Petrographic analysis of fault rock structures from Notre Dame Bay, Newfoundland, Canada

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Abstract

This study investigates fault rocks in the Leading Tickles area of Notre Dame Bay Magmatic Province (NDBMP), Newfoundland, Canada. The NDBMP consists of alkaline mafic intrusions, and the Leading Tickles region is characterized by radial lamprophyre dykes, Leading Tickles Stock and Budgell's Harbour Stock, which fold and fault the surrounding Ordovician host rocks. This region is within an eastern peri-Gondwanan exploits subzone which was affected by the Appalachian orogenic events including the Taconic, Salinic and Acadian orogenies. The primary objectives of this study were to examine fault rock deformation processes, investigate interactions between the fault rocks and lamprophyre dyke fragments, and examine fault rock kinematics and reactivation.

This thesis presents a petrographic analysis of two fault rock samples collected from Cull Island, near the town of Leading Tickles in NDBMP. The first sample is identified as a non-foliated Protocataclasite, displaying features of both brittle and ductile deformation, consistent with formation in the brittle to ductile transition zone and late-stage fluid infiltration. The second sample is classified as a non-foliated mosaic fault breccia, indicative of brittle deformation at shallower crustal levels in a fault zone with late-stage carbonate infiltration. The absence of lamprophyre dyke fragments within the samples suggests faulting processes predate the dyke intrusion. In addition, the observed fault rocks are likely related to the Luke's Arm Fault Zone (LAFZ), which crosses the study area, and may reflect broader fault reactivation along Newfoundland's margin during the Mesozoic.

Introduction

PURPOSE OF STUDY

Background Information

Newfoundland, Canada is a significant location for analyzing geology due to its intriguing characteristics. Its current landscape reflects its well-preserved geological record, which is useful for studying earth's history of plate tectonic movement, magmatic history, and rock deformation. Newfoundland's margin, off the east coast of Canada, in the North Atlantic Ocean, formed from lithospheric stretching and rifting, and reactivation of the present-day Appalachian orogen (Peace et al., 2018). Newfoundland can be separated into four geological zones that formed during the Appalachian orogeny when the ancient continental masses, Laurentia and Gondwanaland, had assembled. The zones from west to east are the Humber, Dunnage, Gander and Avalon zones (Williams, 1995).

This research focuses on the Dunnage Zone which can be subdivided into the western peri-Laurentian Notre Dame subzone and the eastern peri-Gondwanan Exploits subzone. These subzones are separated by a suture zone known as the Mekwe'jit Line (ML) and are influenced by distinct orogenies that formed the Appalachians (Williams, 1995). The subject of this research is Notre Dame Bay Magmatic Province (NDBMP) or more commonly referred to as Notre Dame Bay (NDB), located within the exploits subzone and contains mafic intrusions, including units of Budgell Harbour Stock, Dildo Pond Intrusion, Leading Tickles Stock and marginal lamprophyre dykes (Peace et al., 2018). This thesis specifically investigates the Leading Tickles study area on Cull Island, located off coast of north-central Newfoundland.

Recently a study from Keefe (2024) examined structures associated with the ML in the Leading Tickles and NDB area to observe interactions between pre-existing structures and lamprophyres, impacts of magmatism and lamprophyre intrusion on the host rock, and post-intrusive deformation of lamprophyres. The lamprophyre dykes in the region were represented as the youngest structure based on K-Ar age dating of biotite minerals from Wanless (1965) that showed linkage to the Cretaceous to Jurassic periods of the Mesozoic era approximately 145 Mya. This time frame aligns with the opening of the North Atlantic Ocean when the mid-Atlantic ridge opened 150 Mya (USGS, 2022). The goal of the Keefe (2024) study was to emphasize the significance of ML Mesozoic deformation on Newfoundland's continental margin during the North Atlantic Ocean opening, despite the many Appalachian orogeny reconstructions that assume the deformation is negligible (White & Waldron, 2022). The conclusion was drawn from many previous studies that demonstrated the presence of significant stretching of Newfoundland's margin during the opening of the North Atlantic (Ady & Whittaker, 2018). Results from these studies confirmed that the structures associated with the ML reactivated to deform NDB post-intrusion. Deformed dykes were identified which raised the possibility that other structures in the area may have also reactivated during the same period.

Keefe (2024) also collected fault rock samples that are likely associated with the Luke's Arm Fault Zone (LAFZ) in the region, although analysis of these samples was limited. Potential post-intrusion deformation was identified in Figure 1 (see Appendix), where a dike was observed to terminate a reverse fault plane and was absent from the hanging wall, however, no other instances of dike termination were observed during the study. This left ambiguity on whether the fault crosscuts the lamprophyre dykes, but it is also possible that this was an isolated case where the dyke simply terminated.

Objectives

This thesis builds on the work of Keefe (2024) by conducting microstructural analysis on the fault rock samples, which received limited attention. The main purpose is to document any significant interactions between fault rocks and other structures, thus providing a better understanding of how these fault rocks influence the overall geological structures and tectonic evolution of the Notre Dame Bay and Leading Tickles region.

This study will focus on:

- Investigating fault rock deformation
- Interpreting fault rock kinematics and reactivation processes
- Examining interactions between the lamprophyre dyke and fault rock

By analyzing these processes, interpretations can be made regarding the broader scale tectonic history of the fault rock samples within the study area and it can help with enhancing reconstruction of Newfoundland's margin and the Appalachian orogeny. In addition, it could provide insight into fault reactivation of ancient fault systems along the Newfoundland margin.

TECTONIC HISTORY

Supercontinent Assemblage

Throughout Earth's history, several supercontinents have formed and broken apart, driven by processes of the supercontinent cycle, which models continent assembly and fragmentation, and the Wilson cycle, which models the opening and closing of ocean basins (Li et al., 2008). One of the first supercontinents was Rodinia which formed 1.3 to 0.9 billion years ago. Rodinia was made up of many large landmasses including Laurentia or the North American Craton, Baltica or the East European Craton, the Amazonian Craton, and the West African Craton. This supercontinent assembled through worldwide orogenic events with continental blocks that collided around the Laurentia margin to make Laurentia the main core of Rodinia. Rodinia lasted approximately 150 million years after it had completely assembled (Li et al., 2008).

40 to 60 million years after Rodinia assembled, mantle avalanches and thermal insulation caused the supercontinent's mantle to superplume and create widespread continental rifting between 825 to 740 million years ago (Li et al., 2008). Rodinia broke up diachronous, with the first break up event occurring 750 million years ago near the western margin of Laurentia and the second event occurring 600 million years ago between the Amazonian craton and southeastern margin of Laurentia (Li et al., 2008).

Grenville Orogeny

The Rodinia assemblage resulted in the Grenville orogeny where the exposed segments were derived from the reworking of Archean to Paleoproterozoic Laurentian crust, based on lead isotope data from the DeWolf & Mezger (1994) study, and they were products of continental back-arcs and island-arc terranes. The rocks of the orogeny are preserved in the Grenville Province, which has 2000 km extension from Lake Huron along the northern shore of the St. Lawrence River to the eastern coast of Labrador in Canada (Hynes & Rivers, 2010).

The Iapetus Ocean

The break-up of Rodinia has been associated with the opening and closing of the Iapetus Ocean (Robert et al., 2021). The Iapetus Ocean, also originally known as the 'proto-Atlantic' ocean, was born from this three-way break-up of Rodinia when the continents Laurentia, Baltica, and Amazonia separated, and from magmatic pulses 615 to 570 million years ago. This separation resulted in the opening of three oceans: the West Iapetus Ocean, the East Iapetus Ocean, and the Tornquist Ocean (Robert et al., 2021).

APPALACHIAN MOUNTAIN EVENTS

Appalachian Orogeny and Mountains

The Paleozoic Appalachian orogeny resulted in a complete Wilson cycle following the breakup of Rodinia and the continent assemblage that created Pangaea, with a series of diachronous orogenies over the last 1.2 billion years of Earth's history (Hatcher, 2010). The Appalachian orogenies consist of the Ordovician Taconic orogeny, Salinic orogeny, Devonian Acadian orogeny and the Alleghenian orogeny, which helped form the Appalachian Mountains (Hatcher, 2010). The North American Appalachian Mountains are a current erosional remnant of the larger ancestral mountains that were created through the orogenic process, and stretches from Newfoundland, Canada to Alabama, United States (Williams, 1995).

The Opening of the Rheic Ocean

In the Early Ordovician, around 500 million years ago, the southern continent Gondwana or Gondwanaland, consisting of South America, Africa, India, Madagascar, Australia and Antarctica, was experiencing a combination of Precambrian rifting, subduction and collision of an ocean ridge on its northern margin known as Avalonia (Nance et al., 2010). Avalonia, a Neoproterozoic arc terrane, eventually drifted off Gondwana becoming a microcontinent that reduced the size of the Iapetus Ocean and opened the Rheic Ocean in the process. The Rheic Ocean attained its greatest width of 4000 kilometers in the Silurian Period when Laurussia formed (Nance & Linnemann, 2008).

Taconic Orogeny

In the Ordovician Period, around 450 million years ago, a volcanic island arc developed from subduction of the western margin of the Iapetus Ocean beneath the Avalonia margin, resulting in closure of the Iapetus western basin and collision with eastern Laurentia (Encyclopedia, 2024). This collision resulted in deformation and angular unconformities from

New York to the Humberian area of Newfoundland, and the formation of a mountain belt, known as the Taconic Mountains. The Taconic Mountains are a North to South component of the Appalachians located to the east of Hudson River, New York, which caused igneous intrusions and regional metamorphism (Encyclopedia, 2024).

Salinic Orogeny

The Salinic orogeny began during the Late Ordovician to Silurian, 30 million years after the Taconic orogeny, and was caused by the collision of the Ganderia microcontinent to Laurentia. Ganderia was the first Gondwana-derived terrane to assemble with Laurentia and reduce the size of the Iapetus Ocean (Staal et al., 2017). The collision of the land masses resulted in the creation of the Iapetus Suture, which is a fault zone marking the location of the ancient ocean, and it now encompasses the former Gander zone and parts of the Avalon and Dunnage zones (Staal et al., 2017).

Acadian Orogeny

During the Late Silurian to Late Devonian, approximately 350 million years ago, the continental fragments of Laurentia, Baltica and Amazonia from the Rodinia supercontinent re-assembled to form the continent of Laurasia, later known as Laurussia (Rafferty & Young, 2006).

This assembly was associated with the collision of the Avalonia microcontinent, which collided specifically with Baltica and rotated north towards Laurentia. This process resulted in the high-grade metamorphism, intrusive igneous activity, closure of the Iapetus Ocean and widening of the Rheic Ocean (Tucker et al., 2001). The collision overprinted the Taconic and Salinic metamorphic ages and built a mountain range known as the Acadian Mountains, which extended from the Canadian maritime provinces towards Alabama and greatly impacted the northern Appalachian region that includes New England and the Gaspé region of Canada (Rafferty & Young, 2006).

Alleghenian Orogeny

During the Late Carboniferous to Permian, the Alleghenian orogeny was caused by the collision of Laurussia with Gondwanaland. This was the final phase of deformation in the Appalachian region and was most pronounced in the central and southern areas (Dykeman, 2019). Evidence of the Alleghenian orogeny included Paleozoic folding and igneous intrusions along Newfoundland and other maritime provinces in Canada. This orogeny marked the full closure of the Rheic Ocean, forming the supercontinent Pangaea 335 to 299 million years ago (Dykeman, 2019).

Pangaea and the Opening of the Atlantic Ocean

Pangaea broke apart around 175 million years ago, starting a new Wilson cycle that opened a rift 150 million years ago, known as the mid-Atlantic ridge (USGS, 2022). This ridge provided volcanic materials for the expanding ocean basin, and the final continent separation of Pangaea formed the following: the North Atlantic Ocean, central Atlantic Ocean, southwestern Indian Ocean, and the South Atlantic Ocean. The opening of the Atlantic Ocean isolated the Appalachian Mountains as separate ranges on different continents such as North America (USGS, 2022).

The Newfoundland Margin

The magma-poor Newfoundland margin formed from lithospheric stretching, rifting and continental breakup in the Late Triassic to Early Cretaceous, and from reworking and reactivation of the present-day Appalachian orogen (Peace et al., 2018). The current landscape reflects its history with the west coast representing the continental margin of the Iapetus Ocean, the central zone preserving volcanic and intrusive island arc rocks, and the east coast representing the remnants of Gondwanaland. The central part of the margin includes continental diabase dykes, volcanic rocks, and alkaline and ultramafic lamprophyres (Peace et al., 2018).

STUDY AREA HISTORY

Canadian Geological Regions

Canada can be divided into seven geological regions including the Canadian Shield, which is the largest and oldest of the regions, with the other six regions forming rings around it. The older and outer ring consists of the Western Cordillera, Canadian Arctic and Appalachian Region. The younger ring consists of the Interior Plains, Hudson Bay Lowlands and the St. Lawrence Lowlands (Slaymaker et al., 2012).

Appalachian Region

Newfoundland, Canada is included in the Canadian Appalachian geologic region, along with Nova Scotia, New Brunswick, Prince Edward Island, and the southern part of Quebec. The Appalachian region, as shown in Figure 2 (see Appendix), is a Paleozoic geological mountain belt or orogen with a total area of approximately 500,000 km^2 (Williams, 1995).

The Appalachian orogen occupies the edge of the undeformed rocks of the North American craton that overlies the Precambrian basement. The exposed basement rocks form the Canadian shield, and the overlying rocks define the St. Lawrence Platform. The Appalachian region lies between the Grenville Structural Province of the Canadian Shield to the southwest, the St. Lawrence Platform to the northwest, and the Atlantic Continental Shelf to the southeast (Williams, 1995).

Newfoundland Dunnage Zone

Along this Appalachian region there are many different rock layers and geological zones. The western part contains mostly undisturbed Paleozoic rocks overlying the Grenville rocks, whereas the eastern part has more rock type variations and different basement layers. Shown in Figures 3 and 4 (see Appendix), these differences are what divides the region into distinct zones, named as follows from west to east: Humber, Dunnage, Gander, Avalon and Meguma (Williams, 1995).

The Newfoundland Dunnage zone comprises of many ancient oceanic terrane remnants which originally developed in the Iapetus Ocean between the crust of the Gondwanan and Laurentian cratons (Piercy et al., 2023). It is comprised of many geologic features forming different sections of the Iapetus Ocean, either in volcanic arcs, or the regions behind them known as back-arcs (Piercy et al., 2023).

The Dunnage zone can be subdivided into the western peri-Laurentian Notre Dame Subzone and the eastern peri-Gondwanan Exploits Subzone as shown in Figures 5 and 6 (see Appendix; O'Brien, 2003). This subdivision is based on separation by the Mekwe'jit Line (ML), formally known as the Red Indian Line (RIL), which is a major tectonic boundary across Newfoundland separating the terranes of Laurentian and Gondwanan origin. The ML shows regional differences in geology as the Notre Dame Subzone was affected by the Taconic orogeny and displays rocks with greenschist, and the Exploits Subzone was influenced by more complex processes including the Taconic, Salinic and Acadian orogenies (Williams, 1995).

The Notre Dame Subzone interacted with the Early to Middle Ordovician phase of the Taconic orogeny and Laurentian continental crust during the Cambrian (O'Brien, 2003). It has one of the widest ophiolite recurrences in the Appalachian Orogen and increasing intensity of metamorphism and deformation easternly and upwardly (Williams, 1995). The Exploit Subzone has a more structurally complex rock collection with varying ages and tectonic environments due to its preserved record of orogenic assembly. During the Early Ordovician, some of the oceanic rocks in this subzone were deposited on the Gander Zone continental margin and during the Early Silurian, a collision produced submarine uplift and mélange tracts (O'Brien, 2003).

Exploit Subzone Stratigraphy

This study focuses near the Leading Tickles area, that runs along the north-central coast of Newfoundland in the Exploits Subzone of the Dunnage Zone (Keefe, 2024). Within the Leading Tickles area of the exploit subzone, there are a variety of stratigraphic rock units including the Wild Bight Group, Shoal Arm Formation, and Badger Group (O'Brien, 2003).

As shown in Figure 7 (see Appendix) of the O'Brien (2003) study, the Wild Bight Group is the oldest out of these units from 460 Mya to 490 Mya during the Middle Ordovician to Early Ordovician periods. The volcaniclastic turbidite sequences of the group move upwards stratigraphically into different variations of chert and the boundaries of the group are mostly thrust faults. In the northern area, the group is composed of pillowed basalts overlayed by green volcaniclastic wackes, turbidities, argillites, and felsic pyroclastic rocks of the Shoal Arm Formation and middle member of the Penny's Brook Formation. The eastern Wild Bight Group has many gabbro sill mafic intrusions that are likely the same age as the Gummy Brook gabbro sills in the western area of the group. These Gummy Brook gabbro sills are part of the Notre Dame Bay Magmatic Province and intrude the Wild Bight Group to the east (O'Brien, 2003).

The Shoal Arm Formation is from 450 Mya to 460 Mya during the Late Ordovician to the beginning of the Middle Ordovician periods. This formation lies above the Wild Bight group with distinct red chert and minor grey siltstone turbidites overlayed by sandstone turbidites and siliceous argillites, that is all overlayed by black carbonaceous shale. This black shale unit is highly deformed and shows evidence of brecciation, which is the process of breaking rock down into angular fragments, and evidence of shearing (O'Brien, 2003).

The Badger Group is from 445 Mya to 450 Mya during the Late Ordovician period. It formed before Silurian volcanism and after Dunnage Zone rocks drowned in the Middle to Late

Ordovician and buried by black shale. This shale overlies the Wild Bight Group arc volcanic sequences in the Leading Tickles area (O'Brien, 2003).

Notre Dame Bay Magmatic Province

The Notre Dame Bay Magmatic Province (NDBMP), also more commonly known as Notre Dame Bay (NDB) is a small magmatic province comprising a group of Jurassic to Cretaceous igneous rocks found in the exploits Subzone of the Dunnage Zone in north-central Newfoundland, Canada (Peace et al., 2018). The NDB includes the gabbroic Budgell Harbour Stock (BHS), Dildo Pond Intrusion (DPI), Leading Tickles Stock (LTS) and marginal lamprophyre dykes (Peace at al., 2018).

The BHS are poorly exposed unfaulted rocks characterized by southward dips, weak joints and irregular geometry. From the Helwig et al. (1974) study, the BHS were found to have varying mineral abundancies based on location. A sample from the southeastern margin contained approximately 50% plagioclase, in contrast to a sample from the western side with over 50% pyroxene and less than 20% plagioclase (Helwig et al., 1974). The DPI is likely related based on high gravity and magnetic susceptibility and contains many Mesozoic alkali gabbro intrusions (Peace et al., 2018). The marginal lamprophyre dykes were considered the youngest and likely deformed post-intrusion by pre-rift faults (Heyl, 1937). The dykes were represented as the youngest based on K-Ar dating from the Wanless (1965) study to obtain biotite ages of 115 ± 20 Ma, 129 ± Ma, and 144 ± 2 Ma, which links them to the Cretaceous to Jurassic period.

STUDY AREA GEOLOGY

Leading Tickles Structural Geology

The study area is located on Cull Island near the town of Leading Tickles, which is on the northeastern shore of NDB, Newfoundland, as seen in Figure 8 (see Appendix). The location is 25 km northwest of Port Leamington, with positioning of approximately 49°31'N latitude and 55°26'W longitude (Keefe, 2024).

The structures in this study area reflect the geologic history of the Dunnage Zone where four major deformation events were recorded. D1, the first deformation event, involved the formation of folds and thrust faults from the Taconic Orogeny during the Late Ordovician (O'Brien, 2003). The lithology of this event included the black shale found in the Ordovician rocks of the Shoal Arm Formation that were displaced and removed from the thrusting. This deformation created folds of both anticlines and synclines with dome shapes, trending northwest. The D2 event created a new set of folds and faults in a different direction, trending northeast, likely from the Late Silurian Acadian orogeny. D2 also produced oblique-slip fault zones and new cleavage planes. D3 minor structures and D4 shear system components occurred later with small adjustments to the already deformed rocks (O'Brien, 2003).

Running through the study area is the Luke's Arm Fault Zone (LAFZ), which was a term applied to all the faults associated with and that have surface connections to the Lukes Arm and Lobster Cove faults (Horne and Helwig, 1969). The LAFZ is known as a Late Silurian thrust fault zone of the Iapetus suture ML, and it was dominated by oblique-slip thrusting that was likely active during the D1 and D2 phase (O' Brien, 2003).

The Lukes Arm fault was interpreted and modified by Williams (1995) as a high angle thrust fault with the north side moved to the east and the same stratigraphic units on both sides of the fault. The Lobster Cove fault was first recognized as a high angle thrust fault, offset 6 km by the Davies Pond fault, and was later recognized as a vertical fault (MacLean, 1947; Strong 1972).

The LAFZ had initiated deformation in the region and likely developed the Notre Dame Bay Flexure, which is an East to West trending flexure of the Appalachian orogen (O'Brien, 2003). The flexure is an oroclinal Z-shaped fold, that regionally bent and deformed the area and was created by two parts of the ML, which trends in both the northeast and northwest directions.

Fault Reactivation Processes

The ML LAFZ faults involve both vertical or dip-slip and horizontal or strike-slip movement, which can be linked to oblique tectonics. This oblique movement may occur when the applied stresses acting on a region are not orthogonal to pre-existing weaknesses, where these weaknesses can come from old faults such as the Lukes Arm and Lobster Cove faults (O'Brien, 2003). The faults are likely to guide the direction of rifting and faulting of today where deformation would follow the weakness zones and cause the faults to reactivate. This was the case with the Newfoundland to Iberia margins where the breakup followed the Rheic suture zone and resulted in the Grand Banks separating from Iberia (Keefe, 2024).

Notre Dame Bay Structures

In the study conducted by Keefe (2024) host rock and lamprophyre dykes were examined from the LTS in the Exploits Subzone and from the southeast of Cull Island. The host rocks, which deformed during the Ordovician-Silurian closure of the Iapetus Ocean, commonly exhibited subparallel fracturing that depended on the rock type. For example, the fracturing was more pronounced in brittle host rock such as chert and less pronounced in ductile units like shale. Additionally, sub-parallel dykes were more prevalent in host rock with extensive subparallel fracturing (Keefe, 2024).

The lamprophyre dykes interacted with these host rock structures through bedding, shears, folds, faults, and fractures. By examining sequences of siltstone and sandstone turbidite from the Shoal Arm Formation, Keefe (2024) discovered that most of the lamprophyres were offset laterally along the bedding planes. This led to a pattern where the dykes initially followed a consistent stepping direction, but later shifted to a “zigzag” formation, disrupting the regular stepping sequence. As a result, the overall trend shifted from the dike openings being perpendicular to the rock walls, to becoming oblique.

In addition, Keefe (2024) collected various host rock thin section samples and Peace et al. (2018) collected lamprophyre thin sections from different locations to be used for petrographic analysis. The host rock thin sections ranged from light to dark brown in plane-polarized light, with high concentrations of dark clay and quartz veinlets. The lamprophyres ranged from aphyric to porphyritic textures with varying mineral assemblages. Some dykes are rich in amphibole and classify as camptonites with alkaline composition, whereas others are rich in phlogopite and classify as kersantite with calc-alkaline composition (Keefe, 2024; Peace et al., 2018).

Methods

The data for this study was collected by Keefe (2024) who obtained two major fault rock samples from separate locations on the northeast shore of Cull Island, near the Leading Tickles town in Notre Dame Bay. Both samples are located offshore of East Bear Cove. The first sample, FB1, is located at coordinates 49.5113804 N, -55.4464766 W, and FB2 is located at 49.5099212 N, -55.4447998 W, as shown in Figure 8 (see Appendix).

The samples were collected using a geological hammer and chisel and labeled based on location and orientation. For thin section preparation, the samples were cut into thin slices, grinded flat and sent to a laboratory to be mounted on glass slides using epoxy resin in the Keefe (2024) study. The fault rock samples were observed using these thin sections for petrographic analysis. The thin section slides were examined under a Nikon Eclipse Ci POL microscope at varying magnifications including 4X, 10X, and 20X. Varying light types were also used including transmitted light, such as plane-polarized light and cross polarized light, as well as reflected light. Digital images were captured using NIS-Elements D software. Analysis was conducted to identify key features such as texture and foliation, mineral types, and other microstructural features.

Examining the relationships between the fault rocks and other structures is crucial for gaining better insight into the geological processes and tectonic history of Newfoundland. Additional research would need to be conducted with other fault rock samples of other units to fully understand the full regional scale interactions. Further studies could explore other methods including 3D structural or microstructural modeling of the fault rock, and other analytical techniques to cross-check the results and reduce possibility of misinterpretation.

Results

FAULT ROCK OBSERVATIONS

This section presents the physical observations of the two fault rock samples collected from the northeast shore of Cull Island, Leading Tickles area of Notre Dame Bay. The samples were analyzed to observe appearance, grain sizes, texture, lithology, and more.

Fault Rock 1 (FB1)

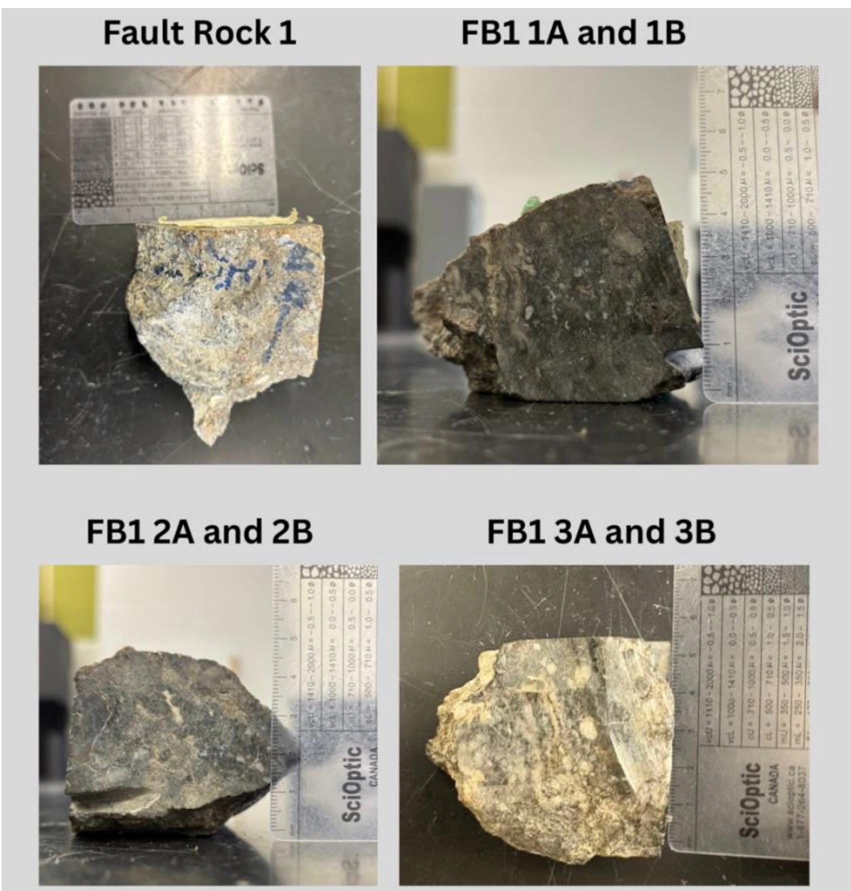

Image 1. Fault rock 1 (FB1) images showing rock thin section sides: FB1-1A and 1B, FB1-2A and 2B, and FB1-3A and 3B.

Fault Rock 1 Description

The first fault rock sample has a brownish grey appearance, as shown in Image 1, and a matrix with grain sizes ranging from 0.002 to 0.088 mm and phi values of approximately 9.0 to 3.5. Based on the Wentworth Size Class, the matrix can be classified as clay or silt. FB1 also contains larger rock fragments with grain sizes from 0.2 to 0.5 mm and phi values of approximately 2.0 to 1.0. Most of the fragments are angular quartz with some feldspar. The clasts comprise approximately 70% of the rock mass based on the percent abundance estimation chart (Fichter, 2000). This sample represents the down-dropped side of a fault, indicated by the letter “D”, where FB1-2 is the bottom of the sample and FB1-1 and FB1-3 are the sides.

Fault Rock 2 (FB2)

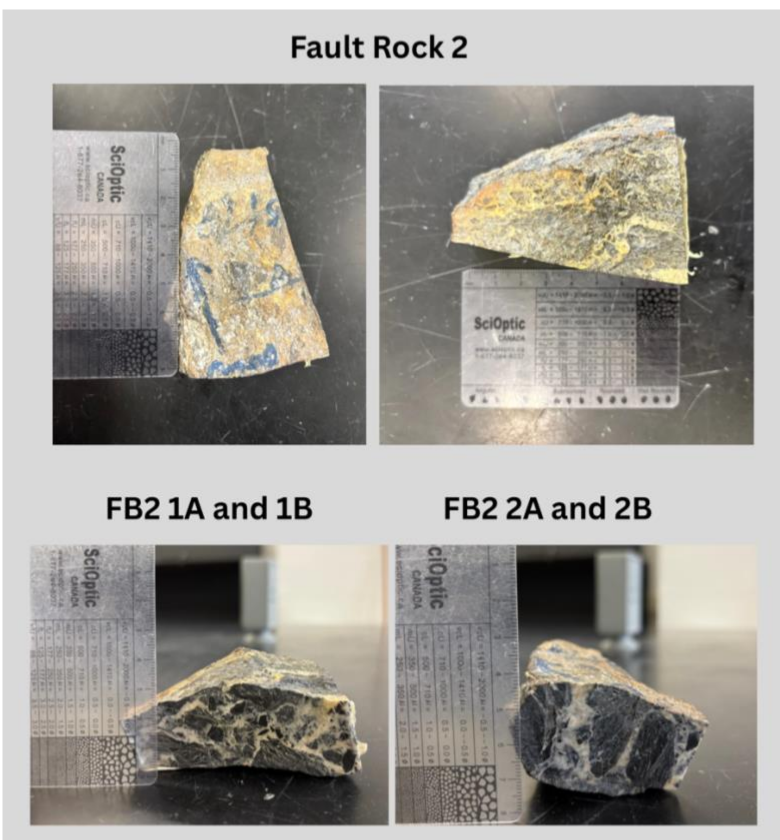

Image 2. Fault rock 2 (FB2) images showing rock thin section sides: FB2-1A and 1B, and FB2-2A and 2B.

Fault Rock 2 Description

The second fault rock sample has a reddish-black appearance, as shown in Image 2. It has matrix and fracture areas with grain sizes varying from less than 1 mm and up to 2 mm, with phi values greater than 3.0. The matrix comprises a small amount of the rock mass and includes mainly coarse-grained calcite and quartz based on the Wentworth Size Class. Fault rock 2 (FB2) is comprised of many dark pyrite and clay mineral fragments with a mass abundance of 60% based on the percent abundance estimation chart (Fichter, 2000). The fragment sizes range from 0.5 mm to approximately 3 mm, with phi values around 1.0 to -1.5, and angular shapes. This sample represents the down-dropped side of a fault, with FB2-1 as the top and FB2-2 as the side.

THIN SECTION ANALYSIS

This section presents the petrographic analysis of the fault rock thin sections, FB1 and FB2 slides, prepared from the Notre Dame Bay fault rock samples. The analysis was conduct using a Nikon Eclipse Ci POL microscope with plane-polarized light, cross-polarized light, and reflected light types. The thin sections were examined to determine mineral composition, unique textures, foliation or lineation, and any other microstructural features including potential lamprophyre dyke fragments to determine if there was pre or post dyke intrusion.

Fault Rock 1 Thin Sections

The first fault rock was divided into three sections or rock sides, with two thin sections prepared for each side: FB1-1A, FB1-1B, FB1-2A, FB1-2B, FB1-3A, and FB1-3B.

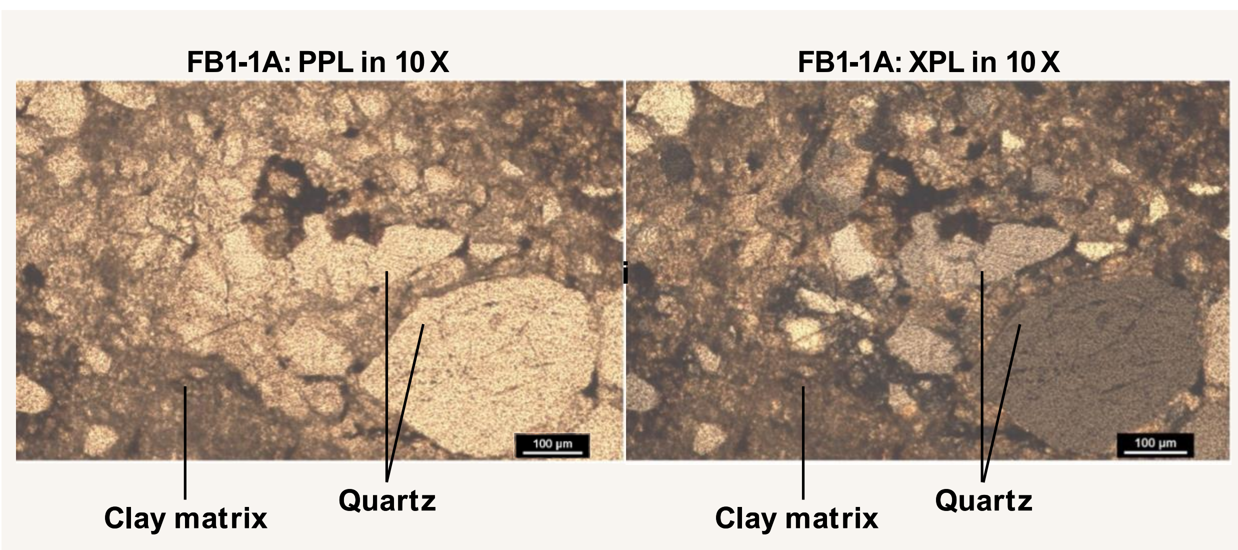

Image 3. Thin sections of fault rock 1 with slide 1A shown in plane-polarized light (PPL) and in cross-polarized light (XPL).

General observations illustrated in Image 3 include a great abundance of angular quartz minerals among the fine-grained clay matrixes. Other minerals in the rock include feldspar and some opaque minerals. Textures in this rock show no signs of foliation and lineation, instead the mineral grains are highly fragmented with varying rotations within the matrix. Also, there are no lamprophyre dyke fragments present.

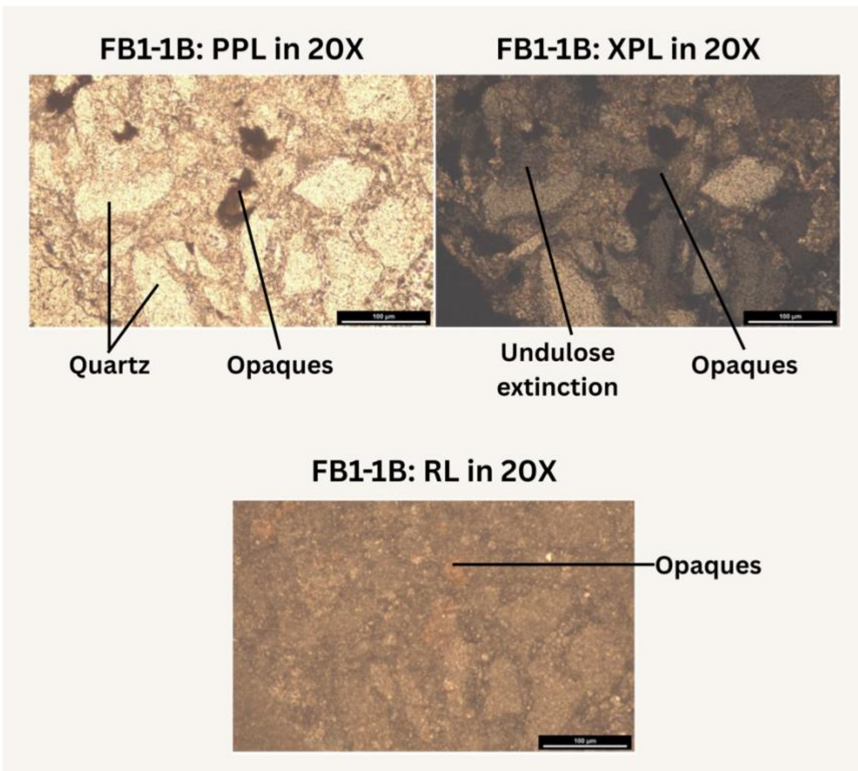

Image 4. Thin sections of fault rock 1 with slide 1B shown in plane-polarized light (PPL), cross-polarized light (XPL), and reflected light (RL).

Observations illustrated in Image 4 show anhedral quartz as colorless to light brown with moderate relief in plane-polarized light. In cross-polarized light, the quartz has low first-order interference colours of yellow, grey, and white. Some of the quartz grains also have undulose extinction, indicative of internal deformation. The grains that appear black in both PPL and XPL with no interference colours represent opaque accessory minerals, likely metallic sulfides including pyrite or chalcopyrite. Chalcopyrite exhibits a strong yellow color, and pyrite exhibits a brassy yellow to orange colour, which is difficult to identify due to the strong red reflectance in the reflected light image. Texture is consistent with the previous thin section slide, where crystal boundaries are present with no strong alignment or foliation of grains. Lamprophyre dyke fragments are absent.

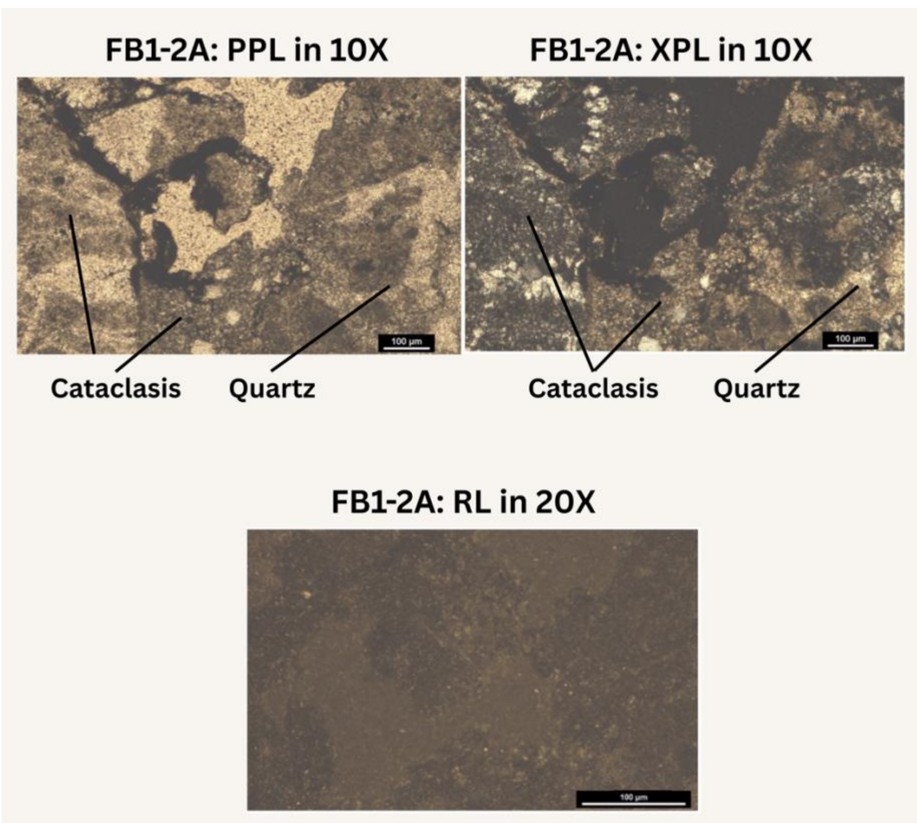

Image 5. Thin sections of fault rock 1 with slide 2A shown in plane-polarized light (PPL), cross-polarized light (XPL), and reflected light (RL).

Illustrated in Image 5 are more anhedral quartz and feldspar grains surrounded by fine grained matrix. It shows the cataclasis process quite well, which is driven by mechanical stress and often associated with faulting and tectonic activity (Wu et al., 2022). The process involves brittle fracturing and grinding of rocks and is characterized by grain size reduction, resulting in this fine-grained texture. The overall texture is consistent with previous results of high fragmentation and angularity, and no foliation. The absence of lamprophyre dyke fragments is also consistent with previous thin sections.

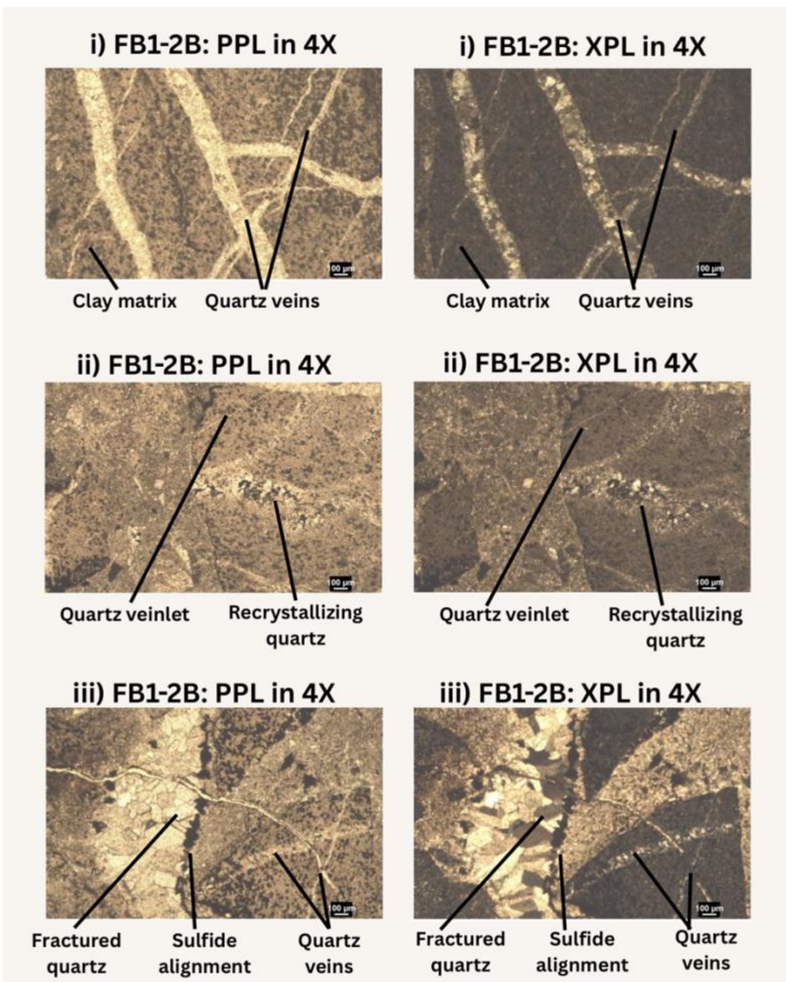

Image 6. Thin sections of fault rock 1 with slide 2B shown in plane-polarized light (PPL) (i, ii, iii), and cross-polarized light (XPL) (i, ii, iii).

These thin sections show bright, angular quartz grains with strain-related recrystallization and undulose extinction, and the dark brown colours show the fine-grained clay mineral matrix (Image 6, ii, iii). The network of mineral-filled fractures suggests quartz vein formation and the quartz grains show internal strain (Image 6, i). The vein networks show relative timing of formation, where the smaller and cut quartz veins formed first and deformed eventually, and the continuous veins formed later as part of a different deformation event and could represent a late-stage fluid infiltration (Image 6, i). There are also many fractured quartz and small fractures or veinlets cutting across grains, indicating ductile deformation. The alignment of opaque minerals shows weak alignment and progressive cataclasis. These minerals are separating the high strain zone of small angular quartz fragments in a fine matrix, and a lower strain zone with larger quartz grains (Image 6, iii). This thin section does not have consistent texture with the previous thin sections due to the weak fabrics. On the other hand, it does not have any lamprophyre dyke fragments, which is consistent with other thin section results.

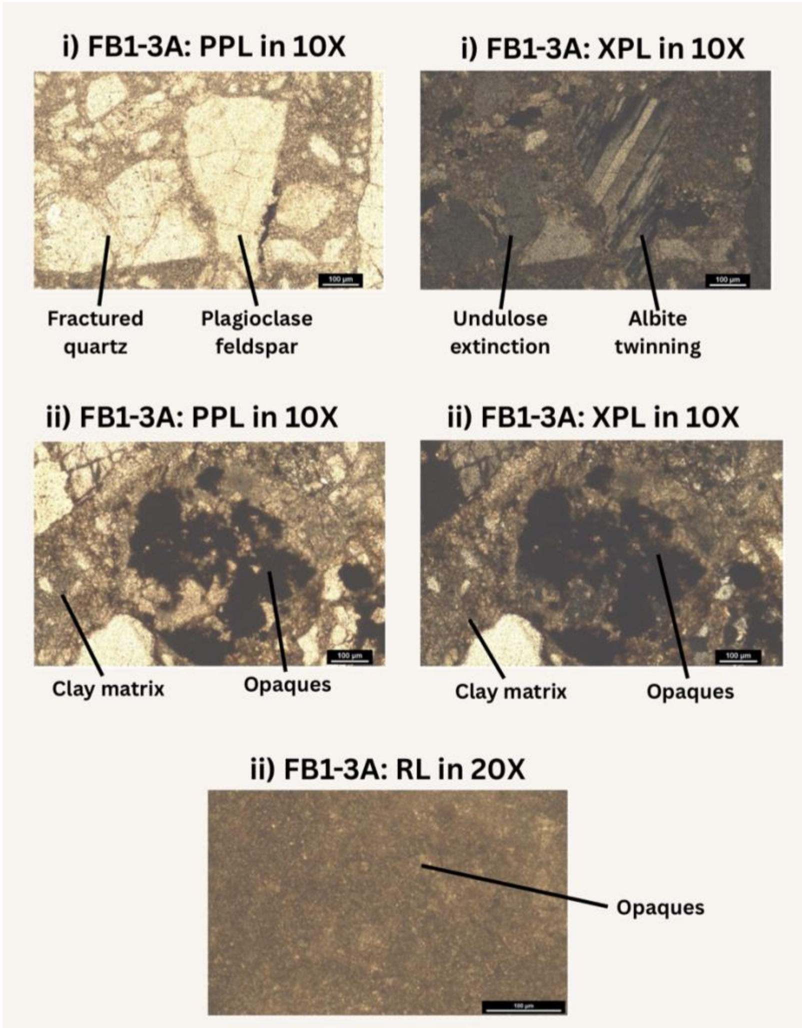

Image 7. Thin sections of fault rock 1 with slide 3A shown in plane-polarized light (PPL) (i, ii), cross-polarized light (XPL) (i, ii), and reflected light (RL) (ii).

Cataclasis can be seen where the quartz minerals are fragmented, have variable rotations, and exhibit undulose extinction (Image 7, i). Another mineral includes plagioclase feldspar with two cleavages intersecting approximately at 90 degrees, noticeable in plane-polarized light, and it has a form of twinning, noticeable in cross-polarized light. This feature specifically has no cross-hatching, alternating bands from rotation in XPL, and evenly spaced bands, which indicates diagonal albite twinning (Image 7, i).

Fault Rock 1 Identification

The absence of foliated texture with FB1 is likely due to the large amount of quartz grains being present, as foliation is unable to develop from platy minerals. This rock sample can be classified using the Woodcock & Mort (2008) criteria where cataclastic rocks, which exhibit cataclasis and a fine-grained matrix, typically have clasts less than 2 mm in size and form from intense shearing in fault zones. In addition, Mommio (2020) indicates that cataclastic rocks can be subdivided into protocataclasites with 10-50% matrix, cataclasites with 50-90% matrix, or ultracataclasites with greater than 90% matrix, which makes FB1 classified as a Protocataclasite rock.

Fault Rock 2 Thin Sections

The second fault rock was divided into two sections or rock sides, with two thin sections prepared for each side: FB2-1A, FB2-1B, FB2-2A, and FB2-2B.

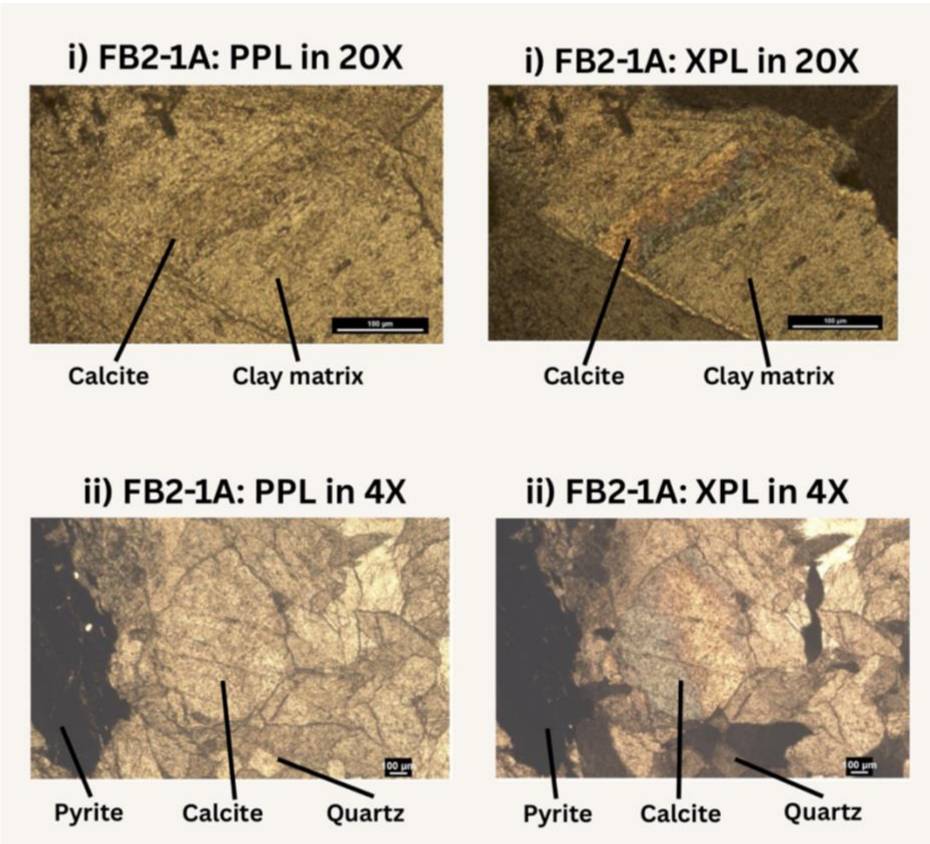

Image 8. Thin sections of fault rock 2 with slide 1A shown in plane-polarized light (PPL) (i, ii), and cross-polarized light (XPL) (i, ii).

General observations illustrated in Image 8 include the pyrite mineral grains which appear irregular, black and opaque in both plane-polarized light and in cross-polarized light. The calcite and carbonate mineral grains, which are mainly colorless in plane-polarized light and have moderate to high birefringence which resulted in the high-order interference colours of blue, pink and yellow within the cross-polarized light. There are also some quartz grains which have lower relief with lower interference colours than the calcite in cross-polarized light. The clay minerals make up part of the matrix and are difficult to distinguish individually, resulting in a low-birefringence mass appearance (Image 8, i). Texture in this thin section show no signs of foliation, instead mineral grains are mostly subangular and have varying rotations. There are no lamprophyre dyke fragments present.

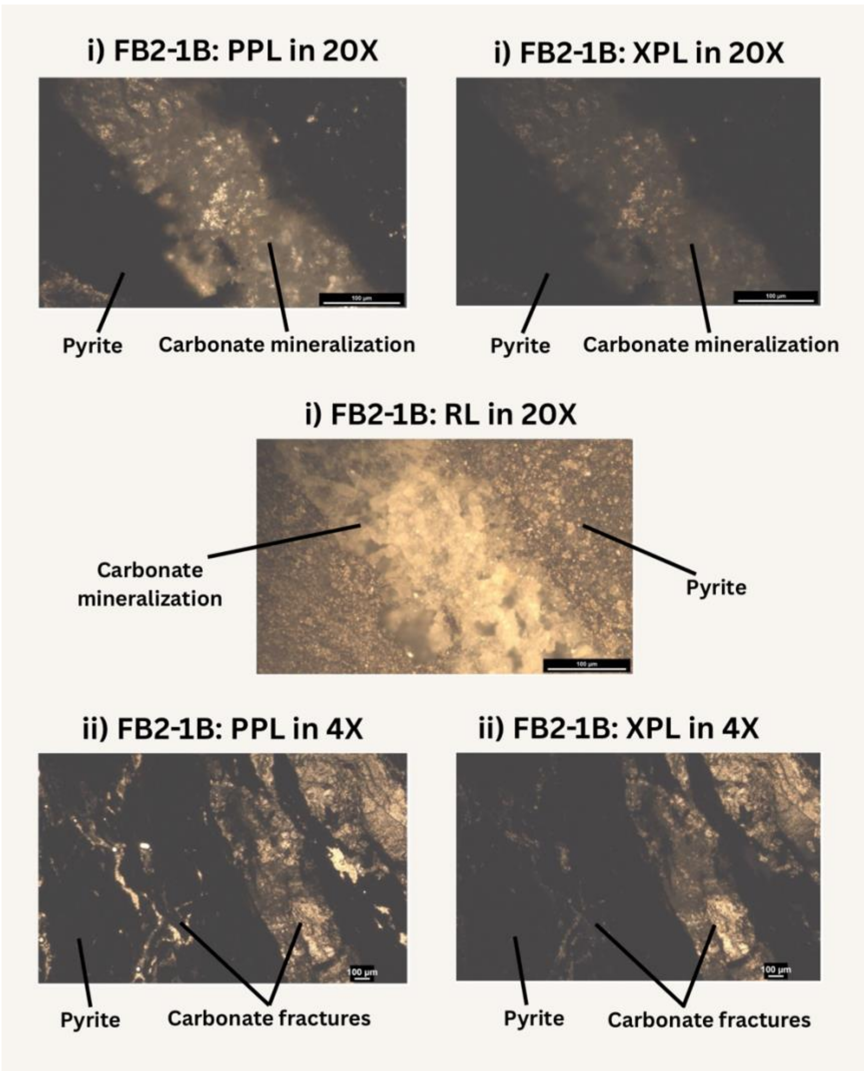

Image 9. Thin sections of fault rock 2 with slide 1B shown in plane-polarized light (PPL) (i, ii), cross-polarized light (XPL) (i, ii), and reflected light (RL) (i).

Image 9 shows the fault rock sample at a higher magnification to particularly view the pyrite minerals. As shown with reflected light, the pyrite grains appear bright and reflective with a yellow to gold luster. In comparison to the pyrite, the carbonate and quartz minerals infilling the fractures appear duller. The dark cloudy area in PPL and XPL that brightens under reflected light are likely small pyrite particles that do not have sharp reflections (Image 9, i). For a more detailed analysis of this, a scanning electron microscope (SEM) should be used for better identification.

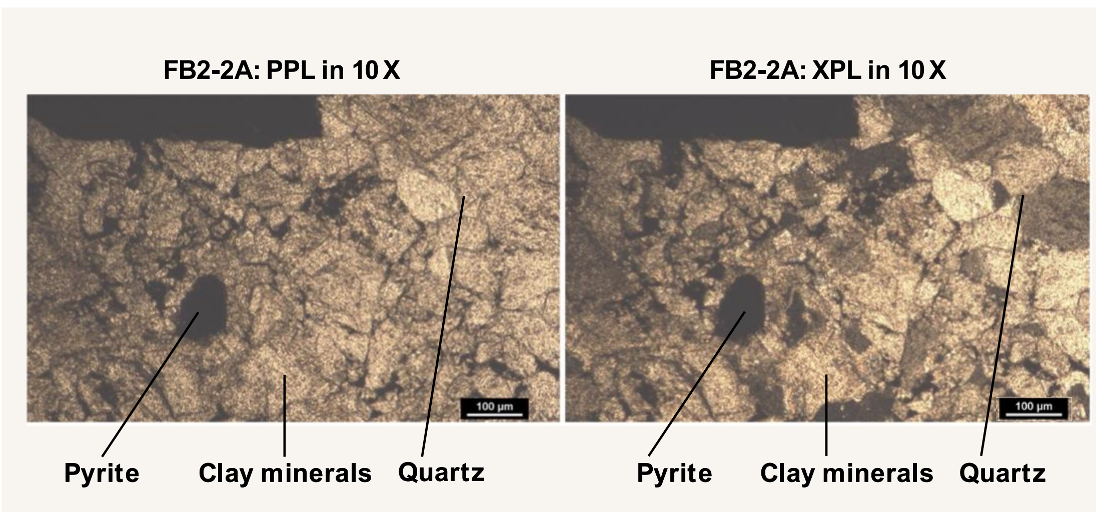

Image 10. Thin sections of fault rock 2 with slide 2A shown in plane-polarized light (PPL) and in cross-polarized light (XPL).

Observations in Image 10 are consistent with the other FB2 thin sections. The main minerals include the pyrite, calcite and quartz. This texture is highly fragmented with no grain alignment or foliation. No lamprophyre dyke fragments are present.

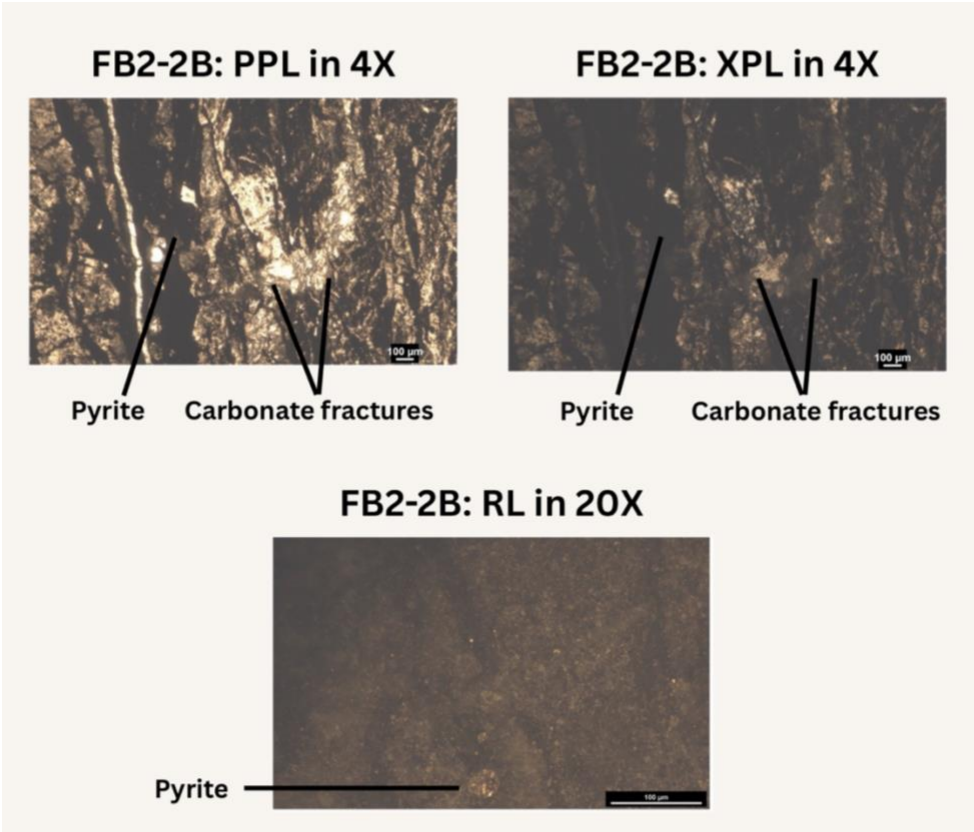

Image 11. Thin sections of fault rock 2 with slide 2B shown in plane-polarized light (PPL), cross-polarized light, and reflected light (RL).

Image 11 confirms the presence of the linear features indicating the carbonate fracture fillings. The plane-polarized light shows the light-colored carbonates, and the reflected light shows the gold luster pyrite grains. The FB2 thin sections all have very low transparency due to the pyrite mineralization, lack major foliation and cataclasis zones and lack both lamprophyre classifications of camptonites with alkaline composition and kersantite with calc-alkaline composition (Keefe, 2024).

Fault Rock 2 Identification

This sample has a non-foliated texture and can be classified as a breccia based on its larger than 2 mm size variations of angular fragments and coarser-grained matrix. This rock is specifically a type of fault breccia, or tectonic breccia. According to the study from Woodcock & Mort (2008), fault breccia can be subdivided into either a crackle breccia, mosaic breccia or chaotic breccia based on degree of separation and rotation. This sample is considered a mosaic fault breccia due to the clasts having moderate rotations and spacings.

Discussion

INTRODUCTION

This section will discuss the findings from the petrographic analysis to help gain an understanding regarding the fault rock deformation, kinematics and intrusion history of FB1 and FB2 samples from the north-east shore of Cull Island, NDB of Newfoundland. Key findings of this research include the absence of major foliation and lineation, and absence of lamprophyre dyke fragments in both samples. These findings can be integrated within existing research of the study area for consistency and to address the significance within the broader context of rifting and tectonic orogenic events in Newfoundland. This section also provides future research and limitations of this work.

FAULT ROCK CHARACTERISTICS

From examining the samples, both the protocataclasite, fault rock 1 (FB1), and mosaic fault breccia, fault rock 2 (FB2), have no foliation and little to no alignment of mineral grains, however, instead the minerals are fragmented. According to Sibson's fault rock classification criteria from Fossen (2016), fragmentation of mineral grains is a common characteristic of non-foliated rocks. This suggests that the rocks are not subjected to high ductile deformation, which would typically result in foliation or lineation (Mommio, 2020).

In line with this observation, these non-foliated fault rocks can be classified as either cohesive or incohesive based on their behavior. Incohesive rocks are active at shallow crustal levels and can occur in fault zones with variable thickness, this includes fault breccia that would form in the upper part of brittle crust and act as a channel for fluid flow. In contrast, cohesive rocks, such as cataclasites, have more internal pressure and commonly show evidence for abundant pressure (Mommio, 2020). Given these characteristics, FB1 is a non-foliated, cohesive, protocataclasite and FB2 as a non-foliated, incohesive, fault breccia.

FAULT ROCK DEFORMATION AND KINEMATICS

Fault Rock 1 Processes

The observations of angular fragments and absence of foliation collectively suggests that FB1 and FB2 deformed mainly under brittle faulting conditions (Fossen, 2016). This supports the interpretation that the deformation occurred under lower temperature and pressure conditions, which are typical of upper crustal fault zones.

FB1 specifically exhibited cataclasis and reduced grain sizes, which suggests minimal ductile shearing and reinforces the brittle faulting nature and process along fault zones. However, FB1 also exhibits undulose extinction from quartz grains, has quartz veins and veinlets, and has albite twinning from plagioclase feldspar, which are all ductile characteristics. This suggests association with different geological phases in the Brittle-Ductile transition zone, which is a zone typical for cataclastic rock formation, approximately at 4 to 10 km depths (Mommio, 2020). It is most likely that the undulose extinction and albite twinning features occurred prior to the brittle fracturing of the cataclasis due to the higher temperature and pressures needed, or they were inherited from the protolith. The quartz veins likely formed after the cataclastic brittle deformation event using the fracture spaces for hydrothermal fluids. The vein formation of small veins and larger continuous veins suggests multiple stages of fluid movement post-deformation.

These results are consistent with other studies conducted on fault rocks from shear zones. For example, the Chetty (2023) study examined a cataclastic shear zone from the East Dharwar Craton, which was characterized by breccias and cataclasites that suggested brittle to ductile transitional deformation from the intense fracturing and quartz vein formations.

Fault Rock 2 Processes

FB2 was characterized by its large 2 mm angular fractured fragments, and varied grain rotations, which are significant signatures of brittle deformation and grinding activity at shallow crustal levels in fault zones, approximately at 1 to 4 km depths (Mommio, 2020; Kneuker et al., 2020). However, this fault breccia lacks cataclasis, likely indicating limited shearing during deformation, as evidenced by the coarser grained matrix of quartz and carbonates. FB2 also contains carbonate fractures and pyrite mineralization which highly suggests later stage fault activity where the rock experienced fluid infiltration.

LAMPROPHYRE DYKE POST FAULT INTRUSION

The absence of lamprophyre dyke fragments in both the fault rock samples can provide insight into the timing of faulting and lamprophyre dyke intrusions. Previous interpretations by Wanless (1965) proposed that the lamprophyres represent the youngest structures in the area, supported by K-Ar dating of biotite aging that suggested linkage to the Cretaceous to Jurassic Period from 145 Mya. This finding is consistent with this study, as the lamprophyre absence in thin section implies that the fault rocks predate the intrusion, suggesting that faulting occurred first within the existing zones of weakness. This is also consistent with the fault rock evidence of fragmentation, as they already experienced brittle deformation processes.

In addition, the possibility of fault reactivation is supported by dyke terminations along fault planes observed in the Keefe (2024) study. Previous research has shown that fluid infiltration in fault zones can increase pore pressure and reduce stress on a fault plane, promoting fault movement and reactivation (Leclere et al., 2012). This aligns with the evidence of late-stage fluid infiltration seen in both fault rock samples, which could be connected to reactivation events. However, without kinematic indicators and precise geochronological data of fault rocks, this continues to remain uncertain.

BROADER IMPLICATIONS

Unfortunately, neither of the rock samples exhibited any significant kinematic indicators to reveal or determine the fault direction and movement, however, based on their deformation characteristics and geographic proximity, the rocks could likely be related to the LAFZ that runs along the Leading Tickles study area. This inference is consistent with the Keefe (2024) study which noted potential association to the LAFZ.

In addition, the fault rocks, particularly FB1, is characterized by many quartz veins and veinlets which were reflected in the original host rock structures. Previous research from Keefe (2024) indicates that these host rocks were deformed during the Ordovician-Silurian closure of the Iapetus Ocean, suggesting that initial faulting likely occurred around this period, unless reactivated. This interpretation aligns with the structural history of the LAFZ Late Silurian thrust fault that was likely active during deformation D1 and D2 Taconic events within the NDB region due to thrusting styles. This again infers potential fault rock connection to the LAFZ and the nearby Exploit Subzone stratigraphic units which experienced displacement and partial brecciation during the earlier deformation events. This connection remains a plausible but unconfirmed interpretation. It is proposed here based on fault rock thin section results, proximity, deformation styles and alignment with the tectonic history of the area.

The results of this study also align with the lithospheric stretching and reactivation of fault systems along Newfoundland's margin during the North Atlantic Ocean opening. The interaction between the fault rocks and post-intruding dykes reflects the structural inheritance that controlled magmatism and the deformation processes during margin evolution.

LIMITATIONS AND FUTURE RECCOMENDATIONS

While this analysis contributes valuable insight into the structural history of the NDB study area, the examined fault rock samples are not fully representative of all faulting events or fault types present within the region due to the complexity. Additionally, interpretations may vary depending on the scale of observation, which can influence the understanding of fault zone heterogeneity.

This research aimed to shed light on the fault rock deformation, fluid flow, lamprophyre dyke intrusion, and broader tectonic processes, however, it is impossible to know the exact order of events and full geological history from petrographic analysis alone. Future recommendations for this study include examining other fault rock samples, using a variety of reference scales, detailed fault rock field mapping, fluid inclusion analysis, or using advanced analytical techniques including scanning electron microscopy (SEM) and electron microprobes.

Conclusion

This thesis investigated the petrographic characteristics of two fault rock samples, a Protocataclasite and mosaic fault breccia collected from the northeast shore of Cull Island near Leading Tickles town, Notre Dame Bay, Newfoundland. Through thin section analysis, it was determined that both fault rocks lack foliation and lamprophyre dyke fragments suggesting mainly brittle deformation processes and post fault intrusion. The evidence of fluid infiltration and mineralization suggests possible fault reactivation events. These findings contribute to broader interpretations of faulting and tectonic inheritance in Newfoundland in relation to the opening of the North Atlantic Ocean. Further research is needed and should integrate other techniques to further enhance the understanding of fault evolution along Newfoundland's margin.

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Appendix

FIGURES

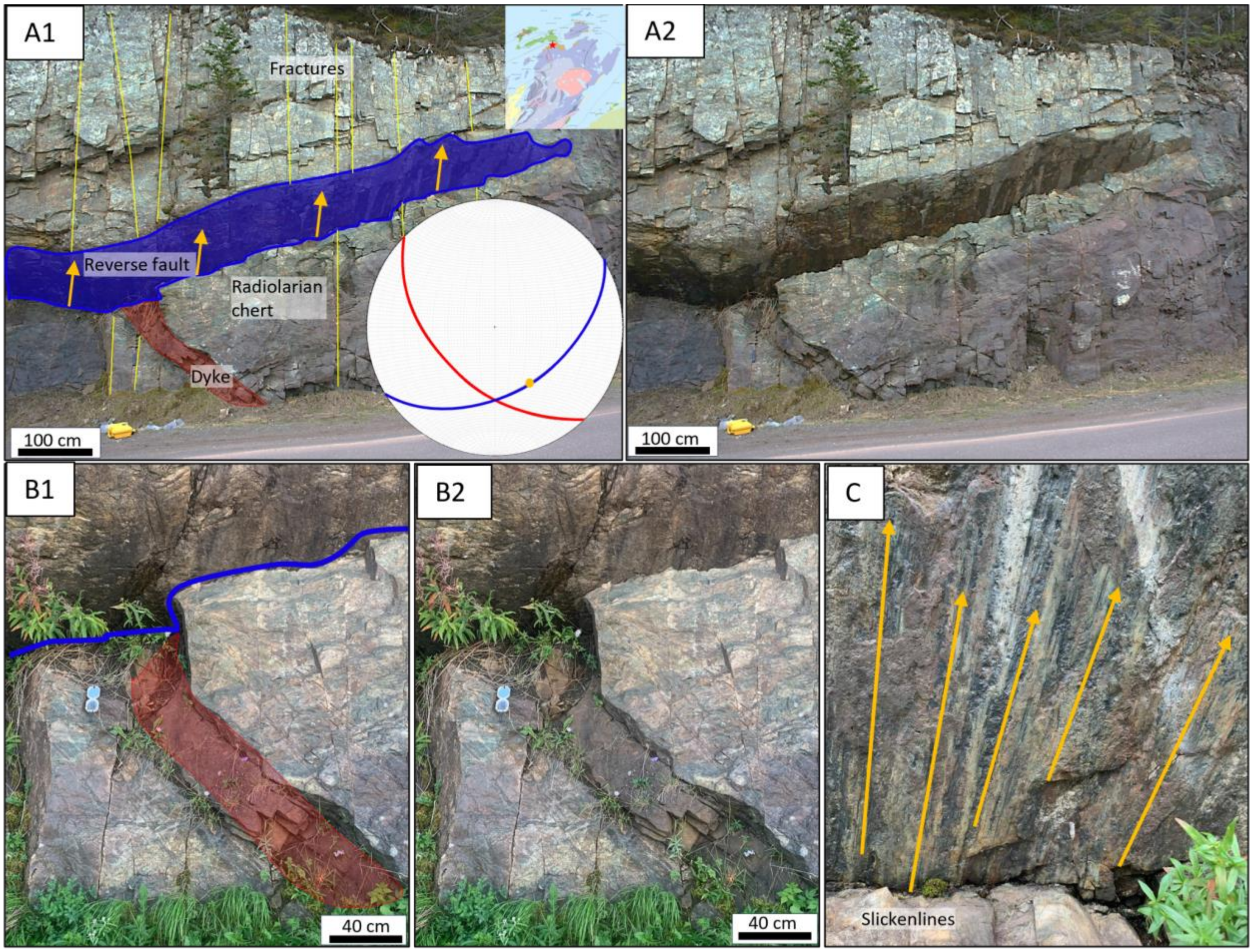

Figure 1. Interpreted (A1, B1) and uninterpreted (A2, B2) photos of a dyke terminating at a fault plane with slicken lines. Data are from "Influence of pre-existing structures on emplacement and deformation of Late Jurassic rift-related magmatism, Newfoundland, Canada," by E. Keefe, 2024, *McMaster University*. Copyright 2024 by Emma Keefe.

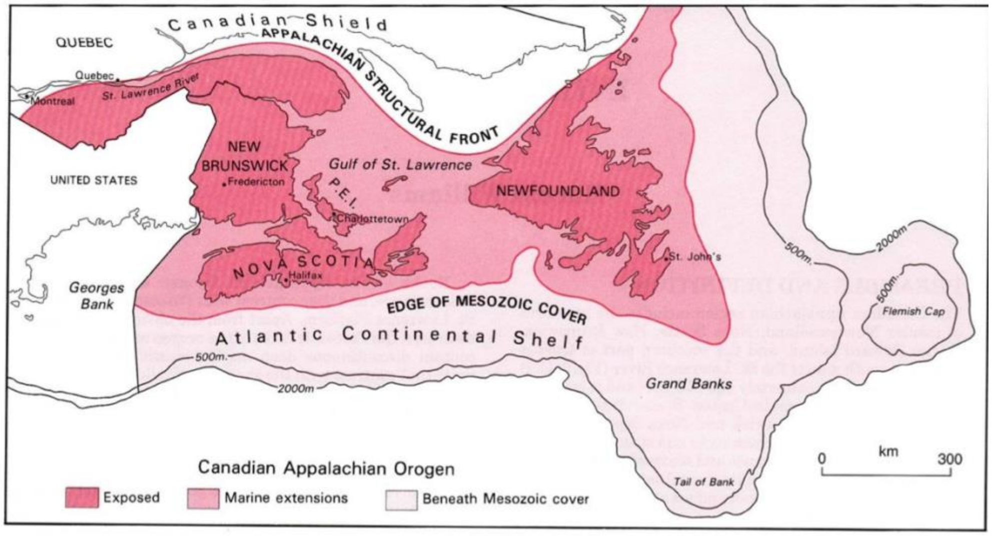

Figure 2. Geological map of the Canadian Appalachian regions. Data are from "Geology of the Appalachian-Caledonian Orogen in Canada and Greenland," by H. Williams, 1995, *Geology Society of America,* 6. Copyright 1995 by GeoScienceWorld.

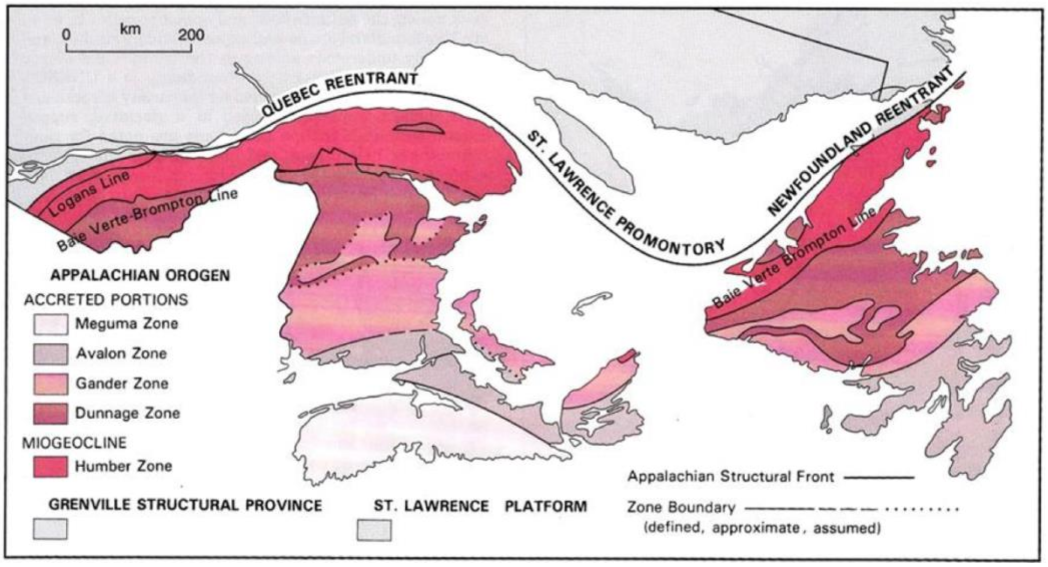

Figure 3. Geological map of the following Canadian Appalachian zones: Meguma, Avalon, Gander, Dunnage and Humber. Data are from "Geology of the Appalachian-Caledonian Orogen in Canada and Greenland," by H. Williams, 1995, *Geology Society of America,* 6. Copyright 1995 by GeoScienceWorld.

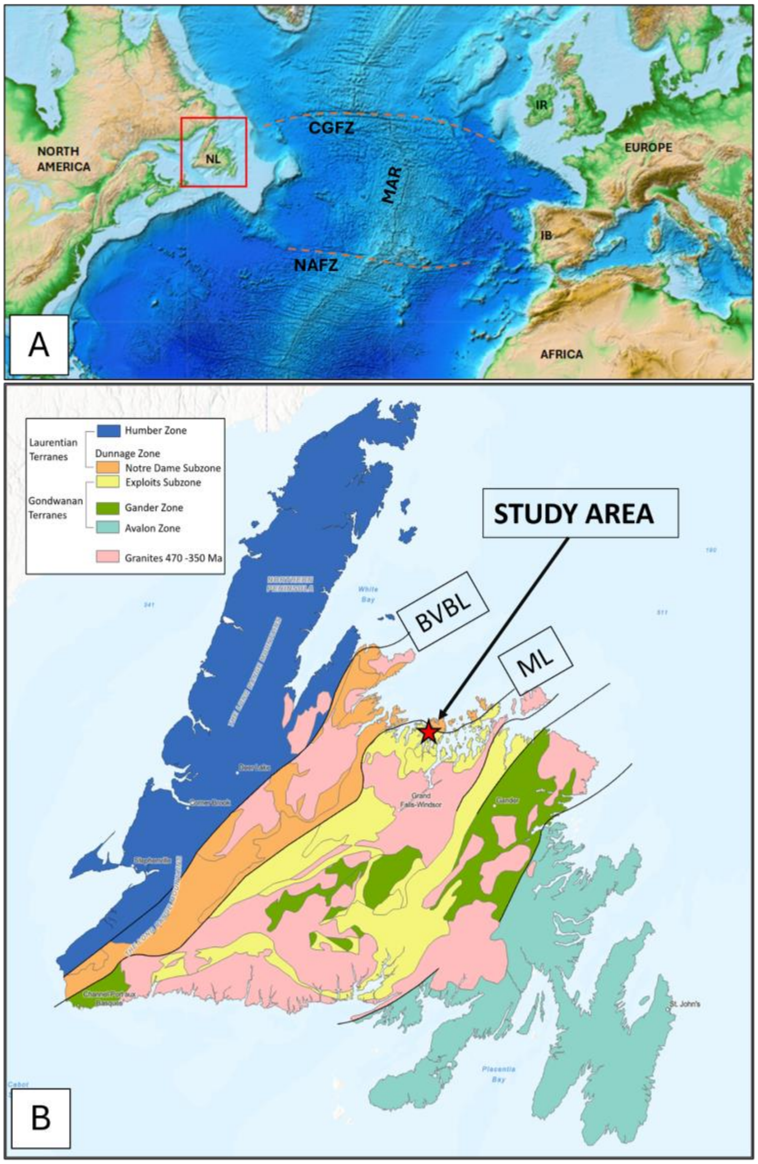

Figure 4. A) Topographic and bathymetric map of the North Atlantic region created from Global Topography Data. B) Simplified map of onshore Newfoundland geology. Data are from "Influence of pre-existing structures on emplacement and deformation of Late Jurassic rift-related magmatism, Newfoundland, Canada," by E. Keefe, 2024, *McMaster University*. Copyright 2024 by Emma Keefe.

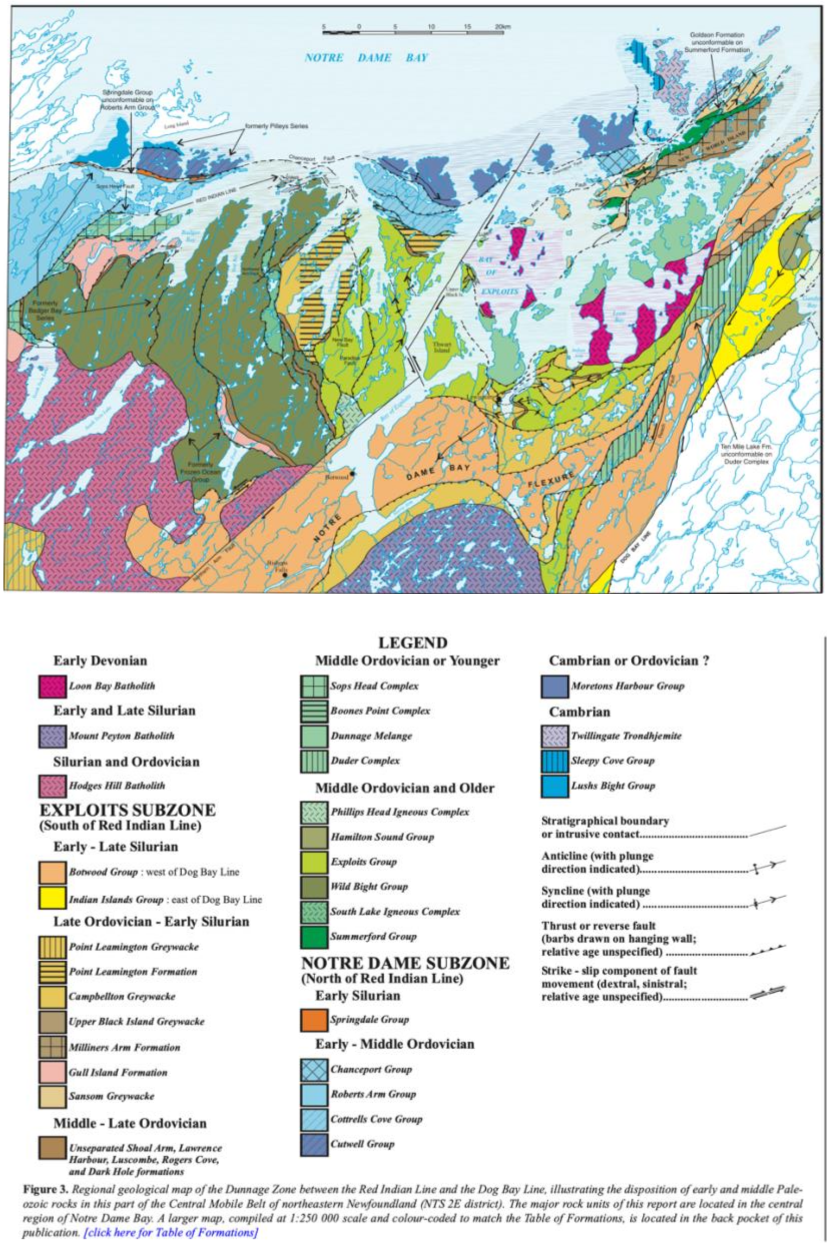

Figure 5. Regional geological map of the Dunnage Zone between the Red Indian Line and the Dog Bay Line. Legend includes the subzones: Exploits Subzone and Notre Dame Subzone. Data are from "Geology of the Central Notre Dame Bay Region (Parts of NTS Areas 2E/3,6,11), Northeastern Newfoundland," by B.H. O'Brien, 2003, *Geological Survey*. Copyright 2003 by Geological Survey.

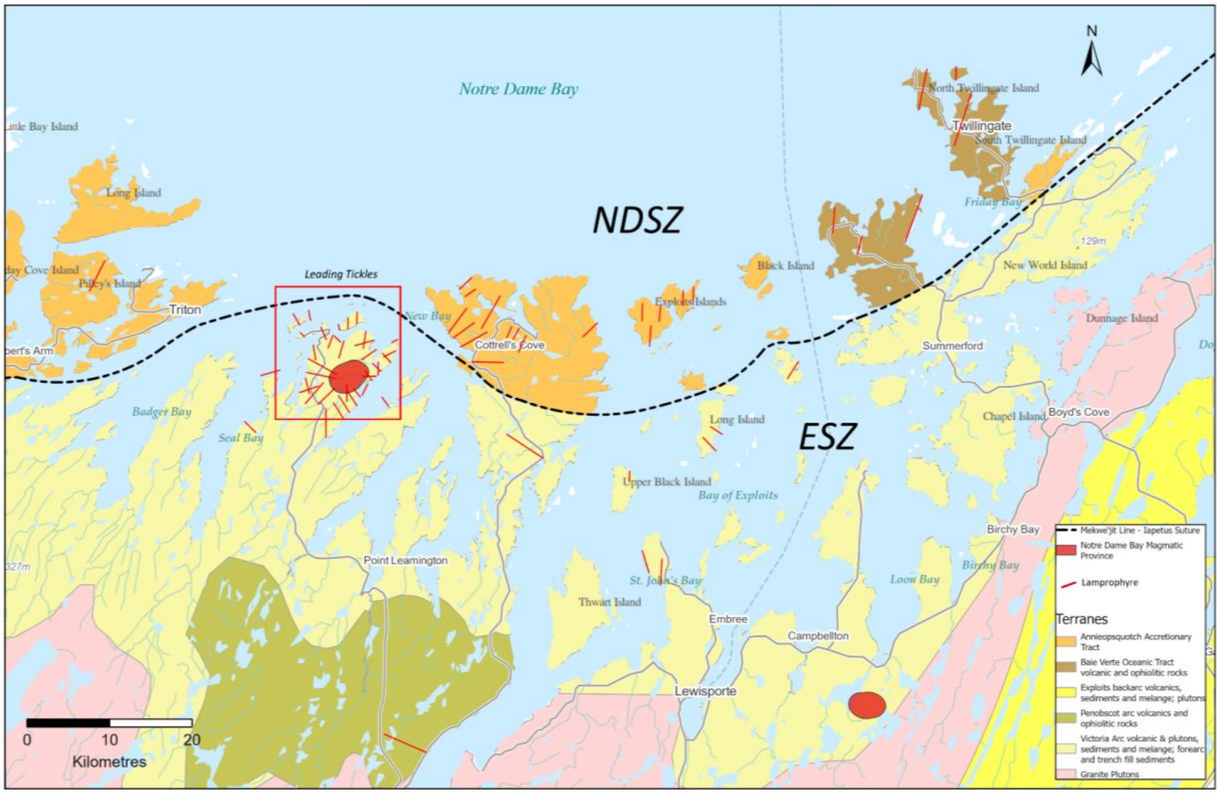

Figure 6. Geological map of the Notre Dame and Exploit subzones within the Dunnage zone. Data are from "Influence of pre-existing structures on emplacement and deformation of Late Jurassic rift-related magmatism, Newfoundland, Canada," by E. Keefe, 2024, *McMaster University*. Copyright 2024 by Emma Keefe.

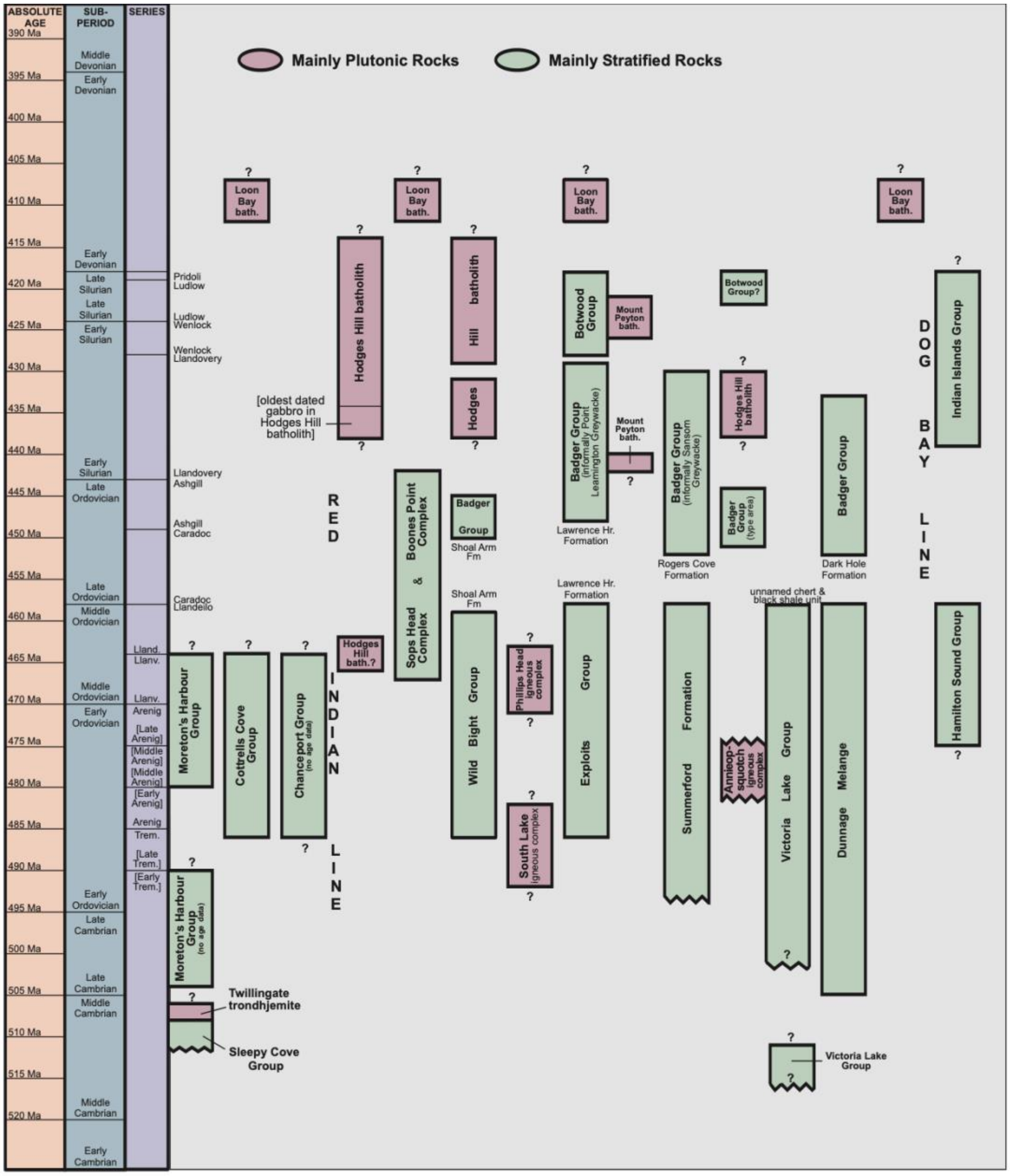

Figure 7. Periods and ages of the stratigraphic units within the Exploits subzone. Study area units include the Wild Bight Group, Shoal Arm Formation, and Badger Group. Data are from "Geology of the Central Notre Dame Bay Region (Parts of NTS Areas 2E/3,6,11), Northeastern Newfoundland," by B.H. O'Brien, 2003, *Geological Survey*. Copyright 2003 by Geological Survey.

Figure 8. Google earth images of the fault rock sample coordinates on Cull Island, Notre Dame Bay, Newfoundland. Data are from Google Earth Pro using imagery data from 07/29/2024. Copyright 2024 by Google Earth.