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**Ontario Geological Survey
Open File Report 6394**

**Multiscale and Polyphase
Deformation Structures in the
Grenville Front Tectonic Zone
near Sudbury: A Geological
Guidebook**

2023

ONTARIO GEOLOGICAL SURVEY

Open File Report 6394

Multiscale and Polyphase Deformation Structures in the Grenville Front Tectonic Zone near Sudbury: A Geological Guidebook

by

D. Jiang and C. Li

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Preface

This geological field trip guidebook was prepared initially for use with a field trip (trip number FT06) for the joint annual meeting of the Geological Association of Canada, the Mineralogical Association of Canada and the Society for Geology Applied to Mineral Deposits (GAC–MAC–SGA) held in Sudbury, Ontario, May 25–27, 2023.

Sudbury is one of the world’s premier nickel-copper mining districts, a significant platinum group element (PGE) producer, and one of the oldest, largest, and best-exposed meteorite impact sites on Earth. As the world’s largest integrated mining technology cluster, Sudbury has a vibrant mineral exploration and mining community that includes several major producers, numerous junior exploration companies, dozens of mining supply and service companies, 3 post-secondary educational institutions and associated exploration and mining centres, and several Ontario government mining and mineral ministry offices, making Sudbury one of the best places in the world to host a multidisciplinary meeting of this type. The City of Greater Sudbury, the largest city by landmass in Ontario, lies amidst glacially shaped ridges, green boreal forests, and contains 330 lakes over 10 hectares in size and 112 lakes over 100 hectares in size. The success of more than 40 continuous years of environmental reclamation efforts has led to numerous national and international awards, including a Government of Canada *Environmental Achievement Award*, a United States *Chevron Conservation Award*, and a United Nations *Local Government Honours Award*. And, as part of Sudbury’s continuing greening efforts, the milestone 10 millionth tree was planted in July 2022.

The theme of the GAC–MAC–SGA meeting—“Discovering Ancient to Modern Earth”—reflects the location of the meeting at the intersection of the Archean Superior Province and Proterozoic Southern and Grenville provinces, and Paleozoic–Quaternary cover sequences. The hybrid conference included a technical program of oral and poster presentations in Symposia, Special Sessions and Regular Sessions covering the complete spectrum of geoscience disciplines, which were complemented by 10 field trips, 6 workshops and 1 short course.

The meeting was hosted by the Harquail School of Earth Sciences and the Mineral Exploration Research Centre (MERC) at Laurentian University.



2023 SUDBURY

Abstract

This one-day field trip focusses on the deformation structures present near Sudbury in the Grenville Front Tectonic Zone that formed during the Grenvillian Orogeny. In this guidebook, 7 key outcrops are briefly described, upon which the geometry, overprinting relationships and kinematics of these structures can be established. Three of these outcrops are field trip stops. These structures record polyphase and multiscale deformational events in the middle and lower crust during the Grenvillian Orogeny, including the contractional (D_1) deformation associated with the earlier Ottawa phase thickened orogen, the extensional (D_2) deformation related to orogen collapse of the later Ottawa phase, the contractional (D_3) deformation of the Rigolet phase that produced the Grenville Front shear zone, and the post-shear zone (D_4) deformation. Whereas D_1 and D_2 deformations affect a broad area of the Grenville orogen, D_3 deformation is localized in the Grenville Front Tectonic Zone. The Grenville Front shear zone is a well-exposed ductile shear zone that developed at the contact between the Grenville Province and the Southern Province. The shear zone is a D_3 structure. Spectacular mylonites derived from a variety of rock types are exposed across the shear zone with a top-to-the-northwest thrust shear sense indicated by the S-C-C' fabric geometry, the down-dip stretching lineation, and lineation-parallel isoclinal folds intrafolial to the mylonitic C-foliation. A post-shearing phase of deformation (D_4) is clearly observable in the mylonite zone. The mylonitic C-foliation and compositional layering are openly folded with fold hinge lines parallel to the stretching lineation and fold axial planes perpendicular to the C-foliation. The D_4 deformation is interpreted to have resulted from the relaxation of stress normal to the mylonite foliation following the D_3 contraction.

Multiscale and Polyphase Deformation Structures in the Grenville Front Tectonic Zone near Sudbury: A Geological Guidebook

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Ontario Geological Survey
Open File Report 6394
2023

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Introduction

The Grenville Front refers to the boundary between the Grenville Province and the Southern, the Superior, the Churchill and the Nain geological provinces (Figure 1A). The Grenville Front Tectonic Zone (GFTZ) is the northwesternmost deformation zone in the Grenville Province (*see* Figure 1A) and the segment within Ontario is about 10 to 30 km wide. This field trip shows the geometry and the kinematics of the structures developed in the GFTZ near Sudbury. In the literature, the GFTZ near Sudbury is reported to record only the Rigolet phase (*circa* 1000–980 Ma) of the Grenvillian Orogeny (*circa* 1090–980 Ma). The field trip shows that the deformation structures in the GFTZ record all phases of the Grenvillian Orogeny. Participants can observe the overprinting relationships of the polyphase deformation structures and evaluate the kinematic significance of the structures.

SAFETY

One stop is located on Trans-Canada Highway 17 and another on Highway 537. Traffic on both highways is busy, and transport trucks and logging trucks are common. These big trucks have great momentum and take a much longer time to brake to slow down or to stop. Depending on weather, fog may occur and can cause additional risk. The authors have selected field trip stops that have enough parking space off the highway. A safety vest or bright clothing is recommended on the field trip. Care should always be exercised when slowing down, parking, and exiting vehicles. All drivers and participants should use extreme caution and always stay away from the road once out of the vehicle.

Some outcrops may be wet and slippery if it is early in the morning or if it rained the night before. Participants should be aware of this and wear good boots for the field trip. There are outcrops worthy of climbing to the top, but be mindful of the slippery surface and other participants around you when getting on and off an outcrop. Access to Stop 3 (Outcrop VI) requires approximately 45 minutes of hiking on locally up and down steep slopes. At the last stop, participants should be aware of the potential for railroad traffic and “slips, trips and falls” hazards. A personal first aid kit and extra water are recommended.

Stop 2 (Outcrop III) is near a private property. Please be respectful and do not approach or enter any private property. Participants should walk and stay together. Cell phone service coverage should be available in all stops on the field trip. Make sure that your cell phones have an adequate connection to their networks.

Geological Setting

The Grenville Province lies in the southeast part of the Canadian Shield and is the youngest geological province in the Shield. Its northwest boundary with other geological provinces of the Canadian Shield is referred to as the Grenville Front, which is defined geologically by mylonite zones and brittle faults (Brooks 1967; Brown 1967, 1968; Currie et al. 1970; Baer 1976; La Tour 1979; Davidson 1984, 1986; Davidson and Ketchum 1993; Krogh 1994). From the Grenville Front to 10 to 30 km southeast of it is a northeast-trending deformation zone, known as the Grenville Front Tectonic Zone (GFTZ; Wynne-Edwards 1972; Davidson 1984). The GFTZ separates the rest of the Grenville Province from the older geological provinces (Southern Province, the Superior Province, the Churchill Province and the Nain Province) to its northwest. The older provinces were at the southeastern margin of the Laurentia before some volcanic islands and/or terranes and arc-associated metasedimentary rocks accreted from the southeast onto the Laurentia from late Paleoproterozoic to late Mesoproterozoic (Culshaw et al. 1997; Rivers 1997; Mosher 1998; Carr et al. 2000; Gower and Krogh 2002; Whitmeyer and Karlstrom 2007; Papapavlou et al. 2022). Rocks from the older provinces and the terranes at the southeast margin of the Laurentia were deformed and metamorphosed during the continent–continent collision between Laurentia

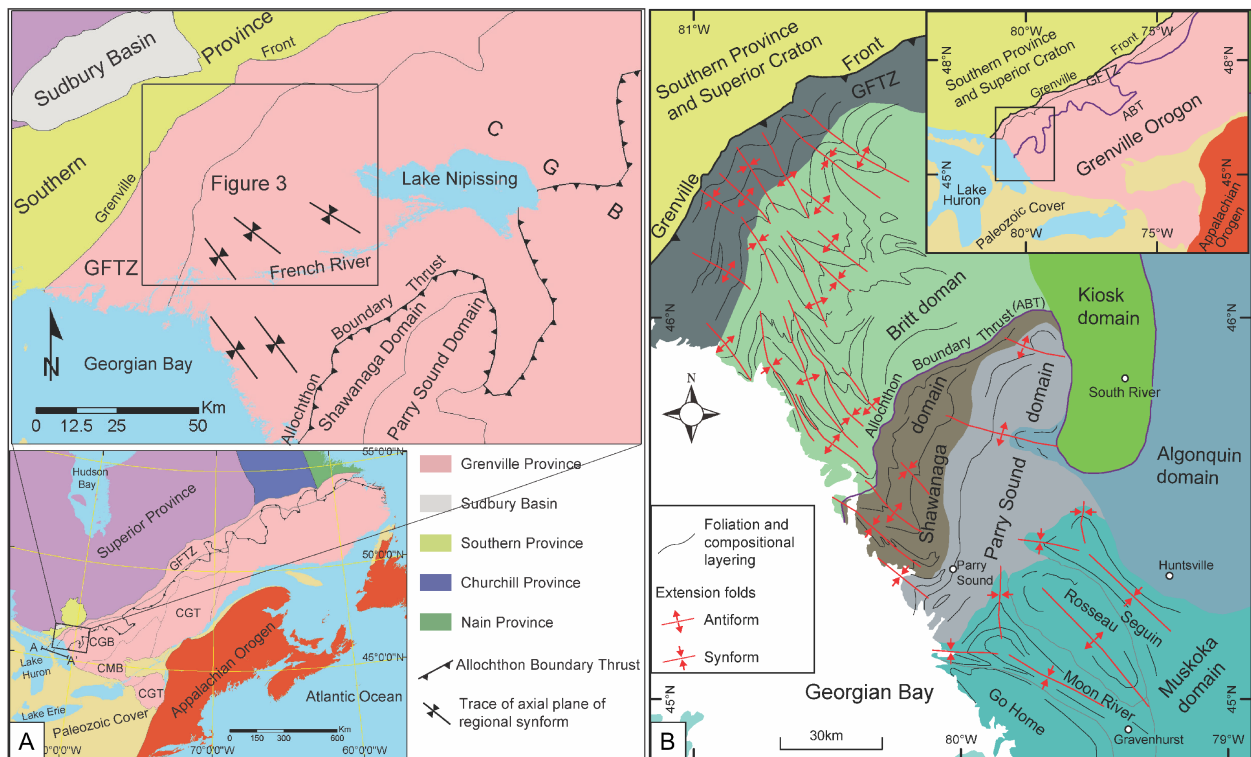


Figure 1. A) Outline map showing the location of the study area in the Grenville Province and some transverse F_2 folds as shown by Culshaw et al. (1994). Subdivisions of the Grenville Province are based on Wynne-Edwards (1972) and Culshaw et al. (1994). Abbreviations: CGB = Central Gneiss Belt, CGT = Central Granulite Terrane, CMB = Central Metasedimentary Belt, GFTZ = Grenville Front Tectonic Zone. Line A–A' is the location for the seismic reflection profile in Figure 2. The boxed area in the upper diagram shows the location of Figure 3. Modified from Davidson (1984) and Li (2012). B) Simplified map showing more upright F_2 folds (formed in the D_2 deformation phase *circa* 1020 Ma) in the high-grade nappe association in southwestern Grenville Province in Ontario. The surfaces being folded are a transposition foliation S_{T1} formed during D_1 crustal thickening (Culshaw et al. 1994; Li 2012). The fold hinge lines are nearly orthogonal to the Grenville Front which is the northwest boundary of the Grenville orogen. In the Grenville Front Tectonic Zone (GFTZ), the F_2 folds were overprinted in the D_3 deformation phase. The upper-right inset map shows the extent of the main map. Compiled from Lumbers (1975), Davidson (1984), Culshaw et al. (1994), Li (2012) and Schwerdtner et al. (2016).

and the Amazonian craton (Moore 1986; Hoffman 1991; Karlstrom et al. 2001; Whitmeyer and Karlstrom 2007; Gower, Kamo and Krogh 2008) during the Grenvillian Orogeny (*sensu stricto*; circa 1090–980 Ma; Gower and Krogh 2002; Rivers 2008, 2009). The suture zone for this Grenvillian collision has not been identified (Dewey and Burke 1973; Rivers 1997; Bartholomew and Hatcher 2010).

There are 2 orogenic phases of the Grenvillian Orogeny (*sensu stricto*) in the literature: the Ottawan phase (circa 1090–1020 Ma) and the Rigolet phase (circa 1000–980 Ma) (Rivers 2008). The GFTZ shows dominant southeast-dipping foliations (Figure 2; Jamieson, Culshaw and Corrigan 1995; Culshaw et al. 1997). Our study shows that both Ottawan and Rigolet deformation structures are present in the GFTZ. Detailed field mapping and structural analysis in the GFTZ by Li (2012) identified 3 phases of deformation structures: D₁, D₂ and D₃. The D₁ and D₂ deformations can be associated with the Ottawan phase. The D₁ and D₂ structures are present in both the GFTZ and the Central Gneiss Belt, but D₃ deformation is localized only in the GFTZ. The D₃ deformation is a southeast-to-northwest contraction and top-to-the-northwest thrust shear. Spectacular mylonites were developed at the northwesternmost of the GFTZ as a result of D₃ thrusting. A post-shearing phase of D₄ deformation is recognized from open folds of the mylonitic foliation and compositional layering. The major structures, their geometry and overprinting relationships are described in the next section.

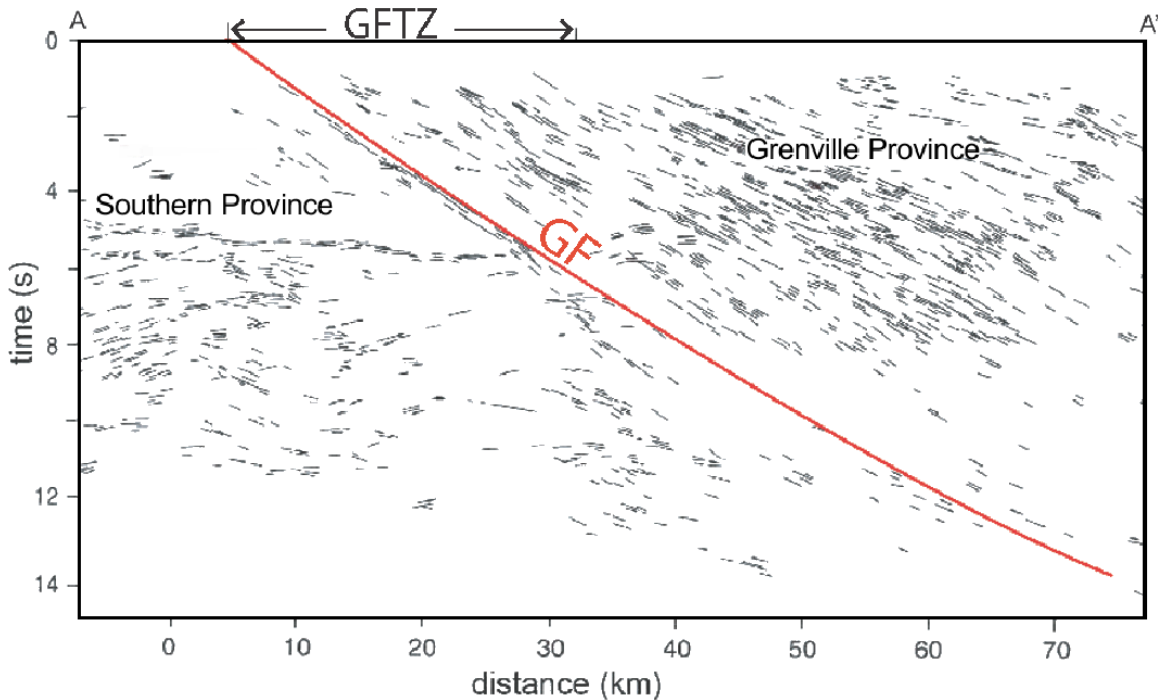


Figure 2. Cross section along line A–A' based on the seismic reflection profile in Green et al. (1988). The red line is the Grenville Front, which is the boundary between the Grenville Province and the Southern Province in the cross section. The southeast-dipping fabric in the hanging wall is interpreted to reflect the deformation present within the GFTZ.

Deformation Structures

Four phases of deformation were identified based on the geometry and overprinting relationships of field structures in the study area. Foliation patterns and rock units in the study area, shown in Figure 3, display fold interference patterns and shear zones that can be resolved into 3 principal phases of deformation (D_1 , D_2 and D_3). The D_1 deformation produced isoclinal folds and a compositional layering transposition foliation (S_{T1}) that formed the regional marker of subsequent deformations. The D_1 fabrics were deformed to form regional-scale folds during D_2 deformation. The F_2 folds have generally upright axial planes. Their hinge lines plunge shallowly to the southeast. The F_2 folds are nearly orthogonal to the strike of the GFTZ. The regional transverse folds of Culshaw et al. (1994) (*see* Figure 1B), southeast of the study area in the Central Gneiss Belt, are F_2 folds. Schwerdtner et al. (2016) interpreted these folds using a kinematic transtensional model; however, the horizontal shortening perpendicular to the fold hinge line predicted by the transtensional folding model is too small to account for the F_2 folds. The F_2 folds are extensional folds (Cerdeña and Mahadevan 2003) formed during D_2 extension orthogonal to the Grenville orogen. Such extension also led to the formation of multiscale boudinage structures widely observed in the Grenville orogen.

The D_3 deformation is localized solely in the GFTZ. The D_3 deformation overprinted F_2 folds and D_2 boudinage structures in the GFTZ. On southeast-dipping limbs of F_2 folds, northeast-plunging S-shaped F_3 folds formed, whereas on southwest-dipping limbs of F_2 folds, southwest-plunging Z-shaped F_3 folds formed (Figure 4). The axial surfaces of the F_3 folds are subparallel to the GFTZ. The D_3 deformation also produced the Grenville Front shear zone—a well-exposed mylonite zone. The mylonites have down-dip stretching lineations, lineation-parallel isoclinal folds, and S-C-C' fabrics, all suggesting top-to-the-northwest thrust shearing.

The mylonitic C-foliation and layering are folded again during D_4 deformation producing F_4 open folds. The F_4 fold axes are parallel to stretching lineation and the axial planes are orthogonal to the mylonitic foliation. The D_4 deformation is interpreted to have resulted from the relaxation of the stress normal to the Grenville Front following D_3 contraction. The D_4 deformation cannot be identified outside the shear zone because its kinematic axes are coaxial with those of D_2 . The D_4 deformation simply tightened F_2 folds slightly.

For simplicity, the study area is divided into 4 structurally homogeneous domains (Turner and Weiss 1963) called A, B, C and D, each of which is dominated by fabrics of one or more deformation phases (*see* Figure 3). The GFTZ coincides approximately with domain D (*see* Figure 3).

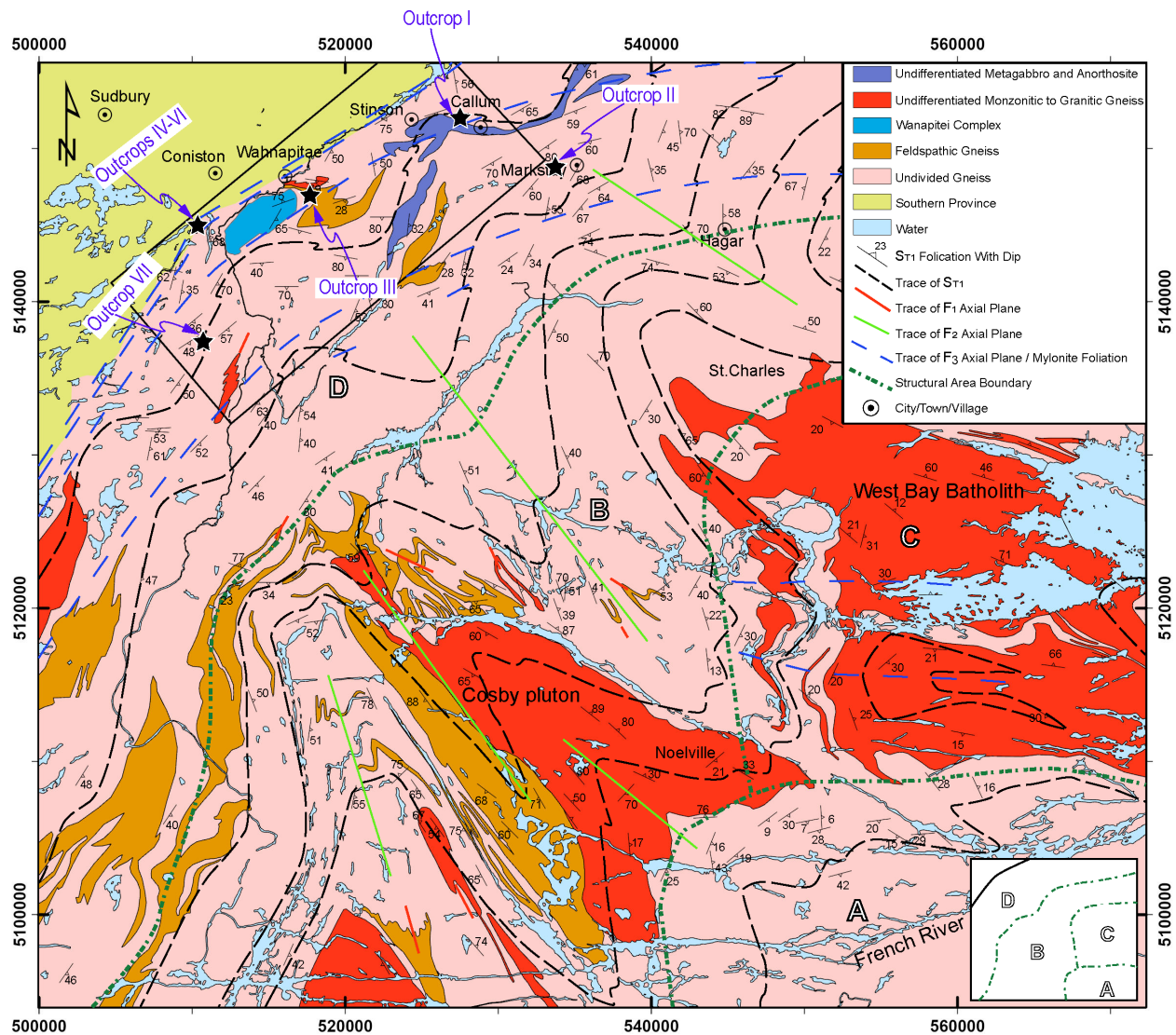


Figure 3. Detailed structural geology map with outcrop locations. Several generations of folds are shown in this map. The F_1 folds and the accompanying transposition foliation S_{T1} belong to the D_1 deformation. The F_2 folds belong to the D_2 deformation and F_3 folds belong to the D_3 deformation. The map area is divided into 4 homogeneous domains (A, B, C and D) by the dark green multi-dashed lines. A small index map (bottom right) shows the 4 homogeneous structural domains. The rectangle at the top left is the area of the block diagram shown in Figure 4. Locations of Outcrops I, II, III, IV, V, VI and VII are shown as black stars on the map. Outcrop II is Stop 1. Outcrop III is Stop 2. Outcrop VI is Stop 3. Highways and main roads are not shown for the purpose of clarity. The bedrock geology is based on Lumbers (1975). The structural analysis is based on Li (2012).

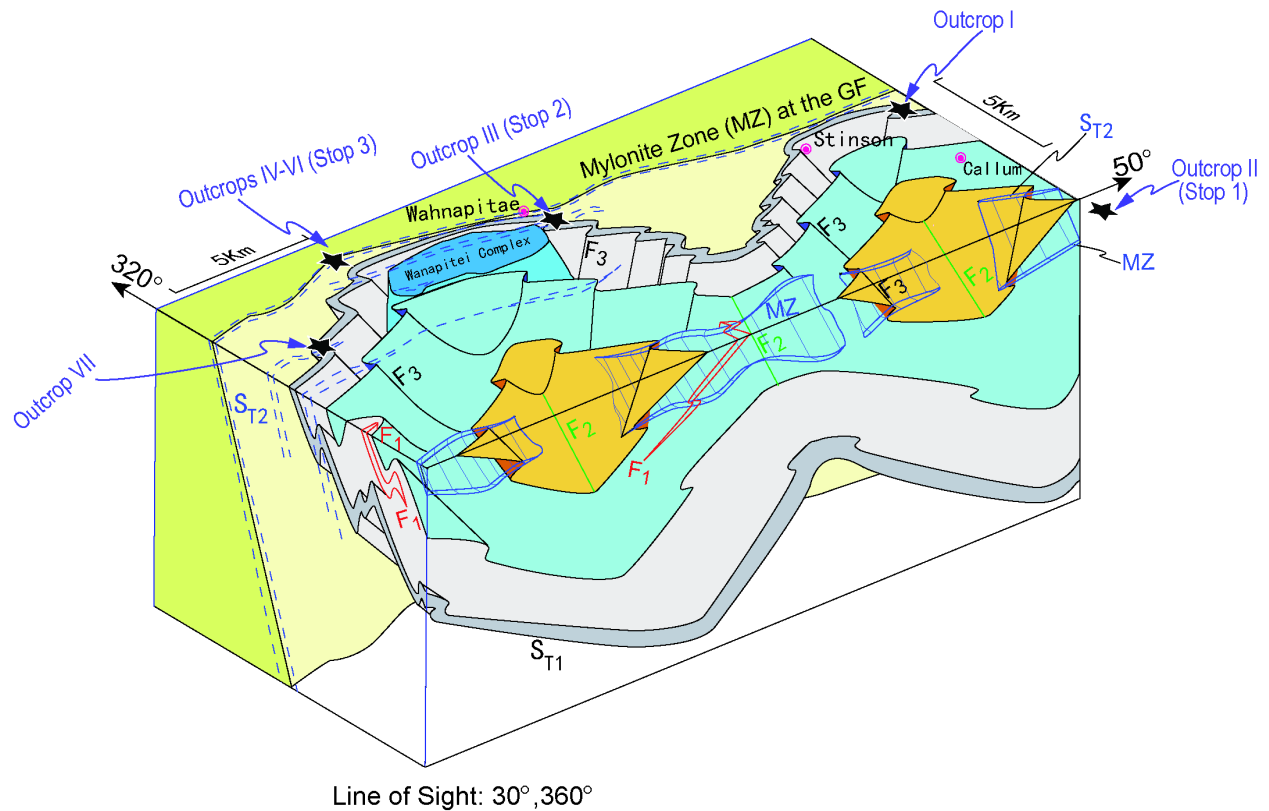


Figure 4. Block diagram showing the geometry and overprinting relationships of deformation structures developed in 3 deformation phases (D_1 , D_2 and D_3) (modified from Li 2012). The D_4 deformation is not shown as it is observable only in the mylonite zone. Transposition foliation S_{T1} and isoclinal F_1 folds were developed in D_1 deformation phase. Axial planes of F_1 folds are parallel to local S_{T1} foliation. The S_{T1} foliation was folded by regional fold F_2 in D_2 deformation phase. One limb of F_2 dips toward the southeast and the other dips to the south-southeast. The D_2 deformation also produced boudins, boudin-neck folds and extensional shear bands, which are not shown in this diagram. The F_3 folds overprinted the S_{T1} foliation in D_3 deformation phase. Depending on which F_2 limb the F_3 folds are observed, their asymmetry and hinge-line plunge vary. On the southeast-dipping limb of F_2 , F_3 folds are mainly S folds with hinge lines plunging toward the northeast. On the south-southeast-dipping limb of F_2 , F_3 folds are mainly Z folds with hinge line plunging toward the southwest. Where the D_3 deformation strain is high, a new transposition foliation (S_{T2}) was developed. Where D_3 deformation is extremely localized, mylonite zones were developed. Both the transposition foliation S_{T2} and mylonite zones are parallel or subparallel to the Grenville Front. In fact, the Grenville Front itself is mainly defined by mylonite zones. Communities are indicated by red circles. Locations of outcrops are shown by the stars on the top face of the block. Note that Outcrop II (Stop 1) is slightly outside of the block.

D₁ DEFORMATION PHASE

Fabrics developed in the D₁ phase are the transposition foliation (S_{T1}) and tight to isoclinal F₁ folds. The S_{T1} foliation is present and identifiable everywhere, except locally, where it is transposed by D₃ high-strain zones and, in the Grenville Front shear zone, where it is transposed by the D₃ mylonitic C-foliation (see below). On the outcrop scale, S_{T1} is a compositional layering defined by rock units of various origins (e.g., sedimentary layers, plutons and dikes) (Williams and Jiang 2005). At least 2 generations of folds have been recognized (Photo 1B). They are referred to as F_{1A} and F_{1B}. The F_{1A} and F_{1B} folds have similar styles and are distinguishable only when they are present on the same outcrop and show overprinting relationship (see Photo 1B). Where an overprinting relationship is not observed, it is not possible to distinguish between them (Photo 1A). Because of this, they are denoted as F₁ folds. These folds may have an axial plane foliation in some places. The F₁ folds are typically isoclinal, rootless, and vary in scale from hand specimen to regional scale. The geometrical axial surfaces of F₁ folds are always parallel to the S_{T1} foliation because of the isoclinal nature of the folds. The F₁ folds may have various origins (Carreras, Druguet and Grier 2005). Some may have been inherited from pre-D₁ deformation and were subsequently tightened, transposed and reoriented by D₁ deformation. The F₁ folds also may have formed during the D₁ deformation, either by folding of existing layers (sedimentary bedding, dike, or an earlier transposition foliation) or transposed layers that were themselves formed during the D₁ progressive deformation. As these folds are highly transposed and most are rootless, it is very difficult or impossible to decipher the origins of each individual fold (Carreras, Druguet and Grier 2005).

On the planes of transposition foliation S_{T1} generally develops a mineral lineation (L_1) that is commonly defined by elongated minerals. Dismembered and rootless F₁ folds generally have their fold hinges approximately parallel to or inclined at acute angles to the local L_1 mineral lineation.

The D₁ structures represent a typical high-grade nappe association (Williams and Jiang 2005). The structural geometry and kinematics of the D₁ structures are consistent with non-coaxial deformation at a mid- to lower crust level related to a thickened orogen present in the early Ottawa phase of the Grenvillian Orogeny (*sensu stricto*).

D₂ DEFORMATION PHASE

Fabrics developed in the D₂ phase are mainly F₂ folds and boudinage structures of the S_{T1} foliation. The axial planes of F₂ folds are mostly upright and strike mainly north-northwest, about orthogonal to the GFTZ. Typically, F₂ fold axes plunge shallowly to the south-southeast. The F₂ folds are generally symmetrical and of regional scales with amplitudes of more than 5 km. Most F₂ folds are visible in aerial photos and the geological map of domain B (see Figure 3). The F₂ folds overprinted F₁ folds (see Figure 3). However, because of its large scale, a complete F₂ fold cannot be observed in a single outcrop. The F₁ folds are present in the limbs of F₂ folds. The axial planes of F₁ folds and the S_{T1} foliation define the fold surface of F₂ folds (see Figure 3). The F₂ folds are open to tight without an axial plane cleavage. They are distinct from F₁ folds in style, orientation, continuity and scale. At the regional scale, F₂ folds are disharmonic folds (see Figure 3).



Photo 1. Photos showing D₁ structures. **A)** F₁ folds and transposition foliation S₇₁ developed at Outcrop II (see Figure 3 for location). The S₇₁ foliation is defined by alternating light-colour (quartz- and feldspar-rich) and dark-colour (biotite-rich) compositional layers. The F₁ folds here are isoclinal rootless folds intrafolial to the S₇₁ foliation. The S₇₁ foliation is overprinted by S-shaped F₃ folds. **B)** Although at least 2 generations of these isoclinal folds developed in the D₁ phase, they are not distinguishable unless an overprinting relationship is observed, as in Cosby pluton near Noelville (see Figure 3 for its location). There, isoclinal F_{1A} and F_{1B} folds developed in the D₁ progressive deformation. Several metres away from the folds (below the person), where the strain is high, transposition foliation S₇₁ is present and both axial planes of the F_{1A} and the F_{1B} folds are parallel locally to the S₇₁ transposition foliation.

In the field, no axial plane foliation or lineation has been observed in association with F_2 folds. In domain A, the D_2 effect is minor. In domain B, F_2 folds are tight folds with limbs dipping east-southeast or west-southwest. In domain C, F_2 folds are absent. In domain D, F_2 folds exist, but have not been reported previously. The F_2 folds in domain C are open folds, typically with limbs dipping east-southeast or south. Compared to those in domain B, F_2 folds in domain D have larger interlimb angles, which is a consequence of D_3 superposition (see “ D_3 Deformation Phase”). Lineations in domains A, B and C are inherited L_1 lineations. Lineations in domain D are also L_1 , except at the Grenville Front, where they were completely erased by D_3 deformation.

In addition to folds, boudinage structures (boudins and associated boudin-neck folds) are developed locally in this deformation phase in the study area (Photos 2 and 3). The D_2 boudinage structures are clearly overprinted by D_3 deformation in the GFTZ. Similar boudinage structures are observed south of the study area in the Central Gneiss Belt (Photo 4). There, the boudinage structures are not overprinted by D_3 deformation. In the GFTZ, boudins and their associated boudin-neck folds vary in scale from centimetres (see Photo 2) to tens of metres (see Photos 3 and 4). Boudin-neck folds overprint F_1 folds and S_{T1} transposition foliation (see Photos 2 and 3). The boudinage structures are themselves overprinted by F_3 folds (see Photos 2 and 3).

The structural geometry of D_2 structures is best explained by orogen-orthogonal extension. The F_2 folds are extension folds (Cerda and Mahadevan 2003) and the boudinage structures of D_2 deformation are also consistent with orogen-scale extension. They may be related to the extension stage of deformation of the late Ottawa phase of the Grenvillian Orogeny (*sensu stricto*).



Photo 2. Photo showing D_3 deformation that overprinted D_1 and D_2 deformation structures in metasedimentary rocks located within the Grenville Front Tectonic Zone. Compositional layering is the S_{T1} transposition foliation. The S_{T1} foliation is boudinaged by D_2 deformation. The boudinaged S_{T1} foliation is folded further by the upright F_3 fold. Brunton compass (middle of the photo) for scale. Vertical lines are drill-hole marks.



Photo 3. Photo showing F_3 folds that overprinted transposition foliation S_{T1} in a north-northeast-striking limb of a regional-scale F_2 fold opposite of the outcrop shown in Photo 2. The F_3 folds are upright folds with fold hinge lines plunging toward the northeast. In the centre, a little bit to the right on the outcrop, S_{T1} transposition foliation is transposed into a vertical zone interpreted as having developed by D_3 contraction of a D_2 boudin neck fold. Vertical lines are drill-hole marks.

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Photo 4. Photo showing D_2 boudins, boudin-neck fold and extensional shear band in a roadcut outcrop on Highway 400 in Parry Sound, Ontario. Boudins in horizontal compositional layers are present locally at different places in the outcrop. In the left part of the field photo, the upright fold is interpreted as a boudin neck fold. Near the right edge of the photo, an extensional shear band is present. Vertical lines are drill-hole marks.

D₃ DEFORMATION PHASE

In the study area, F₃ folds are commonly developed. They have northeast-striking axial planes subparallel to the strike of the Grenville Front. These folds folded the S_{T1} foliation (Photos 1A and 5A). They vary in scale from outcrop to map scale. The F₃ folds overprinted F₂ folds in domain D and F₁ folds in domains C and D (*see* Figure 3; *see* Photo 1A). A direct overprinting relationship between F₂ and F₃ folds (fold overprinting interference pattern) is not observable on the outcrop scale because of the difference in the wavelength between F₂ and F₃ folds. The overprinting relationship is clear, however, from the regional variation in F₃ fold geometry (*see* Figure 4). On southeast-dipping limbs of F₂ folds, F₃ folds are consistently S-shaped and plunge toward the northeast, whereas on southwest-dipping limbs of F₂ folds, F₃ folds are Z-shaped and plunge toward the southwest (*see* Figure 4). No F₃ folds developed in domains A or B.

High-strain zones parallel to the axial planes of F₃ folds are commonly observed (Photo 5B) in the migmatitic gneiss in the Wahnapiatae area. These high-strain zones are defined by a transposition layering of highly strained heterogeneous rock units.

A ductile shear zone is exposed in the Baby Lake and Alice Lake area about 2 km south of Coniston (Figure 5). This shear zone is parallel to the local Grenville Front and is a D₃ structure. Spectacular mylonites, most likely derived from a variety of Southern Province rocks (granites, sandstone of the Mississagi Formation, and the Nipissing gabbro) are exposed, nearly continuously, across a zone 400 m wide (*see* Figure 5). This mylonite zone has an average strike of ~060° and dips at about 70° southeast. The mylonites have downdip stretching lineations and show consistent top-to-the-northwest thrust shear sense as indicated by the S-C-C' fabric, stretching-lineation-parallel isoclinal folds intrafolial to the mylonitic foliation and, locally, sheath folds (Figure 6; *see also* “Road Log” for more details). This D₃ ductile shear zone separates the hanging-wall high-grade migmatitic gneisses of the Grenville Province from the footwall Southern Province sandstone of the Mississagi Formation. A strain gradient is clearly observed along the Canadian Pacific Railway, which, from north to south, changes from a weakly deformed or undeformed sandstone, with primary thick-bedded cross bedding, to variably transposed bedding to mylonitized sandstone (banded mylonite) and, eventually, quartz and quartz-feldspar ultramylonites (*see* Figure 5).

The D₃ deformation is clearly a result of orogen-orthogonal contraction. The Grenville Front shear zone reflects the progressive propagation of the deformation toward the foreland (and footwall) of the orogen. This kinematic sense is consistent with D₃ deformation being part of the Rigolet phase (*circa* 1000–980 Ma) (Rivers 2008) of the Grenvillian Orogeny.

D₄ DEFORMATION PHASE

Whereas the ductile shear zone at the Grenville Front and the accompanying mylonitic foliation and layering are D₃ structures, the mylonitic C-foliation and compositional layering are folded again by F₄ open folds. The F₄ fold axes are parallel to the stretching lineation formed during D₃ deformation. The axial planes of F₄ folds are perpendicular to the C-foliation. The F₄ folds vary in style from round-hinge sinusoidal open folds to box-like folds (*see* “Road Log” for more details).

Kink bands of mylonitic foliation and compositional layering are observed in the granite mylonites in the area between Baby Lake and Alice Lake (Outcrop IV). They are also D₄ structures.

The D₄ structures reflect (mylonitic C) foliation-perpendicular extension, and likely resulted from the progressive relaxation of the stress normal to the mylonite foliation as D₃ contraction waned.

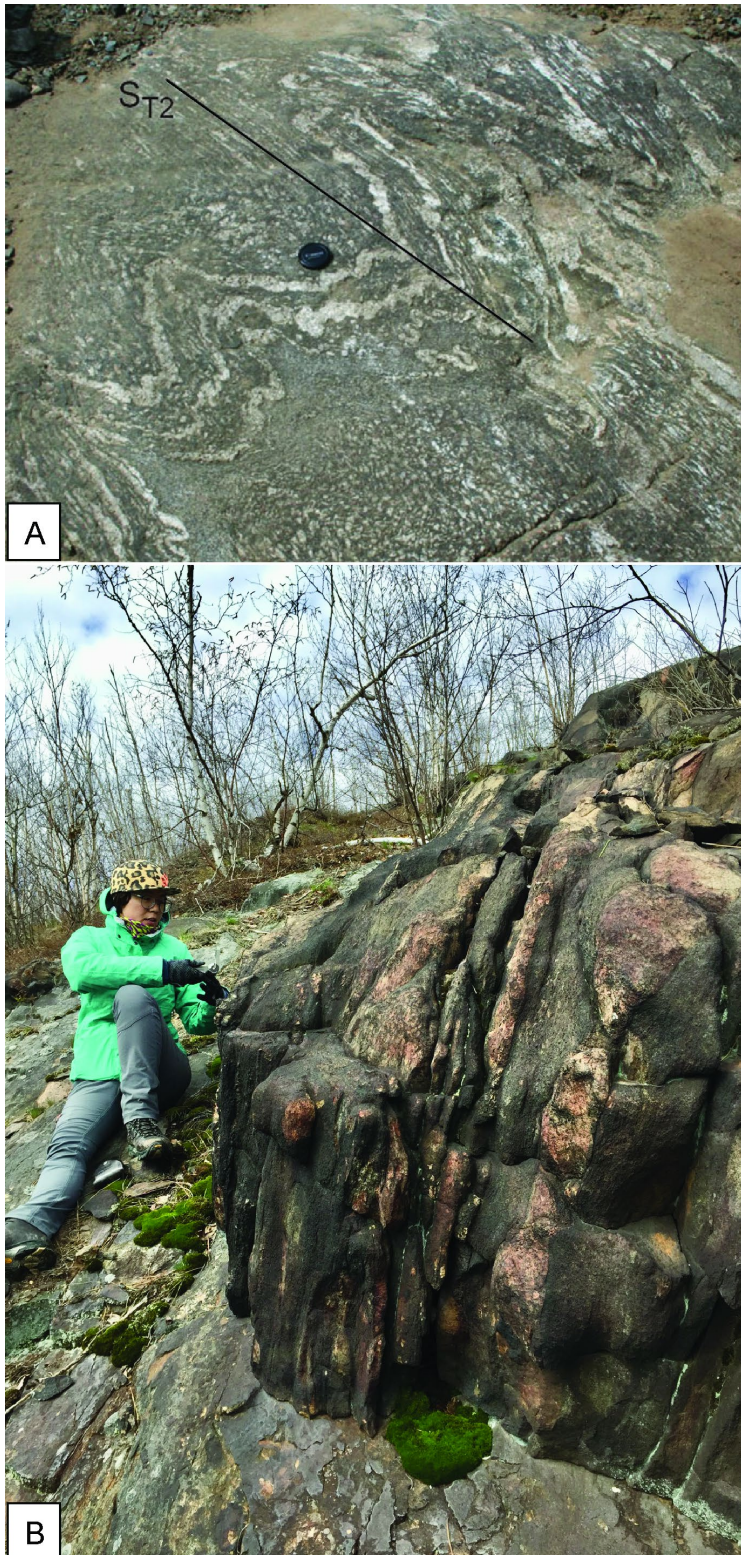


Photo 5. A) Photo of transposition foliation S_{T1} folded by F_3 folds and, in some places, transposed to develop a new transposition foliation S_{T2} . In domain D, when approaching the Grenville Front from the southeast, the interlimb angles of F_3 folds become smaller. Close to the Grenville Front, at some places where the D_3 strain is high, another transposition foliation S_{T2} developed axial planar to F_3 folds. Lens cap, for scale, is 6 cm in diameter. B) High-strain zones parallel to the axial planes of F_3 folds are common in the migmatitic gneiss in the Grenville Front Tectonic Zone. At the Grenville Front, mylonite zones are developed.

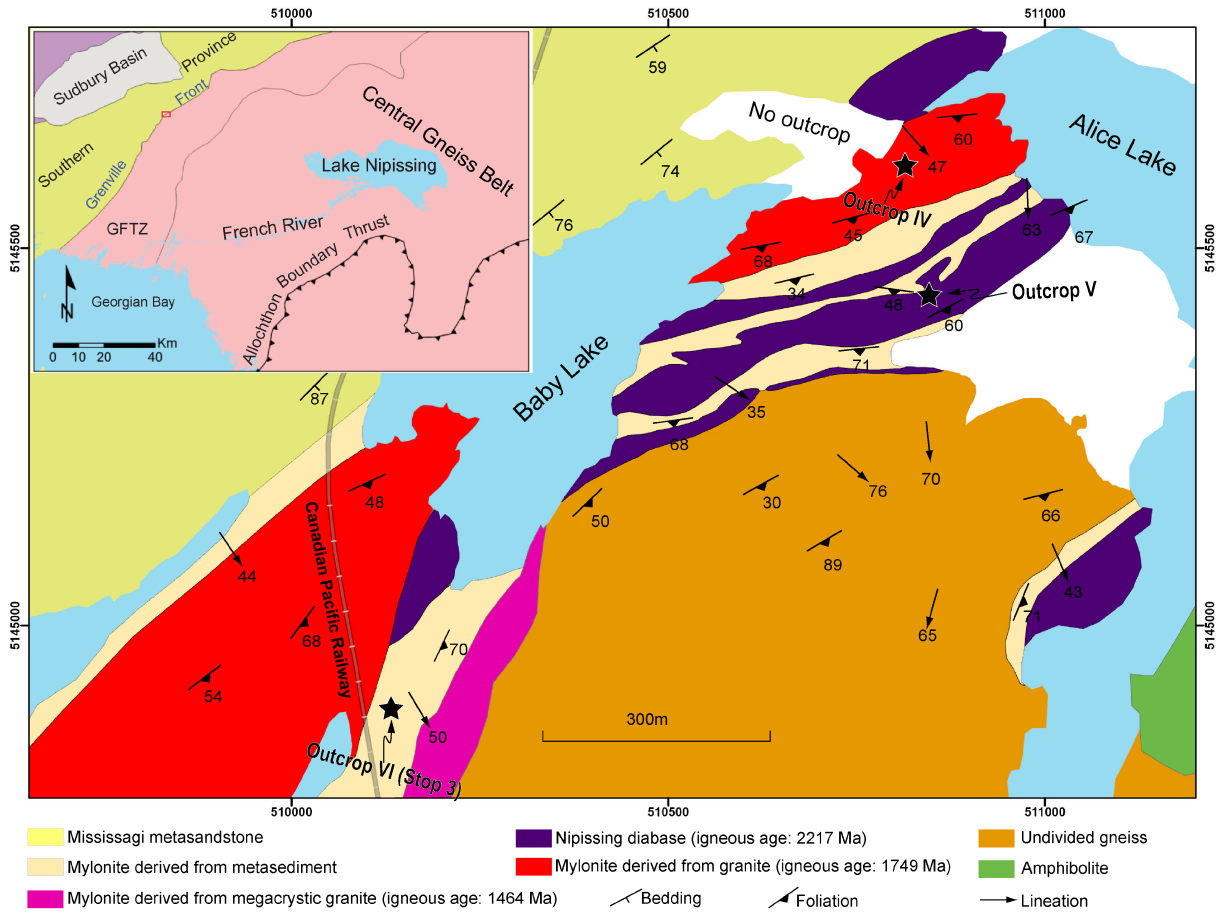


Figure 5. Mylonite zones at the Grenville Front south of Coniston, Ontario (*modified from Li 2012*). The small red rectangle in the inset map indicates the location of the area shown in the detailed map. Outcrops IV, V and VI (Stop 3) are labelled on the detailed map.

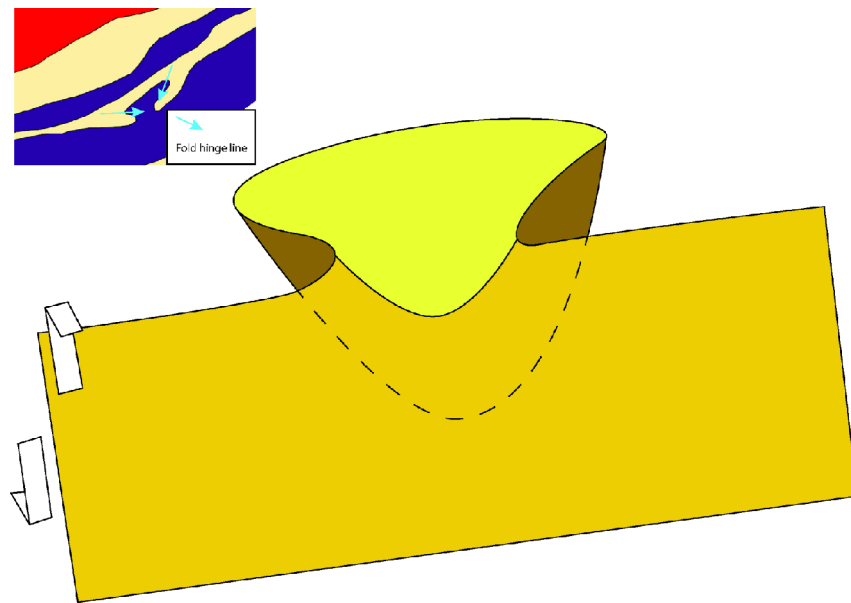


Figure 6. Sheath fold in mylonite derived from Huronian Supergroup metasedimentary rocks. The orientation of the sheath fold indicates top-to-the-northwest shear sense.

Road Log

The road log portion of the guidebook consists of 2 sections. The first section, “Description of Some Key Outcrops”, provides detailed descriptions of structural features present in 7 different outcrop areas. The second section, “Travel Directions”, provides directions and mileage information to get to those outcrop areas (called “Stops”) that can be publicly accessed relatively easily. The road log is organized in this fashion to provide flexibility during the field trip itself, and so as to only provide directions to those outcrop areas that can be publicly accessed after the GAC–MAC–SGA meeting.

DESCRIPTION OF SOME KEY OUTCROPS

Outcrops I, II and III focus on foliations and folds developed during the D_1 and D_3 deformation phases. Outcrops IV, V and VI show deformation structures developed in a mylonite zone that formed during the D_3 deformation phase. Outcrop VII illustrates overprinting relationships among D_1 , D_2 and D_3 structures (see Photo 3). All Universal Transverse Mercator (UTM) co-ordinates provided use North American Datum 1983 (NAD83) in Zone 17.

Outcrop I. Z folds (F_3) on the south side of Highway 17

UTM 528017E 5151700N

This outcrop is located on the south side of Highway 17, near civic address sign No. 3241 on Highway 17. Garnet-hornblende-biotite-plagioclase paragneiss shows well-developed transposition foliation (S_{T1}) folded by F_3 folds which have consistent Z geometry. On the top surface of the outcrop, 2 rusty layers stand out by colour; one of these rusty layers is highlighted in Photo 6. These 2 layers represent iron sulphide-containing sedimentary beds that were rotated to be parallel to the transposition foliation (S_{T1}) in D_1 deformation phase. Leucosomes and melanosomes are present and help define the transposition foliation. This outcrop is on a south-southwest-dipping limb of a regional F_2 fold. A bird’s eye view of the outcrop is shown in Photo 7.

Outcrop II (Stop 1). Overprinting of F_3 S folds on F_1 folds

UTM 533607E 5149243N

The outcrop is on the north side of Highway 17. The exposure is continuous from the intersection of Pioneer Street West westward for about 100 m. An $F_2(?)$ synform is observed at the parking spot. The other rock exposures westward on Highway 17 are on the west limb of this F_2 fold. At least 2 generations of folds (F_1 and F_3) can be observed in the migmatitic paragneiss. The compositional layering here defines the S_{T1} foliation. Locally, the compositional layers are boudinaged and boudin neck folds developed. The F_1 folds are isoclinal with axial planes parallel to local S_{T1} foliation. The S_{T1} foliation and isoclinal F_1 folds are folded by chevron or kink-like F_3 folds (Photo 8). They are S shaped, with axial planes striking east and dipping steeply toward the north. The hinge lines of these F_3 folds all plunge toward the northeast. The enveloping surface of F_3 -folded layering is part of a north-northeast-striking limb of an F_2 fold (see Figure 3).



Photo 6. Photo showing F_3 Z folds in migmatitic paragneiss at Outcrop I. Migmatitic gneiss shows folded S_{71} foliation. The foliation is folded to form metre-scale F_3 Z folds. The F_3 folds are outlined by the black line. The enveloping surface of the F_3 Z folds is part of the south-dipping limb of the F_2 fold between the communities of Stinson and Callum (see Figure 4). Geological hammer on top surface of the outcrop, for scale, is 30 cm long.



Photo 7. A bird's eye view of Outcrop I. Broom, for scale, is 130 cm long.

Zircons from a diorite dike have been analyzed using laser ablation inductively coupled mass spectrometry to determine ages for the dike. The dike intersects the migmatitic layers (S_{T1}) at a low angle and is nearly parallel in places. It is interpreted that the dike experienced all 3 phases (D_1 , D_2 and D_3) of deformation. A single near-concordant zircon from the east segment of the dike yielded a $^{206}\text{Pb}/^{207}\text{Pb}$ age of 2655 ± 23 Ma, whereas 2 other near-concordant zircons yielded $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 1732 ± 26 and 1723 ± 36 Ma, respectively (Li 2012). Five metamorphic zircons yielded $^{206}\text{Pb}/^{207}\text{Pb}$ ages in the range of 1044 to 1003 Ma. If the errors are considered, the metamorphism recorded in the 5 zircons is within the range of 1079 to 962 Ma. The interpretation is that the dike intruded in the Archean metasedimentary rock at 2655 Ma, and experienced metamorphism and deformation at *circa* 1700 Ma and from 1044 to 1003 Ma (Li 2012).



Photo 8. Photo showing F_3 S folds in migmatitic paragneiss at Outcrop II. The F_3 folds overprinted F_1 isoclinal folds.

Outcrop III (Stop 2). Z folds (F_3) and F_1 folds overprinting relationships

UTM 516572E 5147361N

The outcrop is on the east side of Highway 537, south of Dryden Road in Wahnapiatae. The F_1 isoclinal folds and F_3 tight-to-isoclinal folds occur in paragneiss in the continuous outcrop (Photo 9). The F_3 folds here are Z folds with east-northeast-striking axial planes and southwest-plunging hinge lines. The F_3 folds that overprinted F_1 folds can be observed at many places in the continuous outcrop.

A pegmatite dike cuts F_1 folds and S_{T1} at a high angle and a small branch of the pegmatite is gently folded by F_3 folds (Photo 10). Flanking folds can be observed along the contact of the pegmatite and the paragneiss. The pegmatite dike contains feldspar, quartz and muscovite. Under the microscope, large feldspar crystals are fractured and quartz fills the fractures of the feldspar. Quartz fill in the vein shows undulatory extinction. Quartz outside of the fractures is either elongated into ribbons or dynamically recrystallized. Muscovite in the sample occurs commonly along the fractures in feldspars and in the matrix. The brittle deformation of the feldspar indicates that the temperature at the time of the brittle deformation was not high.

This pegmatite is interpreted to have been emplaced at the late stage of D_3 deformation and possibly at a relatively shallow depth in the crust. Zircons from the dike yield a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 953 ± 33 Ma (5 grains, MSWD=0.56) (Li 2012). This age is interpreted as the minimum age of D_3 deformation.



Photo 9. Photo showing F_3 folds (Z folds; in the centre of the photo) that overprinted S_{T1} and F_1 folds at Outcrop III. The F_1 folds can be seen at some places, especially the area close to the hammer in the photo where the overprinting relationship can be observed. In the photo, F_3 folds are isoclinal to tight folds and, for some of them, it can be difficult to differentiate them from F_1 folds. Broom, for scale, is 130 cm long.



Photo 10. Pegmatite dike at Outcrop III emplaced into folded gneisses before the end of the D_3 deformation event. Please note that the isoclinal F_1 folds and S_{71} foliation are present in the country rocks (metasedimentary rocks). The pegmatite dike cuts the F_1 fold and the S_{71} foliation, but is folded by F_3 folding. Near the centre of the photo, note the flanking folds in the metasedimentary rock near the contact with the pegmatite. Handheld GPS unit, for scale, is 14.5 cm long.

Outcrops IV, V and VI (Stop 3). Mylonites, folds and contact zone deformation

Outcrops IV, V and VI are in the Grenville Front shear zone south of Coniston and in the Baby Lake and Alice Lake area; the locations are shown in Figure 5. This shear zone is a D₃ structure with a 400 m wide, nearly continuous outcrop exposure of mylonites. The mylonitic C-foliation and compositional layering is folded by D₄ deformation. A more detailed description is as follows.

Outcrop IV. Mylonites derived from granite at the Grenville Front

UTM 510800E 5145600N

The outcrop is located between Baby Lake and Alice Lake, south of outcrops of the metasandstone of the Mississagi Formation and an undeformed Nipissing gabbro sill (*see* Figure 5). The Mississagi Formation metasandstone is part of the Huronian Supergroup supracrustal sequence that was deposited on the southeast margin of the Superior Province between 2480 and 2217 Ma (Krogh, Davis and Corfu 1984). Nipissing diabase sills were emplaced into the Huronian Supergroup at *circa* 2217 Ma (Davey et al. 2019). The mylonitized granite is part of the Grenville Front mylonite zone, which is a product of D₃ deformation. Clear mylonitic foliations and lineations are present at the outcrop. South of this granitic mylonite is an ultramylonite layer, called banded mylonite in the field, approximately 30 m thick, derived predominantly from Mississagi Formation metasandstone.

Outcrop V. Sheath fold in mylonite derived from metasandstone

UTM 510836E 5145458N

This outcrop is at the contact between banded mylonites and ultramylonites, mostly derived from Mississagi Formation metasedimentary rocks and variably strained to mylonitized Nipissing gabbro (*see* Figure 5). Chang (2022) estimated the deformation temperature using titanium in quartz in samples mainly collected from the banded mylonites and ultramylonites and obtained deformation temperatures of 425 to 567°C. Sheath folds are developed in the banded mylonites. One large sheath fold is shown in Figure 5 (*see also* inset map in Figure 6). Its fold hinge-line orientations can be measured in the field and the plunge directions are marked by arrows in Figure 6. The geometry of the sheath fold indicates top-to-the-northwest shear sense.

The banded mylonites are mostly derived from Mississagi Formation sandstone with minor bands derived from granite or gabbro. All layers are mylonites or ultramylonites. All mylonites have down-dip or nearly down-dip stretching lineations. For detailed microstructural studies of these rocks, *see* Chang (2022). The S-C-C' fabrics and quartz c-axis fabrics all suggest south-side-up top-to-the-northwest thrust shear sense. A photomicrograph of the mylonitic metasedimentary rock shows S-C and C' structures that also indicate top-to-the-northwest shear sense (Photo 11).

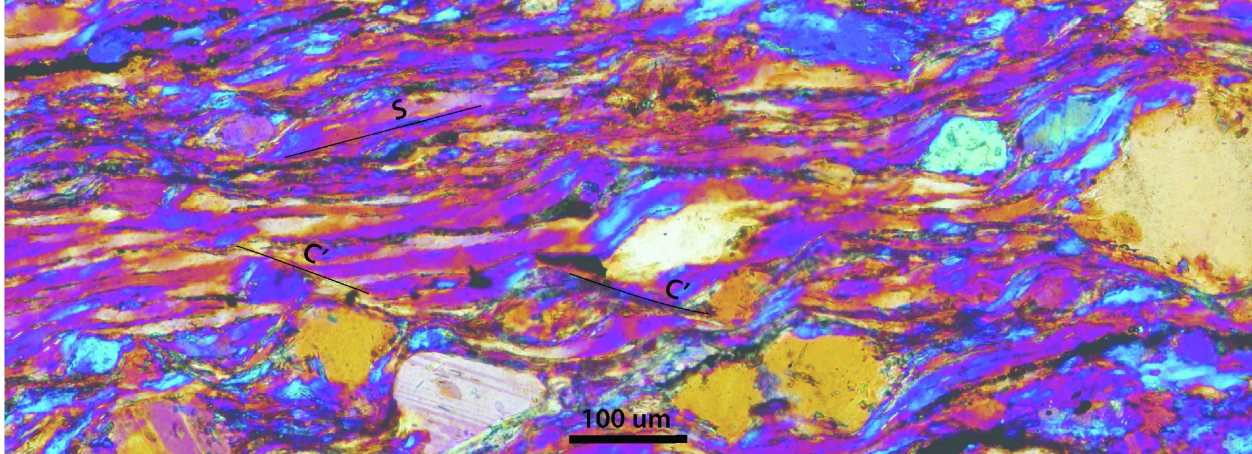


Photo 11. Photomicrograph of mylonite derived from Mississagi Formation metasandstone. The photomicrograph was taken under cross-polarized light using a gypsum plate. The S foliation is defined by elongated quartz grains. The C foliation is horizontal.

Outcrop VI. Mylonites, folds, and contact zone deformation in the Grenville Front shear zone

UTM 510135E 5144862N

This outcrop is approximately 200 m southwest of Baby Lake and 40 m east of the Canadian Pacific Railway (*see* Figure 5). The banded ultramylonite here is derived from Mississagi Formation sandstone and is part of the Grenville Front mylonite zone. Mylonitization and associated fabrics, including a down-dip stretching lineation, isoclinal lineation-parallel folds intrafolial to the mylonitic foliation (Photos 12A and 12B) and the S-C-C' fabrics (*see* Photo 11), are all products of the D₃ deformation.

These folds were produced by non-coaxial progressive deformation in the shear zone and cannot be geometrically correlated with the folds to the northwest of the Grenville Front in the Mississagi Formation in the Southern Province as was done by Brown (1968), Dalziel et al. (1969) and Brocoum and Dalziel (1974). La Tour (1981) did not agree with the fold correlation proposed by the aforementioned authors. Furthermore, La Tour (1981) points out that the mylonites at the Grenville Front and the isoclinal folds within them were created mainly by progressive simple shearing at *circa* 1.0 Ga.

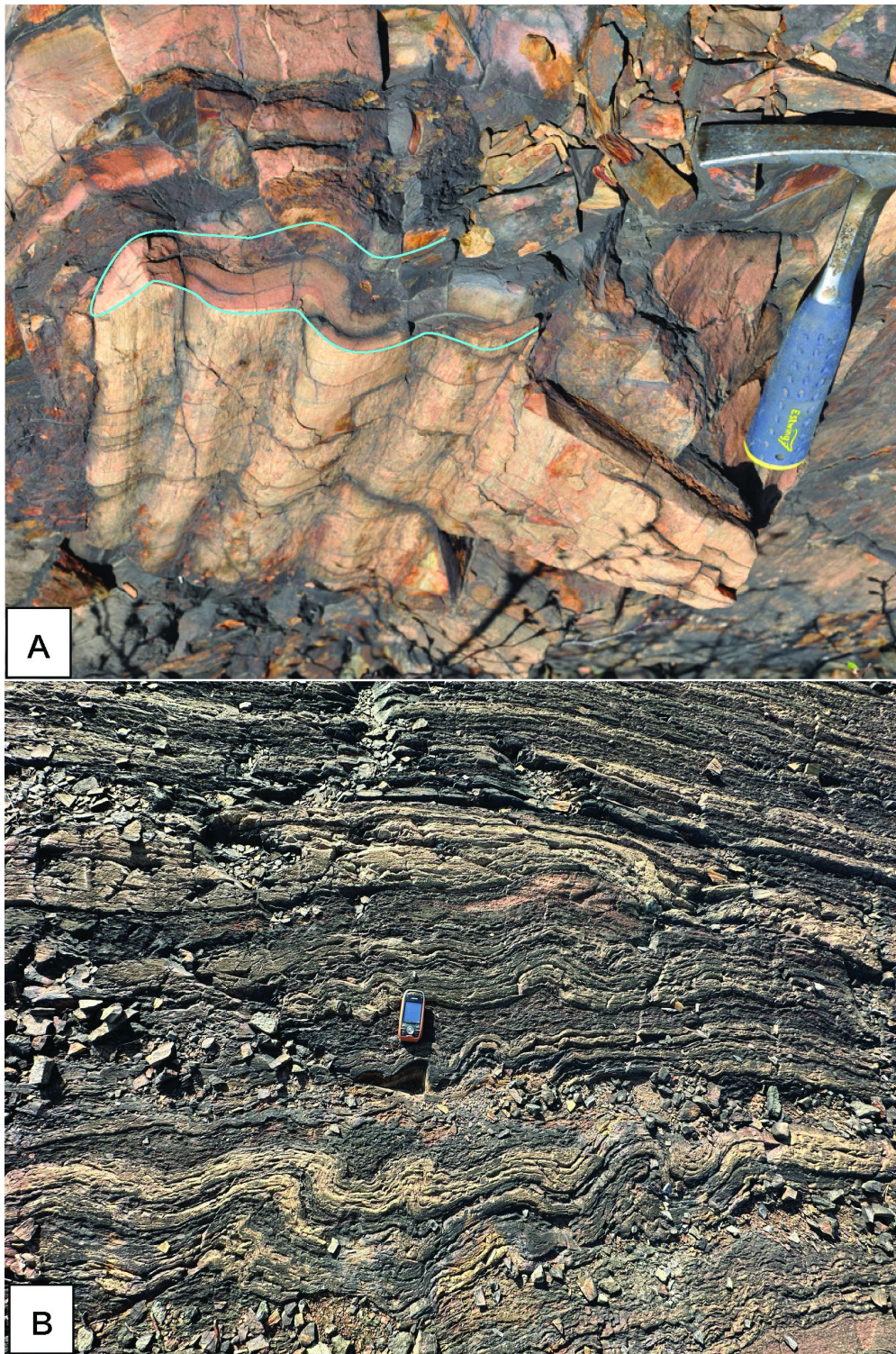


Photo 12. **A)** Folds within the ultramylonite derived from Mississagi Formation sandstone at Outcrop VI. The isoclinal fold, intrafolial to the mylonitic foliation (outlined by the blue line), is a product of D_3 deformation formed during mylonitization. The fold hinge line is parallel to the stretching lineation. This fold is overprinted by open, round-hinge F_4 folds, the hinges of which are also parallel to the stretching lineation. The axial planes of F_4 folds are nearly perpendicular to the C foliation. Geological hammer, for scale, is 30 cm long. **B)** The F_4 folds of the mylonitic C foliation and compositional layering in ultramylonites derived from the Mississagi Formation sandstone at Outcrop VI. The F_4 folds vary in style from round-hinge folds to box-like folds. The length of the GPS device is 14.5 cm.

Outcrop VII. F₃ folds on a north-northeast-striking limb of F₂ fold

This outcrop is located on a southeast-dipping limb of an F₂ fold (*see* Figure 3). The orientations of the F₂ fold limb and the F₃ fold axial plane determine the plunge of F₃ folds. At this outcrop, the overprinting relationships among D₁, D₂, and D₃ structures are observed (*see* Photos 2 and 3). First, the transposition foliation S_{T1} is defined by compositional layers of the paragneiss and is visible everywhere. Some layers are rich in garnet. Locally, F₁ isoclinal folds intrafolial to S_{T1} can be recognized. Second, the compositional layering of S_{T1} is boudinaged by D₂ deformation. Varying scales of boudins and boudin-neck folds of D₂ overprinting S_{T1} and F₁ isoclinal folds are clear in the outcrop (compare Photos 2 and 3). Third, the S_{T1} compositional layers (e.g., the dark layer in the middle of Photo 2) and D₂ boudinage structures were folded in D₃ deformation phase into upright F₃ folds (*see* Photos 2 and 3). All F₃ folds here are northeast plunging and have northeast-striking axial planes because they are located on the southeast-dipping limb of an F₂ fold. The F₃ folded boudins in the middle part of Photo 3 are extremely instructive: the boudins suggest that the vertical zone (shown to their right, in the middle of Photo 3) was most likely a larger boudin-neck fold of D₂ initially (similar to the boudin-neck folds shown in Photos 2 and 4), overprinted by D₃ contraction.

TRAVEL DIRECTIONS

Stops 1 and 2 focus on foliations and folds developed during the D₁ and D₃ deformation phases. Stop 3 shows deformation structures developed in a mylonite zone that formed during the D₃ deformation phase. At the beginning of each stop description, safety hazards specific to the stop are described.

- 0.0 km Start at the front entrance of the Willet Green Miller Centre, on the Laurentian University campus. Drive westward along Ramsey Lake Road.
- 2.0 km Turn right onto Paris Street and head northward.
- 4.4 km Turn right onto Brady Street.
- 4.9 km Follow the right-hand curve onto Greater Sudbury Regional Road 55 (also marked as “The Kingsway”) and continue to the intersection with Trans-Canada Highway/Highway 17.
- 40.3 km Turn left onto Pioneer Street West (turn off into Markstay). Pull over and park in the open space on the south side of Pioneer Street West.

Walk back northwestward to the roadcut on Highway 17.

Stop 1 (Outcrop II). S folds (F₃) and F₁ folds overprinting relationships

UTM 533607E 5149243N

Potential hazards and/or caution statements specific to this outcrop:

- Steep and/or slippery slopes; loose rocks; it can be slippery on the slope and on the top surface of the outcrop
- Busy road with high speed traffic; stay off road shoulder if possible; high-visibility vests required

After having visited this stop, return to vehicles and turn right back onto Highway 17 and drive westward for approximately 19 km.

- 59.1 km Turn left onto Highway 537 (also known as Rue Hill Street).
- 59.7 km Pull over into the parking lot of the post office at the left (east) side of the road. Hike southward for about 400 m and past Dryden Road. The outcrop is on the left (east) side of Highway 537.

Stop 2 (Outcrop III). Z folds (F₃) and F₁ folds overprinting relationships

UTM 516572E 5147361N

Potential hazards and/or caution statements specific to this outcrop:

- Some steep and/or slippery slopes
- Busy road with high speed traffic; stay off road shoulder

After having visited this stop, return to vehicles and retrace route north on Highway 537 northward for about 0.6 km and turn left onto Highway 17 and head west.

- 60.3 km Turn left onto Highway 17 heading west.
- 65.5 km Turn left at the traffic lights at Coniston onto Second Avenue (Regional Road 93) and head south.
- 66.4 km Turn right onto Government Road (Regional Road 67).
- 66.6 km Turn left onto Edward Avenue and continue south until it ends.
- 68.3 km Pull over and park.

Stop 3 (Outcrop VI) (optional: Outcrops IV and V). Structures in the Grenville Front mylonite zone

Outcrop VI: UTM 510135E 5144862N

Outcrop IV: UTM 510800E 5145600N (optional)

Outcrop V: UTM 510836E 5145458N (optional)

Potential hazards and/or caution statements specific to these outcrops:

- On the way to the stop, there may be steep slopes and slippery surfaces. Please wear a pair of good boots (e.g., backpacking or hiking boots). Watch out for swampy or wet ground when walking on low-lying areas.
- Outcrop VI is about 40 m from the Canadian Pacific Railway track. Watch out for trains when you visit the outcrop.
- It takes approximately 45 minutes to hike to the outcrop. Please bring water and lunch.

Hike back to the vehicle.

End of the field trip. Return to the vehicles and retrace route along Edward Avenue and Second Avenue back to Highway 17 into Sudbury.

End of road log.

Acknowledgments

DJ thanks the Natural Sciences and Engineering Research Council of Canada (NSERC) for a Discovery Grant supporting the work presented here. A significant part of the material in this guidebook is based on the PhD thesis study by Changcheng Li in the Department of Earth Sciences at the University of Western Ontario. CL thanks Ruikun Liu, Frank Joris, Yushan Su and Bonnie Young for field assistance. Dr. Yin Chen is thanked for carrying out the U/Pb geochronology using the laser ablation inductively coupled plasma mass spectrometry. Drs. Yvette Kuiper, Chenglong Xie and Jian-feng Gao are thanked for help on zircon data analysis. Drs. Bill Church, Desmond Moser and Shoufa Lin are thanked for discussions. We thank Bruno Lafrance (Laurentian University), Michael Easton (Ontario Geological Survey) and Monica Gaiswinkler Easton (Ontario Geological Survey) for review comments of this guidebook. We also thank the Department of Earth Sciences at the University of Western Ontario and the Department of Earth and Environmental Sciences at the University of Waterloo for sponsoring the field trip.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
<i>SI Unit</i>	<i>Multiplied by</i>	<i>Gives</i>	<i>Imperial Unit</i>	<i>Multiplied by</i>	<i>Gives</i>
LENGTH					
1 mm	0.039 37	inches	1 inch	25.4	mm
1 cm	0.393 70	inches	1 inch	2.54	cm
1 m	3.280 84	feet	1 foot	0.304 8	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	1.609 344	km
AREA					
1 cm ²	0.155 0	square inches	1 square inch	6.451 6	cm ²
1 m ²	10.763 9	square feet	1 square foot	0.092 903 04	m ²
1 km ²	0.386 10	square miles	1 square mile	2.589 988	km ²
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm ³	0.061 023	cubic inches	1 cubic inch	16.387 064	cm ³
1 m ³	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m ³
1 m ³	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m ³
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	4.546 090	L
MASS					
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	31.103 476 8	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	0.453 592 37	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	907.184 74	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	0.907 184 74	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	1016.046 908 8	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	1.016 046 9	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	<i>Multiplied by</i>	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

*Note: Conversion factors in **bold** type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*

ISSN 0826-9580 (print)
ISBN 978-1-4868-7223-7 (print)

ISSN 1916-6117 (online)
ISBN 978-1-4868-7224-4 (PDF)