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The Chief Lake complex revisited, and the problem of correlation across the Grenville Front south of Sudbury, Ontario

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Abstract

South of Sudbury, the boundary between the Southern and Grenville provinces, the Grenville Front, is placed along the faulted southeastern edge the ca. 1.46 Ga Chief Lake complex (CLC). A southeast-dipping, thrust-sense mylonite zone lies in the immediate hanging wall of the Grenville Front boundary fault (GFBF), separating the CLC in the Southern Province from metasedimentary, granitoid, anorthositic and amphibolitic gneiss in the Grenville Province to the southeast. The GFBF also coincides with an abrupt break in the continuity of southeast-trending diabase dykes of the 1.24 Ga Sudbury swarm. The northern CLC is a composite intrusion whose units include, and are separated by, large rafts of the early Paleoproterozoic Huronian Supergroup in which relict stratigraphy outlines engulfed folds. Mafic rocks along the northwest contact of the CLC, previously interpreted as metasomatized Nipissing gabbro (2.22 Ga), are in fact a phase of the Chief Lake intrusive suite, commingled with granite. The northwest contact coincides in part with a steep, southeast-side-down, pre-intrusion fault that was later reactivated with reverse sense of displacement. The Chief Lake granitoid rocks become increasingly foliated southeast toward the Grenville Front, but two features suggest that at least some of the deformation of the Chief Lake intrusive suite was syn-emplacement: (1) the granitoid component of commingled rocks may be strongly foliated in places where the mafic component is undeformed, and (2) included Huronian metasedimentary rocks in general lack the constrictional fabric of their enveloping plutonic rocks. Sudbury dykes cut across the fabric of the CLC, but the facts that they are themselves buckled, locally metamorphosed to greenschist facies, and are offset by faults marked by ultramylonite and cataclasite attest to tectonism of Grenvillian age in the footwall for a limited distance northwest of the GFBF. Granitoid rocks dated at 1.74 and 1.47 Ga southwest of the study area, and Archean tonalitic rocks and 2.47 Ga anorthositic gabbro to the northeast, occur on both sides of the Grenville Front. In the study area, units of paragneiss in the hanging wall of the GFBF cannot be assigned to specific Huronian formations in the Southern Province footwall. However, although not proven, it is reasonable to correlate other hanging wall rocks, namely mylonitic gabbroic anorthosite, amphibolite, and granitic gneiss, to the 2.47 Ga East Bull Lake intrusive suite, Nipissing gabbro, and Chief Lake granite, respectively, in the Southern Province. Whereas Sudbury dykes do not intrude the mylonitic rocks immediately above the GFBF, they do reappear to the southeast as dyke segments and pods within mylonite-bounded panels where they cut earlier isoclinal folds and exhibit a progressive increase in metamorphic

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grade across a gradient shallower than that in the enclosing gneissic rocks. They document that much of the tectonic history recorded by their host rocks is pre-Grenvillian. Even so, there is no evidence that the Grenville Front was ever the locus of a suture. © Published by Elsevier Science B.V.

1. Introduction

The Grenville Front marks the boundary between the Grenville Province and several older structural provinces of the Canadian Shield (Fig. 1, inset). In a broad sense, it is the common locus of major differences in geological and geophysical parameters, and by any non-genetic definition it is a terrane boundary (cf. Howell, 1989). The front is characterized by faulting and mylonitization along all of its exposed, 2000-km length. In a very few places, it can be placed unequivocally at a single, major fault, generally steeply inclined and having a reverse (south-side-up) sense of displacement. In most places, however, it is better described as a zone of branching and rejoining faults and mylonite zones, together several kilometres wide, across which the state of rock deformation intensifies as it changes character southeastward from brittle to ductile. Concomitant with this change is either a rise in recorded metamorphic grade or an overprinting of younger metamorphism on older high-grade rocks, and an increasing difficulty in recognizing the derivatives of rock units defined in the footwall. The faults and mylonite zones that mark the front are generally inclined to the south or southeast, and relative uplift of the Grenville Province with respect to its foreland is everywhere implied.

Thanks in large part to modern radiometric age determination, we now know that crust on the immediate Grenville side of the front is the re-

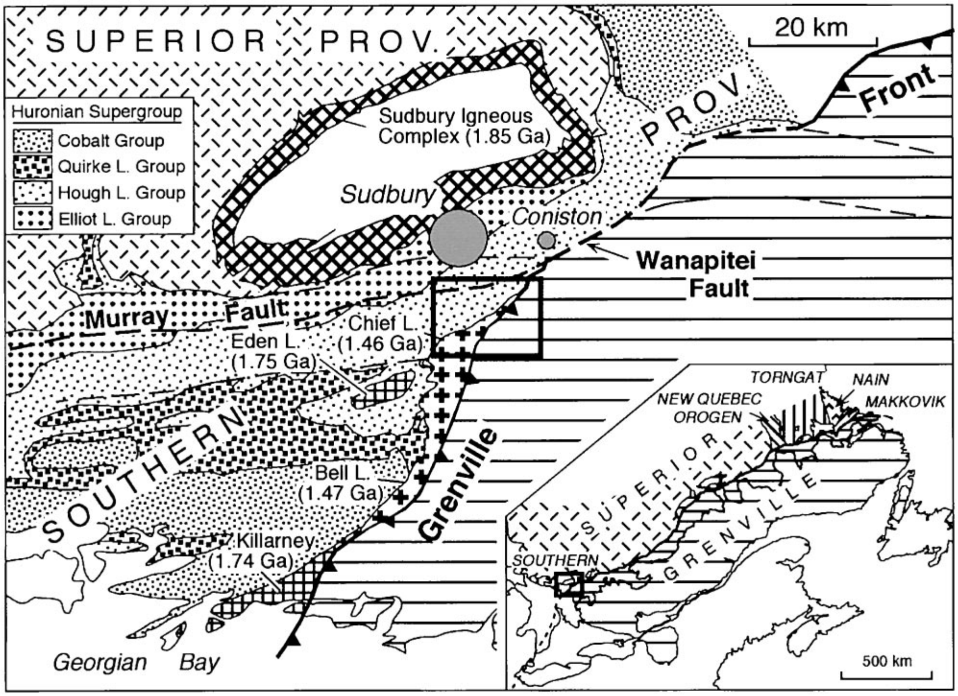

Fig. 1. Location of study area at the southwest end of the exposed Grenville Front. Generalized distribution of the four groups of the early Paleoproterozoic Huronian Supergroup and locations of late Paleoproterozoic and early Mesoproterozoic plutonic rocks adjacent to the front are shown.

worked equivalent of adjacent foreland crust, of whatever age, and thus that the front itself is not the locus of a Grenvillian suture (see Davidson, 1998a, and references therein). However, correlation by age alone does not solve the difficulty, in many places, of making lithologic correlation across the front. In addition, although accepted as the northwestern margin of the Grenville Province, the structural front of the mid- to late Mesoproterozoic Grenville orogen, and the site of ca. 1.0 Ga tectonic activity (e.g. Krogh, 1994), there is evidence in many places for a pre-Grenvillian tectonic history. This is manifested mainly by a record of tectonism in the early Mesoproterozoic and perhaps late Paleoproterozoic whose effects do not extend beyond the immediate vicinity of most of the front in the Canadian Shield, but which may have their counterparts in the buried Grenville foreland in mid-continental North America (e.g. van Breemen and Davidson, 1988), eastern Labrador (Gower et al., 1992), and Scandinavia (Larsen et al., 1990). At present it is not certain whether the Grenville Front in part coincides with a major, in situ, pre-Grenvillian tectonic boundary, or whether it conceals one that was transported toward the craton during Grenvillian orogeny. This paper outlines some new findings in one such area, near Sudbury, Ontario, and in effect revisits the problem of the 'disappearance of the Huronian' perceived 70 years ago by Quirke and Collins (1930), a problem that, despite more recent work in the general region, still remains to be satisfactorily resolved. It concludes that the Grenville Front in the Sudbury region, although the site of pre-Grenvillian tectonism, was at no time the locus of a suture, and that the Huronian, although disguised, is not likely to have 'disappeared'.

1.1. The Sudbury area

The Grenville Front in the Sudbury area (Fig. 1) marks the boundary between the Southern and Grenville structural provinces. It is well exposed, not only along two major highways, but also over a broad area that has undergone soil erosion following deforestation by smelter fumes. Systematic mapping along the front south and east of Sudbury was first undertaken in the late 1950s (Phemister, 1960, 1961; Grant et al., 1962). The front subsequently received much attention for detailed study, particularly in the form of university theses (e.g. Brooks, 1964; Spaven, 1966; Henderson, 1967a; Brown, 1968; Hsu, 1968; Kwak, 1968; La Tour, 1979), and it is featured in numerous field trip guidebooks produced over several decades (e.g. Brown, 1967; Henderson, 1967b; Henderson et al., 1967; Lumbers, 1978; Davidson, 1986, 1994; Easton et al., 1999). Mapping by Lumbers (1975) and Frarey (1985) has placed this section of the Grenville Front in a regional context (see also Card and Lumbers, 1977). Publications during the last four decades provide considerable insight on the way interpretations of this major geologic structure have evolved with time, dependent to some extent on the 'fashion of the day', but also reflecting advances in the geologic database, especially in fields such as precise isotope geochronology, modern thermobarometry, and seismic reflection geophysics. They illustrate that we have progressed from the concept of a metasomatic front through recognition of the importance of faulting and then of the kinematics of mylonite associated with the front, but in none of these works is it ever suggested that the front itself may be an ancient suture, i.e. a terrane boundary in the plate tectonic sense.

Northwest of the Grenville Front, the Southern Province is underlain predominantly by supracrustal rocks of the early Paleoproterozoic Huronian Supergroup (Fig. 1). This succession lies unconformably on, and successively overlaps, crystalline rocks of the Archean Superior Province to the north. The lower age limit of the Huronian Supergroup is constrained to be ca. 2.47 Ga based on ages obtained from volcanic rocks at its base and from related intrusive rocks (East Bull Lake intrusive suite) within its basement (Krogh et al., 1984). It is composed of four groups, the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt groups (Fig. 1, legend), with an aggregate thickness in the Sudbury area between 10 and 15 km (Bennett et al., 1991, Fig 14.2). Following folding and metamorphism no higher than greenschist facies, the Huronian Supergroup was invaded by voluminous, sill-like intrusions of Nipissing gabbro whose age, 2.22 Ga (Corfu and Andrews, 1986; Noble and Lightfoot, 1992), currently represents the only constraint on the younger age limit for the early deformation of the Huronian succession (Blezardian orogeny; Stockwell, 1982; Bennett et al., 1991, p. 574). Further east–west folding and greenschist-grade regional metamorphism is generally attributed to Penokean orogeny (1.9–1.83 Ga; Hoffman, 1989). In addition, the Sudbury area was disturbed by the extraterrestrial impact that gave rise to the Sudbury structure and intrusive complex at 1.85 Ga (Krogh et al., 1984). Near the Grenville Front south of Sudbury the Huronian Supergroup and Nipissing gabbro were subsequently intruded by granitoid rocks of two ages, ca. 1.74 and 1.47 Ga (Fig. 1; van Breemen and Davidson, 1988; Davidson and van Breemen, 1994). These intrusive events were accompanied by relatively low-pressure metamorphism locally reaching amphibolite grade (cordierite–staurolite–andalusite assemblages in pelitic rocks), and by more widespread deformation (Fueten and Redmond, 1997), including that of the southern part of the Sudbury structure (Shanks and Schwerdtner, 1991a,b; Riller and Schwerdtner, 1997; Boerner et al., 2000). All of these Southern Province rocks are cut by two younger sets of undeformed diabase dykes: the southeast-trending Sudbury swarm (ca. 1.24 Ga; Krogh et al., 1987; Dudás et al., 1994) and the east-trending Grenville swarm (0.60 Ga; Kamo et al., 1995).

The neighbouring part of the Grenville Province is underlain by supracrustal and plutonic rocks at high metamorphic grade. These rocks are commonly so intensely deformed and disrupted that it is difficult to recognize their protoliths and thus to make direct correlations across the Grenville Front mylonite zone (GFMZ; Davidson, 1992). This frontal zone of brittle-ductile faulting and mylonitization has been widely attributed to Grenvillian orogeny at ca. 1.0 Ga, but it has certainly overprinted early structure, even though evidence of the former is largely obliterated within the zone itself. Three main rock groups are recognized: schist and gneiss of sedimentary origin, amphibolite and hornblende–garnet gneiss of intrusive and possibly in part volcanic origin, and foliated granitoid gneiss. Minor units include small bodies of ultramafic rock, disrupted remnants of Sudbury diabase dykes, and pegmatite.

As was recognized by earlier workers (Grant et al., 1962; Dalziel et al., 1969), the Grenville Front near Sudbury is expressed in different ways in different places along its length (Fig. 1; Davidson, 1992, 1998b). South of Sudbury, it is a complicated zone of bifurcating faults whose attitudes vary, west to east, from vertical to moderately SE-dipping. This zone encloses lenticular slivers of less deformed rock tens to hundreds of metres thick and many kilometres long. Associated mylonite invariably carries kinematic evidence for reverse shear sense (Grenville side up to the northwest), as do minor structures within the intervening, less mylonitized slivers. The immediate Southern Province footwall is occupied by the ca. 1.74 and 1.47 Ga granitoid suites, although large enclaves of Huronian rocks are also present locally. Change in metamorphic grade across the front is recorded, in aluminous supracrustal rocks in the hanging wall, by (1) the sudden appearance of garnet (Fig. 6); (2) a one- to two-kilometre-wide zone in which kyanite appears and staurolite disappears; and (3) the appearance of sillimanite with K-feldspar in migmatitic leucosomes within 2 km of the front (Kwak, 1968).

East of Sudbury, the Grenville Front is defined by a single fault, the Wanapitei Fault (Davidson, 1998b). At Coniston (Fig. 1) this fault diverges from the Grenville Southern province boundary and continues westward for more than 200 km within the Southern Province, where it is known as the Murray Fault and records a long pre-Grenvillian history (e.g. Card et al., 1972). The Wanapitei segment of the fault truncates the bifurcating mylonite zone and the metamorphic zonation associated with it, described above. It is also the northeastern limit of granitoid rocks in the immediate footwall; east of Coniston, Huronian rocks and Nipissing gabbro lie against the Wanapitei Fault. Southwest of Coniston, other faults also diverge westward from the mylonite zone.

2. Previous work and the problem of lithologic correlation

Past studies in the Sudbury area have paid relatively scant attention to direct correlation across the Grenville Front, at least on a unit-to-unit basis. This is hardly surprising when one considers the marked differences in appearance of the rock assemblages on either side. Most workers have assumed that the rocks on either side of the front are the same, but some have gone to considerable length to explain why those on the Grenville side are hard to recognize (e.g. Phemister, 1961; Lumbers, 1975, 1978). As will be shown later in this paper, part of the problem has been incorrect identification of particular rocks on both sides of the front, but equally as important has been lack of precise isotopic dating.

The map produced by Grant et al. (1962) was published at a time when it was considered that the sedimentary rocks on the Southern Province side of the front may not be direct correlatives with Huronian formations in the type area farther west and north of the Murray Fault, so the individual formation names assigned earlier by Collins (1936) were not used. Moreover, granitoid rocks adjacent to the front were interpreted to be granitized sedimentary rocks, and associated mafic rocks, partly granitized equivalents of Nipissing gabbro (Phemister, 1961). Even though the Grenville Front was designated on this map as a major fault, it was considered not so much as a structural front but as a metamorphic/metasomatic transition, an interpretation similar to that of Quirke and Collins (1930) and Quirke (1940).

Recognizing the importance of mylonitization associated with the front in the southwest part of the area Grant et al. (1962) mapped; Lumbers (1965, 1975); Henderson (1967a, 1972) and Card et al. (1975) took issue with these interpretations; they established that the granitic rocks of what Henderson named the Chief Lake batholith intrude the Huronian Supergroup and Nipissing gabbro, and also that the Huronian rocks can be assigned to specific formations. Henderson (1967a) attempted to define the Grenville front as the northwestern limit of penetrative deformation within the Chief Lake batholith, but nevertheless recognized that the eastern side of the batholith is the locus of a major shear zone that separates foliated and lineated granitic rocks from gneiss and migmatite with small-scale ductile folds, roughly coincident with the first appearance of garnet. Henderson (1967a, p. 103), stated that the '…Chief Lake batholith separates Huronian metasedimentary rocks from Grenville province gneisses and prevents direct correlation of paragneisses with Huronian rocks…', although he did speculate that the '…gneisses east of the batholith also may be primarily of Huronian age.' He also equated a unit of granitoid orthogneiss in the Grenville Front hanging wall (south of Fig. 2) to Chief Lake granite.

At about the same time, Dalziel and co-workers (Dalziel et al., 1969; Brocoum and Dalziel, 1974) interpreted the tectonic history, and by inference the rocks, to be the same on either side of the Grenville Front in the Sudbury region, and the deformation recorded by these rocks to be pre-Grenvillian, except for a modest overprint of Grenvillian tectonism on the Grenville side. However, despite this tectonic correlation and the assertion that rocks on the Grenville side are the modified equivalents of those to the northwest, the only lithologic correlation attempted was to equate diabase dykes on both sides of the front.

Lumbers (1971a, 1975) introduced the term 'Grenville Front tectonic zone' to describe a zone of deformation straddling the Grenville–Southern province boundary; he defined the 'Grenville Front boundary fault' (GFBF) within this zone. (The Grenville Front tectonic zone was defined somewhat differently by Wynne-Edwards (1972), to whom the term is generally attributed; he restricted it to southeast of the Grenville Front, while recognizing that Grenvillian deformation extended for some distance northwest of the front within what he termed the 'Grenvillian Foreland Belt'.) Like earlier workers, Lumbers also had trouble making lithologic correlation across the front, stating (Lumbers, 1975, p. 49) that 'Detailed stratigraphic correlations between metasediments of the Grenville and Southern Provinces … are unjustified…', a conclusion also reached by Frarey (1985). Lumbers (1978) called upon facies changes in the Huronian Supergroup, in particu-

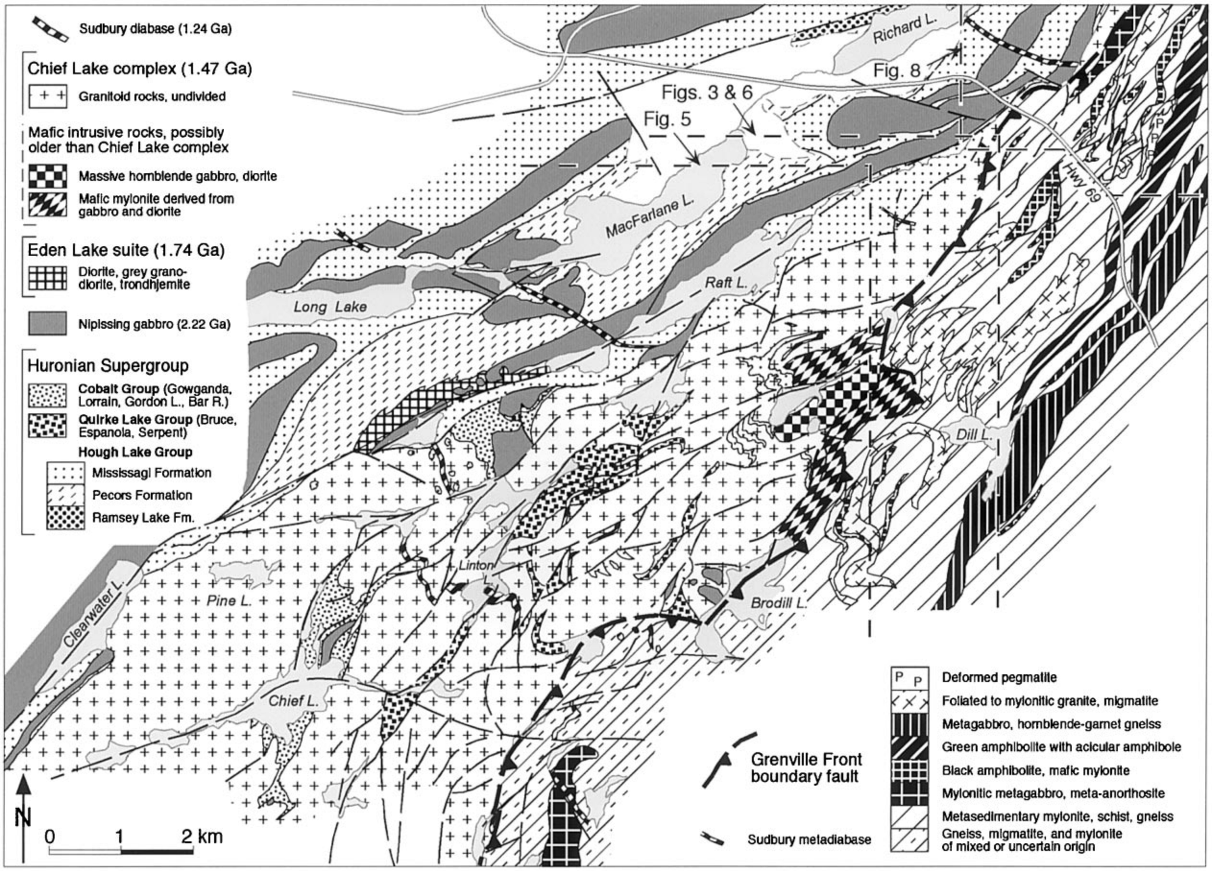

Fig. 2. General geology of the northeastern part of the CLC and the adjacent parts of the Southern and Grenville provinces south of Sudbury. Limits of map Figs. 3, 5, 6 and 8 are indicated.

lar the Mississagi Formation, to account for lack of obvious correlation across the front, thus allowing that paragneiss units in the Grenville Province are Huronian equivalents. He also suggested that amphibolite bodies within the Grenville gneiss complex may correlate with Nipissing gabbro. In addition he made a distinction between olivine diabase dykes and diabase dykes in the Grenville foreland (the Sudbury and Grenville swarms mentioned earlier), and noted that only the diabase (Grenville) dykes cross the front in this region. He also recognized segments of deformed dykes within the Grenville hanging wall (which he identified as 'cataclastic metadiabase'), but he did not equate these with the Sudbury swarm, a correlation suggested previously by Fahrig et al. (1965), subsequently by Palmer et al. (1977) and Frarey (1985), and now proven by geochemical correlation (Merz, 1976; Bethune, 1993; Bethune and Davidson, 1997) and dating (Dudás et al., 1994).

Lumbers (1971b, 1973) also mapped across the Grenville Front farther northeast, where he recognized that a particularly distinctive body of anorthosite gabbro (River Valley anorthosite) lies astride what he mapped as the GFBF in that region. He traced this unit southwestward within the Grenville Province to close to Coniston (Card and Lumbers, 1977).

More recently, detailed remapping and re-evaluation of the Grenville Front from the Chief Lake batholith to northeast of Coniston (Davidson, 1992; Davidson and Ketchum, 1993; Davidson, 1998b) have corroborated many of the observations made by earlier workers, in particular the difference in the nature of the front northeast and southwest of Coniston, and the clear record of pre-Grenvillian deformation and metamorphism. Furthermore, new interpretations or identifications of rocks and their relationships, presented herein, that had previously been contentious or overlooked have helped to narrow down some of the problems of lithologic correlation across the front south of Sudbury.

3. Southern Province footwall

3.1. Huronian Supergroup, Nipissing gabbro, and 1.74 Ga plutonic rocks

The region between the Sudbury Igneous Complex and the Grenville Front is underlain primarily by the two lower groups of the Huronian Supergroup, the Elliot Lake and Hough Lake groups (Fig. 1). Near the Sudbury Igneous Complex these strata form a steeply south-dipping, essentially homoclinal succession. Closer to the front, the uppermost unit of the Hough Lake Group, the 3-km-thick Mississagi Formation (chiefly composed of distinctively cross-bedded feldspathic arenite in 1–3-m-thick beds) is thrown into a number of large, east-northeast-trending, open to close folds which become tighter south of the Murray Fault (Fueten and Redmond, 1997). Conglomeratic rocks present along part of the south side of this fault (north shore of Richard Lake in Fig. 2) were assigned to the Ramsey Lake Formation by Collins (1936). Although this assignment has not been followed on more recent maps, these rocks being interpreted as a coarse facies of the Mississagi Formation (e.g. Lumbers, 1975; Dressler, 1984), Collins' original interpretation is supported by the observation that a poorly exposed unit of slate and greywacke lies stratigraphically between it and the overlying Mississagi Formation (Davidson, 1992). This unit corresponds to the Pecors Formation, first described in this stratigraphic position farther to the west by Card (1978), where it is locally as much as 900 m thick. Moreover, the Pecors Formation is now recognized to crop out in a large area to the southwest in the vicinity of MacFarlane Lake and Long Lake (Davidson and Ketchum, 1993, Fig. 2). Nowhere in this area, however, do the Ramsey Lake conglomerate or formations of the underlying Elliot Lake Group come to the surface.

Nipissing gabbro, generally carrying greenschist-facies metamorphic mineral assemblages, occurs as large sill-like masses within all the Huronian formations. Many of these intrusions follow the curvature of pre-existing folds in stratified Huronian host rocks; however, the fact that massive Nipissing gabbro cuts across fold axial planar foliation, for example in silty interbeds in the Mississagi Formation, attests to pre-Nipissing (Blezardian) folding of the Huronian Supergroup. In other places, especially close to the Grenville Front, folds in Huronian rocks have been tightened subsequent to Nipissing sill emplacement; the sills behaved relatively competent, pulling apart into large blocks.

Small masses of grey, uniform trondhjemite and granodiorite intrude Huronian rocks and Nipissing gabbro in a kilometre-wide zone that diverges from the Grenville Front southwest of Coniston, passing westward just north of the Chief Lake batholith. A narrow, irregular mass of this rock southeast of Long Lake (Fig. 2) gave a U–Pb titanite age of 1749 Ma (Davidson and van Breemen, 1994), the same age, within error, as the Eden Lake complex (Sullivan and Davidson, 1993) and the Killarney granite (van Breemen and Davidson, 1988) (Fig. 1), and also the Cutler batholith farther west (Davidson et al., 1992).

3.2. Chief Lake complex — a reassessment

Re-examination of the northern part of the Henderson's 'Chief Lake batholith', and detailed mapping of its northeastward continuation along the footwall of the GFMZ toward Coniston (Davidson and Ketchum, 1993), has shown it to be composed of a number of distinct, areally restricted phases (Fig. 3), constituting an intrusive suite. Some granitoid phases are intimately associated, and in places commingled, with mafic rocks that are an integral part of the suite; some of the mafic rocks were originally mapped as agmatite by Henderson (1967a), whereas others were misidentified as Nipissing gabbro or its metasomatized equivalent (Grant et al., 1962; Henderson, 1967a; Lumbers, 1975), an error perpetuated on more recent compilation maps (e.g. Card and Lumbers, 1977; Dressler, 1984). Furthermore, the different intrusive phases include, and in places are separated by, rafts and screens of metamorphosed Huronian sedimentary rocks and true Nipissing gabbro. For these reasons this composite batholith and its enclaves are best termed a complex (cf. North American Commission on Stratigraphic Nomenclature, 1983).

Davidson and van Breemen (1994) reported an age of 1464 + 2/ − 1 Ma for megacrystic granite of the Chief Lake complex (CLC) (Raft Lake unit; see below). This is very close to the 1471 ± 3 Ma age reported by van Breemen and Davidson (1988) for the lithologically similar Bell Lake granite along the Grenville Front to the south (Fig. 1), but is at odds with previously reported ages of 1.75 Ga (Rb–Sr isochron, Davis et al., 1966) and 1.72 Ga (U–Pb zircon, recalculated; Krogh and Davis, 1968) for granite from the CLC sampled farther southwest. The reason for this discrepancy is unresolved, but given the proximity of the ca. 1745 Ma Eden Lake complex (Fig. 1) and the 1749 Ma granodiorite just west of Raft Lake (Fig. 2), and also that the CLC contains numerous rafts of Huronian country rocks, Davidson and van Breemen (1994, p. 111) suggested that '…it is possible that the original samples were collected from unrecognized rafts of older granitoid rocks'.

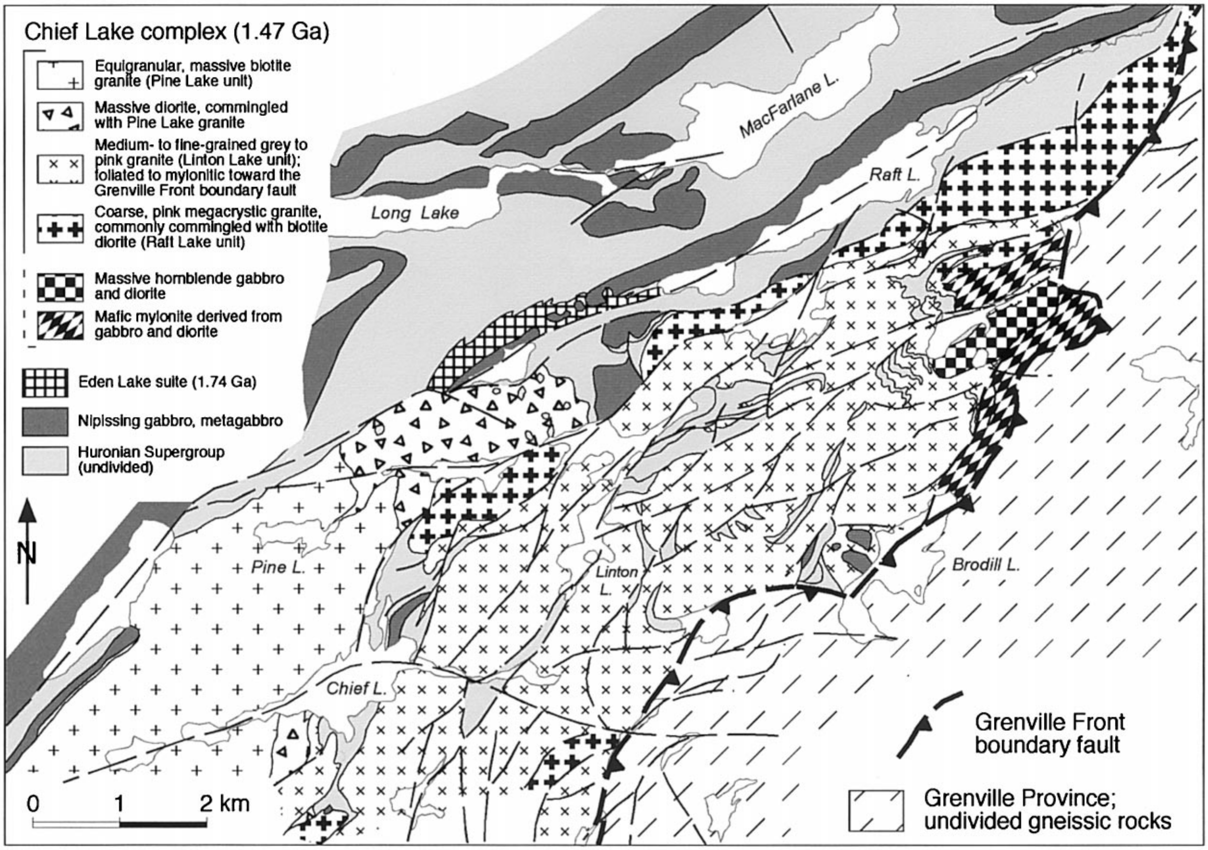

Fig. 3. Plutonic units of the CLC. Gabbro and diorite units adjacent to the GFBF are cut by dykes of Linton Lake granite and Raft Lake diorite and may be older than the Chief Lake intrusive suite.

3.2.1. The plutonic rocks

The western part of the CLC is underlain by uniform, pink, medium- to fine-grained, equigranular, leucocratic biotite monzogranite, referred to here as the Pine Lake unit. It is predominantly massive, but is locally foliated and even mylonitic along its western contact. It intrudes feldspathic sandstone of the Mississagi Formation and Nipissing gabbro along its northwest contact (Figs. 2 and 3). At its northeast end and on the south shore of Chief Lake it intrudes a heterogeneous unit of grey dioritic rock containing dark cognate inclusions, large xenoliths of Lorrain Formation quartzite, and patches that are commingled with fine-grained quartz syenite or granite. Dykes of commingled rock as much as 10 m wide penetrate the Huronian Supergroup along the south shore of Chief Lake and west of the main contact of the complex (Fig. 4A), but were not seen to cut the Pine Lake granite.

North of Chief Lake, the diorite unit is overthrust from the southeast by a characteristically coarse, pink, megacrystic biotite monzogranite that is variably foliated and is reduced to porphyroclastic mylonite and ultramylonite at the thrust contact. South of this lake, similar megacrystic monzogranite extends southwestward to the outer contact of the CLC at Wavy Lake (Spaven, 1966; Henderson, 1967a). The same granite extends along the whole outer contact of the complex to the northeast where its contact with the Mississagi Formation and Nipissing gabbro is a steeply south-dipping reverse fault. In many places this granite is intimately associated with dark brownish grey, medium-grained hornblende–biotite diorite or quartz diorite containing xenocrystic quartz and feldspar as well as primary plagioclase laths; these two phases, not separated in Fig. 3 for reason of scale, are referred to collectively as the Raft Lake unit. In the interior parts of the mafic masses, diorite grades to hornblende gabbro containing relict augite. Broad zones of commingling are present at some contacts between diorite and megacrystic granite (Fig. 4B). In places, bulbous masses of dioritic rock with randomly oriented plagioclase laths have what appear to be chilled contacts against the coarse granite (Fig. 4C). In others, irregular zones and patches of spaced feldspar megacrysts in the dioritic rock may indicate incorporation in mafic magma of crystals detached from adjacent partly consolidated granite (cf. Pitcher, 1993, pp. 127–129). Granite of the Raft Lake unit has a U–Pb zircon age of 1464

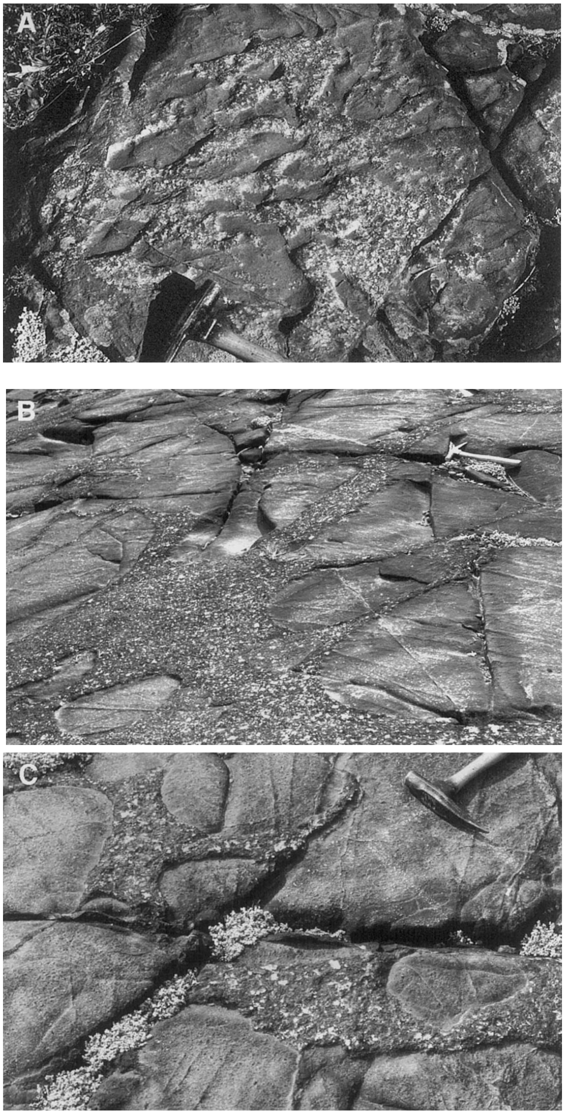

Fig. 4. Examples of commingled rocks in the CLC. (A) 10-m-wide dyke within Lorrain Formation at the west side of the complex, (B) coarsely commingled rock composed of Raft Lake megacrystic granite and biotite diorite, southwest of Raft Lake, (C) detail at the same locality showing chilled margins of mafic component. Dark appearance of coarser granite component is due to stain on outcrop surfaces caused by smelter fumes.

+2/−1 Ma (Davidson and van Breemen, 1994); the evidence presented above demonstrates that the associated dioritic rocks are coeval with the megacrystic granite phase and refutes the former interpretation that all the mafic rocks along the northern CLC margin are derivatives of Nipissing gabbro. Moreover, 4 km northeast of Chief Lake (Fig. 3), commingled dioritic rock intrudes distinctive Nipissing metagabbro where it is associated with Cobalt Group metasedimentary rocks within the complex.

The rest of the CLC is composed primarily of pink to light grey, sub-porphyritic biotite granite or granodiorite with feldspar phenocrysts, referred to as the Linton Lake unit. It is distinctly finer grained than the Raft Lake granite, which it intrudes, and is compositionally more variable than either the Pine Lake granite or the granite phase of the Raft Lake unit. It probably includes several intrusive phases, now separated by faults. Unlike the adjacent Raft Lake unit, it lacks an associated coeval mafic phase. The Linton Lake unit is massive to weakly foliated near the east side of Chief Lake, but farther east and southeast toward the Grenville Front it becomes increasingly, though inhomogeneously, foliated and lineated, developing a protomylonitic fabric and grading to flaggy mylonite and ultramylonite along faults.

Adjacent to the GFBF northeast of Brodill Lake (Fig. 3) lies an irregular mass of hornblende metagabbro. Parts of this unit are little deformed and display relict igneous texture, but most of it has been reduced to fine-grained, amphibole-rich schist (mafic mylonite). Where less deformed it can be seen to be cut by both Linton Lake porphyritic granite dykes and commingled dykes related to the Raft Lake unit. It is not known, however, whether the metagabbro is an early phase of the CLC or is entirely older and unrelated. Moreover, its well-preserved parts do not have the characteristic appearance of Nipissing gabbro or metagabbro.

The CLC narrows progressively northeastward in the GFBF footwall, from ≈6 km wide south of Chief Lake to a matter of a few tens of metres at Highway 69 (Fig. 2) where it and Mississagi sandstone at its northwest contact have been reduced respectively to cataclasite and quartz-rich ultramylonite, obscuring the original nature of the contact (faulted or intrusive). The Raft Lake unit, including locally well-preserved commingled rock, can be traced as a continuous strip from Highway 69 northeast for about 4 km, almost to the point south of Coniston where the Murray/Wanapitei Fault cuts across the GFMZ (Davidson, 1992, Fig. 1). In this study, the GFBF is placed at the southeast limit of recognizable CLC rocks; on this basis, its position southwest of Highway 69 is farther southeast than shown by Lumbers (1975) and it does not mark the northwest limit of deformation spatially associated with the Grenville Front (cf. Henderson, 1967a).

3.2.2. Contact relationships and old folds in included Huronian rocks

The northwest contact of the CLC is for the most part in structural contact with the Mississagi and Pecors formations of the Hough Lake Group, as well as with Nipissing gabbro (Fig. 5). Only north and west of Chief Lake is the intrusive nature of the contact with the Mississagi Formation preserved. Farther to the southwest, earlier geological mapping (Henderson, 1967a; Card et al., 1975) showed successively higher Huronian stratigraphic units (up to the Lorrain Formation; see legend in Fig. 5) against and incorporated within the western CLC, forming a steeply east-plunging syncline. Within the complex at Chief Lake, Henderson (1967a) recognized a large enclave of Gowganda and Lorrain formation rocks (Cobalt Group) east of the Pine Lake granite, and Davidson and Ketchum (1993) recognized the same two units plus underlying Serpent Formation farther northeast, faulted against Mississagi Formation (Fig. 5). The fact that the Gowganda Formation lies east of the Lorrain in these two occurrences, thus opposing the facing direction to the southwest beyond the map-area, implies that a large synclinal basin is engulfed in this part of the complex. Moreover, small remnants of the uppermost formations of the Cobalt Group, the Gordon Lake and Bar River formations, were recognized during this study in the core of this structure on the south shore of Chief Lake.

Farther east, the CLC includes many slivers and rafts of metasedimentary rock. Although for the most part deformed to the extent that primary sedimentary structures are rarely preserved, local low-strain zones in some enclaves reveal cross-bedded metasandstone or mildly distorted pebbles in biotite-rich rock. The presence among these rafts of a unit of thinly layered calcareous metasiltstone with scapolite and acicular amphibole porphyroblasts, locally associated with diopside–grossularite marble, is important because the only calcareous formation within the Huronian Supergroup is the Espanola Formation, in the middle of the Quirke Lake Group (see legend, Fig. 5). Recognition of the Espanola Formation allows assignment of adjacent rock units either to the overlying Serpent (feldspathic quartzite) or underlying Bruce Formation (matrix-supported polymict conglomerate). Moreover, feldspathic metasandstone separated from the Espanola Formation by Bruce metaconglomerate can only be Mississagi Formation, and some occurrences of this metasandstone have cross-bedding preserved well enough for facing direction to be determined directly, corroborating the facing sense determined by superposition of formations. The sense of younging determined in these two ways in turn allows recognition of former folds within the Huronian succession (Fig. 5), now largely engulfed by the different intrusive phases of the CLC which, although deformed, does not appear to be folded.

As would be expected under circumstances of incorporation within an intrusive complex, the Huronian enclaves exhibit relatively high-temperature metamorphic mineral assemblages, for example garnet–biotite–andalusite–sillimanite in Gowganda hornfels near Chief Lake. Argillaceous rocks of the Pecors Formation along the northwest contact south of MacFarlane and Long lakes are knotted schist with porphyroblasts of staurolite, andalusite and cordierite (now mainly re-

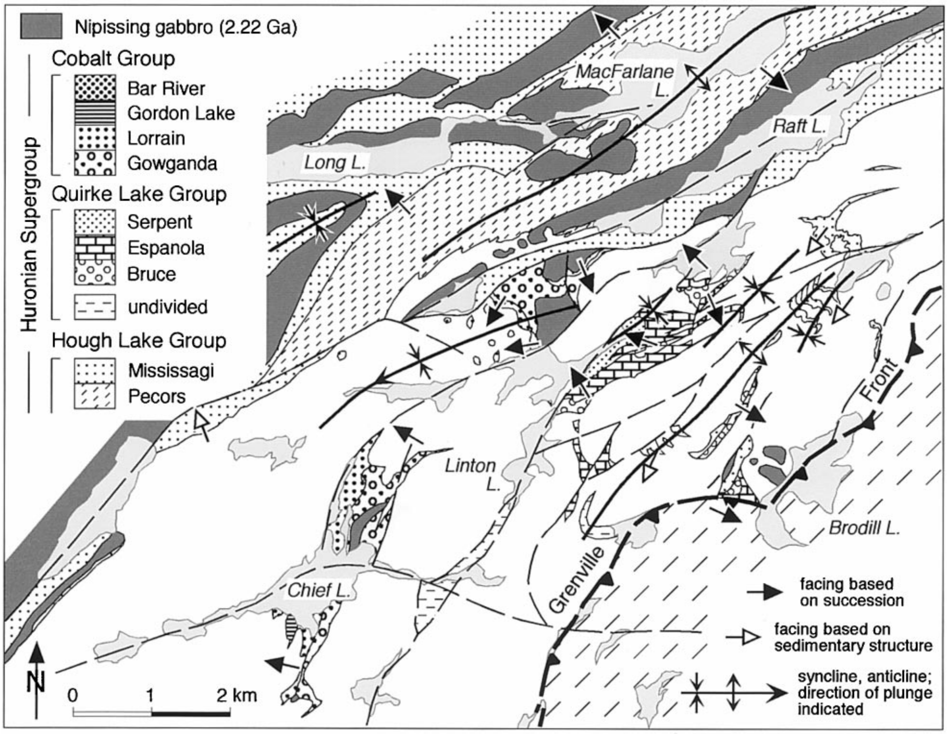

Fig. 5. Relict stratigraphy, younging directions, and traces of pre-intrusion folds in enclaves of Huronian sedimentary rocks within the CLC. Note that the latter are parallel to fold traces northwest of the complex.

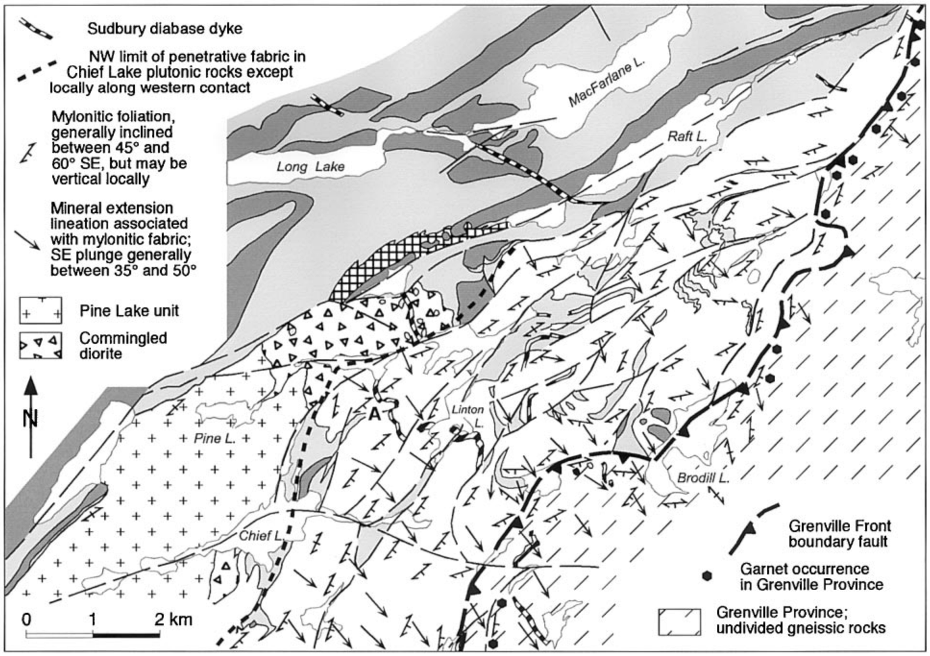

Fig. 6. Generalized orientation of mylonitic foliation and lineation in the Raft Lake and Linton Lake units (not patterned) of the CLC in the footwall of the GFBF, first appearance of garnet in the hanging wall, and distribution of Sudbury diabase dykes. Note that foliation in the footwalls of faults, including the GFBF, is commonly discordant with that in their hanging walls. All Huronian sedimentary rocks are shown in light grey, Nipissing gabbro in dark grey. Sudbury diabase clearly cuts across foliation in Raft Lake granite at A.

placed by lower-grade hydrous minerals), but it is not known whether this is related to emplacement of the Chief Lake or the nearby Eden Lake suite granodiorite. Similar assemblages are present in the “Eden Lake node” farther southwest (Frarey, 1985). In any event, mineral assemblages are suggestive of relatively low pressure facies, implying that both intrusive suites were emplaced at fairly high crustal level.

3.2.3. Structure

Henderson (1967a, p. 106) defined the Southern–Grenville province boundary as the limit of penetrative foliation and lineation within the Chief Lake granitoid rocks, noting that ‘…this places the ‘structural Grenville front’ as much as six miles west of the metamorphic boundary (the garnet isograd)…’, the latter coinciding closely with the GFBF as defined above. Henderson’s position of this limit coincides with the northwest thrust contact of the Raft Lake unit north of Chief Lake, and with the eastern margin of the Huronian enclave farther south. These structural elements, respectively, dip and plunge moderately southeast within the remapped area (Fig. 6), but to the west, according to Henderson (1967a, Fig. 6), the foliation swings westward and the lineation becomes south-plunging, diverging from parallelism with the GFBF. In addition, even close to the GFBF the trace of foliation is not everywhere parallel to it. The GFBF cuts across fault-bounded panels and truncates the foliation within them as well as open warps defined by local variations in foliation orientation. West of Brodill Lake, it also cuts across folds defined by included Huronian rocks. It this appears that much of the fabric displayed by Chief Lake granitoid rocks predates development of the GFBF, its former easterly trend having been distorted toward parallelism with the Southern–Grenville province boundary.

An important observation concerns the differential development of foliation between Chief Lake granitoid and Huronian metasedimentary rocks, particularly within the Linton Lake unit. It was noted during fieldwork that metasedimentary rocks in enclaves northeast and southwest of Linton Lake (Fig. 5) show relatively little obvious internal deformation. Pebbles in Bruce Formation metaconglomerate, though observed in only a few places, are not particularly elongate. Similarly, bedding in Espanola Formation metasiltstone commonly shows little distortion of primary features such as load-casts and flame structure, and meta-arenite of the Mississagi Formation within the complex south of Raft Lake locally contains cross-bedding preserved well enough for unequivocal determination of facing direction (Fig. 5). In addition, minerals of metamorphic origin, such as biotite flakes in Bruce metaconglomerate and amphibole needles and scapolite prisms in Espanola metasiltstone, show little to no preferred orientation. This is in marked contrast to the protomylonitic augen structure of the enclosing granitoid rocks.

The same duality of fabric development is present in commingled parts of the Raft Lake unit, in which the granitoid phase commonly has a protomylonitic fabric, yet the rounded pillows of finer grained mafic rock do not, preserving randomly oriented plagioclase laths. This duality may be explained in terms of preferential deformation of the granitic phase, suggesting that it was a quasi-crystalline mush when invaded by the mafic magma. At least some of the deformation recorded by the granitic rocks may therefore have occurred during the period of emplacement of the CLC, and perhaps some component of the solid-state foliation present in the Raft Lake and Linton Lake units developed shortly therafter (cf. Paterson et al., 1989).

There is no question, however, that southeast-dipping foliation and -plunging lineation becomes increasingly well developed as the GFBF is approached from the northwest. For example, Mississagi Formation metasandstone preserved in folded strips within the Linton Lake unit between Raft and Brodill lakes (Fig. 5) itself displays numerous mesoscopic folds whose axial planes and axes conform to the regional fabric trend. Diabase dykes of the 1.24 Ga Sudbury swarm help to distinguish between pre- and syn-Grenvillian deformation.

3.3. Sudbury dykes and their significance

Vertical olivine diabase dykes of the Sudbury swarm trend southeast across the folded Huronian formations and Nipissing gabbro intrusions in the Southern Province northwest of the CLC (Figs. 2 and 6), where they are not metamorphosed and are deformed only by brittle faults. Henderson (1967a) noted some segments of diabase dykes within the CLC but, not knowing their age, did not recognize their significance and interpreted them to be post-Grenvillian. Detailed mapping has revealed several previously unmapped segments of Sudbury diabase dykes in the northern part of the CLC, many of which appear to belong to the same dyke. The dykes, which may be as much as 75 m thick, illustrate the following: (1) they cut across some major faults without apparent displacement, including some faults along the mylonitized northwest margin of the CLC; (2) they are offset at other faults, and display internal brittle deformation in the form of broken mineral grains and networks of cataclasite-filled fractures adjacent to these faults; (3) between faults that offset them they follow increasingly sinuous courses toward the southeast, but nevertheless retain chilled margins at their contacts where they cut across mylonitic fabric in the Chief Lake granitoid rocks (well exposed where a dyke cuts the Raft Lake unit northwest of Linton Lake, locality A in Fig. 6), and folds within the Huronian enclaves; (4) diabase in most dyke segments between faults appears massive in outcrop, and in thin section is seen to laced by randomly oriented fractures at grain scale; (5) diabase is variably metamorphosed, with hydration commonly localized at faults; chlorite and serpentine replacement of olivine in the northwest gives way to the southeast to replacement by colourless amphibole with blue–green rims, implying an increase in metamorphic grade toward the Grenville Front; (6) metadiabase lacks a metamorphic mineral fabric and preserves the ophitic texture typical of its parent rock.

The relationships described above are identical to those documented several kilometres farther southwest in the footwall of the front (Bethune, 1993, 1997). In both places they imply that deformation of the ca 1.47 Ga granitoid rocks took place before introduction of the 1.24 Ga Sudbury dykes and is thus pre-Grenvillian. Subsequent deformation in the footwall has rotated formerly east–west fabrics into parallelism with the Grenville Front, and caused buckling and fault disruption of the Sudbury dykes at metamorphic grade no higher than greenschist facies. Much of the mylonitic and protomylonitic fabric in the Chief Lake granitoid rocks, therefore, resulted from pre-Grenvillian deformation, and may have developed both during and shortly after emplacement. There is no known orogenic event in the Southern Province between the time of granite emplacement and intrusion of the Sudbury dyke swarm at 1.24 Ga, for which a quiescent or extensional environment, not a compressive one, would have been required, these dykes in every respect representing a typical continental swarm (cf. Fahrig, 1987).

3.4. Summary

The immediate footwall of the GFBF in the Sudbury area southwest of Coniston is composed of mylonitized plutonic rocks of the ca 1.47 Ga CLC containing enclaves of previously folded metasedimentary rocks assignable to specific Huronian Supergroup formations, of Nipissing metagabbro, and of unspecified gabbroic rocks, generally severely deformed, that may be either an early mafic phase of the CLC or an unrelated, older intrusive unit. The CLC comprises several intrusive phases, characteristic among which is the mixed unit of megacrystic granite coarsely commingled with diorite. This unit forms the border phase of the complex near Raft Lake and is the only unit of the complex preserved in the footwall northeast toward Coniston (Figs. 1 and 2). It is in fault contact with northwestward-younging formations of the Hough Lake Group, with Nipissing metagabbro, and locally with older granitoid rocks (ca. 1.74 Ga Eden Lake suite). All of these rocks are cut by southeast-trending olivine diabase dykes of the ca. 1.24 Ga Sudbury swarm. Southeast of a line between Chief and Raft lakes, the CLC, its enclaves, and the Sudbury dykes become increasingly deformed, but nevertheless retain good evidence that the Huronian rocks were folded before emplacement of the various phases of the Chief Lake intrusive suite, that deformation in the Chief Lake rocks occurred before introduction of the Sudbury dykes, and that this occurred at the time of, or shortly after, emplacement of the complex. This then is the make-up and history of the footwall of the Grenville Front with which to compare the rocks in the immediate hanging wall.

4. Grenville Province hanging wall

4.1. Introduction

Most of the area southeast of the Grenville Front outlined in Fig. 2 is within the region originally mapped by Grant et al. (1962) and remapped by Lumbers (1971c, 1975). Different parts of it were mapped and studied in detail by Henderson (1967a), southwest of Brodill Lake, Hsu (1968), between Brodill and Dill Lakes, and Kwak (1968), northeast of Dill Lake. Lumbers was able to show only three main rock units at the scale of his map (1 inch = 2 miles), namely metasedimentary gneiss, mafic gneiss, and granitoid gneiss. Henderson, Hsu, and Kwak showed more diversity among the first two categories. Kwak, for example, outlined several different metasedimentary gneiss units and distinguished three types of amphibolite. There is, however, little or no correlation between the units outlined on the three detailed maps.

For the purposes of the present study, much of the well-exposed area northeast of Brodill Lake was remapped in detail for a distance as far as 3 km southeast of the GFBF in order to establish a common legend. Few traverses were made southwest of Brodill Lake, where outcrop is more sparsely distributed. Continuity of rock units was established along much of the 15-km-long strip of the hanging wall illustrated in Fig. 2.

4.2. Rock units

In most places immediately above the GFBF, thin, highly attenuated units of strongly mylonitized rocks define the GFMZ. These rocks are derived from the three main types mentioned above, although recognition of protolith may be obscure where ultramylonite has developed. At structurally higher level to the southeast, however, generally within one or two hundred metres of the GFBF, mylonitization is less severe, grain size increases, and rock units are thicker and more easily distinguished.

4.2.1. Supracrustal rocks

Metasedimentary schist and gneiss adjacent to the GFMZ northeast of Brodill Lake (Fig. 2) are derived mainly from shaly or silty precursors, judging by the preponderance of dark-coloured rocks containing biotite and garnet. These are intercalated locally with muscovite-bearing schist with kyanite and staurolite, although these two minerals are commonly altered to chlorite, phengite, and rarely margarite (Davidson et al., 1990). Intercalations of muscovite-bearing, quartz-rich schist are present locally.

In the northeast part of the remapped area near Highway 69 (Fig. 8), a more varied assemblage of metasedimentary gneiss and schist lies structurally above these aluminous rocks; it is composed mainly of cream-grey, commonly rusty-weathering quartz–feldspar–biotite schist and gneiss which includes thin but continuous units of (1) impure quartzite, (2) biotite-rich gneiss with minor garnet, in places containing extremely elongate pebbles (now indistinct quartzofeldspathic lenticles with aspect ratios of 20:1 or more), and (3) pink and grey, fine-grained, thinly laminated gneiss containing K-feldspar, amphibole and diopside. Judging by the extreme flattening of pebbles in the metaconglomeratic layers, the individual units may once have been an order of magnitude thicker. Next southeastward in the same area, about one kilometre from the GFBF, is a unit characterized by discontinuous strands of coarse garnet–muscovite–quartz schist locally rich in kyanite within grey, thinly layered garnet–biotite gneiss, compositionally similar to some of the pelitic schist and mylonite close to the GFBF. This unit commonly encloses large masses of deformed pegmatite (Fig. 8). Farther southeast is a characteristic, well-layered unit of pale grey, muscovite-bearing quartzofeldspathic gneiss, likely derived from sandstone.

4.2.2. Mafic rocks

As recognized by Kwak (1968), the mafic rocks in the hanging wall are of several types. At the southern boundary of the remapped area (Fig. 2), a north-tapering unit mapped by Henderson (1967a) as ‘massive amphibolite’ is in fact a sheet of highly-disrupted anorthosite and leucogabbro in which massive-textured rock is preserved only in pods of various size, separated by mylonitic schist. A similar but unconnected unit lies in the immediate hanging wall northeast of Highway 69 (Fig. 8); it is composed primarily of fine-grained, dark green chlorite–amphibole mylonite which locally encloses discontinuous layers of light grey, plagioclase–zoisite mylonite and pods of fairly well preserved anorthosite.

Most of the mafic lenses associated with metasedimentary schist and gneiss structurally above the GFMZ are black, simple amphibolite and hornblende schist. On the east side of the kyanite-bearing schist lies a relatively thick (200 m), ridge-forming unit of uniform, pale green schist composed primarily of acicular amphibole containing minor plagioclase and augite. East of this, and interfolded with metasedimentary schist and gneiss is another relatively thick mafic unit, but in this case coarser grained and composed of plagioclase and blocky hornblende; in places this unit is layered and is characterized by the presence of garnet and quartz-bearing, plagioclase-rich leucosomes. In some occurrences, such as along the east shore of Dill Lake (Fig. 2), it is interlayered at metric scale with garnet–biotite gneiss that locally contains gedrite or kyanite.

In addition to these four varieties of mafic schist and gneiss, ultramafic schist composed of green, acicular amphibole enclosing large, poikilitic ovoids of orthopyroxene and olivine occurs as isolated, decametre-scale pods, two of which are shown in Fig. 8. All of these occur within metasedimentary gneiss and do not seem to be associated directly with other mafic rocks.

4.2.3. Granitoid rocks

Foliated granitoid rocks, generally pink, equigranular, biotite-bearing, and relatively leucocratic, are common as sheets within the assemblage of metasedimentary and mafic rocks described above. Lenses of this unit close to the GFBF northeast of Highway 69 (Fig. 8) are fine grained and strongly mylonitic, but are devoid of all but the smallest feldspar augen. Like the amphibolite layers in this zone, some mylonitic granitoid units are exceedingly thin, yet are clearly distinct from the enclosing metasedimentary mylonite. Those to the southeast are not mylonitic, and in places are associated with grey phases grading into hornblende-rich orthogneiss of quartz dioritic to dioritic composition. Nowhere are intrusive relationships with country rocks preserved; inclusions were not observed and contacts are invariably conformable with foliation, even where folded.

4.3. Structure

4.3.1. Grenville Front boundary fault

Placement of a structural province boundary such as the Grenville Front at a specific fault may be appropriate for a short segment, but rarely holds for any great length along the boundary because the significance of an individual fault may vary along its length, and because faults may branch or be cut by younger faults, making the choice of a particular segment difficult. The Grenville Front in the Sudbury region is no exception; although parts of it are clearly defined by a single, major fault, such as the segment northeast of Coniston (Wanapitei Fault in Fig. 1), other parts are marked by a zone, kilometric in scale, of anastomosing faults across which metamorphic grade and style and intensity of deformation change in a stepwise fashion. This character has led to different placements of the Grenville Front by different mappers. Nevertheless, the important aspect is that many parts of this major boundary have finite but locally considerable widths across which the incremental effects of superimposed deformation and metamorphism are expressed.

The lack of coincidence between the position of the GFBF shown by Lumbers (1975; Map 2271) with that shown in Fig. 2 is a function of the greater detail of ground observations on which the present location is based. As outlined earlier, the GFBF in this study is located adjacent to and northwest of a zone of intense mylonitization whose planar fabric dips southeast, within and beyond which CLC rocks and Huronian enclaves are not recognizable – ‘adjacent to’ because there is almost invariably a linear valley lacking outcrop, even if only a few tens of metres wide, that conceals the major break. Where exposed close by, rocks on the northwest, footwall side are also highly deformed, but normally exhibit effects of low-temperature ductile deformation if quartz-bearing (Mississagi Formation, Chief Lake granitoid rocks), or cataclastic deformation if not (Nipissing gabbro, amphibolitic rocks at the southeast side of the CLC, Sudbury diabase). Given lack of outcrop, it is conjectured that this depression conceals cataclastic rocks that formed at the last stage of Grenvillian displacement along the front, when the rocks were relatively cool and at high crustal level. This position of the GFBF also coincides closely with the first southeastward appearance of deformed pegmatite dykes and folded leucosomes in quartzofeldspathic rocks in the hanging wall. In the vicinity of Brodill Lake this position lies about 1.5 km west of Henderson’s garnet isograd. As documented elsewhere (cf. Bethune, 1997), Sudbury dykes, although present on both sides of the GFBF, cannot be traced individually across it.

4.3.2. Grenville Front mylonite zone

Most of the hanging wall rocks within approximately one kilometre of this position of the GFBF are fine to very fine grained; some are porphyroclastic and have a well-developed mylonitic fabric with shear-sense indicators giving thrust-sense displacement toward the northwest (Fig. 7A). Porphyroclasts of metamorphic minerals, particularly garnet, are common in mylonite developed from metasedimentary rocks. Glassy ultramylonite is developed in parallel strands within the GFMZ. In contrast, more resistant rocks in this zone, such as gabbro and anorthosite, may be remarkably well preserved in blocks and boudins of various size (Fig. 7B). Metasedimentary schist and gneiss with relict bedding is very rarely preserved in isolated, detached fold hinges in the footwalls of subsidiary mylonitic faults.

4.3.3. Structure and metamorphism above the mylonite zone

Southeast of the GFMZ, the metasedimentary, mafic, and granitoid gneiss units previously described are disposed about reclined, tight to isoclinal folds whose axes generally plunge moderately to the east or southeast. The folds are particularly well outlined where terminations of thin amphibolite layers define closures of highly attenuated isoclines. Folds of this early generation are openly refolded in the area southwest of Dill Lake (Fig. 2). In the vicinity of Highway 69 (Fig. 8), they lie in panels between southeast-dipping, front-parallel faults that are commonly the loci of mylonite. Several of the larger mafic units lie in the hanging walls of such faults, many of which can be identified as thrusts on the basis of kinematic indicators.

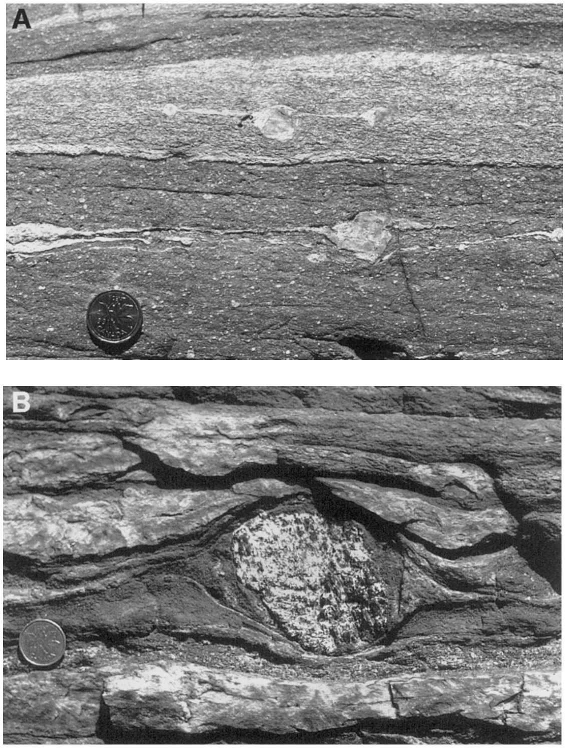

Fig. 7. Structural features in the GFMZ. (A) rotated feldspar augen in mylonite, (B) small tectonic block of anorthosite. Coin in both photographs is 1.9 cm in diameter.

In detail the structural pattern is complex and unpredictable, but overall it may be summarized as follows: (1) planar fabric, tabular map units, and the long limbs of folds dip moderately southeast, and carry dip-parallel linear elements; (2) the extensive mylonite zone above the GFBF gives way southeastward to progressively less mylonitic rocks within which reclined isoclinal folds are apparent; (3) the hanging wall is laced by numerous faults, many of which exhibit intense, localized mylonitization and cut off folds; (4) within a km of the GFBF (ca. 500 m of structural thickness), folds become less tight and evidence for large-scale refolding of earlier folds is expressed in map patterns. It is likely that the same multiple folding affected the rocks lower in the structural section, but that the relationship between different fold generations has been progressively obscured by the increasing amount of flattening toward the base of the hanging wall.

There is a clear tendency for a general increase in grain size southeastward from the GFBF, with gradual replacement of mylonitic fabric by 'normal' mineral foliation and the incoming of quartzofeldspathic leucosomes. In these non-mylonitic rocks, extreme thinness and extensive along-strike continuity of rock units and wide spacing of isolated boudins of mafic rock in metasedimentary schist together imply considerable flattening of rock units, and it is likely that the mineral foliation represents a recrystallized mylonitic fabric. This change is accompanied by an abrupt southeastward increase in metamorphic grade, ranging from staurolite-out within a few hundred metres of the GFBF to sillimanite replacing kyanite in the presence of K-feldspar within 2–3 km (Kwak, 1968). If the mineral isograds are parallel to foliation, which dips moderately southeast, then the inferred thermal gradient may be as high as 100° km^{-1}, and likely therefore to represent a tectonically telescoped gradient (La Tour, 1981; Davidson et al., 1990).

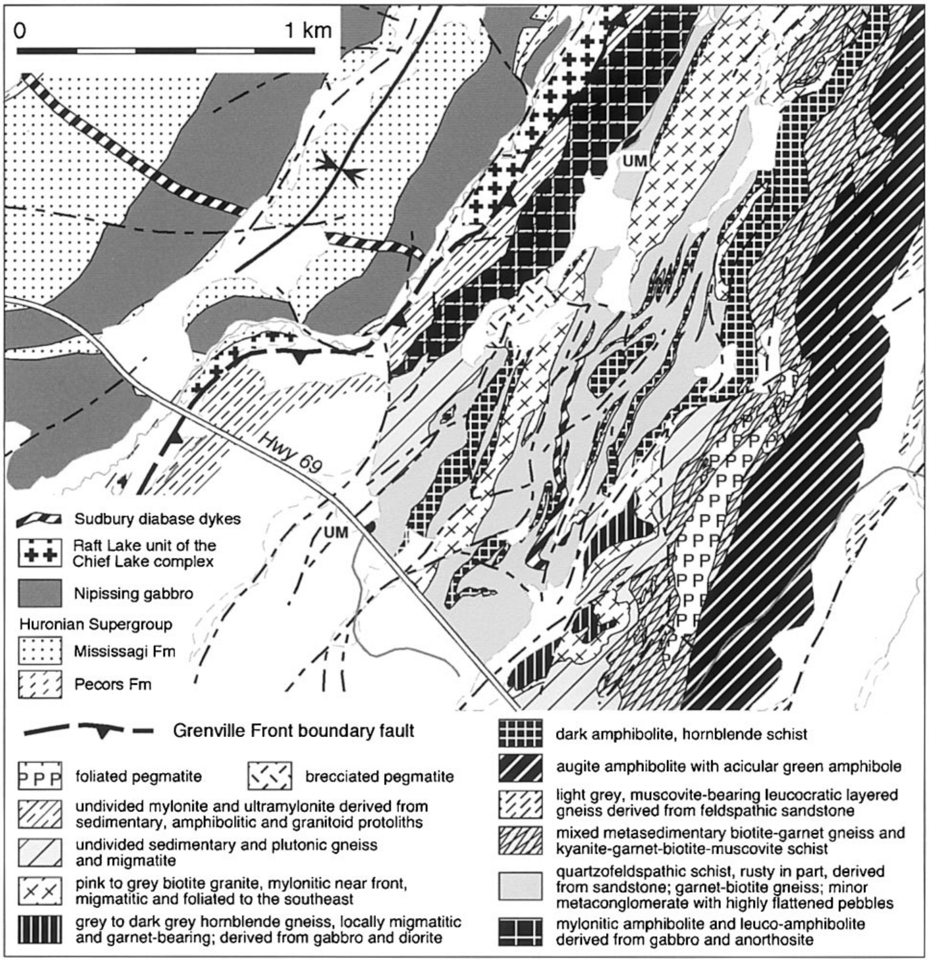

Fig. 8. Detailed geology of the hanging wall of the GFBF northeast of Highway 69 (northeast corner of Fig. 2). Small black units designated UM are occurrences of ultramafic rock. Note that a north-trending dyke of Sudbury metadiabase (central part of the figure) cuts across an isoclinally folded unit of amphibolite.

4.4. Sudbury metadiabase

Henderson (1967a) mapped a southeast-trending diabase dyke segment within the disrupted anorthositic gabbro sheet southwest of Brodill Lake (Fig. 2), and Hsu (1968) identified isolated pods of diabase to the northeast. Diabase at these occurrences is distinctly metamorphosed, having pale orthopyroxene with green amphibole coronas replacing olivine, and Ti–biotite, brown amphibole, and garnet symplectite coronas around cores of primary Fe–Ti oxide. The metadiabase segments and pods nevertheless have preserved chilled contacts along their long sides, where they cut cleanly across the fabric of mylonitic gabbroic anorthosite, and of foliated migmatitic quartzofeldspathic gneiss near Brodill Lake.

A previously unrecognized, one-kilometre-long segment of a metadiabase dyke just northeast of Highway 69 (Fig. 8), which dips moderately to steeply east, cuts foliation and isoclinal folds at a shallow angle, but itself exhibits pinch-and-swell structure and is folded at its southern end. Although in large part internally massive, it grades to foliated amphibolite where pinched, and also where it thins northward as it approaches the

GFMZ, within which it has not been recognized. A sample from its southern part, containing primary augite and plagioclase with well-preserved ophitic texture, shows a slightly lower grade of metamorphism than metadiabase near Brodill Lake; garnet is absent from Fe–Ti oxide coronas, and olivine is replaced by acicular cummingtonite, rather than orthopyroxene, surrounded by blue–green hornblende. In both localities, however, it is clear that the grade of metamorphism recorded in metadiabase is lower than in its country rocks. This accords with the observation that the higher grade assemblages in the gneissic rocks are commonly partly or wholly retrograded, e.g. chloritization of garnet, staurolite and biotite, development of muscovite and margarite rims on kyanite (Davidson et al., 1990).

5. Correlation of rock units across the Grenville Front

5.1. Supracrustal rocks

The metasedimentary gneissic rocks in the Grenville Front hanging wall in the study area are too varied in composition to be directly correlative with the Huronian rocks exposed in the immediate footwall (predominantly Mississagi and Pecors formations). Most of the biotitic gneiss is not rich enough in quartz to be equated with the Mississagi Formation, although thin layers of impure quartzite do occur locally. Because potential representatives of the other quartz-rich Huronian formations (Serpent, Lorrain, Bar River) are not present in the hanging wall, correlation would have to be with sub-Mississagi formations of the Hough Lake and Elliot Lake groups. However, the local presence of thin but persistent layers with calc-silicate minerals, rarely with calcite, suggests derivation from the Espanola Formation of the succeeding Quirke Lake Group, yet the absence of the stratigraphically higher quartz-rich units mentioned above would seem to preclude the presence of anything higher in the Huronian succession. The rusty-weathering metasedimentary gneiss in the vicinity of Highway 69 (Fig. 8) does not have an obvious Huronian counterpart. Metaconglomerate in this package is too highly strained to retain characteristics diagnostic of a particular Huronian conglomerate formation, although if nearby calcareous gneiss is assigned to the Espanola Formation, the most likely correlation would be with the Bruce Formation. The favoured Huronian equivalents of the kyanite-rich rocks would be the argillaceous McKim (uppermost Elliot Lake Group) or Pecors formations, but their association with quartzite is at odds with this correlation.

The same problem of trying to evaluate what are the potential formational correlatives of the paragneiss units in the Grenville Front hanging wall has been addressed by Easton et al. (1996, 1999), and Davidson (1998b) in the same zone northeast of Coniston, where mappable units of similar but less flattened metasedimentary gneiss display a relatively coherent ‘stratigraphy’ that does not resemble the Huronian succession. Easton et al. (1999) correlated a narrow strip at the front with lower Huronian stratigraphy, but were unable to suggest correlation for higher-grade gneissic rocks farther southeast. Davidson (1998b) suggested that differences could be accounted for by appealing to tectonic juxtaposition of formerly distal facies, equivalent in age to the Huronian Supergroup if not directly correlative. This potential correlation differs from that envisaged by Lumbers (1978), who favoured an essentially in situ facies change coincident with the Grenville Front.

Dickin and McNutt (1989) reported Nd depleted mantle model ages for gneissic rocks collected along Highway 69 south of the Grenville Front. Only one of their samples, a paragneiss, is from the package under consideration here; its reported T_{DM} is 2.78 Ga. However, although the Huronian Supergroup has an Archean provenance, correlation on this basis is only permissive, since there is no reason why post-Huronian rocks should not also have had an Archean provenance (Easton et al., 1999). Moreover, two samples of migmatitic paragneiss collected farther southwest, respectively 3 and 8 km from the GFBF, have Nd model ages of ca. 2.12 Ga (F.Ö. Dudás, unpublished data, 1991, quoted in Davidson, 1994), which is too young for these rocks to be correlative with the Huronian Supergroup. Thus, it must be allowed that not all supracrustal rocks in the Grenville Front tectonic zone (in the sense of Wynne-Edwards, 1972) are necessarily Huronian equivalents.

5.2. Mafic rocks

On the basis of composition, it is clear that not all of the sheets of mafic rock can be correlated with Nipissing gabbro. The remnants of a substantial anorthositic component in the two mafic bodies close to the GFBF are similar to other units of this type mapped farther northeast in the Grenville Front tectonic zone, the nearest being only 6 km northeast of Highway 69 (Lumbers, 1975). Similar bodies of anorthositic gneiss extend for 50 km farther northeast, parallel to the front, where they link with the well-preserved River Valley anorthositic gabbro, dated at 2475 Ma (L.M. Heaman, personal communication, 1999), and equated by Easton et al. (1999) with the East Bull Lake intrusive suite in the Southern Province. The distinctive ultramafic rock in pods within the hanging wall is also common farther northeast (Davidson, 1998b; Easton et al., 1996, 1999). It has no known counterpart in the foreland, but it contains zircon whose U–Pb age is coeval with the East Bull Lake intrusive suite (Corfu and Easton, 1998).

The units designated as ‘black amphibolite’ and ‘green amphibolite with acicular amphibole’ in Figs. 2 and 8, distinguished by Kwak (1968) but not by Lumbers (1975), are distinctly different in appearance. It may be, however, that this is a function of the amount of deformation and recrystallization they have undergone. The black amphibolite units are closer to the GFBF and are much more highly attenuated and folded. Both are reasonable candidates for correlation with Nipissing gabbro, but correlation would have to be based on whole-rock chemistry because deformation and recrystallization negate making comparison on a textural basis. Analyses of similar amphibolite bodies within paragneiss close to the Grenville Front farther northeast (Easton et al., 1999, Table 2) do not closely resemble ‘average’ Nipissing gabbro. However, since Nipissing gabbro is quite variable in composition (e.g. Card and Pattison, 1973), correlation is not ruled out.

The origin of the type of mafic rock identified as ‘metagabbro, hornblende–garnet gneiss’ in Fig. 2 is enigmatic. Elsewhere in this region, where intimately interlayered not only with pelitic gneiss but with calc-silicate marble, garnet amphibolite has been interpreted to have a supracrustal precursor (Davidson, 1998b). If layered garnet amphibolite is indeed derived from a calcareous sedimentary protolith, then, using the same argument as for the calcareous metasedimentary rocks engulfed in the CLC, the logical Huronian correlative is the Espanola Formation. Analyses of equivalent rocks northeast of the study area are unlike those of mafic volcanic rocks in the Elliot Lake Group (Easton et al., 1999).

5.3. Granitoid rocks

The map-pattern of folded sheets, generally less than 500 m thick, of mylonitic or foliated granitoid rocks suggests superficially that these may have been sill-like intrusions within the enclosing metasedimentary gneiss. However, their state of internal deformation in the basal hanging wall is more in keeping with derivation by ductile distortion of more equant bodies. Those with non-mylonitic fabric structurally higher in the hanging wall are recrystallized and no longer have an igneous texture. Except southwest of Brodill Lake, they are not in fault contact with granitoid rocks of the CLC, the two being separated by metasedimentary mylonite and schist. None of the units of foliated granitoid shown in Fig. 2 contains feldspar augen, so the rocks do not look like deformed Raft Lake or Linton Lake units in the immediate footwall, to which they are otherwise similar in bulk composition. Potential equivalents to the characteristic mafic commingled phase of the Raft Lake unit were not recognized. A possible alternative correlation is with migmatitic granitoid gneiss in the hanging wall farther northeast, which has been dated at ca. 2.47 Ga (Easton et al., 1999), correlative in age with rhyolite of the Elliot Lake Group (Krogh et al., 1984) and associated granitoid intrusions (Krogh et al., 1996). To the southwest, however, granitoid rocks of both 1.74 and 1.47 Ga are present on both sides of the front (Krogh et al., 1971; van Breemen and Davidson, 1988; Davidson et al., 1992; Davidson and van Breemen, 1994). Without further dating, therefore, correlation between granitoid gneiss in the hanging wall southeast of the CLC with a particular foreland suite cannot be made.

5.4. Sudbury metadiabase

Of all the correlations across the Grenville Front in the Sudbury region, that of Sudbury diabase dykes in the footwall with metadiabase dyke remnants in the hanging wall is the most certain. Unpublished chemical analyses of samples from localities within the CLC and southeast of the GFBF show that they have the characteristic chemistry of Sudbury diabase (Bethune, 1993; Bethune and Davidson, 1997). Moreover, U–Pb ages of primary baddeleyite from diabase and metadiabase on opposing sides of the front are the same (Dudás et al., 1994), confirming their role as an important time marker in the structural and metamorphic history of the Grenville Front.

5.5. Summary of structure and metamorphism, and their age relationships

Relative age relationships between structures and Sudbury metadiabase above the GFMZ make it clear that a large component of the deformation is pre-Grenvillian. Inability to track individual Sudbury dykes across the GFBF and their occurrence only as small, isolated boudins in the GFMZ suggest that the intense flattening in with this zone reduced them to isolated boudins or thin mafic layers of unrecognizable protolith. This interpretation is supported by the way in which the dyke remnant northeast of Highway 69 becomes thinner northward as it curves toward parallelism with the GFBF, and by the fact that much more continuous segments of Sudbury metadiabase are preserved farther southeast (Bethune, 1997).

The discrepancy between the grades of metamorphism exhibited by the dykes and their host rocks implies that the amphibolite-facies metamorphism prevalent in the gneissic rocks is also pre-Grenvillian, and that the Grenvillian metamorphic overprint did not exceed greenschist facies within a kilometre or so of this part of the GFBF. However, dyke remnants less than 5 km southeast of the GFBF are two-pyroxene–garnet coronite, illustrating a Grenvillian metamorphic gradient also increasing southeastward (cf. Bethune and Davidson, 1997). The age of pre-Grenvillian metamorphism in the Grenville hanging wall southeast of the CLC has not been determined. However, in analogous locations along this part of the Grenville Front, metamorphic ages of ca. 1.45 Ma have been obtained farther southwest for zircon (Krogh, 1994), monazite (Dudás et al., 1994) and titanite (Haggart et al., 1993), and two metamorphic ages, ca. 1.47 Ga and ca. 1.72 Ga, have been reported farther northeast (Easton et al., 1999). These data suggest that the Grenville hanging wall records evidence of two periods of tectonism that are coeval with the two Proterozoic plutonic suites in the neighbouring Southern Province.

6. Conclusion

The following can be said about the CLC and the Grenville Front adjacent to it:

(1) Grenvillian and pre-Grenvillian structure and metamorphism can be distinguished using the ca. 1.24 Ga Sudbury dykes. Grenvillian effects are manifested by an increase in deformation and metamorphism exhibited by the dykes, with a progressively deeper crustal level being exposed to the southeast. Displacement that brought this about was concentrated on faults, the greatest displacement being on the master fault referred to as the GFBF.

(2) The Sudbury dykes must originally have been emplaced across what is now the Grenville Front, presumably at a time of crustal quiescence. Southeast of the front, their higher grade of metamorphism and involvement in ductile deformation imply that they must have been deeply buried during Grenvillian orogeny (cf. Bethune, 1997).

(3) The dykes were emplaced cleanly across earlier structures on both sides of the front. The earlier deformation fabric in the CLC footwall can be no older than ca. 1.47 Ga, and may have

developed during emplacement of the granitic rocks (i.e. while they were still hot) on the basis that Huronian metasedimentary rocks and Nipissing gabbro in rafts and septa do not have the same fabric as the granitoid rocks that enclose them. The age of the earlier structures southeast of the Grenville Front is not known, but U–Pb ages in the hanging wall near Georgian Bay point at least to regional metamorphism at ca. 1.45 Ga.

(4) Elements of stratigraphic succession preserved in the enclaves of Huronian rocks within the CLC allow delineation of earlier folds, now disrupted by faults. Juxtaposition of vastly different stratigraphic levels along the northwest contact of the CLC implies either that intrusion exploited an older major fault, or that the contact was subsequently faulted, in both cases displacement being down to the southeast; another alternative is that the original Huronian roof foundered within granite magma. The NW-directed thrust sense of shear of the pre-Grenvillian foliation, if syn-emplacement, may point to magmatism at the NW margin of a developing orogen at that time.

It has been recognized for some time that the Grenville Front is *not* a terrane boundary of Grenvillian age in the plate tectonic sense. The gneissic rocks in the tectonic zone adjacent to the front do not belong to an exotic or far-travelled terrane, a conclusion reached earlier by many authors on the basis that the same rock units can be recognized on both sides of the front in many places along its length. In the Sudbury region the presence of plutonic rocks of 1.47, 1.74, and possibly of 2.47 Ga age on both sides of the front agree with this, but in addition support the contention that the front itself was never such a boundary in all of Proterozoic time. The presence of sedimentary protoliths on the Grenville side that cannot be unequivocally correlated with the Huronian Supergroup in the adjacent Southern Province is still an enigma, and must be explained by interpreting these rocks as either Huronian facies equivalents or a younger supracrustal succession that is not now preserved, if ever present, northwest of the front. Compressive closure toward the front is not in question, but this has taken place within contiguous crust.

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References

Bennett, G., Dressler, B.O., Robertson, J.A., 1991. The Huronian Supergroup and associated intrusive rocks. In: Thurston, P.C., Williams, H.R., Sutcliffe, R.H., Stott, G.M. (Eds.), Geology of Ontario. Ontario Geol. Surv. Spec. Vol. 4, pp. 540–591.

Bethune, K.M., 1993. Evolution of the Grenville Front in the Tyson Lake area, southwest of Sudbury, Ontario, with emphasis on the tectonic significance of the Sudbury diabase dykes. PhD thesis, Queen's University, Kingston, Ont., Canada, 263 pp.

Bethune, K.M., 1997. The Sudbury dyke swarm and its bearing on the tectonic development of the Grenville Front, Ontario, Canada. Precambr. Res. 85, 117–146.

Bethune, K.M., Davidson, A., 1997. Grenvillian metamorphism of the Sudbury diabase dyke-swarm: from protolith to two-pyroxene–garnet coronite. Can. Mineral. 35, 1191–1220.

Boerner, D.E., Milkereit, B., Davidson, A., 2000. Geophysical impact: a synthesis of studies of the Sudbury structure. Can. J. Earth Sci. 37, 477–501.

Brocoum, S.J., Dalziel, I.W.D., 1974. The Sudbury Basin, the Southern Province, the Grenville Front, and the Penokean Orogeny. Geol. Soc. Am. Bull. 85, 1571–1580.

Brooks, E.R., 1964. Nature and Origin of the Grenville Front North of Georgian Bay. PhD thesis, University of Wisconsin, Madison, Wisconsin, 183 pp.

Brown, J.M., 1967. The Grenville Front south of Coniston, Ontario. In: Jenness, S.E. (Ed.), Guidebook, Geology of Parts of Eastern Ontario and Western Quebec. Geol. Assoc. Can., pp. 11–12.

Brown, J.M., 1968. Structure and Origin of the Grenville Front South of Coniston, Ontario. PhD thesis, University of Wisconsin, Madison, Wisconsin, 168 pp.

Card, K.D., 1978. Geology of the Sudbury–Manitoulin area, districts of Sudbury and Manitoulin. Ontario Geol. Surv. Rep. 166, 238 pp.

Card, K.D., Church, W.R. Franklin, J.M., Frarey, M.J., Robertson, J.A., West, G.F., Young, G.M., 1972. The Southern Province. In: Price, R.A., Douglas, R.J.W.

(Eds.), Variations in Tectonic Styles in Canada. Geol. Assoc. Can. Spec. Pap. 11, pp. 335–380.

Card, K.D., Lumbers, S.B., 1977. Sudbury–Cobalt. Ontario Geol. Surv., Geological Compilation Series, Map 2361, scale 1:253 440.

Card,K.D., Palonen, P.A., Siemiatkowska, K.M., 1975. Geology of the Louise–Eden Area, District of Sudbury. Ontario Div. Mines, Geol. Rep. 124, 66 pp. and Map 2299, scale 1:31 680.

Card, K.D., Pattison, E.F., 1973. Nipissing diabase of the Southern Province, Ontario. In: Young, G.M. (Ed.), Huronian Stratigraphy and Sedimentation. Geol. Assoc. Can. Spec. Pap. 12, pp. 7–30.

Collins, W.H., 1936. Sudbury Series. Geol. Soc. Am. Bull. 47, 1675–1679.

Corfu, F., Andrews, A.J., 1986. A U–Pb age for mineralized Nipissing diabase, Gowganda, Ontario. Can. J. Earth Sci. 23, 107–109.

Corfu, F., Easton, R.M., 1998. Extension of the Huronian magmatic suite inside the Grenville Province: new zircon U–Pb evidence from the Grenville Front tectonic zone in Street Township, Sudbury region, Ontario. Proc. 44th Ann. Inst. Lake Superior Geology 44, 59–60.

Dalziel, I.W.D., Brown, J.M., Warren, T.E., 1969. The structural and metamorphic history of the rocks adjacent to the Grenville Front near Sudbury, Ontario, and Mount Wright, Quebec. In: Wynne-Edwards, H.R. (Ed.), Age Relations in High-grade Metamorphic Terrains. Geol. Assoc. Can. Spec. Pap. 5, pp. 207–224.

Davidson, A., 1986. A New Look at the Grenville Front. Geol. Assoc. Can., Field Trip 15, Guidebook, 31 pp.

Davidson, A., 1992. Relationship between faults in the Southern Province and the Grenville Front southeast of Sudbury, Ontario. In: Current Research, Part C, Geol. Surv. Can. Pap. 92-1C, pp. 121–127.

Davidson, A., 1994. Grenville Front relationships in the Sudbury area, Ontario. Geol. Assoc. Can., Field Trip B2 Guidebook, 39 pp.

Davidson, A., 1998a. An overview of Grenville Province geology, Canadian Shield. In: Lucas, S.B., St-Onge, M.R. (Co-ords.), Geology of the Precambrian Superior and Grenville Provinces and Precambrian Fossils in North America. Geol. Surv. Can., Geology of Canada, no. 7, pp. 205–270 (chapter 3).

Davidson, A., 1998b. Questions of correlation across the Grenville Front east of Sudbury. Geol. Surv. Can. Current Res. 1998-C, pp. 145–154.

Davidson, A., Carmichael, D.M., Pattison, D.R.M., 1990. Metamorphism and Geodynamics of the Southwestern Grenville Province, Ontario. Internat. Union Geol. Sci., Internat. Geol. Correlation Program, Project 235-304, Field Trip # 1 Guidebook, 123 pp.

Davidson, A., Ketchum, J.W.F., 1993. Grenville Front studies in the Sudbury region, Ontario. In: Current Research, Part C, Geol. Surv. Can. Pap. 93-1C, pp. 271–278.

Davidson, A., van Breemen, O., 1994. U–Pb ages of granites near the Grenville Front, Ontario. In: Radiogenic Age and Isotopic Studies, Rep. 8, Geol. Surv. Can. Pap. 1994-F, pp. 107–114.

Davidson, A., van Breemen, O., Sullivan, R.W., 1992. Circa 1.75 Ga ages for plutonic rocks from the Southern Province and adjacent Grenville Province: what is the expression of the Penokean orogeny? In: Radiogenic Age and Isotopic Studies, Rep. 6, Geol. Surv. Can. Pap. 92-2, pp. 107–118.

Davis, G.L., Hart, S.R., Aldrich, L.T., Krogh, T.E., Munizaga, F., 1966. Rb/Sr chronology of the granitic rocks southeast of Sudbury, Ontario. In: Carnegie Inst. Washington Yearbook 65, pp. 383–386.

Dickin, A.P., McNutt, R.H., 1989. Nd model age mapping of the southeast margin of the Archean foreland in the Grenville province of Ontario. Geology 17, 299–302.

Dressler, B.O., 1984. Sudbury Geological Compilation; Ontario Geol. Surv., Map 2491, Precambrian Geology Series, scale 1: 50 000.

Dudás, F.Ö., Davidson, A., Bethune, K.M., 1994. Age of the Sudbury diabase dykes and their metamorphism in the Grenville Province, Ontario. In: Radiogenic Age and Isotopic Studies, Rep. 8, Geol. Surv. Can. Pap. 1994-F, pp. 97–106.

Easton, R.M., Buckley, S.G., Lobanok, E., James, R.S., 1996. Grenville–Southern province relationships in Street Township, District of Sudbury. In: Report of Field Work and Other Activities. Ontario Geol. Surv. Misc. Pap. 166, pp. 66–69.

Easton, R.M., Davidson, A., Murphy, E., 1999. Transects across the Grenville Front near Sudbury, Ontario. Geol. Assoc. Can., Field Trip A2 Guidebook, 52 pp.

Fahrig, W.F., 1987. The tectonic settings of continental mafic dyke swarms: failed arm and early passive margin. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geol. Assoc. Can., Spec. Pap. 34, pp. 331–348.

Fahrig, W.F., Gaucher, E.H., Larochelle, A., 1965. Palaeomagnetism of diabase dykes of the Canadian Shield. Can. J. Earth Sci. 2, 278–298.

Frarey, M.J., 1985. Proterozoic geology of the Lake Panache–Collins Inlet area. Geol. Surv. Can. Pap. 83-22, 61 pp.

Fueten, F., Redmond, D.J., 1997. Structural history between the Sudbury Structure and the Grenville Front, Ontario, Canada. Geol. Soc. Am. Bull. 109, 268–279.

Gower, C.F., Schärer, U., Heaman, L.M., 1992. The Labradorian orogeny in the Grenville Province, eastern Labrador, Canada. Can. J. Earth Sci. 29, 1944–1957.

Grant, J.A., Pearson, W.J., Phemister, T.C., Thomson, J.E., 1962. Geology of Broder, Dill, Neelon, and Dryden Townships, District of Sudbury. Ontario Dep. Mines Geol. Rep. 9, 1–24.

Haggart, M.J., Jamieson, R.A., Reynolds, P.H., Krogh, T.E., Beaumont, C., Culshaw, N.G., 1993. Last gasp of the Grenville orogeny: thermochronology of the Grenville Front Tectonic Zone near Killarney, Ontario. J. Geology 101, 575–589.

Henderson, J.R., 1967a. Structural and Petrologic Relations Across the Grenville Province–Southern Province

Boundary, Sudbury District, Ontario. PhD thesis, McMaster University, Hamilton, Ont., Canada, 119 pp.

Henderson, J.R., 1967b. The Grenville Front in the region east and south of Sudbury, Ontario. In: Jenness, S.E. (Ed.), Guidebook, Geology of Parts of Eastern Ontario and Western Quebec. Geol. Assoc. Can., pp. 5–9.

Henderson, J.R., 1972. Deformation of the Chief Lake Batholith, Ontario, Canada. 25th Internat. Geol. Congress, Sect. C, pp. 505–515.

Henderson, J.R., Kwak, T.A.P., Brown, J.M., 1967. The Grenville Front at Sudbury, Ontario. In: Jenness, S.E. (Ed.), Guidebook, Geology of Parts of Eastern Ontario and Western Quebec. Geol. Assoc. Can., pp. 277–283.

Hoffman, P.F., 1989. Precambrian geology and tectonic history of North America. In: Bally, A.W., Palmer A.R. (Eds.), The Geology of North America – an Overview. Geol. Soc. Am., The Geology of North America A, pp. 447–512.

Howell, D.G., 1989. Tectonics of Suspect Terranes. Chapman & Hall, New York, 232 pp.

Hsu, M.-Y., 1968. Structural Analysis along the Grenville Front near Sudbury, Ontario. MSc thesis, McMaster University, Hamilton, Ont., Canada, 104 pp.

Kamo, S.L., Krogh, T.E., Kumarapeli, P.S., 1995. Age of the Grenville dyke swarm, Ontario–Quebec: implications for the timing of Iapetus rifting. Can. J. Earth Sci. 32, 273–280.

Krogh, T.E., 1994. Precise U–Pb ages for Grenvillian and pre-Grenvillian thrusting of Proterozoic and Archean metamorphic assemblages in the Grenville Front tectonic zone, Canada. Tectonics 13, 963–982.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenhough, J.D., Nakamura, N., 1987. Precise U–Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geol. Assoc. Can. Spec. Pap. 34, pp. 147–152.

Krogh T.E., Davis, D.W., Corfu, F., 1984. Precise U–Pb zircon and baddeleyite ages for the Sudbury area. In: Pye, E.G., Naldrett, A.J., Giblin, P.E. (Eds.). The Geology and Ore Deposits of the Sudbury Structure. Ontario Geol. Surv. Spec. Vol. 1, pp. 431–446.

Krogh, T.E., Davis, G.L., 1968. Geochronology of the Grenville Province. In: Carnegie Inst. Washington Yearbook 67, pp. 224–230.

Krogh, T.E., Davis, G.L., Frarey, M.J., 1971. Isotopic ages along the Grenville Front in the Bell Lake area, southwest of Sudbury, Ontario. In: Carnegie Inst. Washington Yearbook 69, pp. 337–339.

Krogh, T.E., Kamo, S.L., Bofor, B.F., 1996. Shocked metamorphosed zircons with correlated U–Pb discordance and melt rocks with concordant protolith ages indicate an impact origin for the Sudbury Structure. In: Basu, S., Hart, S.R. (Eds.), Earth Processes: Reading the Isotopic Code. Am. Geophys. Union, Geophys. Monograph 95, pp. 343–353.

Kwak, T.A.P., 1968. Metamorphic Petrology and Geochemistry Across the Grenville Province, Southern Province Boundary, Dill Township, Sudbury, Ontario. PhD thesis, McMaster University, Hamilton, Ont., Canada, 200 pp.

Larsen, S.Å, Berglund, J., Stigh, J., Tullborg, E.-L., 1990. The Protogine Zone, southwest Sweden: a new model – an old issue. In: Gower, C.F., Ryan, A.B., Rivers, T. (Eds.), Mid-Proterozoic Laurentia-Baltica. Geol. Assoc. Can. Spec. Pap. 38, pp. 317–333.

La Tour, T.E., 1979. The Nature and Origin of the Grenville Front near Coniston, Ontario: a Reinterpretation. PhD thesis, University of Western Ontario, London, Ontario, 344 pp.

La Tour, T.E., 1981. A clue to the tectonic evolution of the Grenville Front. Can. J. Earth Sci. 18, 884–898.

Lumbers, S.B., 1965. Lake Nipissing area, districts of Sudbury, Nipissing, and Parry Sound. In: Thomson, J.E. (Ed.), Summary of Field Work, 1965. Ontario Dep. Mines Prelim. Rep. 1965-3, pp. 53–57.

Lumbers, S.B., 1971a. Some aspects of the northwest margin of the Grenville Province between Sudbury and Lake Timiskaming, Ontario. Abstracts of Papers, Geol. Assoc. Can., Annual Meeting, Sudbury, Ont., pp. 36–37.

Lumbers, S.B., 1971b. River Valley area. In: Summary of Field Work 1971. Ontario Dep. Mines and Northern Affairs Misc. Pap. 49, pp. 90–97.

Lumbers, S.B., 1971c. Burwash area (west half), districts of Sudbury and Parry Sound. Ontario Dep. Mines and Northern Affairs, Prelim. Map P.860.

Lumbers, S.B., 1973. River Valley area. Ontario Div. Mines, Prelim. Map P.844.

Lumbers, S.B., 1975. Geology of the Burwash Area, Districts of Nipissing, Sudbury, and Parry Sound. Ontario Div. Mines, Geol. Rep. 116, 158 pp.

Lumbers, S.B., 1978. Geology of the Grenville Front Tectonic Zone in Ontario. In: Currie, A.L., and Mackasey, W.O. (Eds.), Toronto '78, Field Trips Guidebook. Geol. Assoc. Can., pp. 347–361.

Merz, B.A., 1976. Potassium–argon dating, paleomagnetism, and geochemistry of the Sudbury diabase dykes. MSc thesis, University of Western Ontario, London, Ont., Canada, 102 pp.

Noble, S.R., Lightfoot, P.C., 1992. U–Pb baddeleyite ages of the Kerns and Triangle Mountain intrusions, Nipissing diabase, Ontario. Can. J. Earth Sci. 29, 1424–1429.

North American Commission on Stratigraphic Nomenclature, 1983. North American stratigraphic code. Bull. Am. Assoc. Petroleum Geologists Bull. 67, 841–875.

Palmer, H.C., Merz, B.A., Hyatsu, A., 1977. The Sudbury dikes and the Grenville Front region: paleomagnetism, petrochemistry, and K–Ar ages. Can. J. Earth Sci. 14, 1867–1887.

Paterson, S.R., Vernon, R.H., Tobisch, O.T., 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. J. Struct. Geol. 11, 349–363.

Phemister, T.C., 1960. The nature of the contact between the Grenville and Timiskaming subprovinces in the Sudbury

District of Ontario, Canada. In: The Granite–Gneiss Problem. XXI Internat. Geol. Congress, pt. 14, pp. 108–119.

Phemister, T.C., 1961. The boundary between the Timiskaming and Grenville subprovinces in the townships of Neelon, Dryden, Dill and Broder, District of Sudbury. Ontario Dep. Mines, Prelim. Rep. 1961-5.

Pitcher, W.S., 1993. The Nature and Origin of Granite, First ed. Blackie, Glasgow, 32 pp.

Quirke, T.T., 1940. Granitization near Killarney, Ontario. Geol. Soc. Am. Bull. 51, 237–254.

Quirke, T.T., Collins, W.H., 1930. The Disappearance of the Huronian, Memoir, vol. 160. Geol. Surv. Can., Memoir 130, 129 pp.

Riller, U., Schwerdtner, W.M., 1997. Mid-crustal deformation at the southern flank of the Sudbury Basin, central Ontario, Canada. Geol. Soc. Am. Bull. 109, 841–854.

Shanks, W.S., Schwerdtner, W.M., 1991a. Structural analysis of the central and southwestern Sudbury Structure, Southern Province, Canadian Shield. Can. J. Earth Sci. 28, 411–430.

Shanks, W.S., Schwerdtner, W.M., 1991b. Crude quantitative estimates of the original northwest–southeast dimension of the Sudbury Structure, south-central Canadian Shield. Can. J. Earth Sci. 28, 1677–1686.

Spaven, H.R., 1966. Granite Tectonics in Part of Eden Township, Sudbury District, Ontario. MSc thesis, McMaster University, Hamilton, Ont., Canada.

Stockwell, C.H., 1982. Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield; part I: a time classification of Precambrian rocks and events. Geol. Surv. Can. Pap. 80-19, 135 pp.

Sullivan, R.W., Davidson, A., 1993. Monazite age of 1747 Ma confirms post-Penokean age for the Eden Lake complex, Southern Province. In: Radiogenic Age and Isotopic Studies, Rep. 7. Geol. Surv. Can. Pap. 93-2, pp. 45–48.

van Breemen, O., Davidson, A., 1988. Northeast extension of Proterozoic terranes of mid-continental North America. Geol. Soc. Am. Bull. 100, 630–638.

Wynne-Edwards, H.R., 1972. The Grenville Province. In: Price, R.A., Douglas, R.J.W., Variations in Tectonic Styles in Canada. Geol. Assoc. Can. Spec. Pap. 11, pp. 263–334.