Canadian Tectonics Group workshop field guide 2023

Mylonites, mylonites and mylonites: the Saint-François-de-Sales shear zone, Grenville Province

October 20-22

Lac Bouchette, Lac St. Jean, Québec

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1981 2021

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Overview

The 2023 CTG Fall workshop will be held in the Grenville Province, a Mesoproterozoic to early Neoproterozoic orogenic belt that covers an extensive area north of the St. Lawrence River from Lake Ontario to Labrador. The Grenville Province is mostly composed of amphibolite to granulite facies metamorphic rocks and provides a window into the structural styles of deformation at various levels in the continental crust. The field trip will take place around Lac Bouchette, south of Lac St. Jean, an area that has been mapped by the *Ministère des Ressources naturelles et des Forêts du Québec* in 2018 (Moukhsil and Daoudene, 2019a). The area exposes 1520–990 Ma orthogneiss, metasedimentary units and intrusive magmatic suites. Several phases of deformation affected the area, ranging from mid-crustal folding and shearing to upper-crustal brittle faulting. The field trip will provide an overview of the local geology, with a strong focus on the Saint-François-de-Sales shear zone (Moukhsil and Daoudene, 2019b), a prominent structure that marks a transition from exhumation to strike-slip and/or thrust tectonics at the end of the Ottawan phase of the Grenvillian orogeny. The group will convene at Auberge Eva, in Lac Bouchette, on the evening of Friday October 20. The field trip will run on Saturday and Sunday October 21-22. Posters will be presented on Saturday evening.

Field safety

Much of the field area overlaps with hunting territory (zone #28), as you will notice from the abundant signs saying *Chasseurs à l'affût*. Field visits during the fall are likely to overlap with hunting season, which can lead to safety issues, or create frictions with local hunters. We recommend avoiding the area completely during hunting season. Dates for the CTG fieldtrip were chosen specifically outside of deer and moose hunting seasons, but there might be small game hunters in the area.

Wear high-visibility clothing and avoid walking away from the main group on larger outcrops.

Three stops are adjacent to highway 155, in a zone where the speed limit is 90 km/h. Be extremely careful when crossing the highway. Cross all at once as a single group. Wear high-visibility clothing. Stay off the pavement except when crossing.

Several outcrops are accessible by logging roads whose condition is variable. Pick up trucks or high-clearance 4x4 SUV are necessary. If you are subject to motion sickness, don't forget your medication.

There is no washroom available during the fieldtrip, so please be prepared.

Weather in late October is extremely variable, so be prepared for a wide range of temperatures. We are as likely to get a dry, sunny + 20 °C as a cold, humid 0 °C with rain or snow. Dress-up

accordingly: rain suit, fleece, sturdy footwear, sunscreen, hat, etc. and bring a water bottle.

Insects (wasps, bees, mosquitoes, deer flies, black flies, midges, ticks) should not pose a major risk due to the time of the year. Nonetheless, consider wearing light-colored long sleeve clothing and bring insect repellent. The risk for anaphylactic shock or allergic reactions is greater for Non Canadians that have not been exposed to local insects. We suggest that international participants bring some antihistamine (e.g., Benadryl) with them just in case. If you have any known severe allergies, please carry your medication at all time (e.g., Atarax, EPIPEN, etc.) and disclose known allergies to the fieldtrip leader.

The risk of encounter with animals (deer, moose, wolves, lynx, skunks, foxes and black bears) is low, especially if you stick with the group. If you see a wild animal, do not approach it.

Exposure at most outcrops is fantastic. Fresh surfaces are available. Please refrain from hammering the rock. If you must break rock (far from the well-exposed areas), wear safety glasses and make sure that other people are at a safe distance and are wearing safety glasses.

Cell phone service coverage varies by service provider, and will not always be available, especially around Stops 1.1 and 1.2. A satellite phone will be available in case of emergency.

Please discuss with field trip leaders any particular risks you may foresee and that need clarified prior to accepting risks and taking part in this field trip. The leaders have prepared thoroughly for the field trip and will take every possible precaution for ensuring the safety of the participants, but ultimately each participant is responsible for their own safety and must be vigilant and self-reliant in terms of safety awareness. Participants must act in a manner that is safe for themselves and their co-participants and use personal protective equipment when necessary. The field trip leaders and the local organizing committee of the GAC Canadian Tectonic Group meeting and their parent organization cannot assume any liability for accidents. Participants must sign a RELEASE OF LIABILITY form in order to participate to the field trip. Participants must agree to follow the instructions and precautions as written in the field trip guidebook and/or stated by the field trip leaders. Participants must assume responsibility for attending all safety briefings, and if they observe any unusual significant hazard during the trip, they are asked to ensure their safety and bring such particular conditions to the attention of the field trip leaders.

Geological context

The Grenville Province is the youngest orogenic belt of the Canadian Shield. It extends from Labrador to Lake Ontario and continues southwestward beneath the surface to Texas. The Grenville Province comprises reworked Archean to Paleoproterozoic Laurentian crust and remnants of accreted terranes that formed outboard and along the southeast margin of Laurentia. Rocks in the Grenville Province variably record several mid-Mesoproterozoic deformation and metamorphic events related to the ca. 1680-1600 Ma Labradorian orogeny, the ca. 1520–1460 Ma Pinwarian orogeny, the ca. 1400-1370 ma accretion of the Quebecia arc belt, the ca. 1245–1225 Ma Elzevirian orogeny, and the ca. 1190–1140 Ma Shawinigan orogeny that preceded the final ca. 1090–980 Ma Grenvillian orogeny, sensu stricto (Gower et al., 2008; Rivers et al., 2012; Groulier et al., 2020). The exact timing of these events varies along the belt, and these temporal boundaries are only loosely constrained. The Grenville orogeny refers to the final continent-continent collision between Laurentia and Amazonia during the formation of the supercontinent Rodinia (Li et al., 2008; Rivers et al., 2012). The Grenville orogeny is separated in two phases (Rivers et al., 2012; Indares et al., 2020). The Ottawan phase (1090-1020 Ma) is the dominant large-hot orogenic phase that metamorphosed most rocks in the hanging wall (southeast) of the Allochthon Boundary thrust at amphibolite to granulite facies (Fig. 1). The Rigolet phase (1005-980 Ma) was shorter and restricted to a narrow belt in the footwall (northwest) of the Allochthon Boundary thrust (Fig. 1). These two belts are composed of substantially displaced (but not necessarily exotic) Late Paleoproterozoic to Mesozoic terranes and reworked Archean to Paleoproterozoic Laurentian crust, respectively, and are referred to as the Allochthonous and Parautochthonous belts. In some localities of the western, eastern and potentially central Grenville, rocks have escaped the effects of the Grenville orogeny, suggesting that they were positioned in the upper crust during that time (Ottawan Orogenic Lid; Rivers, 2008, 2012).

In the Lac St. Jean and Mauricie areas (Fig. 2), amphibolite to granulite facies metamorphism is variably recorded during the Shawinigan and early Ottawan orogenies. Near Saguenay, amphibolite facies metamorphism overprinting granulite facies metamorphism has been associated with the intrusion of the ca. 1160-1140 Ma Lac St. Jean Anorthosite Suite (Fig. 2; Corriveau, 1982), whereas Ottawan-aged zircon concordia and lower intercept discordia dates indicate an Ottawan metamorphic overprint (Hébert and van Breemen, 2004). Zircon from units south of Lac St. Jean also yielded Shawinigan and Ottawan metamorphic ages (Moukhsil et al., 2015; Papapavlou et al. 2018; Papapavlou 2019). Further south, monazite (1094 ± 2 Ma) and zircon (1087 ± 2 Ma) from a syn-kinematic leucosome lens indicate that rocks were deformed at suprasolidus conditions during the early Ottawan (Corrigan, 1995). From <1200 to ca. 1080 Ma, rocks of the Central Grenville Province were likely deformed in the middle crust. One exception is the Portneuf-Mauricie domain (Fig. 2), which is interpreted to record amphibolite to granulite facies metamorphism related to the accretion of the Montauban arc at ca. 1400-1370 Ma, and a lower-pressure and lower-temperature Ottawan-aged metamorphic overprint (Corrigan, 1995; Corrigan and van Breemen, 1997).

Mid-crustal units in the Mauricie area were exhumed at ca. 1065-1035 Ma along the SE-dipping

eastern Taureau shear zone (Soucy La Roche et al., 2015) and the E-dipping Tawachiche shear zone (Corrigan and van Breemen, 1997; Fig. 2). The timing of exhumation of mid-crustal units further north is unconstrained. The SE-dipping St. Fulgence deformation zone (Fig. 2) might have been active as a dextral strike-slip shear zone prior to ca. 1050 Ma until ca. 1008 Ma (Owens et al., 1994; Hébert et al., 2009). The St. Fulgence shear zone likely reactivated an older thrust-sense structure; kinematics and timing of each deformation event along this deformation zone are not precisely constrained.

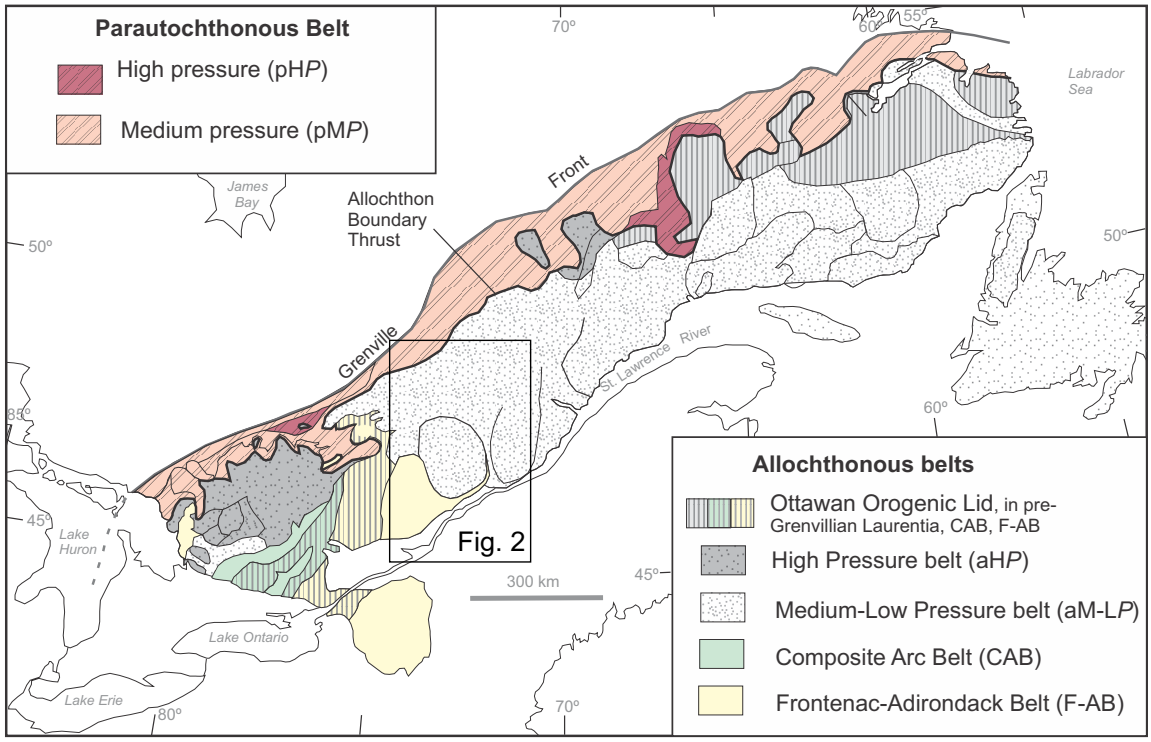

Fig. 1. Map of the Grenville Province after Rivers et al. (2012).

Regional geology

The field trip takes place in the Allochthonous belt of the Central Grenville Province, South of Lac St. Jean (Fig. 2, 3). The oldest meta-plutonic units in the area include the calc-alkaline ca. 1400-1370 Ma La Bostonnais Complex (Nadeau et van Breemen, 1994; Corrigan, 1995) and the undated intermediate to felsic Belley Plutonic Suite (possibly ca. 1350 Ma (?); Moukhsil and Daoudene, 2019a). These intrusive suites are overlain by the Wabash Complex, a metamorphosed supracrustal sequence that yielded maximum deposition ages of 1204 ± 12 Ma (Moukhsil et al., 2015) and 1309 ± 38 Ma (Papapavlou et al., 2022).

Younger intrusive suites make up most of the field trip area. The Ouiatchouan Anorthosite Suite (undated, likely ca. 1150 Ma (?); Moukhsil and Daoudene, 2019a) is in tectonic contact with the Thaddé and Travers plutonic suites on the western margin of the field area. The Thaddé Plutonic Suite (undated, likely ca. 1150 Ma (?); Moukhsil and Daoudene, 2019a) occurs at the westernmost limit of the field area. Both suites are apparently injected by granite and syenite dykes of the

Travers Suite. The Travers Suite (1076 ± 8 Ma; Papapavlou et al., 2018) is the most volumetrically important unit and is composed of syenite, granite, mangerite, monzonite and gabbronorite. It is intruded by the Lachance Mangerite (1044 ± 7 Ma; Papapavlou, 2019), which forms a well-defined N-S elliptical body. The majority of outcrops visited during the field trip are located in the Travers Suite. The preponderance of Grenvillian-aged units in the fieldtrip area is a fortunate coincidence because it simplifies the interpretation of the structures associated with the Saint-François-de-Sales shear zone. The Travers suite contains a weakly to moderately-defined, steeply SE-dipping regional metamorphic foliation, referred to as S_{n-1}, whereas the Lachance Mangerite is generally massive. With few exceptions (stops 1.1, 2.1 and 2.2), pre-Ottawan deformation events can be ignored.

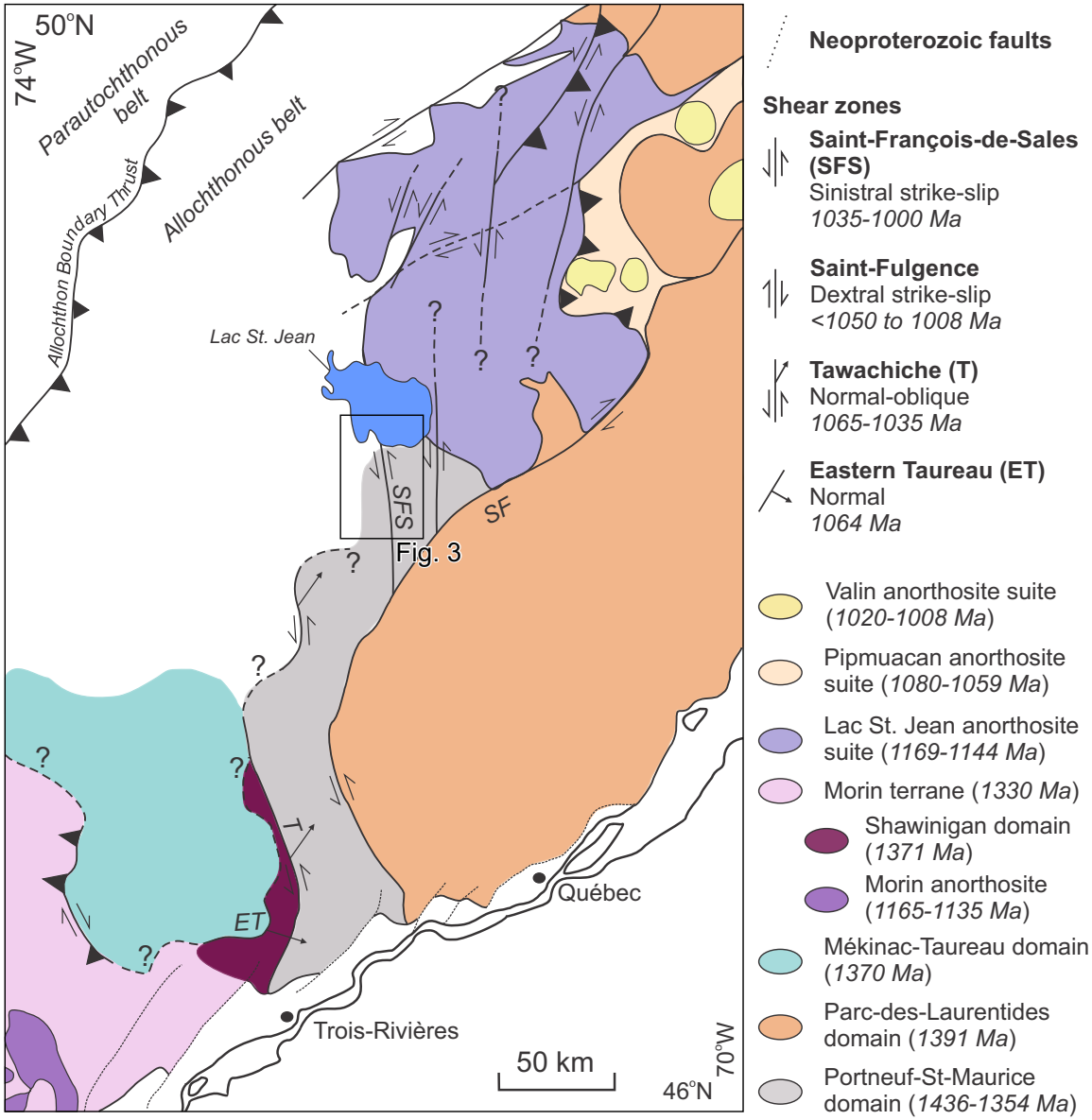

Fig. 2. Regional map of lithotectonic domains and regional shear zones. Modified from Gosselin et al. (2022) and references therein.

The Saint-François-de-Sales shear zone

The Saint-François-de-Sales shear zone (Fig. 3; Moukhsil and Daoudene, 2019b) is a N-S oriented, anastomosing network of meter-thick protomylonitic to mylonitic zones and millimeter to decimeter-thick ultramylonite zones that deform the magmatic units of the Travers, Thaddé and Belley plutonic suites, and the Lachance Mangerite. The main shear fabric, referred to as S_n, is a moderately ENE-dipping mylonitic foliation with a subhorizontal stretching lineation, except on the eastern side of the shear zone where it dips to the west. The S_n shear foliation crosscuts the S_{n-1} metamorphic foliation, where present. Shear sense indicators are compatible with a sinistral-sense strike-slip movement. A second, less abundant shear fabric is characterized by a dextral sense of shear. It dips steeply to the SE or NW and the associated lineation is subhorizontal. Cross-cutting relationships between these two fabrics, as observed at stop 1.7, indicate that they were formed synchronously in a conjugate shear system. At the margins of ultramylonite and in mylonite, quartz exhibits dynamic recrystallization through subgrain rotation and plagioclase is characterized by kinked albite twins and undulose extinction. K-feldspar porphyroclasts in ultramylonite display undulose extinction, fractures with incipient bulging recrystallization and flame perthite. In protomylonite and mylonite, K-feldspar is characterized by core-and-mantle structures. Foliation-parallel chlorite, epidote and actinolite-tremolite, in the sheared rocks indicate retrograde upper greenschist to lower amphibolite facies metamorphic conditions during shearing. These observations are consistent with a deformation temperature of ~400–500 °C. Ductile deformation along the Saint-François-de-Sales shear zone occurred after ca. 1060 Ma (stop 2.5), and was active between ca. 1035 and ca. 1000 Ma (stops 1.1 and 1.4), Gosselin et al., 2022; Gosselin, unpublished data).

Brittle deformation within the Saint-François-de-Sales shear zone is evidenced by cataclasite and epidote-chlorite-filled fractures, commonly associated with hematite alteration of the host rock, that crosscut the ductile shear fabrics. Fractures, referred to as the S_{n+1} fabric, strike from NW-SE to NE-SW, approximately parallel to the Saint-François-de-Sales shear zone.

Tectonic implications

The Saint-François-de-Sales shear zone accommodated strike-slip displacement, continuously or episodically, between ca. 1035 Ma and ca. 1000 Ma. There is no evidence for significant normal-sense displacement and mid-crustal exhumation along that structure. Furthermore, it is younger than the normal-sense shear zones that exhumed mid-crustal units in the Mauricie area to the south (Fig. 2; ca. 1065-1035 Ma Eastern Taureau and Tawachiche shear zones; Corrigan and van Breemen, 1997; Soucy La Roche et al., 2015). Consequently, the Saint-François-de-Sales shear zone seems unrelated to the episode of gravitational collapse and crustal spreading that occurred during the mid-Ottawan in the Mauricie area.

The Saint-François-de-Sales shear zone is, however, potentially synchronous with a phase of dextral deformation along the St. Fulgence deformation zone (Owens et al., 1994; Hébert et al., 2009). Rare dextral shear fabrics in the Saint-François-de-Sales shear zone are parallel to the St. Fulgence deformation zone. Furthermore, localized NNE-striking sinistral strike-slip shear zones

parallel to the Saint-François-de-Sales shear zone crosscut the main NE-striking shear fabric of the St. Fulgence deformation zone (Hébert et al., 2004).

The Saint-François-de-Sales shear zone and the St. Fulgence deformation zone were apparently both active from the end of the Ottawan to the onset of the Rigolet. The time interval between these two orogenic phases is commonly associated with limited tectonic activity in the Allochthonous Belt (e.g. Rivers, 2008; Hynes and Rivers, 2010). This ca. 15 Myr interval is interpreted as the time taken for crustal reorganization following an episode of gravitational collapse and crustal spreading and before migration of crustal shortening structures within the Parautochthonous Belt (Rivers, 2008). The Saint-François-de-Sales shear zone therefore represents a rare example of tectonic activity in upper crustal levels of the Allochthonous Belt during this tectonic transition period.

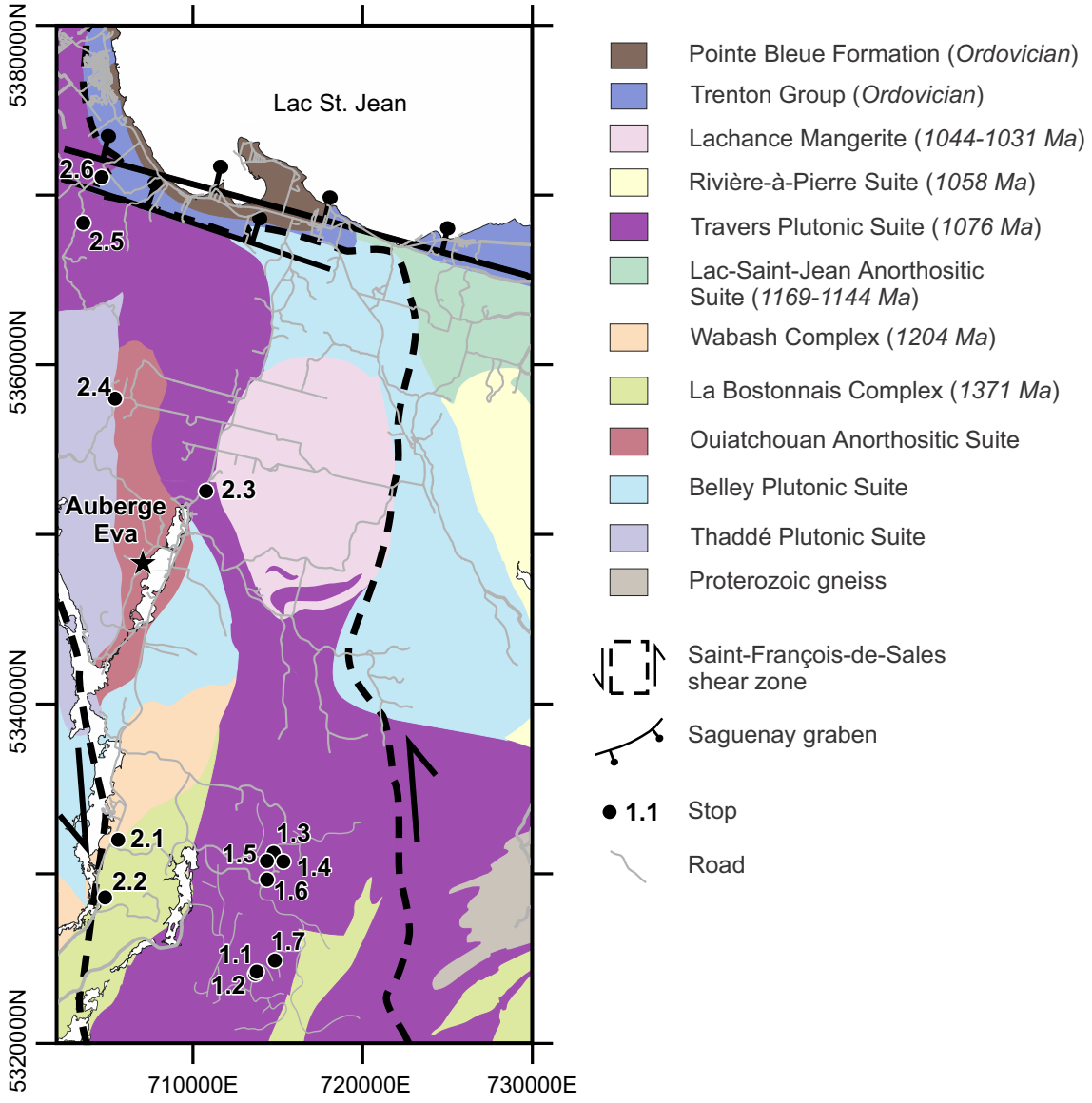

Fig. 3. Lithological map of the Lac Bouchette area with locations of visited outcrops and Auberge Eva. Modified from Gosselin et al. (2022) and references therein.

Fieldtrip road log

Aerial imagery of the Government of Quebec is superior to Google and Bing! satellite imagery, and shows the most up-to-date logging roads (although you should still expect surprises!). The imagery is available online only (e.g. on SIGEOM, Vue aérienne du Québec) and cannot be downloaded. As of October 2023, the roads to stops 1.1, 1.2, 1.4 and 1.7 are not visible on Google's satellite imagery. If you are doing the fieldtrip on your own, plan your trip accordingly. Unfortunately, the order of the stops is dictated by driving efficiency rather than geological logic – sorry!

Table 1. Stop locations

Stop	Latitude	Longitude	Easting	Northing
1.1	48.035921	-72.132979	713709	5324270
1.2	48.034647	-72.134204	713623	5324125
1.3	48.098515	-72.116186	714700	5331273
1.4	48.093656	-72.108681	715279	5330754
1.5	48.094322	-72.121551	714318	5330792
1.6	48.084420	-72.122118	714317	5329690
1.7	48.041456	-72.118314	714779	5324926
2.1	48.108372	-72.238609	705547	5332034
2.2	48.078128	-72.250542	704779	5328641
2.3	48.291259	-72.158938	710725	5352575
2.4	48.341995	-72.228461	705365	5358025
2.5	48.434853	-72.248224	703530	5368292
2.6	48.459510	-72.232738	704576	5371074
Bonus	47.739719	-72.498663	687462	5290324

UTM zone 18, NAD83

Day 1

Stop 1.1. Sinistral mylonite and ultramylonite and timing constraints

Location: 48.03592079°N, 72.13297930°W
Horizontal outcrop next to the road. Please don't park on the rocks!

This outcrop is key to constrain the timing of events within the Saint-François-de-Sales shear zone. The mangerite contains a weak SE-dipping metamorphic foliation S_{n-1} that is crosscut by a meter-thick NW-striking S_n sinistral-sense mylonite at the northeast end of the outcrop. Millimeter-thick ultramylonite layers range in strike from NNW to N. One of these layer appear to merge with the mylonite without any deflection, suggesting that both structures are synchronous.

Several granitic dykes intrude the mangerite and provide constraints on apparent displacement and timing of deformation. One dyke, oriented parallel to S_{n-1} in the host rock, is offset by a few tens of centimeters across the thin ultramylonite layers, whereas it is offset by approximately five meters across the mylonite (Fig. 4a). It is possible to follow the dyke almost continuously across the mylonite despite significant stretching and thinning. Where unsheared, the margins of the dyke contain an internal foliation parallel to S_{n-1}. This dyke yielded a crystallization age of ca. 1120 Ma (U-Pb on zircon; Gosselin, unpublished data). This age indicate that the metamorphic foliation and the shear fabrics must be post-1120 Ma. Interestingly, the crystallization age of the dyke is older than the crystallization age of a sample from the Travers Suite (1076 ± 8 Ma, Papapavlou et al., 2018), which indicates that this suite may include several generations of magmatic rocks, including pre-Ottawan ones.

A thin layer of ultramylonite was sampled with a rock saw at the southwestern end of the outcrop, which provides an excellent 3D view to observe its orientation (000°/89°; Fig. 4b). U-Pb petrochronology on titanite from this ultramylonite provided the most robust timing constraints on deformation along the Saint-François-de-Sales shear zone (Gosselin et al., 2022; Fig. 4c). In the low-strain portions of the host mangerite, titanite occurs as rare, small (100–200 µm), randomly oriented lobate grains associated with magnetite and rimming ilmenite, consistent with absence of igneous titanite in the mangerite (Fig. 4d). Titanite yields a 1015 ± 12 Ma lower intercept age that constrain the timing of metamorphic replacement of ilmenite by titanite at upper greenschist to lower amphibolite facies. In contrast, titanite in the ultramylonite is abundant, large (200–500 µm), and elongate parallel to the foliation. Grains are sigmoidal with sinistral-sense asymmetric magnetite wings (Fig. 4e). Titanite displays deformation twins and variation in crystal lattice orientation from core to tip paired with increased density of misorientations (Fig. 4f). Titanite grains in the ultramylonite yield a lower intercept age of 1002 ± 10 Ma interpreted as the timing of shearing.

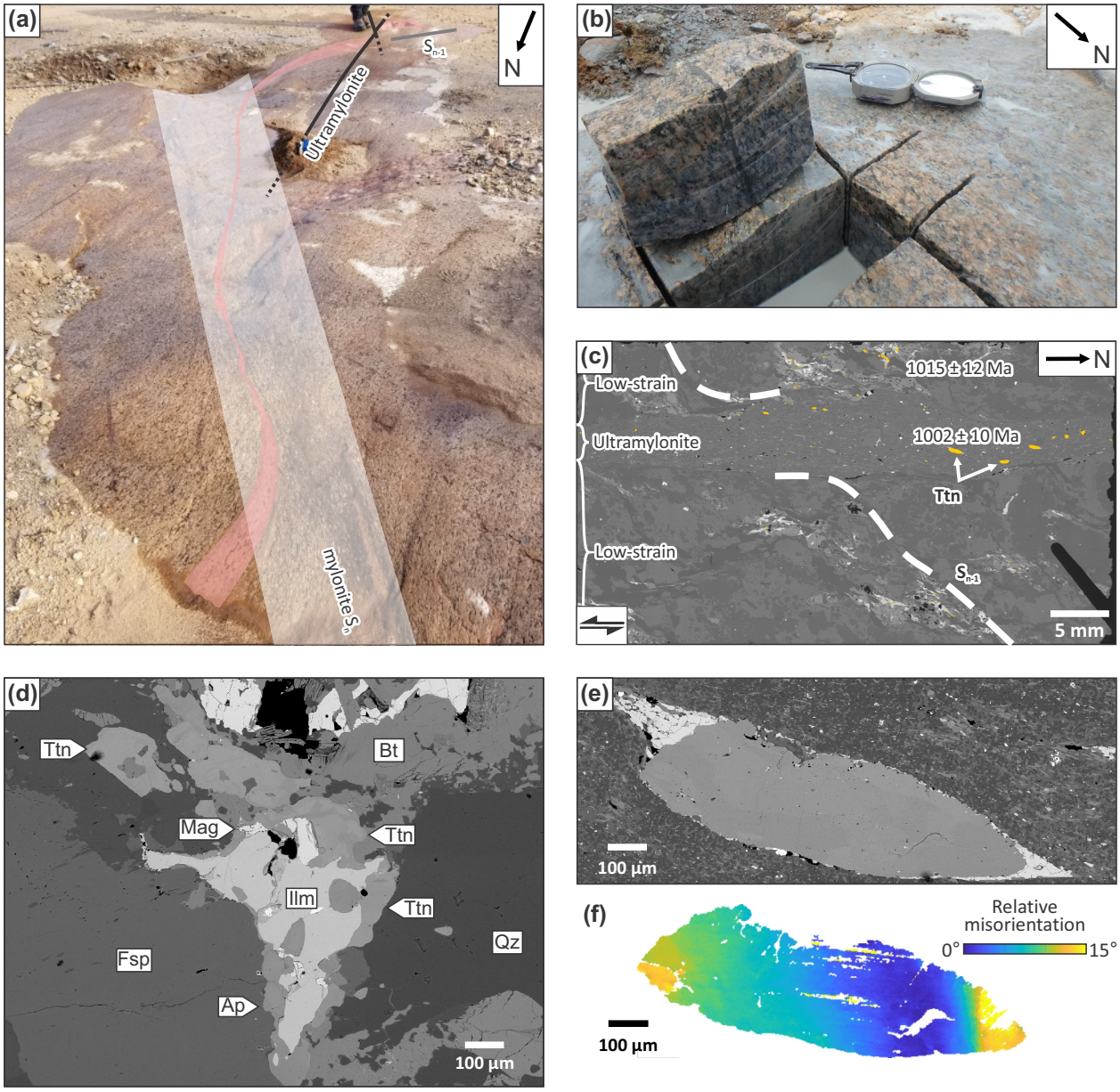

Fig. 4. (a) Pegmatite highlighted in pink offset by a sinistral-sense mylonite. (b) Vertical, north-striking ultramylonite. (c) Backscattered electron image of an entire thin section displaying the ultramylonite. Note the deflection of the metamorphic foliation Sn-1. Titanite grains are highlighted in orange, along with the U-Pb lower intercept ages of titanite inside and outside the ultramylonite. (d) Titanite outside the ultramylonite. (e) Sigmoidal grain of titanite with asymmetric magnetite wings from the ultramylonite. (f) Misorientation map of the same titanite grain, showing core to tip variation in crystal lattice orientation.

Stop 1.2. Pre-shearing structures

Location: 48.03464661°N, 72.13420385°W
Interesting outcrops on both sides of the road.

In contrast to most mangerite of the Travers suite that is homogenous and displays relatively simple tectonic fabrics, lithology at this location is variable and several fabrics can be identified. Fine-grained biotite-rich layers commonly contain an approximately NW-striking foliation that is locally crenulated (Fig. 5a). Folding of a metamorphic foliation is also common. This outcrop likely represents a lens of wall-rock material included within the Travers Suite, and these fabrics probably predate the Saint-François-de-Sales shear zone. Rocks locally contains a strong north-striking mylonitic fabric associated with the Saint-François-de-Sales shear zone. Keep an eye out for 3D exposures and foliation-parallel surfaces to observe beautiful examples of the strong subhorizontal lineation (Fig. 5b). Highly stretched K-feldspar porphyroclasts with aspect ratios >10:1 provide a qualitative idea of the amount of finite strain.

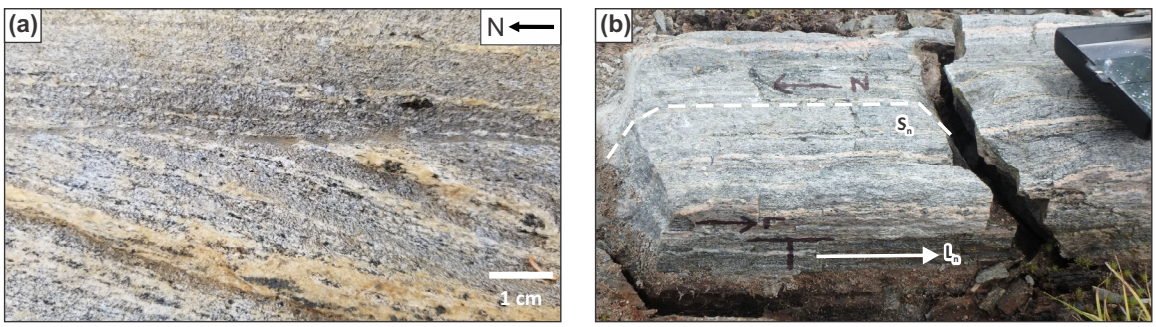

Fig. 5. (a) Relict fabric in a fine-grained xenolith. Note the weak crenulated foliation defined by biotite in the melanocratic layers. (b) Strong foliation defined by stretched K-feldspar porphyroclasts in a mylonite.

Stop 1.3. Interference between sinistral and dextral mylonite

Location: 48.09851518°N, 72.11618575°W
Park along the road just after the right turn. Outcrops are on the south side of the road.

A large part of the exposure consists of typical homogeneous mangerite of the Travers Suite with a weak metamorphic foliation. Deformation fabrics associated with the Saint-François-de-Sales shear zone are expressed as millimeter to decameter-scale protomylonite to ultramylonite. Although these fabrics are pretty, the main attraction of this stop consists of a ~10 m^2 exposure with some 3D relief located next to the road. This small outcrop exposes ultramylonite that is apparently folded (Fig. 6a, b). Fabric orientation is much less systematic, and inspection of shear-sense indicators reveal the presence of abundant sinistral-sense and dextral-sense σ-type and δ-type porphyroclasts (Fig. 6c). Dextral-sense ultramylonite seems to crosscut sinistral-sense ultramylonite, and interference between the various zones of (synchronous?) deformation result in a highly complex finite strain pattern. This outcrop is an excellent example of a rare, small piece of the puzzle that can provide critical information to understand shear zone systems – if we are able to read it! Luckily, stop 1.7 that we will see at the end of the day displays similar structures where cross-cutting relationships are easier to observe and interpret.

The outcrop also displays several NW- to NNE-striking late epidote-filled fractures that cross-cut ultramylonite. Few of these fractures display evidence for sinistral offset, such as deflected foliations at their margins (Fig. 6d). These fractures are common in the area and seem to represent the last increments of strain associated with the Saint-François-de-Sales shear zone.

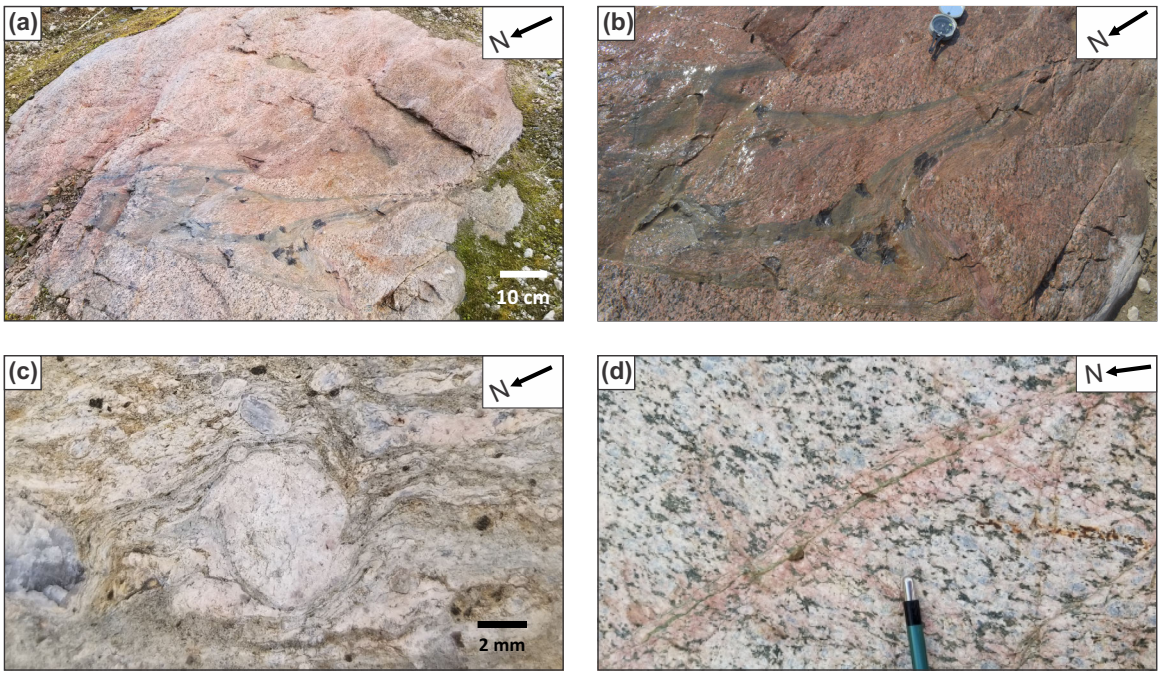

Fig. 6. (a) Folded dextral-sense ultramylonite (dark). (b) Close-up on folds. (c) Dextral δ-type porphyroclast. (d) Late, NNW-striking epidote-filled fracture with minor sinistral movement.

Stop 1.4. Hematitized ultramylonite

Location: 48.09365634°N, 72.10868067°W
Drive up the steep and rough hill. There is room to turn around past the outcrop, which is in the ditch at the top of the hill on the west side of the road.

Mylonitization changes the appearance of rocks to the point of making them unrecognizable. In this spectacular, approximately five meter thick steeply east-dipping layer of mylonite to ultramylonite, the original Travers Suite mangerite has been completely recrystallized to a fine-grained matrix in which float porphyroclasts of feldspar. Some layers have been entirely recrystallized. Hematitization of the ultramylonite is common, pointing to oxidizing conditions during deformation, possibly due to oxidizing fluid circulation (Fig. 7a). You can observe the original texture and centimeter-scale crystals of the mangerite in unstrained portions of the outcrop. The contact is marked by a series of thin ultramylonite layers interlayered with weakly strained layers. σ-type and δ-type porphyroclasts and asymmetric folds consistently point to a sinistral sense of shear.

U-Pb petrochronology on titanite from a layer of ultramylonite collected at this location provided a second timing constraint on deformation along the Saint-François-de-Sales shear zone (Gosselin

et al., 2022). The youngest group of titanite analyses is characterized by a distinct geochemical composition compared to analyses of other groups. It has lower LREE/MREE, lower Zr, less pronounced negative Eu anomaly, and more pronounced positive Ce anomaly. The chemical composition of these grains is consistent with crystallization at lower temperature (lower Zr), under oxidizing conditions (higher positive Ce anomaly), and after feldspar breakdown (less pronounced negative Eu anomaly). Furthermore, these analyses are located in parts of the grains located in the extensional quadrants of a strain ellipse under sinistral-sense shearing (Fig. 7b). Overall, these observations indicate that this 1036 ± 5 Ma titanite group crystallized during shearing along the Saint-François-de-Sales shear zone. It is thus possible that wide layers of mylonite to ultramylonite formed up to ca. 20 Myr earlier than thin localized ultramylonites such as the one observed at stop 1.1.

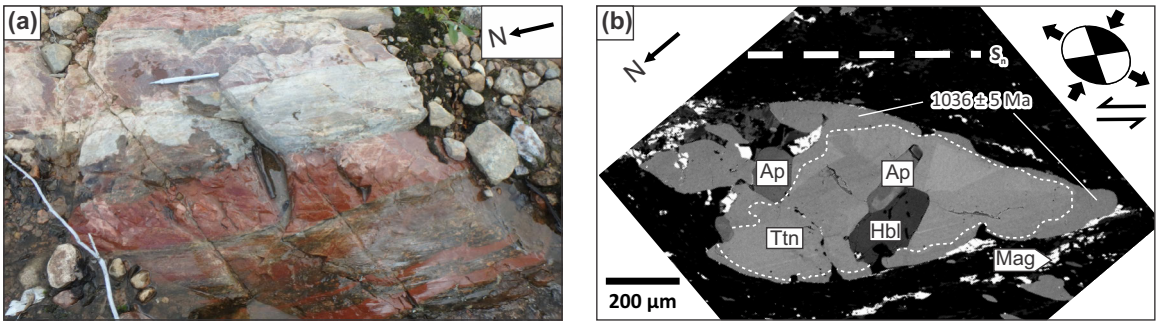

Fig. 7. (a) Hematitized ultramylonite layers (b) Titanite grain with a chemically distinct asymmetric overgrowth located in the extensional quadrants of an instantaneous strain ellipse under sinistral shear, indicating that shearing was active at 1036 ± 5 Ma (Gosselin et al., 2022).

Stop 1.5. Du Curé prospective zone (Ni-Cu)

Location: 48.09432166°N, 72.12155145°W
The outcrop is easily visible on the northwest side of the road.

The Du Curé prospective zone has potential for Ni-Cu mineralization hosted by a highly rusted gabbronorite of the Travers Suite (Fig. 8a; Moukhsil and Daoudene, 2019a). This zone is approximately 2 km long and 300 m wide. The gabbronorite is cut by an anastomosed network of millimetre-scale fractures that are partially filled with sulfides (pyrite, pyrrhotite, and chalcopyrite). The two main sets of fractures strike 048° and 103°. Intact lenses of gabbronorite apparently lack a metamorphic foliation and contains <1% of sulphides forming grain clusters. Pyrrhotite grains are commonly rimmed by pyrite and a finer rim of chalcopyrite. Fractures in pyrrhotite are filled with chalcopyrite. A sample containing ~1% of sulphide clusters analyzed for bulk-rock chemical composition returned values of 408 ppm Cu, 488 ppm Ni, 2.01 % TiO_2, 160 ppm Zn, 284 ppm Zr, and 0.56-0.72 % S. A detailed geometallurgical assessment on a mineralized surface sample demonstrated that Ni is mainly hosted by inclusions of violarite (~33% Ni) in pyrrhotite, and to lesser extent in pyrrhotite (0.5% Ni; Fig. 8b; Lavaure, 2022). Violarite is an alteration sulfur of pentlandite, although it is still uncertain if it is present in subsurface samples. Cu is hosted in chalcopyrite, whereas Co is present in violarite and in pyrrhotite.

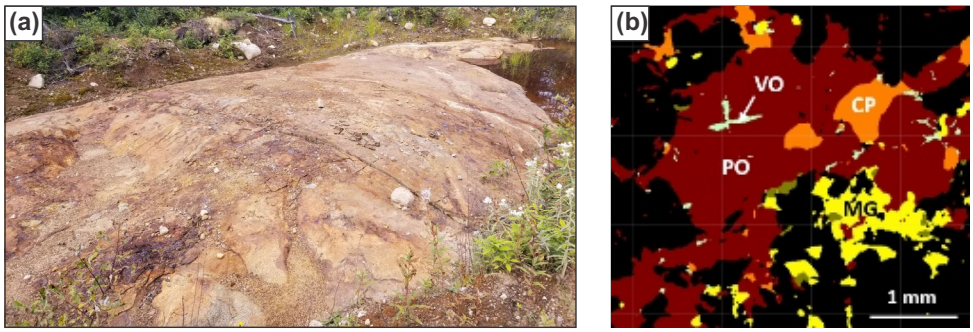

Fig. 8. (a) The Du Curé Ni-Cu prospective zone hosted by a gabbronorite of the Travers Suite. (b) Inclusions of violarite (VO) in pyrrhotite (PO). CP: chalcopyrite; MG: magnetite. Automated mineralogy analysis image from Lavaure (2022).

Stop 1.6. Fault breccia

Location: 48.08441977°N, 72.12211785°W
The outcrop is on the northwest side of the road.

The youngest and lower temperature deformation related to the Saint-François-de-Sales shear zone is represented by brittle fractures. Here, a meter-scale fault breccia deforms mangerite of the Travers Suite. The extent of brittle deformation is significantly larger than in most other outcrops of the area. Hematite and epidote alteration is important, as observed along the small fractures common in the area (Fig. 9).

Fig. 9. (a) Freshly cut surface of a breccia sample.

Stop 1.7. Cross-cutting relationships between sinistral and dextral mylonite

Location: 48.04145650°N, 72.11831445°W
Park in the large open area where it is possible to turn around. Walk down the trail over a few hundred meters, keeping your eyes on the rocks. Interesting outcrops are dispersed along the way. This is by far one of the most spectacular outcrops. It's worth the long drive and the short walk. You may notice on the map that we are <1 km NE of the first outcrop of the day. Unfortunately, the road does not connect between stops 1.1 and 1.7 on the south side, forcing the ~27 km detour to the north.

Several layers of protomylonite, mylonite, and ultramylonite can be observed at this location. Few layers of ultramylonite have a distinctive red color, indicating hematite alteration. The boundaries between unstrained host rock and ultramylonite is commonly sharp (Fig. 10a), but gradual strain gradients over the complete spectra of finite strain state over a few centimeters can be observed in a few places (Fig. 10b).

Most of the mylonite layers are NW-striking and sinistral-sense, but few NE-striking dextral mylonite bands can also be observed. Cross-cutting relationships are common at this location: sinistral-sense mylonite is cross-cut by dextral-sense mylonite and vice-versa, indicating that they formed synchronously (Fig. 10c). Where this conjugate shear system is best exposed, the thickest layer of sinistral-sense ultramylonite outlines fold hinges. The axial plane of these folds is vertical and parallel to the mylonite, and the fold axis is parallel to the transport direction (i.e. subparallel to the subhorizontal surface of observation). This geometry results in the illusion of two fold closures facing opposite directions. The presence of folds near the intersection of conjugate shear zones is common within the Saint-François-de-Sales shear zone (see also stops 1.3 and 2.5). These folds possibly accommodate local contractional strain related to the interference between opposite-sense shear zones.

Fig. 10. (a-b) Sharp (a) and gradual (b) strain gradients between unstrained protolith, protomylonite, mylonite and ultramylonite. (c) Mutually cross-cutting sinistral- and dextral-sense mylonite layers.

Day 2

Stop 2.1. Quartzite layers in the Wabash Complex

Location: 48.10837211°N, 72.23860945°W
The outcrop is on the west side of HW155, just north of the intersection of Chemin Lizotte. Park on Chemin Lizotte and **be extremely cautious when crossing the highway. High visibility clothing and hard hats are mandatory. Do not stand under overhanging parts of outcrop and do not walk on top of outcrop to avoid creating rock falls**.

The Wabash Complex, is a metamorphosed volcano-sedimentary sequence that is intruded by the Travers Suite. An impure quartzite sample collected at this location yielded a maximum depositional age of 1309 ± 38 Ma and dominant age peaks in the detrital zircon spectrum at ca. 1.61 Ga, 1.80 Ga, 1.90 Ga and 2.68 Ga (Papapavlou et al., 2022). The large age gap between major detrital zircon populations and the maximum depositional age is consistent with deposition in an intracratonic extensional sedimentary basin (Fig. 11a, Papapavlou et al., 2022).

Tectonic fabrics are typical of high temperature deformation: "straight gneiss", rootless isoclinal folds, quartz displaying chessboard extinction and grain boundary migration at the microscopic scale. There are also several late NE-dipping, low-angle brittle-ductile extensional structures that overprint these fabrics (Fig. 11b). At the southern end of the outcrop, a slightly deformed granitic dyke intrudes the slip plane. Similar structures were reported from the Mauricie area to the south (e.g., Fig. 4B in Soucy La Roche et al., 2015), where they have been interpreted to accommodate minor displacement during the waning stages of tectonic exhumation of the Mékinac-Taureau domain.

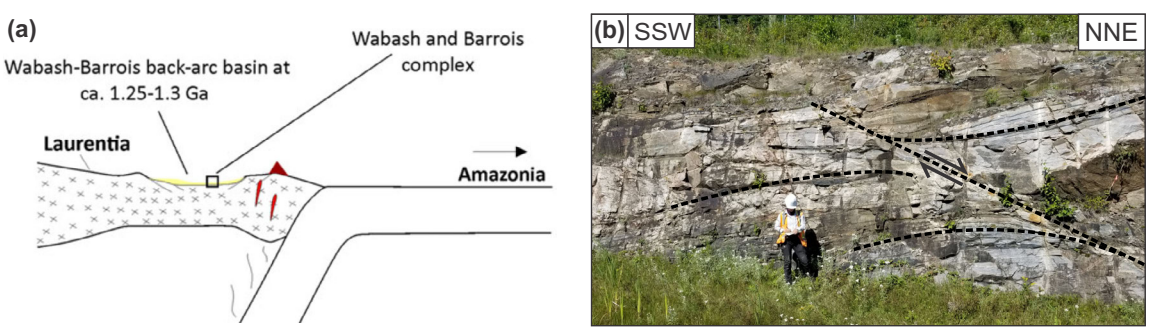

Fig. 11. (a) Tectonic setting of deposition of the Wabash Complex metasedimentary rocks (Papapavlou et al., 2022). (b) Low-angle brittle-ductile extensional structure.

Stop 2.2. Paragneiss lens in the Wabash Complex (optional)

Location: 48.07812770°N, 72.25054192°W
The outcrop is across the ditch, on the west side of HW155 (speed limit is 90 km/h). The shoulder is narrow, but there is a small trail entrance on the west side of the highway ~75m to the north. **High visibility clothing and hard hats are mandatory. Do not stand under overhanging parts of outcrop and do not walk on top of outcrop to avoid creating rock falls.**

This lens of paragneiss of the Wabash Complex is surrounded by the La Bostonnais Complex. It contains the peak metamorphic assemblage Grt-Bt-Sil-Kfs consistent with medium-pressure upper amphibolite to granulite facies metamorphism (>650 °C, ~0.4 to 0.8 GPa). These conditions are typical in the Allochthonous Belt of the Grenville Province. Timing of regional metamorphism, however, is not constrained. It might be the result of the Shawinigan or Ottawan orogenies.

Andalusite overgrows sillimanite, indicating that peak metamorphism was overprinted by an episode of low-pressure metamorphism (Fig. 12). Exact timing is not constrained, but low-pressure overprint could be associated with the intrusion of the Travers Plutonic Suite based on its proximity. This would indicate that the exposed rocks were at relatively shallow crustal levels (<0.4 GPa) during its intrusion.

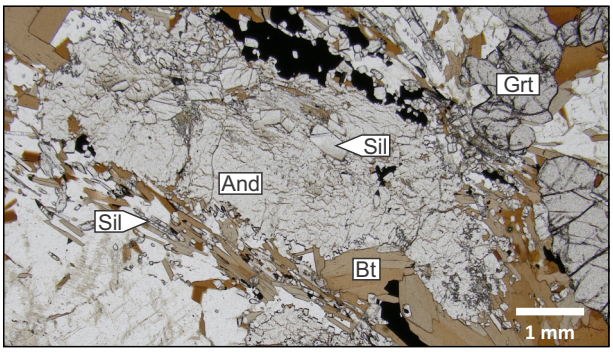

Fig. 12. Andalusite overprinting sillimanite in a Grt-Bt-Sil-Kfs paragneiss of the Wabash Complex.

Stop 2.3. Fault zone

Location: 48.29125855°N, 72.15893773°W

The outcrop is across the ditch, on the northwest side of HW155 (speed limit is 90 km/h). Park along the shoulder, as far away from the road as possible. **Be extremely careful when crossing the highway. High visibility clothing and hard hats are mandatory. Do not stand under overhanging parts of outcrop and do not walk on top of outcrop to avoid creating rock falls.**

The Travers Suite commonly displays brittle fractures filled with epidote and associated with hematite alteration. They are typically striking NW to NNE, vertical to steeply dipping, and display apparent sinistral displacement or no displacement. Here, the orientation of epidote-filled brittle faults is more variable, striking NNW to NE and dipping 45° to 90°. Fault striations are commonly vertical or steeply south-plunging, and more rarely subhorizontal. Both orientations may be visible on the same epidote-coated surface (Fig. 13). Rare sense of slip indicators associated with steeply plunging striations are consistent with inverse slip. The relationship between these fractures and deformation associated to the Saint-François-de-Sales shear zone is ambiguous.

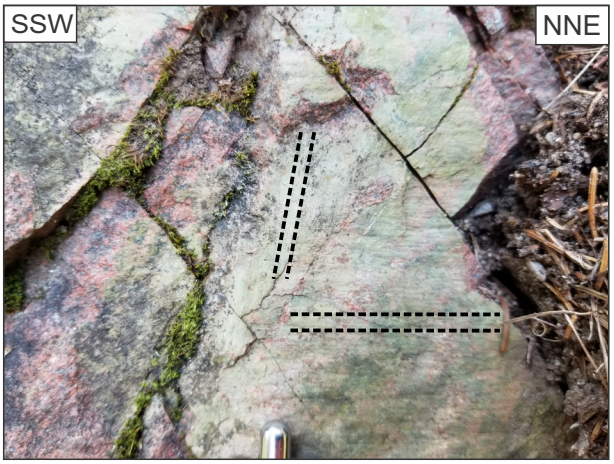

Fig. 13. Steeply south plunging and subhorizontal fault striations in epidote-filled fault.

Stop 2.4. 3D protomylonite (optional)

Location: 48.34199485°N, 72.22846069°W

Park in the large open area north of the road just before it turns south, where Chemin du Moulin becomes Chemin de la Bleuetière. Walk straight up the ATV trail. This small outcrop is in and a couple meters north of the trail near the top of the hill.

The outcrop is located in a mangerite of the Thaddé Plutonic Suite at the contact with gabbro of the Ouiatchouan Anorthosite Suite to the east. Lithological boundaries like this one might have preferentially localized deformation within the Saint-François-de-Sales shear zone.

A rare 3D view of the protomylonite allows the observation of feldspar porphyroclasts in all directions, and an assessment of the finite strain state. Porphyroclasts are symmetric and almost round perpendicular to the subhorizontal lineation (Fig. 14a), whereas recrystallization tails can stretch over >10 cm in the direction of the lineation (Fig. 14b). The asymmetry of porphyroclasts (σ-type and δ-type) is consistent with sinistral-sense shearing.

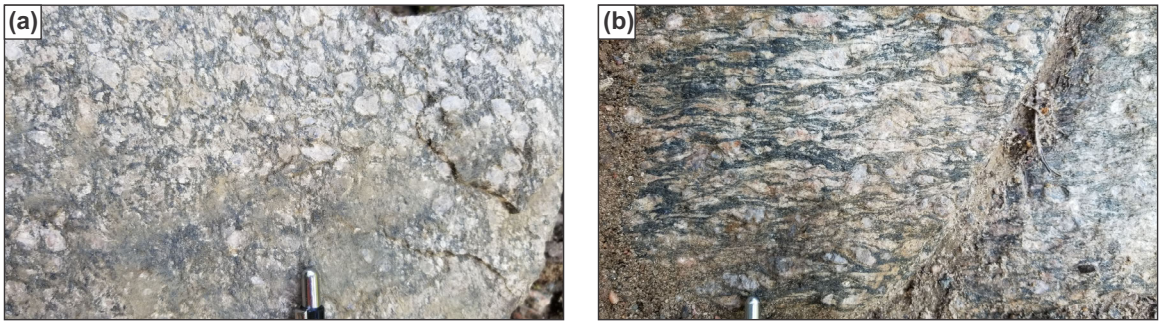

Fig. 14. 3D view of feldspar porphyroclasts. View perpendicular (a) and parallel (b) to the stretching lineation.

Stop 2.5. Sheared dyke and timing constraints

Location: 48.43485300°N, 72.24822400°W
Horizontal outcrop on the east side of the road, just below the electric lines. Please don't park on the rocks!

This is another important outcrop to constrain the timing of deformation and relationships between the metamorphic fabric and opposite-sense mylonites formed in the Saint-François-de-Sales shear zone. On the main section of the outcrop, the mangerite of the Travers Suite contains a NNW-striking S_{n-1} metamorphic foliation. This foliation is deflected by a two meter-thick N-striking sinistral-sense mylonite. A syenogranite dyke is perpendicular to the S_{n-1} metamorphic foliation and is straight over a few meters outside the mylonite (Fig. 15a). The dyke is transposed and stretched by the sinistral mylonite, and exposure is not sufficient to trace it across it (Fig. 15b). A second boudinaged dyke is also present in the mylonite, but it cannot be traced on either sides of the mylonite on the exposed surface. These dykes attest for displacement of at least a dozen of meters, and probably much more.

The dyke is folded next to the pegmatite. However, these z-shaped folds are incompatible with sinistral-sense movement in the mylonite. A dextral-sense mylonite can be observed at the northern end of the main exposure and a few meters to the northeast on a small exposed rock patch (Fig. 15c). It seems to be crosscut by the sinistral-sense mylonite and is the thickest dextral-sense mylonite we observed in the Saint-François-de-Sales shear zone. The Z-folds are likely the result of dextral shear along this NE-striking mylonite, or interference at the intersection of the two opposite-sense mylonites.

The syenogranite dyke yielded a crystallisation age of the ca. 1060 Ma (Gosselin, unpublished data), providing a minimum age constraint on the metamorphic foliation and a maximum age constraint on shearing. Metamorphic zircon grains yielded an age of ca. 1030 Ma. Although it is not possible to link metamorphic zircon crystallization with shearing unambiguously, deformation and fluid circulation in and around the shear zone could have provided a mechanism for metamorphic crystallization.

Combined with timing constraints acquired at stops 1.1 and 1.4 (Gosselin, unpublished data; Gosselin et al., 2022), the metamorphic foliation S_{n-1} in the Travers Suite formed between ca. 1120 Ma and ca. 1060 Ma, whereas the Saint-François-de-Sales shear zone was not yet active at ca. 1060 Ma, and accommodated strike-slip displacement continuously or episodically between ca. 1035 Ma and ca. 1000 Ma.

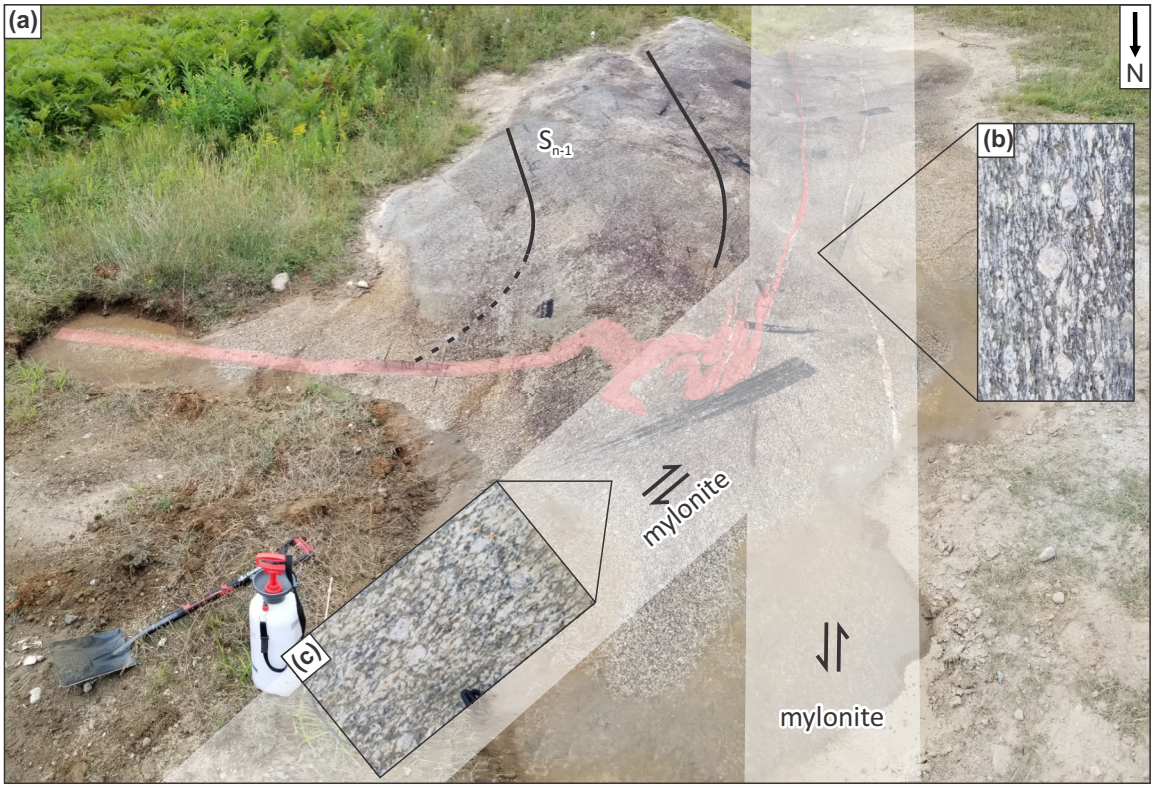

Fig. 15. A syenogranite dyke highlighted in pink is perpendicular to the Sn-1 metamorphic foliation and straight over a few meters outside a N-striking sinistral-sense mylonite that deforms it. Z-shaped folds next to the mylonite are incompatible with sinistral-sense movement and may be the result of dextral shear along a NE-striking mylonite, or interference at the intersection of the two opposite-sense mylonites. (b) and (c) Close-up of sinistral and dextral shear sense indicators, respectively.

Stop 2.6. Protomylonite and mylonite for 100s of meters (optional)

Location: 48.45951010°N, 72.23273814°W

When driving back towards Roberval, stop on Route Allaire. Outcrops are visible on the road beneath the gravel, and on the northwest side of the road.

Sheared rock layers in the Saint-François-de-Sales shear zone are typically a few millimeters to a few meters thick. Here, strain is less localized, and continuous protomylonite to mylonite can be observed over hundreds of meters across-strike. Quartz ribbons, recognizable by their clear appearance, are particularly visible in slightly weathered parts of the outcrop (Fig. 16).

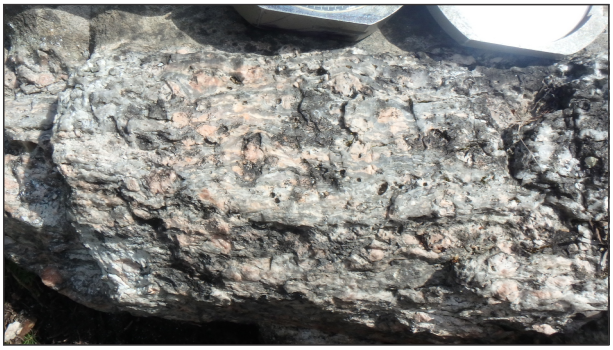

Fig. 16. Feldspar porphyroclasts wrapped by clear quartz ribbons.

Bonus stop. Langelier anorthosite

Location: 47.739719°N, -72.498663°W
For those driving back south on HW155 towards Trois-Rivières. **Be extremely careful along the highway. High visibility clothing is mandatory.**

The Langelier anorthosite (age unconstrained) is a round anorthositic body hosted by the Borgia magmatic suite. It is locally completely recrystallized, giving plagioclase a white color (Fig. 17a). Here, pyroxene crystals are highly strained, defining a subvertical stretching lineation (Fig. 17b).

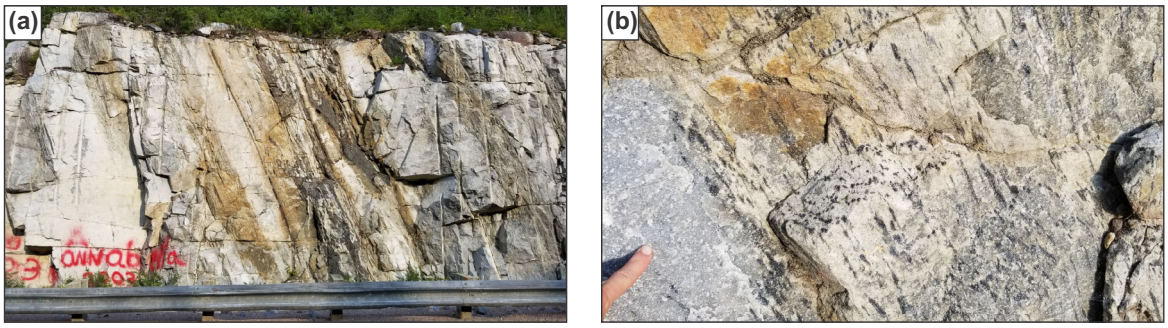

Fig. 17. (a) The Langelier anorthosite. (b) Strained pyroxene crystals defining a subvertical stretching lineation.

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