Natural Resources

Mines Branch

BATTLE ISLAND - A GEOLOGICAL TREASURE IN COASTAL EASTERN LABRADOR

Charles F. Gower

Open File 003D/05/0031

St. John's, Newfoundland
July, 2009

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Cover: Aerial view of Battle Island, looking northeast.

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ABSTRACT

Battle Island is a popular tourist destination in southeast Labrador, mainly because of its cultural heritage, as represented by the once-abandoned fishing settlement of Battle Harbour (now restored by the Battle Harbour Historic Trust). It is not only its cultural heritage that has significance, however: amongst its many natural attributes, Battle Island displays some superb geological features.

Most of the island is underlain by a sequence of metamorphosed supracrustal rocks derived from arenaceous and calcareous protoliths, deposited between 1500 and 1030 Ma. The supracrustal sequence of rocks, from northeast to southwest across the island, consists of i) crossbedded psammite, ii) calc-silicate and semi-pelitic schist, iii) psammite, iv) calc-silicate rocks and minor marble, and v) calcareous psammite. This sequence probably represents the original stratigraphic depositional order. The calc-silicate and semi-pelitic schist unit contains a wide, concordant amphibolite that, in detail, comprises two subunits. The amphibolite is interpreted as representing two now-metamorphosed mafic sills that both followed the same intrusive conduit. All of these rocks were subject to severe deformation, are now steeply dipping and, probably, stratigraphically overturned. Accompanying metamorphism (dated to be 1030 Ma in the amphibolite) reached amphibolite facies, later declining to greenschist conditions.

These rocks were synchronously or subsequently intruded by large volumes of pegmatite that exhibit a wide range of boudinage and buckling features. Judging from their varied deformational states, they were emplaced over an extended period, during transition from ductile to brittle conditions. An amazonite-bearing pegmatite has yielded a Grenvillian age of 1024 ± 6 Ma.

Final events include the development of north-northeast-trending hematized brittle fractures and faults, interpreted to be related to rifting that led to the formation of the Iapetus Ocean (615–540 Ma). The youngest bedrock feature on the island is an east-northeast-trending undeformed and unmetamorphosed dyke, the age of which is only constrained to postdating brittle faulting.

INTRODUCTION

The settlement of Battle Harbour, situated on Battle Island in eastern Labrador (Figure 1), was established in the 1770s as a fishing station. Throughout the 19th century, it was the site of a thriving saltfish, salmon, and seal-processing complex, and was the economic and social centre of southern Labrador. The once-abandoned settlement has recently been given a new lease on life as a result of a 7-year restoration project undertaken by the Battle Harbour Historic Trust, and is now a major tourist destination in southern Labrador (Cover, Plate 1). Access to the settlement is gained during the summer months by a 45-minute ferry trip from Mary's Harbour, which, itself, can be reached via Highway 510 (Figure 2). The settlement is uninhabited during the winter.

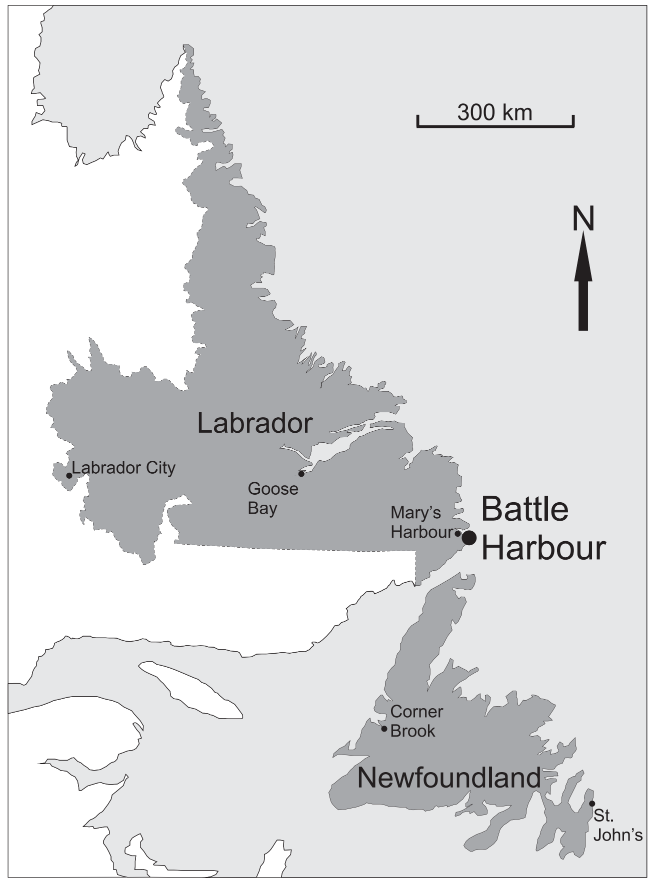


Figure 1. *The location of Battle Harbour in Labrador.*

The settlement of Battle Harbour takes advantage of a narrow sheltered channel (a tickle) between Battle Island and neighbouring Great Caribou Island to the west, utilizing the channel as an excellent natural harbour. In addition to Battle and Great Caribou islands, there are a number of smaller islands in the surrounding area and several offshore reefs, especially to the northeast.

The island is elongate in the northwest–southeast direction and can be divided topographically into two parts (Cover). The northeastern part is higher, more rugged and has more rock exposure, in contrast to the lower southwestern third, which is largely covered by vegetation. The two parts are separated by a west-facing cliff which terminates at either end of the island to form the precipitous northeastern walls of small gulches. The settlement of Battle Harbour is located entirely on the sheltered lower southwestern part. The contrast in elevation and vegetation cover is easily explicable in terms of the underlying bedrock (see detailed descriptions that follow).

Plate 1. *Part of the settlement of Battle Harbour; looking southwest to Great Caribou Island.*

Battle Island has remarkable geological diversity for its small size (1 km long by 0.5 km wide). It includes rocks of arenaceous and calcareous supracrustal parentage, now metamorphosed to

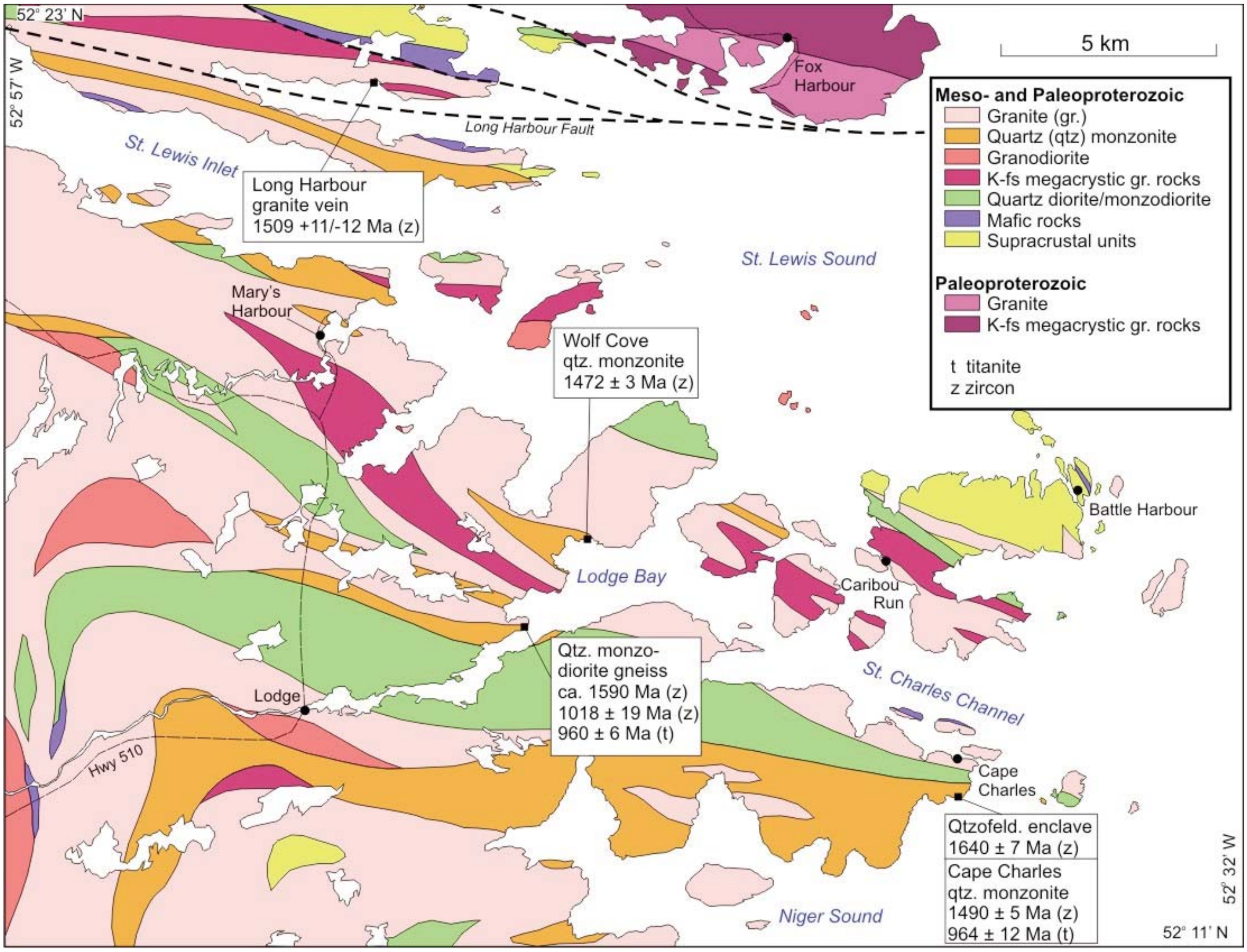


Figure 2. *Regional geological setting for Battle Harbour.*

amphibolite facies, but still preserving some original sedimentary features. It has metamorphosed mafic igneous rocks (amphibolite) that originally formed as two basaltic sills. Battle Island also hosts an impressive display of pegmatites that, sporadically, contain atypical minerals, but, ubiquitously, display a spectacular range of deformational states. The youngest rock is an unmetamorphosed basaltic dyke, the exact age of which is unknown. All geological features on the island are superbly exposed and easily accessible.

PREVIOUS INVESTIGATIONS

The earliest geological description of Battle Island is that of Kranck (1939), who, in general, recognized most of the units described herein. He recorded quartz-rich gneiss on the higher, northeastern side of the island, noting that primary bedding, including crossbedding, was preserved. He also mentioned the amphibolite that transects the central part of the island and described lime-rich gneiss (containing quartz, calcite, actinolite, epidote, and brown mica), interbedded with impure limestone and quartzitic layers on the lower, southwestern side of the island. He noted numerous pegmatite dykes and irregular intrusions, and recorded evidence of strong deformation and a well-developed schistosity.

The area was visited during 1:100 000-scale reconnaissance geological mapping of the St. Lewis River region (Gower *et al.,* 1988a, b). In the report of Gower *et al.,* (1988a), the metamorphosed supracrustal rocks are described in more detail and photographs of the crossbedded quartz-rich rocks and calc-silicate units are included. A previously undocumented, undeformed and unmetamorphosed mafic dyke, situated at the southern end of Battle Island, was also recorded. Reference to the surrounding region, but not specifically Battle Island, is included in the geochronological reports of Tucker and Gower (1994) and Wasteneys *et al.* (1997). A field guide for part of southeast Labrador prepared by Gower *et al.* (1996) includes Battle Harbour as one of the excursion stops.

The most recent previous work is that carried out in 1999 under the leadership of Carr, accompanied by Coleman, Czajkowski and Peressini (Czajkowski *et al.,* 2000; Peressini, 2000). Collectively, they carried out detailed mapping of Battle Island, parts of Great Caribou Island, and some of the small islets in the vicinity of Battle Island. Peressini (2000) provides a geological map of Battle Island, gives descriptions of the metasedimentary units, includes structural information, describes one of the pegmatites in detail (termed the Battle Harbour pegmatite), and reports preliminary U/Pb data for it. Details of the Grenvillian age obtained from the pegmatite are given subsequently. The report of Czajkowski *et al.* (2000) focuses on the structural history of Battle Harbour and adjoining Great Caribou Island, identifying three deformational events, the first two of which are considered to have occurred during Grenvillian deformation.

PRESENT INVESTIGATION

The present investigation was carried out at the invitation of the Battle Harbour Historic Trust as part of its Expert-in-Residence program, which involved the author spending a week at Battle Harbour (August 11–19, 2007), and a return visit in 2008. In addition to acting as a resource person for visitors to Battle Harbour, time was spent carrying out a detailed geological remapping of Battle Island and collecting samples for petrographic, whole-rock geochemical, and geochronological follow-up studies. It should be noted that although Battle Island was entirely remapped during the present investigation the map does not differ substantially from that of Carr and colleagues.

Petrographic descriptions of units and representative whole-rock geochemical analyses are included in this report and preliminary geochronological results are mentioned (complete geochronological data will be reported elsewhere when finalized). Although this is intended to be a scientific document, to make it more accessible to the lay reader it has been augmented by:

i) Boxed explanations of some geological features that are well displayed on the Island.
ii) A glossary of technical terms; and
iii) A list of minerals that are mentioned in the text, and their chemical formulae.

A non-technical brochure/walking guide created specifically for visitors to Battle Harbour has also been prepared and is included as part of this report as Appendix 4.

REGIONAL SETTING

Battle Island is situated in the Pinware terrane (Gower *et al.,* 1988a), which is the most southerly of those recognized within the eastern Grenville Province. The northern boundary of the Pinware terrane passes just south of Fox Harbour (Figure 2). Gower (2005) interpreted the boundary to be a fault (Long Harbour fault) and to define the southern flank of a zone of oblique dextral and north-side-up movement forming a major shear belt extending 200 km to the northwest.

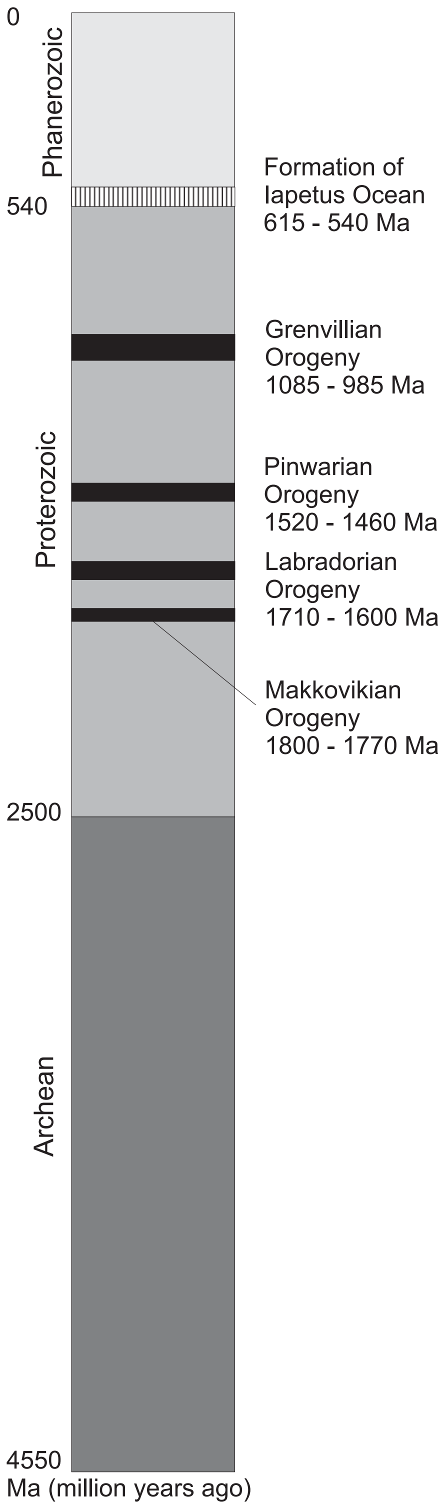
In the Pinware terrane, rocks interpreted to be of supracrustal origin are considered to be among the oldest present. They include quartzite, calc-silicate rocks, pelitic schist, inhomogeneous-textured quartzofeldspathic rocks thought to have been derived from felsic volcaniclastic rocks, and a minor component of mafic rocks probably derived from an extrusive basaltic protolith. These rocks are mostly situated in the Henley Harbour–Red Bay area, well south of Battle Harbour, but minor remnants are found throughout the Pinware terrane. Labradorian (1710–1600 Ma; *cf.* Box 1 for context) ages of 1640 ± 7 Ma and 1637 ± 8 Ma have been obtained from rocks of probable volcaniclastic origin (Tucker and Gower, 1994; Wasteneys *et al.,* 1997, respectively). The 1640 ± 7 Ma age was obtained from an enclave within the Cape Charles quartz monzonite emplaced at 1490 Ma (see later in this section). (For non-technical readers 'Ma' can be read as meaning 'million years ago')

The supracrustal remnants are contained within, and structurally concordant with, quartzofeldspathic gneisses and foliated to gneissic granitoid rocks. The gneisses and granitoid rocks are Labradorian or Pinwarian age, but reliable discrimination between the two age groups has yet to be achieved. Ages of 1650 +18/-9 Ma and 1649 ± 7 Ma were reported by Wasteneys *et al*. (1997) from Labradorian gneiss, and an age of 1632 ± 8 Ma was obtained from a K-feldspar megacrystic granitoid rock by Heaman *et al.* (2004). A quartz monzonite gneiss from Lodge Bay yielded equivocal data that suggested a Labradorian protolith (Wasteneys *et al.,*1997).

In the district surrounding Battle Harbour, three Pinwarian (1520–1460 Ma) ages have been obtained (Figure 2). Quartz monzonites from Cape Charles and Wolf Cove have ages of 1490 ± 5 Ma and 1472 ± 3 Ma, respectively (Tucker and Gower, 1994), and a granite vein at Long Harbour gave an age of 1509 +11/-12 Ma (Scott *et al.,* 1993). Numerous Pinwarian ages have been reported from foliated granitoid rocks in the Pinware terrane beyond the confines of Figure 2 (Tucker and Gower, 1994; Wasteneys *et al.,* 1997; Heaman *et al.,* 2004). The quartz monzonite gneiss from Lodge Bay contains evidence of a Pinwarian metamorphic imprint. Neither Labradorian nor Pinwarian plutonic rocks occur on Battle Island.

Granitoid plutons ranging in age from 1043 to 951 Ma, emplaced during and immediately following Grenvillian orogenesis (1085–985 Ma), have been mapped and dated from various areas within the Pinware terrane (Tucker and Gower, 1994; Wasteneys *et al.,* 1997; Heaman *et al.,* 2004; Gower *et al.,* 2008), but are not known in the district surrounding Battle Harbour, where most Grenvillian effects are metamorphic. Minor granitoid intrusive activity accompanied the metamorphism and was widespread, including on Battle Island, much of which is made up of pegmatite emplaced during Grenvillian orogenesis.

Post-Grenvillian activity in the Pinware terrane (but largely beyond the Battle Harbour district) is represented by minor occurrences of pebbly sandstone (Bateau Formation) and basaltic flows (Lighthouse



Geological time and eastern Labrador

The Earth is believed to be about 4550 million years old.

Geologists have traditionally recognized three main divisions of geological time, namely **Archean**, **Proterozoic** and **Phanerozoic**.

Almost all the rocks in southeastern Labrador are Proterozoic. They formed during relatively short (geologically speaking), but very active, mountain-building periods of time that are termed **orogenies**.

The oldest recognized rocks were formed between 1800 and 1770 million years ago. These are more common farther north, in the Makkovik region, hence the name **Makkovikian Orogeny**.

The next period of activity, for which evidence is found across southern Labrador, occurred between 1710 and 1600 million years ago, and is now well known to geologists by the name **Labradorian Orogeny**.

After another (relatively short) break in geological upheavals, the region was again in turmoil, between 1520 and 1460 million years ago, during the **Pinwarian Orogeny**, which takes its name from southeasternmost Labrador.

The final major and most cataclysmic event occurred between 1085 and 985 million years ago, and is termed the **Grenvillian Orogeny**. This event is recognized throughout the southern part of the Canadian Shield and time-equivalent orogenic events are known throughout the world during one of the biggest re-organizing of crustal plates the Earth has ever known.

The last major event in the region was a period of crustal break-up between 615 and 540 million years ago that lead to the formation of an ancient, and now vanished, sea, which geologists have named the **Iapetus Ocean**.

Still younger events, minor and of uncertain specific age, have been recognized in eastern Labrador.

Box 1. *Geological time and eastern Labrador*

Cove Formation). Quartz- or hematite-filled north-northeast-trending fractures, related to normal and strike-slip faults are also post-Grenvillian. All of these features are related to rifting preceding the opening of the Iapetus Ocean between 615 and 540 Ma.

An east-northeast-trending Phanerozoic dyke of unknown more specific age, part of which is present on Battle Island, is the youngest rock type in the district.

Proterozoic Supracrustal Rocks

The following sections give detailed descriptions, including petrographic information, of all the units recognized on Battle Island. A geological map is shown as Figure 3. Supracrustal units are described from east to west across the island.

Crossbedded psammite (Unit 1)

The easternmost unit (Plate 2) has a light grey, sugary texture where it is weathered, and where its brownish crust has been removed by erosion. It is a relatively homogeneous, fine- to medium-grained grey-brown psammite, about 100 m thick at its widest part, but of unknown total width, as its eastern boundary is not exposed. The rock is maroon where hematized. Three features are characteristic of this unit.

Plate 2. *General view of crossbedded psammite intruded by concordant and discordant pegmatite dykes.*

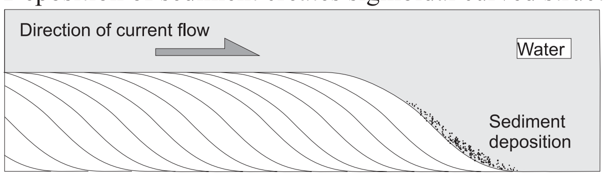
The first feature is the presence of bedding in the form of parallel and crossbedding lamination (Plate 3; *cf.* Box 2). The laminae are enriched in biotite and opaque minerals. The crossbedding laminations, which were first described by Kranck (1939), are confined to particular layers, which are commonly about 30 cm thick. Tops are generally to the west, but, as tight folds were seen, some tops to the east may also be present. This is the only locality in the Grenville Province in eastern Labrador where sedimentary structure in pre-Grenvillian rocks is unequivocally preserved. A thin section (Sample CG07-130A) that includes two heavy mineral laminations consists mostly of recrystallized quartz, lesser plagioclase and interstitial well-twinned microcline associated with aligned flakes of buff-green biotite. Plagioclase is light to moderately sericitized. The heavy mineral layers consist mostly of an opaque oxide (*cf.* ilmenomagnetite), but rounded zir-

Plate 3. *Crossbedding in psammite.*

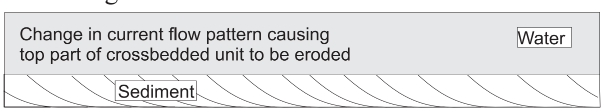
Crossbedding

In some rocks, especially sandstones, it is common to see certain bedding layers oblique to the general 'lie' of the geological formation as a whole. This structure, formed during sediment deposition, is called crossbedding, and can be the result of either water or wind action. It is created when there is a decrease in water or wind velocity, thus allowing the sediment to drop and be deposited. Crossbeds related to water currents tend to be small because their development is influenced by complex, changing current-flow patterns, whereas wind-related crossbeds are typically large because air flow is commonly constant for long periods.

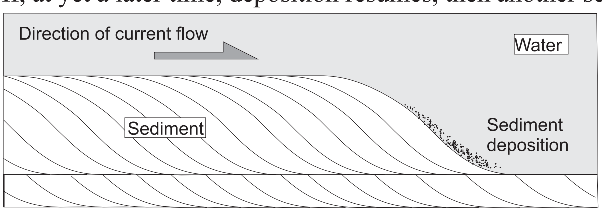
Deposition of sediment creates sigmoidal curved structures as shown in the diagram below.



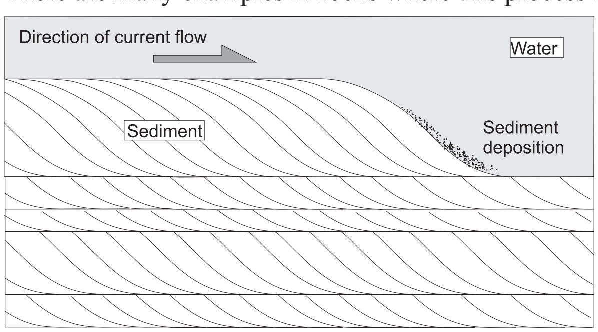
At some later stage, the pattern of water or wind flow might change and, instead of sediment being deposited, it could then be eroded. When this happens, part or all of the sigmoidal crossbedded structure will be destroyed. Changes in flow patterns occur frequently in deltas, for example, as some sediment channels get blocked and new routes to the sea are established.



If, at yet a later time, deposition resumes, then another set of crossbeds might be deposited on top.



There are many examples in rocks where this process has been repeated many times.



The structures are useful to geologists in two ways. First, by measuring the orientation of the crossbedding relative to the overall planar bedding (which requires the three-dimensional shape of the crossbeds to be known), the geologist can infer the direction of current flow at the time of deposition. Second, from the way one set of crossbeds is truncated by an overlying set, the original upper depositional surface can be determined. This is very valuable information in folded rocks, which may well have been rotated from horizontal to vertical, or even turned up-side-down.

Box 2. *The formation of crossbeds*

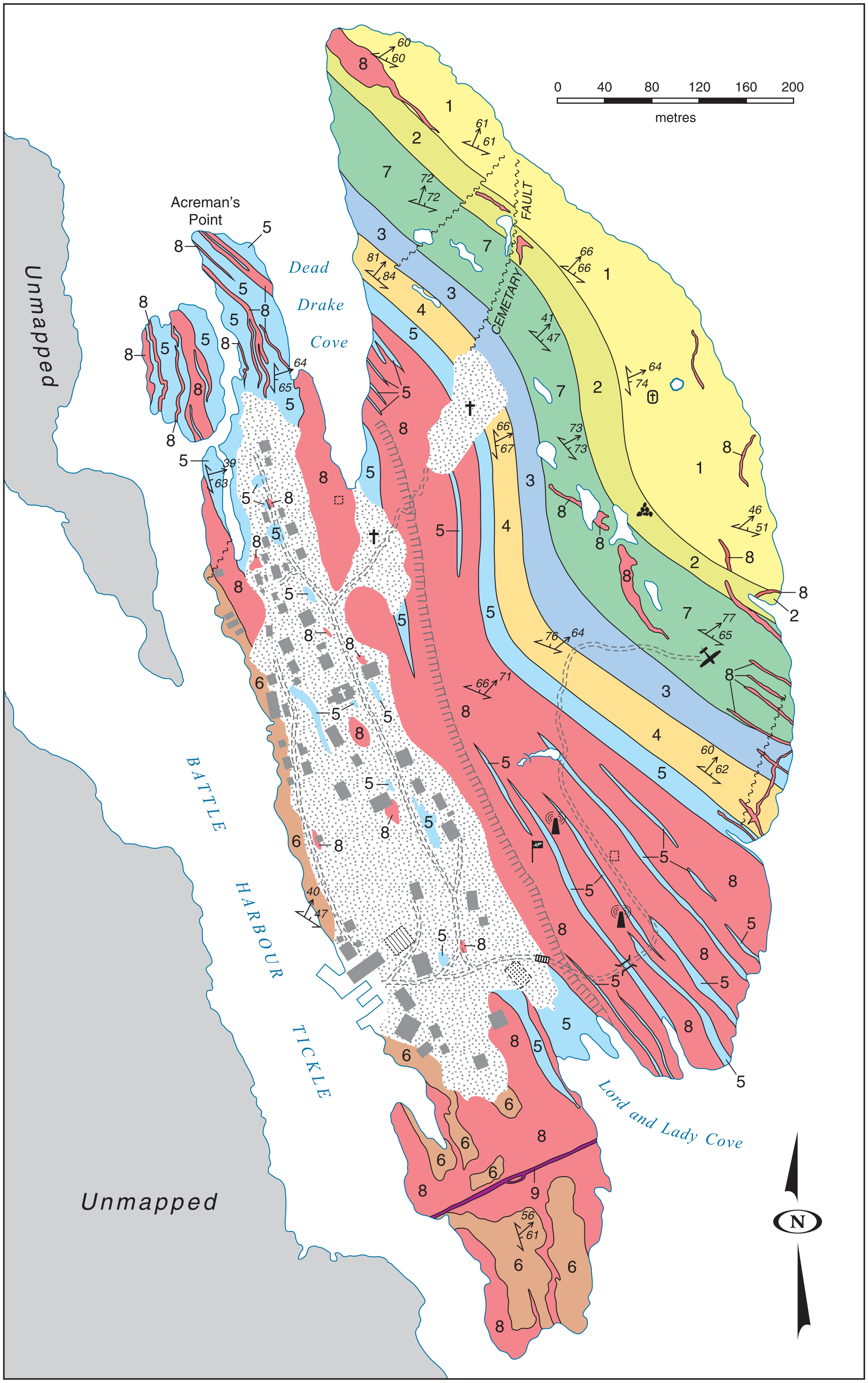


Figure 3. *Geological map of Battle Island.*

LEGEND

PHANEROZOIC

Surficial deposits

9 Diabase dyke: Brown-weathering, 2 m wide, fine grained

PROTEROZOIC

Intrusive rocks

8 Granitic pegmatite: Pink-weathering, coarse to very coarse grained. Biotite or hornblende are typical mafic minerals, but, except in a few veins, are not abundant. Rare examples of pegmatite containing amazonite, fluorite, garnet or muscovite exist. Deformational state varies from severely boudinaged or buckled, to undeformed and planar

7 Amphibolite: Two types are present, interpreted to represent two separate sills following a common conduit. They are separated by discontinuous tabular lenses of calc-silicate rock. The eastern amphibolite is light-grey weathering, medium grained and strongly lineated. The western amphibolite is dark-grey to black-weathering, medium grained and weakly to moderately foliated

Supracrustal rocks

6 Calcareous psammite: Pale-grey to brownish-weathering, fine to medium grained, thin to thick bedded. The psammite is interculated with calc-silicate layers

5 Calc-silicate rocks: Light to dark, green-grey-weathering, medium grained, thinly and continuously bedded; compositionally varied. Includes thin layers of psammite, semipelite, and rusty-weathering, sulphide-bearing pods

4 '20-m-wide' psammite: Grey, creamy or reddish-weathering, fine to medium grained, thin to thick bedded, but, overall, homogeneous in appearance

3 Schistose, micaceous calc-silicate rocks: Grey, greenish or black-weathering, fine to medium grained, very well bedded. Includes some psammitic layers. Alternation of rock types on centimetre to decimetre scale

2 Mixed psammite, calc-silicate schist, semipelitic schist, quartzite and calc-silicate hornfels: Grey, brown, green, creamy and white-weathering, medium to coarse grained, thin to thick bedded. Compositionally heterogeneous on centimetre to decimetre scale

1 Crossbedded psammite: Grey to brownish-weathering, fine to medium grained, thin to thick bedded and cross-bedded. Calcareous in part and characterized by amphibole porphyroblasts surrounded by mafic-mineral-depleted haloes

GEOLOGICAL SYMBOLS

Geological contact ....

Foliation and/or bedding with dip value 70

Lineation with plunge value 60

Brittle fault ....

OTHER FEATURES

Aircraft crash site

Flag pole

Radio mast

Garden

Dam

Cemetery

Bulldozer's (pet dog) grave site

Fish flake

Steps

Bridge

Pathways

Building

Building foundation

Church

Cairn

Rock cliff

con and apatite grains are common. Titanite is also common in these layers, partly mantling the opaque oxide. Minor epidote and chlorite are found throughout. A whole-rock chemical analysis of the thin-sectioned sample is given in Appendix 3 (note the 86.5 % SiO_2 content).

The second feature is a spotted appearance resulting from amphibole poikiloblasts up to about 1 cm across and surrounded by a haloes depleted in mafic minerals (Plate 4; Box 3). In places, where the poikiloblasts are close together, the leucocratic haloes merge to enclose two or more cores, and, commonly, they are concentrated into particular zones typically extending along original bedding planes. Outside of the amphibole poikiloblasts, the mineral assemblage is similar to that seen in the previously described sample. The hornblende poikiloblasts are dark green to blue-green and are thoroughly sieved with abundant quartz, plagioclase and microcline. It seems fairly clear that as the poikiloblasts grew they simply enveloped the felsic minerals. The area around the poikiloblasts is depleted in biotite, which was consumed at the expense of amphibole growth. Other mineral present are an opaque oxide, apatite, epidote, chlorite and minor zircon. The epidote and chlorite are secondary, or late-stage metamorphic. The zircons are small and show a spatial affinity with the hornblende porphyroblasts and may be a metamorphic product themselves (thin section CG07-130B).

Plate 4. *Hornblende porphyroblasts in eastern psammite. The light-coloured haloes around the porphyroblasts result from depletion of matrix biotite during porphyroblastesis.*

The third feature is the presence of a few yellowish-green layers, generally less than 1–2 centimetres in width. In thin section (CG07-130C), these are seen to be quartz-rich compared to the typical psammite described above, although still containing some plagioclase and microcline. The yellow-green colour is due to markedly pleochroic epidote. Other minerals include relict, dark-green to blue-green amphibole, an opaque oxide, titanite (associated with the opaque mineral and epidote), apatite, minor chlorite (after amphibole), and a few small grains of zircon.

Mixed psammite, calc-silicate schist, semi-pelitic schist, quartzite and calc-silicate hornfels (Unit 2)

West of the crossbedded psammite, a very variable metasedimentary unit, about 25 m thick, is present. The rocks weather to various hues of grey, brown, green, creamy and white, are mostly medium to coarse grained, and are thinly to thickly bedded. Lenses of quartz or feldspar, representing dismembered felsic intrusions and quartz veins, are also common.

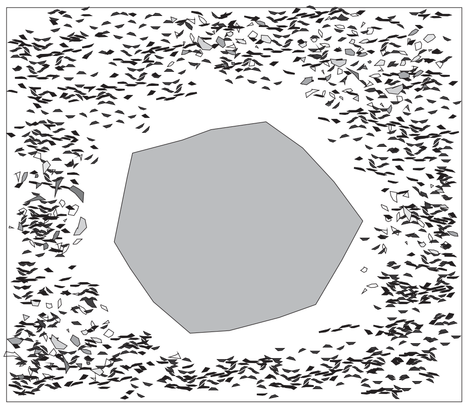
From east to west, the following rock types were noted forming individual layers having widths ranging from about 0.5 m up to 4 m:

i) Dark-grey micaceous amphibolite with quartz pods.
ii) Greenish epidote-rich rock with amphibole porphyroblasts.
iii) Light grey, homogeneous, less micaceous rock.
iv) Grey-brown psammite.

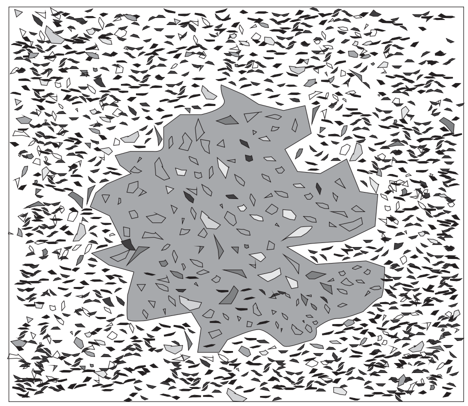
Porphyroblasts and poikiloblasts

A **porphyroblast** is a large mineral crystal in a metamorphic rock that has grown within a finer-grained matrix as a result of chemical reactions that took place in the solid state when the rock was hot. Commonly, porphyroblasts are surrounded by haloes. These are the result of minerals being consumed by the growing porphyroblast.

In some cases, if the porphyroblast does not require the surrounding minerals to enable its growth, it shoulders them aside; in other cases, it simply grows around them. If the porphyroblast grows around other minerals, the latter eventually end up as inclusions within the porphyroblast. A porphyroblast with lots of inclusions is known as a **poikiloblast**.



Porphyroblast with halo



Poikiloblast

The word ‘porphyroblast’ has obscure roots. The ‘porphyr’ part comes from a related Greek word meaning purple, which is the colour of an attractive rock containing large crystals that was used of ornamental purposes. The ‘blast’ part comes from a Greek word meaning germ, reaching geology through medical terminology for tumours.
‘Poikilos’ is a Greek word for irregular or varied, which is apt usage as many poikiloblasts have very ill-defined shapes as a result of the way they grow.

Box 3. *Porphyroblasts and poikiloblasts*

v) Pale green, schistose, fine- to medium-grained semi-pelite.
vi) A pale-green unit made up of alternating amphibole-rich material with psammitic partings.
vii) Brown, homogeneous psammite.
viii) Psammite with narrow amphibole-rich partings.
ix) Grey to greenish, medium-grained homogeneous psammite with some lighter coloured partings.
x) Variable psammite with dark amphibole-rich layers.
xi) Pale-green, fine-grained very schistose material.
xii) Brown-grey psammite with lens-like, discontinuous layers grading westward into homogeneous psammite; and
xiii) Elongate lens of a white-weathering calc-silicate rock occur up to a few metres in length, but rarely more than 30-cm thick in contact with amphibolite located to the west. Pale green epidote lenses, typically 5- to 10-cm thick, are common throughout the unit.

Four samples from this unit, representing the main lithological variants, were examined in thin section. The most mafic-mineral-rich rock type is hornblende–biotite schist also containing quartz, plagioclase, microcline, titanite, epidote, apatite, allanite and minor chlorite (CG07-131A). A mesocratic rock (CG07-131C) was found to consist of quartz, plagioclase, phlogopitic mica, tremolite, clinozoisite and titanite. A leucocratic variant (CG07-131B) is carbonate-rich calc-silicate rock, containing quartz, plagioclase, K-feldspar, carbonate, clinozoisite, actinolite, opaque mineral(s) and titanite. A white-weathering, hornfelsic-textured rock (CG07-131D), which is devoid of mafic minerals, occurs as discontinuous lenses adjacent to the amphibolite to the west and consists of quartz, carbonate, and diopside.

The protolith for this unit was probably a heterogeneous sequence of muddy calcareous rocks, grading into limestone in places.

The next unit to the west, geographically, is amphibolite, but as this unit is interpreted to be intrusive, description of it is given following the supracrustal rocks.

Schistose micaceous calc-silicate rocks (Unit 3)

West of the amphibolite is a grey, greenish and black weathering, fine to medium grained, very well layered unit displaying alternation of rock types at the centimetre to decimetre scale. It consists mostly of schistose micaceous calc-silicate rocks, but also includes some psammitic material. A distinctive 3-m-wide pale green rock (Plate 5) containing pods of orange-brown garnet (*cf.* andradite; Plate 6) is present immediately west of the contact with the amphibolite.

Plate 5. *Contact between dark amphibolite (left) and schistose micaceous calc-silicate unit (centre and right), showing distinctive pale-weathering, garnet-bearing zone.*

Plate 6. *Detail of pale-weathering calc-silicate unit, showing garnet.*

The four samples of this unit examined in thin section are all calc-silicate rocks, although their mineral assemblages differ. The garnet-bearing rock (CG07-133A) also contains clinozoisite/zoisite, quartz, carbonate, diopside, highly sericitized plagioclase, titanite and minor, possibly secondary, tremolite. Clinozoisite/zoisite is partly symplectic with quartz, which commonly also occurs as inclusions in garnet.

Diopside is also a major constituent of sample CG07-133B, where it is associated with plagioclase, phlogopitic mica and titanite. A few tremolite blades and chlorite flakes are also present. Sample CG07-133C contains tremolite as a major mineral, along with phlogopitic mica, clinozoisite, plagioclase and quartz. Minor titanite and allanite are present. The fourth sample (CG07-133D) contains plagioclase, tremolite, phlogopitic mica, microcline and titanite.

The mineral assemblages in this unit are very similar to those in the mixed unit on the eastern side of the amphibolite. If it is accepted that the amphibolite is intrusive, then it is not unreasonable to regard the rocks flanking the eastern and western sides of the amphibolite as being parts of a single unit prior to being separated by emplacement of the amphibolite.

'20-m-wide' Psammite (Unit 4)

The contact between the schistose micaceous calc-silicate rocks and the psammite to the west is sharp and regular. The psammite is about 20 m wide, grey, creamy or reddish weathering, fine- to medium-grained, homogeneous, and thinly to thickly bedded. The contact with calc-silicate rocks farther west is also sharp (Plate 7).

Plate 7. *Contact between 20-m-wide psammite (right) and calc-silicate rocks (centre and left).*

A single thin section from this unit (CG97-134) comprises quartz, plagioclase, and microcline (all polygonal, equant and clearly thoroughly recrystallized), together with buff-brownish, ragged short laths of biotite, and small accessory grains of apatite, zircon, titanite and chlorite. The biotite is concentrated at grain interfaces between felsic minerals and is a typical example of the texture described by Gower (2007) in which the phyllosilicates flakes are of similar length to the adjacent felsic minerals, and interpreted as the product of metamorphism of an intergranular mud. The titanite and chlorite are secondary and derived, at least in part, from the retrogression of biotite. Most of the opaque mineral is secondary hematite or limonite, from the breakdown of primary opaque oxide, and perhaps from minor sulphide also.

Calc-silicate rocks (Unit 5)

The calc-silicate unit occupies a wide swath from the northwest tip of Battle Island to the central part of the southeastern shoreline, albeit heavily injected by pegmatite. The rocks are generally light to dark green weathering, medium grained, thinly and well bedded, mineralogically variable, both in mineral composition and their habits of (metamorphic) growth. Typically, the rocks have a markedly ribbed or pitted surface appearance due to alternating positively and recessively eroding layers and differential weathering of the various minerals present (Plate 8).

Apart from calc-silicate rocks, amphibolitic, semi-pelitic and psammitic layers are also present. Rusty-weathering, sulphide-bearing patches are common, locally forming pods up to about 1 m thick and

Plate 8. *Typical example of well-bedded calc-silicate unit.*

Plate 9. *Rusty-weathering pods enriched in sulphide (probably pyrite) within calc-silicate rocks.*

2 m long. Although rubiginous and having a sulphurous smell on fresh surface, sulphide content is minor (Plate 9).

Four samples were collected near the contact with the psammite to the east and examined in thin section. Two of them (CG07-135A,-135C) and the leucocratic part of a third (CG07-135D) have very similar mineral assemblages, although mineral proportions differ. The minerals are plagioclase, carbonate, K-feldspar, diopside, tremolite and titanite. The plagioclase, carbonate and K-feldspar are typically anhedral, show straight grain boundaries and 120° triple junctions, and are clearly recrystallized. Plagioclase is typically very sericitized and poorly twinned. K-feldspar is well-twinned microcline. Identification of diopside is tentative; other possibilities not entirely ruled out are clinozoisite and idocrase. It is locally altered to tremolite, which, growing discordantly to the prevailing fabric, is clearly post-tectonic in places. Titanite is typically dark brown and anhedral to subhedral. Sample CG07-135B and the melanocratic part of sample CG07-135D consist mostly of a pale orange mica (*cf.* phlogopitic mica), diopside, tremolite, minor plagioclase, with minor oxide opaque mineral, apatite and possibly zircon (very small inclusions showing pleochroic haloes in phlogopitic mica). In sample CG07-135B, the diopside occurs as large poikiloblastic grains containing abundant inclusions of phlogopitic mica and plagioclase.

Five samples were examined in thin section from the western part of the calc-silicate unit, in the Acreman's Point area (CG07-136A to -136E). All contain plagioclase, K-feldspar, phlogopitic mica, (an) opaque mineral(s), and titanite. Plagioclase is typically anhedral with straight grain boundaries and 120° triple junctions and heavily sericitized. K-feldspar shows the same habit, and is characteristically well-twinned microcline. The phlogopitic mica ranges from pale orange to reddish orange and commonly defines a strong fabric. Both oxide and sulphide opaque minerals are present in all five samples except CG07-136E, in which only oxide was observed. Sulphide is especially abundant in CG07-136A and CG07-136B, which were both described as gossanous in the field. The sulphide is thought to be mostly pyrite, but some is suspected to be pyrrhotite in CG07-136A. Titanite varies from anhedral and amoeboid to euhedral. It is abnormally large in sample CG07-136E, where it occurs as grains up to 3 mm long. Other minerals include diopside and minor secondary tremolite (in sample CG07-136E) and tremolite (as a stable phase in CG07-136A, C and D). Neither diopside nor tremolite is present in CG07-136B, which is more psammitic than the other samples.

Whole-rock analyses were obtained for gossanous calc-silicate samples CG07-136A and CG07-136B (Appendix 3). Neither sample is especially anomalous in elements typically of interest to mineral explorationists. The most noteworthy chemical feature of both of them is their high F content.

Calcareous psammite (Unit 6)

The calcareous psammite, forming the westernmost supracrustal unit on Battle Island, is pale-grey-, green-, or brownish-weathering, fine to medium grained, and thinly to thickly bedded. Bedding is defined by darker, amphibole- or biotite-rich layers. Locally oblique layering is present that could be relict cross-bedding. Some layers have a mottled texture that is attributed to incipient melting. The psammitic rocks are intercalated with calc-silicate layers, which locally also show oblique layering that resembles cross-bedding. Three samples were examined in thin section from this unit (CG07-137A, B, and C).

Sample CG07-137A is a calcareous psammite and is distinct in the wide range of minerals present. Twelve minerals were identified in thin section; these are quartz, plagioclase, K-feldspar, diopside, garnet, clinozoisite/epidote, hornblende, tremolite, carbonate, titanite, apatite and leucoxene. The rock is clearly recrystallized, as shown by polygonization of several minerals; most notably quartz, plagioclase and carbonate, which all have straight grain boundaries and 120° triple junctions. K-feldspar is a very minor phase, more obvious in stained slab than thin section. Diopside occurs as pale green, anhedral poikiloblasts, enclosing quartz and plagioclase, especially. Garnet is also poikiloblastic, enclosing quartz, clinozoisite/epidote, diopside, plagioclase and K-feldspar. The clinozoisite/epidote is colourless and shows its characteristic anomalous birefringence. No formal attempt was made to distinguish between clinozoisite and epidote, but the fact that the diopside is green (in contrast to colourless diopside seen in other Battle Island samples) suggests that the Fe content is higher in this sample than elsewhere, and that the mineral is epidote. Hornblende and tremolite are both secondary, as alteration products from diopside. Of the other minerals: titanite occurs as dark brown euhedral grains; apatite forms small euhedral crystals; and leucoxene is the name applied to granular, amorphous-looking opaque material that is white in reflected light. This is clearly a disequilibrium assemblage.

Samples CG07-137B and -137C are both psammitic rocks and, like CG07-137A, are mineralogically varied. Both contain quartz, plagioclase and K-feldspar, all of which have polygonal form and show straight grain boundaries. The mafic and accessory minerals differ between the two, however. Sample CG07-137A contains dark green (sodic?) amphibole, dark brown titanite, zircon, apatite, biotite, epidote, and chlorite (the latter three secondary after amphibole), whereas CG07-137C lacks amphibole, epidote and zircon.

Proterozoic Intrusive Rocks

Amphibolite (Unit 7)

The contact between the amphibolite and the 'Mixed psammite' unit farther east is sharp and concordant. The amphibolite is subdivided into two sub-units, separated by discontinuous lenses and tabular bodies of greenish-weathering calc-silicate rocks (Plate 10).

Plate 10. *Boundary between light-coloured amphibolite (on right) and darker amphibolite (on left), separated by a lens of calc-silicate rock.*

Plate 11. *Dark-weathering western amphibolite intruded by pegmatite; contact with supracrustal units farther west in the right-side background.*

Amphibolite in the eastern half of the unit is more leucocratic than in the west, but both sub-units are medium to coarse grained, black- to grey-weathering, and everywhere very strongly lineated. The lineation is defined by hornblende, whereas the foliation is defined partly by biotite. The eastern leucocratic part shows streaky textures, due to variable concentrations of plagioclase and mafic minerals. Apart from this streakiness, the rock is fairly uniform, except for the presence of small elliptical, more melanocratic enclaves, which are common in some places. The amphibolite in the west (Plate 11) is melanocratic near its contact against the lighter amphibolite, where it is also rusty-weathering and locally schistose.

Samples from both the eastern and western amphibolites were examined in thin section. The eastern amphibolite (CG07-132A) has a very strong fabric, defined by strings of segmented plagioclase grains, interspersed with elongate grains of pale-green amphibole (*cf.* actinolitic hornblende) and laths of orange-brown biotite, both of which define the same strong fabric. Other minerals are opaque minerals (mostly oxide, but some sulphide also occurs, as both elongate strings and beads), yellow-brown rutile and minor chlorite after biotite. The sample from the western amphibolite (CG07-132B) lacks the fabric of its eastern counterpart, showing a granoblastic texture instead. It also shows some mineralogical differences. The amphibole is typical hornblende, rather than being actinolitic and the rock contains very abundant titanite. The titanite occurs in clusters of equant grains, commonly cored by an opaque oxide. Minor sulphide, chlorite and K-feldspar are present, the latter two minerals being found as secondary spindles in biotite.

Whole-rock chemical analyses were obtained for both samples examined in thin section, and are given in Appendix 3. The two amphibolite types are clearly chemically distinct, as shown by marked contrast in TiO_2, Al_2O_3, Fe_2O_3t and several trace elements.

The lack of internal variability in both units suggests that they are more likely intrusive than extrusive. They are interpreted as two separate sills and the variation in colour index to indicate some differentiation. If the units are differentiated then top is to the west, consistent with crossbedding evidence in the easternmost unit. The western contact is not as obvious as that in the east, and appears to be semi-gradational into the next unit to the west. The stronger fabric and mineralogical contrasts in the eastern amphibolite provide evidence for a slightly lower-grade, stretching deformational event not seen in the western amphibolite.

Pegmatite (Unit 8)

Pink- and white-weathering pegmatites are found in all parts of Battle Island, but is particularly abundant along the spine of the island. The pegmatites vary in width from dykes tens of metres to veins less than 1 cm, but most intrusions typically have decimetre- to metre-scale widths. Contacts against the host metasedimentary rocks are sharp and commonly irregular due to post-emplacement deformation. Concordant and discordant pegmatites are both present. Concordant screens of psammite and calc-silicate rock are common in the larger pegmatites, and have maintained their original pre-pegmatite-injection orientation, suggesting a passive, *lit-par-lit* type of intrusion (Plate 12).

Plate 12. *Screens of calc-silicate rock within pegmatite. These have maintained their pre-pegmatite-intrusion orientation, suggesting fairly passive injection of magma along bedding surfaces.*

En echelon pegmatites exhibiting bayonet terminations and bridge features are common (Plate 13, 14 and 15; *cf.* Box 4).

Crosscutting relationships indicate several emplacement events, possibly over an extended period. The state of deformation varies greatly, suggesting syn- to post-tectonic emplacement times. The rocks are almost entirely coarse or very coarse grained; aplitic rocks are extremely rare.

Plate 13. *Bayonet and bridge terminations in en echelon pegmatite veins.*

Plate 14. *Example of block of host rock contained within pegmatite, as a result of linkage of two, originally separate, pegmatite veins. The feature is somewhat distorted, due to subsequent deformation.*

Plate 15. *Previously en echelon segments of pegmatite now linked by bridge structures, but preserving bayonet terminations.*

Plate 16. *Boudin of amazonite-bearing pegmatite. Amazonite is the green mineral.*

Plate 17. *An unidentified non-magnetic mineral in a pegmatite that discordantly intrudes one of the amazonite-bearing pegmatites described above.*

Two pegmatites containing amazonite (green, Pb-bearing K-feldspar) were found on the east side of Battle Island. Each was traced about 50 m (Plate 16). Both pegmatites are strongly boudinaged and appear to be among the earliest present on the island. One of the amazonite-bearing pegmatites was examined in thin section (CG07-138A). It comprises slightly recrystallized quartz, moderately sericitized, well-twinned plagioclase having albitic borders, well-twinned microcline, interstitial muscovite, an opaque oxide, partially metamict monazite, zircon, traces of chlorite, and a dark brown poorly preserved mineral that is suspected to be allanite. The accessory minerals are unusually abundant in this pegmatite. A whole-rock analysis of sample CG07-138A is given in Appendix 3. The high Pb content of the rock indicated by the amazonite is confirmed by the analysis. High Nb and Ta suggest that this type of pegmatite might have potential for columbite–tantalite mineralization elsewhere.

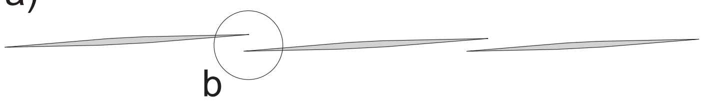
The amazonite-bearing pegmatites are crosscut by near planar, but still deformed, later pegmatites. In one of them, an unidentified, opaque, non-magnetic mineral showing iridescent weathering colours is common (Plate 17). This pegmatite was also examined in thin section (CG07-138B). It contains unrecrystallized quartz, moderately sericitized plagioclase, well-twinned microcline, but very little else (very minor traces of muscovite and an opaque oxide). The iridescent-weathering opaque mineral was not captured in the thin section.

A sample of pegmatite from Acreman's Point examined in thin section (CG07-136F) contains well-twinned, lightly altered plagioclase, well-twined microcline, quartz, rare red-brown biotite, euhedral

Bayonets and bridges: Emplacement mechanisms of dykes

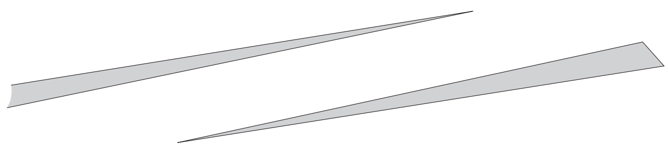
An igneous dyke is a tabular body of rock that forms from the crystallization of molten rock (magma) , injected into a pre-existing fracture. What happens at the ends of the fractures is the topic addressed here. Although dykes are commonly drawn as continuous linear features on maps, more commonly they form en echelon, as shown below.

a)



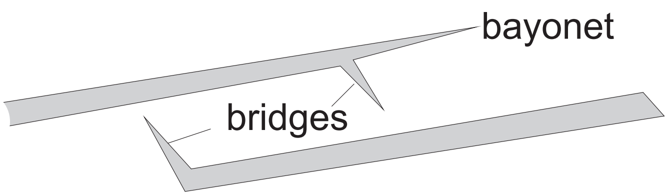
As magma continues to be injected into the fracture, separate en echelon segments will join. This happens in the following way. As the fracture continues to fill with magma, it both lengthens and gets wider, and the ends (**bayonets**) of individual fractures overlap.

b)



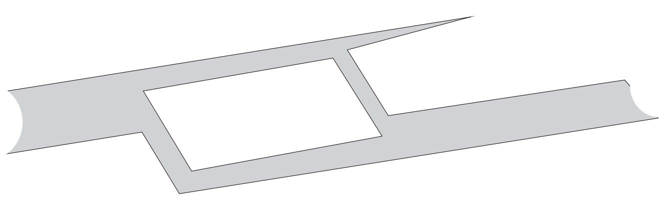
The next stage is the development of cross fractures (**bridges**) between two bayonets. The bridges can form at the tip of the bayonet, or at several points along its side. The bridges fill with magma as they develop.

c)



Eventually the bridges will extend completely across the gap and link up two bayonets. If only one bridge forms, the dyke will have a simple stepped appearance, with or without bayonets preserved. If two or more bridges develop, blocks of the host rock will be trapped within the now-composite dyke.

d)



Box 4. *Bayonets and bridges*

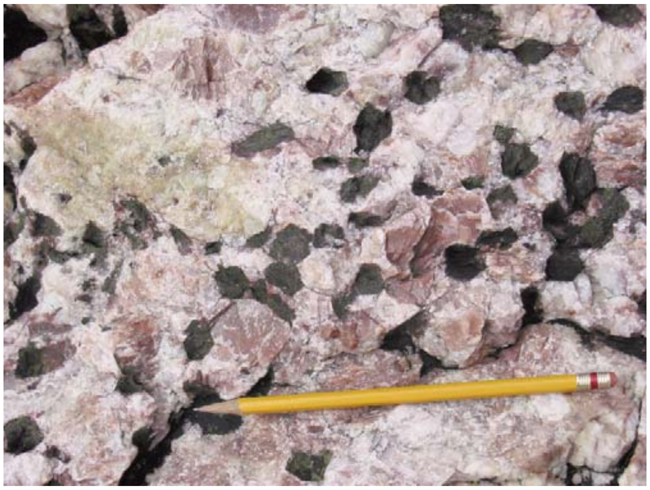


Plate 18. *Crystals of hornblende (six-sided, black mineral) in pegmatite.*

Plate 19. *Boudin of fluorite-bearing pegmatite. Fluorite is the purple mineral in the central part of the boudin.*

pyrite, and garnet (symplectically intergrown with quartz). It also contains an uncertainly identified mineral thought to be metamict monazite. The mineral has square and rectangular cross sections, shows overgrowths and commonly is surrounded by radiating fractures. This mineral also occurs as inclusions in the garnet.

Other pegmatites, not examined in thin section, were noted in the field as containing hornblende (in places as euhedral crystals 2-3 cm in cross section and several centimetres long; Plate 18), sparse biotite (up to about 5 cm across), minor muscovite, magnetite, or rare purple fluorite (Plate 19).

A pegmatite from the southern end of the island was previously collected for U/Pb geochronological study (Peressini, 2000). Six zircon fractions (three single zircons and three multi-grain) were analyzed by Carr at Carleton University and yielded $^{207}Pb/^{206}Pb$ ages between 883.2 +33.2/-34.0 Ma and 1137.8 +251.6/-300.9 Ma. High errors from three fractions were recognized as due to analytical problems and discarded. The remaining fractions give a $^{207}Pb/^{207}Pb$ age of 1017 +/- 9 Ma.

More recently, two other pegmatites were collected for geochronological study, namely a deformed, amazonite-bearing pegmatite and a younger planar pegmatite that clearly crosscuts it. The older, amazonite-bearing pegmatite yielded a zircon age of 1024 ± 6 Ma. Zircons analyzed from the younger dyke all have ages that predate the older pegmatite and are therefore interpreted to be inherited (Kamo, 2008). Inherited zircons are common in pegmatites, so the fact that the ages obtained contradict the field relationships neither invalidates the field observations nor the geochronological method.

Phanerozoic Intrusive Unit

Diabase dyke (Unit 9)

A single, vertical, east-northeast-trending diabase dyke is present on Battle Island at its southern end (Plate 20). The dyke is about 2 m thick and has a smaller dyke (20 cm thick) branching off from it on its south side. It discordantly intrudes pegmatite and earlier psammite, and also truncates north-northeast-trending, hematite-filled brittle fractures.

The dyke varies from fine to medium grained at its centre, to very fine grained at its chilled margins. The dyke is recessive weathering with respect to its host rocks. It has a distinctive jointing pattern across the width of the dyke, considered to be related to cooling normal to the dyke walls. The K-feldspar in pegmatite adjacent to the dyke takes on a greenish hue, in contrast to its vivid pink farther away. This is interpreted as reduction of ferric to ferrous Fe in the feldspar due to dyke emplacement. The dyke is unmetamorphosed and mineralogically fresh. It is the youngest bedrock unit on the island.

Plate 20. *Phanerozoic diabase dyke (exact age uncertain) discordantly intruding pegmatite (pink) and older psammite (grey).*

In thin section (CG07-139), the dyke is seen to consist of plagioclase, clinopyroxene, biotite, an opaque oxide and fine grained, granular brown material. Plagioclase forms primary, well-twinned, and locally skeletal laths, and also occurs as local clusters of larger grains suggested here to represent slightly earlier crystallizing crystals that aggregated during magma ascent. The clinopyroxene occurs as brown primary grains in ophitic texture with plagioclase. The biotite is orange brown and ragged. The granular, brown material is too fine grained to be unequivocally identified, but it is suspected to be a Ti-bearing phase, possibly titanite. A whole-rock geochemical analysis of sample CG07-139 is given in Appendix 3.

STRUCTURE

FOLDING

The supracrustal units trend north-northwest, and mostly dip between 55 and 75° east-northeast. This means that the rocks are overturned, if the top-to-the-west facing evidence given by crossbedding is accepted.

The earliest recognizable structures are isoclinal (Plate 21) and tight folds (Plate 22), mostly within the calc-silicate units, but present elsewhere. Although the isoclinal folds initially appear to be contained within the general layering of the unit, their form is defined by a more attenuated version of the compositional layering, so there is no robust jus-

Plate 21. *Isoclinal fold within rusty weathering calc-silicate unit.*

Plate 22. *Tight fold in calc-silicate unit*

Plate 23. *Gneissose rock made up of calc-silicate and psammitic rocks injected by numerous pegmatites, subsequently flattened and mylonitized. The slightly sigmoidal form of layers in the central area provides a poor example of a kinematic indicator, suggesting a right-side-up sense of movement.*

tification for considering the isoclinal folds to be the result of a different generation of deformation from the tight folds. Rather, they are interpreted here as having formed earlier (or subjected to higher strain) than the less flattened folds. The fold axes of both the isoclinal and tight folds are parallel to a ubiquitous down-dip stretching lineation. There is also evidence of considerable layer-parallel extension in the form of extremely dismembered early minor intrusions. One, somewhat equivocal example of a sigmoidal shear-sense indicator was seen on the south side of the island that suggests east-side-up sense of ductile movement (Plate 23). All these structures are modified by open folding that has warped the units into an open Z pattern.

Carr and colleagues (Czajkowski *et al.,* 2000; Peressini, 2000) refer to the original bedding as S1 surfaces. The deformation that produced most of the deformation is assigned as D2 and considered to be Grenvillian. The tight to isoclinal folds, northeast-plunging folds are termed F2 folds, the axial surfaces of which and the penetrative foliation are labelled S2, and strong down-dip lineation that is co-axial with the fold axes as L2. The deformation that produced the open folding (F3) is assigned as D3, and is interpreted to be a waning, post peak-metamorphic manifestation of the D2 deformation event. Thus, essentially, all the ductile deformation is considered to be Grenvillian. Although this conclusion was received with reservation by the present author (Gower, 2008), given the regional context and widespread earlier orogenic events (Pinwarian, and, especially, Labradorian) known to have affected the area (Gower and Krogh, 2002, 2003; Gower, 2005), recent geochronological data (Kamo, 2008) provides strong support for Carr and colleagues. Gower (2008) noted that this is not a new source of controversy, as the relative impact of Grenvillian, versus earlier orogenesis, has been disputed for decades in the eastern Grenville Province – and, from the most recent data, seems likely to continue for some time!

PEGMATITE DEFORMATION

The pegmatite dykes clearly postdate the tight to isoclinal folding and associated stretching lineation, but are themselves openly folded and otherwise deformed to varying degrees. The multiple branching

Plate 24. *Boudins of pegmatite (creamy rock extending diagonally down to the right across the photograph); caused by flattening and extension of a once-planar-sided vein.*

Plate 25. *Buckled pegmatite, climbing to the right and showing S-folds*

Plate26. *Buckled pegmatite, climbing to the left and showing Z-folds*

dykes, en echelon features, boudinage, buckling and crosscutting relationships testify to emplacement in all directions over an extended period during evolution from a ductile regime at the start, to brittle conditions at the end (Plates 24, 25 and 26; Box 5).

The latest pegmatites occupy brittle fractures. The deformation that affected the pegmatites is grouped as part of the D3 event by Carr and colleagues (Czajkowski *et al.,* 2000).

BRITTLE FAULTS

The latest structures are brittle faults (Plate 27). They characteristically have a north to northeast trend and are maroon weathering due to hematization. In appearance, the faults range from hairline fractures to zones up to about 2 m wide. Slickensides were measured on two of the fault surfaces (Plate 28). Both plunge to the southwest at 22°.

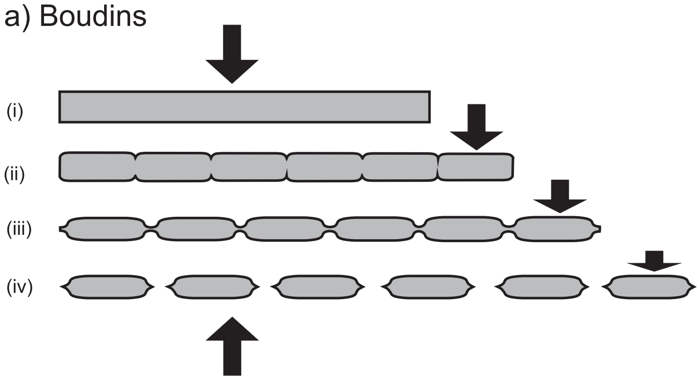
The wider zones commonly contain angular fragments of fault breccia, within comminuted to fine-grained material. The faults have both dextral and sinistral apparent displacement, but dextral movement seems to be most common. Although displacements are typically 0 – 1 m, two faults in the northeast part of the island have approximate apparent displacements of 15 and 5 m. The fault with the 15 m displacement has been named the Cemetery fault, as it can be traced from shoreline exposure into a gully containing surficial sediments where the most easterly of two small cemeteries on Battle Island is located.

The brittle faults occur in all units, except the basaltic dyke, which truncates them. They are therefore post-pegmatite and pre-basaltic dyke. Given their predominantly north-northeast trend, and age relation-

Boudins and buckles: Deformation of dykes

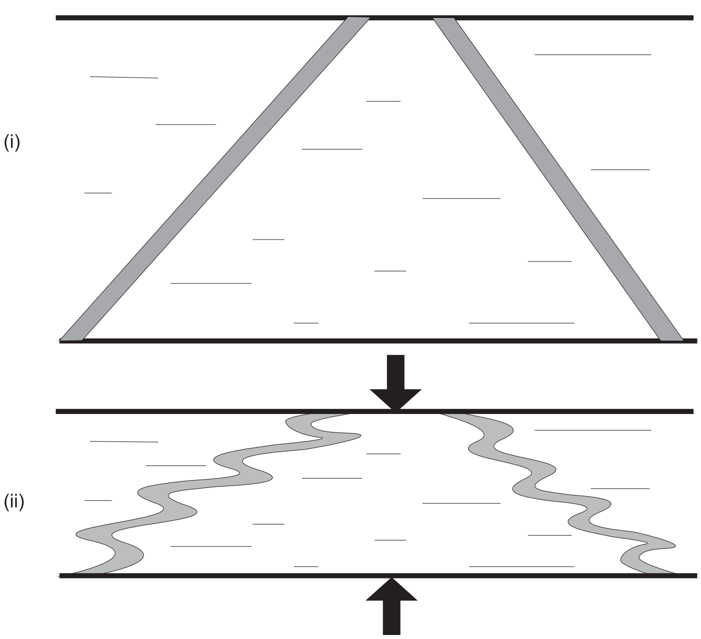
When thin sheets of rock, such as dykes, are deformed, they experience either **boudinage** or **buckling**, depending on their original orientation relative to how they are being squashed. Remember that the rocks, although not molten, were hot at the time and ductile (capable of flowage).
If the sheet of rock is oriented at right angles to the direction of squashing, it will either break or stretch depending on its ductility contrast relative to its host rock. If ductile, it will start to thin at points of weakness (necking), and eventually break into pods. These pods are called boudins, a word that has it origin in French, meaning sausage. The process of their formation is called boudinage. In three dimensions, the boudins may be either disc-shaped or cylindrical, according to the nature of the stresses that caused them.

a) Boudins



If the sheet of rock is in a plane at an oblique angle to the direction of a squashing, it will shorten by buckling. If the sheet of rock is inclined to the right it will shorten into a series of S shapes; conversely, if the sheet of rock ia inclined to the left, it shortens into a series of Z shapes. These ‘snake rocks’ are found all over Battle Island, making it a veritable geological serpents’ nest.

b) Buckles



Box 5. *Boudins and buckles*

Plate 27. *Brittle faults showing dextrally displaced pegmatite veins.*

Plate 28. *Slickensides on brittle fault plane. The main minerals in the slickenside are epidote (yellow-green), hematite (maroon), quartz and feldspar (both white). Minor chlorite (darker green) is also present.*

ships to the pegmatite and basaltic dyke, it seems mostly likely that they belong to the same set of fractures as those occupied by the Long Range dykes and that they are related to the rifting that preceded the opening of Iapetus Ocean.

The final structural event recognized was creation of the east-northeast fracture now occupied by the undeformed and unmetamorphosed basaltic dyke.

METAMORPHISM

A detailed study of the metamorphic assemblages has not been undertaken, and the information presented below is intended to offer only a preliminary grouping of the rocks into metamorphic assemblages (Table 1), to deliver some empirical observations regarding textures and possible reactions, and to make some general statements regarding metamorphic conditions.

PSAMMITIC ROCKS

These rocks all contain quartz + plagioclase + K-feldspar + bronzy to green biotite + an opaque oxide. Amphibole is found in four samples, and differs in each sample. It is clearly a prograde poikiloblastic phase in two samples, appears to be a stable member of the mineral paragenesis in a third and is likely relict in the fourth. Where it is poikiloblastic it is surrounded by biotite-depleted haloes, so biotite is certainly one of the reactants. The amphibole poikiloblasts contain rare epidote and titanite, so, if these were also reactants, they were not entirely consumed. In the sample in which amphibole is likely relict, the

Table 1. Grouping of metamorphic rocks by mineral assemblages

Sample	Fabric	Qtz	Plag	K-fs	Bio	Bio colour	Diop	Clz	Carb	Gnt	Amph	Amphibole type	Oxd	Sul	Tit	Apt	Zir	All	Epid	Chl	Rut	Comments
Psammitic rocks																						
CG07-130A	Granoblastic	X	X	X	X	Bronze							X		x	x	x	x	s	s		Heavy mineral layers rich in accessory phases
CG07-130B	Granoblastic	X	X	X	X	Bronzy green					x	Relict(?) blue-green hornblende	X		s	x			s	s		
CG07-130C	Granoblastic	X	X	X	X	Bronzy green					X	Blue - dark green (Na?) hornblende	X		s	x	x		s	s		Amphibole poikiloblastic
CG07-131A	Schistose	X	X	X	X	Bronze					X	Stable hornblende			x	x		x	s	s		
CG07-134	Granoblastic	X	X	X	X	Bronzy green							X		x	x	x			s		
CG07-137B	Granoblastic	X	X	X	s	Green					X	Blue - dark green (Na?) hornblende			x	x	x		s	s		Amphibole poikiloblastic
CG07-137C	Grano/Schist	X	X	X	X	Bronze							X		x	x				s		
Calc-silicate rocks with quartz																						
K-feldspar-Diopside-Carbonate																						
CG07-131B	Granoblastic	X	X	X			X	X	X		s	Actinolite	x		x							Amphibole poikiloblastic
CG07-131D	Granoblastic	x	x	x			X		X		s	Tremolite			x							
CG07-133A	Granoblastic	X	x	x			X	X	X	X	s	Tremolite	x	x	x							Garnet poikiloblastic
CG07-137A	Granoblastic	X	X	x			X	X	X	X	s	Blue-green amph. & Tremolite	x		x	x						Garnet poikiloblastic
Phlogopitic mica																						
CG07-131C	Schistose	X	X		X	Pale orange		X			X	Tremolite			x							Clinozoisite (poikiloblastic) identification uncertain, relict
CG07-133C	Schistose	X	X		X	Orange		X			X	Tremolite			x			x				Clinozoisite (poikiloblastic) identification uncertain; relict
Calc-silicate rocks lacking quartz																						
K-feldspar-Diopside-Carbonate																						
CG07-135A	Granoblastic		X	x			X		X		s	Tremolite			x							Diopside and/or Clinozoisite?
CG07-135C	Granoblastic		X	X			X		X		s	Tremolite			x							Diopside and/or Clinozoisite?
CG07-135D - light	Granoblastic		X	X			X		X		s	Tremolite										Diopside and/or Clinozoisite?
K-feldspar - Phlogopitic mica																						
CG07-133D	Schistose		X	X	X	Pale orange					X	Tremolite			x							
CG07-136B	Schistose		X	X	X	Orange					s	Tremolite		X	x	x						High opaque mineral content
CG07-136C	Schistose		X	X	X	Orange	x				X	Tremolite	X	x	x							
CG07-136D	Schistose		X	X	X	Orange	X				X	Tremolite	X	x	x							
CG07-136E	Granoblastic		X	X	X	Orange	X				s	Tremolite										
Phlogopitic mica																						
CG07-133B	Granoblastic		X		x	Pale orange	X				s	Tremolite			x					s		
CG07-135B	Schistose		X		X	Pale orange	X		s		X	Tremolite	x			x						Tremolite is post-tectonic
CG07-135D - dark	Schistose		X		X	Orange	X				X	Tremolite										Tremolite is post-tectonic
CG07-136A	Schistose		X		X	Orange	X				X	Tremolite	X	x	x							Tremolite is post-tectonic
Amphibolite																						
CG07-132A	Schistose		X		X	Orange-brown					X	Actinolite	X	x		x				s	x	
CG07-132B	Granoblastic	x	X	s	X	Orange-brown					X	Hornblende	X	x	X	x				s		

Qtz - quartz; Plag - Plagioclase; K-fs - K-feldspar; Bio - Biotite; Diop - Diopside; Clz - Clinozoisite; Carb - carbonate; Gnt - garnet; Amph - amphibole; Oxd - opaque oxide; Sul - opaque sulphide; Tit - titanite; Apt - apatite; All - allanite; Epid - epidote; Chl - chlorite; Rut - rutile X - Essential mineral or important accessory mineral x - Minor mineral s - Secondary and minor mineral products are biotite, titanite, epidote and an opaque oxide, with subsequent breakdown of the biotite to yield chlorite, although some of the titanite appears to have been part of the pre-existing higher grade assemblage.

The assemblages indicate amphibolite-grade metamorphism and later localized retrogression to greenschist-facies conditions. The psammitic rocks contain a wide range of accessory minerals, and the opaque mineral is generally an oxide, in contrast to the calc-silicate rocks which contain sulphide but otherwise lack accessory minerals, apart from titanite (which is commonly abundant and forms large grains).

QUARTZ-BEARING CALC-SILICATE ROCKS

The quartz-bearing calc-silicate rocks can be further divided into those having K-feldspar, diopside and carbonate versus those having phlogopitic mica. This subdivision correlates with a lower colour index and lower proportion of mafic minerals in K-feldspar-diopside-carbonate-bearing samples. The two subgroups may be partly equivalent and linked by the reaction:

Phologopite + Calcite + Quartz = Tremolite + K-feldspar + CO_2 + H_2O ……(1).

Two of the K-feldspar–diopside-bearing samples contain an orange- to red-brown-weathering garnet (*cf.* andradite/grossularite; Plate 29).

Petrographic characteristics clearly demonstrate that these two samples represent disequilibrium assemblages (the samples would probably be rewarding to study in detail). Sample CG07-131D contains so little quartz that it is questionable whether it can be regarded as part of the stable paragenesis.

The identification of the mineral listed as clinozoisite in the two phlogopitic mica samples is tentative. It occurs as colourless, anhedral (but having hint of hexagonal form), poikiloblastic grains containing abundant quartz inclusions. There are indications that it is partly replaced by tremolite. It has moderate birefringence and is biaxial positive.

Plate 29. *Garnet poikiloblasts (red) in calcareous psammite (mottled grey and creamy rock in upper half of image). Although the hollowed-out cores of the garnet suggest that their composition varies from core to rim, the exact cause is unknown. The mottled appearance of the calcareous psammite may be the result of partial melting. The lower third of the image shows a later, discordant hornblende-bearing pegmatite.*

QUARTZ-ABSENT CALC-SILICATE ROCKS

The quartz-absent calc-silicate rocks have also been subdivided into three groups containing or lacking phlogopitic mica or K-feldspar, or containing both. The presence of K-feldspar in some samples, but its absence in others, could be due to the inability of Reaction 1 (above) to proceed to the right because of exhaustion of quartz.

Although some doubt is expressed regarding the identification of diopside versus the possibility that it is clinozoisite, it is probably diopside. The difficulty stems from the low Fe content in the rocks, which, if present, normally provides both colour and refractive index contrasts between the two phases. In some of the samples, tremolite is clearly secondary, mostly as an alteration of diopside, and in some samples it is seen growing across the penetrative fabric, thus postdating it and not part of the stable mineral assemblage.

AMPHIBOLITE

The two samples of amphibolite have similar mineral assemblages, but the more schistose of the two has experienced some retrogression, perhaps related to the deformation generating the schistosity. Evidence of the regression is seen by the presence of actinolite, alteration of biotite, and traces of rutile. A sample of amphibolite was collected for U/Pb geochronological study. An age of 1030 ± 4 Ma was obtained, and is interpreted to date the time of metamorphism (Kamo, 2008).

GEOLOGICAL HISTORY

The earliest event that can be inferred was the deposition of sandstones, siltstones, calcareous sandstones and siltstones, grading into limestone in places. These were probably deposited in a shallow-water fluvial or marine environment. The time of deposition is uncertain. Until recently, deposition was suggested to have been between 1800 and 1665 Ma (Gower, 2008), based on regional information (Gower and Krogh, 2002, 2003), but unpublished geochronological data obtained by Kamo (2008) suggests that it was younger, between *ca*. 1500 and 1030 Ma. In contrast, in the surrounding area, there is abundant evidence of major granitoid emplacement events at *ca.* 1650 and 1500 Ma, but those events have not been recognized on Battle Island.

Deposition of the supracrustal rocks was followed by burial and metamorphism, and the emplacement of two mafic sills, the second one following the conduit of the first. As there are hints of fractionation it is surmised that the sills were emplaced while the sediments were still flat-lying.

During the severe deformation that followed sill emplacement, the rocks were folded and achieved their present overturned attitude. The prominent down-dip lineation, and tight folds with fold axes co-axial to the lineation are also considered to have formed at this time. This deformation was suggested to have occurred during Labradorian thrusting at 1665 Ma by Gower (2008), but unpublished data obtained by Kamo (2008) suggests that it is Grenvillian, as previously interpreted by Carr and colleagues.

During Grenvillian orogenesis (*ca.* 1030–1000 Ma in this area; *cf.* Gower and Krogh, 2002), the rocks were around the ductile–brittle transition. This is inferred from the various deformational features exhibited by the pegmatites. Some have clearly been buckled or boudinaged, whereas others occupy planar fractures and were emplaced under brittle conditions.

The next event was the formation of hematite-filled, north-northeast brittle faults showing both apparent sinistral and dextral sub-horizontal displacements, The faults were formed at *ca*. 615 Ma, or earlier, during early stages of rifting leading to the formation of Iapetus Ocean. The 615 Ma constraint is imposed by the age of the Long Range dykes, which occupy some of the north-northeast fractures elsewhere in eastern Labrador (Kamo *et al.,* 1989; Kamo and Gower, 1994).

The final event was the emplacement of an east-northeast-trending basaltic dyke at an unknown age, but later than the hematite-filled brittle faults, which the dyke crosscut.

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APPENDIX 1

MINERALS MENTIONED IN TEXT AND THEIR CHEMICAL COMPOSITION (SIMPLIFIED)

Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Albite	$NaAlSi_3O_8$
Allanite	$Ca_2(Al,Ce,Fe)_3Si_3O_{12}(OH)$
Amphibole	Group of minerals that includes actinolite, tremolite and hornblende
Amazonite	$KAlSi_3O_8$ having Pb substitution for some K
Andradite	$Ca_3Fe_2Si_3O_{12}$
Apatite	$(Ca,F,Cl)Ca_4P_3O_{12}$
Biotite	$K_2(Mg,Fe)_2AlSi_3O_{10}(OH)$
Calcite	$CaCO_3$
Carbonate	Group of minerals that includes calcite and dolomite
Chlorite	$(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8$
Diopside	$CaMgSi_2O_6$
Dolomite	$(Ca,Mg)CO_3$
Clinozoisite	$Ca_2Al_3Si_3O_{12}(OH)$
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$
Feldspars	Group of minerals that includes albite, plagioclase, amazonite, microcline and K-feldspar
Fluorite	CaF_2
Garnet	Group of minerals that includes andradite and grossularite
Grossularite	$Ca_3Al_2Si_3O_{12}$
Hematite	Fe_2O_3
Hornblende	$Ca_2(Mg,Fe,Al)_5Si_8O_{22}(OH)_2$
Idocrase	$Ca_2Al_2Si2_2O_7(OH,F)$
Ilmenomagnetite	$(Fe,Ti)_3O_4$
K-feldspar	Group of K-bearing feldspars that includes microcline
Leucoxene	Alteration product of Ti-bearing minerals – no fixed composition
Magnetite	Fe_3O_4
Mica	Group of minerals that includes biotite, muscovite and phologopite
Microcline	$KAlSi_3O_8$
Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$
Opaque oxides	Group of minerals that includes hematite, leucoxene, magnetite and sulphide
Phologopite	$KMg_3AlSi_4O_{10}(OH)$
Plagioclase	$(Na,Ca)Al_{3-2}Si_{2-3}O_8$
Pyrite	FeS_2
Pyrrhotite	$Fe_{1-x}S$
Quartz	SiO_2
Rutile	TiO_2
Sulphide	Group of minerals that includes pyrite and pyrrhotite
Titanite	$CaTiSiO_5$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Zircon	$ZrSiO_4$
Zoisite	$Ca_2Al_3Si_3O_{12}(OH)$

APPENDIX 2

GLOSSARY OF TECHNICAL TERMS USED IN TEXT

Note that these are informal definitions, presented without full regard for various genetic or other subtleties of meaning that might be implied.

Amphibolite	A metamorphic rock composed mostly of hornblende and plagioclase – typically derived from a basaltic igneous rock
Amphibolite facies	A grade of metamorphism characterized by 450-700°C temperatures and 4-7 kb pressures
Anhedral	Used to describe minerals without well-defined crystal shape
Arenaceous	Used to describe sandstones
Boudin	A sausage-shaped pod of rock produced by deformation
Colour index	The percentage of dark minerals in a rock
Crossbedding	Bedding in sediments at a angle to the general stratification
Diabase	A fine- to medium-grained basaltic igneous rock composed of plagioclase and clinopyroxene
Euhedral	Used to describe minerals having well-defined crystal shape
Felsic	Used to describe rocks composed mostly of feldspar and quartz
Geochronology	The science of dating rocks (especially by using isotopic methods)
Gneiss	A metamorphic rock having alternating layers of light and dark minerals; generally produced by partial melting
Granoblastic	A metamorphic texture in which all minerals are all roughly the same size
Greenschist facies	A grade of metamorphism characterized by 300-450°C temperatures 2-4 kb pressures
Grenvillian	A mountain-building event that occurred between 1085 and 985 million years ago
Hematization	A low-grade metamorphic process involving the formation of hematite
Hornfels	A fine-grained metamorphic rock having an equidimensional mineral texture; usually formed adjacent to a hot intrusive body
Iapetus	The name given to an ancient ocean that existed between 540 and 450 million years ago
Isoclinal	Used to describe folds having parallel limbs
Labradorian	A mountain-building event that occurred between 1710 and 1600 million years ago
Lit-par-lit	Bed-by-bed, or layer-by-layer
Lithological	Adjective of lithology, which is the description of rocks
Mafic	Used to describe rocks composed mostly of dark minerals
Makkovikian	A mountain-building event that occurred between 1800 and 1770 million years ago
Melanocratic	Used to describe rocks having a colour index of at least 60%
Metamict	Used to describe minerals that have experienced radiation damage, but retain their external form
Metasedimentary	Used to describe a metamorphosed sedimentary rock
Micaceous	Used to describe rocks having abundant mica
Mylonite	A finely laminated rock produced by extreme deformation

Ophitic	Used to describe an intergrowth texture in igneous rocks that involves plagioclase and pyroxene
Orogeny	A process that involves mountain building; generally occurring at crustal plate margins
Paragenesis	An association of contemporaneously formed minerals
Pegmatite	A very coarse-grained rock, generally of granitic composition and found in dykes and veins
Pelite	A metamorphosed mudstone
Petrography	The science of describing rocks, especially applied to microscope studies
Phanerozoic	A division of time younger than 540 million years
Phyllosilicate	A class of sheet-like minerals, especially micas
Pinwarian	A mountain-building event that occurred between 1520 and 1460 million years ago
Pleochroic	Used to describe minerals that show different colours in different directions, especially when applied to microscopic observations
Pluton	A deep-seated igneous intrusion
Poikiloblast	An abnormally large crystal formed during metamorphic recrystallization and containing abundant inclusions
Porphyroblast	An abnormally large crystal formed during metamorphic recrystallization
Proterozoic	The period of time between 2500 and 540 million years ago
Protolith	The original rock before it was metamorphosed
Psammite	A metamorphosed sandstone
Rubiginous	Rusty coloured
Schist	A metamorphosed rock easily split into thin layers
Sericitization	A low-grade metamorphic process involving the formation of sericite (a muscovite-like mineral)
Slickensides	Striations on a fault surface resulting from friction during fault movements; indicates direction of fault displacement.
Subhedral	Used to describe minerals with some well-defined crystal shapes
Supracrustal	Used to describe rocks formed at the surface
Symplectic	Used to describe a mineral texture formed by the intergrowth of two minerals
Terrane	A geologically distinct region, typically bounded by faults
Volcaniclastic	A clastic rock made up of volcanic material

APPENDIX 3

MAJOR- AND TRACE- ELEMENT GEOCHEMICAL DATA FOR SAMPLES FROM BATTLE ISLAND

Labno	642024	642025	642026	642027	642028	642029	642031
Sampleno	CG07-130A	CG07-132A	CG07-132B	CG07-136A	CG07-136B	CG07-138A	CG07-139
Rocktype	Battle Harbour psammite	Battle Harbour amphibolite, biotitic	Battle Harbour amphibolite, mela	Calc-silicate, gossanous	Calc-silicate, gossanous	Pegmatite, amazonite	Battle Island dyke
Major elements							
SiO_2	86.50	48.36	46.26	57.39	45.91	75.14	48.09
TiO_2	0.342	1.224	5.183	0.507	2.391	0.048	2.148
Al_2O_3	6.56	18.10	13.33	10.96	15.23	13.21	13.51
Fe_2O_3	1.24	1.40	3.19	6.09	13.03	0.08	4.57
FeO	0.69	8.07	10.23	nd	nd	0.22	8.68
MnO	0.018	0.138	0.204	0.075	0.051	0.035	0.262
MgO	0.68	7.13	5.30	9.87	6.16	0.08	6.03
CaO	0.78	8.16	10.22	6.10	3.30	0.15	11.04
Na_2O	1.74	3.64	3.31	3.46	4.27	2.17	2.43
K_2O	1.65	0.98	0.65	3.57	3.97	8.29	0.44
P_2O_5	0.066	0.300	0.403	0.103	0.877	0.005	0.200
LOI	0.51	1.32	0.41	2.71	4.23	0.51	0.98
Total	100.84	99.72	99.81	99.93	98.49	99.95	99.33
Trace elements							
Ag	nd	nd	nd	nd	nd	nd	nd
As	0.5	nd	1.2	nd	nd	nd	nd
Au	nd	nd	nd	nd	nd	nd	4
Ba	259	354	215	471	38	980	66
Be	1.1	1.1	nd	1.3	1.2	5.7	nd
Br	1	1	nd	3	3	1	nd
Cd	nd	0.1	0.5	nd	0.3	nd	0.5
Ce	36	26	30	21	77	56	18
Co	nd	49	41	9	44	nd	52
Co	6	46	72	11	53	nd	55
Cr	13	164	14	37	12	nd	108
Cs	1.4	1.7	nd	3.2	13.0	1.8	5.3
Cu	nd	37	nd	23	145	12	225
Dy	2.5	2.5	4.5	4.3	5.2	24.4	6.6
Eu	nd	2	2	nd	2	nd	2
F	214	469	715	2140	1940	115	197
Hf	4	2	3	4	5	84	4
Ir	nd	nd	nd	nd	nd	nd	nd
La	16	12	15	7	32	17	8
Li	12.7	27.7	11.1	18.8	56.8	3.1	12.2
Lu	0.2	0.3	0.4	0.4	0.4	12.0	0.5
Mo	nd	nd	nd	nd	nd	nd	nd
Nb	4	9	21	10	22	534	16
Nd	nd	140	nd	nd	32	nd	66
Ni	nd	118	nd	3	23	nd	54
Pb	8	nd	6	7	7	256	4
Rb	57	35	29	88	147	230	26
Sc	4.7	15.6	53.3	16.0	23.0	2.2	48.8
Sb	0.3	0.2	0.5	nd	nd	nd	nd

(table continued overleaf)

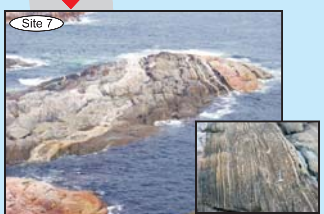
Labno	**642024**	**642025**	**642026**	**642027**	**642028**	**642029**	**642031**
Sampleno	CG07-130A	CG07-132A	CG07-132B	CG07-136A	CG07-136B	CG07-138A	CG07-139
Rocktype	Battle Harbour psammite	Battle Harbour amphibolite, biotitic	Battle Harbour amphibolite, mela	Calc-silicate, gossanous	Calc-silicate, gossanous	Pegmatite, amazonite	Battle Island dyke
Sc	5.0	17.0	57.7	15.0	23.8	2.1	50.6
Se	nd	nd	nd	nd	nd	nd	nd
Sm	3.6	3.4	5.3	3.2	9.2	11.9	5.1
Sn	nd	nd	nd	nd	nd	nd	nd
Sr	64	597	470	274	594	150	207
Ta	0.5	0.7	1.1	0.9	1.6	140.0	0.8
Tb	0.6	0.5	0.8	0.8	1.2	2.8	1.3
Th	4.8	0.7	1.4	9.2	1.4	258.0	0.6
U	1.2	0.3	0.6	3.3	0.7	34.4	0.4
V	25	111	355	68	226	nd	389
W	nd	nd	nd	nd	4	nd	nd
Y	16	15	26	31	30	175	34
Yb	nd	nd	3	3	3	62	3
Zn	17	76	103	74	75	20	104
Zr	143	81	139	119	179	879	128

nd – not detected

APPENDIX 4

BROCHURE ON THE GEOLOGY OF BATTLE ISLAND

Site 6
Site 6 shows the boundary between **psammite** and **calc-silicate** rocks, derived from sand and muddy or sandy limestone. These were originally deposited on top of similar rocks at Site 4, in a shallow-water river or marine environment. After burial and metamorphism, the basalt sill was injected. Rare fluorite and garnet occur in this area (see obverse).



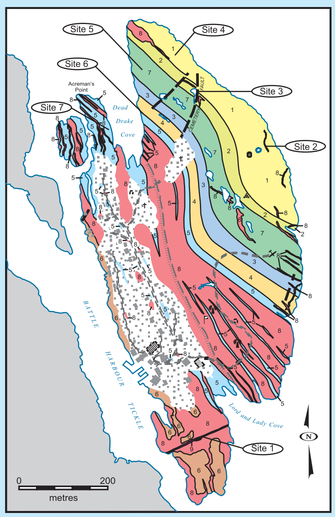
Site 7
At Site 7 (Acreman's Point) **calc-silicate rocks**, intruded by abundant pegmatite, are superbly exposed. The calc-silicate rocks were derived from muddy limestone and the ribbed appearance reflects original bedding layers. These have been deformed into tight folds, providing evidence of the severe deformation these rocks have experienced. Note rusty-looking pods, which get their colour from the weathering of pyrite (iron sulphide - also known as fool's gold).

Battle Harbour- a geological treasure in eastern Labrador

No hammers, chisels, knives, etc., please!

Battle Island provides a window into the facinating world of geology - especially events affecting eastern Labrador during the last 1500 million years.This brochure summarizes geological features on Battle Island using seven sites, numbered 1 to 7 on the map. If time is short, just visit Site 1, which captures the key elements of the geological history of the island. Allow 3-4 hours to visit all sites. For information beyond that given here, consult a detailed report on the geology of Battle Island, available from the Battle Harbour Historic Trust.

Site 5
The black rock at this site is **amphibolite** (metamorphosed basalt) forming a **sill** about 75 m thick. Sills form when magma (in this case basalt) is injected along layers in its host rock and wedges them apart (whereas dykes form when magma fills fractures that cut across layering). The basalt sill was intruded between 1500 and 1030 million years ago, when it was metamorphosed - about the same time as the pegmatites were emplaced (some of which also intrude the amphibolite). In detail, two sills are present, separated by remnants of psammite.



LEGEND

PHANEROZOIC (younger than 570 million years old)
- Soil
- 9 Basaltic dyke

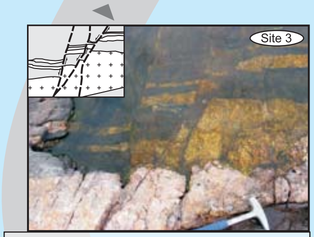
PROTEROZOIC (older than 570 million years old)
Intrusive rocks
- 8 Pegmatite (granitic magma intruded along fractures in rock)
- 7 Amphibolite (basaltic magma injected between older rock layers, later metamorphosed)

Supracrustal rocks
- 6 Calcareous psammite (metamorphosed lime-rich sandstone)
- 5 Calc-silicate rocks (metamorphosed muddy limestones)
- 4 Psammite (metamorphosed sandstone)
- 3 Calc-silicate rocks (metamorphosed muddy limestone)
- 2 Mixed unit of psammite, calc-silicate schist and pelitic schist
- 1 Cross-bedded psammite (metamorphosed sandstone; see reverse side for explanation of cross-bedding)

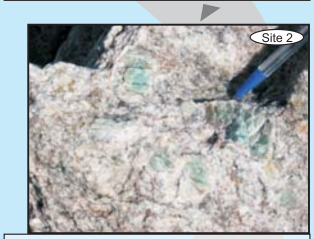
- Aircraft crash site
- Flag pole
- Radio mast
- Garden
- Dam
- Cemetery
- Bulldozer's grave (pet dog)
- Fish flake
- Steps
- Bridge
- Pathways
- Building
- Building foundation
- Church
- Cairn
- Rock cliff
- Fault

Site 1
The key feature at this site is the brown weathering rock (see photo to left). This is a **basaltic dyke**, formed from magma (molten rock) injected along a fracture. The dyke's age is uncertain but younger than 570 million years.
The basaltic dyke cuts across two rock types, one pink and the other grey. The pink rock is **pegmatite**, which, like the basaltic dyke was injected along fractures, but, in this case, the magma was granitic. The pegmatites are about 1000 million years old (see Site 2), and have been bent and buckled due to deformation at that time.
The grey rocks were originally deposited as sand between 1500 and 1030 million years ago. After deposition they were buried and transformed by heat and pressure (metamorphism) into their present state (to a rock termed **psammite** by geologists - with a silent p!)

Site 4
The light grey rocks are termed **psammite** (silent p), which was deposited as sand, then buried, heated and deformed. The black streaky layers in the rock are concentrations of heavy minerals defining **cross-bedding**, and the black spots in the inset photo are **porphyroblasts** (see explanations on obverse). This is the only place in eastern Labrador where cross-bedding in psammite is preserved. West of Site 4, and east of amphibolite (metamorphosed basalt) at Site 5, is a 25-m-thick unit of mixed psammite, calc-silicate rock and pelitic schist (metamorphosed sand, lime-rich sand and mud).

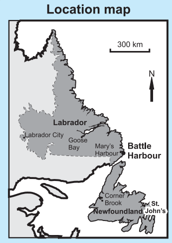


Site 3
Surfaces across which rocks have been offset are termed **faults**. Fault movements take place very quickly and are the cause of earthquakes. At this location, the rocks have been displaced roughly 20 m from one side to the other. This site is located on the most significant fault on the island, named the Cemetery fault. A detail of the fault is shown in the photo above. The yellow (under water) and pink are the same rock type.



Site 2
The specific point of interest here is the green, semi-precious mineral **amazonite** (see obverse for details). The amazonite is confined to a deformed pegmatite intruded 1024 million years ago (an age determined by isotopic methods). The pegmatite is one of two on Battle Island containing amazonite, and similar pegmatites are known elsewhere in southeast Labrador.

Location map

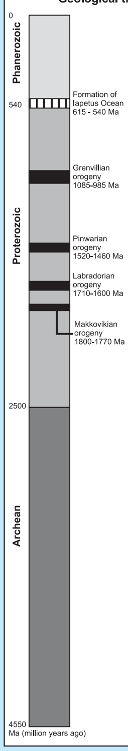


*Brochure prepared for the **Battle Harbour Historic Trust** by Dr. Charles F. Gower, Geological Survey, Government of Newfoundland and Labrador*

www.battleharbour.com
www.gov.nl.ca

Battle Harbour: Time, Geological Processes and Minerals

Geological time and eastern Labrador



The Earth is believed to be about 4550 million years old.

Earth scientists have traditionally recognized three main divisions of geological time, namely **Archean**, **Proterozoic** and **Phanerozoic**.

Almost all the rocks in southeastern Labrador are Proterozoic. They formed during relatively short (geologically speaking), but very active, mountain-building events termed **orogenies**.

The oldest recognized rocks were formed between 1800 and 1770 million years ago. These are more common farther north, in the Makkovik region, hence the name **Makkovikian Orogeny**.

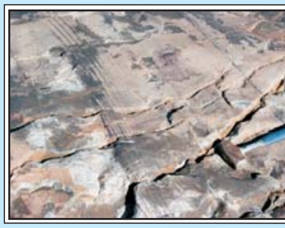
The next period of activity, for which evidence is found across southern Labrador, occurred between 1710 and 1600 million years ago. It is known as the **Labradorian Orogeny**.

After another (relatively short) break in geological upheavals, the region was again in turmoil, between 1520 and 1460 million years ago, during the **Pinwarian Orogeny**, which takes its name from southeastern Labrador.

The final major and most cataclysmic event occurred between 1085 and 985 million years ago, and is termed the **Grenvillian Orogeny**. This event is recognized throughout the southern part of the Canadian Shield. Time-equivalent orogenic events are known throughout the world resulting in one of the biggest re-organizing of crustal plates the Earth has ever known.

The last major event in the region was a period of crustal break-up between 615 and 540 million years ago. This lead to the formation of an ancient, and now vanished, sea, to which geologists have given the name **Iapetus Ocean**.

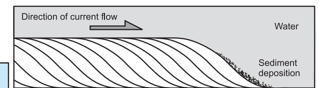
Still younger events, minor and of uncertain exact age, have been recognized in eastern Labrador.



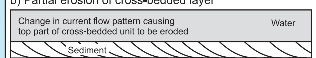
Cross-bedding

In some rocks, especially sandstones, it is common to see certain bedding layers oblique to the general 'lie' of the geological formation. In the photo to the left, these are the dark streaks, rich in heavy minerals. These are truncated by the lighter layer to its left. This structure, formed during sediment deposition, is called **cross-bedding**. It results when there is a decrease in current velocity, thus allowing the sediment to be deposited, creating the sigmoidal curved structures shown in the diagrams below. A good analogy is repeatedly filling and then emptying a wheelbarrow down a slope.

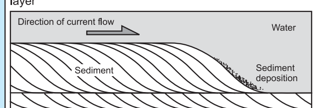
a) Deposition of cross-bedded layer



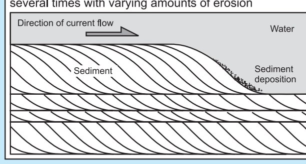
b) Partial erosion of cross-bedded layer

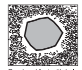


c) Renewed sedimentation on top of previously eroded layer

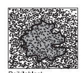


d) The cycle of deposition and erosion repeated several times with varying amounts of erosion





Porphyroblast with halo



Poikiloblast

Porphyroblasts and poikiloblasts

A porphyroblast is a large mineral crystal in a metamorphic rock that has grown within a finer grained matrix as a result of chemical reactions that took place when the rock was hot (say 400-700°C). Commonly, porphyroblasts are surrounded by haloes, which result from material that the prophyroblast needed to grow being 'sucked' out of the matrix.

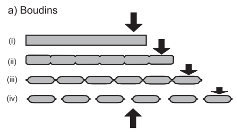
If the porphyroblast does not require the surrounding minerals for growth it shoulders them aside, or simply grows around them. The unwanted material ends up as inclusions in the porphyroblast. A porphyroblast with lots of inclusions is known as a poikiloblast.

The word porphyroblast has obscure roots. The 'porphyr' part comes from a related Greek word meaning purple, the colour of an attractive rock containing large crystals and used for ornamental purposes. The 'blast' part comes from a Greek word meaning germ, reaching geology through medical terminology for tumours.

Boudins and Buckles

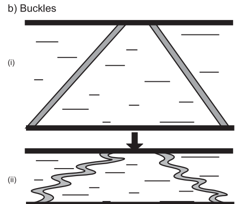
When thin sheets of rock, such as dykes, are deformed, they experience either **boudinage** or **buckling**, depending on their original orientation relative to how they are being squashed. Remember that the rocks, although not molten, were hot and capable of flowage (*i.e.*, ductile).

a) Boudins

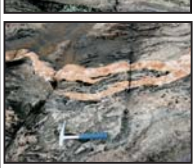


If the sheet of rock is oriented at right angles to the direction of squashing, it will either break or stretch depending on its ability to flow relative to its host rock. If ductile, it will start to thin at points of weakness (necking) and eventually break into pods (photo, top left, light-coloured rock). These pods are called boudins, a word which has it origin in French, meaning sausage.

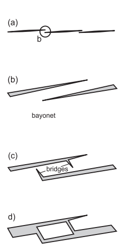
b) Buckles



If the sheet of rock is in a plane at an oblique angle to the direction of a squashing, it will shorten by buckling. If the sheet of rock is inclined to the right it will shorten into a series of S shapes (photo, middle left). If inclined to the left it will shorten into Z shapes (photo, bottom left). These 'snake rocks' are found all over Battle Island, making it a veritable geological serpents' nest.



Bayonets and Bridges



a) An igneous dyke is a tabular body of rock formed when molten rock (magma) is injected into a pre-existing fracture. Although dykes are typically drawn as continuous linear features on geological maps, commonly they form *en echelon*, as shown to the left (a and, in detail, b)

b) As magma continues to be injected into the fracture, separate en echelon segments will join. The process starts by the fractures lengthening and getting wider, resulting in the ends (**bayonets**) of fractures overlapping.

c) The next stage is cross fracturing (**bridges**) between two bayonets. The bridges can form at the tip of the bayonet, or at several points along its side. The bridges are filled with magma as they develop (photo, top left in this box).

d) Eventually the bridges will extend completely across the gap and link up two bayonets. If only one bridge forms, the dyke will simply have a stepped appearance, with or without bayonets preserved. If two or more bridges develop, blocks of the host rock will get trapped within the now-joined dyke (photo, bottom left).

Minerals

All these minerals are on Battle Island. If you find them, please do not damage. Leave for others to see.

Amazonite. The pale green mineral in the pegmatitic pod is amazonite, a lead-bearing feldspar. The amazonite here is not very high quality, but where it has a deeper, richer blue-green colour it is considered semi-precious. Amazonite was regarded as sacred by the ancient Egyptians. It is reputed to cool and sooth the mental state, to inspire hope and confidence, make your married life happier, and to be useful in activating lazy teenagers.

Microcline and Hornblende. The pink mineral is microcline and the black mineral is hornblende. Microcline (a potassium feldspar) is the major mineral in pegmatites on Battle Island. Feldspar is used in the ceramics and glass industries.
Hornblende is a member of a complex group of iron-magnesium aluminum silicates. It does not have major ornamental or industrial use. It is credited with improving wisdom, communication and balance.

Quartz. The pod in the centre of the photo is made of quartz (silicon dioxide). Quartz is abundant in most rocks on Battle Island and can easily be seen in the pegmatites. It is used in ceramics, glass, optical instruments, electronics, and abrasives. Quartz is favoured by mystics, who recommend it for aligning one's consciousness with electromagnetic forces of the universe.

Fluorite. Fluorite (calcium fluoride) is the purple mineral in the centre of the pod. This is the only known example of fluorite on Battle Island, but, in general, fluorite is not uncommon in pegmatite. Fluorite is used as a flux in steel making (a flux reduces the melting temperature of materials to which it is added), and in the glass, ceramics and optical industries. It is known as a 'brain' stone, aiding concentration, objectivity, truth and the intellect.

Garnet. Garnet comes in many varieties, depending mainly on its iron, magnesium, calcium or manganese content. It is the red-brown mineral in the photo - probably an iron- and calcium-rich variety. Because of its hardness, garnet is prized as a gemstone and used extensively as an abrasive (e.g. sandpaper). It is claimed to combat lethargy and depression, blood deficiency diseases, and to be good for sexual desire.