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GRANULITE- AND AMPHIBOLITE-FACIES METAMORPHISM IN A CONVERGENT-PLATE-MARGIN SETTING: SYNTHESIS OF THE QUEBEC–BAFFIN SEGMENT OF THE TRANS-HUDSON OROGEN*

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ABSTRACT

The tectonometamorphic histories of basement and cover units in the eastern Trans-Hudson Orogen attest to the importance of structural, geohydrological, and magmatic controls on the attainment of metamorphic conditions in a convergent-plate-margin setting. In northern Quebec, two metamorphic suites are recognized in the parautochthonous (lower-plate) Superior Province basement. An older metamorphic suite comprises arc-related, granulite-facies assemblages (less than 5 kbar and 860 to 920°C) dated at *ca.* 2.70 Ga. A younger, overprinting, collision-related metamorphic suite comprises amphibolite-facies assemblages (7.7 kbar at 640°C to 9.8 kbar at 715°C) dated at *ca.* 1.80 Ga. Within the overlying Paleoproterozoic Cape Smith Belt (lower-plate, south-verging thrust belt), thermal-peak mineral growth is syn- to post-thrusting; a relatively high-pressure, greenschist- to amphibolite-facies metamorphism (6.3 kbar at 400°C to 9.1 kbar at 575°C) is interpreted to be a result of *ca.* 1.80 Ga collision-related thickening. At higher structural levels, upper-plate mid-crust plutonic and metasedimentary units of the 1.86–1.82 Ga Narsajuaq arc contain granulite-facies assemblages (7–10 kbar and 800–900°C) retrograded to amphibolite-facies conditions (7–9 kbar and 700–775°C) during collision-related thrusting. At the structurally highest level, granulite-facies metamorphism of the (upper-plate) Lake Harbour Group and Blandford Bay assemblage is related to emplacement of the 1.86–1.85 Ga Cumberland batholith. Between *ca.* 1820 and 1795 Ma, accretion and collision-related thickening resulted in retrogression of the granulite-facies assemblages in the Narsajuaq arc, Lake Harbour Group and Blandford Bay assemblage, thermal peak metamorphism of lower-plate cover rocks, and re-equilibration of the parautochthonous Superior Province basement, all at greenschist- to amphibolite-facies conditions. The integration of field, thermobarometric and U–Pb data establishes a causal relationship between arc plutonism and development of granulite-facies assemblages in a convergent-plate-margin setting. In contrast, the attainment of greenschist- to amphibolite-facies conditions at mid-crust levels during plate collision is primarily a function of structural and geohydrological controls.

Keywords: Trans-Hudson Orogen, Quebec–Baffin segment, amphibolite facies, granulite facies, polyphase deformation, geothermobarometry, U–Pb geochronology, tectonics, arc plutonism, collision.

SOMMAIRE

Dans le secteur est de la ceinture orogénique trans-hudsonienne, l'évolution tectonométamorphique du socle et des unités de couverture démontre l'importance des contrôles structuraux, géohydrologiques et magmatiques sur les conditions métamorphiques atteintes dans un milieu de bordures de plaques convergentes. Dans le nord du Québec, deux suites métamorphiques sont reconnues dans le socle parautochthone (plaque inférieure) de la Province du Supérieur. La suite métamorphique la plus ancienne comprend des assemblages du faciès granulite (moins que 5 kbar, et 860 à 920°C) datés d'environ 2.70 Ga. La suite métamorphique la plus jeune comprend des assemblages du faciès amphibolite (7.7 kbar et 640°C à 9.8 kbar et 715°C) datés d'environ 1.80 Ga. Dans la ceinture du Cap Smith (plaque inférieure, ceinture de chevauchement d'âge paléoprotérozoïque à déplacement vers le sud), la croissance de minéraux durant l'apogée thermique est synchrone à postérieure au chevauchement. Un épisode de métamorphisme au faciès schiste vert à amphibolite et de pression relativement élevée (6.3 kbar et 400°C à 9.1 kbar et 575°C) résulterait d'un épaississement tectonique dû à une collision datée à environ 1.80 Ga. A des niveaux structuraux plus élevés, au niveau de la croûte médiane, les unités plutoniques et métasédimentaires de la plaque supérieure provenant de l'arc de Narsajuaq, dont l'âge est 1.86–1.82 Ga, contiennent des assemblages du faciès granulite (7–10 kbar et 800–900°C). Ces assemblages sont marqués par une rétrogression au faciès amphibolite (7–9 kbar et 700–775°C) pendant le chevauchement dû à la collision. A un niveau structural le plus élevé, le métamorphisme au faciès granulite du groupe de Lake Harbour et de l'assemblage Blandford Bay (plaque supérieure) est associé à l'emplacement du batholithe de Cumberland, datant d'environ 1.86–1.85 Ga. Entre environ 1820 et 1795 Ma, l'accrétion et l'épaississement tectonique dû à la collision ont donné lieu à la croissance d'assemblages de minéraux au faciès amphibolite suite à la rétrogression des assemblages de minéraux du faciès granulite dans l'arc de Narsajuaq, le groupe de Lake Harbour et l'assemblage de Blandford Bay, à l'apogée thermique du métamorphisme des roches de couverture (plaque

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inférieure), ainsi qu'au ré-équilibrage du socle parautochthone de la Province du Supérieur. L'intégration des observations de terrain et des données thermobarométriques et U–Pb établissent une relation de cause à effet entre le plutonisme d'arc et la croissance d'assemblages de minéraux au faciès granulite dans un milieu de bordure de plaques convergentes. D'autre part, l'acquisition de conditions métamorphiques typiques du faciès schiste vert à amphibolite au niveau de la croûte médiane pendant une collision est principalement le résultat de processus structuraux et géohydrologiques.

Mots-clés: ceinture orogénique trans-hudsonienne, secteur Québec–Baffin, faciès amphibolite, faciès granulite, déformation polyphasée, géothermobarométrie, géochronologie U–Pb, reconstruction tectonique, plutonisme d'arc, collision.

Introduction

Within the northeastern segment of the Paleoproterozoic Trans-Hudson Orogen, in northern Quebec and southern Baffin Island (Figs. 1, 2), the stratigraphic and structural basement of the orogen is exposed in a series of tectonic half-windows (Lucas & Byrne 1992, St-Onge *et al.* 1999a). Overlying the basement, lower-plate cover units (sedimentary and volcanic rocks initially accumulated on the exposed basement) and upper-plate assemblages (units accreted to the northern margin of the Superior Province during Paleoproterozoic plate-margin convergence) are exposed in a series of complementary synclinoria (klippen) (Figs. 1, 2) (Hoffman 1985, Lucas 1989, St-Onge *et al.* 1999a). These exposures provide a unique opportunity to study the geology, the assemblages, metamorphic minerals, and the thermotectonic evolution of the orogenic belt along a 400 km orogen-perpendicular transect.

The tectonic history of the orogen on both sides of Hudson Strait (Fig. 1) is marked by tectonothermal events (Lucas 1990, Bégin 1992, Lucas & St-Onge 1992, Monday 1994, St-Onge & Lucas 1995, Wodicka *et al.* 1997, Copeland 1999) that both predate and are synchronous with a collision between the northern continental margin of the Superior Province and a set of allochthonous Paleoproterozoic crustal assemblages. In this contribution, we identify the structural and temporal framework for tectonothermal events on southern Baffin Island, and combine these data with a summary of published information from northern Quebec. We present a synthesis of the quantitative thermobarometric results, which are based on mineral-composition data published elsewhere, and were obtained for assemblages of metamorphic minerals on both sides of Hudson Strait. We then integrate these results with the established structural and temporal framework for the orogen and use this as a basis for evaluating the potential magmatic, geohydrological, and structural controls on the attainment of granulite- *versus* amphibolite-facies metamorphism in a convergent-plate-margin system.

Regional Geology

Tectonostratigraphic elements

The Quebec–Baffin segment of Trans-Hudson Orogen (Lewry & Stauffer 1990) comprises tectonostratigraphic elements accumulated on, or accreted to, the northern margin of the Archean Superior Province during greater than 200 m.y. of divergent- and convergent-margin tectonic activity (Lucas *et al.* 1992, St-Onge *et al.* 1992, Scott 1997). Numerous distinct elements are preserved within a crustal-scale thrust stack (Fig. 2), from the external zone peripheral to the Superior Province in northern Quebec to the internal zone of the orogen exposed on southern Baffin Island (Fig. 1).

Demonstrably underlying a large portion of the orogen in northern Quebec and southern Baffin Island (Fig. 2, St-Onge *et al.* 1999a), are lower-plate parautochthonous plutonic and supracrustal rocks of the Archean Superior Province (St-Onge *et al.* 1992, 1996) and parautochthonous sedimentary and volcanic cover units (Povungnituk and Chukotat groups) associated with multiple rifting of the Superior Province at 2.04 and 1.92 Ga (St-Onge *et al.* 1999b, and references therein).

Structurally overlying the parautochthonous units (Fig. 2) are upper-plate (*i.e.*, allochthonous) Paleoproterozoic crustal elements interpreted as (i) an ophiolite (Watts Group) (Scott *et al.* 1992), (ii) a fore-arc clastic apron (Spartan Group) (St-Onge *et al.* 1992), (iii) a magmatic arc (Parent Group and Narsajuaq arc) (Dunphy & Ludden 1998) and arc-derived detritus (Sugluk Group) (St-Onge *et al.* 1992), (iv) a clastic–carbonate platform sequence (Lake Harbour Group) (Scott *et al.* 1997) and its potential basement (Ramsay River orthogneiss, Scott & Wodicka 1998; not shown separately on Fig. 2 because of scale), (v) a foreland-basin (?) sequence (Blandford Bay assemblage) (Scott *et al.* 1997), and (vi) an extensive suite of monzogranitic plutons (Cumberland batholith) (Jackson *et al.* 1990) that intrude rocks of both the platform and the foreland basin.

On the eastern end of Hall Peninsula (Baffin Island, Fig. 1), an upper-plate domain of Archean orthogneiss and Paleoproterozoic supracrustal and metaplutonic rocks was interpreted by Scott (1999) as the western edge of the North Atlantic craton.

U–Pb age determinations of plutonic and supracrustal units

The details of the U–Pb geochronology summarized in this section are taken from the following papers: Parrish (1989), Jackson *et al.* (1990), St-Onge *et al.*

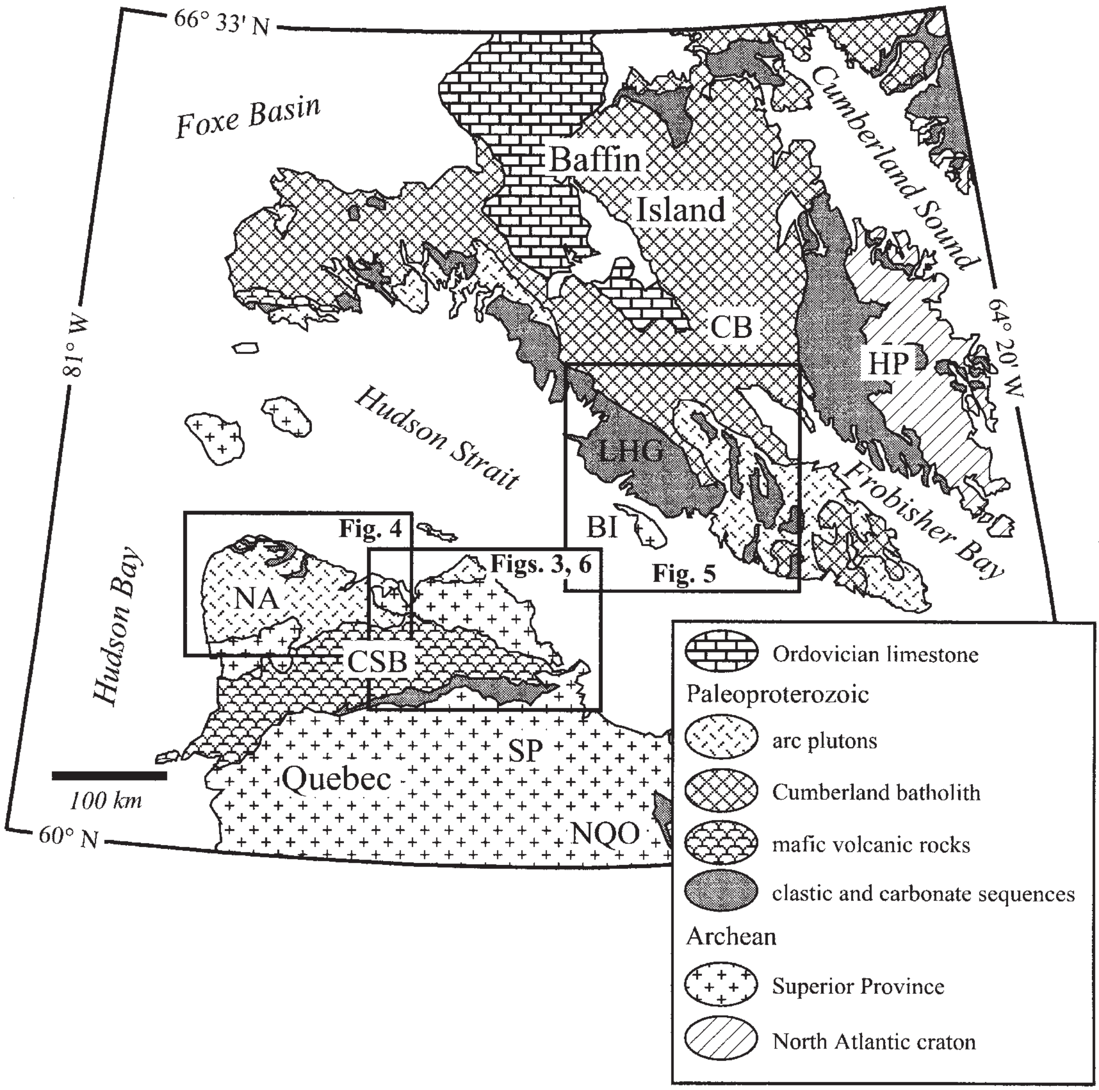

FIG. 1. Geological map of northern Quebec and southern Baffin Island modified from Wheeler *et al.* (1996). Boxes outline map areas shown in Figures 3, 4, 5, and 6. Abbreviations: BI: Big Island, CB: Cumberland batholith, CSB: Cape Smith Belt, HP: Hall Peninsula, LHG: Lake Harbour Group, Blandford Bay assemblage and Ramsay River orthogneiss, NA: Narsajuaq arc, NQO: New Quebec Orogen, SP: Superior Province basement.

(1992), Machado *et al*. (1993), Scott & St-Onge (1995), Scott & Gauthier (1996), Scott (1997, 1999), Wodicka & Scott (1997), and Scott & Wodicka (1998).

The Superior Province basement of northern Quebec and southern Baffin Island has yielded radiometric age dates between *ca.* 3.22 and 2.74 Ga. Rhyolite flows and gabbro sills from the Povungnituk and Chukotat groups (multiple rifting in the northern Superior Province) yield zircon and baddeleyite ages of *ca.* 2.04, 1.96, 1.92 and 1.87 Ga. Zircon separates from a gabbroic layer in the Watts Group (ophiolite) yield an age of *ca.* 2.00 Ga. Plutons and felsic volcanic rocks of the Narsajuaq arc and Parent Group (magmatic arc) range in age between *ca.* 1.86 and 1.82 Ga, whereas monzogranites of the Cumberland batholith yield ages between *ca.* 1.86 and 1.85 Ga. Constraints based on field observations and U–Pb zircon geochronology indicate that the Lake Harbour Group (platform sequence) and the Blandford

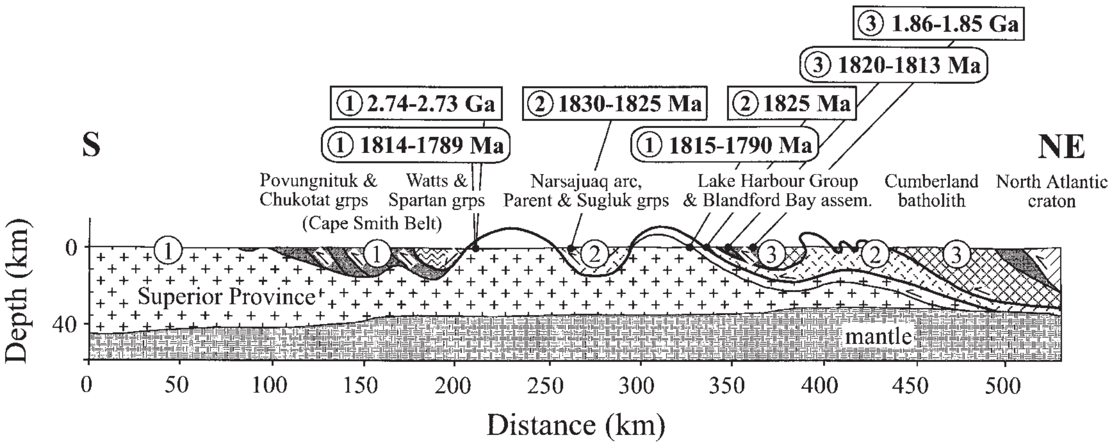

FIG. 2. Schematic cross-section of the Quebec–Baffin segment of Trans-Hudson Orogen (after St- Onge *et al.* 1999a) showing U–Pb data for pre-M1 and M1 granulite-facies domains (boxes with square edges) and M2 amphibolite-facies domains (boxes with rounded edges). Large circled numbers refer to structural levels discussed in the text. References for age dates are given in the text. Tectonostratigraphic elements discussed in the text are shown in the cross-section, but because of scale, the Ramsay River orthogneiss has been grouped with the Lake Harbour Group and Blandford Bay assemblage.

Bay assemblage [foreland-basin (?) sequence] were deposited between *ca.* 1.93 and 1.86 Ga (Scott *et al.* 1997). The stratigraphic basement to the Lake Harbour Group (Ramsay River orthogneiss) has yielded a U–Pb age of *ca.* 1.95 Ga. Finally, the upper-plate orthogneisses correlated with the North Atlantic craton have been dated between *ca.* 2.92 and 2.80 Ga.

Tectonic assemblages

The tectonostratigraphic elements in northern Quebec and southern Baffin Island (Fig. 1) can be grouped into a number of orogen-scale, stacked tectonic assemblages (Fig. 2) (Wodicka & Scott 1997, St-Onge *et al.* 1999a). From lowest to highest structural level, these include the following: *Level 1* (lower plate): Superior Province basement, Povungnituk, and Chukotat groups, *Level 2* (upper plate): Narsajuaq arc, Watts, Parent, Spartan, and Sugluk groups, and *Level 3* (upper plate): Ramsay River orthogneiss, Lake Harbour Group, Blandford Bay assemblage, and Cumberland batholith.

The parautochthonous sedimentary and volcanic units of Level 1 (Povungnituk and Chukotat groups, Fig. 2) define the Paleoproterozoic continental-margin sequence of the northern Superior Province (present coordinates) and are largely preserved within a thrust belt (Cape Smith Belt, Fig. 1) (Lucas 1989). These parautochthonous cover rocks form an integral part of the lower plate (St-Onge *et al*. 1992).

The distinct plutonic and supracrustal elements of Level 2 show no tectonostratigraphic or intrusive relationships with the rocks of Level 1, and a tectonic contact separating the two structural levels is exposed well into the internal zone of the orogen (Figs. 1, 2). The absence of (pre-assembly) tectonostratigraphic links between Levels 1 and 2, the MORB and OIB character of the Watts Group within Level 2 (Scott *et al.* 1992), and the fault-bound nature of all Level-2 assemblages (Lucas & St-Onge 1992) are first-order observations utilized by St-Onge *et al*. (1992, 1999a) to argue that the Watts, Parent, and Spartan groups of northern Quebec, and the Narsajuaq arc and Sugluk Group of northern Quebec and southern Baffin Island are allochthonous with respect to the northern margin of the Superior Province. On Baffin Island, no (pre-assembly) tectonostratigraphic link exists between the rocks of Level 2 and Level 3 (Fig. 2), and the boundary between the two levels corresponds to a zone of retrogression and high strain (St-Onge *et al*. 1998). In addition, there are no rocks of the same age between the two levels (Wodicka & Scott 1997). Tectonic juxtaposition of Levels 3 and 2 must postdate 1.82 Ga, the youngest dated arc-related magmatic unit in Level 2 (St-Onge *et al.* 1998).

DISTRIBUTION OF GRANULITE- AND AMPHIBOLITE-FACIES ASSEMBLAGES

Mineral assemblages in key tectonostratigraphic units from structural Levels 1 to 3 (described above) have been mapped and studied. These assemblages can be utilized to provide first-order constraints on the distribution of granulite- and amphibolite-facies rocks at the scale of the orogenic belt. In this section, we summarize the salient features of assemblages from the Superior Province basement and the Povungnituk and

Chukotat groups (Level 1), the Narsajuaq arc and Sugluk Group (Level 2), and the Lake Harbour Group, Blandford Bay assemblage and Cumberland batholith (Level 3).

Level 1: Superior Province basement

Mineral assemblages in the Superior Province of northern Quebec and southern Baffin Island (Fig. 1) record conditions ranging from the amphibolite to the granulite facies (Lucas & St-Onge 1991, 1992, St-Onge *et al.* 1996). However, all lithological units contain, at least locally, granulite-facies assemblages. Preserved orthopyroxene-bearing diorite to tonalite orthogneisses within the Superior Province are massive, brown-weathering, granular, and contain orthopyroxene – clinopyroxene – hornblende – plagioclase – quartzofeldspathic pods ± ilmenite ± quartz ± biotite ± scapolite. Mafic tonalitic gneiss predominates, but several compositional phases can typically be identified on glaciated surfaces. Large, dominantly monzogranitic plutons, which are intrusive into the orthogneisses, contain subsets of the mineral assemblage orthopyroxene – clinopyroxene – hornblende – K-feldspar – plagioclase – quartz ± ilmenite ± biotite.

In northern Quebec, the distribution of two-pyroxene ± ilmenite (titanite-absent) assemblages defines large areas of granulite-facies rocks, which are generally found *ca.* 5–25 km north of the Cape Smith Belt (Fig. 3a). Important exceptions to this regional pattern are small (meter- to decameter-scale) patchy areas of relict orthopyroxene-bearing rocks within the regional amphibolite-facies domain. These patches occur relatively close to the thrust belt (St-Onge & Lucas 1995).

Within the *ca.* 5–25 km wide domain adjacent to the base of the Cape Smith Belt (Fig. 3a), and for most of the exposed Superior Province basement on southern Baffin Island (Fig. 1), pervasive formation of amphibolite and metasomatism of variable intensity have affected the pyroxene gneisses (St-Onge & Lucas 1995, St-Onge *et al.* 1996). Tonalitic gneisses and granitic units are characterized by biotite – plagioclase – quartz ± garnet ± titanite ± epidote ± muscovite ± K-feldspar assemblages, whereas more mafic rocks contain hornblende – epidote – plagioclase – quartz ± garnet ± titanite assemblages. The amphibolite-facies minerals (hornblende, epidote, muscovite, sodic plagioclase, garnet, titanite) occur as pseudomorphs after peak metamorphic minerals (St-Onge & Ijewliw 1996). Textural relics including orthopyroxene, clinopyroxene, megacrysts of hornblende, calcic plagioclase, and scapolite, may remain in partly retrograded rocks. In some regions, retrogression has been more complete, as indicated by the presence of the lower-temperature phases throughout the matrix. Ilmenite, which is a common accessory mineral in the granulite-facies basement, is generally partly to completely replaced by coronitic titanite in the amphibolite-facies assemblages (Scott & St-Onge 1995).

Locally within the granulite-facies domains (Fig. 3a), amphibolite-facies mineral assemblages are found in rocks compositionally similar to those containing orthopyroxene (St-Onge & Lucas 1995). The amphibolite-facies assemblages are characterized by garnet coronas around plagioclase, clinopyroxene, and by cummingtonite coronas on orthopyroxene, hornblende coronas on clinopyroxene ± orthopyroxene, sodic rims on calcic plagioclase cores, and titanite coronas on ilmenite (St-Onge & Ijewliw 1996). As a result, orthopyroxene is generally either completely replaced or is present only as ≤1 mm ragged relict grains. The new assemblage comprises garnet – clinopyroxene – hornblende – plagioclase – quartz ± titanite ± cummingtonite.

Level 1: Povungnituk and Chukotat groups

A greenschist- to amphibolite-facies regional metamorphic culmination (M2, see below) has been documented in the Povungnituk and Chukotat groups of northern Quebec and southern Baffin Island (Bégin 1992, St-Onge *et al.* 1996). The geometry of the culmination in the Cape Smith Belt (Fig. 3b) was established at the regional scale by systematic mapping of assemblages of metamorphic minerals in mafic extrusive and intrusive rocks. Four resulting mineral isograds (hornblende, oligoclase, actinolite-out, and garnet or clinopyroxene) separate five regional mineral zones (Bégin 1992): (1) actinolite – albite, (2) hornblende – actinolite – albite, (3) hornblende – actinolite – oligoclase, (4) hornblende – oligoclase (no actinolite), and (5) hornblende – oligoclase – garnet or clinopyroxene. Figure 3b shows the mineral zones of Bégin (1992) in terms of greenschist-facies and amphibolite-facies domains. The distribution of these domains indicates an increase in metamorphic grade from west to east. This increase in grade is coincident with a gradual change from higher structural levels preserved in the west to lower structural levels exposed in the east (Fig. 3b), and is attributed to the postmetamorphic cross-folding of the thrust belt (Lucas 1989).

A northward increase in metamorphic grade is documented by pelitic mineral assemblages in the Povungnituk Group. The pelitic rocks occur along the base of the Cape Smith Belt and in thin thrust imbricates beneath the Narsajuaq arc in both northern Quebec and southern Baffin Island (Fig. 1, St-Onge & Lucas 1991, St-Onge *et al.* 1996). Assemblages of metamorphic minerals display a transition from garnet – muscovite – biotite – plagioclase – quartz – ilmenite – graphite ± kyanite ± staurolite ± chlorite in the Joy Bay – Wakeham Bay area (Fig. 3b) to garnet – kyanite – biotite – K-feldspar – plagioclase – quartz – granitic pods ± sillimanite in the Cap de Nouvelle-France area (Fig. 3b), and finally garnet – sillimanite – biotite – K-feldspar – plagioclase – quartz – granitic pods on Big Island (Fig. 1).

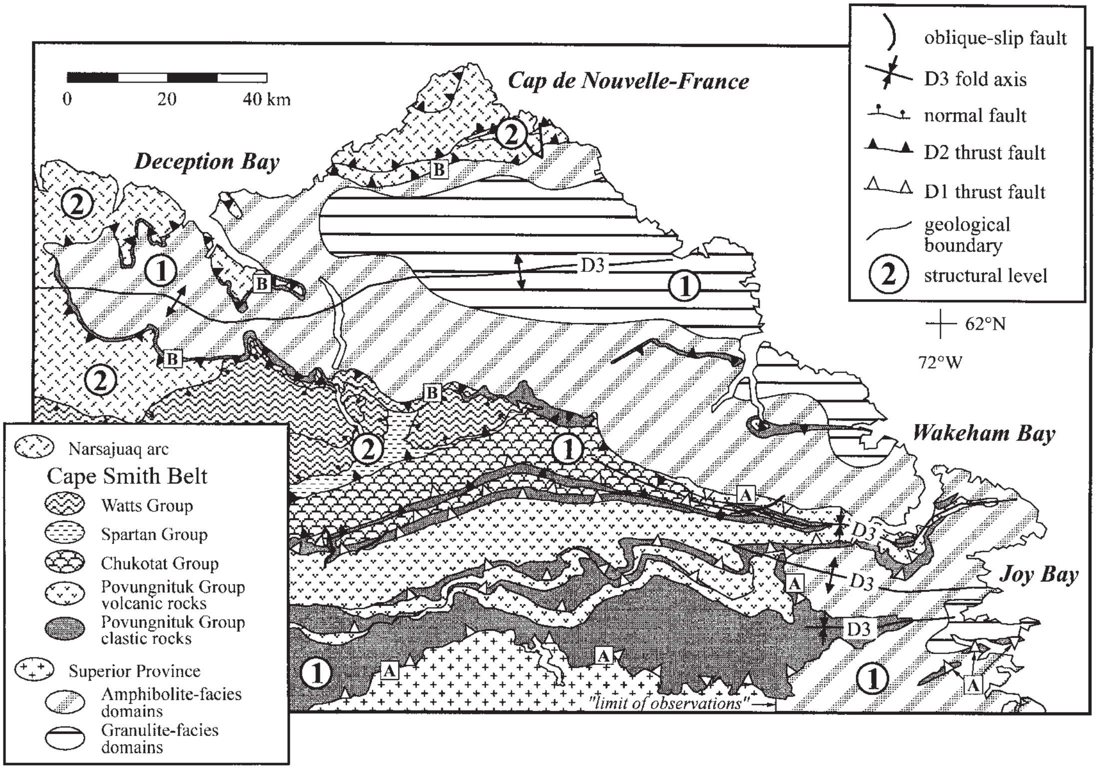

FIG. 3a. Geological map of the northeastern portion of the Ungava Peninsula (Fig. 1), modified from St-Onge *et al.* (1992) and St-Onge & Lucas (1995). "A" and "B" denote the D1 and D2 basal *décollements*, respectively; large circled numbers refer to structural levels discussed in the text. The map highlights the distribution of granulite- and amphibolite-facies domains in the lower-plate Superior Province basement.

Level 2: Narsajuaq arc and Sugluk Group

Metaplutonic rocks of the Narsajuaq arc in northern Quebec and southern Baffin Island contain mineral assemblages that range from the middle amphibolite to the granulite facies (Fig. 4, Lucas & St-Onge 1992, St-Onge & Lucas 1992, Monday 1994, St-Onge *et al.* 1998). However, all metaplutonic units at least locally contain assemblages consistent with granulite-facies conditions. Mafic gneisses contain subsets of the mineral assemblage orthopyroxene – hornblende – plagioclase – biotite ± clinopyroxene ± garnet ± quartz. Tonalitic and granitic gneisses contain subsets of the mineral assemblage orthopyroxene – biotite – hornblende – plagioclase – quartz ± garnet ± clinopyroxene (plus K-feldspar in the granites). In general, however, the granulite-facies gneisses are characterized by orthopyroxene – biotite ± hornblende assemblages, with clinopyroxene and garnet appearing in more strongly mafic layers.

A variety of mineral assemblages is present in the metasedimentary rocks of the Sugluk Group (Lucas & St-Onge 1992, Monday 1994). Pelites generally contain subsets of the mineral assemblage sillimanite – K-feldspar – garnet – cordierite – biotite – plagioclase – quartz – granitic pods ± spinel, and locally contain orthopyroxene – cordierite – garnet – biotite – plagioclase – quartz – granitic pods assemblages. Calc-silicate rocks contain diopside – garnet – phlogopite – calcite – spinel assemblages, and semipelites, in general, are characterized by garnet – biotite – quartz – plagioclase ± granitic pods. Quartzites are garnet-, orthopyroxene- or clinopyroxene-bearing, whereas quartzites with thin pelitic interlayers contain the assemblage garnet – sillimanite – biotite. The mineral assemblages in the Sugluk Group metasedimentary rocks are consistent with the granulite-facies assemblages documented in the adjacent metaplutonic rocks.

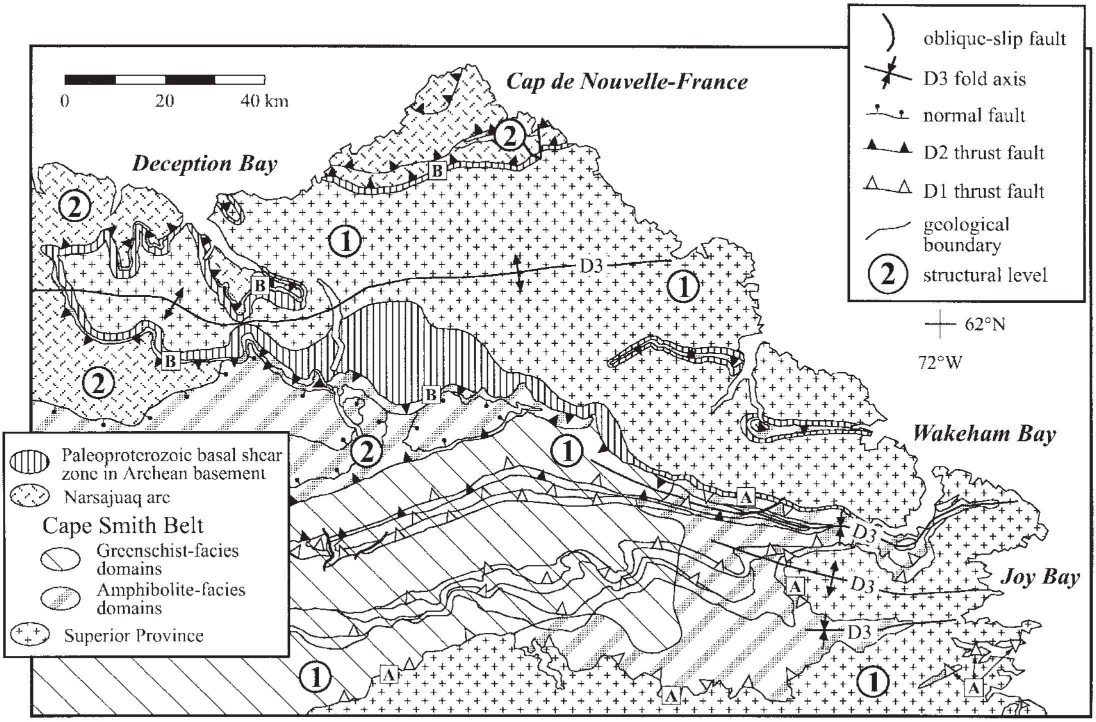

FIG. 3b. Geological map of the northeastern portion of the Ungava Peninsula (Fig. 1), modified from St-Onge *et al.* (1992) and Bégin (1992). "A" and "B" denote the D1 and D2 basal *décollements*, respectively; large circled numbers refer to structural levels discussed in the text. The map highlights the distribution of greenschist- and amphibolite-facies domains within the lower- and upper-plate units of the Cape Smith Belt.

Level 3: Lake Harbour Group, Blandford Bay assemblage and Cumberland batholith

Metamorphic mineral assemblages in the supracrustal rocks of the Lake Harbour Group and Blandford Bay assemblage document a largely retrograde transition from granulite- to amphibolite-facies conditions (Fig. 5, St-Onge *et al.* 1998; I. Russell, pers. commun., 1998). Pelites generally contain subsets of the granulite-facies mineral assemblage K-feldspar – garnet – cordierite – biotite – plagioclase – quartz – granitic pods ± sillimanite, and locally contain the assemblage K-feldspar – orthopyroxene – cordierite – biotite – plagioclase – quartz – granitic pods. Away from the Cumberland batholith and in proximity to post-thermal peak faults (Fig. 5, see below), the pelites are characterized by the amphibolite-facies mineral assemblage sillimanite – K-feldspar – biotite – plagioclase – quartz – granitic pods ± garnet.

Metamorphic mineral phases in the siliceous marbles of the Lake Harbour Group include diopside, phlogopite, humite, wollastonite, spinel, forsterite, and tremolite. A systematic variation in the assemblages across the area studied was not observed.

Finally, the Cumberland batholith contains coarse assemblages of K-feldspar – orthopyroxene – biotite – plagioclase – quartz ± hornblende ± clinopyroxene ± garnet.

DEFORMATION HISTORIES AND TIMING OF GRANULITE-VERSUS AMPHIBOLITE-FACIES METAMORPHISM

The tectonostratigraphic units of northern Quebec and southern Baffin Island record polyphase deformation and metamorphic histories. Distinct pre-collisional Archean or Paleoproterozoic tectonic histories [pre-D1, D1lp–M1lp (lp: lower plate), D1up–M1up (up: upper plate), Table 1] are documented for rocks of the lower-plate basement (Superior Province), lower-plate cover (Povungnituk and Chukotat groups) as well as for various metaplutonic and supracrustal units of the orogenic upper-plate (Narsajuaq arc, Sugluk Group, Lake Harbour Group and Blandford Bay assemblage) (Lucas & St-Onge 1992, St-Onge *et al.* 1998). Younger, syn- to post-collisional tectonic events (D2–M2, D3 and D4) are common to units of both the lower and upper plate,

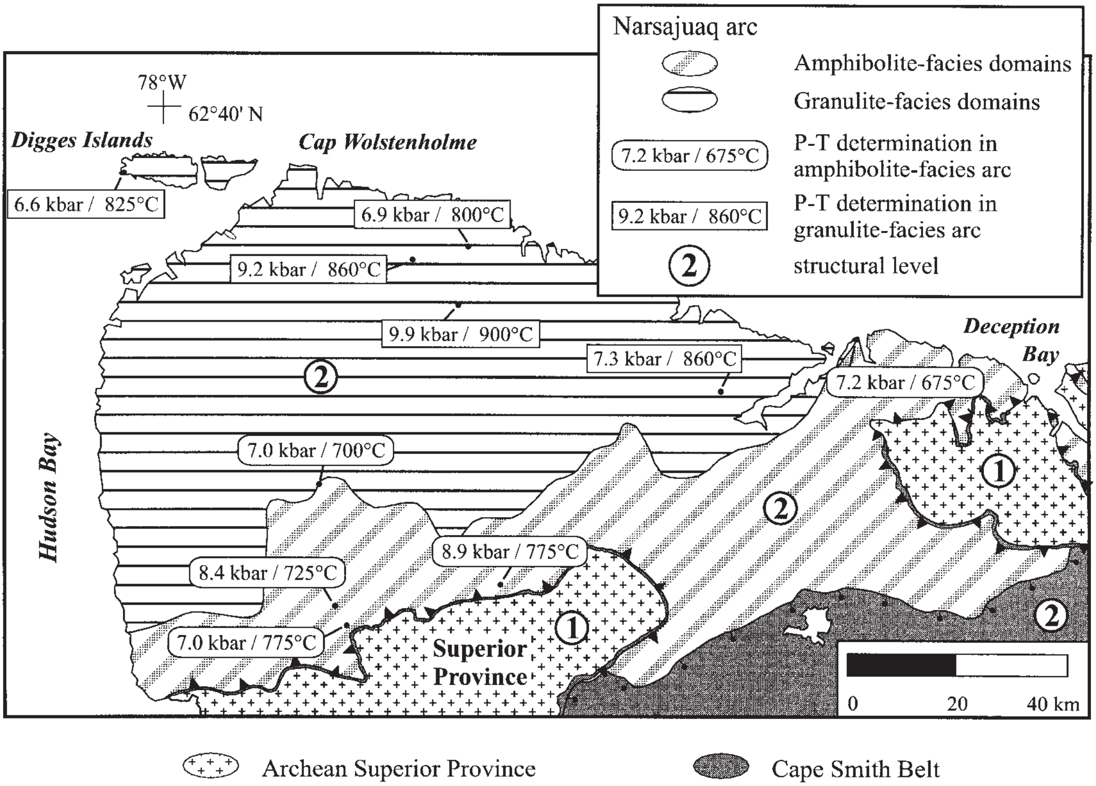

FIG. 4. Geological map of the northwestern portion of the Ungava Peninsula (Fig. 1), modified from Monday (1994) and Lucas & St-Onge (1995). Large circled numbers refer to structural levels discussed in the text. The map highlights the distribution of granulite- and amphibolite-facies domains and P–T results (from Monday 1994) within the upper-plate Narsajuaq arc of northern Quebec.

and stem from the juxtaposition of all tectonic assemblages during the main D2 collision–accretion event (Table 1). In this section, we examine the deformation and metamorphic events across the orogen in a pre-D1 – D1 – D2 framework. The subsequent regional folding events (D3 and D4) are discussed in detail elsewhere by Lucas & Byrne (1992) and Lucas & St-Onge 1992). The pre-D3 tectonothermal evolution of the orogen is outlined in Table 1 and illustrated in Figure 2.

Pre-D1 deformation and metamorphism (Level 1)

Archean orthogneisses of the Superior Province both south and north of the Cape Smith Belt and on Big Island (Fig. 1) preserve the oldest deformation-induced structures and mineral assemblages (Table 1, Lucas & St-Onge 1992, 1995, St-Onge & Lucas 1995). In northern Quebec, tonalitic orthogneisses and monzogranitic plutons are, at least locally, characterized by granulite-facies assemblages that include metamorphic zircon that has yielded U–Pb ages of *ca.* 2.74–2.73 Ga (Fig. 2, Scott & St-Onge 1995, R. Parrish, unpubl. data). Coupled with observations on deformation – mineral-growth relations, these results suggest that granulite-facies metamorphism in the Superior Province basement was coeval with Neoarchean plutonism and synmagmatic deformation (Lucas & St-Onge 1995).

D1lp deformation and M1lp metamorphism (Level 1)

The oldest map-scale structures observed in the Povungnituk and Chukotat groups of Level 1 are a system of D1lp thrust faults that imbricate metasedimentary and metavolcanic rocks above a regional basal *décollement*. The D1lp *décollement* separates allochthonous Paleoproterozoic rocks from underlying Superior Province basement and autochthonous Paleoproterozoic cover (Fig. 3a). Fault displacement was in a southerly direction, and imbrication occurred in a piggyback sequence toward the foreland. West of Wakeham Bay (Fig. 3a), cumulative displacement along the D1lp *décollement* is estimated to be at least 100 km

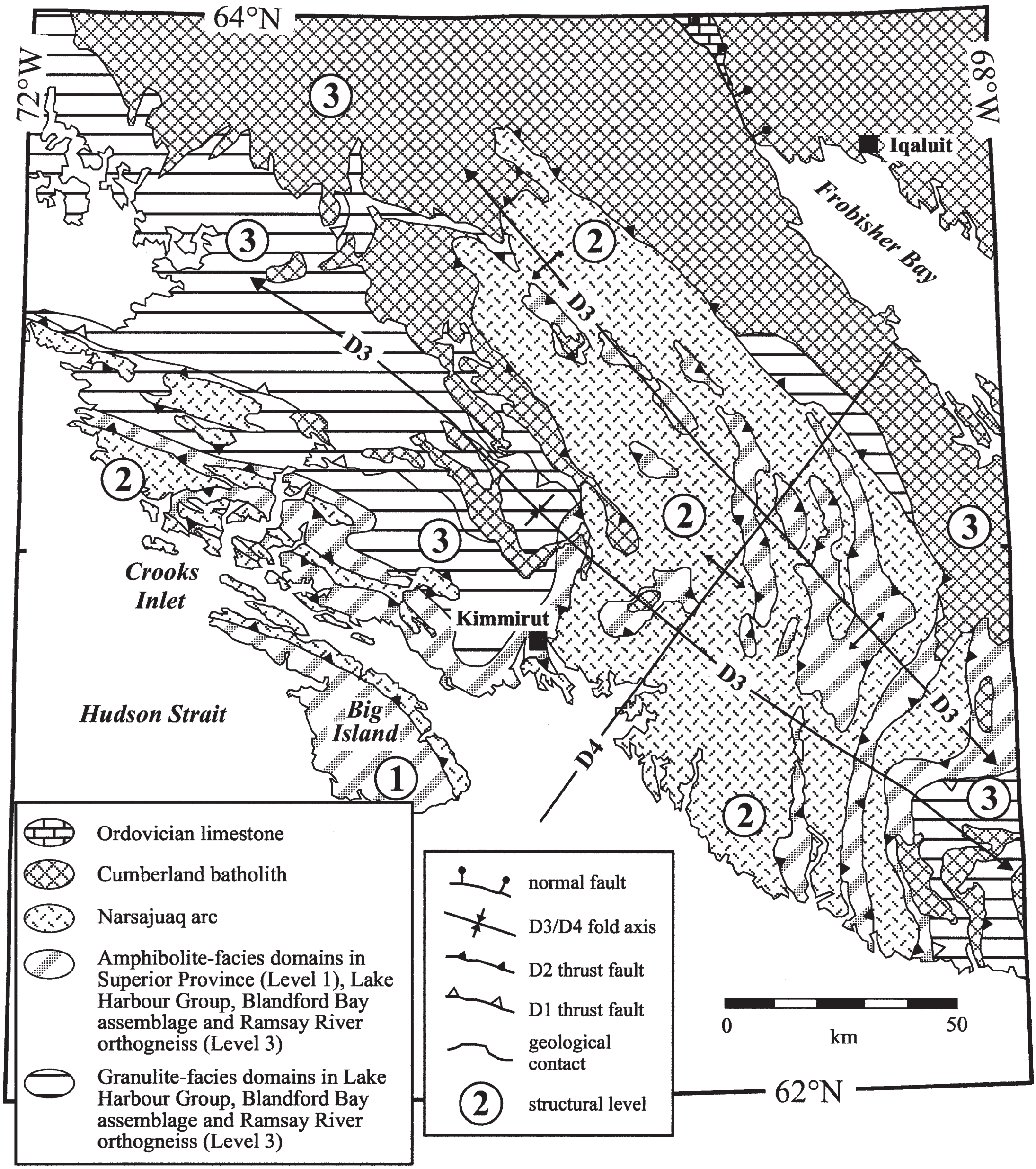

FIG. 5. Geological map of southern Baffin Island (Fig. 1), modified from St-Onge *et al.* (1998). Large circled numbers refer to structural levels discussed in the text. The map highlights the distribution of granulite- and amphibolite-facies domains within the upper-plate Lake Harbour Group and Blandford Bay assemblage, and the lower-plate Superior Province basement.

(Lucas 1989). Adjacent to the D1lp basal *décollement*, the Superior Province basement is marked by a narrow zone of penetrative strain (Fig. 3b). The zone is characterized by a foliation that transposes the Archean gneissosity, a N–S stretching lineation, plastic deformation of quartz and feldspars, and the growth of retrograde mineral assemblages (Lucas 1990, St-Onge & Lucas 1995).

The M1lp greenschist- to amphibolite-facies regional metamorphism documented in the Povungnituk and

TABLE 1. DEFORMATION-METAMORPHISM FRAMEWORK FOR THE QUEBEC-BAFFIN SEGMENT OF TRANS-HUDSON OROGEN*

	Lower Plate		**Upper Plate**			
	Superior Province	**Povungnituk and Chukotat groups**	**Narsajuaq arc, Parent and Sugluk groups**	**Lake Harbour Group**	**Ramsay River orthogneiss**	**Blandford Bay assemblage**
Structural level	**-1-**	**-1-**	**-2-**	**-3-**	**-3-**	**-3-**
Age (Ga)						
3.22-2.74	Pre-D1 Granulite-facies arc plutonism, transcurrent (?) deformation					
ca. 1.95					Pre-D1 Granulite-facies arc (?) plutonism, deformation	
ca. 1.87(?)	D1lp Basal shear zone deformation	D1lp SW-directed thrusting and folding (Cape Smith Belt), basal shear zone deformation				
	M1lp Retrograde greenschist to amphibolite facies metamorphism	M1lp Prograde greenschist to amphibolite facies metamorphism				
>1.86				D1up SW-directed (?) imbrication and folding	D1up Imbrication	D1up Imbrication
1.86-1.85				M1up Prograde granulite facies metamorphism		M1up Prograde granulite facies metamorphism
1.86-1.82			D1up-M1up Transcurrent (dextral) deformation Granulite-facies arc plutonism			
1.82-1.79	D2 SW-directed basement imbrication	D2 SW-directed thrusting	D2 Accretion to Superior margin	D2 Accretion to Narsajuaq arc, SW-directed thrusting, recumbent folding	D2 Accretion to Narsajuaq arc, SW-directed thrusting, recumbent folding	D2 Accretion to Narsajuaq arc, SW-directed thrusting, recumbent folding
	M2 Retrograde amphibolite facies metamorphism	M2 Prograde greenschist to upper amphibolite facies metamorphism	M2 Retrograde amphibolite facies metamorphism	M2 Retrograde amphibolite facies metamorphism	M2 Retrograde amphibolite facies metamorphism	M2 Retrograde amphibolite facies metamorphism
1.79-1.78		emplacement of post-accretion syenogranite			emplacement of post-tectonic syenite	

*References for age dates are given in text.
lp: lower plate
up: upper plate

(after St-Onge et al. (1999a))

Chukotat groups and in the underlying re-equilibrated basement units is characterized by the alignment of chlorite, biotite, and muscovite in metasedimentary rocks, and of chlorite, actinolite, epidote, and hornblende in mafic rocks. The M1 metamorphism is interpreted to be a consequence of the relaxation of isotherms in the tectonically thickened thrust belt and underlying basement (St-Onge & Lucas 1991).

D1lp thrusting deformation and associated M1lp prograde metamorphism within the Cape Smith Belt were initiated after 1.87 Ga, the age date obtained for a gabbroic sill in the Chukotat Group and currently the youngest dated unit from the imbricated lower plate (Table 1). The cause of D1lp thrusting remains difficult to resolve with the present dataset. Lucas & St-Onge (1992) speculated that oblique impingement of an (unrecognized) upper-plate oceanic accretionary prism or an island-arc terrane (or both) against the underthrust Superior Province continental margin could have generated the continent-verging D1 thrust belt in a manner analogous to the ongoing collision in Taiwan (Suppe 1987), with subsequent lateral translation out of the exposed part of the orogen. Alternatively, the D1lp deformation may record early terrane accretion or subduction of the lower-plate crystalline basement (or both) prior and leading up to the main (D2) collisional event. D1lp–M1lp deformation structures and assemblages have not been recognized on Big Island (Fig. 5) because of overprinting by subsequent D2 structures and assemblages.

D1up deformation and M1up metamorphism (Level 2)

In northern Quebec, plutonic rocks of the Narsajuaq arc (Fig. 4) and sedimentary rocks of the Sugluk Group are characterized by steeply dipping orogen-parallel foliations containing a subhorizontal stretching lineation. D1up deformation related to (dextral) transcurrent shear of the arc complex began prior to voluminous tonalite–granite magmatism at *ca.* 1.84–1.83 Ga and had ended by 1826 Ma, the age of a cross-cutting tonalitic intrusion (Lucas & St-Onge 1992). M1up granulite-facies assemblages grew during D1up deformation and syntectonic arc plutonism, possibly in response to heat advected by arc magmas (Monday 1994, Lucas & St-Onge 1995). U–Pb dating of monazite and metamorphic zircon in rocks of the Sugluk Group suggests that the M1up metamorphism culminated at *ca.* 1830–1826 Ma (Fig. 2) (Parrish 1989).

On southern Baffin Island (Fig. 5), similar arc plutonism (Thériault *et al.* 1997) and D1up deformation structures are bracketed between *ca.* 1842 and 1820 Ma (Scott 1997, Scott & Wodicka 1998). As in northern Quebec, metamorphic zircon and monazite in M1up granulite-facies supracrustal rocks of the Sugluk Group yielded U–Pb ages of *ca.* 1825 Ma (Fig. 2) (Wodicka & St- Onge 1998).

D1up deformation and M1up metamorphism (Level 3)

Intrusive relationships indicate that early, map-scale D1up tectonic contacts between panels of Lake Harbour Group, Ramsay River orthogneiss, and Blandford Bay assemblage on southern Baffin Island predate emplacement of the *ca.* 1.86–1.85 Ga Cumberland batholith (Scott *et al*. 1997). The repetition of units is suggestive of thrust imbrication, but the direction, geometry, and constraints on displacements are not known.

Prograde M1up granulite-facies metamorphism of the Lake Harbour Group and Blandford Bay assemblage postdates D1up thrusting, and may have resulted from heat advected during emplacement of the orthopyroxene-bearing Cumberland batholith (Fig. 5) (Wodicka & St-Onge 1998). U–Pb geochronology indicates that supracrustal rocks of the Lake Harbour Group cooled through closure temperatures of monazite (greater than 750–700°C, Spear & Parrish 1996) between *ca.* 1845 and 1836 Ma (Wodicka & Scott 1997, Wodicka & St-Onge 1998), immediately following peak M1up metamorphism.

D2 deformation and M2 metamorphism

The D2 deformation event represents the oldest event of compressional deformation that affected *all* tectonostratigraphic units of the orogen (Table 1). The collisional event involved (1) accretion and overthrusting of the Ramsay River orthogneiss, Lake Harbour Group, Blandford Bay assemblage, and Cumberland batholith (Level 3) to the metaplutonic rocks of Narsajuaq arc (Level 2), (2) accretion of the Narsajuaq arc (and Sugluk Group) and Watts, Spartan, and Parent groups (Level 2) to the northern margin of the Superior Province (Level 1), and (3) (re)-imbrication of the northern Povungnituk and Chukotat groups and underlying Archean basement (Level 1) (Table 1) (St-Onge *et al*. 1999a). The D2 event postdates the youngest dated magmatic unit of the Narsajuaq arc (*ca.* 1820 Ma, Scott & Wodicka 1998) and predates the age of emplacement of postkinematic syenite plugs and syenogranite dykes (*ca.* 1795–1784 Ma, Scott 1997, Wodicka & Scott 1997).

Level 1: Superior Province basement: The D2 deformation event in the Superior Province basement in northern Quebec is characterized by pervasive shearing in the footwall of the D2 basal *décollement* (Fig. 3b) and by thrust imbrication of relatively thin slices of basement with both Level 1 and 2 units along the northern margin of the Cape Smith Belt (basement imbricates not shown on Figures 3a and b because of scale) (Lucas 1989). In this segment of the orogen, the basal shear-zone associated with D2 deformation varies in *true thickness* between 10 and 400 m. On Big Island, basement imbricates up to several kilometers thick are separated by panels of Povungnituk Group supracrustal rocks a few hundred meters in thickness that extend the length of the island (basement imbricates not shown on Fig. 5 because of scale) (Copeland 1997). The associated D2 basal shear-zone varies in true thickness between 400 and 700 m.

Within the Archean basement, regionally extensive M2 amphibolite-facies domains broadly parallel the basement–cover contact both in northern Quebec and on Big Island (Figs. 3a, 5). Microstructures in the amphibolitized basement (alignment of hornblende, epidote, biotite, and muscovite defining a strong L–S fabric) indicate that re-equilibration of the Archean granulites occurred during D2 collision–accretion-related deformation (Lucas 1990, Copeland 1997) and predated subsequent folding of the basement and cover units (Lucas & Byrne 1992). Growth of coronitic titanite, a mineral found only in re-equilibrated basement units (St-Onge & Ijewliw 1996), occurred between *ca.* 1814 and 1789 Ma (Fig. 2) (Scott & St-Onge 1995). The titanite ages are interpreted as dating a distinct thermal overprint (and not cooling from the 2.74–2.73 Ga thermal event) since *ca.* 2.04 Ga supracrustal rocks locally rest unconformably on the Archean orthogneisses (St-Onge *et al*. 1992). Taken together, these observations indicate that amphibolitization of the Archean granulites occurred in response to D2 overthrusting, and consequent M2 metamorphism and dehydration of overlying cover units (see below, St-Onge & Lucas 1995).

Level 1: Povungnituk and Chukotat groups: A distinct suite of late or out-of-sequence thrust faults and fold structures that clearly postdates development of the D1lp thrust faults has been mapped within the Povungnituk and Chukotat groups in northern Quebec (Fig. 2) (Lucas 1989). These younger structures are interpreted as D2 in age (Lucas & St-Onge 1992), as they can be linked to faults bounding Level 2 units. The faults cut through the hanging walls of D1lp thrust faults, deform pre-existing structures in their footwall, and truncate the zonation of metamorphic assemblages (Fig. 3b).

The greenschist- to amphibolite-facies metamorphic isograds mapped in the mafic rocks of the Povungnituk and Chukotat groups (see above) cross-cut D1lp thrust faults, and are locally overturned adjacent to D2 thrust faults (Fig. 3b) (Bégin 1992). On the basis of these observations, St-Onge & Lucas (1991) argued that prograde M2 thermal-peak conditions were achieved during southward overthrusting of Level-2 units along D2 fault structures. Within the northern part of the Cape Smith Belt, Povungnituk Group rocks are characterized by thermal-peak growth of minerals contemporaneous with D2 deformation (Lucas & St-Onge 1992). U–Pb dating of M2 zircon and monazite in rocks of the Povungnituk Group on Big Island (Fig. 5) (St-Onge *et al.* 1999a, c) yielded ages between *ca.* 1815 and 1790 Ma (Fig. 2) (Wodicka & Scott 1997, N. Wodicka, unpubl. data). These ages are similar to the *ca.* 1814 to 1789 Ma ages obtained from the amphibolitized basement of northern Quebec (Fig. 2) and are broadly coincident with the 1820–1795 Ma age bracket on D2 overthrusting (Wodicka & Scott 1997, Scott & Wodicka 1998). The metamorphic re-equilibration of lower-plate (Level 1) basement and cover units can thus be temporally (and we would suggest kinematically) linked to southward D2 overthrusting of Level-2 units in both northern Quebec and southern Baffin Island.

Level 2: In northern Quebec, D2 out-of-sequence faults act as basal thrusts for the Narsajuaq arc and the Watts, Spartan, and Parent groups (Figs. 2, 3a) (Lucas & St-Onge 1992). These faults generally overlie a thin imbricate of Povungnituk Group rocks. The regional geometry of the D2 thrust faults, and kinematic indicators from associated zones of ductile deformation, document southward displacement of Level-2 rocks relative to the Archean basement. The zones of ductile deformation adjacent to the D2 faults vary in thickness from less than 5 m in the central portion of the Cape Smith Belt to several hundred meters in the Cap de Nouvelle-France area (Fig. 3a) (Lucas & St-Onge 1992).

Exposed along the northern edge of Big Island (Fig. 5) near the structural base of the Narsajuaq arc, a steeply to moderately northeast-dipping belt of ribbon mylonites 2–3 km wide is developed and forms part of the 7-km-wide Mina mylonite zone (Hanmer *et al.* 1996, Copeland 1997). Deformation associated with movement along the shear zone began after *ca.* 1820 Ma and had terminated by *ca.* 1795 Ma, suggesting that this shear zone is D2 in age (Wodicka & Scott 1997). The shear zone is characterized by a gently northwest-plunging extension lineation, and kinematic indicators document dextral strike-slip movement (Hanmer *et al*. 1996). Copeland (1999) has interpreted the dextral strike-slip deformation recorded in the zone of mylonites as a result of partitioned transpression during D2 thrust-juxtaposition of the various tectonic levels within the orogen.

In northern Quebec, Narsajuaq arc metaplutonic rocks are characterized by amphibolite-facies assemblages immediately above the arc's basal thrust (Fig. 4) (Monday 1994). Two principal observations suggest that the amphibolite-facies assemblages are retrograde and were derived from the arc-related M1up granulite-facies assemblages: (1) at the outcrop scale, numerous patchy occurrences of granulite-facies assemblages are preserved within the southern, dominantly amphibolite-facies domain, and (2) at the thin-section scale, textures indicative of retrograde reactions are common in a number of transitional granulite- to amphibolite-facies samples. These textures include hornblende rimming clinopyroxene, and biotite replacing hornblende (Monday 1994). Lucas & St-Onge (1992) suggested that the amphibolite-facies overprint is likely related to D2 overthrusting of the relatively dry granulite-facies arc domain (Level 2) onto the dehydrating supracrustal rocks of Level 1.

Level 3: The presence of numerous repetitions and truncations of distinct tectonostratigraphic units, and an overall ramp-flat geometry (subsequently folded during D3 and D4) (St-Onge *et al.* 1999c) suggest that juxtaposition of Level-3 rocks against the Narsajuaq arc (Level 2) occurred along a system of southwest-verging thrust faults (Scott *et al.* 1997). The D2 faults are typically associated with the development of mylonitic fabrics ranging in thickness from meters to tens of meters. D2 deformation was also accompanied by outcrop- to map-scale recumbent folding (St-Onge *et al.* 1998) that deforms D1–M1 fabrics in both Level-2 and Level-3 rocks.

Within rocks of the Lake Harbour Group and Blandford Bay assemblage, zones of D2 deformation and recumbent folds are characterized by distinct retrograde M2 assemblages. D2 structures within psammites are marked by the growth of M2 sillimanite – biotite – quartz at the expense of M1up garnet ± cordierite, and consequent development of new schistose axial planar fabrics. New growth of monazite in Lake Harbour Group rocks indicate that M2 retrograde metamorphism occurred at *ca.* 1820–1813 Ma (Fig. 2) (Wodicka & St-Onge 1998).

Results of Thermobarometry

Low-variance assemblages of metamorphic minerals suitable for quantitative thermobarometric work were systematically mapped and sampled from all three structural levels of the orogen. A summary of resulting multi-equilibrium and standard thermobarometry results is presented here. Detailed accounts of mineral textures, chemistry, and reactions may be found in Bégin (1989, 1992), Lucas (1990), St-Onge & Lucas (1991, 1995), Bégin & Carmichael (1992), Lucas & St-Onge (1992), Monday (1994), Scott & St-Onge (1995), St-Onge & Ijewliw (1996), and Copeland (1999); these themes form part of the on-going graduate thesis work by Ian Russell at Queen's University.

Level 1: pre-D1 granulite-facies assemblages in the Superior Province basement

Granulite-facies samples from the Superior Province basement are generally unsuitable for multi-equilibrium thermobarometry because of the general absence of appropriate garnet-bearing assemblages. St-Onge & Lucas (1995) suggested that this absence might indicate that the high-T rocks are relatively low-pressure granulites (*cf.* Green & Ringwood 1967, Wells 1979, Hansen 1981, Mengel & Rivers 1991). On the basis of limited thermobarometric data for samples bearing garnet (non-coronitic, see below) and calcic plagioclase ($An_{70–75}$), St-Onge & Lucas (1995) also suggested that the granulitic rocks may have equilibrated at pressures as low as *ca.* 3.5 kbar.

Temperature estimates for the granulite-facies metamorphism were derived using two-pyroxene thermometry (Anderson *et al*. 1993). Results for an approximate pressure of 3.5 kbar range between 859 and 919°C (Fig. 6) using the QUILF software (Anderson *et al*. 1993). These results (*i.e.*, uniformly high temperatures of ≥860°C) are in contrast to those obtained for the re-equilibrated amphibolite-facies samples (585–757°C, see below) (Fig. 6).

Level 1: M2 amphibolite-facies assemblages in the Superior Province basement

Phase relations in the M2 amphibolite-facies coronitic assemblage garnet – clinopyroxene – hornblende – plagioclase – quartz were investigated by St-Onge & Ijewliw (1996) in the simplified chemical system CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O (CFMASH) utilizing TWEEQU (Thermobarometry With Estimation of EQUilibrium state; Berman 1991) and an internally consistent thermodynamic database (Berman 1988, Mäder *et al.* 1994) to derive multi-equilibrium P–T estimates. Sodium was omitted from the model chemical system since calibration of the thermodynamic model for amphibole is less reliable for the Na-rich species (Mäder *et al*. 1994).

The P–T determinations for amphibolite-facies basement samples range from 7.7 kbar and 640°C in the Joy Bay area to 9.8 kbar and 715°C in the Douglas Harbour area (Fig. 6) (St-Onge & Ijewliw 1996). Such a progression is consistent with deeper levels in the crust being exposed in the core of the D3 basement antiform (Fig. 3b). These results are also consistent with P–T determinations obtained from pelitic schists at the base of the Paleoproterozoic thrust belt (St-Onge & Lucas 1991, see below) and are in strong contrast to the estimates obtained for the granulite-facies rocks (see above). The M2 results corroborate the mineral zone (St-Onge & Lucas 1995), petrofabric (Lucas 1990), and geochronological (Parrish 1989, Scott & St-Onge 1995) data, which indicate that granulite-facies metamorphism in the Superior Province basement was coeval with Neoarchean plutonism, whereas growth of the amphibolite-facies minerals was a consequence of the construction of the overlying Cape Smith Thrust Belt.

Level 1: M2 amphibolite-facies assemblages in the Povungnituk Group

Pelitic layers with M2 mineral assemblages appropriate for thermobarometric work were sampled within 200 meters of the basement–cover contact along the east and north sides of the Cape Smith Belt. Garnet (chemically zoned) – muscovite – biotite – plagioclase – quartz ± kyanite ± staurolite ± chlorite assemblages were analyzed by St-Onge & Lucas (1991) and evaluated in the simplified system SiO_2 – Al_2O_3 – MgO – FeO – MnO – CaO – Na_2O – K_2O – H_2O following Spear & Selverstone (1983) and Spear (1989).

Thermochemical modeling of the zoning profiles in garnet (St-Onge & Lucas 1991) indicates an increase in

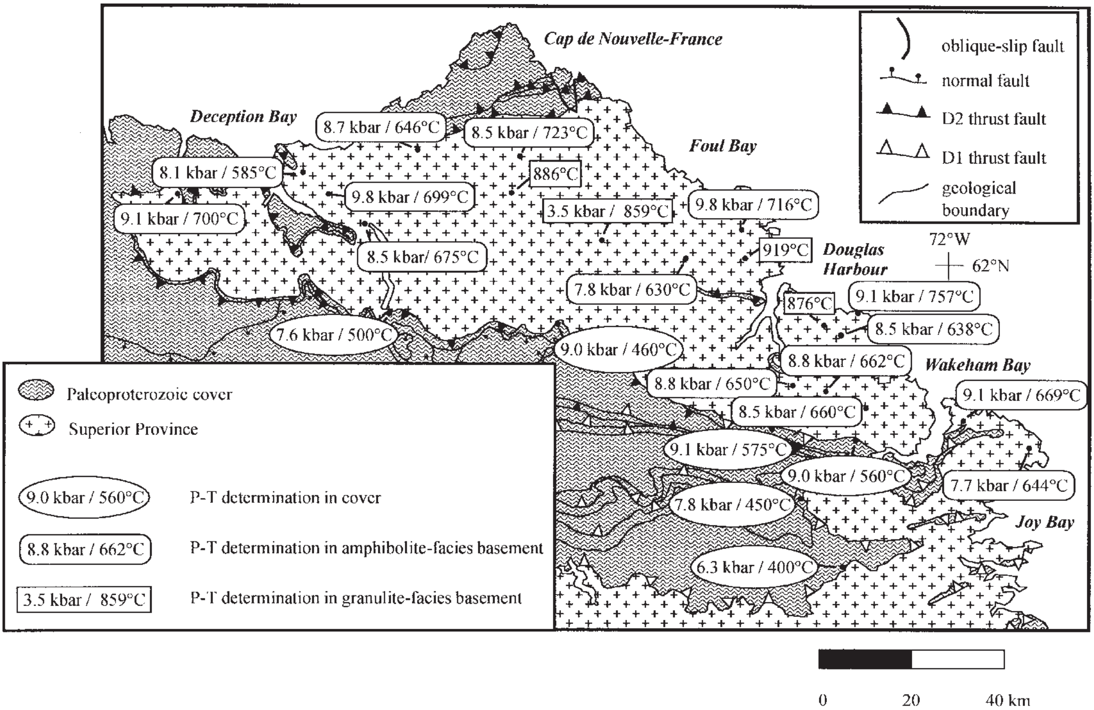

FIG. 6. Compilation of P–T results for granulite- and amphibolite-facies samples from the lower-plate Superior Province basement (St-Onge & Lucas 1995, St-Onge & Ijewliw 1996) and overlying Povungnituk Group (St-Onge & Lucas 1991) in northern Quebec.

the recorded conditions of maximum pressure for four eastern samples (Fig. 6), from 6.3 kbar at 400°C for the most southerly sample to 9.1 kbar at 575°C for a sample west of Wakeham Bay. The documented northward increase in the recorded maximum pressures is consistent with the interpretation of the Cape Smith Belt as a southward-tapering thrust wedge (Lucas 1989).

The P–T paths derived by St-Onge & Lucas (1991) are curvilinear and display a clockwise core-to-rim direction on a standard P–T diagram. This array is consistent with theoretical models relating metamorphism to heat conduction in thickened crust undergoing decompression due to erosional exhumation (*e.g.*, England & Richardson 1977, England & Thompson 1984). The nested morphology of the four P–T paths (Fig. 12 in St-Onge & Lucas 1991) further suggests that the samples experienced similar decompression-induced histories (*cf.* England & Thompson 1984).

On Big Island (Fig. 5), the analysis of M2 clinopyroxene – hornblende – garnet – plagioclase – quartz assemblages in mafic rocks of the Povungnituk Group has yielded *ca.* 800°C temperature estimates and 10.6 to 12.3 kbar pressure estimates (Copeland 1999).

Level 2: M1up granulite-facies assemblages in the Narsajuaq arc and Sugluk Group

Monday (1994) investigated phase relations in several M1up granulite-facies samples from mafic orthogneisses of the Narsajuaq arc, utilizing the TWEEQU approach. He studied the assemblage garnet – orthopyroxene – clinopyroxene – hornblende – plagioclase – quartz in the simplified chemical system CaO – FeO – MgO – Al_2O_3 – SiO_2 – H_2O (CFMASH). In addition, Monday analyzed sillimanite – garnet – cordierite – biotite – plagioclase – quartz ± orthopyroxene assemblages from the pelitic rocks of the Sugluk Group.

The P–T determinations for granulite-facies mafic and pelitic samples are consistent and range from 6.9 kbar and 800°C to 9.9 kbar and 900°C (Fig. 4) (Monday 1994). No pressure or temperature progression was noted at the map scale within the granulite-facies domain.

The analysis of garnet – orthopyroxene – clinopyroxene – hornblende – plagioclase – quartz assemblages from Big Island (Fig. 5) has yielded *ca.* 800°C and 11 kbar estimates for mafic units of the Sugluk Group (Copeland 1999).

Level 2: M2 amphibolite-facies assemblages in the Narsajuaq arc and Sugluk Group

Monday (1994) also studied phase relations in M2 amphibolite-facies samples from the southern portion of Narsajuaq arc in northern Quebec (Fig. 4). Analyzed mafic samples contain garnet – clinopyroxene – hornblende – plagioclase – quartz assemblages and pelitic samples (from the Sugluk Group) contain sillimanite – garnet – biotite – plagioclase – quartz assemblages.

P–T determinations for the mafic and pelitic amphibolite-facies samples range from 7.2 kbar and 625°C to 8.9 kbar and 775°C (Fig. 4) (Monday 1994). These results are in strong contrast to the estimates obtained for the older M1up granulite-facies assemblages (see above). The M2 determinations are consistent with the mineral zone and petrofabric observations, which suggest that growth of the amphibolite-facies minerals was a retrograde event resulting from hydration and re-equilibration of the arc rocks as a consequence of overthrusting onto (dehydrating) Level-1 supracrustal units.

Level 3: M1up granulite-facies and M2 amphibolite-facies assemblages in the Lake Harbour Group and Blandford Bay assemblage

Preliminary thermobarometric work on thermal peak M1 assemblages from the Lake Harbour Group and Blandford Bay assemblage by I. Russell (unpubl. data) indicate conditions of *ca.* 800°C and <7 kbar, consistent with the mineral assemblages observed in the field and listed above. In contrast, the M2 retrograde assemblages yield P–T estimates of *ca.* 5.0 kbar and 650°C.

Temperature–Time Constraints on the Re-Equilibration of M1up Granulite-Facies Rocks

The retrograde re-equilibration of M1up granulite-facies rocks on southern Baffin Island is relatively well constrained for supracrustal units from structural levels 2 and 3 by U–Pb data on metamorphic zircon and monazite. In Figure 7, U–Pb ages of events and minerals (Scott 1997, Wodicka and Scott 1997, N. Wodicka,

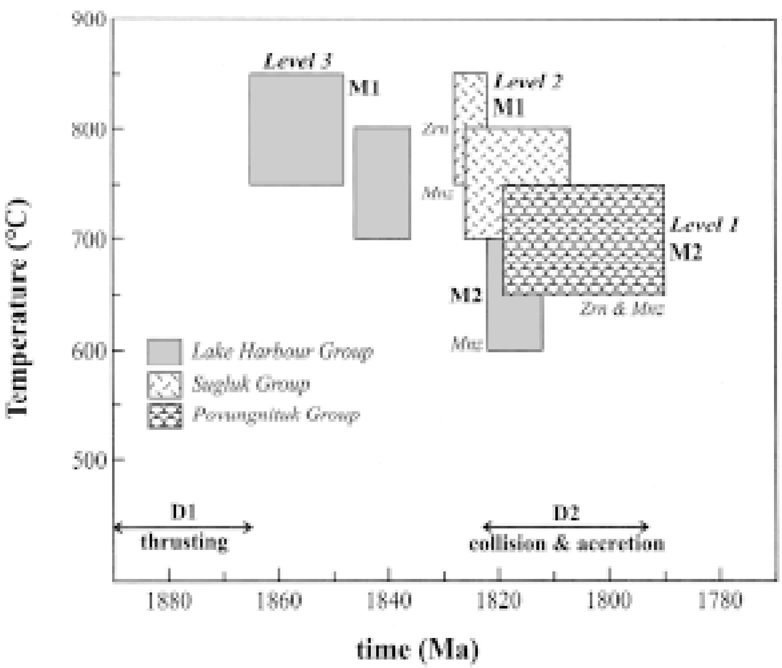

FIG. 7. Temperature–time diagram depicting the M1–M2 thermal history of the Lake Harbour Group (Level 3) and Sugluk Group (Level 2), and the M2 thermal constraint for the Povungnituk Group (Level 1) on southern Baffin Island. Isotopic age of events and minerals (Scott 1997, Wodicka & Scott 1997, N. Wodicka, unpubl. data) are plotted against estimates of temperature for M1 and M2 metamorphism (from I. Russell and D. Copeland, unpubl. data) or monazite-closure temperature given in Spear & Parrish (1996). Mnz: monazite, Zrn: zircon. See text for a discussion of the convergence of the M2 data.

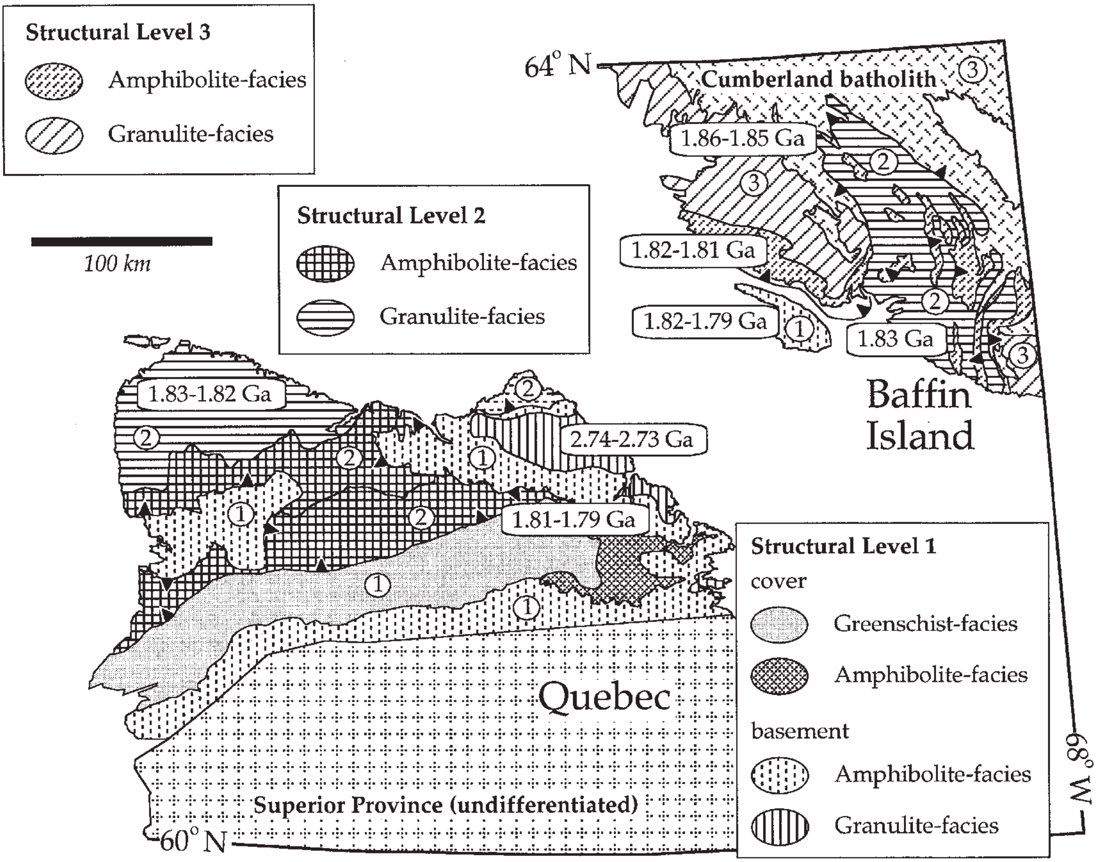

FIG. 8. Metamorphic compilation for northeastern Trans-Hudson Orogen. Large circled numbers refer to structural levels discussed in the text. The principal D2 thrust faults are identified with black teeth. The map highlights the distribution of early arc-related granulite-facies domains, subsequent collision-related greenschist- and amphibolite-facies domains, and principal D2 collisional faults. References for the ages of metamorphism are given in the text.

unpubl. data) are plotted against temperature estimates for M1up and M2 metamorphism (Copeland 1999; I. Russell, unpubl. data) or the closure temperature for monazite (>700–750°C for monazite, *cf.* Spear & Parrish 1996). The age of the M1up thermal peak metamorphism of the Lake Harbour (Level 3) and Sugluk (Level 2) groups, as inferred both from zircon and monazite ages and field relations, is indicated, as is the age of retrograde M2 metamorphism of Lake Harbour Group rocks. Immediately following granulite-facies M1up metamorphism but prior to syncollisional amphibolite-facies M2 metamorphism, Level-3 Lake Harbour Group rocks cooled through the closure temperature of monazite between *ca.* 1845 and 1836 Ma (Wodicka & St-Onge 1998), further constraining the path from granulite-facies to amphibolite-facies conditions. At intermediate structural levels, M1up granulite-facies metamorphism of Level-2 Sugluk Group rocks was followed, over a short period of time, by re-equilibration at M2 amphibolite-facies conditions as indicated by broadly coeval metamorphic zircon (1825 ± 4 Ma) and monazite (1825 ± 1 to 1808 ± 1 Ma) ages. Lastly, mafic rocks from the Level-1 Povungnituk Group have yielded M2 estimates of temperature and ages (see above) that broadly overlap with the results obtained from Levels 2 and 3. The mutual overlap shown on Figure 7 strongly corroborates the suggestion that tectonic juxtaposition of all three levels occurred during D2 (St-Onge *et al.* 1999a) and that the collision–accretion event generated the M2 amphibolite-facies metamorphism.

MAGMATIC, GEOHYDROLOGICAL, AND STRUCTURAL CONTROLS ON METAMORPHIC HISTORIES

The structural, metamorphic, and U–Pb data summarized above emphasize the importance of magmatic, geohydrological, and structural controls on the attainment of metamorphic conditions in upper- and lower-plate units within a convergent-plate margin setting, and specifically in the Quebec–Baffin segment of the Trans-Hudson Orogen (St-Onge *et al*. 1997, Wodicka & St-Onge 1998). The data indicate that the attainment of granulite-facies *versus* amphibolite-facies conditions at mid-crust depths is a function of whether the magmatic or the structural and geohydrological controls predominate; granulite-facies conditions can be reached in an upper-plate magmatic arc setting, whereas a collisional setting leading to thickening of the crust favors regional greenschist- to amphibolite-facies thermal peak conditions.

Thermal peak, pre-D1 granulite-facies mineral assemblages in the lower-plate Superior Province basement, and thermal peak M1up granulite-facies mineral assemblages in the upper-plate Narsajuaq arc, Sugluk Group, Lake Harbour Group and Blandford Bay assemblage, all predate the main 1.82–1.79 Ga D2 collision–accretion event (Table 1, Fig. 7) documented for the orogen. Field, petrological and isotopic data strongly suggest that the M1up granulite-facies metamorphism resulted from heat advected during upper-plate arc plutonism associated with the Narsajuaq arc and the Cumberland batholith (Monday 1994, Wodicka & Scott 1997, Thériault *et al.* 1997, Dunphy & Ludden 1998).

In contrast, collision–accretion deformation and consequent thickening of the crust resulted in growth of thermal-peak greenschist- to amphibolite-facies mineral assemblages in the lower-plate Povungnituk and Chukotat groups during M2 and possibly M1lp (St-Onge *et al*. 1999a). This recrystallization was accompanied by localized hydration and retrogression of older (pre-D1 and M1up) granulite-facies domains in both the lower plate (Superior Province) and the upper plate (Narsajuaq arc, Sugluk Group, Lake Harbour Group and Blandford Bay assemblage). Maps showing the distribution of the amphibolite-facies rocks, the location of D2 structural elements (thrust faults and shear zones), and the location of dehydrating (during M2) lower-plate metasedimentary rocks clearly document a regional structural and geohydrological control on the attainment of greenschist- to amphibolite-facies conditions, in both the lower and upper plate (Figs. 3a, 4 and 5, and summarized at the regional scale on Fig. 8). As outlined in previous sections, the structural and geohydrological controls on the attainment of greenschist- to amphibolite-facies conditions are further corroborated by petrological, thermobarometric and U–Pb isotopic data, with upper- and lower-plate rocks showing broad convergence in temperature–time space during M2 (Fig. 7).

Quite clearly then, at mid-crust levels in a convergent-margin system, granulite-facies conditions are achieved in an upper-plate magmatic arc setting, with magmatism being the dominant heat-source and control on regional metamorphism. In contrast, tectonic thickening in a convergent-margin system leads to, at most, amphibolite-facies conditions at mid-crust levels. As arc-related granulite-facies metamorphic events predate collision-related amphibolite-facies metamorphism in the Quebec–Baffin segment of Trans-Hudson Orogen (Fig. 8), all granulite- to amphibolite-facies transitions in this segment of the orogen (*i.e.,* within the lower-plate Superior Province basement, and upper-plate Narsajuaq arc, Sugluk Group, Lake Harbour Group and Blandford Bay assemblage) can be interpreted as retrograde in origin, with the amphibolite-facies overprint occurring up to hundreds of millions of years following the initial granulite-facies metamorphism (Table 1).

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