THE 2.00 GA PURTUNIQ OPHIOLITE, CAPE SMITH BELT, CANADA: MORB-LIKE CRUST INTRUDED BY OIB-LIKE MAGMATISM

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ABSTRACT

The Québec-Baffin segment of the Paleoproterozoic Trans-Hudson Orogen comprises a collage of tectonostratigraphic elements that accumulated on, or were accreted to, the northern margin of the Archean Superior craton throughout more than 200 million years of divergent and subsequent convergent tectonic activity. The Cape Smith Belt, on the Ungava peninsula in northern Québec, preserves a series of thrust imbricates of >2.04-1.87 Ga sedimentary and mafic volcanic rocks that record the subsidence and rifting of the Superior craton and subsequent development of an oceanic basin. The structurally highest component of the Cape Smith Belt, the Watts Group, consists of ultramafic and mafic cumulate rocks, gabbros, sheeted mafic dykes, pillowed and massive basalts that are interpreted as the igneous crustal components of a 2.00 Ga ophiolite. Although the rocks have been deformed and metamorphosed, primary igneous features such as cumulate textures, intrusive contacts, chilled dyke margins and pillow selvedges are locally well preserved. The ophiolite is a composite of two physically, chemically and isotopically distinct suites of tholeiitic rocks; the older consists of gabbroic cumulate rocks, pillowed basalts and sheeted mafic dykes, and is similar to suites formed at modern mid-ocean spreading ridges, whereas the younger suite consists of ultramafic and mafic cumulate rocks and mafic dykes, and is analogous to modern hotspot-related oceanic-island complexes such as Hawaii. Reconstructions of the pre-deformation crustal configuration suggest that the mid-ocean ridge suite was at least 5 km thick, and the younger, oceanic-island suite was greater than 4 km thick, a total thickness of this composite oceanic crust of >9 km.

INTRODUCTION

The significance of ophiolitic rocks in plate tectonic interpretations of Phanerozoic orogenic belts has long been recognized (e.g.: Gass, 1968; Moores and Vine, 1969; 1971; Dewey and Bird, 1971; Coleman, 1971). The presence of ophiolites in modern mountain belts is taken as compelling evidence for the existence of a former ocean basin and the nearly complete subduction of its oceanic crust (e.g.: Coleman, 1977). In contrast, the apparent absence of ophiolites from ancient mountain belts has prompted speculation about the nature of Proterozoic (e.g., Moores, 1986) and Archean oceanic crust (e.g.: Sleep and Windley, 1982; Arndt, 1983; Nisbet and Fowler, 1983; Hargraves, 1986; Bickle, 1986). In addition, it has prompted the question: when did plate tectonic processes involving modern-style formation and subduction of oceanic crust begin? (e.g.: Condie, 1976; Kröner, 1983).

Whereas some well-studied ancient mountain belts are interpreted to have formed by processes compatible with modern plate tectonic hypotheses (e.g., the Paleoproterozoic Wopmay Orogen: Hoffman and Bowring, 1984; St-Onge and King, 1987; the Cape Smith Belt: St-Onge et al., 1992; St-Onge and Lucas, 1993, and references within), undisputed oceanic crust has only rarely been identified. The Jormua complex in east-central Finland (Kontinen, 1987) and the Purtuniq complex in northern Québec, Canada (Scott et al., 1991; 1992) are two examples of Paleoproterozoic successions that have been described and interpreted as dismembered but relatively complete segments of ancient oceanic crust (and upper mantle, Jormua) that might be analogous to Phanerozoic ophiolites. In addition to providing information relevant to the tectonic evolution of the orogens in which they are presently preserved, these rocks provide the only opportunity to examine the mode of formation of Paleoproterozoic oceanic crust.

In this contribution, we present an overview of the geology and tectonic setting of northeastern Laurentia at the regional scale, and of the Cape Smith Belt in more detail. This is followed by an in-depth description of the lithologic units that are interpreted as a dismembered section of obducted 2.00 Ga oceanic crust. The present structural configuration of the ophiolite is described using cross-sections from which the original (pre-deformation) geometry is inferred. Possible original environments of formation are discussed, and the resulting composite crustal section is compared to those of Phanerozoic and older analogues of oceanic crust. The geological relationships, combined with lithogeochemical data, suggest that the ophiolite is a composite of two magmatic suites that formed in an oceanic setting. At the scale of the ancient mountain belt, the ophiolite signals the presence of rocks that are "suspect" in origin relative to the Superior craton; in this sense, it marks the fundamental suture at the leading edge of the Paleoproterozoic accretionary collage.

REGIONAL SETTING

Northeastern Laurentia

The Québec-Baffin segment of the Paleoproterozoic Trans-Hudson Orogen (Fig. 1; Lewry and Stauffer, 1990) comprises a collage of tectonostratigraphic elements that accumulated on, or were accreted to, the northern margin of the Archean Superior craton during more than 200 million years of divergent and subsequent convergent margin tectonic activity (Hoffman, 1985; Picard et al., 1990; Lucas and St-Onge, 1992; Lucas et al., 1992; Scott et al., 1992; 1997; St-Onge et al., 1992; 1996; 1999; Scott, 1997; 1999). Preserved within the orogen, from the external zone adja-

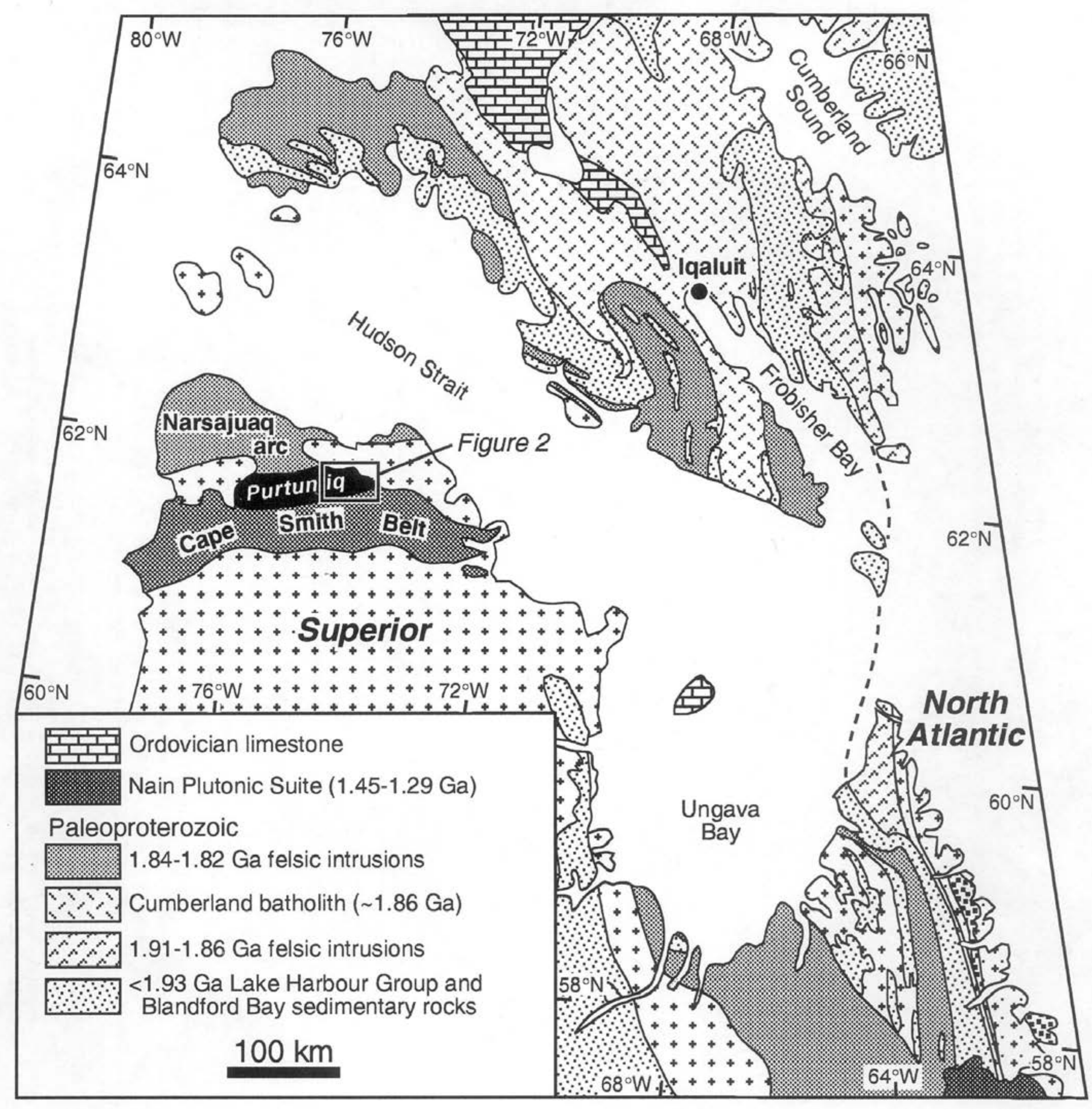

Fig. 1 - Geological map of northeastern Canada modified after Wheeler et al. (1996). Superior and North Atlantic cratons are indicated. Location of Fig. 2, at the eastern end of the Purtuniq ophiolite, is outlined.

cent to the Superior craton in northern Québec to the internal zone exposed on southern Baffin Island, are Paleoproterozoic supracrustal and plutonic rocks that have been transported southward onto the Superior craton. Superb Arctic outcrop combined with two phases of late folding combine to offer an unparalleled, well-exposed three-dimensional view through the crust of the orogen (e.g., St-Onge et al., 1999). The lowest structural level and the foundation for subsequent accretion comprises the Archean plutonic and supracrustal rocks of the Superior craton (Lucas and St-Onge, 1991; St-Onge and Lucas, 1992; St-Onge et al., 1992; 1996). U-Pb (zircon) age determinations for plutonic units within the Superior craton of northern Québec range between ca. 3.22-2.74 Ga (Parrish, 1989; St-Onge et al., 1992; Scott and St-Onge, 1995; Wodicka and Scott, 1997).

The Superior craton is overlain by the Cape Smith Belt, a west-trending synformal structure that comprises parautochthonous and allochthonous sedimentary and volcanic rocks. The basal Povungnituk Group comprises pre-2.04 Ga (Machado et al., 1993) fluvio-deltaic sedimentary rocks derived from the Superior craton; an unconformable relationship to the underlying Archean basement has been demonstrated in the southernmost exposures of the belt (St-Onge et al., 1992; St-Onge and Lucas, 1993). The basal clastic succession is overlain by tholeiitic and rare alkaline volcanic rocks that have been interpreted as remnants of a north-facing continental rift margin (Hynes and Francis, 1982; Francis et al., 1983; Picard et al., 1990; St-Onge and Lucas, 1990a; 1992; Lucas and St-Onge, 1991; Gaonac'h et al., 1992; St-Onge et al., 1992; 1996). A rhyolite flow from the upper Povungnituk Group has been dated at 1.96 Ga (Parrish, 1989). The structurally overlying Chukotat Group comprises a succession of mafic volcanic rocks that records a transition in chemical composition from rift-related to mid-ocean ridge basalt (MORB)-like compositions (Francis et al., 1981; 1983; Picard, 1986; Picard et al., 1990); gabbroic rocks have yielded zircon and baddeleyite ages between 1.92-1.87 Ga (Parrish, 1989; St-Onge et al., 1992). Allochthonous Paleoproterozoic crustal elements that structurally overlie the volcanic rocks of the Chukotat Group include siliciclastic rocks interpreted as a fore-arc clastic apron (Spartan Group; Lamothe et al., 1984; St-Onge et al., 1992), and the package of mafic volcanic rocks, sheeted dykes, and ultramafic to mafic cumulate plutonic rocks interpreted as dismembered oceanic crust (Watts Group; Scott and Bickle, 1991; Scott et al., 1991; 1992). Zircons from a gabbroic layer in the Watts Group yielded an age of 2.00 Ga (Parrish, 1989).

Structurally higher and further outboard from the Superior craton are preserved 1.86 Ga (Machado et al., 1993) intermediate to felsic volcanic and pyroclastic (Parent Group; Lamothe et al., 1984) and plutonic rocks with geochemical affinities to modern subduction-related magmatic arcs (Narsajuaq arc; Lucas and St-Onge, 1991; St-Onge and Lucas, 1990b; 1992; Lucas et al., 1992; Scott, 1997; Dunphy and Ludden, 1998) that range in age between ca. 1.86-1.82 Ga (Parrish, 1989; St-Onge et al., 1992; Machado et al., 1993; Scott, 1997; Wodicka and Scott, 1997; Scott and Wodicka, 1998). Overlying the arc in tectonic contact is a clastic/carbonate platformal succession (Lake Harbour Group; Davison, 1959; Blackadar, 1967; Jackson and Taylor, 1972; Scott, 1997; Scott et al., 1997) deposited between ca. 1.93 and 1.86 Ga (Scott and Gauthier, 1996; Scott, 1997; Scott et al., 1997), possible stratigraphic basement (~1.95 Ga Ramsay River orthogneiss; St-Onge et al., 1998; Scott and Wodicka, 1998), and a foreland basin succession (Blandford Bay assemblage; Scott et al., 1997). An areally extensive suite of monzogranitic plutons (1.86-1.85 Ga Cumberland batholith; Jackson and Taylor, 1972; Jackson et al., 1990; Wodicka and Scott, 1997; Scott, 1999) intrudes the platformal and foreland basin rocks and the 1.95 Ga orthogneisses. The structurally highest (upper-plate) domain comprises ~2.92-2.80 Ga orthogneiss and Paleoproterozoic supracrustal rocks interpreted as the western edge of the North Atlantic craton (Scott, 1999).

Deformation and metamorphism

Detailed mapping of the eastern portion of the Cape Smith Belt (St-Onge et al., 1992; Lucas and St-Onge, 1992; St-Onge and Lucas, 1993) led to the recognition of two generations of southwest-directed thrust faults; an early set of regular, piggyback-style thrusts (D_1), and a subsequent, out-of-sequence set (D_2) (Lucas, 1989; Lucas and St-Onge, 1992). The D_1 thrusts developed above a basal decollement, prior to the thermal peak of regional metamorphism, in a succession in which the faults young in the direction of propagation (i.e. southwards, towards the foreland) (St-Onge et al., 1986; Lucas, 1989). The resultant regional metamorphism reached middle-amphibolite facies (Bégin, 1989; 1992; Lucas, 1989; St-Onge and Lucas, 1990a; 1991). This phase of thrusting and attendant metamorphism has been shown to be younger than 1.87 Ga and to pre-date the accretion of the Narsajuaq arc north of the belt (Parrish, 1989; St-Onge et al., 1992). The D_2 thrusts formed during and after peak metamorphic conditions at ca. 1.80 Ga (Scott and St-Onge, 1995), re-imbricating the earlier thrust stack and basal decollement and incorporating basement gneisses into the thrust stack. This deformation is characterized by growth of thermal-peak or retrograde mineral assemblages (Lucas, 1989) that finally equilibrated at greenschist facies conditions (Bégin, 1989, 1992). Development of these out-of-sequence thrusts has been interpreted as a consequence of the accretion of the Narsajuaq arc (St-Onge et al., 1992, 1999).

The re-imbricated thrust stack and underlying Superior craton basement were folded (D_3) about subhorizontal axes into the present west-trending synclinorium prior to 1.76 Ga (St-Onge et al., 1992, 1999). Refolding of the synclinorium by a northwest-trending set of folds (D_4) resulted in the systematic western plunge of fold axes in the eastern end of the belt and renewed exposure of the Archean basement in a series of tectonic half-windows north of the belt (Lucas, 1989; St-Onge et al., 1992; 1999). The constructive interference of D_3 and D_4 folds has resulted in the development of >18 km of structural relief on the present erosion surface (Lucas, 1989), and the systematic exposure of lower- and upper-plate units throughout the region (St-Onge et al., 1999). Thus, the Québec-Baffin segment of the Trans-Hudson Orogen provides a unique opportunity to study the geology and tectonic evolution of northeastern Laurentia along a 400 km orogen-perpendicular transect (Fig. 1).

In summary, of the Paleoproterozoic tectonic elements of the accretionary collage, only the southernmost can be related to the Superior craton margin. Sedimentological and geochemical evidence link the basal Povungnituk Group clastic sedimentary rocks and tholeiitic basalts to the subsidence and initial rifting of the craton, respectively. Geochemical arguments have been used to relate the evolving composition of the Chukotat Group volcanic rocks to diminishing interaction with the Superior craton with increasing stratigraphic height (Francis et al., 1981). The first truly exotic element, whose oceanic character signals the ultimate rifting of the craton, is the ophiolite (Watts Group) (Fig. 2). Consequently, all elements of the collage that lie outboard (north) of the ophiolite must be considered as "suspect" (sensu Coney et al., 1980) in origin with respect to the Superior craton onto which they have been accreted.

GEOLOGY OF THE PURTUNIQ OPHIOLITE

In the Cape Smith Belt, the Purtuniq ophiolite comprises layered ultramafic and mafic rocks, clinopyroxenite intrusions, sheeted mafic dykes and gabbros, and pillowed and massive mafic volcanic rocks intruded by rare felsic sills and dykes (St-Onge et al., 1988; Scott et al., 1988; 1991; 1992). The rocks that comprise the ophiolite are separated from the underlying sedimentary rocks by a south-verging thrust fault (Fig. 3, 12).

Layered ultramafic rocks

Compositional layering in the ultramafic rocks is defined by centimetre-scale modal variations of relict primary diopside and olivine and respective products of metamorphic recrystallization (hornblende/ actinolite and serpentine). Chromium-rich spinel, rimmed by magnetite, is ubiquitous

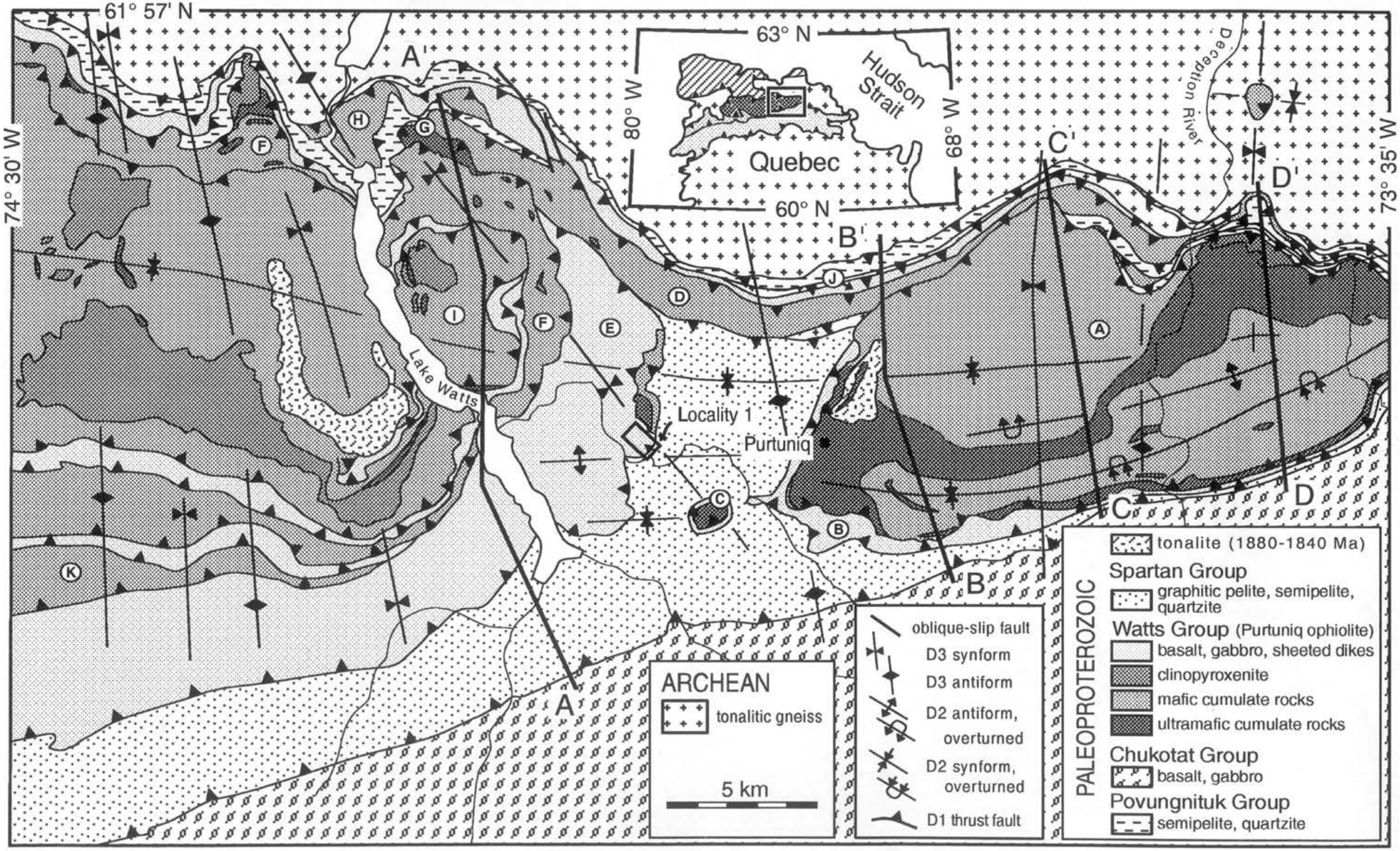

Fig. 2 - Geological map of the eastern part of the Watts Group in the Cape Smith Belt, northern Quebec. Line segments AA', BB', CC', and DD' are the locations of cross-sections shown in Fig. 12. Circled letters A to K identify thrust sheets referred to in the text. Purtuniq is the Inuit name for the former Asbestos Hill Mine. Compiled and modified from St-Onge and Lucas (1989) and St-Onge et al. (1992).

Fig. 3 - Thrust fault (contact at arrow) west of Lake Watts, with basalts of the Watts Group in the hanging-wall, Spartan Group sedimentary rocks in the foot-wall (photo by H. Helmstaedt).

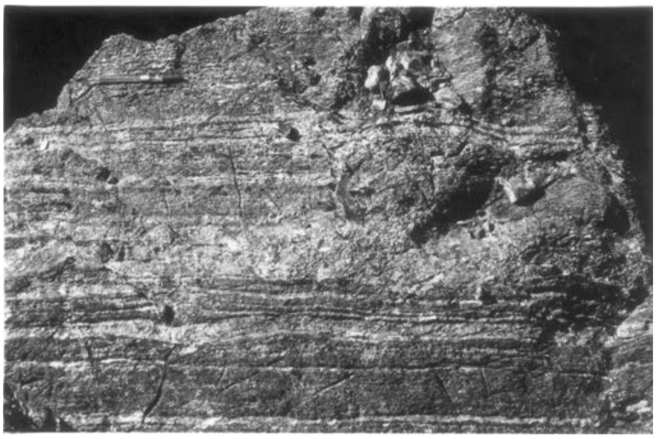

Fig. 4 - Compositional layering in ultramafic rocks. Dark layers are clinopyroxene-rich, light layers are olivine-rich. Pen in upper-left corner is 15 cm.

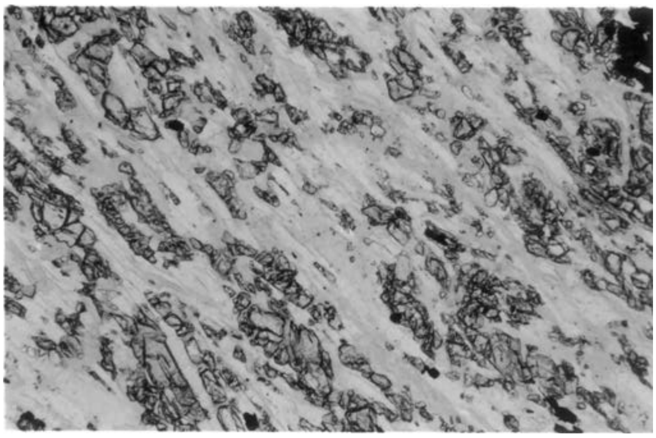

Fig. 5 - Plane-light photomicrograph of neoblastic, mosaic-textured metamorphic olivine (Fo95.3) in a serpentine matrix with well-developed S_1. Field of view is ~8 mm wide.

in trace amounts throughout the layered ultramafic rocks, but plagioclase is rare. The igneous layering comprises alternations from dunite through wehrlite to clinopyroxenite, on scales of centimetres to tens of metres (Fig. 4). The lateral extent of layers ranges from metres to tens of metres depending on layer thickness; decametre-thick layers can be traced for hundreds of metres. Modally-graded layers have dunitic bases that grade abruptly into wehrlitic-clinopyroxenitic tops, over a range of 1-10 cm. In addition to modally-graded layers, homogeneous wehrlitic to olivine-clinopyroxenitic layers form concordant bands up to 0.5 m wide with sharply-defined contacts. Petrographically observed adcumulate textures and evidence of graded layers suggest a cumulate origin for these rocks.

Layered ultramafic rocks of the Watts Group have been observed in two principal modes. The volumetrically most important type is plagioclase-free, such as the large ultramafic body east of Purtuniq (thrust sheet A, Fig. 2). Decametre- to kilometre-scale thrust-bound slices of layered ultramafic rocks (e.g., thrust sheet G, Fig. 2) are interpreted as tectonically isolated portions of an ultramafic body similar to the one east of Purtuniq. The second mode of occurrence is represented by layered ultramafic rocks that contain plagioclase, found as smaller, stratabound lozenges within layered mafic rocks (e.g., within thrust sheets D, F, and I, Fig. 2). These lenses are up to tens of metres thick, and laterally continuous for hundreds of metres. The contacts between these ultramafic lenses and the surrounding layered mafic rocks are gradational on a scale of metres, suggesting that these lenses are an in situ part of the layered mafic succession.

Serpentinization of olivine-rich layers is extensive; the freshest dunitic rocks rarely preserve >5-10% primary olivine. Nevertheless, two texturally distinct olivine populations are recognized in thin-sections of the ultramafic cumulate rocks; the first population consists of relict igneous grains, the second of metamorphic grains. Igneous olivine is recognized by its generally fresh appearance, relatively coarse size (up to 1-2 mm in diameter), anhedral shape, and relict adcumulate textures. These unzoned grains range from Fo92.7 to Fo80.3, interpreted to be the result of variations in primary magma composition (Scott, 1990; Scott et al., 1991). Mineral compositions do not vary systematically with position in the cumulate succession (Scott, 1990). Layers without primary olivine locally contain metamorphic olivine (Fo98.7 to Fo95.3) (Scott, 1990), characteristically present as much finer grained (<100 mm), mosaic-textured neoblastic aggregates (Fig. 5) of uniform composition. Such layers are only observed in the northern portion of the ophiolite (thrust sheet G, Fig. 2), which, at lower- to middle-amphibolite facies, represents the area of highest regional metamorphic grade in the study area (Bégin, 1989; 1992). In addition to metamorphic olivine, secondary mineral assemblages in dunitic layers comprise dominantly serpentine and magnetite, with minor amounts of ferritchromit, chlorite, and calcite (Scott, 1990).

Relict chromium-rich spinel (chromite) is a common accessory phase in the ultramafic cumulate rocks. Grain size is generally less than 1-2 mm, although aggregates of such grains may reach 5 mm in diameter. A full range of grain shapes, from equant to elongate, and euhedral to anhedral is present. Grains commonly display a compositionally homogeneous core overgrown by a sharply-defined, thin magnetite fringe or fully developed rim; in each case, chromite cores generally retain primary grain shapes (Scott, 1990). Less commonly, chromite cores with compositionally zoned ferritchromit overgrowths are present. The overgrowths are Cr-rich adjacent to the chromite core, becoming progressively more Fe-rich further from the core. Well-developed ferritchromit rims have only been observed on chromites from the northern part of thrust sheet G (Fig. 2), suggesting a correlation between development of ferritchromit overgrowths and relatively high metamorphic grade. Magnetite rims on ferritchromit overgrowths are rare and, where present, are not well developed. Concordant chromitite seams up to 15 cm thick, and several metres in length are observed rarely throughout the ultramafic cumulate rocks (Scott and Bickle, 1991).

The magnesium-rich composition of the metamorphic olivine, and the presence of ferritchromit overgrowths on some chromites and magnetite rims on others, suggests that a serpentinization event may have occurred prior to regional metamorphism. Early hydration of igneous olivine may have led to the formation of magnesium-rich serpentine, with the excess iron accommodated as magnetite rims on chromite grains. Subsequently, during regional prograde metamorphism, this early serpentine was dehydrated to produce the observed magnesium-rich metamorphic olivine, and the magnetite rims reacted with the chromite cores to produce ferritchromit (e.g., Bliss and MacLean, 1975). Both of these metamorphic reactions are observed only in areas of lower- to middle amphibolite regional metamorphic grade (Bégin, 1989; 1992). The widespread, but not universal, occurrence of chromite with magnetite rims suggests that this serpentinization event was only locally pervasive. The virtual absence of magnetite rims on ferritchromit overgrowths indicates that only limited amounts of magnetite-producing serpentinization has occurred after ferritchromit growth.

Relict diopside is generally fresh and compositionally homogeneous (Scott, 1990), and shows only minor recrystallization to hornblende/actinolite at grain boundaries. Poikilitic grains enclosing olivine crystals, or their serpentinized pseudomorphs, and/or chromite are common. Individual grains are commonly 3-5 mm in diameter, but range up to 1-2 cm in extreme cases. Secondary chemical homogenization of individual grains is unlikely, as the samples studied are from areas that did not reach clinopyroxene-amphibolite facies during regional metamorphism (Bégin, 1989; 1992). Secondary assemblages in the clinopyroxenitic layers contain varying amounts of hornblende and/or tremolite-actinolite, serpentine and magnetite. Primary igneous hornblende is rare, but has been observed in several samples near the ultramafic-mafic contact east of the Deception River (Fig. 2). Hornblende oikocrysts include partially-serpentinized relict igneous olivine, with trace amounts of fine-grained actinolite developed along grain boundaries.

Layered mafic rocks

Coarse-grained, layered mafic rocks are volumetrically the largest component of the Watts Group in the eastern part of the Cape Smith Belt (Fig. 2). Compositional layering is defined by modal variations of the metamorphic products of primary plagioclase and clinopyroxene (Fig. 6); relict igneous minerals have not been identified in rocks of mafic composition. Individual layers range in composition from anorthosite to clinopyroxenite, with gabbroic compositions most common. Primary calcic plagioclase has been recrystallized to albite and clinozoisite, whereas the primary mafic phases have been replaced by hornblende-actinolite. Individual layers range in thickness from centimetre- to metre-scale. The thinnest layers are rarely continuous laterally for more than several metres, but thicker bands have been traced for several tens of metres. The metamorphic minerals commonly define a schistosity (S_1) that is parallel to compositional layering, interpreted to be due to transposition of primary layering into the S_1 plane during regional deformation and metamorphism (St-Onge et al., 1987; 1988; St-Onge and Lucas, 1990a).

Fine-scale, primary igneous textures are preserved locally in areas of lower strain. Modally-graded gabbroic layers, with sharply defined mafic bases and felsic tops, are rhythmically repeated at centimetre-scale intervals (Fig. 7). Irregularly shaped, decimetre-scale lozenges of gabbroic pegmatite are rare, but have been observed throughout the layered succession. Concordant, centimetre-scale layers of homogeneous gabbro are common, and may represent intrusive sills or, in extremely deformed cases, transposed dykes. Centimetre-scale mafic dykes are rarely observed cross-cut-

Fig. 6 - Relict primary compositional layering in mafic cumulate rocks defined by the metamorphic products of plagioclase- (light) and clinopyroxene-rich (dark) bands. Pen (center) is ~15 cm long.

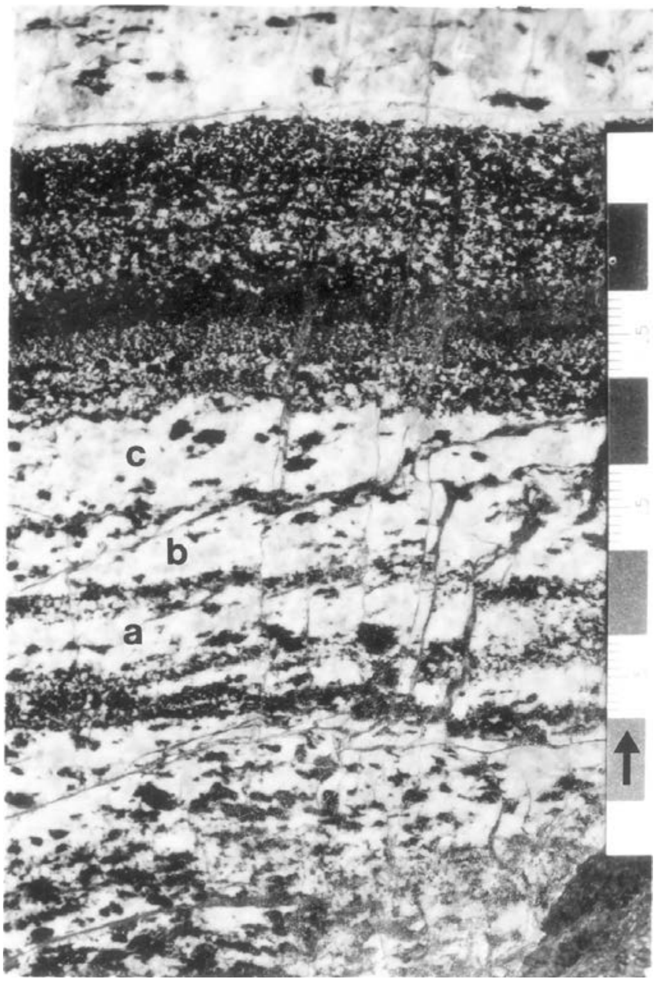

Fig. 7 - Polished slab of cumulate gabbro showing three cm-scale modally-graded layers (a, b, c), with clinopyroxene-rich bases and plagioclase-rich tops. Finest divisions on scale (right) are mm.

ting the dominant compositional layering (Scott and Bickle, 1991).

Zircon from two samples of layered gabbro from the Lake Watts area (Fig. 2) has been dated (Parrish, 1989). The zircons of the first sample were interpreted as igneous in origin and yielded an age of 1998 ± 2 Ma, thus determining the age of formation of the Watts Group. Zircons of the second sample have cloudy igneous cores dated at 1995-2000 Ma, and clearer overgrowths dated at 1977 ± 3 Ma, interpreted as a sea-floor metamorphic event (Parrish, 1989).

Numerous lines of evidence suggest that the layered mafic rocks are more penetratively deformed than the layered ultramafic rocks. Primary igneous textures, such as modally-graded layering, are more common in the ultramafic cumulates than in the mafic cumulates. Relict igneous minerals have been observed only in the layered ultramafic rocks, whereas the layered mafic rocks are completely recrystallized into metamorphic assemblages. Compositional layering (S_0) in the layered mafic rocks appears to have been transposed into parallelism with the principal metamorphic schistosity (S_1); in contrast, where S_1 is developed in ultramafic rocks, it is generally oblique to compositional layering (St-Onge and Lucas, 1989a; 1989b; Scott and Bickle, 1991). These differences, which exist despite identical metamorphic and deformational histories for the two rock types, suggest that the more fully recrystallized, layered mafic rocks record a larger amount of strain than do the ultramafic rocks, probably a consequence of their rheological contrast (Lucas, 1990).

A transitional relationship between ultramafic and mafic rocks is best exposed at the eastern end of thrust sheet A (Fig. 2), where it is gradational over an interval approximately 150 m wide along the Deception River. In the central panel of ultramafic rocks, individual layers that are compositionally graded from olivine- to clinopyroxene-rich, face to the south, and are interpreted as indicating the ‘younging’ direction of the layered succession. The base of the transition zone is marked by the appearance of numerous, <5 cm-thick plagioclase-bearing layers, which increase in abundance and thickness up-section. The virtual absence of dunitic layers defines the upper limit of the transition zone. The progressive change from ultramafic to mafic cumulate compositions is thus interpreted as a primary, igneous transition. Ultramafic rocks are also found within the layered gabbroic rocks above this transition, but they occur as isolated lenses which are tens of metres thick, and tens to hundreds of metres in length (Fig. 2).

Non-layered clinopyroxenite intrusions

Irregularly-shaped bodies of coarse-grained clinopyroxenite are found at all levels within the mafic and ultramafic cumulate rocks, and only rarely show any signs of fine-scale modal- or size-graded layering (Fig. 2). These rocks are composed of generally fresh diopside, comprising ca. 90% of the rock, variably serpentinized olivine (Fo85-80), and accessory Cr-bearing magnetite (Scott, 1990). In some samples from areas of lower-amphibolite facies (Bégin, 1989, 1992), clinopyroxene replacement by hornblende is virtually complete (i.e. northwest of Lake Watts, and east of the Deception River, Fig. 4). The bodies range in size from tens of metres to several kilometres in longest dimension, the largest bodies occurring on the west side of Lake Watts, and east of the Deception River at the northern margin of the belt (Fig. 2). The presence of layered gabbro xenoliths along the margins of the largest body (west of Lake Watts) demonstrates that this clinopyroxenite is intrusive into the layered gabbros. The body on the northern margin of the belt, east of the Deception River (see Fig. 2) cross-cuts primary compositional layering in the ultramafic cumulate host-rocks, demonstrating that it too is intrusive. All of the observed bodies have been deformed and metamorphosed together with their host rocks, suggesting that they are close in age and possibly consanguineous with other units of the Watts Group.

Sheeted mafic dykes and pillowed volcanic rocks

At the base of the thickest thrust sheet of volcanic rocks (thrust sheet E, Fig. 2), a dense swarm of mafic dykes passes stratigraphically upward into overlying pillowed basalts. The transition from essentially 100% dykes to pillowed basalts occurs progressively through a zone of alternating dykes, massive amphibolites, and pillowed basalt upward into exposures of deformed, dominantly pillowed basalts (Scott and Bickle, 1991), shown in detail in Fig. 8. This relationship is strikingly similar to sheeted-dyke - pillowed-basalt transitions observed in Phanerozoic ophiolites, where it is considered as direct evidence for sea-floor spreading.

The swarm of dykes strikes NNE, and dips steeply toward the ESE, roughly normal to the overlying pillowed-basalt flows. Parts of the complex have been subsequently deformed and rotated, described in detail subsequently. Individual dykes range in width from less than 20 cm up to 50-60 cm, and can be traced along strike for tens of metres.

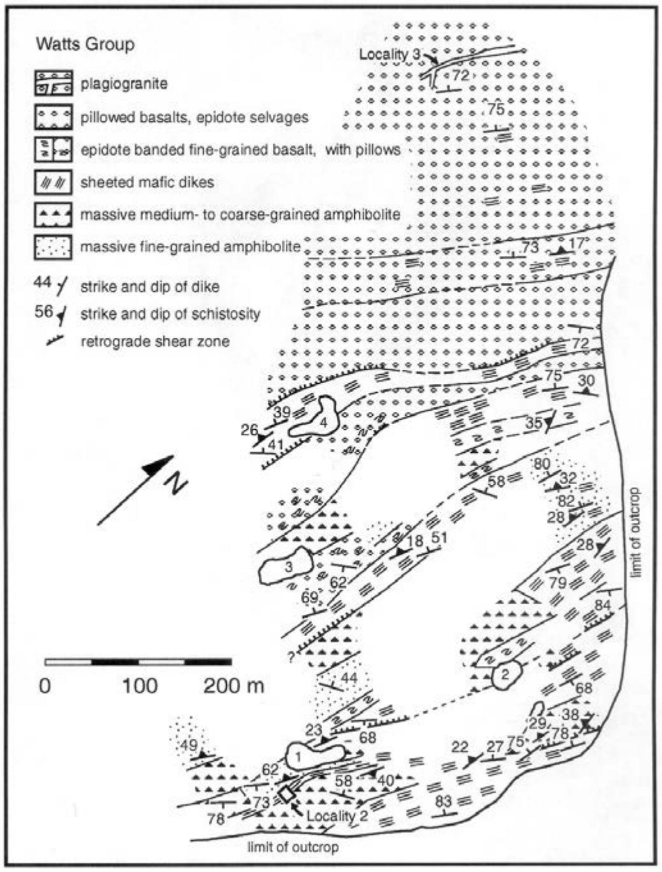

Fig. 8 - Detailed geological map of the area at Locality 1 (Fig. 2, discussed in text), documenting transition from 100% sheeted-dykes to dominantly pillowed basalts. Irregularly shaped areas numbered 1 to 4 are small lakes. Modified from Scott and Bickle, 1991.

The contacts of the dykes are delineated by grain-size changes interpreted as relict chilled margins. Locally dykes are so numerous that entire outcrops consist entirely of dykes, resulting in a ‘sheeted’ aspect (Fig. 9). Many of the dykes have only one chilled margin, the other displaced by subsequent dyke emplacement. Along strike from Locality 1 (Fig. 2), the thrust fault that underlies this exposure cuts obliquely upsection in its hanging wall, thereby eliminating the sheeted dykes from the base of the thrust-bound volcanic succession, and limiting the lateral extent of the preserved zone of intense dyke intrusion. Consequently, only a few individual dykes can be observed in the pillowed basalt section elsewhere at the base of this thrust sheet (Fig. 2).

The overwhelming majority of dykes are fine- to medium-grained (1-2 mm diameter) and massive- to weakly foliated, and characterized by upper-greenschist facies mineral assemblages (Bégin, 1989; 1992) of medium- to dark-green hornblende, variably rimmed by actinolite, in a matrix of actinolite, quartz, plagioclase, and minor amounts of epidote, chlorite, calcite, magnetite and sphene (Scott, 1990). The main petrographic differences between individual dykes are grain-size variations, the presence or absence of coarser amphibole or plagioclase crystals, which are interpreted as pseudomorphs of igneous phenocrysts, and the relative amounts of sphene. A subordinate number of 5-15 cm wide, darker-green mafic dykes (subsequently referred to as ‘chloritic’), intrude the sheeted dykes at low but variable angles (see Fig. 9). These younger, chloritic dykes are generally finer-grained (<1 mm diameter) than the sheeted dykes and are characterized by a similar but more chlorite- and actinolite-rich metamorphic mineral assemblage that defines a strong foliation in these dykes.

In addition to the sheeted and chloritic dykes, massive medium and coarse-grained amphibolites are present in subordinate amounts and are similar in appearance and metamorphic assemblage to the sheeted dykes, but without extensive well-preserved chilled margins. Some of the medium-grained amphibolite shown in Fig. 7 may be sheeted dykes whose contacts have been obscured by lichen. The coarser-grained amphibolite material, which contains up to 10 x 5 mm, darker-green amphibole porphyroblasts partly replaced by a finer-grained, foliated matrix of pale amphibole, chlorite, epidote, plagioclase and calcite, may have been derived from a relatively coarse gabbro; these coarser amphibolites are interpreted as screens of gabbroic material between the sheeted dykes. Alternatively, some may represent the coarse interiors of thicker dykes.

Cross-cutting relationships, exposed in a 3.5 m section of outcrop from which lichen and soil were removed, allow determination of a relative sequence of intrusion among the sheeted dykes at this location (Figs. 9, 10). Relative ages of individual dykes in this outcrop were inferred from grain-size fining directions, using chilled margins identified in the field and subsequently verified in thin section. These chilling directions are marked in Fig. 10a.

Stratigraphically above the zone of 100% sheeted dykes, screens of fine-grained mafic schist with contorted, cm-wide epidote bands become increasingly common. The epidote bands resemble the selvages in well-preserved pillowed basalts found higher in the succession, and suggest that much of the fine-grained mafic schist may represent highly-deformed pillowed basalts (Scott and Bickle, 1991). Sheeted dykes, single dykes, as well as fine- and coarser-grained amphibolites are intercalated with the epidote-banded mafic rocks.

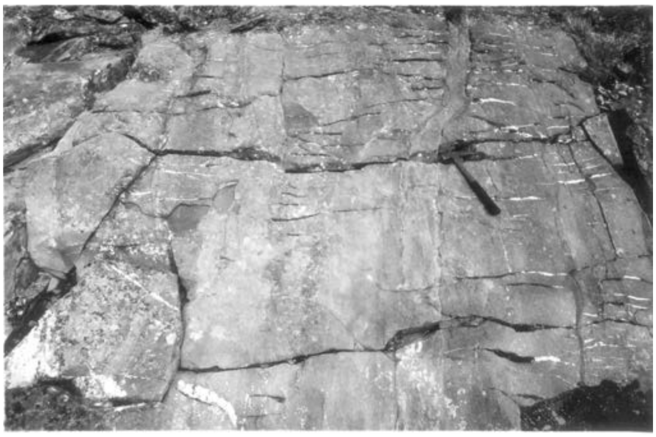

Fig. 9 - Cleaned outcrop of sheeted dykes (Locality 2, Fig. 8). Individual dykes, outlined by colour variations, strike into the photograph, and dip steeply to the right (southeast). Note late, cross-cutting chloritic dyke (immediately to left of hammer). See sketch of same outcrop in Fig. 10a. Hammer is 35 cm long.

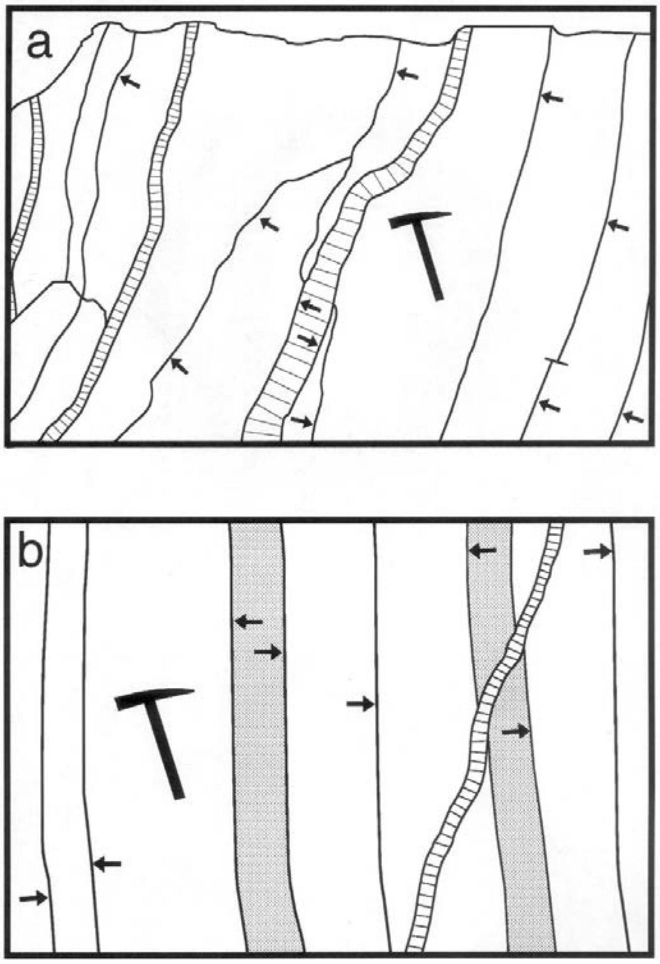

Fig. 10 - a) Outcrop sketch of sheeted dykes in the vicinity of Locality 2 (Fig. 8), the area corresponding to that shown in Fig. 9. Arrows indicate directions of grain-size fining, interpreted as chilled margins. Late chloritic dykes discussed in text are indicated with striped pattern. Modified from Scott and Bickle (1991). b) Sheeted dykes ~15 m southeast of those in Figs. 9 and 11a. OIB dykes, shown in grey, cross-cut MORB dykes.

A large part of the Watts Group, cropping out throughout the study area (Fig. 2), consists of foliated, fine-grained (<1 mm), massive and pillowed mafic volcanic rocks. As a result of the penetrative schistosity (S_1) developed during deformation and regional metamorphism, primary volcanic textures are rarely preserved, except in areas of lower strain. The rocks have been completely recrystallized to greenschist- to amphibolite facies metamorphic assemblages (Bégin, 1989; 1992) that consist of hornblende and actinolite, quartz, plagioclase, epidote, and chlorite, and trace amounts of magnetite, sphene and calcite (Scott, 1990). In the vicinity of post-thermal peak out-of-sequence faults, a greenschist-facies retrograde overprint is developed, characterized by the growth of chlorite and actinolite. Clastic interflow sediments have not been observed, but small amounts of massive quartz have rarely been observed in pillow interstices. The deformed pillowed mafic rocks continue up-section for several kilometres (St-Onge and Lucas, 1989a).

Pillows are generally less than one metre in width, and are commonly outlined by epidote-rich selvedges that are interpreted as former chilled margins. In more strongly foliated rocks, fine-grained mafic schist cut by an anastamosing network of centimetre-scale, epidote-rich bands is interpreted as deformed pillowed basalt. The facing directions determined from pillow shapes, and rare lava-withdrawal shelves show that the succession is upright, and youngs to the northwest (St-Onge and Lucas, 1989a). The orientation of primary flow units based on lava-withdrawal shelves and pillow shapes is interpreted to be approximately parallel to S_1.

Plagiogranite sills and dykes

Small tabular intrusions composed of fine-grained plagioclase and quartz with trace amounts of actinolite or muscovite occur rarely throughout the mafic volcanic succession (Fig. 8). Individual intrusions occur as thin (1-5 m) sills that are laterally extensive for tens of metres, locally observed being fed by dykes that cross-cut pillowed basalt flows. One such sill, 60 m long and less than 1 m thick, was mapped in the northern part of the area (Fig. 11) where it is fed by a narrow dyke of similar composition; both the sill and the dyke cross-cut the host pillowed basalts. In turn, the sill is cut by narrow, late ‘chloritic’ dykes. The felsic intrusions contain a foliation defined by alignment of actinolite and muscovite, parallel to regionally mapped S_1. The radiometric ages of these intrusions are not known.

GEOCHEMISTRY

Two geochemically distinct magmatic suites have been identified within the layered mafic and ultramafic rocks of the Watts Group, on the basis of major and trace element abundances, and Nd isotopic composition (Scott, 1990; Scott et al., 1991; 1992; Hegner and Bevier, 1991). The older of the two has characteristics similar to modern mid-ocean ridge basalt (MORB), while the younger are similar to ocean island basalt (OIB). Samples were collected across much of the area shown in Fig. 2 (Scott, 1990).

Fig. 11 - Felsic dyke (arrow in foreground) crosscutting pillowed basalts, which feeds overlying felsic sill (between arrows) intrusive into the pillowed basalts. Hammer (centre) is 35 cm long. From locality 3 on Fig. 8.

With the exception of thrust sheet A, each thrust sheet preserves rocks of only one of the two magmatic suites (Scott, 1990, Fig. 3.1). Layered rocks of the MORB-like suite are found in thrust sheets A, D, H and I, whereas rocks of the OIB-like suite are found in thrust sheets A, C, F, G and K (Fig. 2). Thrust sheet A, comprising a pair of synforms, separated by a locally overturned antiform, contains mafic and ultramafic cumulate rocks of both magmatic suites. The mafic rocks in the northern synform belong to the MORB-like suite, whereas in the southern synformal structure, chemical and Nd-isotopic analyses of both the mafic and ultramafic cumulate rocks indicate that they belong to the OIB-like suite (Scott, 1990). The sharp contact between the MORB-like mafic cumulate rocks and the overlying package of OIB-like ultramafic and mafic cumulate rocks is only exposed east of the Deception River (Fig. 2); the OIB-like ultramafic rocks truncate layering in the MORB-like mafic rocks, suggesting that the former intruded the latter.

Geochemical analyses of individual dykes in the sheeted complex have revealed that two chemically distinct types are present (Scott, 1990; Scott et al., 1991), although the two populations are not distinguishable in outcrop. Approximately three-quarters of the dykes sampled are compositionally similar to the overlying mafic volcanic rocks, with major and trace element compositions and petrogenetic evolution similar to modern MORB involving fractional crystallization of olivine, plagioclase and clinopyroxene.

MORB-like suite

The first of the two tholeiitic suites is characterized by depleted abundances of elements such as Ti, Zr, Y, and the light rare earth elements (LREE) relative to more compatible elements (Scott et al., 1991), and has εNd(2.0 Ga) values that range from +3.4 to +6.1 (Scott and Hegner, 1990; Hegner and Bevier, 1991). Rocks of this suite are dominantly cumulate gabbros, with subordinate stratabound lenses of layered ultramafic rock (Scott, 1990). This suite has been interpreted as compositionally similar to those which have formed at modern oceanic spreading ridges, and is subsequently referred to as the mid-ocean ridge basalt (MORB)-like suite (Scott et al., 1992). Both of the aforementioned gabbro samples for which U-Pb ages were determined belong to this suite.

OIB-like suite

Rocks of the second suite have incompatible element abundances that are enriched relative to MORB (Scott et al., 1991), εNd(2.0 Ga) values that range from +1.0 to +4.7 (Scott and Hegner, 1990; Hegner and Bevier, 1991), and a bimodal distribution of ultramafic and mafic rock types. Rocks of this suite are compositionally similar to those found in modern hot-spot related oceanic islands; they are subsequently referred to as the ocean island basalt (OIB)-like suite. The absolute age of this suite has not been directly determined, but may be related to the aforementioned younger (1977 Ma) zircon growth event.

Neodymium isotopic compositions of three samples of coarse-grained, non-layered clinopyroxenite range from εNd(2.0 Ga) +2.3 to +3.9 (Hegner and Bevier, 1991), suggesting that the intrusive clinopyroxenite bodies may be part of the younger, OIB-like suite.

The less-numerous population of dykes intrude the sheeted MORB-like dykes (Fig. 10b), and have major and trace element compositions similar to modern tholeiitic OIBs. The petrogenetic evolution of the OIB-like dykes was controlled by fractional crystallization of olivine and clinopyroxene (Scott, 1990). The Nd-isotopic compositions of the MORB-like dykes range from εNd(2.0 Ga) +4.0 to +4.7, whereas those of the ocean island-like suite range from εNd(2.0 Ga) +3.0 to +3.4 (Scott and Hegner, 1990; Hegner and Bevier, 1991).

The MORB-like sheeted dykes and volcanic rocks are interpreted to be consanguineous with the MORB-like cumulate rocks, and the OIB-like dykes with the OIB-like cumulate rocks. Despite geochemical sampling of the entire exposed volcanic section, extrusive rocks that are compositionally similar to the OIB-like dykes have not been identified (Scott, 1990). The two suites of sheeted dykes have been distinguished petrographically; relative to the MORB-like dykes, the OIB-like dykes contain a higher modal proportion of sphene, and contain coarse, inclusion-filled hornblende porphyroblasts rimmed by actinolite (Scott, 1990). The late chloritic dykes intrude dykes of both the MORB- and OIB-like suites, but have not been characterized geochemically.

TECTONIC RELATIONSHIPS BETWEEN UNITS

The various units of the Watts Group include all of the rock types known from typical oceanic crust and Phanerozoic ophiolites. Due to extensive early thrust imbrication, a continuous section showing original relationships no longer exists. In the following section, the tectonic relationships between these thrust sheets are described, and an interpretation of the nature of the original crustal section represented by the Watts Group is presented.

The southward-verging system of thrusts shown in the study area developed during D_1 deformation in the Cape Smith Belt (see Fig. 6 in Lucas, 1989; St-Onge and Lucas, 1990a). The geometry of the thrust units has been complicated by subsequent folding events that generated the major east-west trending synclines and anticlines (D_3) and NNW-striking cross-folds (D_4), resulting in the map pattern shown in Fig. 1. The present three-dimensional configuration of the Watts Group is represented in a series of cross-sections constructed at intervals across the study area (Fig. 12). These sections are used to estimate the thicknesses of each of the units and to construct a composite section representing the pre-deformation configuration of the Watts Group.

Numerous discrete zones of higher strain were identified within the sheeted-dyke - pillowed-basalt transition zone (Fig. 8). The dip of the sheeted dykes shows a correlation with the intensity of foliation development, probably related to the shear regime associated with the development of the thrust faults (Scott and Bickle, 1991). Dykes that are massive or only weakly foliated, interpreted as the least deformed, dip between 70° and 90° to the southeast. As the intensity of the foliation increases, the dykes rotate from steep southeast dips to progressively shallower northwest dips. The most-strongly foliated and highly-strained dykes dip between 27° and 40° toward the northwest, and are interpreted to have been rotated through angles of up to 90° (Scott, 1990; Scott and Bickle, 1991). The association of dyke orientation and internal strain, the consistent direction of rotation of the more-deformed dykes, and the maximum dyke rotations of 90° are all consistent with the interpretation of the observed adjacent high-strain zones as south-verging thrusts (Scott and Bickle, 1991). The sense of rotation of the more-deformed dykes implies a southward hanging-wall displacement, consistent with the regional direction of thrusting (St-Onge and Lucas, 1990a). Based on their chlorite- and actinolite-rich assemblages, the shear zones are inferred to have developed during the post-thermal-peak out-of-sequence thrusting (Lucas, 1989) responsible for the major thrust that underlies the Watts Group in the area (Figs 1, 2). Despite this deformation, the partly tectonized transition from sheeted dykes with screens of gabbro, upward through sheeted dykes and pillowed basalts, to the upper, most extensive unit of dominantly pillowed basalts (Fig. 8), is inferred to represent the primary igneous relationships between these units.

Structural relief provided by D_4 cross-folds was used to construct a series of vertical cross-sections, four of which are presented here (Fig. 12). The location of section AA' was selected so as to include the greatest areal extent of thrust sheet E, which includes at its base the sheeted-dykes - pillowed-basalt transition and overlying thrust sheets of mafic cumulate rocks. Sections BB', CC', and DD' were drawn through thrust sheet A in order to document lateral changes in the largest continuous block of mafic and ultramafic cumulate rocks, including cumulate rocks of both magmatic suites. The southern syncline in thrust sheet A, which varies along strike from upright to locally overturned, preserves the previously described transition zone from ultramafic to mafic cumulate rocks of the OIB-like suite. The geometry of the fold is outlined principally by primary igneous layering in the ultramafic rocks, manifest at map-scale by the contact between ultramafic and mafic cumulate rocks. The mafic cumulate rocks that occupy the northern part of the thrust sheet are part of the MORB-like suite and have been folded into a tight, locally overturned antiform and a broad, open synform (Section CC'). These map-scale folds, which deform the dominant planar fabric (S_1), are interpreted as D_2 structures.

The individual, dismembered segments of the ophiolite can be reassembled to produce a composite section through the Watts Group crustal succession (Fig. 13). The upper portion of the composite crustal section in Fig. 13 (Segment 1) represents information from thrust sheet E, (Section AA', Fig. 12) that preserves at its base the transition from sheeted dykes to pillowed basalts. The total thickness of this thrust sheet is approximately 2800 m. The lower portion of the composite crustal section (Segments 2, 3, and 4) is based on interpretation of information from thrust sheet A (Fig. 2) that is represented in Sections BB', CC', and DD' (Fig. 12). Segment 2 of the composite crustal section represents the mafic cumulate rocks in the southern syncline in thrust sheet A (section DD', Fig. 12), estimated to be 2100 m thick. The top of this segment is an erosional surface, marked by the map trace of the (locally overturned) synclinal axis, whereas the base is taken as the ultramafic-mafic cumulate transition in the OIB-like suite that occurs on the southern limb of the syncline. Segment 3 represents the approximately 2200 m

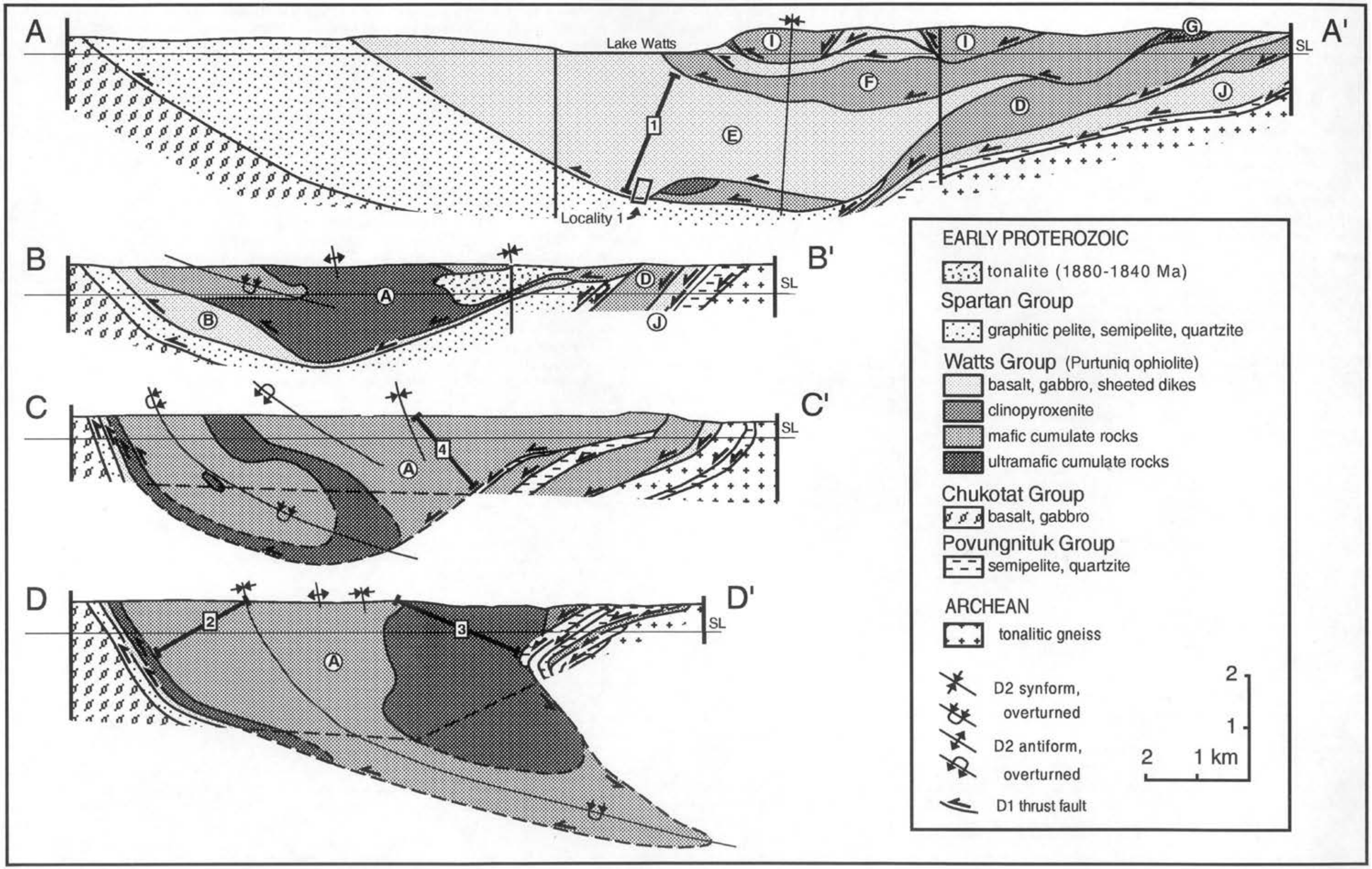

Fig. 12 - Vertical cross-sections along lines AA', BB', CC', and DD' (Fig. 2). Each cross section was constructed by projecting surface geological data parallel to the plunge of D_2 fold axes onto a vertical plane in domains of uniform D_2 plunge (after the method of Stockwell (1950)). This method assumes that the geologic information illustrated on the map (Fig. 2) is predictable (and therefore projectable) at the scale of the structural domain, an assumption shown to be valid for the eastern Cape Smith Belt (Lucas, 1989). In the present example, individual domains have along-plunge dimensions of 3-6 km. The cross sections were constructed without vertical exaggeration. Structural data for individual domains were compiled by Lucas (1989). Sections derived from adjacent domains have not been "stacked" upon one another (cf. Lucas, 1989), so that the series of sections illustrates along-strike variations, rather than providing a composite view of the entire study area. The differences between apparent thicknesses shown and the true thicknesses of units (as viewed in down-plunge fold-profile) are small for the shallow plunge angles in the present case, and are considered to be negligible relative to other uncertainties in the thickness estimates, as discussed in text. Stratigraphic segments labelled 1 - 4 were used to construct the composite crustal section shown in Fig. 13.

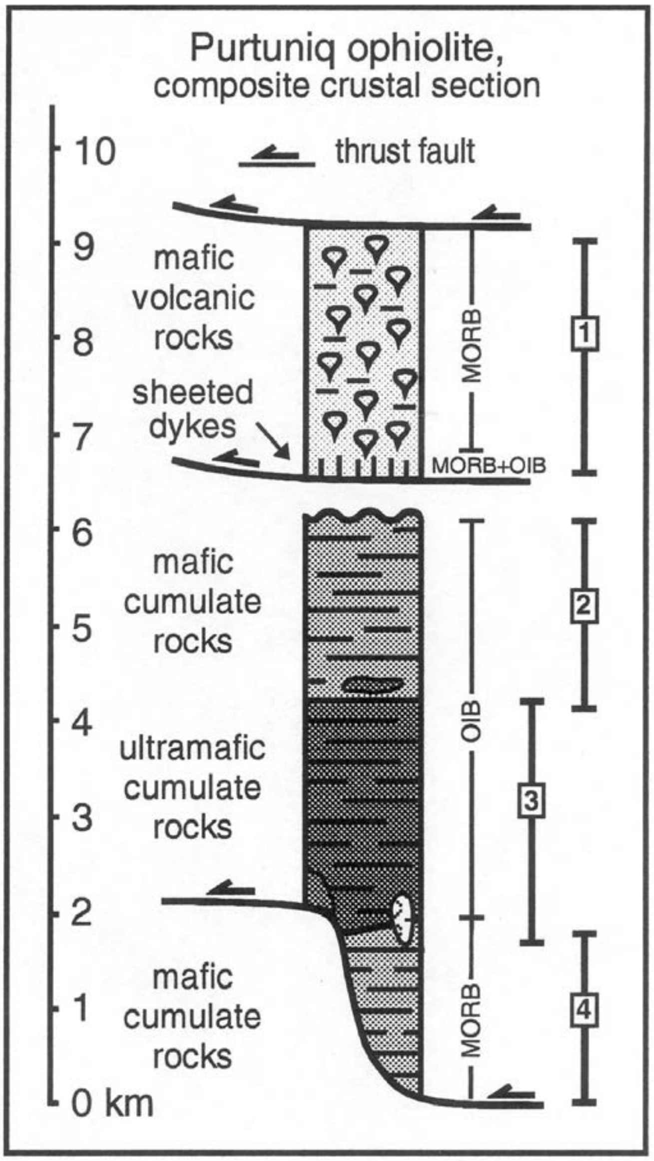

Fig. 13 - Composite crustal section constructed from individual segments (1-4) shown on sections AA', BB', CC', and DD' in Fig. 12, using information from thrust sheets E (segment 1) and A (segments 2, 3, and 4). Minimum estimated thickness of the preserved portion of the Watts Group crust is ~9 km, discussed in text.

thickness of OIB-like ultramafic cumulate rocks that lie below the mafic cumulate rocks of segment 2 (section DD', Fig. 12). The top of segment 3 is marked by the transition into the overlying cumulate mafic rocks on the northern limb of the syncline. The base of the ultramafic cumulate succession is represented by the intrusive contact with the MORB-like mafic cumulate rocks to the north (Fig. 2). The mafic cumulate rocks at the base of the crustal section (Segment 4; section CC', Fig. 12) represent those of the northern synform that have an estimated thickness of 1800 m. The base of this segment is the thrust fault that underlies thrust sheet A.

The individual segments shown in Figs. 12 and 13 are considered to be best-estimates of the thicknesses of thrust sheets that are internally deformed. Structural repetitions along smaller thrusts and folds of S_0 that were not recognized during regional mapping (St-Onge and Lucas, 1989a, 1989b) are present and result in an over-estimation of primary thicknesses. The development of S_1 in the pillowed basalts and mafic cumulate rocks has probably reduced the primary thicknesses of these units somewhat. As flattening due to shearing, and thickening by tectonic repetition, have opposite effects on the primary thicknesses of individual units, and both are likely to have occurred to only a limited extent in the present example, it may be expected that to some degree these effects offset one another. We interpret that the thicknesses represented in Fig. 13 are at least first-order approximations of the primary thicknesses of the individual units of the Watts Group.

Based on petrological, geochemical and isotopic evidence (Scott, 1990; Scott et al., 1991), the rocks of the upper and lower portions of the composite crustal section (Fig. 13) are interpreted to represent volcanic/hypabyssal and plutonic equivalents. The MORB-like pillowed basalts and most of the sheeted dykes (segment 1, Fig. 13) are interpreted as being related to much of the areally extensive MORB-like mafic cumulate rocks, such as those in the northern part of thrust sheet A (segment 4, Fig. 13), and thrust sheets D, H, and I. The OIB-like dykes in the sheeted complex are interpreted to be genetically related to the continuous ultramafic and mafic cumulate rocks of the southern part of thrust sheet A (segments 2 and 3, Fig. 13), and the layered rocks in thrust sheets C, F, G and K. Based on the interpreted consanguineity of the rocks within each of the two suites, and the fact that each suite is represented by hypabyssal (OIB-like suite), or hypabyssal and volcanic rocks (MORB-like suite) in the upper portion of the composite crustal section, and cumulate-textured plutonic rocks in the lower portion, it appears reasonable to consider the two portions of the composite section as an originally continuous piece of mafic-ultramafic crust.

DISCUSSION

The igneous rocks of the Watts Group, described above, represent all of the igneous crustal members of the Penrose-defined ophiolite assemblage (Anonymous, 1972). Tectonized harzburgite and lherzolite, which are interpreted to represent obducted mantle material in Phanerozoic ophiolites, have not been identified in the Cape Smith Belt. Consequently, the base of the crustal section has not been identified. In addition, the Watts Group assemblage is dismembered by thrust faults (Figs. 2, 3 and 13). The Penrose definition explicitly states that "faulted contacts between mappable units are common", and that "whole sections may be missing" (Anonymous, 1972, p. 25). It is thus in keeping with this terminology to refer to the Watts Group assemblage as an incomplete and dismembered ophiolite. The name Purtuniq ophiolite was introduced for this assemblage by St-Onge et al. (1988).

The preservation of oceanic crust as ophiolites must be considered anomalous, as the overwhelming majority of oceanic crust is routinely recycled back into the mantle by subduction. Historically, this has prompted the question of whether ophiolites are representative of typical ancient oceanic crust. This question is difficult to address due to the restricted population (two) of proposed examples of Paleoproterozoic oceanic crust. The dismembered Purtuniq ophiolite is nevertheless interpreted to represent an example of Paleoproterozoic oceanic crust that formed at a spreading center (MORB-like suite), into which was subsequently intruded a suite of ocean-island-like igneous rocks (OIB-like suite). The hypothetical presence of a Hawaii-like oceanic island volcanic edifice, related to the later magmatic suite, may in part have facilitated the obduction and/or prevented the complete subduction of the Watts Group.

Primary thickness of the Purtuniq ophiolite

The total thickness of the preserved portion of the dismembered Purtuniq ophiolite is estimated at ~9 km (Fig. 13); the original thickness must have been greater than this, as primary transition zones are missing (see below), and the upper and lower limits of the composite section are thrust faults. In this section, the possible pre-deformation configuration of the ophiolite section will be discussed, and a reasonable estimate of the total primary thickness proposed.

The physical transition between the mafic cumulate rocks of the MORB-like suite and the chemically- and isotopically-associated sheeted dykes has not been observed in the study area. In Phanerozoic ophiolites, the thicknesses of sheeted dyke complexes range from several hundreds of metres (e.g., Bay of Islands: Rosencrantz, 1983) to several km (Samail: Christensen and Smewing, 1981; Pearce et al., 1981; Troodos: Gass, 1980). In these examples, the transition zones from dykes into pillows, and from dykes into the underlying high-level gabbros, occur over distances of less than 50 m (Pallister, 1981). In the Purtuniq ophiolite, it thus seems reasonable to interpret the missing transition from the MORB-like layered cumulate rocks to the sheeted dykes as at least hundreds of metres in thickness.

The lower limit of the OIB-like cumulate rocks in thrust sheet A (Segment 3 in Fig. 13) is an intrusive contact, whereas the upper limit (segment 2 in Fig. 13) is an erosional surface. This implies that a portion of the section is missing from the top of the OIB-like mafic cumulate rocks, and that MORB-like mafic cumulate rocks, high-level gabbros, or the base of the sheeted-dyke complex, which are assumed to have been the host-rocks, are also no longer preserved in this thrust sheet. The original thickness of these missing rocks cannot be rigorously estimated, but it appears reasonable to suggest that they may have added hundreds to possibly thousands of metres to the original thickness of the Purtuniq crustal section. A rigorous estimate of the missing thickness of the MORB-like mafic cumulate rocks in the northern part of thrust sheet A (segment 4, Fig. 13) is similarly not possible. The total thickness represented by the portions of the composite crustal section which are missing (Fig. 13) was most probably on the order of hundreds to several thousand metres, and thus the primary thickness of the crust represented by the Purtuniq ophiolite could conservatively have been ~10-12 km, and possibly up to 15 km.

Modern analogue

A possible modern analogue that respects both the physical (field relationships, relative ages, thickness) and chemical (major and trace element abundances and Nd-isotopic compositions) characteristics of the two magmatic suites that comprise the Purtuniq ophiolite is the present-day oceanic crust of the Pacific plate and the Hawaiian Islands. A brief overview of the crustal structure of the Hawaiian Islands is presented in the following section.

The higher crustal levels of the Hawaiian Islands are well-exposed, and dominated by prominent basaltic shield volcanoes. A well-developed complex of sheeted mafic dykes is exposed in a rift zone within the eroded volcanic shield of Koolau Volcano on Oahu (Walker, 1986; 1987). The deeper crustal structure of the Hawaiian Islands has been outlined in numerous seismic studies (Hill, 1969; Ellsworth and Koyanagi, 1977; Crosson and Koyanagi, 1979; Zucca and Hill, 1980; Hill and Zucca, 1987; ten Brink and Brocher, 1987; Ryan, 1988). In each of these studies, the Pacific crust distal from the Hawaiian Islands has been shown to be approximately 6 km thick, with the Moho observed at ~10 km below sea level, whereas the Moho is observed at a depth of ~13-14 km below sea level under Kilauea Volcano. Interpretations of the structure of the volcanic edifice differ among these studies, but all show P-wave velocities between 5.0 km/s (Crosson and Koyanagi, 1979) and 7.0 km/s (Hill, 1969). In particular, P-wave velocities are markedly higher under rift zones and volcano summits (Ellsworth and Koyanagi, 1977; Crosson and Koyanagi, 1979; Zucca and Hill, 1980). Whereas Zucca and Hill (1980) have interpreted these high-velocity regions as densely injected zones of dykes, Ellsworth and Koyanagi (1977), Crosson and Koyanagi (1979) and Hill and Zucca (1987) suggested that they are due to the presence of ultramafic cumulate rocks that represent magma chambers established in the Pacific plate. Cumulate-textured dunites that crystallized at depths shallower than 15 km have been reported from the shield of Koolau volcano on Oahu (Sen, 1983), and directly support the cumulate-filled magma chamber hypothesis. The latter interpretation is consistent with the accumulation of the products of crystal fractionation at mid-crustal levels, and the inclusion of cumulate-textured ultramafic xenoliths in late-stage volcanic rocks (Jackson and Wright, 1970; Sen, 1983, 1987).

The high-level crustal cumulate dunites beneath the Hawaiian volcanoes (Sen, 1983; Hill and Zucca, 1987) are possible analogues for the cumulate ultramafic rocks of the Purtuniq OIB-like suite. Relict primary igneous minerals in the cumulate ultramafic rocks of the Purtuniq OIB-like suite (Scott, 1990) are compositionally similar to those that comprise the cumulate-textured dunitic xenoliths from Koolau Volcano, Oahu, (Sen, 1983, 1987). As the Hawaiian cumulate rocks intrude the lower crust of the Pacific plate, so the Purtuniq OIB-like ultramafic cumulate rocks intrude the cumulate gabbros of the MORB-like suite. In the case of the Purtuniq OIB-like suite, the ultramafic cumulate rocks grade upward into cumulate textured gabbros, indicating the appearance of plagioclase as a stable liquidus phase. Gabbroic cumulate rocks have not been identified seismically below Hawaii, nor as xenoliths; whether this indicates that they are not present, or whether they are seismically indistinguishable from oceanic layer 3 (gabbroic cumulate rocks) of the pre-existing Pacific plate is difficult to resolve. Dykes related to the development of the Hawaiian volcanoes cross-cut the Pacific crust and the sheeted dyke complex inferred to have formed during spreading at the East Pacific Rise, analogous to the relationships observed in the well-exposed portions of the Purtuniq sheeted-dyke outcrops at the base of thrust sheet E (Figs. 2, 10, 12).

Obduction and Accretion

In contrast to many Phanerozoic ophiolites, a dynamothermal contact aureole has not been observed below the lowest exposures of the Purtuniq ophiolite. The thrust fault that presently underlies the ophiolite is interpreted as a late D_2 out-of-sequence thrust (St-Onge and Lucas, 1989a, 1989b; Lucas, 1989), and thus it would be fortuitous if an obduction-related contact aureole were presently observed directly below the ophiolite. Whether this fault is the original obduction surface that was subsequently reactivated during D_2 out-of-sequence thrusting, or is a fault initiated during out-of-sequence thrusting is unknown. The importance of out-of-sequence thrusting has been documented in both the Samail (Oman) and Bay of Islands (Newfoundland) ophiolites (e.g., Searle, 1985; Cawood and Williams, 1988; Cawood, 1991), and may have been important in the obduction of the Purtuniq ophiolite. Based on the overlap between the leading edge of the ophiolite and the most northerly surface exposure of Superior craton basement (southern Baffin Island), the tectonic shortening accommodated by the D_1 and D_2 thrusting has been estimated to be a minimum of 160 km (St-Onge et al., 1999).

Comparison to Phanerozoic Ophiolites

The total thickness of igneous crustal components preserved in the eastern portion of the Purtuniq ophiolite (~9 km) includes both ridge-formed (MORB) and subsequent hot-spot related (OIB) suites of rocks, and is somewhat greater than the thickest crustal sections reported from Phanerozoic ophiolites and estimates of modern oceanic crust. If only the MORB suite of the Purtuniq ophiolite is considered, the total preserved thickness is approximately 5 km, and may originally have been up to 7 km when sections that are no longer preserved are considered. Crustal thicknesses between 6 and 7 km have been reported for the Samail ophiolite (Hopson and Pallister, 1980; Hopson et al., 1981; Christensen and Smewing, 1981); 4-5 km are reported for the Bay of Islands complex, Newfoundland (Malpas and Stevens, 1977; Suen et al., 1979); and up to 6 km from the Karm¿y ophiolite, southwest Norway (Sturt et al., 1980).

If the estimates of the thicknesses of missing portions of the Purtuniq ophiolite are considered, the total thickness of the crustal section (10-15 km) approaches that of combined mantle and crustal sections in Phanerozoic examples. The total obducted thickness (crust + mantle) of the Samail ophiolite ranges from 10-15 km from south to north, the preserved thickness of the thrust sheet decreasing in the transport direction (Boudier and Coleman, 1981; Christensen and Smewing, 1981; Hopson et al., 1981). The total preserved thicknesses of both the Bay of Islands (Suen et al., 1979; Malpas, 1978) and Troodos complexes (Gass, 1980) are approximately 10-12 km. Depleted mantle material, which is commonly obducted in Phanerozoic ophiolites, has not been observed in the Purtuniq ophiolite. A possible explanation for this ‘missing mantle’ is that it was initially obducted along with the presently preserved crustal section, but was subsequently separated from the crustal rocks during out-of-sequence thrusting. Alternatively, a possible mechanism to explain this feature is delamination of the lithosphere prior to obduction, occurring at or above the ultramafic cumulate/residual mantle boundary. Such a model has been proposed by Hoffman and Ranalli (1988), wherein a thicker oceanic crust develops a strong-weak-strong rheological layering due to a nominally higher geothermal gradient and its greater thickness. The weak interface is postulated here to have been located within the lowermost levels of the crustal cumulates, facilitating delamination, thus preventing the uppermost part of the mantle from being incorporated in the accretionary assemblage. A thicker oceanic crustal section in the Purtuniq ophiolite may have resulted in delamination within the crustal section, whereas delamination occurring at the same depth in thinner oceanic crust would include a substantial portion of the mantle with the obducted section.

Comparison to other Proterozoic ophiolites

Numerous packages of Paleoproterozoic rocks have been described as dismembered, incomplete and metamorphosed ophiolites (see Helmstaedt and Scott, 1992). The Jormua complex (east-central Finland) comprises serpentinite, gabbro, sheeted mafic dykes, pillowed basalts, black shales and chert, and has been interpreted as the dismembered crustal components of a 1960 ± 12 Ma ophiolite, with a total thickness of preserved units of ~1 km (Kontinen, 1987). In northern Wisconsin, ~1.85 Ga cumulate-textured ultramafic and mafic rocks, a diabase dyke and sill complex, minor sheeted dykes, and a succession of pillowed basalts have been interpreted as the crustal components of a dismembered ophiolite (Schulz, 1987). An example in central Arizona, dated at 1738 ± 5 Ma, comprises a pseudostratigraphic sequence of layered and isotropic gabbros, sheeted mafic dykes and mafic volcanic rocks. Locally abundant screens and roof pendants of older crust overlying dacitic volcaniclastic rocks and turbidites. Collectively, these rocks have been interpreted as crust formed during spreading related to the rifting of an oceanic magmatic arc (Dann, 1991, 1997). With the exception of Jormua, residual mantle material is not present, and structural or intrusive dismemberment is so severe that composite sections, and therefore accurate estimates of original crustal thicknesses, cannot be made. It is thus difficult to rigorously compare the thickness of the Purtuniq ophiolite to other Paleoproterozoic examples.

A Paleoproterozoic hot-spot?

The OIB-like suite of the Purtuniq ophiolite implies the presence of an active mantle plume in the Paleoproterozoic. The volcanic-dominated nature of the ca. 1.96 Ga upper Povungnituk Group that is associated with the breakup of the northern margin of the Superior craton (e.g., Hynes and Francis, 1982; St-Onge and Lucas, 1990a) and the presence of localized centers of alkalic volcanism near the top of this succession (Goanac’h et al., 1992) are additional features that may be consistent with the operation of a mantle plume (Richards et al., 1989; Sleep, 1990; White and McKenzie, 1989; Hooper, 1990). South of the Cape Smith Belt, three Paleoproterozoic dyke swarms in the Superior craton have been interpreted as part of a radiating swarm whose focus may mark the location of a ca. 2.22 Ga mantle plume (Buchan et al., 1998), contributing further evidence for possible hot-spot activity in the region at that time.

SUMMARY

The accumulated field and chemical evidence (Scott, 1990) suggests that the igneous rocks of the Purtuniq ophiolite have counterparts in modern oceanic environments. Relationships observed in the field, such as the outcrops of 100% sheeted mafic dykes, the stratigraphic transition from sheeted dykes upwards into pillowed basalts, rare plagiogranite intrusions in the pillowed basalt section, and the association of these hypabyssal and volcanic rocks with mafic and ultramafic cumulate rocks are consistent with a dismembered ophiolite. Each of the two distinct magmatic suites recognized within the ophiolite is indistinguishable from modern oceanic rocks on the basis of geochemistry, Nd-isotopic composition, and petrography; the older (MORB-like) suite resembles rocks formed at mid-ocean ridges, whereas the younger (OIB-like) suite is similar to suites of rocks formed in intra-oceanic settings (Scott, 1990; Scott et al., 1991). Two magmatic suites in the Purtuniq ophiolite suggests a complex igneous evolution, as is characteristic of many ophiolite bodies (e.g., Troodos and Samail; Coleman, 1977).

The deformed crustal section of the Purtuniq ophiolite, as presently preserved in thrust imbricates, has a minimum thickness of ~9 km; the original thickness may have been up to 10-15 km prior to deformation. This is somewhat thicker, however, than the crustal sections of most of Phanerozoic ophiolites and modern ridge-formed oceanic crust, which are generally less than ~6 km thick. The greater total crustal thickness of the Purtuniq ophiolite is inferred to result from its magmatically composite nature, although the ridge-formed component alone (MORB-like suite) is comparable in thickness to younger ophiolites and modern oceanic crust. The greater thickness of the composite crustal section may have contributed to the obduction and preservation of this fragment of Paleoproterozoic ocean floor.

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