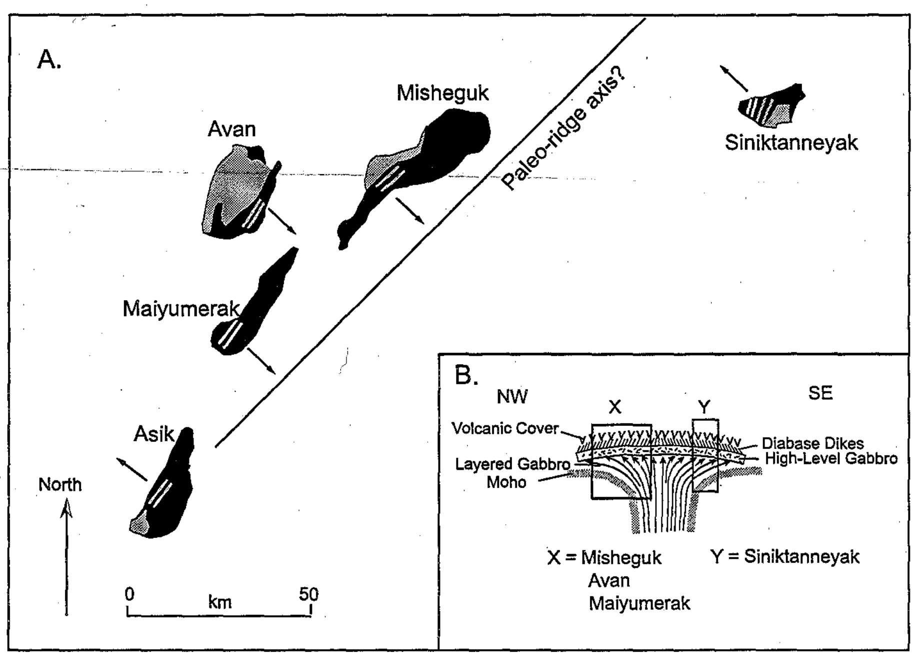

Fig. 9. Interpretation of the internal structural elements of the Brooks Range ophiolite in a spreading-ridge reference frame. (A) Map of the major ophiolite bodies showing exposure of mantle sequence (gray), crustal sequence (black), orientation of Moho and layered gabbro (gray parallel lines), orientation of sheeted dikes (white parallel lines), and facing direction or dip direction of internal layering (arrow). (B) Schematic NW–SE cross-section through a diapiric segment of a spreading ridge (modified from model of Nicolas et al., 1988). The model predicts most of the structural relations observed throughout the Brook Range ophiolite. Two different sections of the diapir, X and Y, may be represented by the ophiolite bodies.

slightly askew with top-to-the-NW sense of shear indicators found along the basal thrust of the Brooks Range ophiolite at Misheguk and Avan (Harris, 1998), and may reflect a post-emplacement event. Gentle folding of the Brooks Range ophiolite nappe may also explain the tilting of its cover sequences, which dip less than 30°. However, the overall structural pattern of the Brooks Range ophiolite cannot be explained by folding of original mostly flat-lying layering because this does not account for the truncation of steeply dipping layers by the zone of serpentinization and sub-parallel basal thrust.

The consistent N–NE trend and steep dip of the petrological Moho at different bodies of the Brooks Range ophiolite that stretch over a distance of 200 km, also argues against any significant rotations about a horizontal axis of the nappes during emplacement. With amounts of rotation of any one ophiolite body relative to the others of no more than 20–30°, it is possible to infer from the consistent strike of the crust/mantle transition, a mostly NE–SW orientation for the paleo-spreading ridge (Fig. 9A). According to this reconstruction, Siniktanneyak would represent a fragment of the NE side of the ridge and the other ophiolite bodies are fragments of the SW side of the spreading axis (Fig. 9B).

6. Conclusion

The Brooks Range ophiolite represents a fragment of Jurassic oceanic lithosphere that formed along a mostly NE–SW spreading ridge above a subduction zone near the Ellesmerian continental margin. Underthrusting of the continental margin beneath the young ocean basin resulted in incorporation of the ophiolite into the Brooks Range fold–thrust. Similarities between the internal structure of the Brooks Range ophiolite and its metamorphic sole indicate that both were modified by post-emplacement deformation that refolded the thrust stack into a series of long-wavelength synforms and antiforms. The Brooks Range ophiolite is preserved in a band of NE–SW trending synforms. Most of its sheeted dikes, and volcanic and sedimentary cover is stripped by erosion, but what remains has a consistent NE–SW strike. The structural relations of the cover sequences with layered gabbro and the mantle sequence is only exposed at the Siniktanneyak ophiolite body, which have a geometric pattern consistent with that predicted by spreading ridge models. The structural features exposed in the mantle and crustal sequences at the Avan and Misheguk are similar to those at Siniktanneyak, but face the opposite direction. Variations in thickness, composition, and dip angle and direction of the mantle/crust transition throughout the Brooks Range ophiolite may reveal patterns of mantle diapirism during the construction of the ophiolite. This implies that most of what remains of the Brooks Range ophiolite nappe are the thicker mantle diapers of the Avan, Misheguk and Siniktanneyak ophiolite bodies that occupy synforms in the fold–thrust belt. Other parts of the Brooks Range ophiolite nappe may be buried under Quaternary deposits of the Noatak River drainage that occupy a large synform at the SW edge, and structurally lower section of the Brooks Range fold–thrust belt.

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