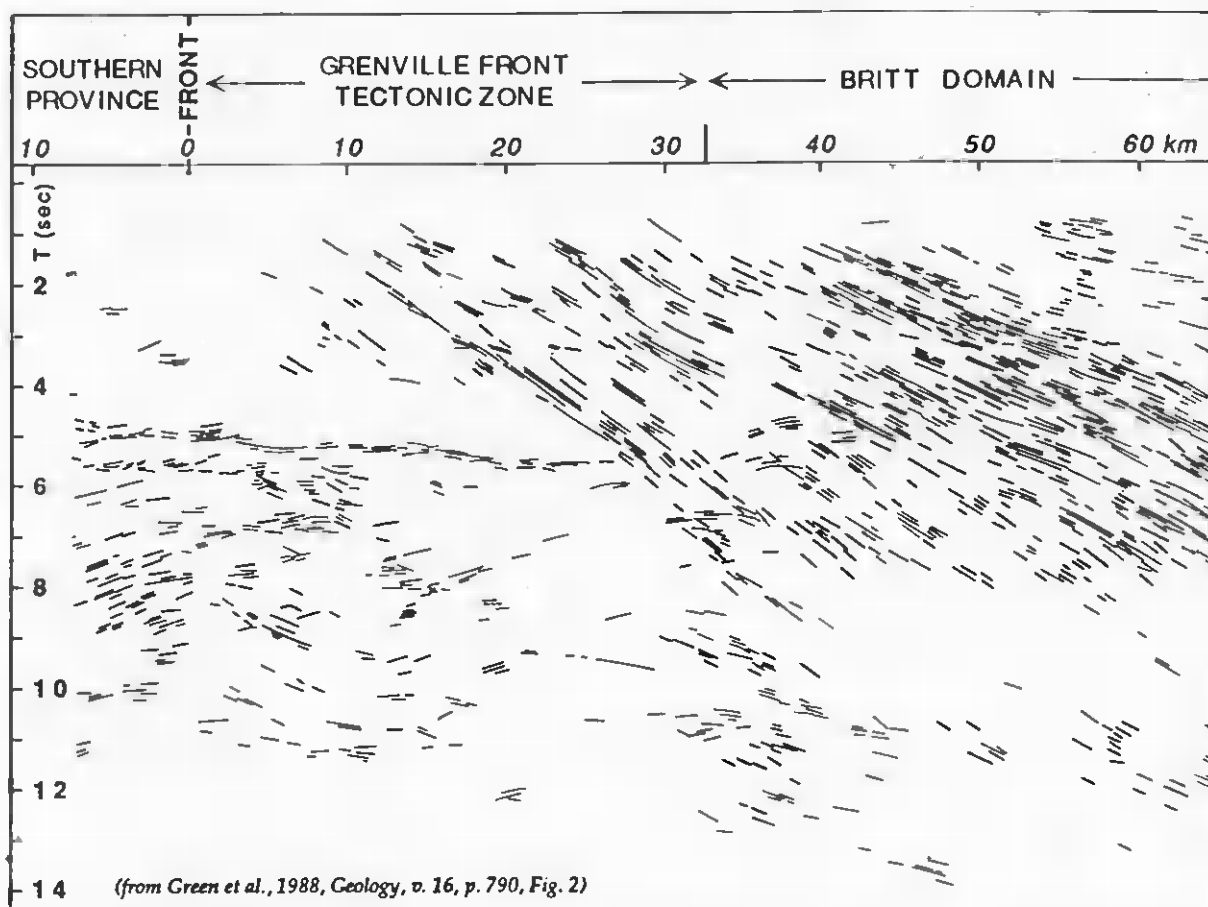


NEW INFORMATION ON THE GRENVILLE FRONT NEAR SUDBURY

BY

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Frontispiece: Line drawing from part of GLIMPCE Seismic reflection Line J, W to E line crossing the Grenville Front in Georgian Bay (from Green et al, 1988, *Geology*, v. 16, p. 790, Figure 2)

NEW DEVELOPMENTS IN GRENVILLE FRONT GEOLOGY, SUDBURY AREA, ONTARIO

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LIST OF CONTENTS

Introduction	1
Southern Province	2
Grenville Province	5
The Grenville Front	6
Sudbury dyke swarm	9
Field trip summary	13
Road log and stop descriptions	15
Stop 1 Mississagi sandstone, Nipissing gabbro and Sudbury diabase	15
Stop 2 Slaty argillite, Pecors Formation, and "trap dyke"	16
Stop 3 Conglomerate, Ramsey Lake Formation	17
Stop 4 The Grenville Front, Highway 69	18
Stop 5 Metasedimentary rocks in the Grenville Province	20
Stop 6 Truncation of the Grenville Front mylonite zone at Alice Lake	21
Stop 7 Comparison of Southern and Grenville Province rocks on opposite sides of the Wanapitei fault	24
Stop 8 Grenville Front relationships near the Stinson hydroelectric dam	25
Stop 9 Metamorphosed Sudbury diabase dyke segments in metasedimentary gneiss	27
Comments – problems of correlation and history of the Grenville Front	29
References	33

LIST OF ILLUSTRATIONS

Figure 1. Generalized geology of the Sudbury region	3
Figure 2. The Sudbury dyke swarm, Southern and Grenville provinces	10
Figure 3. Geology of the Grenville Front southeast of Sudbury	14
Figure 4. Detailed geology, the Grenville Front at Stop 4, Highway 69	19
Figure 5. The Grenville Front between Highway 69 and Coniston	22
Figure 6. Fault interpretations in the Coniston area	23
Figure 7. The Grenville Front at Stop 7, near Stinson	26
Figure 8. Metadiabase dyke remnants; relics of the Sudbury swarm	28
Table 1. Huronian Supergroup stratigraphic succession in the Sudbury area	2

NEW DEVELOPMENTS IN GRENVILLE FRONT GEOLOGY, SUDBURY AREA, ONTARIO

INTRODUCTION

The Grenville orogen, formed during the latter part of mid-Proterozoic time, extends from Scandinavia to Texas and beyond. The Grenville Province is that part of the orogen which is exposed in the southeastern Canadian Shield. Its northwest boundary with older Shield provinces is known as the Grenville Front, and is a major tectonic lineament marked by faults and mylonite zones inclined to the southeast. It is a structural front in the sense that it truncates the structural trends that characterize the older provinces to the northwest. It is a metamorphic front in the sense that high-grade metamorphic rocks characterize the marginal Grenville orogen, whereas metamorphic grade varies along the footwall of the front, depending on the exhumed crustal level exposed in the different provinces that abut it. The high-grade metamorphism in the immediate hangingwall is not everywhere Grenvillian in age; it attests to uplift in Grenvillian time of the Grenville orogen relative to the adjacent Shield provinces.

The Grenville Front is well exposed in the vicinity of Sudbury, Ontario, where the Southern Province constitutes its footwall (Fig. 1). It has been the subject of attention—and in retrospect, controversy—for several decades, and shadows of former attempts to explain some of the more enigmatic features of this structure and the complicated Grenvillian terrane that forms its hangingwall are still evident in recently compiled maps (*e.g.* Card and Lumbers 1977; Dressler 1984). It must be admitted that the Southern Province is known in much more detail, and is thus better understood, than the adjacent Grenville, despite recent advances in interpreting the latter (Davidson 1986*a*, 1995; Easton 1992). This is not to say that there is consensus on the interpretation of the geologic history of the Southern Province—there are several topics of dispute outstanding, and reinterpretations to be made (*e.g.* Davidson *et al.* 1992; Card 1992). Resolution of many of these will have a direct bearing on how the rocks in the adjacent Grenville Province are viewed.

Before outlining the historical development of ideas concerning the Grenville Front in the area southeast east of Sudbury, it is advantageous to be familiar with what is presently known about the local geology. Brief summaries of our current knowledge of the geology of the Southern and Grenville provinces in this area are therefore presented below.

Southern Province

The Southern Province in Ontario, which is characterized above all by well-preserved supracrustal strata of the Huronian Supergroup, early Proterozoic in age ($<2.5 > 2.22$ Ga), can be divided into two parts: i), a northeastern region, the Cobalt Embayment, in which these strata are little deformed and barely metamorphosed, and ii), a southwestern belt of steeply folded and variably metamorphosed strata (though with a less-deformed northern fringe). The Huronian Supergroup, at least 12 km thick within the fold belt, lies unconformably on Archean cratonic rocks. It is divided into four groups, each group consisting of at least three formations (see Table 1). The groups generally have immature clastic (glaciogenic in part) sedimentary rocks at the base, shaly to silty rocks in the middle, and sandstone at the top, defining upward-maturing cycles with each cycle reaching greater maturity than the preceding one. In places, notably near Sudbury, both mafic (Elsie Mountain, Stobie formations) and felsic (Copper Cliff) volcanic rocks occur at the base of the Elliot Lake Group; the mafic flows may be related to coeval diabase dykes (Matachewan swarm) and anorthositic gabbro complexes that intrude the adjacent basement, and the Copper Cliff rhyolite to granites (Murray, Creighton, Skead) which occur only within the volcanic formations. Other features of note are the restriction of

Table 1. Huronian Supergroup stratigraphic succession in the Sudbury area

			Thickness, m
Cobalt Group			
Bar River	orthoquartzite, minor iron formation		>1220
Gordon Lake	siltstone, minor argillite, sandstone		1060-1280
Lorrain	arkose, feldspathic and ortho- quartzite		1500-2400
Gowganda	polymictic conglomerate, argillite		180-1200
Quirke Lake Group			
Serpent	feldspathic quartzite		180-1500
Espanola	calcareous siltstone, limestone, dolomite		150-550
Bruce	polymictic conglomerate		60-460
Hough Lake Group			
Mississagi	cross-bedded feldspathic arenite		760-3000
Pecors	shale, siltstone, wacke		60-600
Ramsey Lake	polymictic conglomerate		60-180
Elliot Lake Group			
McKim	laminated shale, siltstone, wacke		1500-1800
Matinenda	conglomerate, wacke, feldspathic arenite		180-300
Copper Cliff	felsic flow and pyroclastic rocks		≤730
Stobie	pillowed mafic flows, intercalated wacke		≤1500
Elsie Mountain	pillowed mafic flows		≤1000

Abstracted from Card *et al.* (1977), Frarey (1985) and Bennett *et al.* (1991).

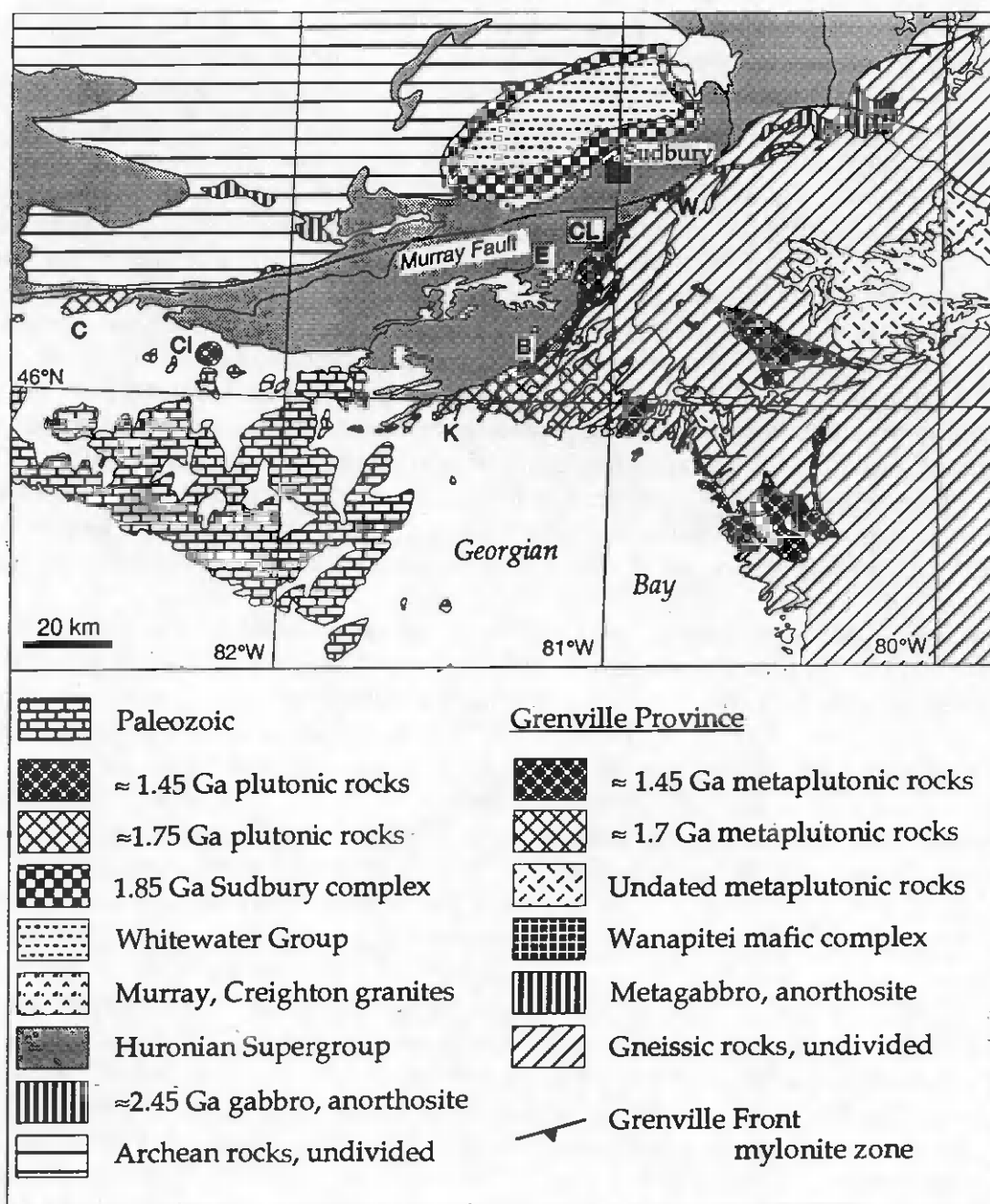


Figure 1. Generalized geology of the Sudbury region. Plutonic units mentioned in the text are: C - Cutler; CI - Croker Islands; K - Killarney; B - Bell Lake; E - Eden Lake; CL - Chief Lake; W - Wanapitei.

carbonate rocks to the middle of the Quirke Lake Group (Espanola Formation), and the immense thicknesses of extremely pure orthoquartzite in the Cobalt Group (upper Lorrain and Bar River formations). Where basement-cover relationships are well preserved in the Cobalt Embayment, it is evident in places that younger cycles successively overlap northward on to the basement (Bennett *et al.* 1991).

Voluminous masses of Nipissing gabbro (formerly called Sudbury gabbro, now commonly referred to as Nipissing diabase) intrude all formations of the Huronian Supergroup and its adjacent Archean basement. Nipissing gabbro has been dated at ~2.22 Ga (U-Pb baddeleyite age 2219 Ma; Corfu and Andrews 1986; Noble and Lightfoot 1993). Although folded with its Huronian host in the Southern Province fold belt, there is some evidence that its intrusion postdated an earlier stage of folding (Bleazardian orogeny of Stockwell 1982).

Major, upright, east-west folds in the fold belt are generally attributed to Penokean orogeny, dated in its type area (northern Michigan) between 1.89 and 1.83 Ga (Bickford *et al.* 1986). Metamorphic culminations within the fold belt, in part associated with intrusion of granitoid rocks, is of low pressure type and appears to overprint an earlier, regional, low-grade dynamothermal metamorphism (Card 1978a). Plutonic rocks with ages in the Penokean range have yet to be identified; recent U-Pb age determinations for the Cutler (titanite) and Eden Lake plutons (monazite), for example, are ~1750 Ma (Davidson *et al.* 1992; Sullivan and Davidson 1993) (Fig. 1).

Although not a player in the Grenville Front story, a world-renowned feature of this area is the Sudbury Igneous Complex, dated at 1849 Ma (Krogh *et al.* 1984). Now widely accepted as the product of a massive impact (though not without vociferous detractors; see Pye *et al.* 1984), to which breccias and shatter cones in its country rocks are attributed, this feature serves to constrain the age of part of the deformation affecting the Southern Province fold belt. The south half of the Sudbury structure, including the sedimentary Whitewater Group which it encloses, is metamorphosed and deformed (Card 1978a), displaying northerly, thrust-sense displacement on faults and ductile deformation zones (Shanks and Schwerdtner 1991).

A belt of elongate granitoid plutons (Killarney batholithic complex of Lumbers 1975) intrudes folded Huronian Supergroup strata adjacent to the Grenville Front from near Sudbury to the coast of Georgian Bay, where the Killarney granite and associated, predominantly felsic volcanic and hypabyssal rocks have been dated at ~1740 Ma (U-Pb zircon; van Breemen and Davidson 1988). A similar age was obtained by Krogh and Davis (1970) for a phase of the Chief Lake batholith nearer to Sudbury, but a new U-Pb analysis of zircon from coarse, pink granite of this unit suggests an age of ~1465 Ma (Davidson and van Breemen 1994). This much younger age is comparable to those reported earlier for the Bell Lake granite farther southwest (1471 Ma; van Breemen and Davidson 1988), and for the Croker Island complex west of Killarney (~1465 Ma; Van Schmus 1965).

All these rocks are cleanly cut by southeast-trending, vertical dykes of fresh olivine diabase belonging to the Sudbury swarm, now reliably dated at ~1235 Ma (U-Pb, baddeleyite; Krogh *et al.* 1987; Dudàs *et al.* 1994). The importance of these dykes is elaborated later in this text. A younger set of east-trending dykes of quartz-bearing

diabase, belonging to the Grenville swarm and dated at 595 Ma (Kamo *et al.* 1995), extends from the Southern Province through the Grenville Province for at least 600 km.

Grenville Province

Geological maps of the Grenville Province adjacent to the front in the Sudbury region (Lumbers 1975; Frarey 1985; Card and Lumbers 1977) portray this terrane primarily as a 'sea of gneisses', a large proportion of which is interpreted to be sedimentary in origin. The gneisses include undoubted metasediments such as quartzite, pelitic gneiss, and rare calc-silicate gneiss and marble, but many are rather ordinary quartzofeldspathic rocks whose specific protoliths are uncertain. These gneisses are interlayered with mafic gneiss and metagabbro near the front southeast of Sudbury, and with anorthositic gneiss farther northeast; they are interspersed with irregular and commonly sinuous units of foliated or gneissic granitoid, particularly toward Georgian Bay. A few small plutons have more equant outlines. Notable among these is an oval body of mafic rock, the Wanapitei complex (Lumbers 1975; Rousell and Trevisiol 1988), situated close to the front east of Sudbury, about which more information is given below. Also present in this area are several large masses of pegmatite, as well as numerous small pegmatite dykes and lenses, and small bodies of mafic rock mapped as 'cataclastic metadiabase' (Lumbers 1975). The latter are now confidently correlated with Sudbury diabase on the grounds outlined below.

It is easy to assume that the metasedimentary gneisses and interlayered metagabbro were derived from the Huronian Supergroup and Nipissing gabbro respectively, but if this is the case, all semblance of stratigraphic order permitting direct correlation with the well-known Huronian succession has been obscured or destroyed during deformation and high-grade metamorphism. Northeast of Sudbury, metasedimentary biotite schist and gneiss (Red Cedar Lake formation), formerly interpreted as a coarse clastic facies of Huronian sediment by Lumbers (1978), are now considered to be Archean, probably representing reworked wacke and siltstone of the Pontiac Group of the adjacent Superior Province; Archean ages are preserved in metagranitoid units in this area. On the other hand, some metasedimentary rocks in the marginal Grenville Province south of Sudbury, extending to the north shore of Georgian Bay, have Nd model ages (≥ 2.32 Ga, Dickin and McNutt 1989; ≥ 2.12 Ga, F.Ö. Dudàs, pers. comm., 1991) which are too young (unless disturbance of Nd systematics is admitted) for them to be correlated with the Huronian Supergroup, whose sediments have Archean provenance and Nd model ages; for example, Nd isotopic analyses of sedimentary rocks from the Lorrain Formation northeast of Sudbury (Lightfoot and Naldrett 1989) yield depleted mantle model ages of 2.85 Ga.

In the same region, however, U-Pb zircon ages provide reason to correlate metamorphosed granitoid rocks with those in the Southern Province, both 1.74 and 1.47 Ga age groups being represented (Davidson *et al.* 1992; van Breemen *et al.* 1986; van Breemen pers. comm. 1993). van Breemen and Davidson (1988) suggested correlation of the Killarney granite and allied volcanic rocks with the ~1.75-Ga granite-

rhyolite association of the Central Plains orogen in the mid-continent (Sims and Peterman 1986), itself part of the larger Yavapai/Mazatzal province exposed farther west (Hoffman 1988). They also noted that the 1.47-Ga age of the Bell Lake granite lies within the range of the older of two so-called anorogenic granite-rhyolite provinces in the buried mid-continent (Bickford *et al.* 1986). In the adjacent Grenville Province, the supracrustal rocks which originally hosted the older of the two granite suites and which appear to be younger than the Huronian Supergroup, have presumably undergone ~1.7-Ga orogeny. Evidence for this event has been recognized in the Key Harbour area of the Georgian Bay coast, where the oldest migmatitic gneisses are associated with deformed granite dated at 1685 Ma (Corrigan 1990). In addition, it now appears that this part of the Grenville orogen also underwent widespread metamorphism and deformation shortly after the ~1.47-Ga plutonism. Monazite in high-grade metasedimentary gneiss (Dudàs *et al.* 1994) and titanite in 1.74-Ga metagranitoid rocks (Haggart *et al.* 1993), both within 10 km of the front, and zircon in orthopyroxene-bearing leucosomes farther into the Grenville orogen (Ketchum *et al.* 1994), all record ages of ~1.45 Ga.

Grenvillian orogeny in this corner of the province appears to be restricted to deformation and metamorphism late in the age-range of ≤ 1.3 –1.0 Ga accorded to the broader 'Grenvillian orogenic cycle' (Moore and Thompson 1980), and presumably associated with tectonic burial accompanied by deep-seated, large-scale thrust imbrication directed toward the front, followed shortly thereafter by rapid uplift and exhumation accompanied by extensional tectonics (Haggart *et al.* 1993; Culshaw *et al.* 1994). There are no supracrustal rocks that can be related to the onset of Grenvillian orogeny, and no plutonic rocks marking its culmination. A growing database of U-Pb ages for zircon, monazite and titanite from this region suggests that tectonic activity was restricted to between ~1040 and ~980 Ma (this seems a relatively short period in Precambrian terms, but nevertheless is equivalent to the whole of the Tertiary!). Much earlier ductile deformation (~1160 Ma; van Breemen and Davidson 1986) was associated with emplacement of the Parry Sound granulite allochthon in the interior of the province, ~100 km from the front, but so far there is no geochronological evidence for any event of this age closer to the front.

The Grenville Front

From Georgian Bay to Coniston, the Grenville Front is marked by a zone of faults and mylonites, inclined generally at moderate angle to the southeast, that cut all but the youngest diabase dykes, the Grenville swarm. It has been well documented that dykes of the Sudbury swarm, although disrupted by faults and not traceable individually across mylonite zones, do cut earlier, front-parallel fabrics within fault-bounded panels (Henderson 1967; Brooks 1976; Frarey 1985; Bethune and Davidson 1988). A means is thus available to distinguish pre- and post-1235-Ma structures. First, however, some lingering misunderstandings about the Grenville Front are best assessed by following the historical development of interpretation of this major structure.

Long before the Shield was divided into structural provinces (Gill 1948), the boundary between the Southern and Grenville Provinces was recognized by Collins

(1916, 1925) as the locus of major change, where well-preserved, broadly-folded Huronian sedimentary rocks and Nipissing gabbro intrusions, at relatively low metamorphic grade, give way southeastward to a complex terrane of high-grade gneissic rocks. Mapping across this boundary in the late 1920s led to the idea that granitization on a huge scale was responsible for the "disappearance of the Huronian" (Quirke and Collins 1930). This hypothesis was championed particularly by Quirke (1927, 1940), although hotly disputed by others (*e.g.* Jones 1930); tracts of metasedimentary gneiss as far as 40 km from the boundary were correlated with specific Huronian formations (Quirke 1930).

In the area directly southeast of Sudbury, the boundary between the Southern and Grenville provinces was interpreted as a metamorphic transition by Phemister (1961; Grant *et al.* 1962) where Huronian sedimentary rocks and Nipissing gabbro were abruptly metamorphosed and granitized to make the gneissic and migmatitic rocks of the Grenville Province. Kwak (1968) and La Tour (1981) documented an abnormally high metamorphic gradient across this transition. Dalziel *et al.* (1969) recognized that mylonitization was an important factor in this transition, and that metamorphism preceded the earliest recorded folds. They expressed some doubt about the equivalence of rocks on opposing sides of the front, but did not invoke large-scale displacement to explain the possibility that different rocks had been juxtaposed or that metamorphic isograds had been 'telescoped'. Without the benefit of modern geochronology, Brocoum and Dalziel (1974, p. 1577) contended that the rocks of the Southern Province, including the Sudbury Structure, and those in the adjacent part of the Grenville Province "... all underwent the same major deformational event after the intrusion of the Nipissing diabases (2.15 b.y. ago) and the Nickel Irruptive (2.0 b.y. ago) and prior to the intrusion of the northwest-southeast-trending olivine diabase dyke swarm (1.46 b.y. ago) ...", which, they stated, cuts the gneisses in the northwestern Grenville Province. This major event was attributed to the Penokean orogeny, which was at that time accorded a wider age-range (2.0–1.6 Ga) than it is today. However, Brooks (1976) pointed out that the same olivine diabase dykes (Sudbury swarm) are deformed and metamorphosed farther southwest along the front, although he did not dispute the fact that they also cut earlier deformation fabrics in granitoid rocks adjacent to the front.

Phemister (1961) recognized the Grenville Front in this area to have two distinct manifestations, a metamorphic transition southwest of Coniston, and a discrete fault to the east. He stated (*op. cit.*, p. 61): "One of the features that makes this region of special interest is that here the Wanapitei fault is seen to cut across the "front" of metamorphism leaving no doubt therefore that it marks a younger event in the structural history of the region.... Thus ... the boundary in the western section is a metamorphic "front" while in the eastern part it is a fault." Dalziel *et al.* (1969, p. 211) described the Wanapitei fault as a brittle fracture, being a later effect which obscures "... the fundamental tectonic character of the front ...". The westward continuation of the Wanapitei fault in the Southern Province aligns with the well-known Murray fault, passing south of Sudbury and extending for at least a further 150 km to the west (Fig. 1).

An alternative interpretation was advanced by Lumbers (1975), who combined the two different segments of the front as a single feature referred to as the

'Grenville Front Boundary Fault'. His map shows the Murray fault as remaining within the Southern Province instead of being continuous with the Wanapitei fault south of Coniston (Fig. 6, A). This interpretation has been reproduced on subsequent geological compilations (Card and Lumbers 1977; Dressler 1984). Reaffirming the faulted nature of the Grenville Front mylonite zone east in the Coniston area, Davidson (1992) argued that post-Grenvillian normal displacement on the Wanapitei fault (*i.e.* Grenville side down) best explains the abrupt opposition of high-grade gneisses and little-affected Southern Province rocks.

The term 'Grenville Front Tectonic Zone' is commonly used in conjunction with the northwest margin of the Grenville Province. First coined by Lumbers (1971a), it was defined as a zone of northeast-trending cataclastic foliation with attendant southeast-plunging lineation manifested mainly in the gneissic rocks of the Grenville Province, but also including a narrow strip in the adjacent Superior and Southern provinces, northwest of the 'Grenville Front Boundary Fault', in which similarly oriented structures occur. The northwest boundary of the Grenville Province, however, was placed at the boundary fault. Wynne-Edwards (1972) defined the tectonic zone a little differently, confining it to southeast of the Grenville Front, while recognizing that front-related deformation is present northwest of the front in the 'Grenville Foreland Zone'. The southeast margin of the Grenville Front Tectonic Zone was not defined rigorously by either author. Subsequently, Rivers *et al.* (1989) used the term 'Parautochthonous Belt' to describe the marginal part of the Grenville orogen containing reworked rocks of the adjacent, older Shield provinces, and not coincident with the Grenville Front Tectonic Zone. To avoid possible confusion, neither of these two terms is used in this guide.

Application of modern kinematic analysis to fabrics in the mylonitic rocks along the Grenville Front between the coast of Georgian Bay and Sudbury consistently yields evidence for thrust-sense displacement toward the northwest (Pryer 1985, 1993; Davidson 1986b, c; Davidson and Bethune 1988). The position of this segment of the front, however, has been a matter of some contention. Frarey and Cannon (1969; Frarey 1985) placed the front along the northwest contacts of the Killarney and Bell Lake granites, on the basis that these contacts are faulted in many places and cut across fold trends in the Huronian rocks. The northeast extension of this 'front', however, was shown to pass into the southern part of the Chief Lake granite. In their regional compilation, Card and Lumbers (1977) placed the 'Grenville Front Boundary Fault' on the southeast side of these granites. Davidson (1986b) favoured the latter position, modified to a somewhat more southeasterly position near Georgian Bay, because it coincided with a major zone of mylonitization across which the most pronounced change in structural style and orientation occurs. Farther northeast, this zone also coincides with an abrupt increase in metamorphic grade; in addition, it marks the southeast limit of continuously traceable Sudbury dykes (Bethune 1993) and is thus identifiable as a feature of Grenvillian age.

It has now become clear that a distinction must be made between the respective northwestern limits of the pre-Sudbury dyke deformation that postdated the ~1.47-Ga granites and post-Sudbury dyke deformation. If the Grenville Front is

taken as the northwest limit of penetrative deformation and metamorphism related to Grenvillian orogeny, then the state of preservation of the Sudbury dykes becomes a crucial factor in locating the front. The youngest pre-Sudbury dyke structures northwest of this limit are unlikely to represent an early phase of Grenvillian orogeny because the Sudbury dyke swarm, which cuts them, was presumably emplaced into stable continental crust. It seems more likely that a distinctly earlier orogenic event at ~1.45 Ga, recorded on both sides of the Grenville Front as defined above, was responsible for the youngest structures cut by the Sudbury dykes. At present, no counterpart of this event has been recognized elsewhere outside the Grenville Province; coeval igneous activity in the buried mid-continent to the southwest is regarded as 'anorogenic' (Bickford *et al.* 1986; Windley 1989). Based on less comprehensive geochronology than is available today, Stockwell (1982, p. 68) proposed that the ill-defined 'Killarnean orogeny', to which he ascribed a terminal age of ~1.5 Ga, has its type region within the Grenville Province. This now seems prophetic in the light of the more recent identification of widespread, pre-Grenvillian plutonism within the adjacent Grenville orogen. Stockwell, however, had no knowledge of the two distinctly different ages of granitic rocks (~1.74 and ~1.47 Ga) that is consistently emerging from geochronological studies in this area; the concept of 'Killarnean orogeny' now seems inappropriate in that the time-span assigned to it embraces both age groups.

The ages and expression of post-Penokean, pre-Grenvillian events in the Southern Province are poorly documented. For example, the age of deformation and metamorphism of the southern part of the Sudbury Structure, and how far the effects of this event extend into the neighbouring Huronian rocks, are not known. It is quite possible that the rocks in the Grenville Front region were affected by two post-Penokean events before emplacement of the 1235-Ma Sudbury dyke swarm – events related to the development of major orogens farther southeast that have been largely overprinted and obscured by later Grenvillian orogeny in the interior of the Grenville Province. Displaced and telescoped remnants of these orogens, whose tectonic fronts appear to coincide so closely with the Grenville Front (Bethune 1993), may explain the abundant evidence for pre-Grenvillian deformation and metamorphism within this part of the Grenville orogen.

Throughout the foregoing, several references have been made to the Sudbury diabase dyke swarm, implying its usefulness as a time-marker for discerning the effects of Grenvillian orogeny in this poly-orogenic terrane. Therefore a more detailed account of this swarm and its recognition within the Grenville orogen is given below. The extent of the Sudbury swarm in the Southern Province southwest of Sudbury and the known distribution of equivalent metadiabase dykes and remnants in the Grenville Province are shown in Figure 2.

Sudbury dyke swarm

Lumbers (1975) mapped two types of diabase dykes in the Southern Province southeast of Sudbury, which he referred to simply as 'olivine diabase' and 'diabase', and which are part of what are now known as the Sudbury and Grenville swarms respectively (Fahrig and West 1986). He stated that the "... olivine diabase dikes

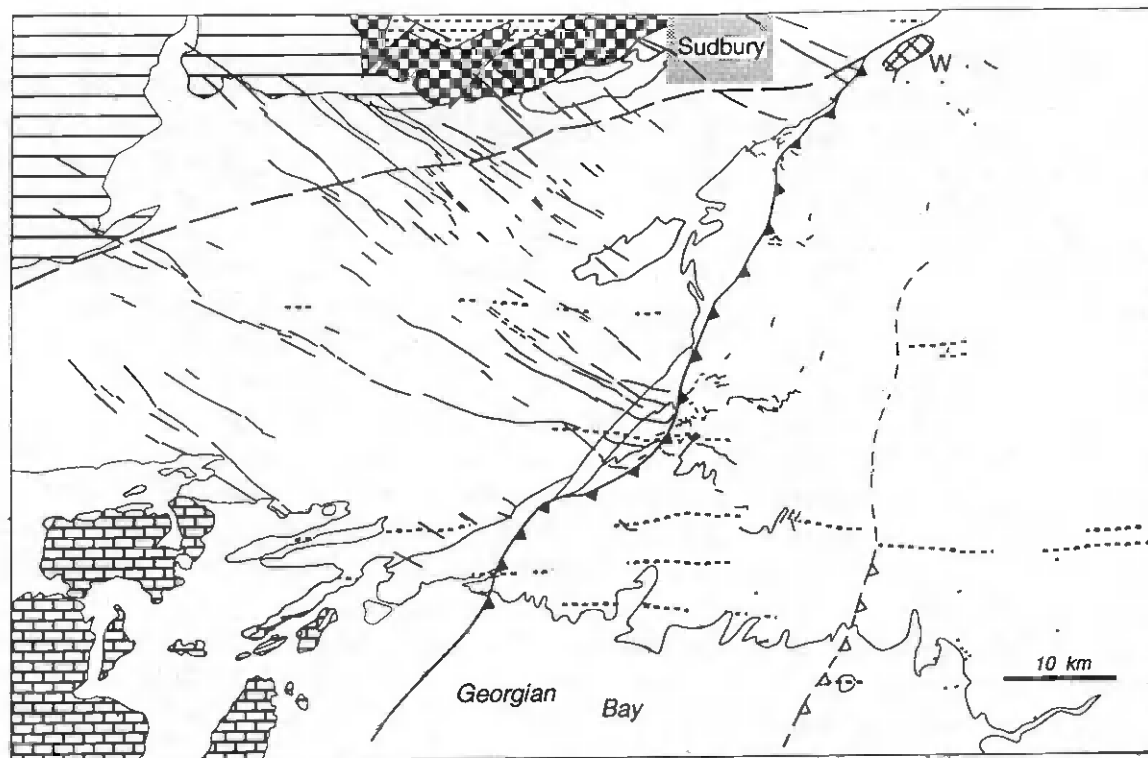


Figure 2. The Sudbury dyke swarm in the Southern Province southwest of Sudbury, and distribution of metamorphosed and deformed Sudbury dykes in the Grenville Province (solid lines and dots). East-west dashed lines are Grenville dykes.

are confined to the Southern Province portion of the area and are part of a regional northwest-trending swarm that intrudes rocks of both the Southern and Superior Provinces but which does not extend across the Grenville Front Tectonic Zone in the Grenville Province." (*op. cit.*, p. 109). Although he mapped occurrences of metadiabase in the adjacent Grenville Province (termed 'cataclastic metadiabase' in his map legend), he did not equate these with the Sudbury dykes. Farther southwest, Palmer *et al.* (1977) also documented two different types of diabase in the Southern Province south of Lake Panache, but Frarey (1985), while acknowledging the distinction, included both types in the same map unit. Frarey, however, did recognize that "Olivine diabase dykes of the "Sudbury swarm", so numerous in the Southern Province, continue east-southeastward into the Grenville Province at least as far as Tyson Lake and possibly much farther." (*op. cit.*, p. 47). His map shows several dyke segments with various orientations in the Grenville Province; some of these have "... curved traces, suggesting late folding that is presumably Grenvillian ..." (*op. cit.*, p. 48), and he recognized the 'cataclastic' nature of the diabase in thin section. At the eastern edge of his map area, some 18 km into the Grenville Province, he mapped one dyke whose eastward continuation in the Burwash map area was classified by Lumbers (1975) as 'cataclastic metadiabase'. Farther east near Key Harbour, 'cataclastic metadiabase' occurs as isolated pods within a ductile gneiss medium (Davidson and Bethune 1988).

It is clear that geologic units which are undisturbed in the foreland of an orogenic front may be used to constrain the tectonic history of the adjacent orogen, provided they can be recognized within it. With respect to the Grenville Front, the Sudbury dykes in the Southern Province foreland are such a unit, and are particularly important for the following reasons:

- 1) they are oriented orthogonally to the front;
- 2) the across-strike width of the swarm is at least 200 km;
- 3) many dykes are thicker than 30 m, some being more than 100 m;
- 4) individual dykes are continuous for many tens of kilometres;
- 5) the diabase has a distinctive, evolved chemistry (undersaturated, enriched in iron, alkalis and high field strength elements);
- 6) the age of the swarm is known (~1235 Ma).

The first four attributes make it reasonable to expect them to be found within the Grenville Province provided that the Grenville Front is not a post-1235-Ma suture juxtaposing exotic crust against the Superior and Southern Province craton, or that there has been no large scale, post-1235-Ma lateral displacement along the front. Their distinctive chemistry should allow them to be recognized within the Grenville Province, provided it has not been unduly disturbed during metamorphism. If they can be traced into the front and recognized beyond it, their known age would make them an invaluable time marker for distinguishing pre- and post-emplacement structures.

Mapping along the Grenville Front has failed to trace individual Sudbury dykes from the Southern into the Grenville Province. Correlation of Sudbury diabase and metadiabase must therefore rely on comparative whole-rock chemistry and isotopic age. The characteristic chemistry of Sudbury diabase, documented by Fahrig *et al.* (1965), Merz (1976) and Condie *et al.* (1987), and unlike that of any other diabase dyke swarm in the Shield, has been corroborated by major and trace element analyses of 40 samples between Sudbury and Georgian Bay, ranging up to 45 km northwest of the Grenville Front. A similar number of analyses of metadiabase samples from the Tyson Lake area, up to 16 km from the front, and smaller numbers from both Key Harbour, ~40 km from the front, and closer to the front east of Sudbury, all have identical chemical signatures to fresh Sudbury diabase. These results are summarized in Bethune (1989) and reported fully in Bethune (1993). The U-Pb age of 1238 ± 4 Ma obtained by Krogh *et al.* (1984) on baddeleyite in Sudbury diabase from Espanola, 65 km west of Sudbury and 40 km from the front, has been corroborated by U-Pb baddeleyite ages determined for three other Sudbury dykes northwest of the front by Dudàs *et al.* (1994), who also obtained similar ages for metadiabase in the Grenville Province. The average age for the three dykes in the Southern Province, at locations 30, 16 and 3 km from the front, is 1234 ± 7 Ma. Baddeleyite was separated from metadiabase at locations 2, 3 and 12 km southeast of the front at Tyson Lake, and 5 km from the front at Wahnapiatae, east of Sudbury. The average age for metadiabase is slightly older (1243 Ma), but all U-Pb analyses lie on a discordia whose upper intercept is 1233 ± 4 Ma. In addition, metamorphic zircon obtained from two of the metadiabase samples gave ages of ~1000 Ma, agreeing well with a Nd-Sm metamorphic mineral isochron age obtained from the sample 12 km from the front. In summary, there is little reason to doubt that diabase dykes of the

Sudbury swarm are represented in the Grenville Province by metadiabase preserved as folded dyke segments and isolated pods. It is the only rock unit in the area that records solely the effects of younger Grenvillian deformation and metamorphism, both in the Southern Province adjacent to the front and within the Grenville orogen.

Approaching the front from the northwest, the dykes are offset by subsidiary faults near which they may show internal cataclasis and low-grade alteration (chlorite, epidote, fibrous amphibole and sericitized plagioclase). In the Lake Panache area they swing to a more easterly trend where they cross the Bell Lake granite and turn abruptly northeast at the main Grenville Front mylonite zone (Frarey 1985; Bethune and Davidson 1988; Bethune 1989, 1993). Although several large metadiabase dykes are present immediately to the southeast, there is no obvious match in the pattern of dyke spacing on opposing sides of this zone. In the Chief Lake complex, Sudbury dykes immediately northwest of the mylonite zone follow irregular courses within fault-bounded panels (Davidson and Ketchum 1993). Farther northeast, dykes can be traced directly to the front, but have no potential counterparts in the Grenville hangingwall.

In all of these localities, an important and consistent observation is that Sudbury dykes within fault-bounded panels adjacent to the front cut across front-parallel mylonitic fabrics in their host rocks; shear-sense indicators, particularly in the Chief Lake complex, imply penetrative northwest-directed thrust displacement. Since this pre-1235-Ma mylonitization is strongly developed in the 1.46-Ma-granitic rocks, deformation must have been active along the Grenville Front in the interval between granite emplacement and dyke intrusion. It is possible that this deformation is related to the ~1.45-Ga metamorphism within the adjacent Grenville orogen. Whatever the age of deformation, the dykes' host rocks are likely to have cooled from conditions suitable for ductile deformation to those cool and stable enough for emplacement of a typical continental mafic dyke swarm.

In the Tyson Lake area close to Georgian Bay, Sudbury metadiabase dykes display a remarkable progressive change in structural style and metamorphism over several kilometres as they are traced into the Grenville Province (Bethune and Davidson 1988; Bethune 1989, 1993). Conditions of metamorphism derived from garnet-pyroxene assemblages within 6 km of the front are estimated at ~6.5 kbar and 690°C, increasing southeastward to ~7.7 kbar and a similar temperature at a distance of 16 km (perhaps 12 km orthogonally from the front at depth) (Bethune 1993). Closer to Sudbury, a similar change is evident in metadiabase dykes southeast of the Chief Lake granite complex, where the front is also marked by mylonites in a zone at least a kilometre thick. In the Wahnapiatae area, however, contrasting with the situation recorded farther southwest, Sudbury dykes in the Grenville Province as little as 400 m from the front are represented by misoriented and dismembered metadiabase dyke segments, in places arcuate, whose sides commonly preserve chilled contacts cutting across gneissic foliation in their host rocks, but whose ends are truncated by gneiss mobilized by ductile flow. Dyke segments are cut by coarse pegmatite, near which the diabase is hydrated to coarse biotite amphibolite. Where not hydrated, it contains metamorphic garnet, clinopyroxene and orthopyroxene with typical coronitic structure around former olivine and Fe-Ti oxide grains.

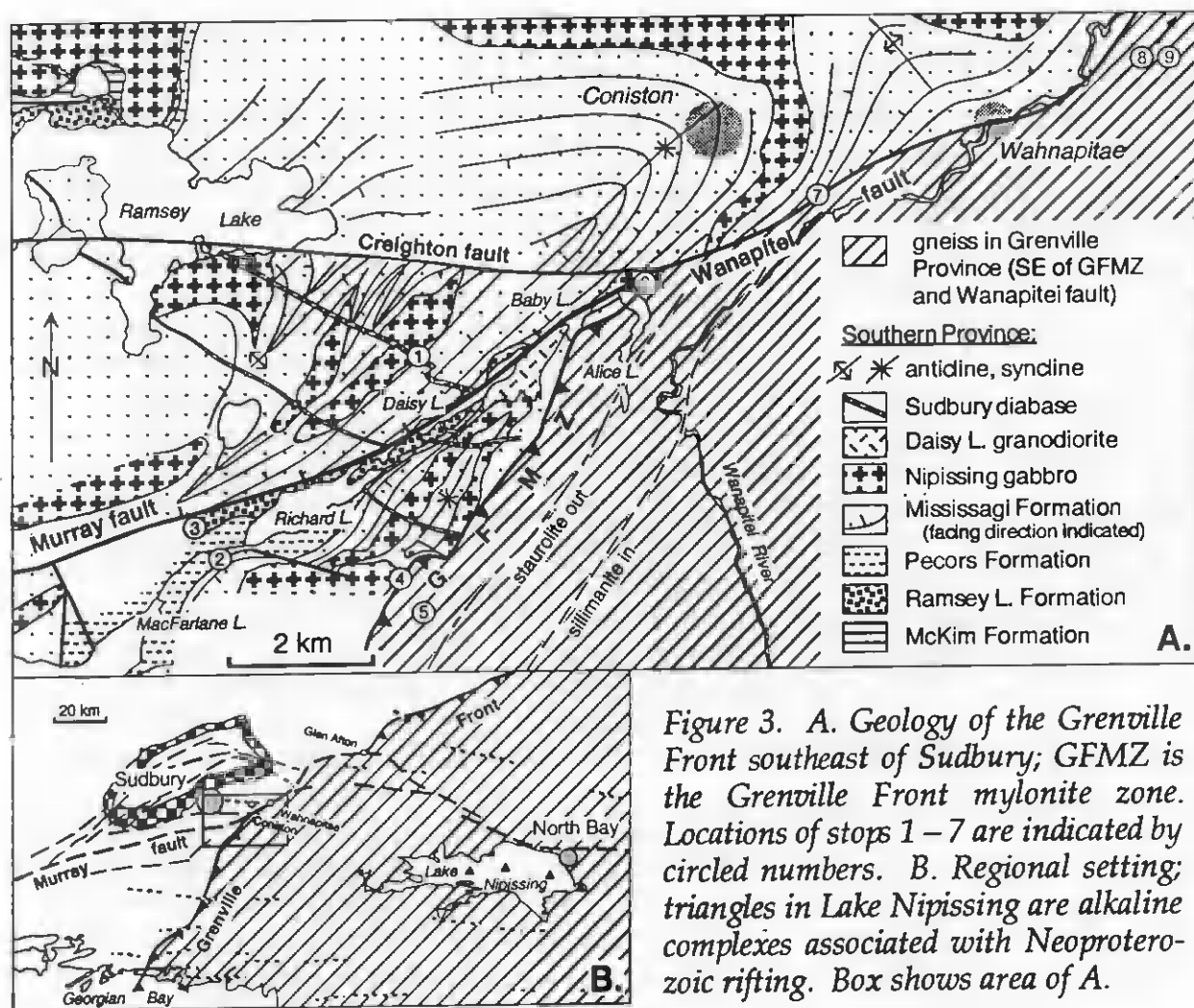
Coronitic metadiabase commonly contains twisted laths of relict plagioclase whose cores are densely clouded with spinel dust. Farther southwest, similar structural and metamorphic features are not attained until at least 15 km southeast of the front (Bethune 1993). A remarkable variation on the theme of Sudbury dyke preservation in the Grenville Province is offered by the occurrence of non-deformed yet thoroughly metamorphosed dykes in the Wanapitei mafic complex, mentioned previously, for which more detailed information is given at the end of this guidebook.

Field trip summary

This field trip is designed to allow evaluation of both aspects of the Grenville Front discussed above, including the truncation of the mylonite zone by the Murray-Wanapitei fault, and to demonstrate the dilemma concerning correlation of metasedimentary gneiss in the Grenville Province with the Huronian Supergroup. The main elements of the geology in the field trip area are illustrated in Figure 3, on which the first seven stops are identified. In the morning, the first three stops will examine rocks in the Southern Province near the Grenville Front, but unaffected by Grenvillian tectonism. Next will come a stop to look at the highly deformed equivalents of some of these rocks in the immediate footwall of the Grenville Front on Highway 69, followed by a short traverse across the highly deformed contact between Mississagi quartzite and Chief Lake granite lying structurally beneath mylonite and ultramylonite that are typical of the Grenville Front south of Sudbury. This will be followed by stops on pelitic gneiss, quartzite and mafic rock near the southeastern edge of the Grenville Front mylonite zone.

In the afternoon, the Grenville Front mylonite zone will be examined where it is truncated by the Murray-Wanapitei fault south of Coniston, just east of Alice Lake. This will be followed by a traverse across the Grenville Front near the Stinson hydroelectric plant during which a tectonic slice of possible Archean basement will be seen, south of which metasedimentary rocks derived in part from conglomerate contrast strongly with the Mississagi Formation on the north side of the front. The last stop visits spectacular outcrops of kyanite gneiss showing evidence for extreme ductility and enclosing segments of highly metamorphosed Sudbury diabase dykes.

The road log included in the following section is intended for those who wish to run the field trip on their own. It gives cumulative distances in kilometres between each stop in the left hand column, and a cumulative log for the whole trip in the right hand column. Persons following this guidebook should be sure to obtain permission from owners of private land for stops 2 to 6 inclusive.



ROAD LOG AND STOP DESCRIPTIONS

<i>km</i>	<i>cum. km</i>	
0.0	0.0	<i>Proceed south from Sudbury to the intersection of Paris and Regent streets (Four Corners), and set odometer to zero. Turn left (east) on Regent Street (old Highway 69).</i>
3.4	3.4	<i>Take the ramp just after the underpass, and go east on the Sudbury bypass (Highway 17E). Outcrops along the roadside for the next 3 km are Nipissing gabbro, and beyond this, Mississagi sandstone which dips steeply south and is overturned.</i>
10.2	10.2	<i>Stop on the right shoulder at a dark outcrop of massive rock.</i>

Stop 1. Mississagi sandstone, Nipissing gabbro and Sudbury diabase

This stop lies within the Southern Province 900 m northwest of the Murray fault, 3 km west-southwest of where this fault truncates the Grenville Front mylonite zone; it is only two kilometres from the Grenville Front. Here a southeast-trending, vertical, 65-m-thick olivine diabase dyke of the 1235-Ma Sudbury swarm cuts across the contact between sandstone of the Mississagi Formation (south side of the road) and Nipissing metagabbro (north side). The sandstone exposed here is typical of the upper part of the Mississagi, being somewhat more quartz-rich and lighter in colour than in the lower part of the formation. Cross-bedding in the sandstone indicates that the steeply dipping beds face north-northwest; we are on the southeast limb of the Coniston syncline, illustrated in Figure 3). The Nipissing metagabbro is massive but metamorphosed, containing secondary green amphibole, epidote and chlorite. This metamorphic assemblage is typical of Nipissing gabbro throughout the Southern Province and does not appear to be a function of proximity to the Grenville Front, a conclusion corroborated by the fact that the pre-Grenvillian Sudbury diabase which cuts it is not metamorphosed.

The Sudbury olivine diabase exposed at this stop illustrates the pristine protolith of cataclased diabase adjacent to the Grenville Front, which we will see at Stop 8, and of equivalent coronitic metadiabase in the Grenville Province, to be seen at Stop 9. The Sudbury dyke's northeast contact is all but exposed on the south side of the road, and must have been excavated during road construction, as blocks containing its chilled contact with Mississagi sandstone can be found at the roadside. Close to this contact the diabase is fine grained and contains xenocrysts of plagioclase which in turn include earlier-crystallized olivine crystals – a common feature near the margins of Sudbury dykes. In thin section, there is no evidence whatsoever for metamorphic reaction between these two minerals at this location (it is principally this reaction which gives rise to the garnet and secondary pyroxenes present in metamorphosed olivine diabase). In the same dyke on the southeast side of the Murray fault and closer to the Grenville front, however, the plagioclase xenocrysts become clouded with fine epidote, and rims of fine actinolite appear between olivine and plagioclase. This particular dyke cannot be traced across the Grenville

Front fault, but where Sudbury dykes have been identified in the immediate hangingwall of the front, olivine in plagioclase xenocrysts has reaction coronas of pale orthopyroxene with outer rims of pargasite-spinel symplectite, and Fe-Ti oxide grains are surrounded by Ti-biotite and garnet symplectite. In the vicinity of the Grenville Front 50 km to the southwest, Sudbury dykes cut across and are chilled against a pre-existing mylonitic fabric that is developed in granitoid rocks as young as 1470 Ma (Bethune 1989; Davidson and Ketchum 1993), pointing to the existence of some kind of pre-Grenvillian tectonic front roughly coincident with the Grenville Front *sensu stricto*. In this regard it is pertinent that, in the hangingwall within a few kilometres of the front, metamorphic monazite in pelitic gneiss (Dudàs *et al.* 1994) and zircon from pegmatitic leucosomes (Krogh 1994) record an age of ~1445 Ma.

km	cum. km	
0.0	10.2	Turn around and return to the interchange.
5.8	16.0	Take the first exit ramp to the right.
6.5	16.7	At the traffic light, turn left on Highway 69, and proceed through the next traffic light.
9.3	19.5	Turn right at the intersection with Poitvin Road and follow it round to the left.
9.7	19.9	Park on the shoulder just before rejoining Highway 69.

Stop 2. Slaty argillite, Pecors Formation, and "trap dyke"

This stop and the next illustrate rock types of the two formations, Pecors and Ramsey Lake, that precede the Mississagi in the Huronian stratigraphic succession. Both are well exposed in the City of Sudbury along the north shore and west of Ramsey Lake, where they lie north of the Creighton fault (Fig. 3). Here, most of the low-lying area around Richard and MacFarlane lakes is devoid of outcrop, although it is shown as underlain by Mississagi Formation on the most recent compilation of Sudbury geology (Dressler 1984) and on the regional map that preceded it (Lumbers and Card 1977). The surrounding hills are underlain by Mississagi sandstone or Nipissing diabase, but sparse exposures at the base of these hills, and in a few places in the valley, are of sedimentary rocks that are not typical of the Mississagi Formation. This was recognized long ago by Collins (1936) who assigned conglomerate that crops out along the north side of Richard Lake to the Ramsey Lake Formation, which will be seen at the next stop.

At this stop, outcrop on the hill to the south is well-bedded sandstone of the Mississagi Formation, but at the base of the slope a few metres of grey argillite are exposed. Similar exposures occur along the south side of the Richard Lake valley to the east. South of MacFarlane Lake, to the southwest, argillaceous rocks in the same stratigraphic position beneath the Mississagi are represented by fine micaceous schist with small porphyroblasts of altered staurolite and andalusite; this higher grade of metamorphism is apparently associated with a number of nearby small intrusions

of granodiorite and granite dated at ~1745 Ma. Low outcrops around the east end of MacFarlane Lake expose rocks that are stratigraphically lower than the argillaceous rocks immediately beneath the Mississagi Formation. These are of fine wacke and siltstone which have a greensish hue and lack the thin, rusty-weathering, shaly interbeds so typical of the Mississagi. What is more, they preserve graded bedding and elements of Bouma cycle sedimentation, suggesting a depositional environment altogether different from that which produced the cross-bedded Mississagi sandstone. Taken together, these sub-Mississagi sedimentary rocks match those of the Pecors Formation in its type area and, given their stratigraphic position, should be assigned to this formation.

At this stop, an added feature is the presence of a fine-grained, greenish grey, altered diabase. Several narrow dykes of this swarm, known as "trap dykes", trend east-west in this area. They have not been dated, but are known to cut "offset dykes" of the 1850-Ma Sudbury Intrusive Complex, and to be cut by the 1235-Ma Sudbury swarm. These dykes are not, therefore, related to Nipissing gabbro.

<i>km</i>	<i>cum. km</i>	
0.0	19.9	Turn left on Highway 69,; immediately get into the right lane.
0.3	20.2	Turn right.
0.6	20.5	At sharp left-hand bend, go straight into parking area by Richard Lake Homecare Building Centre and park. Walk ahead through gate, and go to outcrop on hill to the left of the buildings.

Stop 3. Polymictic conglomerate, Ramsey Lake formation

At this stop, grey, ill-sorted wacke supports sparse pebbles and cobbles, some of granitoid rock; a few are of boulder-size. Look for small, bluish grains of quartz, which typify much of the Ramsey Lake conglomerate in its type area. Bedding dips southward, but is poorly developed and facing direction cannot be determined. Argillite and quartz wacke are exposed in a few places closest to Richard Lake to the east, and are similar to the rocks at the east end of MacFarlane Lake, assigned above to the Pecors Formation. The succession Ramsey Lake – Pecors – Mississagi from north to south across the valley is in accord with a homoclinal succession, although it is possible that faults and folds are concealed beneath the valley floor.

The line of low hills along the north shore of Richard Lake, all underlain by conglomerate, is separated from the higher ridge to the north by a strip in which there is no outcrop, and which conceals the Murray fault. The ridge is underlain by subvertical strata of Mississagi sandstone which faces north, being the same limb of the Coniston syncline as at Stop 1. Sedimentary facing on opposite side of the Murray fault is thus "back-to-back"; the fault occupies what may be a breached anticline, and has a net north-side-down displacement. To the west, however, the Murray fault truncates a north-trending fault, west of which the Mississagi Formation occupies the south side of the fault and is also north-facing.

km	cum. km	
0.0	20.5	Turn around and go back to Highway 69.
0.3	20.8	Turn left on Highway 69.
2.1	22.6	Roadcuts here expose steeply inclined Mississagi Formation.
3.3	23.8	Just after the end of the roadcut on the right, park on the right at swampy valley.

Please note that this is a very busy highway with fast-moving traffic; two lanes of vehicles travelling south must merge into one lane at this point after coming round a blind corner. Exercise extreme caution; keep an eye on traffic and other participants, and do not step back onto the roadway when taking photographs.

Stop 4. The Grenville Front at Highway 69

Figure 4 gives some details of the geology at this location. Looking to the west from Highway 69 at this stop, mylonite and ultramylonite marking the Grenville Front are well exposed along the south side of the broad swamp; mylonitic foliation dips $\sim 35^\circ$ to the southeast and contains numerous shear-sense indicators of northwest-directed thrust displacement. The front passes through the low point in the skyline to the left of the island in the swamp. The island and the high part of the hill behind it are underlain by coarse granite of the Chief Lake complex, continuous in outcrop with a locality 7 km to the southwest where a U-Pb zircon age of 1465 Ma was recently determined (Davidson *et al.* 1992). Mississagi sandstone is in contact with the granite on the right (north) flank of this hill. The contact dips steeply south and is the locus of shearing with south-side-up sense, but the displacement is probably not great, as dykes of granite are present in the Mississagi Formation north of the contact. The ridge to the right of the swamp is Nipissing gabbro, and Mississagi Formation is exposed sporadically along the lower slope.

Walk north on the west side of Highway 69 to examine a small, duplex-like structure in Mississagi sandstone exposed in the roadcut beneath Nipissing metagabbro. Metamorphic grade here is greenschist facies; the metagabbro contains the assemblage albite-chlorite-epidote-actinolite.

Cross the highway when traffic permits and walk back to the nearest point where the ditch can be crossed to have access to outcrop on the south side of the swamp east of the highway. The first outcrop is deformed granite of the Chief Lake complex. Continue along the edge of the swamp to the higher, bare outcrop beyond; the contact between Mississagi sandstone and the granite, both intensely deformed, is exposed here. Note the extremely finely laminated nature of the Mississagi quartzite, locally thrown into small box folds. These rocks are quartz mylonite; is it possible that the laminae represent extremely attenuated bedding? The overlying Chief Lake granite is strongly foliated with a consistent southeasterly dip of 35° and a pronounced dip-parallel lineation. It has undergone principally brittle deformation, but with ductile flattening of its quartz content. Thin sections show cataclasis of feldspar and thin, sinuous laminae of finely polycrystalline quartz with highly



Figure 4. Sketch map of the geology at the Grenville Front, Highway 69. The arrow shows the location of the small duplex in the Mississagi Formation immediately north of the front. The black line indicates the traverse described in the second part of this stop.

preferred orientation. Fine interstitial neoblasts of chlorite, pale green biotite, epidote, microcline and albite attest to low-grade metamorphism overprinting deformation features. The rocks exposed on this ridge are considered to be in the immediate footwall of what Lumbers (1975) referred to as the "Grenville Front boundary fault"

Cross the wooded valley to the south. The next ridge of outcrop exposes dark mylonite and ultramylonite that do not appear to have been derived from Chief Lake complex rocks. The mylonitic rocks exposed between here and the driveway to the south are mainly derived from mafic and semi-pelitic precursors. Large 'porphyroblasts' of garnet occur locally in the latter, but despite their euhedral shape, thin sections show that they are porphyroclasts with late rim overgrowths. Oriented X-Z thin sections also show a pronounced, oblique subgrain orientation in quartz lamellae, indicating thrust-sense displacement to the northwest.

On reaching the driveway, go west to Highway 69 and examine the mylonitized pegmatite for kinematic indicators in the first roadcut to the south on the east side of the highway.

km	cum. km	
0.0	23.8	Continue south on Highway 69.
0.7	24.5	Turn right on Gladu Road.
1.1	24.9	Stop on the right by open grassy area. Follow track across open area to golf course; cross path between fairways to outcrop in open wooded area.

Stop 5. Metasedimentary rocks in the Grenville Province margin – correlatives of the Huronian Supergroup?

The first outcrops are fine-grained, highly deformed and grain-comminuted mafic rock, probably ultimately derived from gabbro. Beyond this is a unit of feldspathic quartz metasandstone which shows some remarkably convolute fold patterns, followed by outcrops of muscovite schist. Kyanite is present in this rock, but is colourless and hard to identify. Garnet is pale and easier to spot. Staurolite is also present as small grains. The metamorphic grade recorded by the pelitic schist at this outcrop, a mere 900 m on the ground from the northwest margin of the Grenville Front mylonite zone and perhaps only 500 m perpendicularly, is clearly much higher (middle amphibolite facies) than that in the Southern Province immediately across the front. A comparable parent rock would be the shaly part of the Pecors Formation (seen at Stop 2), which itself has developed andalusite-staurolite assemblages in nearby parts of the Southern Province. The presence of kyanite at this locality indicates a distinctly higher pressure than that recorded by the andalusite-bearing knotted schists in the the Pecors Formation. In fact this schist records a complex metamorphic history. Early kyanite and staurolite are partly replaced by phengitic mica and margarite, and spongy garnet cores have secondary overgrowths containing staurolite inclusions. A P-T estimate on the younger assemblage, obtained by D.M. Carmichael, Queen's University, is 7 kbar at $\leq 670^{\circ}\text{C}$, and "... the garnet core inclusion assemblage ... gives evidence of earlier equilibration at about 4 kbar." (Davidson *et al.* 1991). As documented by La Tour (1981), the apparent gradient across the front is too steep to be anything but tectonically telescoped, particularly if the paleoisotherms are inclined.

At a locality 1.2 km to the southeast (Davidson 1994), approximately 2 km from the Grenville Front and well beyond the zone of intense mylonitization defining the front in this area, metasedimentary rocks include pelitic gneiss, quartz-rich feldspathic gneiss, and a thin, discontinuous layer of calc-silicate gneiss. These are interlayered with thick units of coarse garnet amphibolite and gedrite-hornblende gneiss of uncertain origin. Association of both kyanite and sillimanite with K-feldspar were reported to occur in this area by Kwak (1968), although the prevalent assemblage in pelitic gneiss here is quartz-plagioclase-biotite-muscovite-garnet-kyanite-sillimanite; staurolite is absent. A P-T estimate obtained by D.M. Carmichael is ~ 8 kbar at 710°C (Davidson *et al.* 1991). The isograd marking the first appearance of sillimanite (which here texturally overprints kyanite), trends north-northwest toward the Wanapitei fault segment of the Grenville Front between

Coniston and Wahnapiatae village (Stop 7). A feature of the pelitic gneiss in this vicinity is the occurrence within it of quartz pods with coarse blue kyanite (up to 10 cm) and minor garnet.

<i>km</i>	<i>cum. km</i>	
0.0	24.9	Return to Gladu Road and Highway 69, and retrace route back toward Sudbury.
6.9	31.8	At traffic light just before overpass, turn left onto ramp for Sudbury bypass (Highway 17E). Beyond Stop 1, note that bedding in the Mississagi Formation changes dip direction from northwest to south as one crosses the Coniston syncline. The big roadcuts on the hills after the long left-hand curve expose spectacular examples of shatter-cones related to the impact that caused the Sudbury structure.
18.5	43.4	Take right lane at traffic light and go east on Highway 17., passing by the town of Coniston with its two defunct smokestacks. The barren blackened rocks in this area are the result of vegetation kill, subsequent severe erosion, and staining by fumes from this former smelter.
24.1	49.0	Turn right on the road to the Coniston hydroelectric generating station. Keep on main gravel road, crossing railway.
26.5	50.4	Gate at entrance to ICI explosives plant. Obtain permission to drive through the fenced compound.
27.6	51.5	End of the road; park. Walk along the south side of the valley to the powerline.

Stop 6. Truncation of the Grenville Front mylonite zone at Alice Lake

Two major faults of the Murray fault system in the Southern Province (Card 1978b), the Creighton fault and the Murray fault itself, converge eastward and meet just north of Alice Lake (Fig. 5). East-northeast of this juncture, a narrow valley in line with the Murray fault marks the Grenville Front. North of this valley are well-preserved Mississagi sandstone strata and Nipissing gabbro at low metamorphic grade, and south of it, high-grade migmatitic gneiss of the Grenville Province. The covered interval between the two conceals the Wanapitei fault, and is as little as 25 m wide in places between Alice Lake and the village of Wahnapiatae 6 km to the northeast. There is no field evidence to suggest that the Murray and Wanapitei faults are not one and the same, contrary to published maps of this area (Lumbers 1975; Dressler 1984); the two interpretations are illustrated in Figure 6.

The southeast-dipping zone of mylonitization which marks the Grenville Front to the southwest converges with the Murray-Wanapitei fault at Alice Lake.

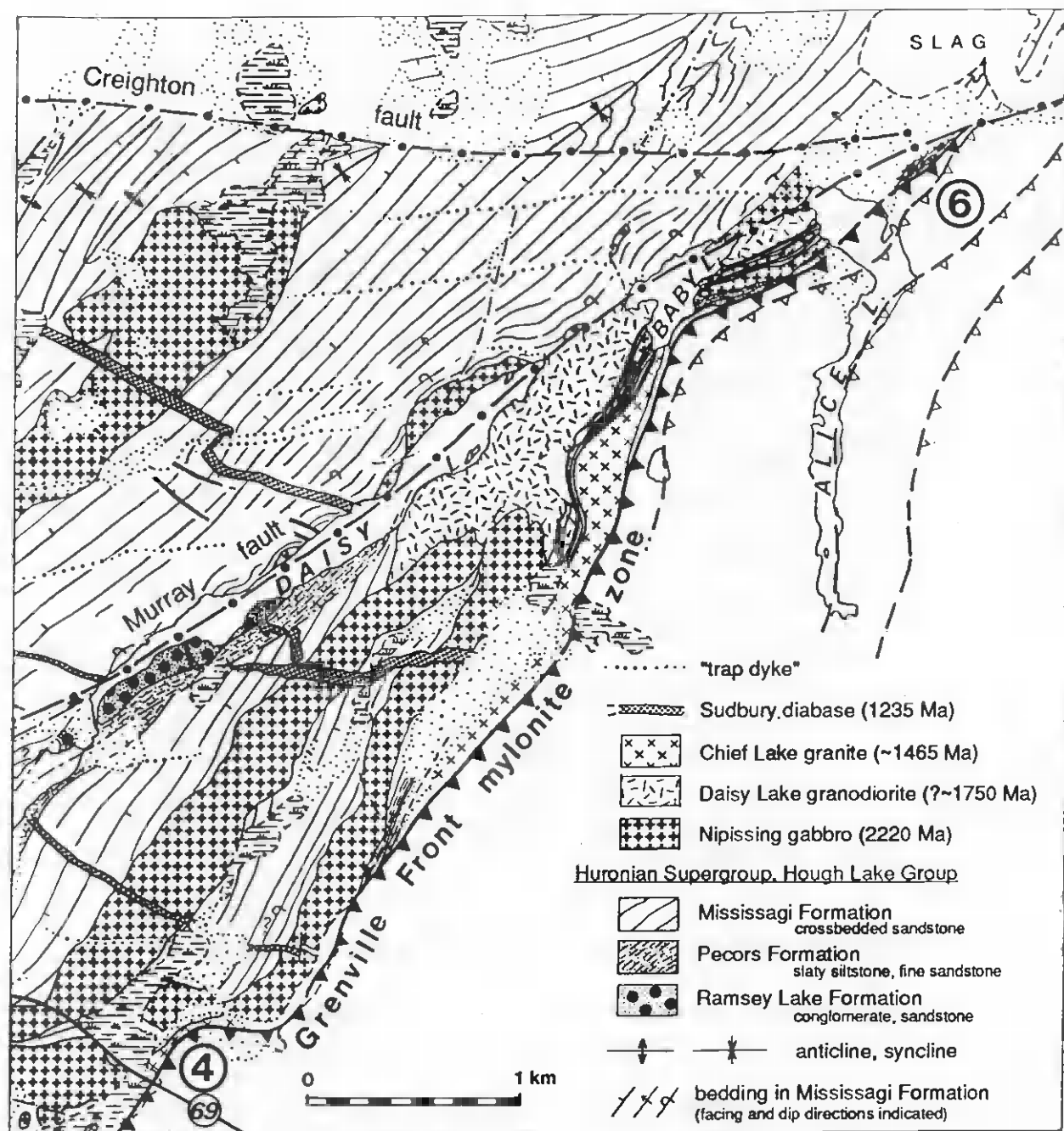


Figure 5 The juncture between the Grenville Front mylonite zone and the Murray-Wanapitei fault south of Coniston.

Four elements of the Grenville Front mylonite zone also converge at this juncture; from northwest to southeast these are:

- 1) highly attenuated Huronian metasedimentary rocks, mainly Mississagi Formation like that seen at Stop 1, Nipissing metagabbro, and protomylonitic

granitoid rocks of both the Daisy Lake (?~1.75 Ga) and Chief Lake (~1.46 Ga) plutonic units;

- 2) migmatitic granitoid orthogneiss of unknown affinity;
- 3) metasedimentary gneiss and schist, including micaceous kyanite-bearing schists like that seen at Stop 5;
- 4) Migmatitic quartzofeldspathic gneiss with mafic layers and pods.

Each of these elements is separated by a relatively narrow (a few metres), southeast-dipping zone of mylonite and ultramylonite carrying thrust-sense indicators. These intense mylonite zones, themselves included within the overall Grenville Front mylonite zone, diverge southwestward from their truncation by the Murray-Wanapitei fault (La Tour 1981). Conventionally, the Grenville Front itself is designated as the mylonite marking the southeastern limit of recognizable Southern Province rocks (Grenville Front boundary fault of Lumbers 1975).

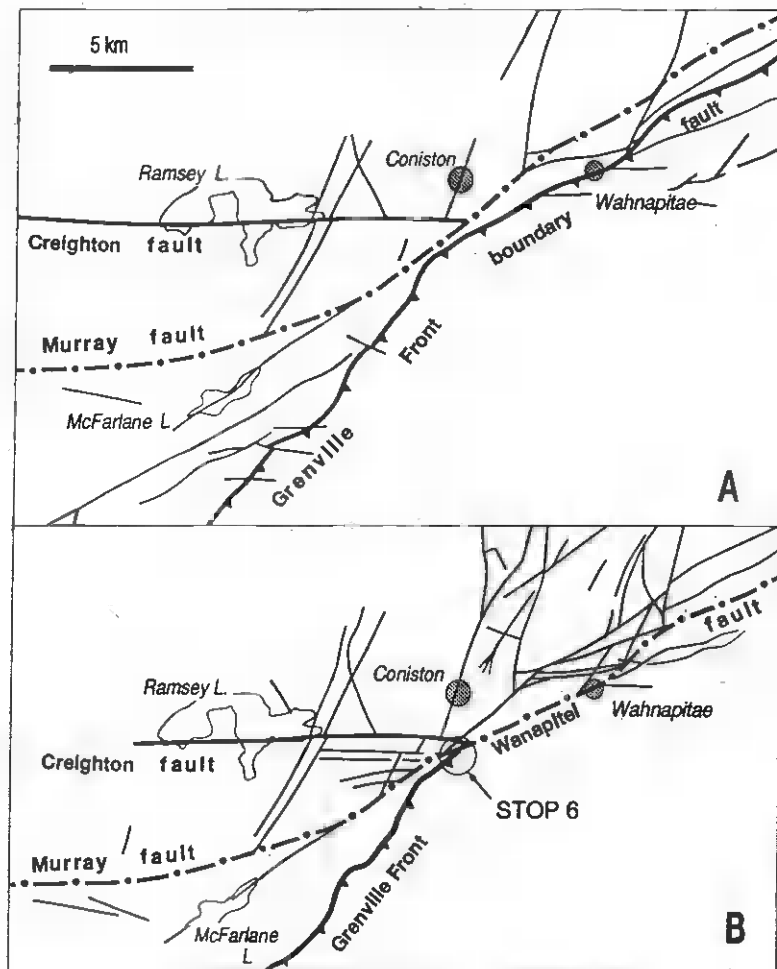


Figure 6. Fault interpretations in the Coniston area. A, after Lumbers (1975); B, modified after Dressler (1984).

At this stop, the granitoid rocks of the Daisy Lake and Chief Lake plutons exposed west of Alice Lake, have been cut out by the Murray-Wanapitei fault, so that only the Mississagi and Nipissing units, both of which have suffered extreme tectonic flattening, represent element 1 (above). The migmatitic granitoid of element 2 is also missing, although it may be represented in the pink mylonite structurally above element 1.

After examining the outcrops close to Alice Lake, climb the hill to the east to see the nature of the heterogeneous migmatitic gneiss of element 4, noting shear sense in the underlying mylonite, and the ductile style of deformation, including sheath folds, in the gneiss above. Thin units of pelitic gneiss are present locally within this unit. There is some resemblance between the migmatitic quartzofeldspathic gneiss seen here and migmatitic granitoid at Stop 8, several kilometres to the northeast, but there is no continuity in outcrop.

0.0 51.5 *Return through compound.*

1.8 53.3 *Park on the right just beyond the railway crossing.*

Stop 7. Comparison of Southern and Grenville Province rocks on opposite sides of the Wanapitei fault near the Coniston hydroelectric dam

This outcrop shows similar features to those in element 4 at the last stop, and includes narrow mylonite zones that diverge southwestward from the Murray-Wanapitei fault line. The remarkably well-preserved state of the Mississagi sandstone north of the fault can be examined on the hillside north of the valley, where cross-bedding shows that the succession faces northwest, away from the Wanapitei fault.

To the southeast, the dark high ground on the other side of the Wanapitei River and the Coniston hydroelectric plant is underlain by predominantly mafic rocks of the Wanapitei complex. There is not time on this trip to visit this 3 x 8 km body of rock, whose northern contact is only 500 m from here. Field work has shown that this complex is not an *in situ* intrusion but in fact a huge tectonic remnant wrapped by a carapace of ductile gneiss (Davidson and Ketchum 1992). This topic is elaborated in the notes that follow the stop descriptions. Suffice it to say that metasedimentary gneiss with garnet and both kyanite and sillimanite lies within the valley north of the Wanapitei complex; the fact that this is less than half a kilometre from the low-grade Mississagi Formation exposed at this stop attests to an enormous net displacement along the Wanapitei fault/Grenville Front at this locale.

- 0.0 53.3 *Continue back to Highway 17.*
- 1.8 55.1 *Highway 17, turn right.*
- 4.4 57.7 *Bridge over the Wanapitei River. The highway crosses the Wanapitei fault and enters the Grenville Province at this point.*
- 10.7 64.0 *Railway crossing.*
- 11.8 65.1 *Turn left on road to Stinson Hydro; keep to the left at all turnings.*
- 13.2 66.5 *At the bottom of the hill after passing under second powerline, take a track to the left, just before the entrance to the parking area by the hydroelectric plant (alternatively, park and walk along the track).*
- 14.0 67.3 *End of track. Park and walk ahead, crossing the weir over the river. Follow instructions under Stop 8, below.*

Stop 8. Grenville Front relationships near the Stinson hydroelectric dam; Mississagi Formation, ultramylonite and cataclasite, metasedimentary gneiss and schist including metaconglomerate, and an Archean (?) migmatitic granite slice south of the Grenville Front

This stop requires a walk of about 2 km (Fig. 7) and will illustrate the abrupt changes of structural style and metamorphic grade associated with this part of the Grenville Front, here marked by the eastward continuation of the Wanapitei fault. From the end of the track which leads west from the lower road to the Stinson hydroelectric plant, cross the weir over the Wanapitei River and follow the track until it meets an improved gravel road, where grey sandstone beds of the Mississagi Formation are well exposed on the north side (a in Fig. 7). Bedding dips steeply northeast, and cross beds indicate that it also faces in that direction, away from the Grenville Front. Bedding strikes southeast at an angle to the trend of the Wanapitei fault. Metamorphic grade is clearly low, and there is no evidence of folding or foliation parallel to the nearby fault.

Return to the weir, but before crossing it, go to the outcrop on the north bank of the river east of the weir (b). Here bedding in the Mississagi Formation has swung toward parallelism with the Wanapitei fault, which lies a short distance to the south. The rocks display a foliation and several small-scale folds.

Cross the weir, walk back along the track, and take a side-track that leads south to the powerline clearing. Before reaching the cleared strip, cut to the left through open bush toward rising ground below the powerline (c). All the outcrop here is brittle-ductile mylonite and ultramylonite that has a grey, closely-fractured surface. Foliation is sub-vertical. At a low, west-facing vertical outcrop face on the side of the hill, small-scale kinematic indicators can be seen with the naked eye and hand-lens that show south-side-up sense of displacement. This sense is corroborated in oriented thin section by a spectacular C-and-S fabric formed by oblique subgrains in thin quartz layers, by rotated porphyroclasts, and by back rotation of

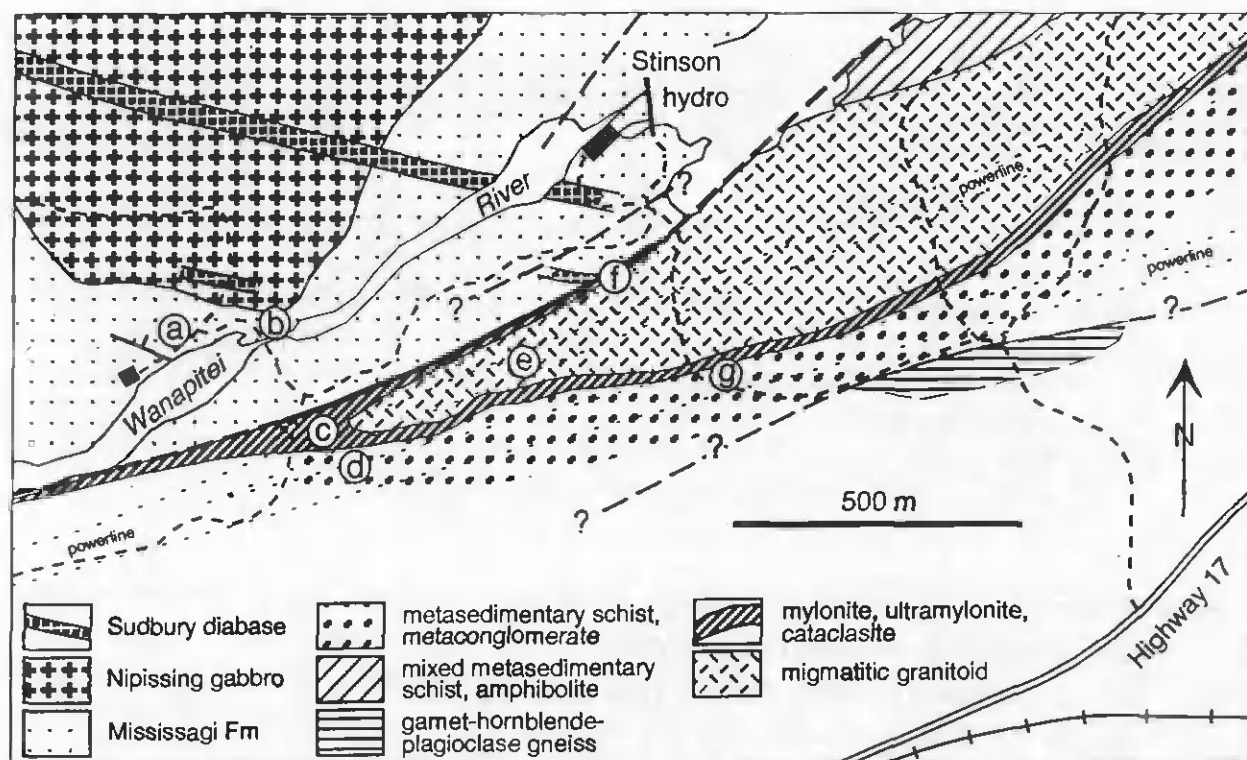


Figure 7. Geological relationships at the Grenville Front near the Stinson hydroelectric generating station.

broken feldspar grains ("collapsed dominoes"). The zone of ultramylonite is particularly thick at this locality because it is where two mylonite strands converge westward. To the east, the northern strand separates mylonitized quartz sandstone to the north from migmatitic granitoid rocks to the south; the southern strand separates this granitoid unit from metasedimentary schist and gneiss to the south.

Walk south through the narrow uncut strip that separates the two powerlines to the outcrop near the base of the hill (d). Dark metasedimentary rocks here are well layered and contain biotite and garnet; some are derived from conglomerate, although the evidence for this is not particularly convincing at this outcrop.

Walk back to the northern powerline and follow the higher ground to the east (e). Outcrop on this hill is migmatitic granitoid which shows a structural trend, given primarily by the orientation of leucosome, that strikes northwest at a marked angle to the mylonite strands. This foliation curves into parallelism with both mylonite strands that enclose the granitoid lens, having an overall Z-sense. The steep northwesterly-plunging lineation within these rocks is clearly not a typical Grenvillian orientation. Neither the age of the granitoid protolith nor of its migmatization is known, but both may be older than the metasedimentary rocks to the south, given that the latter are not migmatitic. In addition, the granitoid and its leucosome are locally cut by thin dykes of metamorphosed mafic rock which are not

found in the metasedimentary rocks. It is possible that the granitoid lens is a slice of Archean crust, but this remains to be tested by U-Pb dating.

Follow the high ground eastward on the north side of the powerline clearing, and where the ground begins to slope away to the east, go north toward the Wanapitei River. On reaching a steep, narrow gully (f), go down-slope to the right. Here a narrow zone of intensely cataclased rock derived from the migmatitic granitoid is exposed on the south side of the gully. Cross the gully, which conceals the Grenville Front boundary fault; on the north side is an outcrop of mylonitized quartz sandstone not unlike that seen at Stop 4. This is cut by a dyke of Sudbury diabase that is replete with cataclastic fractures and shears. It is hard to tell whether or not the dyke actually cuts the mylonitic foliation in the deformed sandstone; the impression that this is the case may be explained alternatively as the result of competency contrast during deformation. This dyke cannot be traced on the south (Grenville) side of the gully; continuous outcrop of migmatitic granitoid along the powerline crosses the strike projection of this dyke. Neither can the dyke be traced to the northwest; it is, however, offset from outcrop of similarly cataclased Sudbury diabase at the south shore of the Wanapitei River just below the dam, which lines up with a thick dyke on the north side; this dyke can be traced northwest for 10 km toward Falconbridge (Dressler, 1984). A mere 500 m northwest of the river, this diabase is as fresh and undisturbed as that seen at Stop 1.

Return to the powerline and go east to the road, then follow the road south to the edge of the second powerline (g). Up-slope to the left, on the north side of the powerline clearing, is an outcrop of metaconglomerate in which pebbles are well preserved. The southern mylonite strand lies farther up the hill to the north, and has been traced northeastward for two kilometres along the south slope of the high ground, everywhere marking the contact between the granitoid unit and the metaconglomerate-bearing metasedimentary rocks.

- | | | |
|-----|------|--|
| 0.0 | 67.3 | Turn round and return to Highway 17. |
| 2.2 | 69.5 | Highway 17, turn right. |
| 4.8 | 72.1 | After the railway crossing, look for the Norvic Motel on the left, cross the highway and park just beyond the motel (at an inoperative restaurant at the time of writing). Walk south to the west of the motel, and take a track into the woods until a low ridge of outcrop appears to the left. Go to the top of this outcrop. |

Stop 9. Metamorphosed Sudbury diabase dyke segments in metasedimentary gneiss showing extreme ductility

Having seen a fresh, undeformed Sudbury dyke at Stop 1, and cataclased Sudbury diabase at the last stop, it is instructive to see the form that Sudbury dykes assume in the highly ductile medium of metasedimentary gneiss that is the common country rock southeast of the front in this area. At this stop (Fig. 8), two parallel, northeast-

oriented segments of relatively thick dykes (perhaps parts of the same dyke?) are enclosed in kyanite-bearing gneiss. They terminate to the northeast with rounded ends wrapped by gneiss. Along their sides, however, they cut across gneissic foliation in their host rocks; this is best observed at the southeast contact of the northern of the two segments. Note the prolific growth of garnet porphyroblasts in the dykes near their contacts.

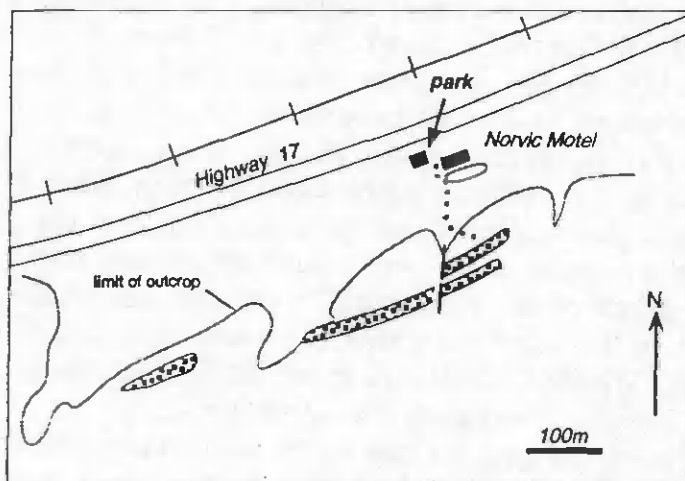


Figure 8. Detail of Sudbury metadiabase dyke remnants in metasedimentary schist and gneiss, 1200 m south of the Wanapitei fault.

No more detached segments of Sudbury metadiabase have been found along strike to the northeast, despite plentiful outcrop; mafic rocks exposed there are amphibolite derived from metagabbro. The southern segment can be followed southwestward for nearly 300 m before it disappears beneath cover; it reappears as a detached pod in the well-exposed area beyond the covered interval. In the central part of this dyke segment, where it is 27 m wide, the outcrop surface of the least altered metadiabase shows the speckled texture typical of Sudbury metadiabase. Whole rock analysis of this rock confirms its chemical affinity with the Sudbury swarm. In addition, metadiabase from another tectonic remnant, 5.5 km from the front south of the village of Wahnapiatae, contains relics of primary baddeleyite which gave a U-Pb age of 1243 Ma; six fractions of metamorphic zircon from coronas around baddeleyite in the same rock gave $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1026 to 988 Ma (Dudàs *et al.* 1994). Zircon from a late, undeformed pegmatite that cuts this enclave gave an age of 979 ± 3 Ma (A. Davidson and O. van Breemen, unpublished).

Cross the narrow wooded draw flanking the north side of the central part of this dyke and go to outcrop in the open area beyond. Here, 'homogenized' kyanite gneiss encloses twisted fragments of mafic rock, representing either a small dyke or

pieces torn from a larger one. This outcrop bears testament to the extremely ductile behaviour of the kyanite gneiss a mere 1200 m south-southeast of the Wanapitei fault.

Return to the highway and to Sudbury. (If time permits, an extra stop will be made to see the succession kyanite schist-quartzite-calcareous gneiss in the core of a fold just north of the highway nearby.)

COMMENTS – PROBLEMS OF CORRELATION AND HISTORY OF THE GRENVILLE FRONT

Metasedimentary schist and gneiss immediately southeast of the Grenville Front boundary fault in this region bear no strong resemblance to the sedimentary rocks of the Huronian Supergroup in the adjacent Southern Province, which here are represented by the Mississagi Formation characterized by a monotonous succession of cross-bedded feldspathic sandstone beds totalling as much as 3 km thick. In the Grenville Province, the metasedimentary rocks display an alternation of contrasting rock types in units only ten to a few hundred metres thick, and although one may appeal to thinning during ductile deformation, the successions themselves do not satisfactorily match any parts of the well-documented Huronian succession (see Table 1). If, for example, the metaconglomerate and kyanite schist present in this area are equated with, say, the Ramsey Lake (Stop 2, conglomerate) and Pecors (Stop 3, slaty argillite) formations, which lie stratigraphically below the Mississagi, then their association with well-layered garnet-hornblende-quartz-plagioclase gneiss, presumably derived from calcareous sedimentary rock, cannot be explained in stratigraphic terms, as the only calcareous unit of consequence in the Huronian succession is the Espanola Formation (composed of calcareous siltstone and wacke with limestone at its base and dolomite at its top), which lies *above* the Mississagi and Bruce formations; this correlation problem is compounded by the fact that a thin but persistent quartzite unit lies between the kyanite schist and the calcareous metasedimentary gneiss. Equating the metaconglomerate with conglomerate higher in the Huronian succession, either the Bruce or Gowganda formations, is equally problematic since both these formations are overlain by thick quartz-rich sandstone units (the Serpent and Lorrain formations respectively) that are not present in this part of the Grenville Province.

One is left with four alternatives, namely: 1) the metasedimentary rocks are facies equivalents of Huronian formations – a conjecture formerly favoured by Lumbers (1975, 1978); 2) they represent sedimentary rocks of formations higher in the Huronian succession (*i.e.* above the Bar River Formation; Table 1) than are currently preserved in the Southern Province; 3) they represent a younger succession that may have been deposited unconformably on the Huronian Supergroup (perhaps equivalent in age to the Marquette Supergroup in the Southern Province of northern Michigan?); 4) they are an entirely different succession tectonically juxtaposed at some time against the Southern Province. The jury is still out on this

matter, but, as stated earlier, an inkling that the metasedimentary rocks are not correlative with the Huronian Supergroup comes from Nd isotope studies which show that, provided Nd isotope systematics have not been disturbed during the polyphase structural and metamorphic history imposed on these rocks, the metasedimentary rocks in the Grenville Province near the front have Nd depleted mantle model ages younger than those of the Huronian Supergroup. If on this basis the last alternative given above is favoured, juxtaposition would probably have occurred before ~1750 Ma, the age of plutonic rocks found on both sides of the Grenville Front. Is this part of the front therefore coincident with a pre-Grenvillian suture? – perhaps Penokean in age? Note that Dickin and McNutt (1989) placed a Penokean suture much farther south within the Grenville orogen.

Two other rock units northwest of the front have potential counterparts within the marginal part of the Grenville Province. One of the characteristic geologic units in the Southern Province, and also in the neighbouring part of the Superior Province, is the Nipissing gabbro, occurring as large, sill-like intrusions. Amphibolite bodies of similar size, derived from gabbro, occur within the metasedimentary rocks in the Grenville Front zone. Another characteristic unit, found near the base of the Huronian Supergroup in the Sudbury region and also adjacent to the front 50 km to the northeast, forms a number of older (~2.45 Ga) intrusions of gabbro and anorthosite. Rocks of similar composition, now mainly metamorphosed to plagioclase-rich hornblende gneiss but locally retaining relict igneous texture where not strained, occur within the adjacent part of the Grenville Province. If it is considered that these two units are correlative across the front (and it does seem likely that the older suite is correlative, as it can be traced directly across the front at River Valley), then it becomes difficult to accept that the associated metasedimentary rocks in the Grenville are not Huronian equivalents. If they are Huronian, then all that can be said is that during their tectonic history they have been so severely sliced up and stacked together out of sequence that all semblance of Huronian stratigraphic order has been obliterated.

With regard to the potential severity of tectonic 'rearrangement', two other units within the Grenville Front zone must be considered. The first is the narrow wedge of migmatitic granitoid examined at Stop 8, and other, smaller slivers of the same rock that occur tucked in with metasedimentary rock and amphibolite toward Wahnapiatae. The age of the granite protolith is not known, but it is possible that it is Archean, and if so, that it represents basement to the Huronian Supergroup brought up in tectonic slices at the front. Its migmatitic nature is characteristic; similar leucosome is not present in orthogneiss derived from post-Huronian granitoid rocks (e.g. Chief Lake granite) adjacent to the front south of Sudbury.

The second is the fascinating Wanapitei mafic complex, mentioned at Stop 7, which time has not allowed to be examined on this trip (see Davidson 1994 for field guidance). This 3 x 8-km body is composed in part of layered, differentiated gabbro, metamorphosed but not deformed, and in part of an incredible jumble of equant to distorted blocks of mafic rocks in a matrix of variably ductile material derived from both the gabbro and an invading swarm of granite dykes. Where the dykes cut undeformed gabbro, they are straight-walled and composite, with abundant evidence for comingling of gabbroic and granitic magma. The granite from one of these dykes

has a U-Pb zircon age of 1747 Ma (Davidson and van Breemen, unpublished), the same age as that obtained by Prevec (1992) on zircon from metagabbro (although it is possible that the zircon from the gabbro is metamorphic). All of these rocks are cut by straight, north-trending, vertical dykes of coronitic olivine metadiabase (just like that in the core of the dyke remnant seen at Stop 9), whose chemistry is identical to Sudbury diabase. In addition, the dykes retain chilled margins, close to which may be found large plagioclase xenocrysts and small, angular xenoliths of quartz sandstone, as do Sudbury dykes in the Southern Province (Stop 1). The outer part of the Wanapitei complex, well exposed along its north and west sides, is entirely tectonic, formed of ductile, recrystallized gneiss whose foliation wraps the complex. Primary layering in the undeformed gabbro is truncated at this contact, and neither the granite nor olivine metadiabase dykes penetrate the ductile carapace – in fact, large boudins of metadiabase are incorporated within the ductile rim, and occur as disconnected and disoriented segments in the more distal country rocks.

If the coronitic metadiabase dykes within the Wanapitei complex are indeed Sudbury dykes, then it follows that the incorporation of the complex as a 'megaboudin' within a ductile medium, was an effect of Grenvillian orogeny. The fact that the northern contact of the Wanapitei complex, in contact with sillimanite-bearing gneiss, lies less than 500 m from outcrops of greenschist-facies Mississagi Formation with preserved sedimentary structures facing away from the front (Stop 7) belies a remarkably steep gradient in metamorphic grade and style of deformation across this part of the Grenville Front. It seems clear that the Grenville Front boundary fault, particularly where coincident with the Wanapitei fault, exhibiting brittle deformation, is the latest manifestation of considerable uplift along part of the Grenville orogenic margin, probably post-dating introduction of pegmatite at 980 Ma, and perhaps related to rebound of the Grenville orogen induced by southeast-directed extensional unloading of the tectonically thickened Grenville interior.

A word remains to be said about possible renewed displacement, of normal sense (south-side-down) along the Wanapitei-Murray fault. The truncation of the moderately southeast-dipping Grenville Front mylonite zone at Alice Lake (Stop 6), and of the parallel Grenvillian metamorphic isograds to the southeast, by the sub-vertical Wanapitei fault is hard to reconcile geometrically with uplift of the Grenville side alone, unless the pre-existent Murray-Wanapitei fault acted as a ramp against which moderately-inclined, thrust-sense displacement (Stop 4) was deflected vertically. Alternatively, the Wanapitei-Murray fault may have been reactivated during post-Grenvillian rifting associated with late Neoproterozoic development of the St. Lawrence rift system, centered far to the east and related to opening of the Iapetus Ocean. In this regard, some 50 km east of Sudbury the Wanapitei fault curves from its position as the Grenville Front boundary fault into the Grenville Province, cutting across thrust faults and mylonite that mark the continuation of the Grenville Front to the northeast; it projects eastward toward south-side-down faults that mark the northern edge of the Ottawa graben (Lumbers 1971b) in which Lake Nipissing lies, and with which are associated several alkalic and carbonatite complexes dated at ~585 Ma.

In conclusion, the Grenville Front (*sensu lato*) in the Sudbury region clearly has a history of activity, albeit sporadic, that lasted for a lot longer than the duration

of the Grenvillian orogeny itself. It may have been the locus of juxtaposition of different blocks of crust (based on differences between the Huronian Supergroup in the Southern Province and the metasedimentary rocks in the adjacent Grenville) before being sealed by igneous rocks at ~1740 Ma. It was active following emplacement of granite plutons at ~1470 Ma, but quiescent at the time of intrusion of the continental Sudbury diabase dyke swarm at ~1235 Ma. It was strongly active during at least the latter part of Grenvillian orogeny, with ductile followed by brittle deformation at ~1000 Ma, and part of it may have been reactivated during the late Neoproterozoic.

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