represent deep-level magmatic products of this subduction.

D_2 deformation was concentrated along the Ablovlak zone, which followed the 160° strike of the Nain continental margin. Crustal-scale sinistral extensional shear bands (Falcoz and Moonbase zones) developed in order to compensate for the obliquity of the colliding margins and may have continued to slip late in the N-S shear regime (*i.e.*, amphibolite-facies mylonite in the Falcoz zone). In the northern part of the orogen, the presence of symmetrical, upright D_2 folds in the Ramah Group (Mengel, 1988; Figure 1) indicates that the group lay beyond the eastern limit of transcurrent shearing and was only affected by the shortening component of the deformation.

The dip-lineated mylonites along the orogenic front are interpreted to have been the loci for continued shortening across the orogen as it was exhumed from amphibolite facies. These mylonites outlived the bulk of the transcurrent component of the deformation. Dip-slip shearing apparently nucleated near the cryptic suture between the Nain and Rae provinces, and was subsequently concentrated along the Hudsonian granulite-amphibolite facies transition, probably due to competency and density contrasts between these metamorphic blocks.

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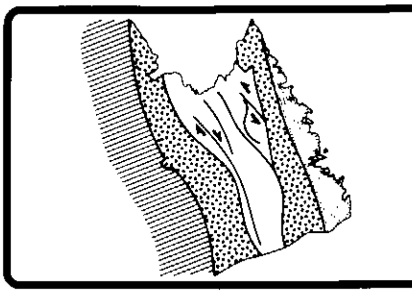

The synmetamorphic P-T-*t* path of granulite-facies gneisses from Torngat Orogen, and its bearing on their tectonic history

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Summary
Granulite-facies gneisses in the Abloviak shear zone in the internides of the Torngat Orogen are characterized by subvertical shear fabrics and associated subhorizontal stretching lineations. P-T vectors, derived from individual samples of these gneisses by conventional geothermobarometry of equilibrium core, rim and replacement symplectite assemblages, yield evidence of over 3 kbars decompression associated with cooling of approximately 150°C. When the sample population is considered together, a P-T-*t* path involving over 5 kbars decompression and 250°C cooling is defined. Such paths are compatible with theoretical models of synmetamorphic uplift following doubling of crustal thickness during thrusting, and imply that transcurrent motion took place in tectonically thickened crust, and was coeval with uplift. In a regional context, the Torngat Orogen preserves evidence of the oblique collision of two Archean cratonic blocks, the Nain and Rae provinces, during the Early Proterozoic and their amalgamation with Laurentia.

Introduction
There are several ways in which P-T-*t* paths can be evaluated in metamorphic rocks. In this study, we have opted to make quantitative estimates of P and T using geothermobarometry, and to couple these with relative estimates of *t* that can be determined from metamorphic microstructures. This

technique allows the determination of *P-T vectors* in individual samples, *i.e.*, changes in P-T with time, even though the absolute amount of time taken for the changes is unknown (Mengel and Rivers, 1989).

Retrogression, common in many granulite-facies terranes, is widespread in the Saglek Fiord granulites, where it is manifested by retrograde zoning and locally by the presence of rim symplectites around pyroxene and garnet. Relative time is derived from the core (oldest) and rim compositions of adjacent minerals and the compositions of coexisting minerals in rim symplectites (youngest).

Regional geology

Figure 1 shows the main tectonic elements of the Torngat Orogen at the latitude of Saglek Fiord (see Korstgård *et al.*, 1987; Van Kranendonk, 1990; Mengel *et al.*, in press).

The Nain Province is the eastern Archean cratonic foreland adjacent to the Torngat Orogen. It is cut by the Early Proterozoic Napaktok dykes and unconformably overlain by the Early Proterozoic Ramah Group. The western part of the Nain Province, adjacent to the Torngat Orogen, is referred to as the **Torngat Foreland zone.** The **Torngat front zone**, which comprises the eastern externides of the Torngat Orogen, is principally occupied by the Ramah Group at the latitude of Saglek Fiord, and is characterized by an east-directed fold and thrust belt that shows evidence of a metamorphic field gradient from greenschist to middle amphibolite facies.

The **Abloviak shear zone** in the internides of the Torngat Orogen is a crustal-scale sinistral transcurrent shear zone up to 30 km wide and over 900 km in length, which is characterized by upper amphibolite- and granulite-facies rocks with steep mylonitic fabrics and associated subhorizontal stretching lineations defined by hornblende or orthopyroxene. The Abloviak shear zone overprints two lithologically contrasting terranes in the Saglek area: the **Komaktorvik terrane** is composed of Archean gneisses (correlated with those in the Nain Province) and remnants of Napaktok dykes, both of which were penetratively reworked under upper amphibolite- and granulite-facies conditions during the Early Proterozoic; and the **Tasiuyak terrane**, which consists principally of leucocratic aluminous gneisses and subordinate two pyroxene-garnet mafic gneisses.

Rocks to the west of the Tasiuyak terrane, and their relationship with the Rae Province, lie beyond the purview of this study.

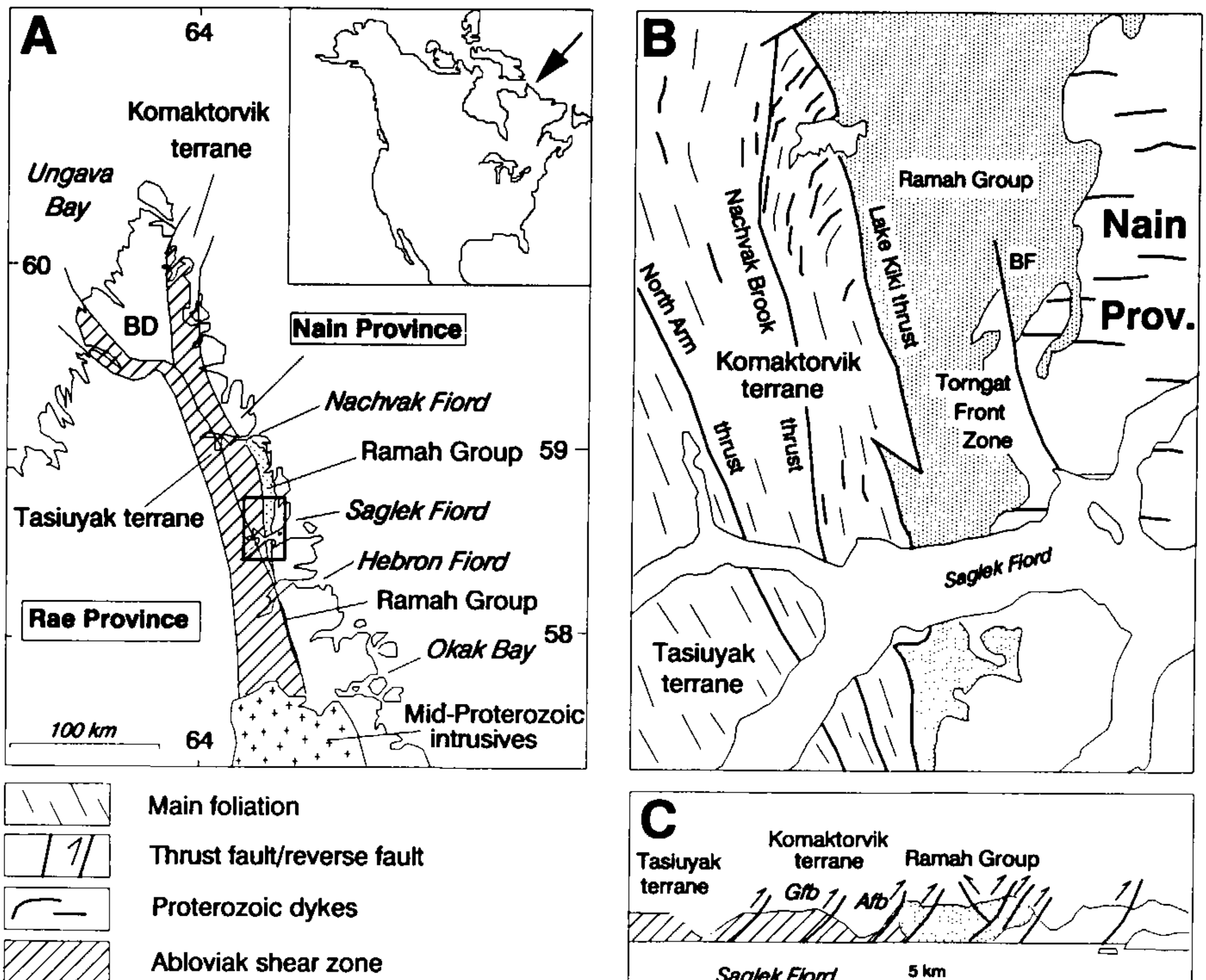

Figure 1 (A) *Map showing the principal tectonic elements of the Torngat Orogen, and the location of the study area at Saglek Fiord;* **BD**, *Burwell domain.*
(B) *Tectonic map of the Saglek area;* **BF**, *Branagin Fault, which marks the western boundary of the Torngat Foreland zone. Short heavy lines represent the orientations of Napaktok dykes (E/W in the Nain Province, NNW/SSE in the Abloviak shear zone.*
(C) *Schematic cross-section of the eastern part of the Torngat Orogen along Saglek Fiord. Positions of late post-metamorphic faults are shown;* **Gfb**, *granulite-facies block;* **Afb**, *amphibolite-facies block.*

Contacts between the tectonic zones, and between the terranes and blocks into which they are subdivided, are steeply west-dipping, post-peak metamorphism, thrust or reverse faults, which, on the basis of metamorphic contrasts across them, are zones of substantial displacement along which high-grade terranes from the internides of the orogen were uplifted onto lower grade rocks at the margin.

Mineral assemblages and reactions
Metamorphic assemblages that developed in granulite-facies rocks during the Torngat orogeny include various combinations of orthopyroxene (Opx), clinopyroxene (Cpx), garnet (Grt), plagioclase (Pla), and quartz (Qtz) in the Komaktorvik terrane and parts of the Tasiuyak terrane, and the widespread occurrence of garnet, plagioclase, sillimanite (Sil), quartz, biotite (Bt), and K-feldspar (Kfs) within the Tasiuyak terrane. Orthopyroxene and sillimanite commonly define the subhorizontal stretching lineations that are characteristic of the Abloviak shear zone, indicating that they grew during transcurrent shearing.

The presence of retrograde mineral zoning in garnets in these granulite-facies rocks is widespread, and the occurrence of mineral reactions during retrograde metamorphism is inferred in some mafic rocks where garnet and clinopyroxene are separated from each other by symplectites of orthopyroxene-plagioclase and/or hornblende-plagioclase. These microstructures suggest operation of the reactions:

Grt + Cpx + Qtz = Pla + Opx [r1]

Grt + Cpx + H_2O = Pla + Hbl + Qtz [r2],

which are shown in their relative positions in P-T space in the end-member CMASH system in Figure 2. Mengel and Rivers (in press) argue that the relative positions of the reactions are not changed significantly by the addition of Fe and other elements as additional compositional variables, and therefore interpreted reactions [r1] and [r2] to be evidence of decompression.

Petrographic evidence of the nature of the syntectonic reactions, in this case implying decompression, is important because it provides an independent check on the direction of the P-T vector determined by geothermobarometry. If the P-T vectors as estimated by the two methods are not qualitatively in accord, the quantitative estimates are of questionable validity and may be an artifact of inappropriate assumptions concerning the synchroneity of closure of the thermometric and barometric systems (see Selverstone and Chamberlain, 1990).

Geothermobarometry
Methods. In this study, we wish to emphasize the relative change in pressure and temperature with time, the P-T vector, rather than the precise estimation of these variables, and hence have restricted the number of geothermobarometric calibrations to a minimum. Mengel and Rivers (in press) have shown that use of alternative calibrations to those chosen here does not significantly alter the slopes of the P-T vectors, although it may have some effect on their absolute positions in P-T space. The following calibrations were used: T1, Opx-Cpx (Wood and Banno, 1973); T2, Grt-Cpx (Ellis and Green, 1979); T3, Grt-Opx (Sen and Bhattacharya, 1984); P1, Cpx-Pla-Qtz (Ellis, 1980); P2, Grt-Opx-Pla-Qtz (Newton and Perkins, 1982, with -0.5 kbar correction); P3, Grt-Cpx-Pla-Qtz (Newton and Perkins, 1982, with +1.5 kbar correction).

P and T estimates are shown without calculated errors in this study in the interest of clarity in the diagrams. Most authors estimate errors of ±50°C for geothermometers and ±1 kbar for geobarometers, which result in an error box in P-T space for simultaneous solution of a barometer and a thermometer. Clearly, if rigorously applied, some of the changes in estimated P-T conditions in individual samples, discussed below, lie within error of each other, and thus it could be argued that the differences between them are not statistically significant. This point of view is disputed here, because the *direction* of change is consistent in all samples. This will not change, even if new calibrations become available which alter the estimates and/or their precision.

P-T results. P-T estimates for mineral cores, rims and rim symplectites from eight samples are shown in Figure 3A, in which it can be seen that P-T vectors for all samples are subparallel, implying that they all followed essentially the same trajectory and were part of the same rock volume. For any individual sample, the highest determined temperatures and pressures are from mineral cores and the lowest are from rim symplectites, with individual samples recording up to 170°C cooling and over 3 kbar decompression, a result that is qualitatively compatible with the evidence of decompression noted from the reactions in symplectites. However, some rim analyses yield higher pressure estimates than cores from other samples, implying that the samples do not all record the same segment of the P-T path, presumably because of heterogeneous equilibration between samples (see Hodges and Royden, 1984). Analysis of a large number of samples from the same rock volume is therefore likely to lead to a longer P-T path, as is borne out by the results of Mengel (1988), who calculated a P-T path from analyses of 34 granulite-facies samples from the Saglek area that extended between 11.5 kbars and 5.5 kbars and 900°C and 550°C.

An important aspect of these results is that the P-T vectors from individual zoned samples are parallel to the P-T path for the whole array. This is a necessary condition for the interpretation of heterogeneous equilibration, and argues against the possibility that the P-T array is a computational artifact (see Selverstone and Chamberlain, 1990).

Interpretation
Figure 3 shows that peak metamorphic conditions, which as noted above were interpreted as synchronous with transcurrent shearing, were in the range 9–10 kbar/800°–880°C. This represents a significant deviation from a steady-state geotherm, and the high pressure suggests that the meta-

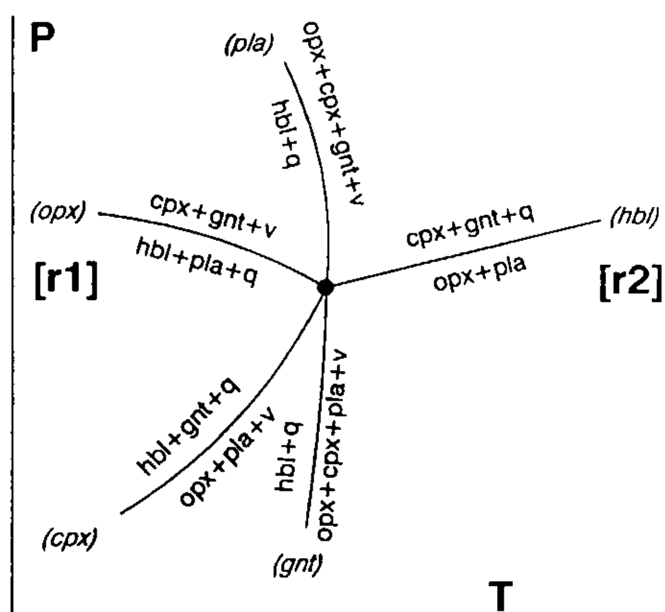

Figure 2 *Phase relations in the CaO-MgO-Al_2O_3-SiO_2-H_2O (CMASH) system for the phases garnet (**gnt**), hornblende (**hbl**), clinopyroxene (**cpx**), orthopyroxene (**opx**), plagioclase (**pla**) quartz (**q**) and H_2O vapour (**v**). (After Wells, 1979). [r1] and [r2] refer to reactions discussed in the text.*

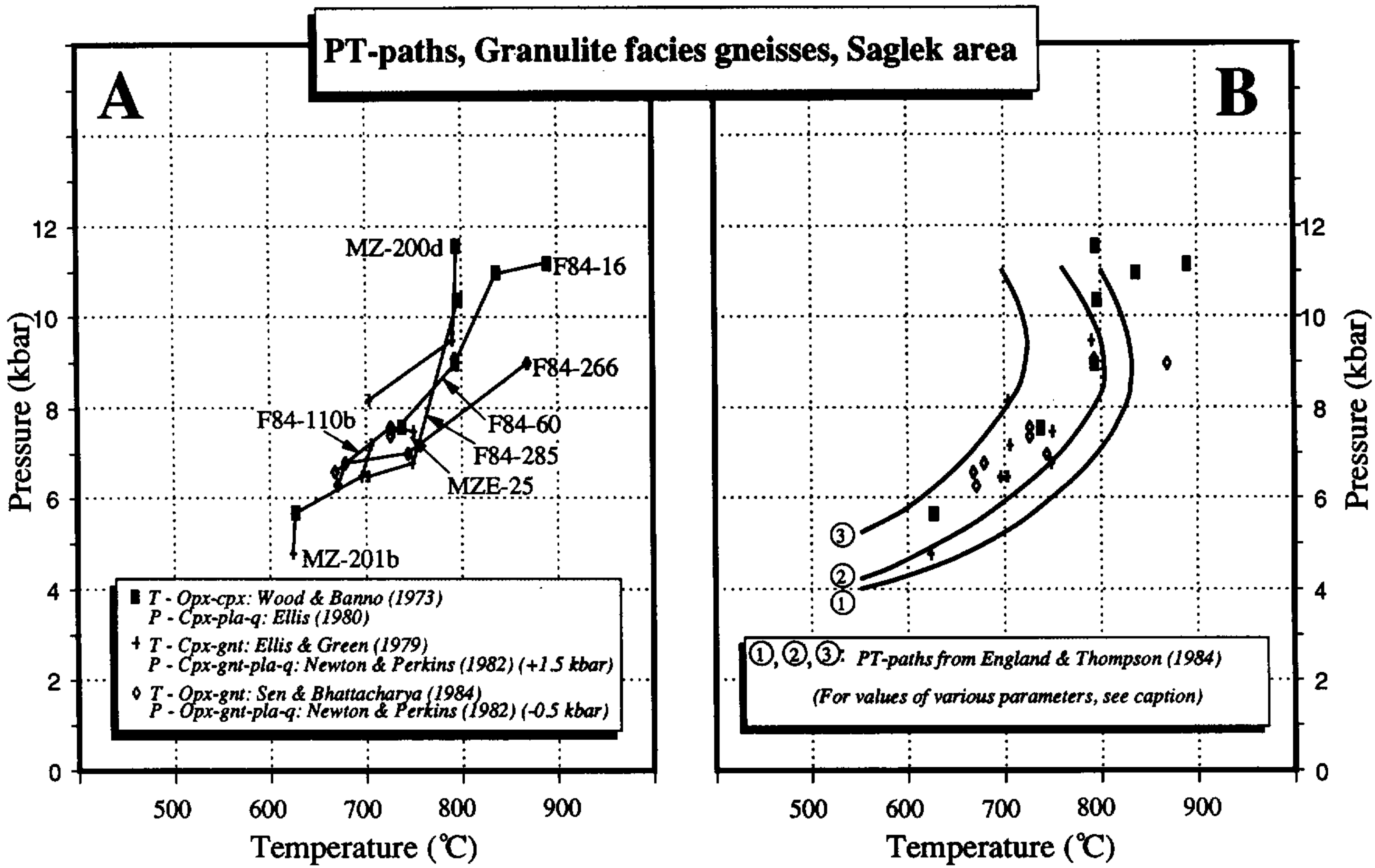

Figure 3 (**A**) *P-T data from granulite-facies rocks in the Komaktorvik terrane. P-T vectors are defined by connecting the P-T estimates from various microstructural settings within individual samples. Highest pressures and temperatures in individual samples are from cores, lowest are from fringing symplectites.*
(**B**) *P-T points from A are compared with three model curves (P-T-t paths) for uplift following doubling of crustal thickness, from England and Thompson (1984) and Thompson and England (1984). Input variables are: uplift rate of 0.3 mm per year, with an erosional time delay of 20 m.y. following thrusting. Curve 1 is for doubling of a 30 km crust with a thermal conductivity (k) of 1.5 $Wm^{-1}K^{-1}$ and the "Heat Source Distribution III" of England and Thompson (1984). Curve 2 is for k = 2.25 $Wm^{-1}K^{-1}$ buried 50 km; curve 3 is for k = 1.5 $Wm^{-1}K^{-1}$ buried 40 km. Both 2 and 3 are based on Heat Source Distribution II, which represents the thermal conditions considered typical of continental lithosphere.*

morphism took place in a deeply buried section of tectonically overthickened crust at depths of about 30 km (*e.g.*, Ellis, 1987; Harley, 1988). Hence crustal thickening must have predated or accompanied the formation of the Abloviak shear zone.

As has been discussed by England and Richardson (1977), overthrusting to double crustal thickness results in heating of the tectonically buried rocks in the lower plate as the disturbed isotherms relax to their initial state (the steady state geotherm). However, the temperature increase is limited by the local geothermal gradient and the thickness of the overlying thrust pile, and Thompson and England (1984) showed that attainment of granulite-facies temperatures is not possible with their model by crustal thickening alone, for reasonable values of the other parameters. They therefore postulated that an additional source of heat must have been present in granulite-facies terranes, and suggested that magmatic heat from plutonic under- or intra-plating was most likely. Alternative explanations include the occurrence of elevated values of the mantle heat flux (Harley, 1988) or advection by hot thrusts, both of which could produce a similar result in terms of the P-T-*t* path.

Figure 3B shows the P-T points from Figure 3A together with three theoretical P-T-*t* paths (from England and Thompson, 1984) that were derived from models involving doubling of crustal thickness by thrusting. Although the measured P-T vectors do not correspond to a unique model path, most of the analyzed points fit closely with the overall shapes of the theoretical uplift curves, suggesting that the curves do represent the process that occurred in nature. Especially noteworthy is the very marked uplift (decompression of 5 kbars is approximately equal to 16 km uplift) associated with cooling of less than 200°C that characterizes the high temperature part of the path. However, three points lie at distinctly higher temperatures than any of the model curves. Sample F84-16 shows an almost isobaric cooling path at high temperature, which may indicate non-synchronous closure of the thermometer and the barometer used, or alternatively may be due to magmatic under- or intraplating (Bohlen, 1987; Harley, 1987).

Tectonic development and timing

With the recognition of a phase of crustal thickening in the Komaktorvik and Tasiuyak terranes that predated or was coeval with transcurrent shearing, a tectonic link with the easterly verging fold and thrust belt in the adjacent Torngat front zone can be proposed. It is interpreted that this fold and thrust belt is the higher level and more external expression of the crustal thickening that occurred early in the tectonic development of the granulite-facies terranes.

Figure 4 is a schematic diagram showing the proposed geological development of the Torngat Orogen as a series of simplified stages. There may have been two discrete stages of crustal shortening and thickening, separated by a stage involving principally transcurrent shearing and uplift, as schematically indicated in the figure, or, as noted above, transcurrent shearing could have been coeval with the first phase of crustal thickening. Nevertheless, in either scenario, there is good evidence that relative plate movements during the Torngat orogeny involved both convergent and transcurrent motions, and a tectonic environment of oblique convergence is therefore inferred.

The absolute timing of the events proposed above is not precisely constrained at present. Bertrand *et al.* (1990) have attempted to date movement on the Abloviak shear zone and on the late thrust/reverse faults by dating syntectonic granites, defined as those which cut the fabrics of the shear zone/fault, yet also contain the fabrics themselves. The ages obtained thus lie within the period at which movement took place on the geological structure in question. Their preliminary results (all U/Pb analyses on accessory minerals) indicate that transcurrent shearing was occurring between 1859 Ma and 1844 Ma, and that east-directed uplift along post-peak metamorphic thrust/reverse faults was taking place at 1805 Ma, allowing a maximum period of some 45 m.y. for retrograde mineral zoning and symplectite reactions in the granulite-facies rocks. Post-tectonic granite has been dated at 1790 Ma, and argon retention in hornblendes began between 1790 Ma to 1750 Ma (Mengel *et al.*, in press), indicating that uplift and cooling continued after the termination of retrograde mineral reactions.

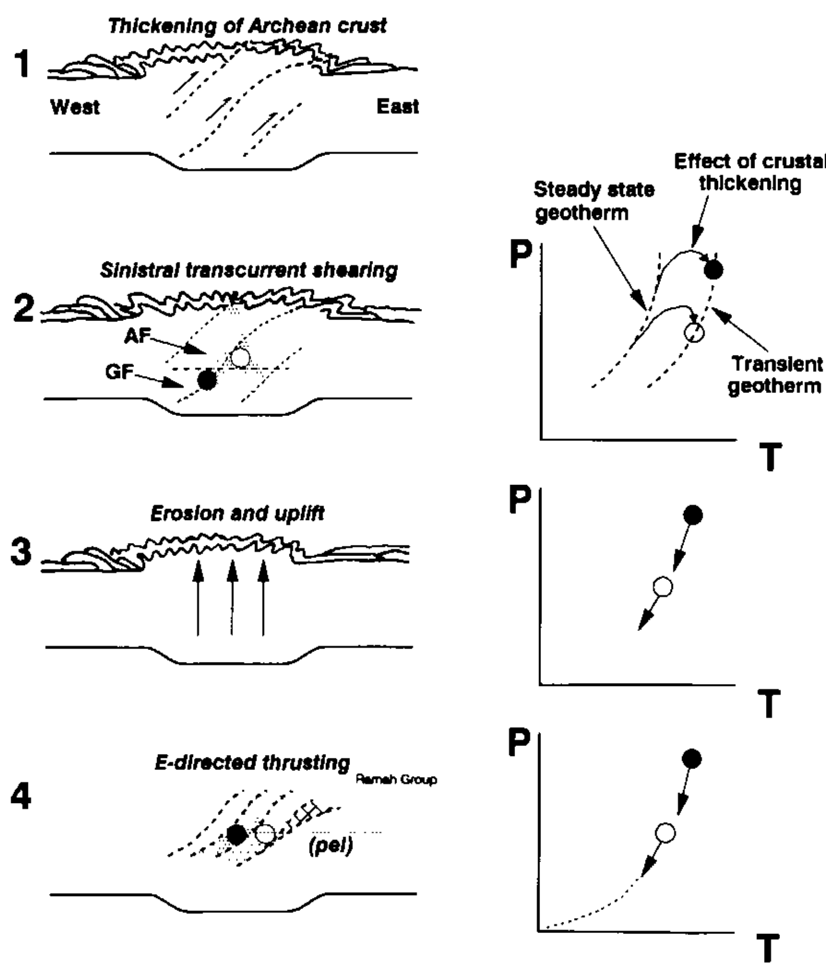

Figure 4 *Schematic representation of the tectonic development of the Torngat Orogen.*
(**1**) *Tectonic thickening of Archean crust and of its Proterozoic cover (Ramah Group in the east, Lake Harbour Group in the west). This resulted in the formation of a fold/thrust belt in the Ramah Group in the Torngat front zone. May be in part synchronous with 2.*
(**2**) *Initiation of transcurrent shearing in the internides of the orogen at the peak of metamorphism. The boundary between granulite facies (**GF**) and amphibolite facies (**AF**) is indicated schematically. Sloping dashed lines represent the locations of future thrust/reverse faults.*
(**3**) *Erosion and uplift, in part synchronous with 2.*
(**4**) *East-directed post-peak metamorphic thrusting resulted in tectonic juxtapositioning of internides (Abloviak shear zone) on to externides (Torngat front zone). Diagrams on the right show the schematic P-T path of rocks in the granulite-facies (filled circle) and amphibolite-facies (open circle) parts of the Abloviak shear zone.*
• N.B. *Separation of some of the events may be artificial, and is for illustrative purposes only.*

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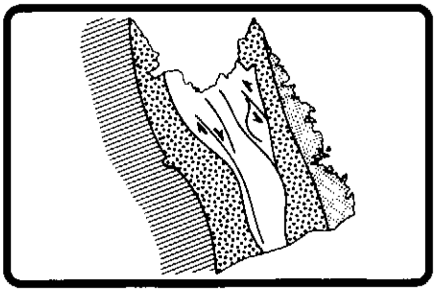

Early Proterozoic orogenic activity adjacent to the Hopedale block of southern Nain Province

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Summary

The Hopedale block of the southern Archean Nain Province forms a wedge between the Early Proterozoic Makkovik and Churchill provinces. Lower Proterozoic supracrustal rocks, deposited on the Hopedale block following intrusion of tholeiitic dykes *ca.* 2200 Ma, were reworked at amphibolite facies, and thrust westward against undeformed portions of the block during orogeny in the Makkovik Province. The Makkovik/Hopedale block structural boundary is marked by a late, greenschist-facies dextral shear. By contrast, the boundary between the Hopedale block and the Churchill Province to the west is a fault zone that separates lower Proterozoic supracrustal rocks, deposited on a protocontinent of Churchill Province rocks, from fundamentally different rocks of the Nain Province. The intensity of Early Proterozoic deformation and metamorphism rises progressively from sub-greenschist facies in the Hopedale block to granulite facies in the interior of the Churchill Province.

Introduction

The Archean Hopedale block of the southern Nain Province (Figure 1)(Taylor, 1971) is part of the pre-Phanerozoic North Atlantic craton (Bridgwater *et al.*, 1976). In the Early Proterozoic, widespread intrusion of tholeiitic dykes preceded deposition of lower Proterozoic supracrustal rocks and Early Proterozoic deformation. These dykes are referred to as the Kikkertavak dykes (*ca.* 2200 Ma) in the