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TEMPERATURE AND PRESSURE VARIATIONS IN SUITES OF ARCHEAN FELSIC PLUTONIC ROCKS, BERENS RIVER AREA, NORTHWEST SUPERIOR PROVINCE, ONTARIO, CANADA

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Abstract

The Berens River area is representative of a broad belt of Archean felsic plutonic rocks in the northwestern Superior Province of Ontario. The plutonic belt (Berens River subprovince) occupies the southern margin of the North Caribou terrane, a regional-scale enclave of pre-2.8-Ga plutonic and greenstone sequences. Plate-tectonic models maintain that the North Caribou terrane is an early continental mass against which other terranes (subprovinces) were rapidly accreted from 2.75 to 2.70 Ga. During accretion, a magmatic arc characterized by voluminous felsic intrusions developed on the southern margin of the old continent. In the Berens River area, five major groups of felsic plutonic rocks have hornblende-bearing assemblages suitable for application of amphibole + plagioclase thermometers and Al-in-hornblende barometers. Cross-cutting relations show that the biotite tonalite suite is oldest; it is cut consecutively by hornblende tonalite of the hornblende suite, hornblende granodiorite of the hornblende suite, the biotite granite suite and the sanukitoid suite. Average temperatures for the major plutonic suites range from 716 to 773°C. Temperature maps show irregular isotherms, with some low-T zones associated with faults in the hornblende tonalite, but not in hornblende granodiorite. The average temperature-corrected Al-in-hornblende pressures for the plutonic suites range from 4.4 to 2.3 kbar and decrease with age of the suites. The distribution of P measurements indicates that the Berens River area was uplifted significantly during magmatism, with uplift concentrated at the southern margin of the North Caribou continent.

Keywords: Superior Province, Ontario, Berens River subprovince, plutonic, pressure, temperature, Al-in-hornblende, barometry.

Sommaire

La région de la rivière Berens est représentative d'une vaste étendue de roches plutoniques felsiques dans le secteur nord-ouest de la province du Supérieur en Ontario. La ceinture de roches plutoniques, appelée ici la sous-province de la Rivière Berens, occupe la bordure sud du socle North Caribou, vaste enclave de séquences plutoniques et de roches vertes antérieures à 2.8 Ga. D'après les reconstructions en termes de la tectonique des plaques, le socle de North Caribou aurait été une masse continentale précoce sur laquelle sont venues s'accoller rapidement d'autres socles (sous-provinces) sur l'intervalle de 2.75 à 2.70 Ga. Au cours de l'accrétion, un arc magmatique de massifs felsiques volumineux s'est développé le long de la marge boréale du vieux continent. Dans la région de la rivière Berens, cinq groupes majeurs de roches plutoniques felsiques possèdent des assemblages à hornblende appropriés pour l'application du géothermomètre fondé sur l'association amphibole + plagioclase et du géobaromètre fondé sur la teneur en Al de la hornblende. D'après les contacts intrusifs, la tonalite à biotite serait l'unité la plus ancienne. Elle est recoupée de façon consécutive par la tonalite à hornblende de la suite à hornblende, la granodiorite à hornblende de la suite à hornblende, une suite de granites à biotite et la suite de roches sanukitoïdes. En moyenne, la température de mise en place des suites plutoniques majeures varie entre 716 à 773°C. Une carte de répartition des températures montre des isothermes irréguliers, avec des zones de faible température associées à des failles dans la tonalite à hornblende, mais non dans la granodiorite à hornblende. La moyenne des mesures de pression de mise en place, d'après la teneur en Al de la hornblende, telle que corrigée pour la température, varie entre 4.4 et 2.3 kbar et diminue avec l'âge des suites. La distribution des mesures de pression fait penser qu'il y a eu un soulèvement important dans la région de la rivière Berens durant le magmatisme, surtout le long de la bordure sud du socle continental de North Caribou.

(Traduit par la Rédaction)

Mots-clés: province du Supérieur, Ontario, sous-province de la Rivière Berens, plutonique, pression, température, teneur en Al de la hornblende, barométrie.

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Introduction

Archean felsic plutonic rocks underlie vast areas of the northwest Superior Province of the Canadian Shield. Despite their large extent, such plutonic suites are less well known than greenstone and sedimentary belts. For example, compilation maps have traditionally made careful distinction of mafic and intermediate to felsic metavolcanic rocks, metasediments and mafic intrusions in greenstone belts, but have left plutonic areas largely unsubdivided (*e.g.*, Davies *et al.* 1970, Ayres *et al.* 1973). Although individual batholiths and suites of plutonic rocks have been studied (Ayres *et al.* 1991, Beakhouse & McNutt 1991), the level of regional-scale geochemical, geochronological and structural information is generally much greater for greenstone belts than for plutonic areas (*e.g.*, Thurston & Fryer 1983, Ayer & Davis 1997, Corfu & Andrews 1987, Ayres & Corfu 1991).

Thermobarometric data are particularly lacking from plutonic areas of the northwest Superior Province. Regional-scale pressure–temperature studies have focused on sedimentary belts (Perkins & Chipera 1985, Chipera & Perkins 1988, Percival 1989), granulites (Mezger *et al.* 1990, Mäder *et al.* 1994) and on plutonic areas of the northeastern Superior Province (Bégin & Pattison 1994). The lack of pressure–temperature data for plutonic rocks arises partly from a lack of mineral assemblages suitable for geothermometry and geobarometry (see summary of Spear & Peacock 1989). Analysis of plutonic rocks is largely restricted to application of feldspar thermometers (*e.g.*, Fuhrman & Lindsley 1988), hornblende + plagioclase thermometers (*e.g.*, Holland & Blundy 1994) and Al-in-hornblende barometers (*e.g.*, Hammarstrom & Zen 1986).

From 1988 to 1993, geologists of the Ontario Geological Survey mapped the Berens River area (35 000 km^2), which represents the largest domain of predominantly intrusive rocks in the northwestern Superior Province. The mapping was supported by U–Pb geochronology (Corfu & Stone 1998a, b) and the petrological work reported here. Goals of the work are broadly to rectify the imbalance in geological data between plutonic and supracrustal areas in aid of mineral exploration and to refine tectonic models for the growth and evolution of the Superior Province. In this paper, I summarize results of hornblende + plagioclase thermometry and Al-in-hornblende barometry on suites of Berens River plutonic rocks.

Regional Setting

The northwestern Superior Province has been subdivided by Card & Ciesielski (1986) into large, mainly east-trending subprovinces on the basis of contrasts in lithology, structure, metamorphic history and geophysical patterns. Four main types of subprovinces, containing dominantly volcano-plutonic, plutonic, sedimentary and high-grade gneisses, were identified (Fig. 1) and traced into the northeastern Superior Province of Quebec (Percival *et al.* 1992), where subprovinces curve to a northerly trend.

Recent work has emphasized the importance of age and isotopic characteristics of rocks and has refined tectonic subdivisions of the Superior Province. For example, although ages of most magmatic rocks span a fairly narrow range of 2.75 to 2.70 Ga, a subset of U–Pb age data (summarized by Corfu & Davis 1992) indicates enclaves of pre-2.8-Ga crust in the Minnesota River, Wabigoon and Winnipeg River subprovinces and in the North Caribou terrane. The North Caribou (Thurston *et al.* 1991) is the largest block of Meso-archean crust; it extends north from the Uchi subprovince and is divisible into plutonic (Berens River) and volcano-plutonic components [part of the Sachigo subprovince of Card & Ciesielski 1986)]. The geochronological and Nd isotopic studies of Heaman *et al.* (1999) and Skulski *et al.* (1999) have identified other Meso- to Paleo-archean blocks associated with the Pikwitonei subprovince, and Stott *et al.* (1998) and Tomlinson *et al.* (1999) have further defined blocks of old crust in the Wabigoon Subprovince.

Models have been proposed (*e.g.*, Card 1990, Stott 1997) whereby the belt-like pattern of subprovinces and terranes developed by accretion of island arcs, segments of ocean floor, microcontinents and sedimentary prisms. The North Caribou possibly represents an early continental mass that acted as a buttress against which other terranes were accreted (Thurston *et al.* 1991). Geochronological and tectonic studies (*e.g.*, Corfu *et al.* 1995) have led to interpretations that subprovinces such as parts of the Uchi, English River and Winnipeg River (Fig. 1) joined successively outboard and southward from the North Caribou microcontinent in the interval 2.75 to 2.70 Ga. Accretion was driven by northward subduction of oceanic crust beneath the microcontinent.

Within the above tectonic context, the present study-area (Fig. 1) occupies the southern, dominantly plutonic part of the North Caribou microcontinent. Although scattered remnants of pre-2.8-Ga supracrustal and plutonic sequences are present, recent studies (Corfu & Stone 1998a, b) indicate that more than 80% of Berens River plutonic rocks were emplaced between 2744 and 2686 Ma. The broad zone of young intrusions possibly represents the core of a magmatic arc developed on the continental margin.

Geology of the Berens River Area

The Berens River area is underlain by voluminous massive to foliated and locally gneissic plutonic rocks and minor amphibolite-facies supracrustal remnants. The area (Fig. 2) is bounded on the south by major greenstone belts at Red Lake and Woman Lake (Birch–Uchi belt) and on the north by a chain of greenstone belts extending through Favourable Lake and North

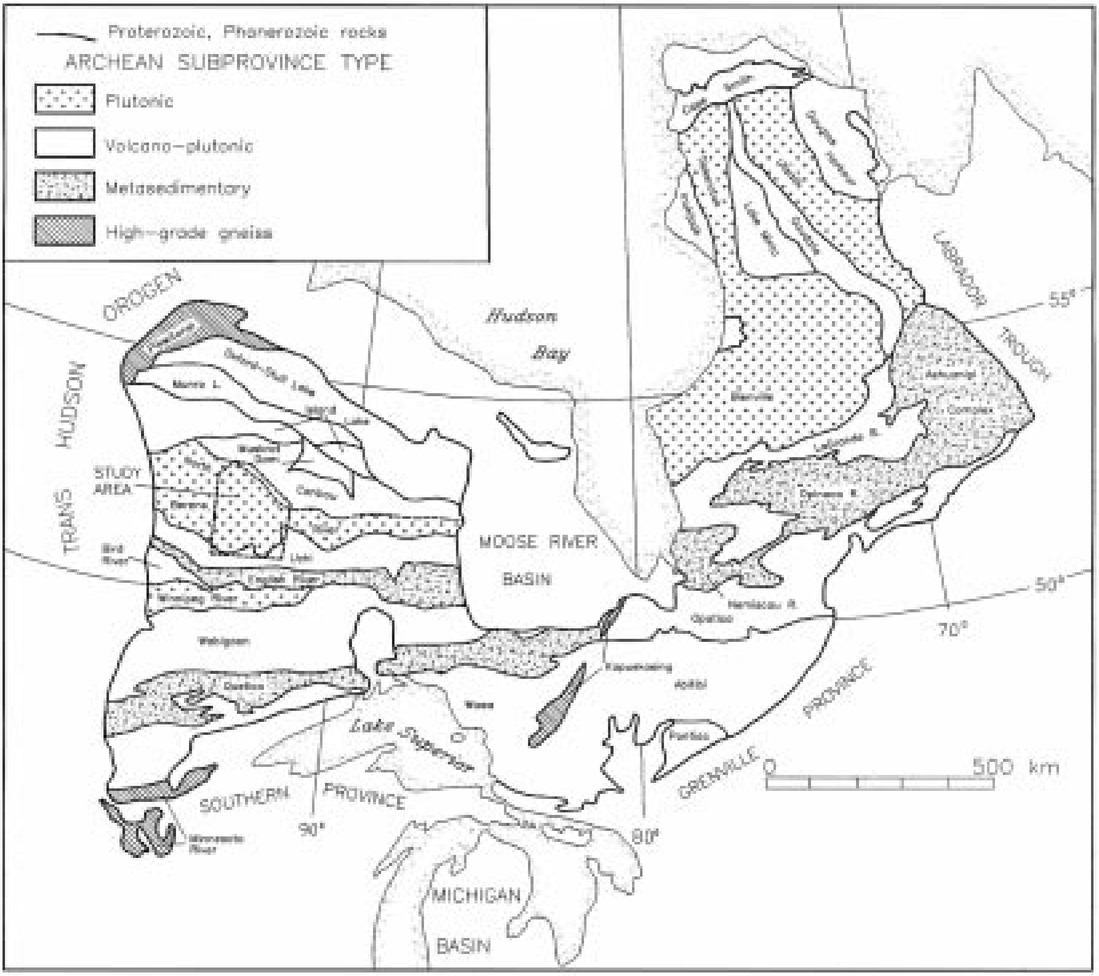

FIG. 1. Subdivisions of the Superior Province, modified from Card & Ciesielski (1986), Thurston *et al.* (1991) and Percival *et al.* (1992).

Spirit Lake. Berens River plutonic rocks extend west of the Ontario–Manitoba border to Lake Winnipeg (Ermanovics 1970a, b) and are overlain by Phanerozoic sediments at the western margin of the Superior Province. Eastward, plutonic rocks characteristic of the Berens River area taper to a narrow magmatic welt at the northern margin of the Uchi subprovince (Fig. 1).

The geology of greenstone belts both within and at the margins of the Berens River area has been described extensively (Ayres & Corfu 1991, Stott & Corfu 1991, Thurston *et al.* 1991). Most authors have favored subdivision of belts into tectonic assemblages [sequences of volcanic or sedimentary rock units (or both) built during a discrete interval of time in a common depositional setting]. Mafic to ultramafic and commonly pillowed flows characteristic of ocean-floor assemblages make up the largest component of greenstone belts. The major belts have cyclical mafic to felsic sequences of volcanic flows, tuffs and breccias typical of volcanic arc assemblages. Although rare, platform assemblages consisting of conglomerate, coarse sandstone, marble and komatiite are a distinguishing component of old greenstone belts such as in the North Caribou terrane (Thurston & Chivers 1990). Timiskaming-type assemblages composed of coarse sedimentary units typical of alluvial fan and fluvial environments and possible alkaline volcanic rocks occur in the Birch–Uchi belt and are associated with the Bear Head fault, which extends along the Favourable – North Spirit greenstone belt (Fig. 2).

Perhaps the most striking characteristic of greenstone belts within the North Caribou terrane, including the Berens River area, is the remarkable variation in age

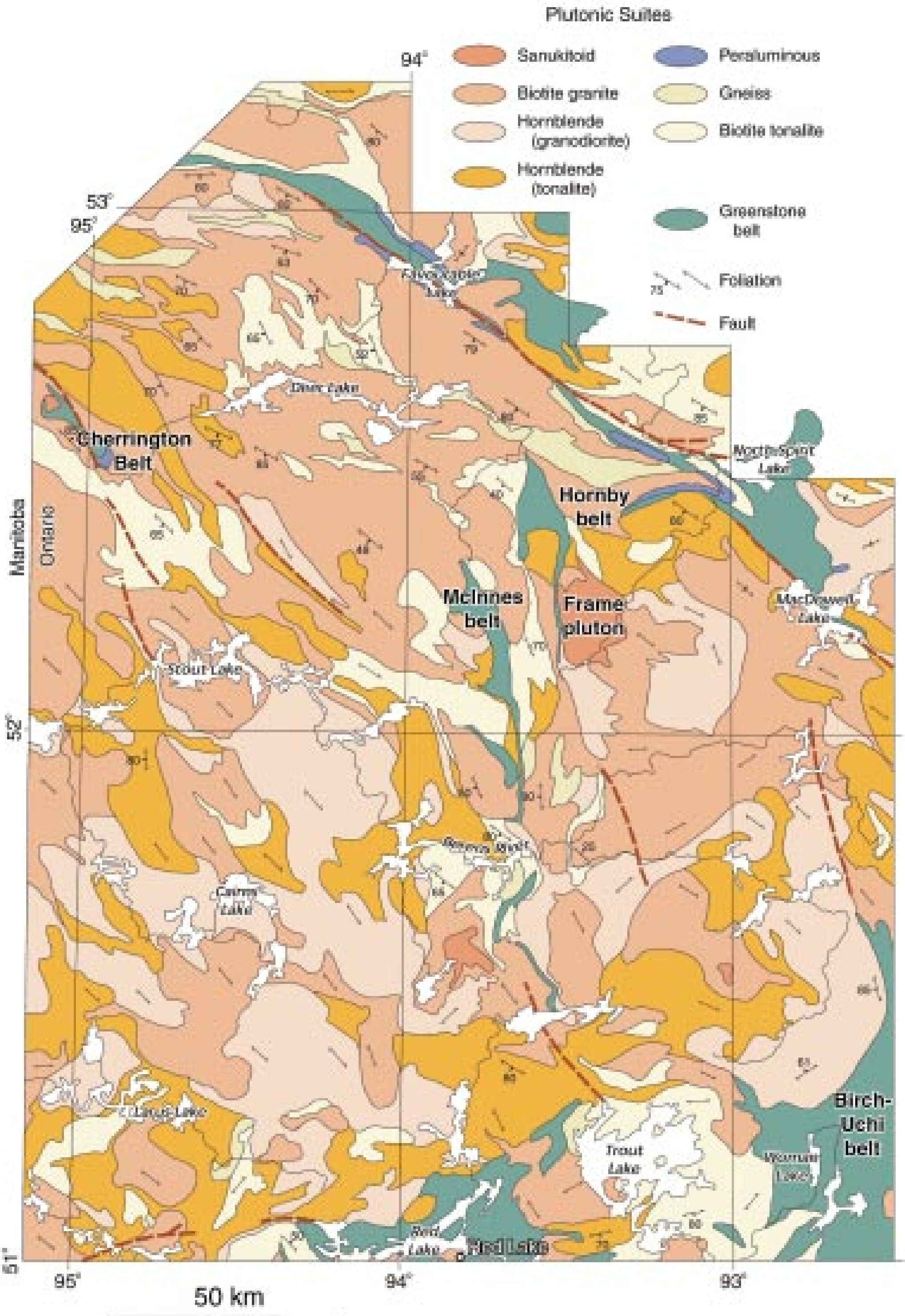

FIG. 2. Geology of the Berens River area.

of assemblages contained within the belts. Whereas assemblages from most greenstone belts in the Superior Province, such as the Abitibi belt (Jackson & Fyon 1991), have relatively narrow age-ranges from 2.75 to 2.7 Ga, those comprising Berens River greenstone belts developed episodically over as much as 300 m.y. For example, felsic pyroclastic rocks of the North Spirit greenstone belt are dated at 3023 ± 2 Ma to 2735 ± 10 Ma (Corfu & Wood 1986). In small belts such as McInnes and Hornby (Fig. 2), ages range from 2973^{+3}_{-2} Ma to 2901 ± 2 Ma (Corfu *et al.* 1998).

Plutonic rocks are named in the field by the proportions of quartz, plagioclase and K-feldspar according to Streckeisen (1976) combined with the predominant mafic mineral (*e.g.*, biotite or hornblende). Color, grain size, fabric and inclusion characteristics as well as composition are used to assign plutonic rocks to suites. In the Berens River area, six suites of felsic plutonic rocks are identified (Table 1) and are briefly described with reference to recent geochronology (Corfu & Stone 1998a, b). The geochemistry and petrogenesis of the plutonic suites were discussed by Stone (1998).

Leucocratic quartzofeldspathic rocks of the biotite tonalite suite occur in irregular to lobate and crescentic bodies at scattered localities in the Berens River area (Fig. 2). The biotite tonalite suite is complex and includes plutons emplaced episodically over nearly 300 m.y., although most biotite tonalite is relatively young, with ages in the range of 2736 to 2705 Ma.

The gneissic suite is comparatively rare in the Berens River area. It is represented by belts and irregular masses of heterogeneous layered rock compositionally variable from tonalite and granodiorite to diorite and amphibolite. Although undated, gneisses are probably similar in age to biotite tonalite, into which they grade compositionally.

Coarse white two-mica granodiorite to granite is the predominant rock of the peraluminous or S-type granite suite. This volumetrically minor suite is restricted to sedimentary sequences of the Favourable Lake – North Spirit Lake area (Fig. 2). Monazite from two-mica granite near North Spirit Lake is dated at 2697 ± 2 Ma.

The hornblende suite is divisible into an early member of tonalite to granodiorite composition and a later member of K-feldspar-megacrystic granodiorite to granite. These members are referred to as hornblende tonalite and hornblende granodiorite, respectively, and occur as large irregular to oval batholiths underlying nearly half of the central and southern Berens River area. U–Pb ages for the hornblende suite range from 2744 to 2715 Ma.

The biotite granite suite is represented by voluminous typically massive pink leucocratic granite that occurs in forms ranging from dikes and masses to oval plutons and batholiths. The largest bodies of biotite granite are situated in the northern Berens River area. Ages for biotite granite are scattered between 2736 and 2697 Ma.

The sanukitoid suite (Shirey & Hanson 1984, Stern *et al.* 1989) is characterized by rare oval stocks and plutons of monzodiorite, monzonite and granodiorite in the Berens River area. Small stocks of sanukitoid are composed of monzodiorite and monzonite, whereas large bodies of sanukitoid, such as at Frame Lake, are typically zoned, with a mesocratic monzodioritic rim and leucocratic granodioritic core, and have distinct high magnetic anomalies (Gupta 1991a, b). Intrusion of sanukitoid magmas from 2700 to 2686 Ma essentially marked the end of Berens River magmatism.

More than 80% of Berens River plutonic rocks were emplaced during a major magmatic event from 2744 to 2686 Ma. On the local scale of two or more abutted plutons, cross-cutting relations consistently show that biotite tonalite is cut by hornblende tonalite, which is in turn cut by hornblende granodiorite, followed by biotite granite and monzodiorite. On the scale of the Berens River area, geochronology indicates that the absolute ages of plutonic suites overlap somewhat. For example, ages of the hornblende tonalite suite range from 2744 to 2715 Ma, and ages of the biotite granite suite range from 2736 to 2697 Ma. Thus, even though on a local scale, biotite granite consistently postdates hornblende tonalite, regionally some biotite granite plutons are older than hornblende tonalite plutons. These data imply a cell-like arrangement to magmatic evolution of the Berens River area. Within each cell, major plutonic suites succeeded each other in a consistent sequence (biotite tonalite → hornblende tonalite → hornblende granodiorite → biotite granite → sanukitoid) as indicated by cross-cutting relations. The overall process of magma evolution, however, may have started later or proceeded faster in some cells than in others. In this way, the absolute ages of suites will vary from cell to cell. The important point, relevant to interpretation of hornblende barometry, is that the relative ages of plutonic suites is everywhere the same in the Berens River area.

Thermobarometry

Aluminum-in-hornblende barometry has evolved since the landmark paper of Hammarstrom & Zen (1986). They noted that in the presence of an appropriate buffer assemblage, the total Al content of hornblende increases linearly with pressure of crystallization. Subsequent field-based and experimental studies (*e.g.*, Hollister *et al.* 1987, Johnson & Rutherford 1989, Schmidt 1992) confirmed the dependence of Al in hornblende on pressure of crystallization and provided slightly modified versions of the original barometer. Schmidt (1992) attributed the Al^{tot} increase with pressure to a Tschermak exchange in which ^{VI}Al substitutes for Mg in the *M*2 site and ^{IV}Al substitutes for Si in the *T* site.

Application of the Al-in-hornblende barometer to natural systems has remained controversial, however, because factors such as temperature and oxygen fugac-

TABLE 1. CHARACTERISTICS OF PLUTONIC SUITES IN THE BERENS RIVER AREA, NORTHWESTERN ONTARIO

Plutonic Suite	Color	Grain Size	Fabric	% of area+	Inclusion type, composition	Mineral Assemblage (average mineral proportion) [no. of samples]
Biotite Tonalite Suite: biotite tonalite to granodiorite	white to grey	fine to coarse	foliated to gneissic; quartz and feldspar megacrystic	12	diorite, gabbro, amphibolite, supracrustal rocks, gneisses	Pl(53) + Qtz(26) + Bt(10) + Kfs(6) + Mgt(2) + Ttn(1) + Ep(1) + Ap(<1) + + Aln(<1) + Ilm(<1) + Zrn(<1) [65]
Gneissic Suite biotite-hornblende tonalite to granodiorite	dark grey to white	variable between layers	foliated; layered; folded	2	amphibolite? inclusions hard to recognize	Pl(47) + Qtz(23) + {Hbl + Bt}(15) + Kfs(11) + Mgt(1) + Ep(1) + Ttn(1) + Ap(<1) + Aln(<1) + Ilm(<1) + Zrn(<1) [12]
Peraluminous (S-type) Suite two-mica granodiorite to granite	white to pink	coarse to pegmatitic	massive; mylonitic	<1	sediments, migmatite, melanosome	Pl(34) + Kfs(31) + Qtz(29) + {Bt + Ms}(4) + Grt(<1) + Ap(<1) + Sil(<1) + Zrn(<1) + Crd(<1) + Mnz(<1) [11]
Hornblende Suite biotite-hornblende tonalite to granodiorite (grades to quartz diorite)	grey to white	coarse	foliated; granular; feldspar megacryst; mafic clots	21	diorite, quartz diorite, tonalite, amphibolite	Pl(49) + {Bt + Hbl}(20) + Qtz(19) + Kfs(7) + Mgt(2) + Ep(1) + Ttn(1) + + Ap(<1) + Aln(<1) + Ilm(<1) + + Zrn(<1) [75]
K-feldspar megacrystic, biotite-hornblende granodiorite to granite	pink to white to grey	coarse	weak alignment of megacrysts	3	diorite, quartz diorite, tonalite, amphibolite	Pl(41) + Qtz(24) + Kfs(19) + {Hbl + Bt}(11) + Mgt(2) + Ttn(1) + Ep(1) + Ap(<1) + Ilm(<1) + Aln(<1) + Zrn(<1) [58]
Biotite Granite Suite: biotite granodiorite to granite	pink to white	variable, usually coarse	massive to weak magmatic layering; inclusion-rich	39	tonalite, gneiss, rare amphibolite, volcanic rocks	Pl(39) + Qtz(27) + Kfs(25) + Bt(6) + Ttn(1) + Mgt(1) + Ep(<1) + Ap(<1) + Ilm(<1) + Aln(<1) + Zrn(<1) [80]
Sanukitoid Suite biotite–amphibole –pyroxene quartz diorite, tonalite, quartz monzodiorite, granodiorite, syenite, granite	grey to pink to red	mainly medium to coarse	massive to weak magmatic layering; inequigranular; mafic clots	1	hornblendite, gabbro, ultramafic rocks	Pl(44) + {Bt + Hbl +Cpx}(28) + Kfs(15) + Qtz(9) + Mgt(2) + Ttn(1) + Ap(<1) + Ep(<1) + Ilm(<1) + Py(<1) + Zrn(<1) [8 quartz monzodiorite]

Plutonic rock names after Streckeisen (1976). Symbols for rock-forming minerals: Kretz (1983), Kfs: K-feldspar, Mgt: magnetite.
+ Two percent of the Berens River area is made up of greenstone belts. Major external greenstone belts are not included.

ity can affect the Al content of hornblende. The overall pressure-dependence of Al in hornblende was assessed by Ague (1997) who evaluated P–T conditions of emplacement of Mesozoic Californian batholiths using the pressure-sensitive reaction

$$\text{tremolite} + \text{phlogopite} + 2\ \text{anorthite} + 2\ \text{albite} = 2\ \text{pargasite} + 6\ \text{quartz} + \text{K-feldspar} \quad (1)$$

coupled with the thermometers of Holland & Blundy (1994). Calculations were performed using the software of Berman (1991) and thermodynamic data and non-ideal amphibole activity model of Mäder & Berman (1992) and Mäder *et al.* (1994). These calculations provided a thermodynamics-based estimate of pressure independent of the constraints and assumptions inherent in Al-in-hornblende barometry. Ague (1997) noted that although there were local discrepancies of up to 1.5 kbar, pressures generated according to equation (1) correspond well with Al-in-hornblende estimates of pressure using calibrations of Johnson & Rutherford (1989) and Schmidt (1992) over a range of 1 to 9 kbar.

Al-in-hornblende barometry has been widely used to estimate emplacement pressure of felsic plutonic rocks (Vyhnal *et al.* 1991, Ghent *et al.* 1991, Anderson & Smith 1995, Ague & Brandon 1996). As implied from the previous discussion, however, application of the barometer requires attention to details discussed below.

Required Mineral Assemblage

All calibration studies have emphasized the need for the assemblage hornblende + biotite + plagioclase + K-feldspar + quartz + titanite + Fe–Ti oxides for application of the Al-in-hornblende barometer. As discussed by Schmidt (1992), hornblende would be expected to equilibrate with this assemblage in addition to melt and a fluid phase at temperatures in the vicinity of the solidus, and the Al content of hornblende would be constrained by ambient pressure. Following solidification and cooling, the equilibration of hornblende with the above minerals would slow and eventually cease, and hence hornblende compositions would potentially reflect the pressure (depth) at which the magma solidified.

For the Berens River samples, combined staining of rock slabs with sodium cobaltinitrite (to identify K-feldspar), petrography, and rapid examination of electron microprobe-derived energy-dispersion spectra were used to ensure that the full assemblage of minerals is present. Certain mafic samples of the hornblende tonalite and sanukitoid suites, which are of quartz diorite to quartz monzodiorite composition, were initially considered to be problematic in that these samples contain low amounts of quartz and K-feldspar. Sanukitoid samples can also contain clinopyroxene. Comparisons suggest that the Al content of hornblende does not vary significantly between quartz dioritic and tonalitic or granodioritic samples of the hornblende suite or between clinopyroxene-bearing and clinopyroxene-absent samples of the same intrusion. Evidently, a few percent of minerals such as quartz and K-feldspar are sufficient to establish a fully buffered assemblage. In the case of clinopyroxene, this mineral is rimmed by hornblende where the two minerals occur in the same sample and, hence, clinopyroxene was potentially isolated from other minerals as the melt approached the solidus.

Oxygen Fugacity

Anderson & Smith (1995) emphasized that amphiboles that crystallized under low-$f(O_2)$ conditions will yield artificially high pressures by the Al-in-hornblende method. The discrepancy arises because amphiboles from the low-$f(O_2)$ magmas have low Mg and a low ratio of Fe^{3+} to Fe^{2+} that promotes increased ^{VI}Al occupancy of the *M*2 site and causes an overestimation of pressure by the Al-in-hornblende barometer. Recognition of such conditions in complex batholithic rocks is difficult. Although ilmenite can be the dominant oxide in low-$f(O_2)$ magmas, the Berens River plutonic rocks overwhelmingly contain magnetite, with sporadic ilmenite typically rimmed by magnetite or titanite. Amphiboles from the Berens River area nonetheless have variable Mg and Fe content, possibly reflecting fundamental differences in the state of oxidation of their source. Anderson & Smith (1995) and Schmidt (1992) established limits in terms of Mg and Fe content of amphiboles that are suitable for Al-in-hornblende barometry; these parameters are adopted for the present study. Amphiboles are rejected for Al-in-hornblende barometry unless they have $0.4 < Fe^{tot}/(Fe^{tot} + Mg) < 0.65$ and $0.2 < Fe^{3+}/(Fe^{3+} + Fe^{2+})$, where Mg and Fe are calculated by the 13eCNK method (discussed below).

Temperature

The Al content of hornblende is not only a function of pressure but also temperature, mainly through an edenitic exchange involving the substitution of Al for Si in the *T* site coupled with Na and K substitution for vacancies in the *A* site (Blundy & Holland 1990). Many Al-in-hornblende studies carry the implied assumption that temperature is essentially invariant. This assumption follows because hornblende equilibration is considered to occur in the vicinity of the solidus, which is relatively invariant in the range of 685°C to 650°C for H_2O-saturated magmas of tonalite to granodiorite composition in the 2–6 kbar range (Piwinskii 1975, Wyllie 1977, Hollister *et al.* 1987). The study of Anderson & Smith (1995) and the present work show, however, that solidus temperatures are typically above 700°C and justify a temperature correction of the Al-in-hornblende pressures.

Anderson & Smith (1995) developed a temperature-corrected Al-in-hornblende barometer calibrated by experiments of Schmidt (1992) at approximately 675°C and those of Johnson & Rutherford (1989) at approximately 760°C. Although Ague & Brandon (1996) criticized the "corrections" to Al-in-hornblende pressures, the criticism focused mainly on use of the earlier thermometer of Blundy & Holland (1990). Ague & Brandon (1996) applied both the Blundy & Holland (1990) and Holland & Blundy (1994) thermometers to plagioclase and hornblende coexisiting with the full assemblage required for the Al-in-hornblende barometer in the tonalite phase-equilibrium experiments of Johnson & Rutherford (1989) and Schmidt (1993). They found that the Holland & Blundy (1994) thermometer performed better than the earlier thermometer at reproducing the known temperatures of the experimental runs from the phase compositions. For this reason, the thermometer of Holland & Blundy (1994) for quartz-bearing assemblages is used with the temperature-dependent formulation of the Al-in-hornblende barometer (Anderson & Smith 1995) in the present study.

Method of Amphibole Recalculation

The structural formulae of amphiboles can be calculated in many ways; in their applications of the Al-in-hornblende barometer, Schmidt (1992) and Anderson & Smith (1995) have used the 13eCNK method. With this method, the number of cations is calculated on the basis of 46 negative charges (23 atoms of oxygen) with the added constraint that the sum of Si + Al + Ti + Cr + Fe + Mn + Mg is 13. The recalculation procedure is complicated by the fact that the electron-microprobe approach cannot distinguish the valence state of iron (Fe_2O_3 and FeO are expressed as FeO^{tot}), so that these components must be estimated by other methods. Schmidt (1992) assumed a fixed value of the ratio of $Fe^{3+}/(Fe^{3+} + Fe^{2+})$, 0.3, whereas a charge-balance method was used by Anderson & Smith (1995). The latter method typically converts sufficient Fe^{2+} to Fe^{3+} so that the total cation (+) charge is 46 and balances the 46 anion (–) charge.

In the present study, amphiboles are recalculated by the method of Leake *et al.* (1997), on the basis of 46 negative charges assuming 22 atoms of oxygen and a combined total of 2 OH, F and Cl anions [22O + 2(OH + F + Cl)]. Fe^{3+} and Fe^{2+} are determined as the average of the maximum and minimum estimates of ferric iron (Fe^{3+}). Fe^{3+}, Fe^{2+} and Mg are also calculated by the 13eCNK method. This is necessary so that Fe:Mg proportions for each composition can be compared with the range of Fe:Mg ratios that Anderson & Smith (1995) calculated by the 13eCNK method and set as acceptable limits for Al-in-hornblende barometry (see previous discussion concerning Oxygen Fugacity). It is noteworthy that the proportions of OH, F and Cl anions do not affect Al-in-hornblende barometry because these anions substitute for one atom of oxygen and hence, do not alter the number of cations.

As pointed out by Cosca *et al.* (1991), the method of recalculation can affect Al-in-hornblende results, although comparisons show that the effect is small. For example, where recalculated by the 13eCNK method, the representative Berens River amphiboles of Table 2 yield temperatures (T_A of Holland & Blundy 1994) that are a few degrees higher than temperatures calculated from amphiboles reduced by the method of Leake *et al.* (1997). Pressures (P_S) determined by the equation of Schmidt (1992) are unchanged (the difference is less than 0.1 kbar); pressures (P_{AS}) inferred by the equation of Anderson & Smith (1995), however, are typically lower by 0.1 kbar as a result of incorporation of the higher T_A. Since T_A is highly sensitive to ^{IV}Al, any recalculation that alters Al or Si in the *T* site will have an effect on T_A, as well as any pressure determination that incorporates T_A.

Sample Collection, Analysis and P–T Determinations

A total of 170 samples of plutonic rocks were selected for the Al-in-hornblende study of the Berens River area. Hornblende is widespread in tonalitic and granitic phases of the hornblende suite, and these constitute the bulk of the samples. Biotite is the main ferromagnesian mineral in the tonalite and granite suites; these suites were sampled in a few localities only, where amphibole is present. Although rocks of the sanukitoid suite contain abundant hornblende, the small size and rarity of sanukitoid plutons in the Berens River area prevented the collection of a large number of samples from this suite. Only the peraluminous suite is completely devoid of amphibole.

Amphiboles and feldspars were analyzed using the JEOL electron microprobe at the University of Western Ontario and the CAMECA microprobe of the Ontario Geoscience Laboratories. Complete results of the analyses are given in Stone (1998). Amphibole compositions representative of the various plutonic suites are listed in Table 2. All amphiboles are classified as calcic amphiboles, and the majority span a narrow compositional range between magnesiohornblende and edenite.

The ratios $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ and $Fe^{tot}/(Fe^{tot} + Mg)$ were calculated for each amphibole by the 13eCNK method; examples are listed in Table 2. The average mole fraction of albite in plagioclase (X_{ab}^{pl}) for each suite is summarized in Table 3.

Pressures and temperatures are calculated in a spreadsheet by a stepwise iterative process. The barometer of Schmidt (1992),

$$P_S\ (\pm 0.6\ \text{kbar}) = -3.01 + 4.76\ Al^{tot} \tag{2}$$

where P_S is in kbar and Al^{tot} is the total Al content of hornblende in atoms per formula unit, is used to obtain an initial estimate of pressure independent of temperature. P_S of equation (2) is substituted for the value of P in the edenite–tremolite thermometer of Holland & Blundy (1994),

$$T_A\ (\pm 40°C) = \left\{ \frac{-76.95 + 0.79P + Y_{ab} + 39.4X^A_{Na} + 22.4X^A_K + (41.5 - 2.89P)\bullet X^{M2}_{Al}}{-0.0650 - R\bullet \ln[(27\bullet X^A_{\square}\bullet X^T_{Si}\bullet X_{ab}^{pl})/(256\bullet X^A_{Na}\bullet X^T_{Al})]} \right\} - 273 \tag{3}$$

where T_A is expressed in °C, $R = 0.0083144$ kJ $K^{-1}mol^{-1}$, $Y_{ab} = 0$ for $X_{ab}^{pl} > 0.5$ or else $Y_{ab} = 12.0(1 - X_{ab}^{pl})^2 - 3.0$ kJ, and various *X* terms are defined in Holland & Blundy (1994). T_A is substituted into the temperature-dependent barometer of Anderson & Smith (1995),

$$P_{AS}\ (\pm 0.6\ \text{kbar}) = 4.76Al^{tot} - 3.01 - \{(T_A - 675)/85\}\bullet\{0.530Al^{tot} + 0.005294(T_A - 675)\} \tag{4}$$

TABLE 2. REPRESENTATIVE AMPHIBOLE COMPOSITIONS, BERENS RIVER AREA, ONTARIO

Sample	90DS115	92DS080	525117-5	92DS057	559104-1	92DS050	93DS038	93DS017	92DS045	559107-4
No.	9	4	4	6	4	6	8	6	6	2
Suite	biotite tonalite	biotite tonalite	Hbl tonalite	Hbl tonalite	Hbl grd	Hbl grd	biotite granite	biotite granite	sanukitoid	sanukitoid
Area	W Knox	Trout	Pikangikum	Madden	S Murfitt	Gar	N Apps	SE Olive	N Frame	N Kirkness
Easting	398800	471200	422600	511500	459300	492000	407600	415000	471300	443700
Northing	5669700	5677200	5732800	5750800	5723300	5773000	5816500	5680600	5792300	5720500
SiO_2 wt.%	43.58	44.05	44.33	44.25	44.94	45.59	44.31	45.11	43.33	46.11
TiO_2	1.03	1.27	1.25	1.09	1.50	0.69	1.25	1.06	0.96	0.96
Al_2O_3	9.45	9.20	9.31	9.00	8.66	7.82	8.74	7.62	9.76	7.37
Cr_2O_3	0.01	0.04	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.05
FeO^{tot}	18.64	17.89	17.94	17.89	15.83	16.97	17.41	18.31	19.04	17.34
MnO	0.54	0.41	0.57	0.53	0.72	0.49	0.47	0.76	0.44	0.57
MgO	9.85	10.50	10.46	10.61	11.42	11.74	11.03	10.62	9.88	11.36
CaO	11.50	11.63	11.92	11.78	11.67	11.80	11.77	11.69	11.83	11.68
Na_2O	1.27	1.21	1.26	1.15	1.38	1.11	1.14	1.34	1.06	1.50
K_2O	1.09	1.02	1.17	0.99	1.09	0.78	1.01	0.97	1.12	0.91
F	–	–	–	–	0.28	–	–	–	–	0.69
Cl	–	–	–	–	0.03	–	–	–	–	0.03
Total	96.96	97.22	98.21	97.29	97.52	97.00	97.15	97.48	97.45	98.57
O≡F	–	–	–	–	0.12	–	–	–	–	0.29
O≡Cl	–	–	–	–	0.01	–	–	–	–	0.01
O≡F≡Cl	–	–	–	–	0.12	–	–	–	–	0.30
Fe_2O_3 calc.	3.78	3.67	3.10	4.07	1.75	4.53	4.09	3.23	5.01	2.18
FeO calc.	15.23	14.59	15.15	14.22	14.25	12.89	13.73	15.41	14.53	15.38
H_2O calc.	1.98	1.99	2.01	2.00	1.86	2.01	2.00	1.99	1.99	1.67
Formula, average of minimum and maximum Fe^{3+} (Leake *et al.* 1997)										
Si *apfu*	6.6018	6.6238	6.6214	6.6444	6.7332	6.8049	6.6497	6.7928	6.5257	6.8846
^{IV}Al	1.3982	1.3762	1.3786	1.3556	1.2668	1.1951	1.3503	1.2072	1.4743	1.1154
Sum *T*	8	8	8	8	8	8	8	8	8	8
^{VI}Al	0.2894	0.2547	0.2603	0.2378	0.2624	0.1802	0.1951	0.1452	0.2587	0.1815
Ti	0.1174	0.1435	0.1404	0.1227	0.1690	0.0775	0.1411	0.1196	0.1092	0.1078
Fe^{3+}	0.4313	0.4154	0.3483	0.4600	0.1978	0.5093	0.4617	0.3657	0.5675	0.2452
Cr	0.0014	0.0047	0.0000	0.0011	0.0000	0.0017	0.0005	0.0011	0.0018	0.0059
Mg	2.2245	2.3549	2.3292	2.3741	2.5508	2.6135	2.4683	2.3844	2.2178	2.5286
Fe^{2+}	1.9295	1.8268	1.8927	1.7861	1.7851	1.6086	1.7235	1.9404	1.8306	1.9203
Mn	0.0065	0.0000	0.0291	0.0182	0.0350	0.0092	0.0098	0.0436	0.0143	0.0107
Sum *C*	5	5	5	5	5	5	5	5	5	5
Mg	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fe^{2+}	0.0000	0.0074	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mn	0.0626	0.0516	0.0431	0.0492	0.0564	0.0530	0.0503	0.0531	0.0423	0.0614
Ca	1.8659	1.8735	1.9076	1.8946	1.8733	1.8863	1.8921	1.8862	1.9092	1.8685
Na	0.0715	0.0675	0.0494	0.0563	0.0703	0.0607	0.0576	0.0608	0.0485	0.0702
Sum *B*	2	2	2	2	2	2	2	2	2	2
Na	0.3028	0.2856	0.3155	0.2789	0.3306	0.2608	0.2742	0.3306	0.2620	0.3641
K	0.2100	0.1963	0.2229	0.1888	0.2083	0.1487	0.1942	0.1861	0.2144	0.1733
Sum *A*	0.5128	0.4819	0.5385	0.4677	0.5389	0.4095	0.4684	0.5167	0.4764	0.5374
F	–	–	–	–	0.1332	–	–	–	–	0.3276
Cl	–	–	–	–	0.0077	–	–	–	–	0.0076
OH	2.0000	2.0000	2.0000	2.0000	1.8591	2.0000	2.0000	2.0000	2.0000	1.6648
Sum OH	2	2	2	2	2	2	2	2	2	2
Σcations	15.5128	15.4819	15.5385	15.4677	15.5389	15.4095	15.4684	15.5167	15.4764	15.5374
Fe ratios by 13eCNK method										
Fe^{3+}/Fe^{tot}	0.28	0.28	0.22	0.28	0.20	0.33	0.29	0.24	0.30	0.21
$Fe^{tot}/(Fe^{tot} + Mg)$	0.51	0.49	0.49	0.48	0.44	0.44	0.47	0.49	0.52	0.46
X_{ab}^{pl}	0.74	0.74	0.74	0.74	0.73	0.73	0.81	0.81	0.52	0.52
Pressure and Temperature parameters										
P_S (kbar)	5.0	4.8	4.8	4.6	4.3	3.5	4.3	3.4	5.2	3.2
T_A (°C)	722	731	730	734	716	737	732	736	810	797
P_{AS} (kbar)	4.4	4.0	4.0	3.8	3.8	2.8	3.6	2.7	2.6	1.3

References: P_S: Schmidt (1992); T_A: Holland & Blundy (1994); P_{AS}: Anderson & Smith (1995) using T_A. No.: number of grains analyzed. Symbols: grd: granodiorite, Hbl: hornblende.

TABLE 3. AGES, PLAGIOCLASE COMPOSITIONS AND AVERAGE T AND P OF BERENS RIVER PLUTONIC SUITES

Suite	Biotite Tonalite	Hornblende Tonalite	Hornblende Granodiorite	Biotite Granite	Sanukitoid Suite
Age (Ma)* Median in bold	2860, 2838, 2806, **2838**; 2736, 2734, 2726, 2727, 2708, 2705 **2727**	2744, 2741, 2736, 2722, 2722, 2715, **2729**	2724, 2723, 2722, 2719, 2717, 2716, **2721**	2736, 2712, 2703, 2699, 2697, 2697 **2701**	2700, 2700, 2696, 2686, **2698**
X_{ab}^{pl}	0.74 (7)	0.74 (5)	0.73 (6)	0.81 (7)	0.52 (3) 0.83 (3)
Ps (kbar)	5.5 (7)	4.8 (83)	4.3 (61)	4.1 (13)	3.9 (6)
T_A (°C)	721 (5)	731 (83)	736 (61)	716 (13)	773 (6)
P_{AS} (kbar)	4.4 (3)	4.0 (70)	3.5 (57)	3.4 (10)	2.3 (3)

* Errors are <20 Ma. Sources are Corfu & Wood (1986), Noble (1989), Corfu & Ayres (1984), Corfu & Stone (1998) and Beakhouse (1998). The number of samples is shown in brackets. P_S: Schmidt (1992); T_A: Holland & Blundy (1994); P_{AS}: Anderson & Smith (1995) using T_A. In the sanukitoid suite, X_{ab}^{pl} is 0.52 in quartz diorite, and 0.83 in quartz monzonite.

to obtain a revised estimate of pressure. P_{AS} of equation 4 is substituted back into equation 3 resulting in a revised T_A, which is then used in equation 4 for an updated estimate of P_{AS}. Normally, after repeating the above substitutions three or four times, the new value of T_A does not change by more than 1°C and the new value of P_{AS} does not change by more than 0.1 kbar from the previous values of T_A and P_{AS}, respectively, and the iteration is terminated. Finally, P_{AS} is judged acceptable if $Fe^{3+}/(Fe^{3+} + Fe^{2+}) > 0.2$ and if $0.4 < Fe^{tot}/(Fe^{tot} + Mg) < 0.65$.

Results

Temperatures for the tonalite, hornblende and granite suites fall in the range 650 to 760°C, with the main hornblende-bearing suites showing average temperatures of 716 to 736°C (Table 3). Mafic phases of the sanukitoid suite yield a higher average temperature, 773°C. Temperatures for the tonalitic and granodioritic members of the hornblende suite are sufficiently abundant and widely distributed for display by contoured maps (Figs. 3a, b). Temperatures of hornblende tonalite (Fig. 3a) are relatively low (<700°C) in the extreme northern Berens River area, with intermediate and high temperatures (700 to 750°C) occurring broadly as a series of north- to northwest-trending temperature "ridges" and "valleys" in the central and southern parts of the area.

Although the average temperature of hornblende granodiorite is nearly the same as that of hornblende tonalite (Table 3), the spatial temperature-distribution patterns for these suites are distinct from each other (*cf.* Figs. 3a, b). Hornblende granodiorite shows low temperatures (<700°C) in the northern Berens River area, as indicated by two samples (Fig. 3b). Hornblende granodiorite isotherms in the central and southern Berens River area, however, lack the strong northwesterly fabric characteristic of hornblende tonalite. Instead, samples of hornblende granodiorite show intermediate temperatures (700 to 725°C) concentrated centrally in the Red Lake – McInnes Lake area, with the highest temperatures (>750°C) distributed widely in somewhat irregular domains.

For any given sample or suite of samples (Tables 2, 3), P_{AS} is less by an amount on the order of 1.0 kbar than P_S. Lowering of P_{AS} relative to P_S occurs because of the incorporation of the temperature correction in equation 4. The extent of the temperature correction increases with anorthite content of plagioclase and hence, is greatest for mafic rocks of the sanukitoid suite (X_{ab}^{pl} = 0.52) and is least for the granite suite (X_{ab}^{pl} = 0.81). Note that approximately 25% of the pressures determined by equation 4 are rejected typically because $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ is less than 0.2 or $Fe^{tot}/(Fe^{tot} + Mg)$ is less than 0.4. Averages of the accepted pressures decrease with relative age of the suites, such as from left to right in Table 3.

The pressure-distribution map for hornblende tonalite (Fig. 3c) is distinguished by sporadic high-P values (>4.5 kbar) at the southern margin of the Berens River area. Low-P domains are distributed somewhat irregularly in the center of the map area and immediately north of the Red Lake greenstone belt. Temperature-corrected pressures are lacking in the northern Berens River area.

As with the temperature results, the pressure distribution is quite different for hornblende granodiorite (Fig. 3d) than for hornblende tonalite (Fig. 3c). The most significant difference occurs in the southern Berens River area, where pressure determinations are typically about 3 kbar for hornblende granodiorite *versus* more than 4 kbar for hornblende tonalite. The highest pressures for hornblende granodiorite (3.5 to 4.0 kbar) define a broad, curved arch extending northwesterly through the central Berens River area.

Discussion

Temperature

Average amphibole + plagioclase temperatures for the plutonic suites (Table 3) are typically 50°C above wet solidus temperatures and do not appear to change systematically with age of the suites. The highest average temperature of 773°C is associated with the sanukitoid suite, which is characterized by a higher proportion of mafic minerals than other suites (Table 1).

The patterns in the temperature-distribution maps of the hornblende suite are enigmatic. In searching for an explanation, several causes can be eliminated. For example, isotherms of Figures 3a and 3b show no great correlation with individual plutons or groups of plutons

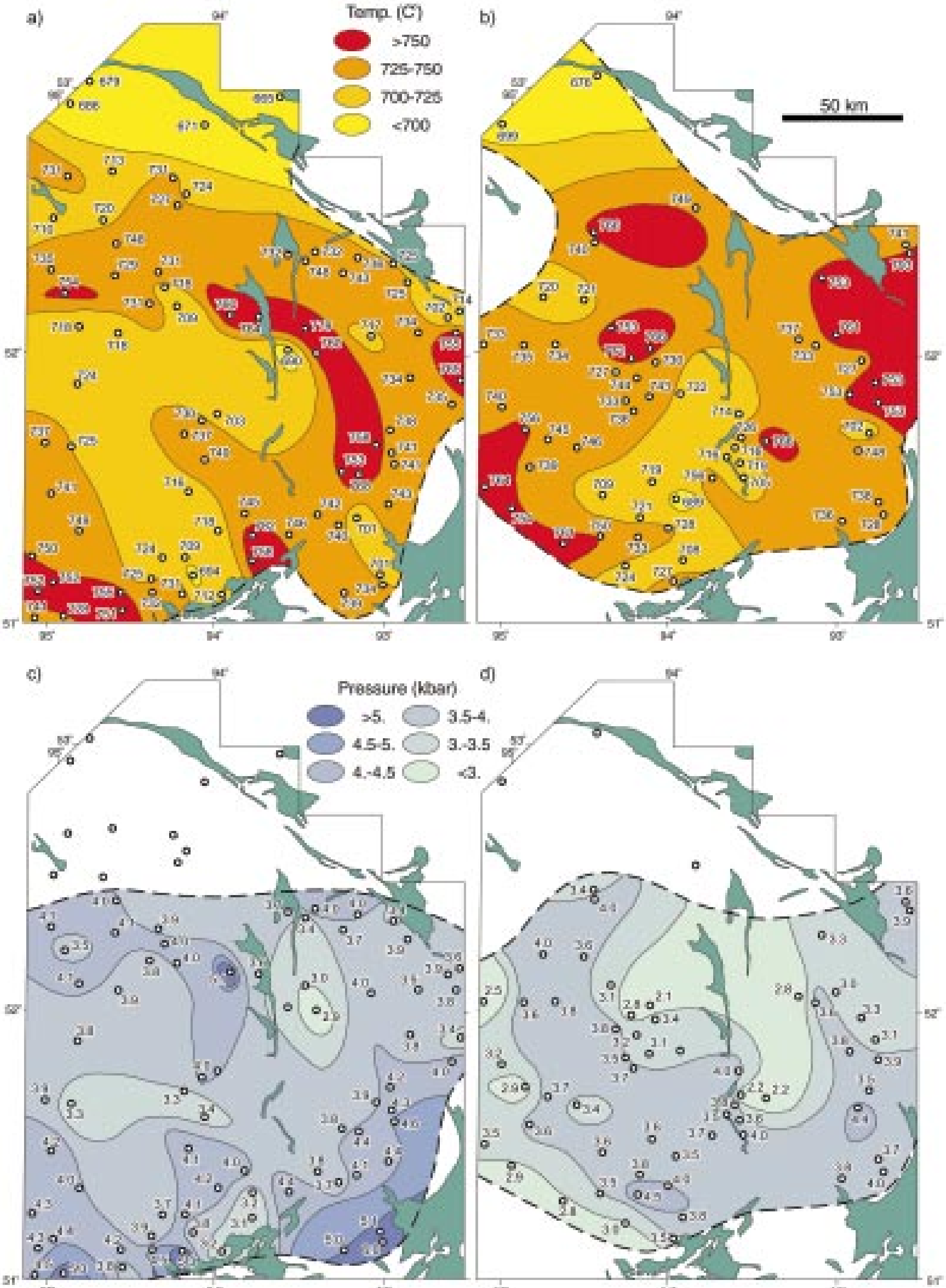

FIG. 3. Contoured maps of the Berens River area for (a) temperature of hornblende tonalite, (b) temperature of hornblende granodiorite, (c) pressure of hornblende tonalite, and (d) pressure of hornblende granodiorite. Sample sites are shown by dots. Outlines of greenstone belts are indicated for reference.

(Fig. 2), indicating that thermal anomalies are not the result of temperatures that varied from one igneous body to the next. Furthermore, high- and low-temperature domains of Figures 3a and 3b do not correspond with high- and low-pressure domains of Figures 3c and 3d. This finding rules out a mechanism in which high-temperature rocks were uplifted from deeper levels in a thermally stratified crust as an explanation for patterns in the temperature-distribution maps.

Isotherms of hornblende tonalite (Fig. 3a) are broadly parallel to the regional structural trends defined by foliations, lithological contacts and faults (Fig. 2). Low-temperature (<725°C) domains are associated with plutons adjacent to the Favourable Lake – North Spirit Lake greenstone belt and the Bear Head fault, and show a weak correlation with northwesterly trending mylonite zones in the central Berens River area. Possibly the faults were active during emplacement of hornblende tonalite and conducted groundwater from strata overlying plutons to locally increase the H_2O saturation and thereby lower the crystallization temperature of magmas. Alternatively, hydrothermal alteration associated with late faulting could have altered plagioclase and amphibole compositions in the subsolidus, leading to low-temperature anomalies along the fault zones. Evidence comparable with the latter alternative was obtained by Corfu & Stone (1998a, b). They noted pronounced recrystallization of titanite and relatively young titanite ages on both sides of the Bear Head fault, and attributed these features to protracted hydrothermal activity associated with the fault.

The temperature-distribution map of hornblende granodiorite (Fig. 3b) shows an irregular and patchy distribution of isotherms. Although one sample of hornblende granodiorite adjacent to the Bear Head fault west of Favourable Lake has yielded the lowest amphibole + plagioclase temperature, the overall temperature pattern of hornblende granodiorite is not well correlated with structural features. This poor correlation may be an indication that structurally controlled movement of groundwater or hydrothermal activity was maximized or spread over broader and more detectable areas during emplacement of hornblende tonalite than with the hornblende granodiorite. Alternatively, the distribution of hornblende granodiorite temperatures may be controlled by unknown factors, such as local variations in the degree of fractionation of the magmas.

Pressure

The Berens River area has traditionally been viewed not only as having a high proportion of plutonic rocks, but also a higher grade of regional metamorphism than most other subprovinces, either due to thermal effects (Wilson 1971) or deep erosion (Goodwin 1977, Ayres 1978). These interpretations were based on the qualitative observation that greenstone and sedimentary belts are rare, thin and commonly gneissic in the Berens River area. The above authors concluded that supracrustal sequences may once have covered the Berens River area, but they have been removed through assimilation by felsic intrusions and erosion. In this way, the Berens River area was considered to be a deeply eroded plutonic complex.

Results of the present survey permit quantitative spatial analysis of pressure, although comparison with other plutonic areas is limited by lack of data. Temperature-corrected pressures, which are typically in the range of 3 to 5 kbar for most suites of Berens River plutonic rocks, are not much different from metamorphic pressures in non-granulite parts of sedimentary subprovinces (Perkins & Chipera 1985, Percival 1989, Pan *et al.* 1994). Comparison of pressure among subprovinces is complicated by the fact that plutonism in the Berens River area preceded peak metamorphism in sedimentary subprovinces. Pressures of 3 to 5 kbar were attained from 2.73 to 2.70 Ga in Berens River batholiths, whereas peak metamorphism did not occur until 2.69 Ga in the English River subprovince (Corfu *et al.* 1995). Uplift occurred earlier in the Berens River area than in the English River subprovince. As an end result, however, the Berens River area is not much more deeply eroded than adjacent subprovinces. Plutonic and supracrustal rocks of the Berens River area lack pyroxene-bearing mineral assemblages and pressures in excess of 7 kbar, and were not uplifted to the extent of the Pikwitonei and Kapuskasing granulites (Fig. 1; Mezger *et al.* 1990, Mäder *et al.* 1994).

The trend of overall decreasing pressure with time, such as from left to right in Table 3, indicates uplift during emplacement of the plutonic suites. The biotite tonalite suite requires special consideration because the number of pressure determinations is small (three), and there appear to be at least two distinct generations of biotite tonalite in the Berens River area, with median ages of 2838 and 2727 Ma (Table 3). Of the three determinations, only sample 92DS080 (P_{AS} = 4.0 kbar; Table 2) comes from a biotite tonalite intrusion of known age, the 2838 Ma phase of the Trout Lake batholith. The other two determinations, 4.4 and 4.6 kbar, are from undated biotite tonalite bodies and hence, may be members of either the young or the old groups or even an as-yet-undated group of tonalite intrusions. It is noteworthy, however, that P_{AS} for the biotite tonalite suite is typically higher than P_{AS} for other suites, and potentially indicates little cumulative uplift from 2838 to 2727 Ma.

Intrusion of the hornblende suite beginning at 2744 Ma marked the onset of extensive magmatism and uplift in the Berens River area. The average P_{AS} (Table 3) decreased from 4.0 kbar for hornblende tonalite to 3.5 kbar for hornblende granodiorite. It must be emphasized, however, that the extent of uplift is regionally variable. In comparison, the most striking difference between the pressure maps for hornblende tonalite and hornblende granodiorite (Figs. 3c, d) is the major change in pressure at the southern margin of the Berens River area. Whereas the south records pressures in excess of 4.0 and locally 5.0 kbar for hornblende tonalite, this area is characterized by pressures of about 3.0 kbar for hornblende granodiorite. In other words, the south was warped upward relative to the north.

The central Berens River area lacks the major change in pressure observed at the southern margin. Part of the central Berens River area corresponding to the broad northwest-trending domain of intermediate (3.5 to 4 kbar) pressure in Figure 3d has remained at constant depth or locally moved down between the time of emplacement of hornblende tonalite and that of hornblende granodiorite. At a smaller scale, an area immediately north of the Red Lake greenstone belt at the southern margin of the area is characterized by three samples defining an anomaly of relatively low pressure (3.0 to 3.5 kbar) within an otherwise high-pressure zone during the emplacement of the hornblende tonalite (Fig. 3c). The anomaly associated with this area has diminished by the time the hornblende granodiorite was emplaced (Fig. 3d), indicating that the small area north of the Red Lake greenstone belt remained at constant depth or moved down as the remainder of the south margin was uplifted.

Although pressure data for the biotite granite and sanukitoid suites are sparse, the data support the trend of regional uplift through time. The average P_{AS} is 3.4 kbar for the biotite granite suite and decreases to 2.3 kbar for the sanukitoid suite. Assuming an average density of the upper crust of 2.7×10^3 kg/m^3, approximately 6.4 km of uplift is recorded between emplacement of the hornblende tonalite and the sanukitoid suites.

Conclusions

Several generalized conclusions can be made from the P–T study of the Berens River area.

1. Felsic plutonic rocks of the Berens River area in northwestern Ontario can be subdivided into five major groups, each of which contains hornblende and plagioclase suitable for application hornblende + plagioclase thermometers and Al-in-hornblende barometers. Crosscutting relations show consistent age-relations between groups of felsic plutonic rocks. The biotite tonalite suite is cut by hornblende tonalite of the hornblende suite, followed by hornblende granodiorite of the hornblende suite, then the biotite granite suite, and finally, the sanukitoid suite.

2. Hornblende + plagioclase thermometers show average temperatures of 716 to 773°C, which are typically 50°C higher than the wet solidus for the major plutonic suites. Temperature maps show a possible association of low temperatures with faults for hornblende tonalite. For the hornblende granodiorite, however, temperatures cannot be readily correlated with regional structure.

3. Average, temperature-corrected Al-in-hornblende pressures decrease from 4.4 kbar for the biotite tonalite suite to 2.3 kbar for the sanukitoid suite and indicate more than 6 km of uplift during magmatism. Uplift was greatest at the southern margin of the Berens River area. Local areas of presumably short-lived negative uplift are identified.

4. The Al-in-hornblende pressures suggest that plutonic suites of the Berens River area are not much more deeply eroded than rocks from the nearby volcano-plutonic and sedimentary subprovinces for which data are available.

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