GEOLOGICAL ASSOCIATION OF CANADA
NEWFOUNDLAND AND LABRADOR SECTION

FALL FIELD TRIP FOR 2011
(September 30 to October 2)

FOGO ISLAND
EXPLORING A COMPOSITE BIMODAL MAGMA CHAMBER AND ITS VOLCANIC SUPERSTRUCTURE

Field Trip Guide and Background Material

Andrew Kerr
Geological Survey of Newfoundland and Labrador
Department of Natural Resources
PO Box 8700
St. John's, NL, A1B 4J6
Canada

September, 2011

TABLE OF CONTENTS

PART TWO - FIELD TRIP STOP DESCRIPTIONS

DAY ONE (Afternoon)

DAY TWO

DAY THREE

ACKNOWLEDGMENTS

The idea of running a field trip to Fogo Island is not a new one, and I must acknowledge many people for helping to finally make it happen. First and foremost, the Shorefast Foundation is thanked for showing such interest in the topic, and for helping so much to set up the logistical arrangements. In particular, the interest and enthusiasm of Zita Cobb, and energetic help from Paddy Barry, Maria Giovannini and Pauline Payne, helped to make this excursion possible. Shorefast's interest in the geology of Fogo Island finally provided my own long-standing curiosity with a purpose beyond mere scientific interest. I also wish to acknowledge Robert (Bob) Wiebe, David Hawkins and several of their coworkers for developing such interesting ideas through their detailed field and laboratory studies of composite bimodal intrusions on the coast of Maine. Bob and David's hospitality in 2009 provided a chance for me to visit these classic areas in person, which did much to convince me that at least some of these concepts could profitably be applied on Fogo Island. In time, I hope that more work on the island will add to this knowledge of what goes on deep within the crust in places that we can never hope to visit.

The Geological Survey of Newfoundland and Labrador (Department of Natural Resources) is thanked for in-kind logistical support for this field trip and for allowing use of Survey vehicles, and Memorial University is thanked for providing a subsidy to assist with a discounted student rate. Nicole's Café and their staff are thanked in advance for excellent food and refreshment, and the Island Bake Shoppe is thanked for helping with sandwiches and lunch arrangements.

All visitors to Fogo Island come away impressed with the friendliness and hospitality of the islanders, and this has certainly been my experience from many visits over many years. I have more recently come to appreciate their strong interest in the natural history and environment of their home, and I hope that this guidbook will help to further develop that interest, and assist in the wider initiatives of the Shorefast Foundation.

PREFACE

Why Fogo Island ?

Fogo Island and Change Islands are amongst the most unique and picturesque places on the northeastern coast of Newfoundland. They are also blessed with interesting and diverse geology. GAC-NL has long wanted to organize a fall field trip to the islands but it never seemed to happen, in part because of logistical constraints such as ferry schedules and limited accommodations.

The framework to finally develop such a field trip came in the last two years, with the establishment and growth of the Shorefast Foundation, aimed at developing the islands' economy in part through tourism and the arts. Anyone who has ever visited Fogo Island knows that geology is written large upon its landscapes, and Shorefast was keen to learn more about this aspect of natural history. This field trip grew in part from efforts to provide ssome geological information to the Foundation, and to awareness of this vital heritage within the community. The work of Shorefast in renovating houses and promoting local enterprises also provided the logistical framework needed for such a trip. It is hoped that this guidebook will have long-term value to the Shorefast Foundation and to the residents of the islands.

Typically, geological field trips highlight areas that are well-understood or the locations of new detailed research. This is not such a trip, for many aspects of Fogo Island geology remain poorly understood, and the area has never received the attention that it merits. Instead, this trip provides a chance to explore interesting outcrops and perhaps collectively find interpretations that might unravel their fascinating disorder. Should that objective not be realized, we can at least strive for some good discussion on the research needed to seek such answers. There is lots of potential for such work in this area, and much to talk about.

Overview of Field Trip

The field trip is focused on Fogo Island, which has the most diverse geology. Although the Change Islands contain some interesting localities, these are not as easily accessible. Fogo Island provides us an opportunity to explore a composite bimodal batholith, formed from a complex magma chamber in which mafic and felsic magmas coexisted in space and time. It is one of several mid- to late Silurian bimodal plutonic suites in east-central Newfoundland, but is the only one that is well-exposed on the coast. Geological elements of Fogo Island represent several levels within this complex magma chamber, perhaps including the floor, the roof and - most importantly - the boundaries between contrasting lower mafic and upper felsic components. To add to the interest, part of the island likely represents the associated volcanic sequences and their feeder systems. These are distributed systematically from northwest to southeast, allowing a transect from the paleosurface to rocks that formed at depths of several kilometres. The wider area also preserves sedimentary rocks of the older Badger and Botwood groups, and also rocks of the Indian Islands Group, which are probably very similar in age to the volcanic and plutonic rocks, but represent a radically different environment.

The first partial day of the trip introduces essential concepts of Fogo Island geology in the form of evidence for coexisting mafic and felsic magmas, emplacement mechanisms and the northwest-southeast zonation from near-surface to deep plutonic environments. The second day focuses on deeper regions of the magma chamber, including the possible floor, variably layered mafic rocks of the Seldom and Tilting areas, and some zones where contrasting mafic and felsic magmas interacted and attempted to mix with variable success. The third day of the field trip will emphasize the high-level granites and varied volcanic rocks of northwestern Fogo Island, and will end (appropriately) at Brimstone Head, reputedly close to one of the four corners of the Flat Earth. Following departure from Fogo Island, there will be an overnight stop in Gander, so as to avoid the perils of night driving in Newfoundland.

A Personal Perspective on Fogo Island Geology

I first visited Fogo Island in 1989, at the outset of a project intended to examine the geology and geochemistry of granites across Newfoundland. In 1991, I stayed for a longer period to complete field work, and quickly became intrigued by its ever-changing and ever-challenging geology. The varied landscapes and superb natural environment of the island just as quickly exerted a lasting attraction. I suggested that I should undertake a detailed mapping project on the islands, but this did not happen for a variety of reasons, and I moved on to other work. The island was eventually mapped as part of a regional Geological Survey of Canada project, but not in the detail truly required. My subsequent visits were mostly for recreational hiking, but I could not resist looking at the geology under my feet, and never lost my interest in understanding it better. Over the same period, work by others - notably in igneous rocks of similar age on the coast of Maine - provided many new insights and ideas on composite magma chambers, which I felt should also apply to Fogo Island. In 2009, I visited the islands off the coast of Maine independently and with local experts Bob Wiebe (Franklin and Marshall College, Pennsylvania, USA) and David Hawkins (Wellesley College, Massachussets, USA). I returned with a firmer conviction that at at least some of these ideas could be applied, and came back to the green shores of Fogo with naïve hopes for more understanding and less confusion.

This field guide integrates scattered observations from previous field work and visits with more recent observations and also material from a long-abandoned draft manuscript. It is far from being an unified explanation for the geology of the island, and questions still outnumber potential answers. Undoubtedly, some interpretations and perhaps a few observations herein will prove incorrect - realistically, I would expect nothing less. Nevertheless, attempting to synthesize data and identifying problems is the first step in developing testable models, and I hope that daytime discussions on outcrops and evening discussions elsewhere might lead further along this road.

SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

Field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

Specific Hazards

Many of the stops on this field trip are in coastal localities. Access to the coastal sections normally requires short hikes, in some cases over rough, stony or wet terrain. This field trip involves some moderate hikes, of which the longest is about 5 km. Participants should be in good physical condition and accustomed to exercise. The coastal sections contain saltwater pools, seaweed, mud and other wet areas; in some cases it may be necessary to cross brooks or rivers. There is a strong possibility that participants will get their feet wet, and we recommend waterproof footwear. We also recommend footwear that provides sturdy ankle support, as localities may also involve traversing across beach boulders or uneven rock surfaces. On some of the coastal sections that have bouldery or weed-covered sections, participants may find a hiking stick a useful aid in walking safely.

Coastal localities present some specific hazards, and participants MUST behave appropriately for the safety of all. High sea cliffs, such as those at Brimstone Head, are extremely dangerous, and falls at these localities would almost certainly be fatal. Participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow instructions from leaders. Coastal sections elsewhere may lie below cliff faces, and participants must be aware of the constant danger from falling debris. Please stay away from any overhanging cliffs or steep faces, and do not hammer any locations immediately beneath the cliffs. In all coastal localities, participants must keep a safe distance from the ocean, and be aware of the magnitude and reach of ocean waves. Participants should be aware that unusually large "freak" waves present a very real hazard in some areas. If you are swept off the rocks into the ocean, your chances of survival are negligible. If possible, stay on dry sections of outcrops that lack any seaweed or algal deposits, and stay well back from the open water. Remember that wave-washed surfaces may be slippery and treacherous, and avoid any area where there is even a slight possibility of falling into the water. If it is necessary to ascend from the shoreline, avoid unconsolidated material, and be aware that other participants may be below you. Take care descending to the shoreline from above. Finally, be aware that some people are convinced that the edge of the Flat Earth lies dangerously close to Brimstone Head. GAC-NL cannot endorse this information, but the field trip leaders will not be coming after you should you stray too close to this mythical feature.

A small number of field trip stops are located on or adjacent to roads. The roads on Fogo Island are not busy, but they are narrow and have many bends. Participants should make sure that they stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Roadcut outcrops present hazards from loose material, and should be treated with the same caution as coastal cliffs. Weather is unpredictable in this area and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, sturdy footwear are essential at almost any time of the year.

The hammering of rock outcrops, which is in most cases completely unnecessary, represents a significant "flying debris" hazard to the perpetrator and other participants. For this reason, we ask that outcrops not be assaulted in this way; if you have a genuine reason to collect a sample, inform the leaders, and then make sure that you do so safely and with concern for others. The trip visits some outcrops that have unusual features, and these should be preserved for future visitors. Frankly, our preference is that you leave hammers at home or in the field trip vans.

Subsequent sections of this guidebook contain the stop descriptions and outcrop information for the field trip. In addition to the general precautions and hazards noted above, the introductions for specific localities make note of specific safety concerns such as traffic, water, cliffs or loose ground. Field trip participants must read these cautions carefully and take appropriate precautions for their own safety and the safety of others.

PART ONE - SUMMARY OF GEOLOGY AND CONCEPTS

INTRODUCTION

LOCATION AND REGIONAL SETTING

Fogo Island lies 10 to 20 km from the Newfoundland coast, north of Carmanville in Gander Bay and east of New World and Twillingate islands in Notre Dame Bay (Figure 1). There are numerous smaller islands in this area, of which the largest of these are the Change Islands, located off the west coast of Fogo Island. The outermost islands are the Little Fogo Islands, sitting within the open Atlantic Ocean, about 8 km north of Fogo Island. The largest of these myriad tiny islands once supported a community, but is now used only on a seasonal basis. Fogo Island is the largest of the "true" offshore islands of Newfoundland (i.e., those that lack causeway or bridge connections) and is also the second most populated (after Bell Island), with about 2800 people distributed amongst 10 communities (Figure 1; Figure 2; Figure 8). Of the other islands, only the Change Islands are inhabited year-round, with a permanent population of less than 300. The economy of Fogo and Change islands was for centuries dominated by the fishing industry, and this continues to be important in modern times. Tourism and other recreational industries are increasingly important, with much recent development in these sectors centred around the efforts of the Shorefast Foundation.

From a geological perspective, Fogo Island sits within the Dunnage Zone of the northern Appalachians, defined by the remnants of volcanic arcs and back-arc basins formed within the early Paleozoic Iapetus Ocean (Williams, 1979; Figure 1). Specifically, it sits within the Exploits Subzone of Williams et al. (1988), representing rocks formed on the peri-Gondwanan side of the Iapetus Ocean. Zonal subdivisions within the Appalachian Orogenic Belt are, of course, defined with reference to Ordovician and older rocks. Although rocks of this age occur in the area around Carmanville, and also on New World Island, they are all but absent from Fogo and Change islands, which are underlain by rocks of Silurian to possibly Devonian age (Figure 1; Figure 2). The sedimentary and volcanic rocks on Fogo Island are assigned to the Silurian Botwood Group (defined by Williams, 1972). The plutonic rocks that underlie most of Fogo Island are not well dated, but have given late Silurian to Devonian U-Pb ages of ca. 420 Ma and ca. 410 Ma (Aydin, 1995). Field relationships indicate that they are at least in part younger than the Botwood Group, as they clearly intrude the sedimentary rocks. The Change Islands are also dominated by rocks assigned to the Botwood Group, but Currie (1997) assigned one small area to the older (partly Ordovician) Badger Group. Plutonic rocks are not present on Change Island, although dykes are abundant. No major fault zones are mapped on Fogo Island, although minor faults occur in several areas. However, important faults in the Hamilton Sound area define the complex zone generally known as the Dog Bay Line (Williams et al., 1993; Currie, 1997). The Dog Bay line was interpreted as an important tectonic boundary during the latest stages of the closure of the Iapetus Ocean. However, the significance of geological contrasts across it were questioned on the basis of more detailed work (Dickson, 2006). The Red Indian Line, interpreted as the complex boundary between the peri-Laurentian and peri-Gondwanan realms of the Appalachian Orogenic Belt (Williams et al., 1988) passes through Twillingate and New World islands, to the west of Fogo Island (Figure 1).

The *Fogo Island Intrusion*, as it is termed here, is one of numerous Silurian to Devonian plutonic suites that form the major magmatic pulse in the Central Mobile Belt of the Newfoundland Appalachians. From a compositional perspective, these are quite unlike modern subduction-related batholiths, and were instead interpreted in terms of post-collisional lithospheric delamination, leading to mantle-derived mafic magmas and subsequent anatectic melting of the crust (e.g., Kerr, 1997). Whalen et al. (2006) suggested that those in the Notre Dame Subzone were related to slab break-off following arc-continent collision, which is essentially a variant of this earlier model. Silurian-Devonian Plutonic suites in the Exploits Subzone are typically bimodal, including abundant mafic rocks, and have generally been studied in less detail than those of the Notre Dame Subzone. The along-strike continuation of the Exploits Subzone is best represented by the coastal regions of Maine, USA, where plutonic rocks of similar age and composition are superbly exposed on several offshore islands. This long-distance connection is important in the context of this field trip.

HISTORY OF GEOLOGICAL INVESTIGATIONS

Fogo Island has very interesting geology, but has seen few detailed studies on an island-wide basis; nevertheless, its bibliography includes some well-known names. The earliest geological maps came from the work of D. M. Baird (1958), who later went on to become director of the Geological Survey of Newfoundland, and a renowned museum director. Baird was assisted by a young graduate student from St. John's named Harold Williams, who focused on the mafic rocks of the Tilting area. Harold became much better known as "Hank", and went on to contribute much to our understanding of the Appalachian Orogen and the application of plate tectonics to the geological record. C. J. Hughes (1972) completed some petrological work on rocks near Fogo Town, and D. F. Strong and W. L. Dickson (1978) discussed the island's geology in general terms as part of a regional study. In the same time period, R. G. Cawthorn, visiting Newfoundland on sabbatical, became interested in the Tilting area, and built upon Hank's work with a petrological study of these interesting rocks (Cawthorn, 1978). Cawthorn went on to become a well-known petrologist and an expert on platinum deposits of southern Africa. Hamish Sandeman (1985) completed a thesis study on the granites and volcanic rocks of western Fogo Island, results of which later formed a short paper (Sandeman and Malpas, 1995). A subsequent Ph.D. Thesis project, involving isotope geochemistry and some geochronology, was undertaken by Nurdin Aydin in the Tilting area (Aydin et al., 1994; Aydin, 1995).

In the early 1990s, the island formed part of a regional geochemical project on granites, which is how I first developed an interest in its geology (Kerr, 1994; Kerr et al., 1994). K. L. Currie of the Geological Survey of Canada published a revised geological map as part of a regional synthesis (Currie, 1997) and a short paper related to the emplaceement mechanisms (Currie, 2003). In many respects, this map is less detailed than that of Baird (1958), although it does indicate some important spatial relationships; Figure 2 shows both maps, rather than choosing between them. There are significant differences between the maps produced by Baird (1958) and Currie (2003), and some of these remain to be resolved. However, some inconsistencies simply reflect the intrinsic difficulty of defining units and positioning boundaries amongst complex and variable rocks. There has been little subsequent work of a formal nature on the island.

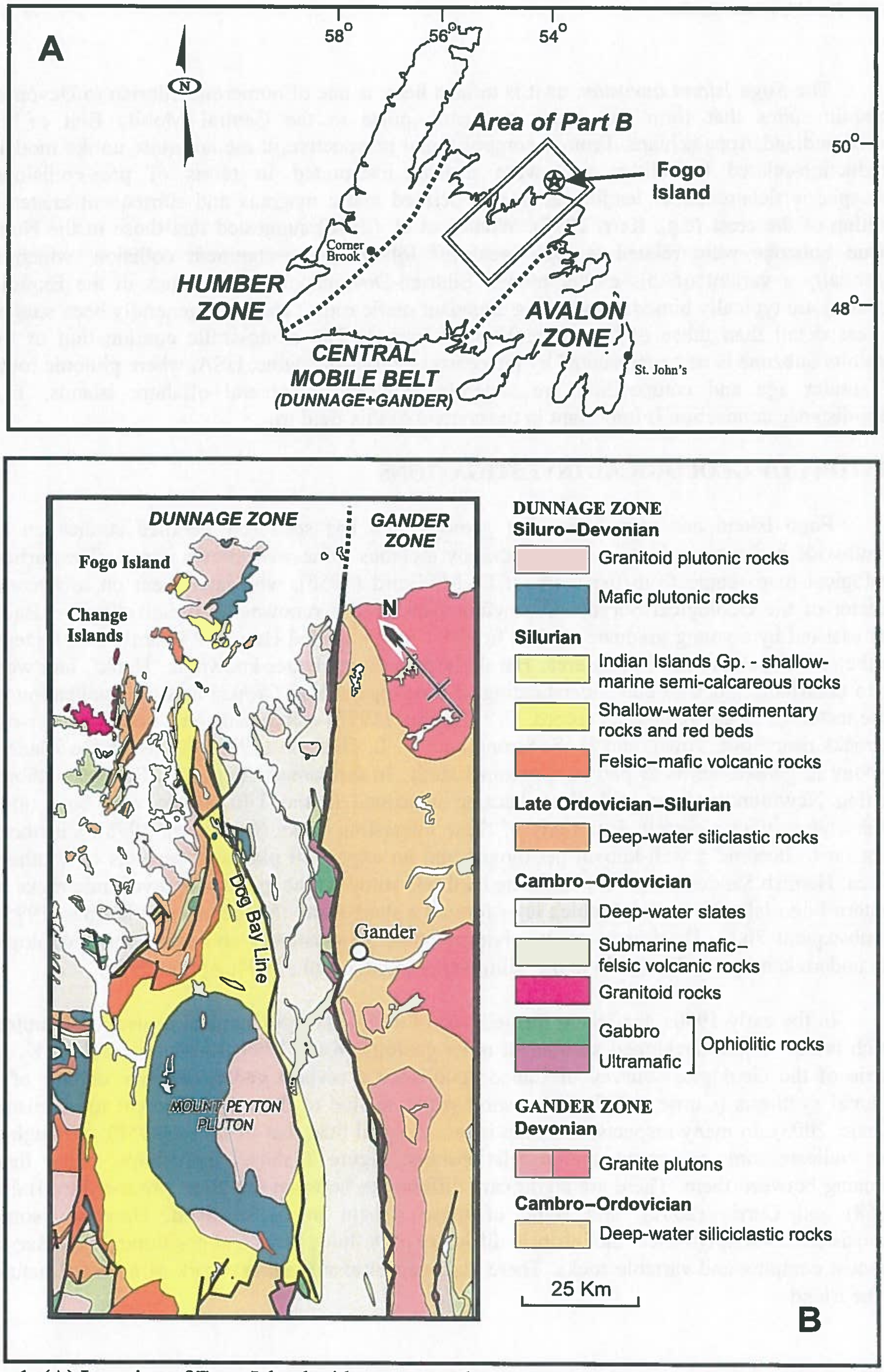


Figure 1. (A) Location of Fogo Island with respect to the tectonostratigraphic zones of the Newfoundland Appalachians. (B) Regional geology of the area surrounding Fogo Island, in the Gander Zone and Exploits Subzone of the Dunnage Zone. After Williams et al., 1988.

GENERAL GEOLOGY OF FOGO AND CHANGE ISLANDS

The geographic distribution of rock types on Fogo Island is important. Rocks assigned to the Botwood Group occur on a mappable scale only in the northwestern and western parts of the island, where they strike east-west, and generally dip to the north (Figure 2). They are divisible into a lower package of sedimentary rocks (the Fogo Harbour Formation) and an upper sequence including felsic volcanic and pyroclastic rocks (the Brimstone Head Formation). Volcanic rocks are also abundant on the Little Fogo Islands. Both components were defined by the initial mapping of Baird (1958). Rocks thought to be equivalent to the Fogo Harbour Formation also occur widely as xenolith-rich zones in younger intrusive rocks. Intrusive rocks dominate the remainder of the island, and these are here collectively grouped as the Fogo Island Intrusion, although their composition and character varies widely. In the south-east of Fogo Island, gabbroic to dioritic rocks are dominant, although granitic rocks occur locally; mafic rocks are also prominent around Tilting, at the northeast corner of the island (Figure 2). The north and central parts of the island are dominated by granites, but the map pattern in these areas is locally complex, with scattered areas of mafic rocks apparently surrounded by granite. The granites are generally homogeneous, but distinctive equigranular, silica-rich, leucocratic granites ("alaskites") occur in the west and northwest, notably adjacent to the contact with the sedimentary rocks. Similar rocks are also seen as dykes and smaller intrusive bodies within the sedimentary country rocks in this region, and were indicated by Currie (1997) more widely in inland areas. The most complex rocks on Fogo Island are heterogeneous "diorites" and confusing intrusive breccias that typically occur in the contact regions between the granitic and gabbroic-diorite units; these zones are truly a topic in their own right. Baird (1958) generally indicated these areas simply as "intrusion breccias", whereas Currie (1997) placed some - but not all - as a discrete diorite unit.

The regional distribution of rock types on Fogo Island is consistent with an interpretation in which regional tilting provides a cross-section through a composite mafic to felsic magma chamber, its country rocks, and associated volcanic products. In this model, the mafic rocks form the lower section of the magma chamber, and the granitic rocks form its upper section. The compositionally evolved and texturally variable granitic rocks of northwestern Fogo Island possibly represent the uppermost section and roof zone of the magma chamber (although other explanations can be considered), and felsic volcanic rocks in this area represent extrusive equivalents of granitic plutonic rocks seen elsewhere on the island. There do not appear to be any mafic volcanic rocks on Fogo Island, although these may occur on the Little Fogo Islands. Thus, a transect from northwest to southeast across Fogo Island is a voyage from the near-surface extrusive environment into regions of a magma chamber that originally lay several kilometres in the subsurface. This concept is certainly implicit in the descriptions and interpretations of Baird (1958), and was also part of the general framework used in subsequent papers by Sandeman and Malpas (1995) and Currie (2003).

More than one interpretation has been proposed for the geology of the Change Islands, notably with respect to volcanic rocks. Baird (1958) correlated mafic and felsic volcanic and pyroclastic rocks in the north of the islands with those of the Little Fogo Islands, but Currie (1997) suggested that they should instead be assigned to the Laurenceton Formation, which is an older component of the Botwood Group. Eastler (1969) interpreted some enigmatic igneous rocks on the larger island as a fine-grained granite, whereas Currie (1997) considered them to be rhyolites older than the Ordovician Badger Group, which he also mapped in a small area. He also grouped volcanic rocks in southern Change Islands with the Brimstone Head Formation, to which he also assigned the rocks of the Little Fogo Islands. Numerous dykes occur within sedimentary rocks on Change Islands, and on nearby islands, and these were equated to the Fogo Island Intrusion by all. Baird (1958) also distinguished sedimentarry rocks of southern Change Islands as a separate formation (South End Formation) that is lithologically distinct and possibly older than the Fogo Harbour Formation. This distinction was also maintained by Sandeman and Malpas (1995).

GEOLOGY OF FOGO ISLAND

NOMENCLATURE AND TABLE OF FORMATIONS

For the purposes of this guide, sedimentary and volcanic rocks on Fogo Island are assigned to the Botwood Group, and all plutonic rocks are assigned to the Fogo Island Intrusion (Fogo Island batholith of Currie, 2003). Individual components of the latter are assigned names to distinguish them for discussion (e.g. Tilting Layered Complex, Hare Bay Granite). The Botwood Group is assumed to be of Silurian age, as indicated by faunal evidence, but the Fogo Island Intrusion is of uncertain age, as geochronological data are in part ambiguous (see later discussion). It is possible that it could be earliest Devonian, rather than Silurian.

BOTWOOD GROUP

Fogo Harbour Formation

This formation was originally defined by Baird (1958) and includes all sedimentary rocks on Fogo Island. The Fogo Island Formation is dominated by thinly-bedded grey to greenish siltstones, intercalated with thin sandstone units. Soft-sediment deformation, and other features such as sand dykes are present in outcrops, and slump-related intraformational breccia and conglomerate also occur. Currie (1997) suggested that volcanic detritus becomes more abundant in the sandstones towards the top of the formation. Sandeman and Malpas (1995) further suggested that thin felsitic igneous units within the formation south of Fogo Town were ash-flow tuffs, although Currie (1997) contended that they were more likely high-level sills. The age of the formation is not known with certainty, as the rocks are generally unfossiliferous, although some poorly preserved shelly fossils occur near Rogers Cove (see later stop descriptions). Currie (1997, 2003) suggests a minimum age of ca. 422 Ma, based on the fact that rocks correlated with the Fogo Harbour Formation at Dog Bay (in Gander Bay, about 15 km to the southwest) are cut by a granite dyke dated at 422 ± 2 Ma (Elliot et al., 1991). The formation is believed to conformably overlie the volcanic rocks of the Laurenceton Formation, but the contact is not exposed.

Brimstone Head Formation

The main area of the Brimstone Head Formation is in the area of Fogo Town, where it forms a semicontinuous belt defining the rugged northwestern tip of the island. Currie grouped

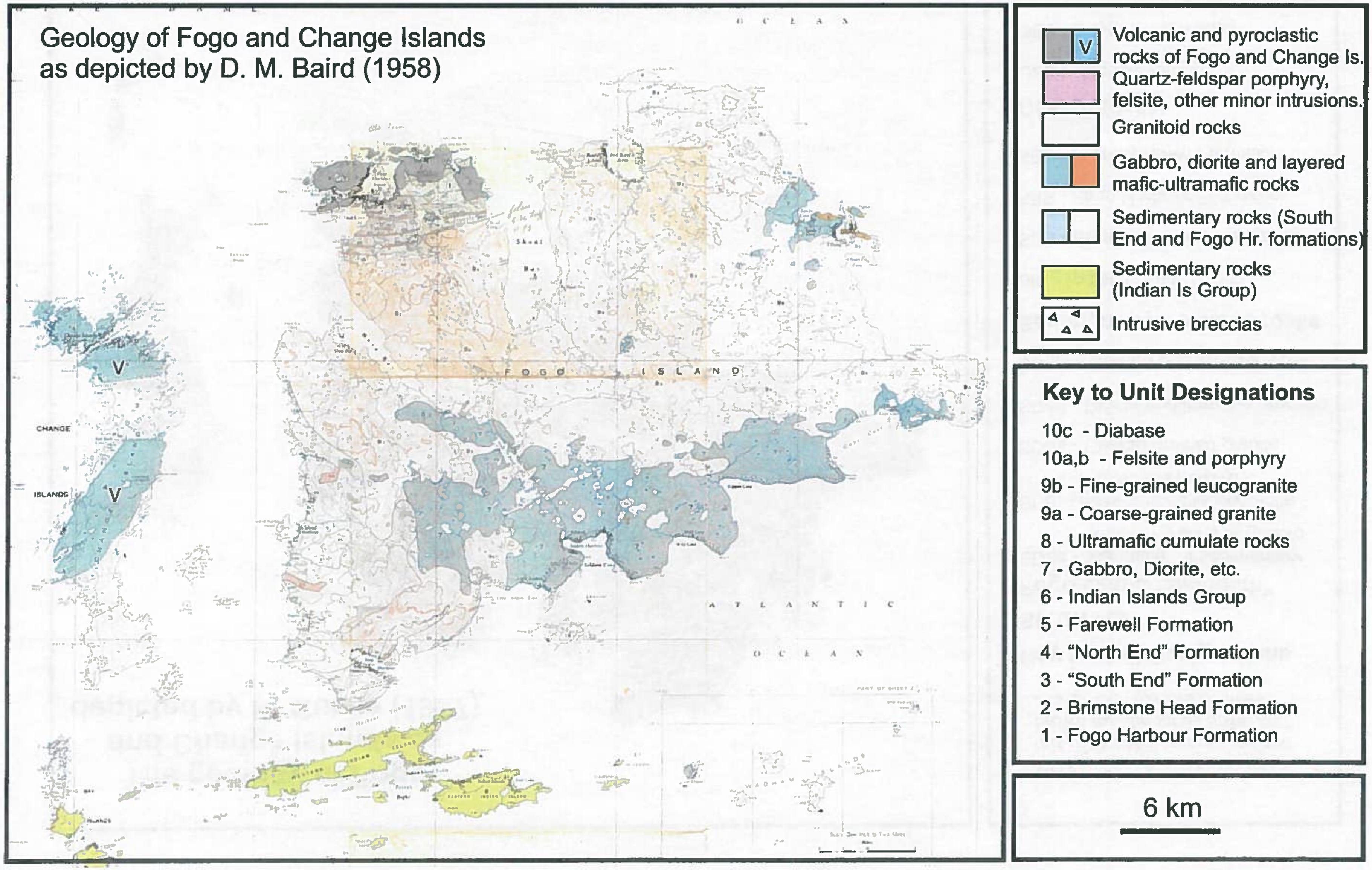
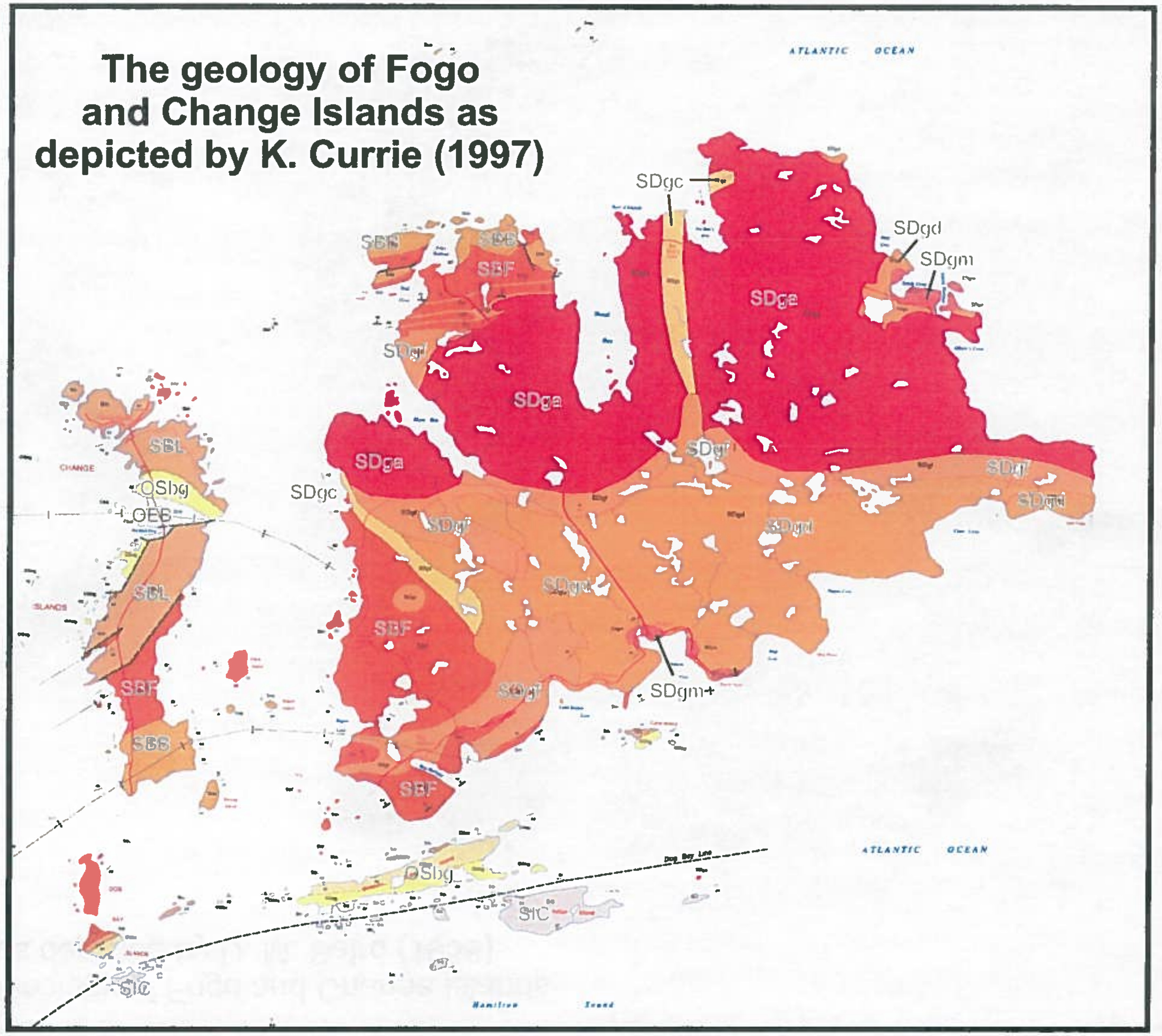


Figure 2(A). The geology of Fogo and Change Islands as depicted by Baird (1958). For locations of field trip stops, see Figure 8.



NOTE: The colour scheme on this map uses orange, red and brown for almost all units, and it is difficult to read at times !

Key to Unit Designations

SILURIAN

Fogo Island "batholith"

SDgc - "Agmatite" of sedimentary rocks in granite or gabbro

SDgf - Fine-grained leucogranite felsite, and porphyry

SDga - Coarse-grained granite

SDgd - Diorite and intrusive breccias

SDgm - Gabbro and layered rocks

Sedimentary/volcanic rocks

SIC - Indian Islands Group

SBB - Brimstone Head Formation

SBF - Fogo Harbour Formation

SBL - Laurencetown Formation

ORDOVICIAN

OSbg - Badger Group

OEB - Baytona Formation

Figure 2(B). The geology of Fogo and Change Islands, as depicted by Currie (1997). For the locations of field trip stops, see Figure 8.

the Little Fogo Islands as part of the formation, which suggests that its thickness is greater than exposures around Fogo Town alone imply. The features of these rocks are best seen in coastal exposures, and inland outcrops are commonly uninformative. Sandeman and Malpas (1995) considered most of the formation to consist of variably welded ash-flow tuffs, overlain by pyroclastic breccias. Currie (1997) refers to three units, presumably these same divisions; lesser rock types include rhyolite sheets, and finer-grained tuffs of possible volcaniclastic origin. True extrusive flows have yet to be recognized on any scale, but the ash-flow tuffs locally exhibit banding that could be flow-related. The Little Fogo Islands are superbly exposed but difficult to access due to sea conditions. A brief visit was made to the islands with Shorefast in 2011, and most outcrops seen were spectacular pyroclastic breccias of felsic composition. Individual breccia units are locally overlain by red conglomerates and sandstones, and locally seem to pass laterally into similar sedimentary rocks, with superb quenched hyaloclastite textures where the two come into contact. Fine-grained, possibly subvolcanic, intrusive rocks were also observed in one area on the islands. More work is required to better define the compositional affinities of these rocks, but they appear mostly felsic, which suggests that they do not correlate with volcanic rocks of northern Change Islands, which are mostly mafic to intermediate pyroclastic rocks. In this respect, the interpretation of Currie (1997) is preferred over that of Baird (1958).

The Brimstone Head Formation has not been dated (although rocks on Little Fogo Islands would appear to be suitable candidates for geochronology). The inference that these rocks might be extrusive equivalents of granites in the Fogo Island Intrusion was made by several workers (Kerr, 1994; Sandeman and Malpas, 1995; Currie, 1997; 2003). However, it remains to be proven through geochronology. The relationship between the Fogo Harbour Formation and the Brimstone Head Formation has generally been viewed as conformable, although a disconformity could be present within the sequence. The attitudes of bedding and structures in the area around Fogo Town suggest some inconsistencies with a simple model in which sedimentary rocks pass upward into a single volcanic sequence.

FOGO ISLAND INTRUSION

Description of the complex intrusive rocks of Fogo Island demands that they be subdivided, although any such system is subjective. A primary division is made here on the basis of composition, into mafic-intermediate rocks (Tilting Layered Complex, and Seldom Gabbro) and granitic rocks (several named units). The dominant granite unit is referred to as the Shoal Bay Granite, but two more restricted units are defined in the west (Hare Bay Granite and Rogers Cove Granite). These terms are after Sandeman and Malpas (1995), although they used the term "microgranite" for the latter two units. To these must be added the numerous dykes and (sills ?) of fine-grained granite that cut the Fogo Harbour Formation, and also cut other units within the Fogo Island Intrusion. The boundary areas between the mafic-intermediate rocks and the granites contain complex rocks that were partly defined as discrete "dioritic" units by Aydin (1995) and Currie (1997); here, these are grouped these with the mafic and intermediate rocks because their exact boundaries are so hard to define. As noted by Currie (1997) these "boundary areas" are in places invaded by younger fine-grained granitoid rocks, which act to obscure geological relations. However, it is not clear if these fine-grained rocks can truly be defined as a separate mappable unit in these areas, especially inland, where some forest cover is impenetrable.

Seldom Gabbro

Mafic and intermediate rocks have their greatest expression in southern Fogo Island, where they form a semicontinuous belt extending from Little Seldom to Cape Cove (Figure 2). The actual contact between mafic rocks and the Fogo Harbour Formation is seen only in one spot near Little Seldom; however, metasedimentary inclusions are widespread in the Seldom Gabbro. Much of the unit is superficially homogeneous in inland exposures, but the coastline reveals its complexity, and there are areas where cumulate layering is present. In detail, it likely consists of several thick sheet-like subunits that are separated by zones rich in metasedimentary xenoliths. These spectacular rocks could be xenolith accumulations within the magma chamber, or products of in-situ dissection of sedimentary sequences during magma emplacement. The southernmost part of the gabbro, around Burnt Point and Kippens Cove, is cut by diabase dykes and composite diabase-felsite dykes. The transition zone between mafic rocks and the granites of the Fogo Island Intrusion is best exposed in the area of Cape Cove and Cape Fogo, where spectacular mixing and mingling textures are developed; unfortunately, this region is not easily accessible without a long hike or a boat ride. I have long wanted to return to the Cape Cove area, because many interesting features are suggested by field notes from the 1990s, but I have yet to accomplish this.

Tilting Layered Complex

The Tilting Layered Complex includes mafic-intermediate rocks around Tilting, where cumulate rocks, including ultramafic rocks, are superbly exposed. These are probably the most extensively studied rocks on the island, starting with the work of Williams (1957) and ending with that of Aydin (1995), but there remain many questions about their origins, and more importantly their relationship to the more extensive Seldom Gabbro, and to the surrounding granites. The most comprehensive published account of the Tilting Layered Complex remains that of Cawthorn (1978), although more detailed information on some aspects is given by Aydin (1995). The geology of the area is indicated in Figure 3.

The Tilting Layered Complex includes gabbro, norite and websterite (a clinopyroxene-orthopyroxene rock). Olivine-bearing cumulates are also present, but this mineral is not abundant. Well-developed cumulate layering in the complex dips at generally steep attitudes to the northeast and northwest, and at least five cyclic repetitions are defined on the shore sections at Tilting Harbour. These consist of basal websterite units, passing upward into norite and gabbro, with coarse-grained hornblende-plagioclase "pegmatite" below the base of the next cycle. On the basis of petrographic and chemical characteristics, Cawthorn (1978) suggested that these represent at least two discrete batches of magma of quartz-tholeiite and olivine-tholeiite affinity; the former possibly directly derived from a mantle source, and the latter from a more fractionated magma. The Tilting Complex is surrounded by granitic rocks (assigned to the Shoal Bay Granite) but separated from these by complex zones, in which dioritic compositions are variably developed. Xenolith-rich zones that resemble those seen in the Seldom Gabbro also exist at least locally. The geometric and genetic relationships between the mafic rocks of the Tilting Layered Complex and the Seldom Gabbro remain enigmatic, but one possibility is that the Tilting area is a "window" through the granite into underlying mafic rocks, created by irregularities in their mutual contact or perhaps by later folding. An alternative view is that the

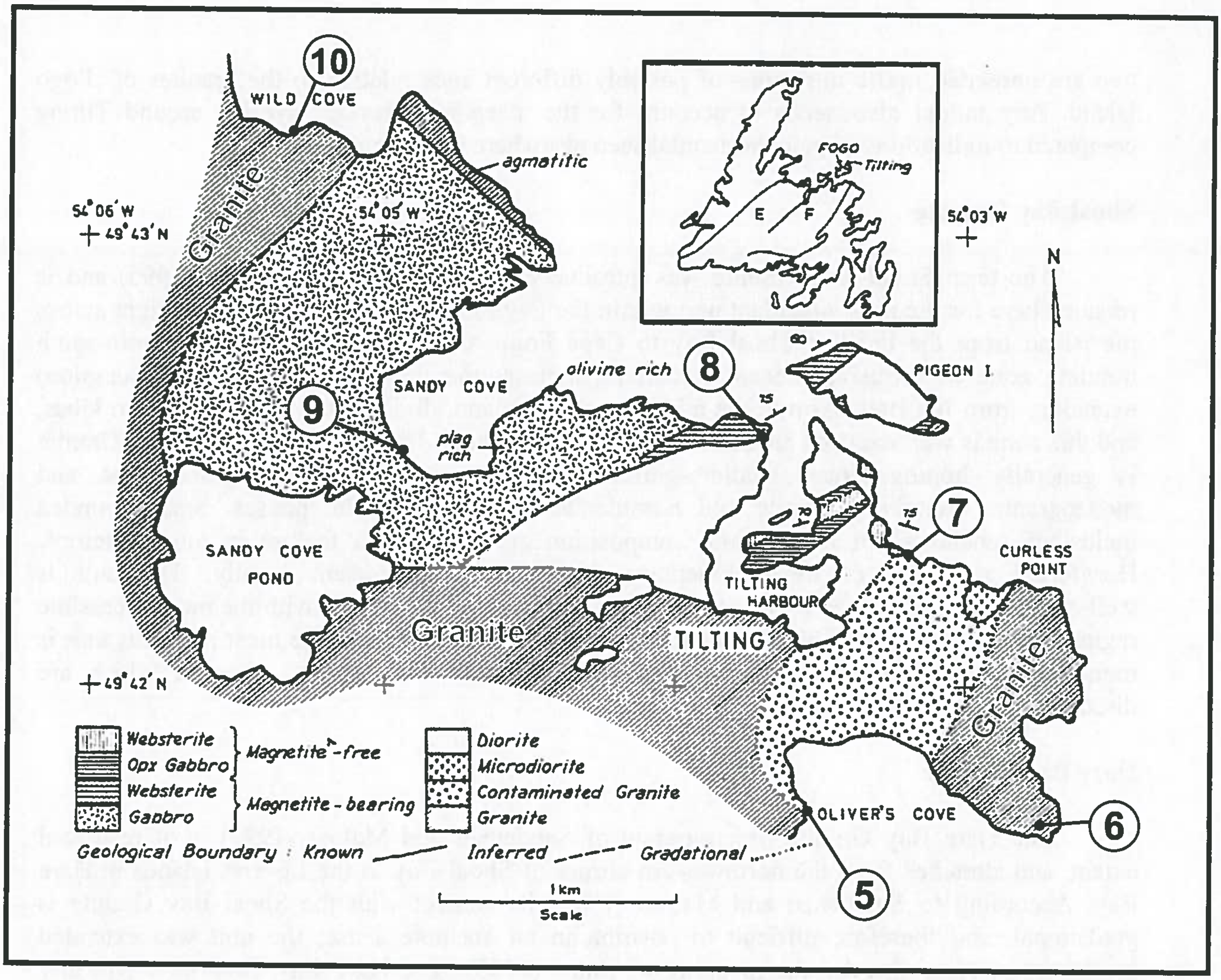


Figure 3. Geological map of the area around Tilting, from Cawthorn (1978), based in large part on the work of Williams (1959). The field trip stops in the area for the afternoon of Day 2 are also indicated for reference purposes.

two are unrelated mafic intrusions of possibly different ages relative to the granites of Fogo Island. Any model also needs to account for the steep attitudes of layering around Tilting compared to indications of paleohorizontal seen elsewhere in the intrusion.

Shoal Bay Granite

The term Shoal Bay Granite was introduced by Sandeman and Malpas (1995) and is retained here for the most abundant unit within the Fogo Island Intrusion. It extends right across the island from the head of Shoal Bay to Cape Fogo. Currie (1997) indicates a north-south trending zone of intrusive breccia containing metasedimentary blocks (see later discussion) extending from Joe Batts Arm to the midpoint of the island, dividing the granite into two lobes, and this zone is well exposed around the site of the new Fogo Island Inn. The Shoal Bay Granite is generally homogeneous, medium-grained white to beige or pink granodiorite and monzogranite containing biotite and hornblende as primary mafic phases. Small rounded inclusions (enclaves) of more mafic composition are a common feature in most outcrops. Hornfelsed xenoliths of metasedimentary origin are also present locally. The unit is well-exposed all around the rocky and barren north coast of the island, with the most accessible regions on the east side of Shoal Bay and around Joe Batts Arm. For the most part, this unit is monotonous, but it does commonly contain mafic and felsic dykes, some of which are discontinuous.

Hare Bay Granite

The Hare Bay Granite (microgranite of Sandeman and Malpas, 1995) is of restricted extent, and stretches from the northwestern corner of Shoal Bay to the Leveret Islands in Hare Bay. According to Sandeman and Malpas (1995) its contact with the Shoal Bay Granite is gradational, and therefore difficult to position in an absolute sense; the unit was extended southwest of Hare Bay by the mapping of Baird (1958). The Hare Bay Granite is typically orange or red in colour, rich in K-feldspar, poor in mafic minerals and contains miarolitic cavities; it locally grades into aphanitic felsites that exhibit features such as spherulites. It generally does not contain abundant inclusions. Sandeman and Malpas (1995) suggested that it was the chilled roof facies of the Shoal Bay Granite.

Rogers Cove Granite

Fine-grained granitoid rocks are also abundant in the southwestern part of Fogo Island, where they apparently form several small intrusions and numerous dykes that cut the Fogo Harbour Formation. These were grouped as the Rogers Cove Granite by Sandeman and Malpas (1995) and also considered to intrude the Shoal Bay Granite in this area. In contrast, Currie (2003) contended that - where contacts are visible - the coarser-grained granites akin to the Shoal Bay unit are actually younger than the fine-grained rocks. Geochemical data (Kerr et al., 1994; Sandeman and Malpas, 1995; Currie, 2003) indicate common trends between the Shoal Bay Granite and finer-grained units for most major and trace elements, with the Hare Bay and Rogers Cove granites being more compositionally evolved. However, these latter units are distinctly richer in Zr, Nb, Ga, and also have higher (FeO/FeO+MgO) ratios, transitional to "A-type" compositions (after Whalen et al., 1987) whereas the Shoal Bay Granite is a more typical "I-type" granite.

Dykes and Minor Intrusions

Dykes and minor intrusions are abundant in many parts of Fogo Island, and include both mafic and felsic compositions; more intermediate dioritic compositions are less common, but they are present. Many of the fine-grained granitic units in southwestern Fogo Island were assigned to the Rogers Cove Granite by Sandeman and Malpas (1995). Composite dykes, in which a felsic core is flanked by basaltic material, or vice-versa, are also common. In some cases, felsic dykes or composite dykes contain innumerable blobs of fine-grained mafic material that display "amoeboid" shapes. These variations suggest that some conduits were used by contrasting magmas at different times, whereas in other cases the mafic and felsic magmas were carried together, with insufficient time for extensive any mixing to occur. Thus, there may be a separation in time of mafic and felsic magmas within the confines of one small intrusion, but the wider pattern implies that they were synchronous on the much longer time-scale of magma chamber evolution.

Agmatites and Intrusive Breccias

Heterogeneous rocks that fall into this general category are exceptionally well-developed on Fogo Island, and are amazingly complex - depending on the state of mind of the observer, they are either frustrating or intriguing. In reality, there are several different types - and probably more types yet to be recognized.

The simplest examples are those where variably hornfelsed metasedimentary xenoliths are included in either gabbro or granite. The most spectacular examples of these are at the site of the new Fogo Island Inn (granite host), and in the Seldom - Little Seldom area (mafic host). Hornfelsing of blocks ranges from minimal to situations where dehydration and partial melting may have occurred, and this range in character can often be seen within the confines of a single outcrop. This implies that metasedimentary fragments had a wide range of "residence times" within the magma. The least-transformed blocks in such zones generally resemble rocks of the Fogo Harbour Formation.

Complex rocks largely of igneous derivation are developed along the interface between mafic and granitic rocks, and these are also highly variable. In many cases there is evidence that mafic and silicic liquids coexisted, such as complex mafic inclusions that have chilled margins, and variable hybridization with the granitic rocks. In such cases, the relative age of the mafic and felsic rocks is difficult to ascertain, but the fact that mafic rocks are "included" in a felsic matrix does not automatically mean that they are older. Such features more likely imply that mafic magma influxes interacted with partially solidified granitic crystal mushes, and were chilled and rapidly solidified as part of this process Other intrusive breccias have a range of fragment types, including layered blocks, and blocks with more angular shapes suggestive of brittle behaviour and large-scale stoping by granitic magmas. To make things worse (or better) there are examples of complex breccias that show evidence for both brittle solid-state stoping and liquid-liquid interaction. There are also places where intrusive breccias are themselves intruded by dyke-like bodies of younger intrusive breccia that exhibit similar textures. To summarize, the interaction of mafic and felsic magmas - or magmas and rocks - was complex, multiphase and episodic.

GEOCHRONOLOGICAL CONSTRAINTS

The ages of plutonic rocks in the Fogo Island Intrusion are not well constrained. The earliest data consist of K-Ar determinations suggesting a Devonian age of 380 ± 16 Ma (Williams et al., 1964). Fryer et al. (1992) quote a Rb-Sr isochron age of ca. 412 Ma for granites, for which the data are probably those reported by Sandeman (1985) with a slightly older (~417 Ma) regression solution. U-Pb geochronology was attempted by Aydin (1995), who obtained a Silurian age of 420 ± 2 Ma for granite in the area west of Tilting. However, this is a lower intercept age as the zircon in the sample contains older inherited material. Titanite from the same sample gave a younger age of about 408 Ma, which is almost identical to the 408 ± 2 Ma age obtained from a "diorite" in the same area. Given the complexity of said diorites, it is very hard to know exactly what the dated material represents from the latter, and interpretation of the granite age is equivocal. Concordia diagrams for these results are shown in Figure 4.

There are many opportunities here for geochronological research, including investigating the relationship between granitic rocks and the volcanic rocks of the Brimstone Head Formation. The compositionally evolved granites that occur in the northwest of the island are also good candidates for geochronology, as they are Zr-enriched. The mafic rocks of the Seldom and Tilting areas are also candidates for geochronology, as they contain "pegmatitic" facies that are more likely to contain primary zircon.

GEOCHEMISTRY

Geochemical data exist for the rocks of Fogo Island (Kerr et al., 1994), but there has been little investigation of such patterns on an intrusion-wide scale. Sandeman and Malpas (1995) investigated the northwestern part of Fogo Island and established compositional similarities between volcanic rocks of the Brimstone Head Formation and granites. They also pointed out the tendencies towards A-type compositions amongst evolved granites. Cawthorn (1978) discussed the affinities of the mafic rocks of the Tilting area in terms of their petrogenesis and source melting relations. There has been little work on the possible relationships between mafic and felsic rocks, and the origins of the complex dioritic rocks, although it has been pointed out that the latter do not have composition intermediate between gabbro and granite in the Tilting area (Cawthorn, 1978). These topics remain to be investigated, as do topics such as detailed petrology and mineralogy. Nd isotope data reported by Fryer et al. (1992) suggest that the granites of the Fogo Island Intrusion have ε Nd of around -1 at the time of formation, which is indicative of some crustal contribution to these magmas. Aydin (1995) completed a more detailed investigation of Nd isotope signatures in the Tilting area, and obtained similar ε Nd values for the granites (-1 to +1.3), and a wide range of values for mafic rocks (0 to +5). The dioritic rocks examined in the study also had a wide range of ε Nd values (+0.3 to +3.1). Such patterns are consistent with the interaction of mantle-derived mafic magmas with melts of crustal origin, and incomplete mixing between these end-members, but they are not diagnostic of such.

STRUCTURAL GEOLOGY

In general, the rocks of Fogo Island do not show signs of significant deformation, aside from a weak cleavage and some small-scale shear zones. Minor folds are present in the Fogo Harbour Formation, but in places are difficult to distinguish from the soft-sediment structures that are visible on an outcrop scale. Regional fold structures defined by Currie (1997) pass through parts of the Fogo Island Intrusion, but their presence would be hard to detect in the intrusive rocks. Currie (2003) suggested that the intrusion was a sheet-like body as much as 7 km thick, based on a simple homoclinal model, but if there is even some gentle folding of the body this would likely be an overestimate. The more complex pattern of mafic and felsic units in inland areas indicated by the more detailed mapping of Baird (1958) might also be explicable in terms of folding, or could indicate topographic irregularities in the boundary between the lower mafic section and the upper felsic section of the intrusion.

ECONOMIC GEOLOGY

There are no significant mineral occurrences known on Fogo Island. Minor sulphides are present locally in the layered rocks of the Tilting area, and might possibly be of magmatic origin, as such rocks commonly contain such material. The most obvious sulphide-rich zone is in a felsic unit representing either a conformable tuff or a high-level sill within the Fogo Harbour Formation, but this seems largely to be related to a cross-cutting late fracture zone.

THE COASTAL MAINE INTRUSIONS AS MODELS FOR FOGO ISLAND

Fogo Island is the only example of a Siluro-Devonian bimodal composite intrusion in Newfoundland that is well-exposed in a coastal area, but a more extensive belt of such rocks occurs in the coastal region of northeastern Maine (Figure 5), which is likely the along-strike continuation of the Exploits Subzone of Newfoundland. Studies of the superbly exposed Pleasant Bay, Mount Desert Island, Isle au Haut and Vinalhaven Island intrusions have provided many ideas on the evolution of complex magma chambers. The following summary is derived from numerous published sources (Wiebe, 1974; Wiebe et al., 1997; 2000; 2001; 2004; 2007; Hawkins and Wiebe, 2004; 2007; Chapman and Rhodes, 1992; Lux et al., 2007). Specifically, the Vinalhaven Island Intrusion (Figure 6) is suggested as an excellent analogue for the Fogo Island Intrusion.

The coastal Maine intrusions are eroded to various levels, and some are tilted, providing inclined vertical sections. Intrusions on Mount Desert Island, Isle au Haut and Vinalhaven Island (Figure 5) include both mafic and felsic plutonic rocks, and associated volcanic sequences that may represent an eruptive component (Hogan and Sinha, 1989; Wiebe et al., 2000). They are interpreted as tilted magma chambers, in exactly the same way that Fogo Island is viewed. The Pleasant Bay Intrusion is dominated by mafic plutonic rocks, and is interpreted to represent a deeper cross-section. Several other intrusions in this area, such as the Deer Isle Intrusion (Figure 5), are dominated by homogeneous granites, but are believed to be underlain by mafic rocks (Lux et al., 2007). Gravity studies (Hodge et al., 1982) generally support the idea that many granitic plutons in the area are sheet-like and underlain by denser mafic rocks. The granitic rocks of the coast of Maine are generally homogeneous, to the extent that they remain important sources of high-quality dimension stone, but the associated mafic and intermediate rocks are very complex and heterogeneous.

Three fundamental concepts developed through studies of these intrusions since the mid 1990s, as summarized by Wiebe et al. (1997; 2000). The first is that magma chambers are constructed from multiple smaller batches of magma that crystallize semi-independently; such increments are most easily recognized within the mafic rocks, because they solidified relatively quickly, but are more diffuse and hard to separate within the granitic rocks. The second is that mafic plutonic rocks dominate the lower sections of magma chambers, whereas more homogeneous granites occupy their upper sections. The third concept is that the mafic and felsic magmas are synchronous on the time scale of the magma chamber. On a more local time-scale, still-liquid mafic magmas are interpreted to have been emplaced into partially solid granites that were mush-like mixtures of accumulated crystals and residual liquids. Such interpretations superficially conflict with field relationships that usually show mafic rocks surrounded by felsic rocks, which would conventionally be interpreted to indicate that the felsic rocks are younger. These relationships result from the different temperatures of the two components as they mingle; the mafic liquid freezes quickly, but the felsic "cumulates" retain considerable mobility because they have a much lower solidus temperature. Specifically, models for the Maine intrusions suggest that mafic magma "pulses" were preferentially emplaced along the transient "floor" where crystal mushes sat below largely liquid magmas of broadly felsic composition (Chapman and Rhodes, 1992; Wiebe et al., 1997; 2000).

The Vinalhaven Island Intrusion (Gates, 2001; Wiebe et al., 2001; 2004; 2007; Figure 6) contains six major components, all of which have analogues on Fogo Island, and is of closely similar age (~420 Ma; Hawkins and Wiebe, 2004). The country rocks are metasedimentary schists of pelitic composition, with higher grades in general compared to the Fogo Harbour Formation. Silurian volcanic and pyroclastic rocks on Vinalhaven Island have closely similar ages to the plutonic rocks, and are thus likely their extrusive equivalents (Hawkins and Wiebe, 2004). The plutonic rocks are domimated by a generally homogeneous granite, which typically contains small rounded inclusions of more mafic composition, and a much more complex zone of gabbros and diorites on the south and eastern side of the island (Figure 6). The remaining component of the magma chamber comprises compositionally evolved, equigranular granites that appear to be the youngest components of the complex. In the case of Vinalhaven, these largely occupy a central region of the intrusion.

In detail, the mafic and intermediate rocks of the Vinalhaven Intrusion consist of myriad individual sheet-like or lobe-like bodies that are separated by thinner zones that resemble the upper granitic rocks, or have intermediate compositions and complex mixing and/or hybridization textures. The lower contacts of mafic zones are commonly chilled, and show loading structures that suggest the emplacement of denser mafic liquid above less dense granitic or intermediate crystal mushes. Many of these structures are directly analogous to primary sedimentary structures such as load casts and "ball-and-pillow" structures. Vinalhaven Island is also well-known for its *magmatic pipes*, which are described also from other areas in Maine, initially from Isle au Haut (Chapman and Rhodes, 1992; Wiebe et al., 2000). Magmatic pipes are miniature diapirs that develop as a consequence of the emplacement of dense mafic magma above more buoyant felsic crystal mush. The latter remains mobile, and rises upward into the mafic liquid, initially as pillar-like structures, which ultimately may become detached from their roots. Pipes typically develop above loading structures in the base of the mafic unit, and are in part a consequence of this process. A simple analogue is provided by a lava lamp, in which heated wax rises through oil in exactly the same manner - in fact, many such "pipe swarms" are very reminiscent of features seen in an operating lava lamp! In some cases, such pipes rise right through the mafic unit, to form a more disorganized zone of pegmatitic-textured material in its upper section. However, it is likely that many such pipes are transient and short-lived, as the lower-melting-point granitic material is assimilated into the mafic magma, thereby changing its composition. Figure 7 shows a schematic illustration of idealized magmatic pipes, derived from the classic exposures on Isle au Haut in Maine (Chapman and Rhodes, 1992). The upper surfaces of mafic lobes in the Vinalhaven Intrusion tend to be complex zones of hybridization and mixing, where chilled mafic inclusions and felsic "host rocks" show more chaotic relationships. It is in these regions that rocks of more intermediate composition tend to be best developed, perhaps in part through hybridization caused by the formation and disappearance of such magmatic pipes (Figure 7).

The granitic rocks of Vinalhaven Island are homogeneneous, to the extent that the island was famous as a source of dimension stone. Vinalhaven granite is present in many famous buildings in the northeastern USA, including the Empire State Building in New York City. However, rounded enclaves of fine-to medium-grained intermediate material are common, and many of these contain small feldspar phenocrysts like those in enveloping granites. A study of closely similar inclusions in the Mount Desert Island Intrusion showed that they matched the

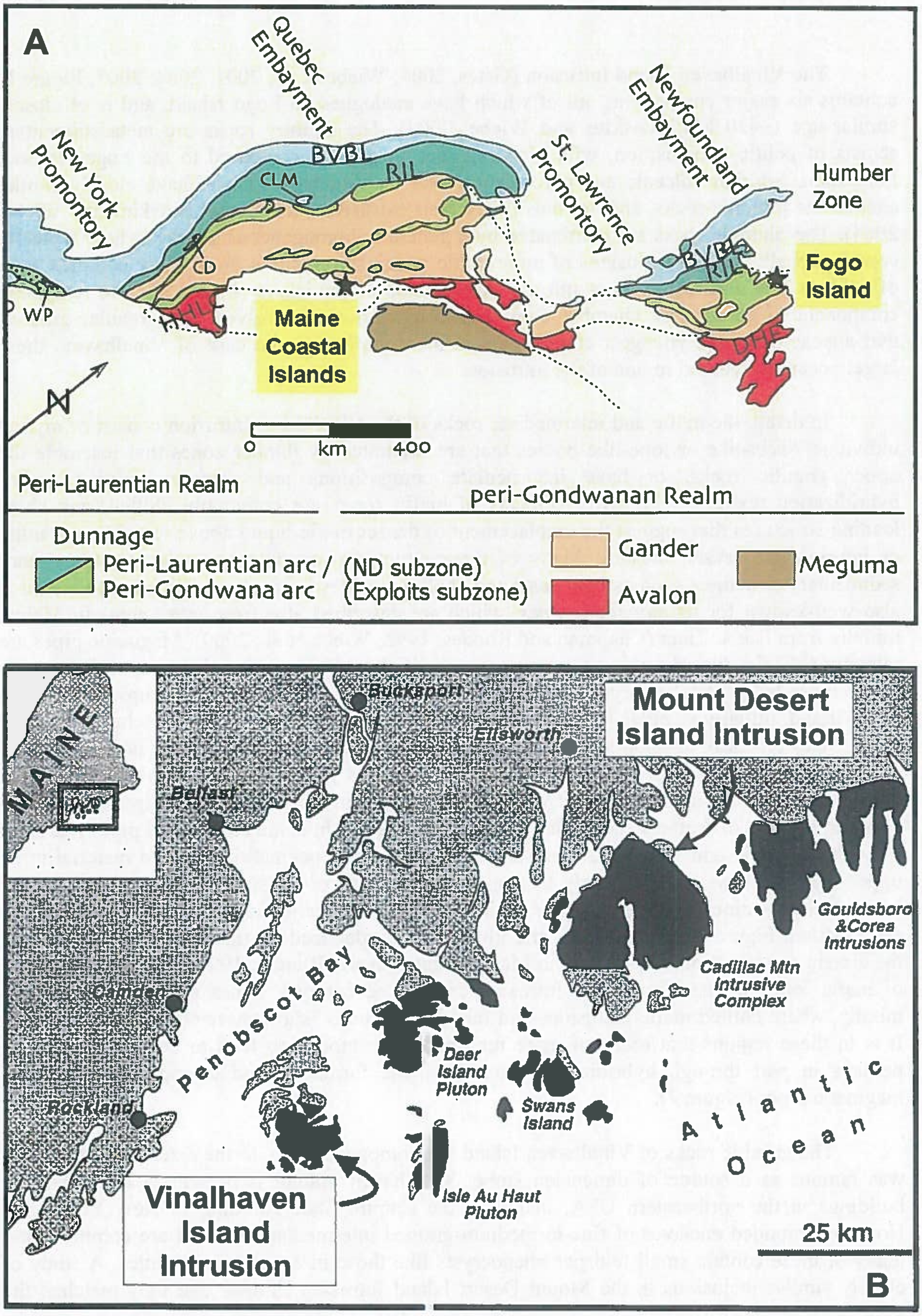


Figure 5. (A) The location of Fogo Island and similarly-aged plutonic complexes in coastal Maine, with reference to zonal subdivisions of the Appalachians after Williams (1979). Base map courtesy of Jim Hibbard. (B). The locations of plutonic complexes in Maine discussed in this guide. Note that the Pleasant Bay Intrusion lies east of this map-area.

varied compositions observed within mafic to intermediate zones in the interpreted lower part of the magma chamber. The inclusions were interpreted to be globular samples of variably hybridized magmas derived from these zones, transported elsewhere within the magma chamber (Wiebe et al., 1997). The development of hybrid compositions through the development and assimilation of magmatic pipes has important geochemical implications, because it is not simple two-component mixing of felsic and mafic magma. To the contrary, magmatic pipes are dominantly residual material from granite crystallization, and thus would be enriched in incompatible elements. Wiebe et al. (1997) demonstrated that models for such selective hybridization process predicted evolved intermediate compositions that corresponded well to observed intermediate rocks and the ubiquitous inclusions seen in the granites.

Evolved, siliceous granitic rocks and quartz-feldspar porphyries in the Vinalhaven Island Intrusion could have several origins. Some could represent high-level magmas associated with the development of coeval volcanic sequences or the roof of the magma chamber, in which case they would likely be older than the dominant coarse-grained granite on at least a local scale. However, it has also been suggested that such rocks could also form as a consequence of the emplacement of mafic magma batches into the chamber, because this would add heat energy, leading to the mobilization of residual liquids in felsic cumulates, or even to remelting of largely solidified granitic rocks (Wiebe et al. 2004). In this scenario, the evolved rocks would generally be younger than the dominant granite, at least on a local scale. Both models could also be applied on Fogo Island, given the distribution of such rocks.

The Vinalhaven Island Intrusion is also well-known for its spectacular *magmatic pillow structures*, described in detail by Wiebe et al (2001). These are also found in the wider zone in which mafic and felsic magmas interacted, and are analogues of pillow lavas that form in the ocean, where hot mafic magma is rapidly chilled by cold seawater. Although the temperature difference between mafic and felsic magmas is less extreme, the same principles apply, and pillows with tube-like flow structures apparently develop at the fronts and margins of lobate mafic "flows" within the lower part of the magma chamber. Such features are best developed in the upper regions of sheet-like mafic units, and also as dyke-like zones that transect granitic rocks. The latter could be conduit-like features through which mafic magmas were emplaced to higher levels in the chamber. Isolated mafic pillows, or clusters of them, are present in some areas visited by this field trip, and field notes from the 1990s suggest that such features are more extensive in the Cape Cove area. Unfortunately, I have not had time to revisit these locations.

A final feature of the Vinalhaven Island Intrusion that invites comparison with Fogo Island are zones that are rich in metasedimentary xenoliths, to the extent that these were initially mapped as discrete units of country-rock schists. These have a regional distribution that corresponds to that of the mafic-intermediate plutonic rocks, and may define several individual zones within this section of the intrusion, broadly parallel to its "stratigraphy". Such zones may form in response to inflation of the magma chamber caused by the emplacement of the mafic magmas near its base, accompanied by eruption of the overlying less-dense felsic liquids (Hawkins and Wiebe, 2004). This expansion process is accommodated by large-scale collapse and foundering of the roof zone, and these blocks - some of enormous size, would founder and sink within the magma, accumulating near its transient floor.

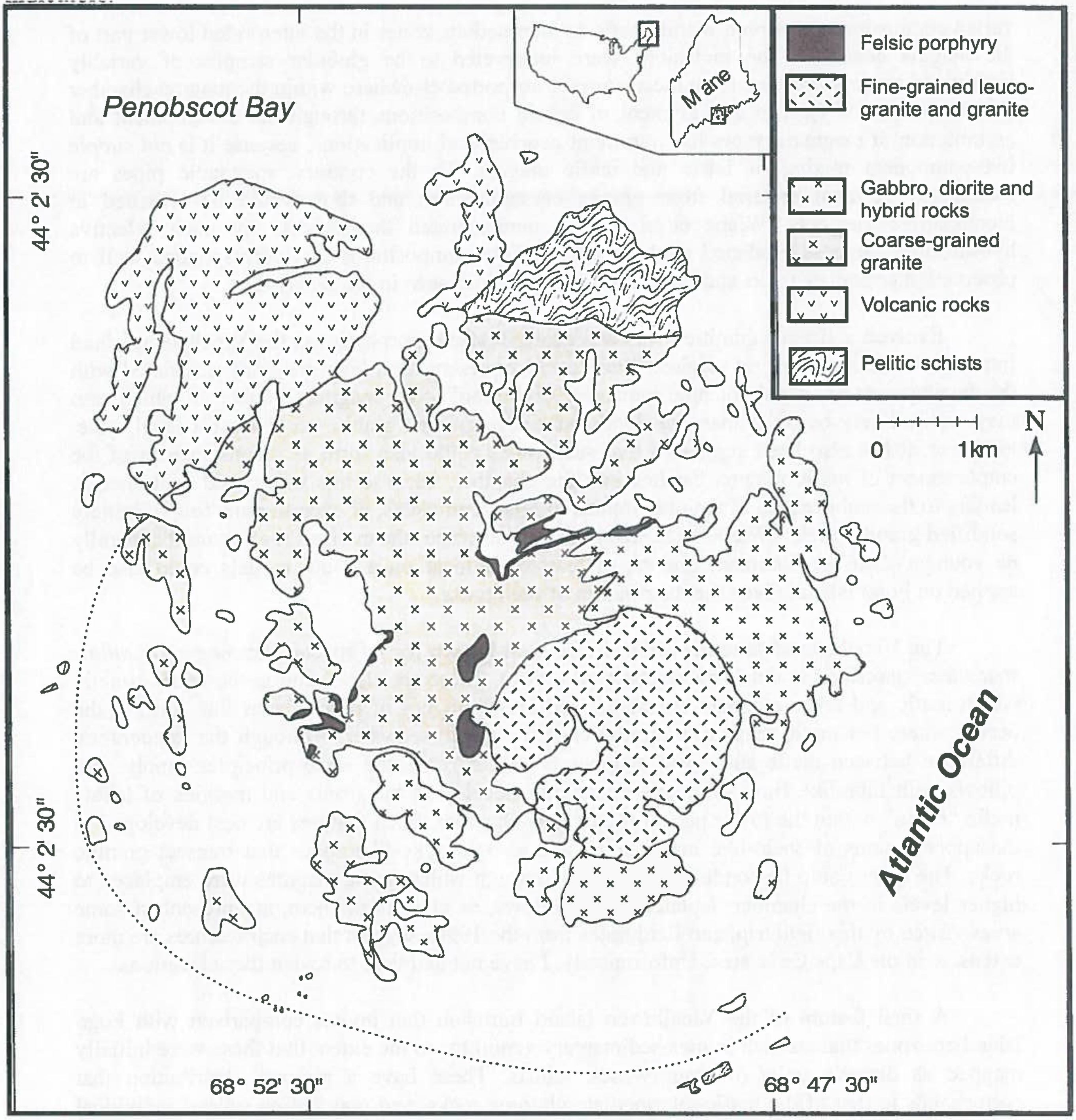


Figure 6. Geological map of the Vinalhaven Island Intrusion, Penobscot Bay, Maine. This body is suggested as an analogue for the Fogo Island Intrusion, and has a broadly similar map pattern.
Map modified slightly from Hawkins and Weibe (2004).

In summary, the concept of coexisting mafic and felsic magmas is amply supported by field evidence on Vinalhaven Island and in other coastal Maine intrusions, and this area has provided many insights into the details of such interaction processes. Many, but not all, of the characteristic features listed in this section can be demonstrated locally on Fogo Island, and I suspect that they are widespread. However, it is much harder to place absolute constraints on timing, as the typical resolution of even the best U-Pb geochronological techniques is ± two million years or so. The lifespan of an individual intrusive complex is likely less than this period, so it is hard to test any models through geochronology. Promise for such results comes in the form of the "chemical abrasion" technique in which zircons are subjected to chemical attack that selectively removes areas most subject to lead loss or other complications. A recent study of this type completed on the Vinalhaven Intrusion suggests that the entire complex developed over a period of less than 2 million years, and that relative age relationships based on field mapping are confirmed by geochronological data that are precise to as short a time as 0.2 Ma (Hawkins et al., 2009). Would it not be wonderful to have such a dataset for Fogo Island?

OUTSTANDING QUESTIONS

A brief discussion of outstanding questions is difficult to construct because there are so many, and there may well be more after this excursion. One thing that these questions have in common is that they cannot be resolved fully through quantitative approaches - above all, they require detailed mapping and field work to develop models that geochemistry or geochronology might later test.

Nevertheless, the most fundamental gap in knowledge is geochronological. Although existing data certainly indicate a latest Silurian to earliest Devonian age for the Fogo Island Intrusion, there are no U-Pb data from the mafic rocks, and the interpretation of the data from the granites remains equivocal because of the inheritance in the zircons (Aydin, 1995). There are no data from the compositionally evolved, high-level granites on the island, or from the volcanic rocks of the Brimstone Head Formation. The rocks all appear amenable to precise geochronology, but such research needs to be constrained through more detailed field information than currently exists. The field relationships summarized in this guide suggest that mafic and felsic magmas coexisted on the time-scale of the magma chamber, although some local relationships indicate discrete intrusive events. However, the latter observation in no way negates the concept of temporal coexistence over the lifespan of the intrusion. If the mafic and felsic magmas were temporally discrete, we should *never* see evidence for their interaction in liquid or semi-liquid form, but synchronous magmas can still possess clear intrusive relationships on a local scale. To *truly* document the evolution of the magma chamber requires highly precise geochronological methods, perhaps through use of the chemical abrasion techniques discussed by Hawkins et al. (2009).

From a regional geology perspective, two problems stand out. The first is the timing relationship between the intrusion of magmas and any penetrative deformation - including folding - of the Fogo Harbour Formation. The presence of folded xenoliths suggests that some deformation predates emplacement of gabbroic magmas at least, but it remains possible that some of these relict fold structures actually record soft-sediment deformation rather than regional patterns. Some gentle folding of the intrusion might also be anticipated to accompany the

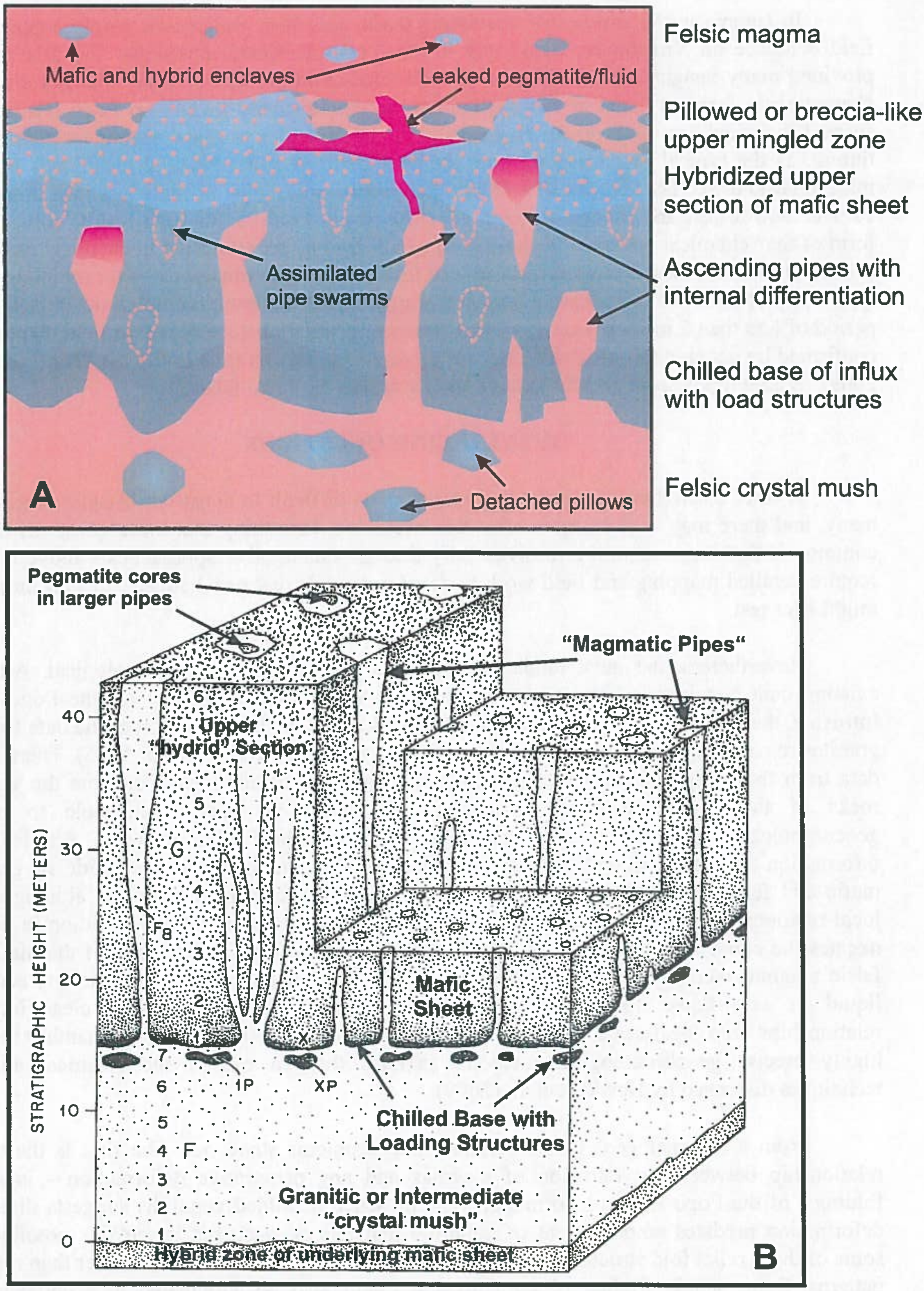


Figure 7. (A) Schematic, idealized section through a mafic sheet representing influx of magma above partially solidified felsic crystal mush, within a magma chamber. (B) Sketch of magmatic pipes described from the Isle au Haut Intrusion, Maine, after Chapman and Rhodes (1992).

regional tilting that provides the depth section through the magma chamber. The second question is related, and concerns the relationship between the Fogo Harbour Formation and the Brimstone Head Formation, generally described as conformable. Clearly, if the latter is equivalent to the granites, but the granites themselves postdate *some* deformation in the sedimentary rocks, there must be stratigraphic and/or structural complications between the two formations. The area around Fogo Town is in many respects confusing in this sense, not least because any primary horizontal features are not easily established in the volcanic rocks. There are, however, certainly some tight folds in the sedimentary rocks. The similarities and differences between volcanic rocks in this area, and those of the Little Fogo Islands, are also a subject that needs investigation. There are red sandstones and conglomerates apparently interbedded with the latter, and these sedimentary rocks are unlike anything seen on Fogo Island itself. The Little Fogo Islands present a perfect natural laboratory for studying these volcanic rocks in detail, and seem never to have been investigated.

Within the Fogo Island Intrusion, an important question is the relationship between the Tilting Layered Complex and other mafic to intermediate rocks, and the related question of the relationship between the Tilting Complex and the granites that envelop it. Outcrops in Olivers Cove strongly suggest emplacement of mafic magmas into partly solidified granites, but are these mafic sheets actually time-equivalent to the rocks of the Tilting Complex? Is the Tilting Layered Complex a window through the granites into the underlying mafic rocks, or is it a discrete mafic intrusion of a different age and origin? Why are the attitudes of primary layering in the Tilting Layered Complex so steep in comparison to inferences from elsewhere on the island? All of these questions remain to be answered. The Tilting Layered Complex has been the subject of some detailed studies (e.g., Cawthorn, 1978; Aydin, 1995), but these have been very "introverted"; there is a need to compare these rocks with other parts of the Fogo Island Intrusion, and consider their wider context.

Although models derived from studies of intrusions along the coast of Maine (see previous section) provide many ideas that seem applicable to Fogo Island, it seems reasonable that every composite bimodal magma chamber would have its own distinct characteristics, and Fogo Island may differ from these type examples in important respects. The distinctive features suggestive of the emplacement of mafic magma batches into granitic crystal mushes exist in the Olivers Cove area, and likely also in the area around Cape Cove and Cape Fogo, based on field observations from the 1990s. Elsewhere, the boundaries between mafic and felsic sections of the magma chamber are obscured by later fine-grained granites, and it is more difficult to evaluate this relationship. Examination of the most extensive "stratigraphic section" of mafic rocks (in the Seldom area), has not to date revealed areas representing granitic material, or interaction-hybridization zones diagnostic of multiple batches of mafic magma. In contrast, it appears that sections of relatively homogeneous gabbro and diorite are separated by xenolith-rich zones that could represent basal accumulations in sheet-like subchambers, or zones of in-situ dissection of the sedimentary country rocks. One interpretation is that the mafic section of the Fogo Island Intrusion grew "downwards" through progressive dissection of its host rocks, with only some magma batches ascending to higher levels and interacting with granitic magmas. These problems cannot necessarily be resolved through geochronology, but systematic petrological, geochemical and mineralogical studies could surely better document individual magma influxes.

Last, but not least, the numerous dykes and small intrusions that abound in this area need to be better linked into the different components identified within the magma chamber. For example, are mafic dykes within the gabbro sequence truly feeders to subsequent magma batches, or are they later and completely unrelated? Although most previous accounts stress the absence of "intermediate" rocks on Fogo Island, there are grey feldspar-porphyritic dykes that seem to have such compositions, and these are visually similar to possible hybrid rocks observed in areas where mafic and felsic magmas seem to have interacted. In a simplistic way, such dykes and sheets are thought of as "escaped hybrids". The ubiquitous mafic to intermediate inclusions in the dominant granites of Fogo Island, some of which also are feldspar-porphyritic, could perhaps be complementary. Following the models of Wiebe et al. (1997), these might instead be "captured hybrids" that record complex processes in the boundary regions of the two contrasting magma types that are now in part obscured by the formation of younger evolved granites.

PART TWO - FIELD TRIP STOP DESCRIPTIONS

DAY ONE (Afternoon)

REGIONAL OVERVIEW

This first part of the field trip is meant to introduce regional concepts and rock types typical of Fogo Island. Note that all coordinates are with reference to the North American Datum of 1927 (NAD27) as shown on most printed topographic maps. They can be converted approximately to the more recent NAD83 system by adding 62 metres to the easting and 217 metres to the northing.

Stop 1.1: Outcrops at the Farewell Ferry Terminal

Unless the takeout is open to allow indulgence in excellent home-made fries, there is not a lot to do whilst waiting for the Fogo Island ferry. The local outcrops also do not provide a great deal in terms of diversion. These were included by Baird (1958) in a separate formation, the Farewell Formation, which was noted to perhaps be laterally equivalent to the Fogo Harbour Formation. Currie (1997) simply included them in the latter. The best part of the exposure is the roadcut where all the signs for local businesses are posted, notably at the end closest to the ferry. The bedding dips towards the road, and there is a steep cleavage, such that most exposed surfaces represent the latter. The rocks are dark green to grey sandstones and siltstones, of possible mafic volcaniclastic origin; they appear to me rather different to the Fogo Harbour Formation as seen on the island. Vague cross-bedding is visible in one area.

Stop 1.2: Ferry Ride from Farewell to Fogo Island

This is not really a stop in the usual sense of the word. The scenic ferry trip from Farewell to Fogo Island passes several islands and, depending on the schedule, it may call at the south end of Change Islands. The largest islands passed (northern Dog Bay Island and Woody Island) consist of sandstones and siltstones that were assigned to the "South End Formation" of Baird (1958), but were subsequently grouped with the Fogo Harbour Formation by Currie (1997). Numerous dykes are visible from the ferry. The majority are fine-grained felsite and quartz-porphyry dykes that contrast with darker sedimentary rocks and are easily visible. They are believed to be satellitic bodies related to the Fogo Island Intrusion. Smaller numbers of mafic dykes are much harder to see due to their dark colour. The dykes on these islands have never been studied in detail.

Stop 1.3: Sedimentary rocks and composite dykes north of Fogo Island Ferry Terminal

These outcrops are a short distance north of the Ferry Terminal, and may instead be visited on the final day (whilst waiting for the boat to arrive) if time is tight on Day One. The shoreline outcrops can be reached by walking along the shore if the tide is low, to a beach area just north of the breakwater. The other route is through the gravel pit just up the hill from the terminal (behind the Ultramar fuel tanks). Climb the slope on the north side of the pit, and then cross a partially open area from which you can see the breakwater. *Whatever you do, do not try and traverse through the woods west of the pit, because I can attest to their impenetrable nature. The outcrop surfaces near the shoreline may be slippery.* The two outcrops described below are located at 694775E/5494480N and 694575E/5494525N, respectively.

The first outcrop contains dykes of both felsic and mafic composition separated by screens of sandstone and siltstone. A larger felsic dyke is a sugary and rather featureless rock that contains quartz phenocrysts and small miarolitic cavities, and is typical of most such rocks on the island. This dyke is in turn cut by a composite dyke, i.e., a dyke that has marginal mafic (diabase) zones and an internal felsic section. The latter contains numerous amoeboid blobs of chilled diabase in a miarolitic quartz-feldspar porphyry matrix. Such features indicate coexisting mafic and felsic liquids, in which the mafic magma froze quickly because it had a higher solidus temperature. Although there must have been more than one mafic magma batch and more than one felsic magma batch involved in the Fogo Island magma chamber, such features illustrate the essential large-scale process involved in its generation. The second outcrop is about 200 m along the shore from here, located on a point just north of a pebble beach. The short walk along the shore crosses other mafic and felsic dykes as well as well-bedded sedimentary rocks. Some cross-bedding is present in the sandy beds. The gently north-dipping bedding planes at the point host circular structures that appear to be shells of some kind. These have not yet been identified, and any ideas on this are welcome.

If the shoreline route is followed back to the ferry terminal, an outcrop of sedimentary rocks just beyond the breakwater contains polygonal structures that resemble mudcracks. This was my original interpretation. However, closer examination of vertical outcrop surfaces shows that small sand dykes are common, and I now suspect that these features are the surface expression of such features. The sedimentary rocks around here are not entirely typical of the Fogo Harbour Formation elsewhere on the island, which is dominated by rather boring grey rocks. This is perhaps why some workers (e.g. Sandeman and Malpas, 1995) chose an alternate stratigraphic designation in which they are equated with the South End Formation of Baird (1958), exposed on Change Islands.

Stop 1.4: Typical Gabbroic and Dioritic Rocks (Seldom Gabbro)

From the Fogo Island Ferry Terminal, drive west along the road towards Seldom, passing both junctions for Stag Harbour, and the Fogo Island boatyard. Park on the shoulder 0.4 km past the access road for the boatyard, and descend to shoreline outcrops on the west side of the small beach. *Be careful of the uneven surface below the road, and possibly slippery outcrops.*

The first feature noticed at this outcrop is the felsite dyke, which obviously cuts the coarser-grained intrusive rocks. The latter are homogeneous pale grey rocks that are gabbroic or dioritic, depending on what criteria are used. The principal mafic mineral here is hornblende, but minor clinopyroxene is likely present also, as a relict phase, and there is minor quartz also. The outcrop does not show any obvious layering, but it does contain two types of inclusions. The most obvious are fragments of hornfelsed sedimentary rocks, which are clearly xenoliths - i.e., foreign rocks. There are also rounded inclusions of mafic intrusive composition, which are likely cognate, i.e., they are closely related to the matrix gabbro-diorite, perhaps part of cumulate zones. The term "enclave" is used subsequently for all inclusions of this type. The outcrop on the east side of the small beach (not visited) is a more mafic variant of the gabbro.

If time permits, walk a short distance to the west, where the outcrop looks totally different, and is totally different - it is actually a zone of sedimentary rocks. These are cut by rectlinear pink felsitic veins, which are obviously late and discordant, but the outcrop also contains a much more subtle network of grey dioritic zones that dissect the sedimentary rocks along bedding planes. The features of this outcrop should be remembered for comparison with the final outcrops for today and other outcrops to be seen on Day Two.

Stop 1.5: Typical medium-grained granite (Shoal Bay Granite)

From the previous stop, drive east through Little Seldom into the town of Seldom, and turn left at the road junction for Fogo. Drive for 6.2 km north to the road junction in Fogo Central (located by the high school), and turn right towards Joe Batt's Arm and Tilting. Drive for 2.3 km, passing the Shorefast Foundation offices, and park on the shoulder opposite the boardwalk trail to the Tower Studio, which is clearly visible on the left. Do not park on the outcrops at this spot, as these are what we need to look at. *Be attentive for traffic on the road here.*

Large, glacially-polished outcrops just off the road illustrate the typical medium-grained to slightly porphyritic biotite-hornblende granite of the Shoal Bay Granite, which underlies most of central and northern Fogo Island. These rocks are generally homogeneous, but do contain some aplitic dykes and sheets up to 30 cm wide. The granite contains xenoliths and enclaves. The former are likely from the Fogo Harbour Formation, and the latter are rounded patches of fine- to medium-grained igneous rocks that are invariably more mafic in appearance than their host. These exist within the Shoal Bay Granite in almost every outcrop, and commonly contain small feldspar phenocrysts. My preferred interpretation is that such features reflect physical mixing before the enclave magma froze within granitic crystal mush. Further discussion on their origins is best deferred until Day Two.

If time permits, walk down the boardwalk trail to the studio. It is further than it appears because the building is much larger than it seems from a distance. There are plenty of outcrops around the studio, but most consist of fine-grained pinkish aplitic leucogranite, quite unlike the typical Shoal Bay Granite by the road. However, this material likely forms a thin flat-lying sheet, because shoreline outcrops below the studio are more typical granite. This illustrates one of the challenges in mapping the distribution of various units, particularly in inland areas.

Stop 1.6: Fine-grained high-level "alaskitic" granite (Hare Bay Granite)

From the previous stop, return to Fogo Central, and turn south towards Seldom again. After 1.3 km, turn right on the road towards Deep Bay and Island Harbour and drive past the Fogo Island airport. After 4.3 km, turn right on the road to Deep Bay and drive another 1.3 km to a parking area by a short trail leading to the Bridge Studio. The best outcrops are located on the shoreline of a small islet just north of here, accessible by a side road, and around a much-photographed leaning house. There are also good outcrops on the studio trail.

These outcrops represent the Hare Bay Granite of Sandeman and Malpas (1995) although they did not actually extend their as far south on their map as did Baird (1958). The pale orange, fine-grained granite is alaskitic (virtually no mafic minerals) and is obviously miarolitic. The cavities are lined with hastingsite amphibole and zircon, but the unit has never been dated. It is considered to be the chilled roof facies of the Shoal Bay Granite, and to pass gradationally into it to the east of here. Thus, the placement of any boundary is unavoidably subjective.

From the shoreline, return to the parking area and follow the trail that leads up the hill to a viewpoint, and then to the studio (if time permits). The view to the north extends across Hare Bay, where similar red-orange granites clearly outcrop on the shores, and includes the prominent jet-black hill of Brimstone Head, near Fogo Town. The sharp transition from grey to black just above the shoreline is the boundary between the Fogo Harbour Formation and volcanic rocks of the Brimstone Head Formation. The distance from here to Brimstone Head is about 6 km as the seagull flies. Given an average dip of about 25° for the sedimentary rocks, and assuming that the top of the magma chamber was roughly horizontal, this suggests that the alaskitic Hare Bay Granite was formed at paleodepths of 1.5 to 2.0 km. Such an estimate does not account for any repetition or folding effects, but it seems reasonable. The stop also indicates a fundamental concept in Fogo Island geology, i.e., that the transition from south and east to west and north records progressively higher levels in a complex composite magma chamber and its volcanic superstructure.

Stop 1.7: Miniature Magma Chambers on the Island Harbour Road

From the previous stop, return from Deep Bay, but turn right at the junction for Island Harbour, rather than left for Fogo Central. Drive 4.4 km south along this road, parking by a prominent series of roadcuts on the east side of the road. The main location is at 694235E/5500910N, but features of interest are visible for at least 150 m in each direction. The outcrops are best visited in late afternoon, when they are illuminated by the sun. *Be attentive for traffic on the road at this location.*

This location contains some remarkable outcrops that may provide an illustration of the mechanisms for development of the Fogo Island magma chamber. These outcrops consist of grey siltstones and sandstones of the Fogo Harbour Formation, typical of this unit in the northwest of the island. The outcrop contains abundant soft-sediment deformation in the form of intraformational folds, some of which are tight, but generally not isoclinal. I have long debated the status of the largest fold structure, but currently consider it not to be a tectonic feature; some may disagree. The outcrop also contains white bands and zones, which I at first took for coarse-grained sandy or conglomeratic lenses, as many seem to be conformable with bedding and (superficially) seem to be affected by the soft-sediment folding. However, these are actually a medium-grained equigranular granite that is intruding the sedimentary rocks. The relationship of this rock to the Fogo Island Intrusion is not known with certainty (although it looks like it), but that is besides the point. Note that most of the contacts of these intrusive zones are generally conformable with bedding planes, but in detail the granitic rocks are discordant - they have clearly exploited the lines of weakness provided by bedding planes in the sedimentary rocks, to the extent of following fold structures. Furthermore, some of the thicker granite "microsills" have stoped material from their roof zones by detaching slabs along bedding planes. In some cases, these xenoliths appear to then have accumulated at the base of the sheets.

These outcrops reveal multiple miniature magma chambers, all of which are likely connected in three dimensions, which have been "frozen in time" in the process of their growth and coalescence. The intrusions in this outcrop have dimensions only barely measured in metres, but they perhaps provide a microcosm of processes that likely operated on a scale of kilometres within the Fogo Island magma chamber. The emplacement of both mafic and granitic magmas likely took place in many stages through dissection of the sedimentary sequence, exploiting its primary stratigraphy and structure. Although are no mafic intrusive rocks in this outcrop, it is likely that the mafic section of the intrusion developed in a rather similar manner, and this can be inferred from outcrops to be visited tomorrow. Remember this outcrop, because it provides an important key to visualizing if not understanding the complexities of Fogo Island.

If time permits, the roadside outcrops immediately south of here show a larger felsitic dyke that is also intruding parallel to bedding, but can be seen to progressively cut out specific argillitic units as xenoliths. An outcrop about 300 m to the north contains more soft-sediment folds and complexities, and includes a grey feldspar-porphyry dyke of probable intermediate composition, which is rare on Fogo Island. This dyke is interpreted as an "escaped hybrid" from a zone of mixing elsewhere in the chamber. These outcrops are best discussed further with an excellent supper and some good wine at Nicole's Cafe.

DAY TWO

The second day of the field trip emphasizes the mafic and intermediate rocks of the Fogo Island Intrusion in two areas, around Seldom on the southcoast, and in the Tilting area. A particular focus is the interaction between mafic and felsic magmas in differing physical states, and on the interpretation of various types of intrusive breccias. The day ends at the site of the new Fogo Island Inn, which will be a remarkable building in its own right.

SELDOM AND LITTLE SELDOM AREAS

Stop 2.1: Little Seldom - The Base of the Magma Chamber ?

These outcrops are located on a small peninsula at the east end of Little Seldom village. From the road junction in Seldom, drive 2.3 km west into Little Seldom, and turn left along the shore. The pavement ends after about 0.2 km (although you may not notice the difference), and there is a parking spot after another 0.2 km, near a large black boulder. It is not wise to drive any further on this road. The first part of the stop is on the other side of the beach, which is easily reached by walking through the meadow or along the shore. The outcrops are located at 702560E/549350N. The other outcrops are on the shoreline walking north; if the tide is low it may be possible to walk right across the small cove by rock-hopping. *The rocks and boulders may be slippery and treacherous in areas.*

It is not certain if the actual base of the Fogo Island magma chamber is exposed on the island, but this is the best candidate for such a location. The rocks here belong to the Fogo Harbour Formation, as do those on Cann Island, about 1 km to the south from here, and just visible beyond the point. The outcrops consist of dark grey, thinly-bedded siltstones, and yellowish-brown sandstones. The latter locally exhibit cross-bedding, and have formed sand dykes in several places. The dip is relatively steep (~60°) towards the northwest, dipping under the gabbro seen at the next outcrop, but this need not indicate the attitude of any contact.

From the sedimentary outcrop, walk north across the cove or along the beach to the outcrops on the other side, at 702530E/5497460N. There are some spectacular blocks of intrusion breccias along here, which are locally derived - the source will be seen in the third outcrop. The first outcrop of gabbro-diorite at the north end of the beach is a homogeneous variety consisting of plagioclase, pyroxene and amphibole and minor quartz; this is cut by pink felsitic dykes (as are most outcrops on the island). Fresh surfaces and weathered surfaces in this outcrop locally show what I believe to be a magmatic fabric, but I am never exactly sure of the orientation, so perhaps its existence should be questioned. Continuing along the shore, there is a another zone of pink granite that obscures relationships, and then a series of xenolith-rich gabbro outcrops that likely are the source of the blocks seen earlier. This outcrop is located at 702460E/5497485N, below some sheds and sawdust piles. The matrix material is pale grey and considered to be extensively contaminated through assimilation; the eastern part of the outcrop contains fewer xenoliths and is noticeably finer-grained, suggesting chilling in this direction. The blocks range from well-preserved bedded sedimentary rocks clearly akin to those at the first part of the stop, to diffuse blotchy relict xenoliths that have likely been partially melted and digested. There is a wide size range, and locally tabular xenoliths have become packed together - or perhaps were disrupted in place. There are some similarities to the "miniature magma chambers" seen on Day One, but the origins are not necessarily the same.

Several things are interesting about these outcrops. The first is the lack of obvious contact metamorphism in the sedimentary rocks that presumably sat below the gabbro, as these must have been exposed to considerable heat flow. Perhaps there is a thin chilled zone that is unexposed, and the homogeneous gabbro actually represents the lowermost section of the gabbro. If this magma crystallized and cooled relatively early, it might have insulated subjacent sedimentary rocks. Second, although a considerable thickness of mafic rocks is thought to sit above this locality, they may not all have been in a hot liquid state at any given time. The xenolith-rich breccias here are not viewed as an in-situ product of stoping, although this likely was part of the original process. They are instead viewed as a physical accumulation of xenoliths by settling to what was at that time the floor of the gabbro chamber, i.e., above previously crystallized material. Some xenoliths were local and had short residence times, but others spent longer periods suspended and settling and suffered more significant metamorphism and ultimately were prone to digestion. They were probably derived in large part from the dissection of the roof zone (s), just as is illustrated by the miniature magma chambers exposed along the Island Harbour road.

Although this zone is the best candidate for the base of the mafic part of the Fogo Island magma chamber, it was likely only a transient floor, because several similar zones of xenolith accumulation occur elsewhere in the succession (see later stops). These are considered to perhaps be new floors developed from successive (younger ?) batches of magma, although we cannot be sure that the laws of superposition would apply strictly in such an environment. It is entirely possible that a new influx of magma could instead pond below a previously established and partly crystallized subchamber. The xenolith-rich zones could also be septa of sedimentary rocks that separated individual mafic magma subchambers. These processes have to be visualized in four dimensions, not just three, and this can really be a challenge!

Stop 2.2: Burnt Point Lighthouse - Gabbro and Diabase Dykes

From the previous stop, return to the main road in Little Seldom, then drive east for 2.3 km into Seldom. Turn right at the junction, instead of turning left for Fogo Town, and follow this road for 2.7 km to the end of the pavement, and then a further 0.9 km to the lighthouse. The probability of not finding a lighthouse is essentially zero but (just in case) the coordinates for the location are 705280E/6497940N. *If it is foggy, be prepared to be periodically startled by the very loud warning device.*

The outcrops here consist of medium to coarse-grained, relatively homogeneous gabbro, and are largely free of xenoliths. The gabbro is transected by several diabase dykes, and locally forms screens between them. Some of the dykes are actually composite in nature and have felsic margins and mafic centres, with little or no sign of interaction between the two compositions, in contrast to the composite dyke near Rogers Cove seen on Day One. There is no proof of any absolute ages here, but the simplest interpretation is that the dykes are feeders to higher parts of the Fogo Island mafic magma chamber, and that felsic magmas must also have used at least one of these conduits at an earlier time. In this case the mafic and felsic magmas apparently did not coexist in liquid form, but this simply reflects their relatively rapid cooling. On the much longer time scale that the magma chamber existed, the mafic and felsic end-member magmas are still considered to have been synchronous. To the east along the shore from here is a larger composite dyke that shows the opposite relationship, i.e., the earlier margins are mafic and the younger centre is felsic. This will not be visited due to time constraints.

Stop 2.3: Country rock screens and Xenolith Accumulation, Seldom

From the previous stop, drive back for about 1 km towards Seldom, and park in the school bus turnout stop near the United Church Cemetery. The shoreline outcrops of interest start just to the north, at 704530E/5498630N. This stop starts here and continues north for some 130 m along the shore to outcrops located at 704385E/5498740N. *The surfaces may be uneven and locally slippery.*

This stop shows a progression through sedimentary rocks of the Fogo Harbour Formation, probably part of an internal screen separating parts of the mafic magma chamber, through a xenolith-rich zone, and then into more homogeneous gabbro and diorite that locally exhibits cumulate layering. The xenolith-rich zone has a well-developed fabric, perhaps indicative of flow within the chamber as well as imbrication of tabular sheet-like blocks. Some previous accounts refer to deformation in southern Fogo Island, but I can see no evidence of a penetrative fabric in the matrix here. There are some blocks that contain folds, obviously truncated by the gabbro matrix. As in the outcrops at Little Seldom, there is a wide variety in the condition of the xenoliths, suggesting a range of residence times within the magma chamber. Some sections are extremely densely packed, to the point where they almost appear to be coherent sedimentary rocks, but on close examination the more subtle gabbroic component becomes evident. These are viewed as xenolith accumulations. A grey to white weathering dyke that cuts the intrusive breccias in this section is thought to be dioritic; perhaps a feeder to another zone, or an "escaped hybrid" from somewhere else?

The final outcrop in this section contains fewer xenoliths, but is interesting because of the presence of pegmatite-like material that is spatially associated with larger xenoliths, some of which also have prominent hornblende-rich reaction rims in the surrounding gabbro. These are interpreted to reflect dehydration (+/- melting) of sedimentary xenoliths during prolonged magma immersion, and the localized effects of higher volatile contents upon the surrounding magma. The reaction rims actually have two separate parts, one of which is in the xenolith and one of which is in the matrix gabbro or diorite. There are also some small pegmatite patches that apparently lack association with xenoliths, and it is suggested that these are the sites of xenoliths that no longer exist - an assertion that is of course unproveable. The pegmatitic gabbro patches are possible candidates for geochronology.

The shoreline section north from this point contains repeated cycles of this nature, which are considered to be individual "subfloors" within different sections of the magma chamber, but it is important to understand that these did not necessarily all exist at the same time, and that there is no guarantee that structurally higher areas are younger than those below.

Stop 2.4: Enigmatic folded xenoliths - The ultimate survivors?

From the previous stop, return to the road and drive north for 1.2 km, and turn left on Rowe's Lane, which is only about 200 m long and leads to a parking area. The outcrops are on the shoreline west of the parking area, at 704050E/5499380N. *Beware of loose blocks in walking to the stop.*

At this point, there is a leucocratic diorite that shows compositional layering and - at least superficially - has a gneiss-like appearance. The compositional layering is largely defined by variations in amphibole content. The gneiss-like aspect is given by numerous tabular to lenticular metasedimentary xenoliths, which display remarkable alignment. As they are not packed or imbricated, this is perhaps an indication of flow processes in the magma. Alternatively, it could be younger tectonic deformation, and actually have nothing at all to do with magma emplacement. This point will surely arise for heated discussion, and I have held the same internal debate, but have yet to find a convincing penetrative fabric in the leucodioritic matrix. The most curious features here are folded xenoliths in which the fold axes are parallel to the general alignment of xenoliths. Is it possible that these xenoliths actually became ductile and "crumpled" in a strong flow regime, or can such features only be interpreted in terms of deformation? A third possibility is that they could be *inherited* folds of the original sedimentary rocks, like those that can be seen in the Island Harbour Road outcrops (Day One), but this has always puzzled me - how could such things survive? And why would they end up in such alignment with the fabric defined by other tabular xenoliths?

TILTING LAYERED COMPLEX AND SURROUNDING AREAS

The remaining stops for the afternoon of Day Two are mostly located in the area around Tilting. They involve a loop hike through Olivers Cove and the area northeast of Tilting (total distance about 4 km) and a return hike to Wild Cove (about 3 km). The idea is to eat lunch on the beach at Oliver's Cove, which is one of my favourite places on Fogo Island, and not just because of its geology. *In contrast to the Seldom area, the coastlines here are more exposed, and it is very important to be attentive to sea conditions, and stay a safe distance from breaking waves.*

Stop 2.5: Oliver's Cove - Mafic Sheets in Felsic Crystal Mushes ?

From the Seldom area, drive north to Fogo Central and then turn right for Joe Batts Arm and Tilting on route 334. Drive into the community and note the mileage at the road junction for the west side of the community. After about 0.6 km, turn right onto a short gravel road that has a signpost for the baseball field and Olivers Cove. The more obvious next side road (Poore's Lane) is the wrong road. The gravel road leads almost to the beach at Olivers Cove, but the space for parking there is limited. The road becomes a trail, which leads around the beach. For the moment, we bypass the outcrops on the beach. Continue on the trail southeast of the beach, to some large granite outcrops located at 711925E/5508760N. The stop starts here, and proceeds back to the outcrops located in the middle of the Olivers Cove beach, ideally located for a lunch stop. *Watch out for waves in the first part of the stop!*

The granite outcrops are generally homogeneous medium-grained equigranular rocks containing biotite and hornblende. They also contain rounded mafic to intermediate enclaves, some of which are hornblende-rich. Elsewhere, diffuse darker patches may represent “ghost” enclaves of slightly more mafic composition. Walking north towards the beach, there are some larger angular enclaves and rafts that exhibit compositional banding possibly of cumulate origin. The diverse enclave population is typical of the granites of Fogo Island, as seen on Day One. Most of the mafic enclaves are rounded or diffuse and ameoboid in shape, and show subtle chilled contacts against the granite host. It is suggested that these represent quenched mafic magmas or intermediate liquids derived from mixing or fractionation of such liquids. Examples of possible sources will be seen in subsequent outcrops. Other enclaves, such as those with diffuse banding, have sharp but curvilinear contacts and likely were solidified (if hot) prior to being caught up in the granite.

There is also a zone of apparent mineral layering that dips gently to the northwest, and does not seem to represent an enclave. This provides the best indication of primary layering within the granite - although it is not necessarily an exact representation of the paleohorizontal. It is reasonable to assume that the rocks are not upside-down, so as we walk towards the beach, we are proceeding “upsection” in stratigraphic terminology.

About 100 m northwest of the granite outcrops, at 711905E/5508865N the shoreline passes abruptly into a fine-grained mafic unit. The contact with the granite is partly unexposed but in one area, best seen at low tide when there are not too many waves, there are signs of chilling in the mafic rock. The shape of this contact is lobate and very complex, but it is believed to dip gently northwest in this particular spot, although this is difficult to ascertain. Lobes of chilled diabase appear to protrude downward, as if they have sagged in response to gravitational loading. Between these “magmatic load casts”, there are “fingers” of granite that protrude northwestward (upward?) into the mafic sheet. A short distance further into the mafic unit, circular and elliptical granitic patches probably represent cross-sections through these structures. Upward, the mafic rock becomes paler in colour and more “intermediate” in appearance, locally with white feldspar phenocrysts that resemble those seen earlier in the granites. This rather diffuse and gradational zone fades once again into granite-like material, and then is succeeded by another chilled mafic sheet, with similar lobate structures on its interpreted lower surface.

The features of this stop are interpreted to record the emplacement of a mafic magma into partly solidified granitic material, likely at the interface between largely liquid felsic magma and accumulating crystal mush. These outcrops and relationships are identical to those described from the coastal Maine plutons, and most closely resemble those seen in the Vinalhaven Island and Isle au Haut intrusions (see earlier section). The upward-protruding granite zones are interpreted as magmatic “pipes”, where more buoyant mobilized granitic mush moved upward through the mafic sheet in response to density contrasts. These magmatic pipes are essentially miniature diapirs, consisting of partially solid material and interstitial liquid. Although it may appear here that the granite is *intruding* the mafic unit, the actual order of emplacement is the reverse; the mafic magma intruded the granite mush and was emplaced above it, and the granite mush then responded due to its greater buoyancy. The “magmatic pipes” were frozen in the process of ascending, but it is likely that many such pipes “stalled” when they achieved neutral buoyancy, and were actually assimilated into the mafic magma, changing its composition, and likely leaving some feldspar phenocrysts within it. Collectively, these processes form a mechanism for the creation of hybrid magma compositions on at least a local scale. The selective nature of such assimilation also has important geochemical implications, as discussed earlier in discussion of the central Maine plutons.

From here, continue across the beach to the outcrops that sit within it, at 711875E/5509035N. There is an unexposed section, but the lower part of this outcrop is a medium-grained intrusive rock suggested to be of granodiorite composition. A sharp, possibly chilled contact separates this from an upper section of medium-grey, fine-grained rock that resembles diabase, but probably has a more fractionated composition, and contains small feldspar phenocrysts. This has some similarities to possible hybrid sections of lower sheets. This outcrop contains excellent examples of magmatic pipes in both horizontal and near-vertical cross-section. Although these are not up to the calibre of magmatic pipes in the Vinalhaven Island, Isle au Haut and Mount Desert Island intrusions, they are the best that I have yet seen on Fogo Island. However, somewhat inadequate field notes from 1991 taken in the Cape Cove area describe very similar features that I found impossibly confusing at the time, but which I now suspect to be identical pipe structures in mafic sheets. It will be interesting to revisit this area in the future.

Some details of these pipes deserve further comment. Note that some contain internal "pegmatite patches" of coarse-grained quartz-rich material; these are residual liquids, trapped as the pipe solidified. One pipe actually seems to have "leaked" its residual volatile-rich fraction into the surrounding rock as it underwent final crystallization. Think of this as akin to a tiny magma chamber, from which a hydrothermal fluid eventually emerged into country rocks! A most peculiar pattern developed within and around one pipe seen in vertical cross-section is caused by bands of amphibole +/- biotite-rich material or "schlieren". I do not fully understand their origins, but suggest that they record the hydration effects around this ascending pipe, which would be significantly more water-rich than the host magma.

The relationship of these mafic sheets to the mafic rocks of the Tilting Layered Complex is uncertain. If the interpreted northwestward dip is persistent, these sheets would lie below it, rather than above it, but the intervening region is so chaotic that I really cannot be sure of anything. The northern coast of Olivers Cove likely contains several more mafic sheets in oblique cross-section and I fully expect that magmatic pipes and similar features can be identified here give sufficiently detailed examination. But this would likely not be an easy or rapidly-completed project!

Stop 2.6: Point Northeast of Olivers Cove - Attempted Mingling in Action ?

From the beach, follow a well-defined system of trails that lead around the shore and eventually to the point on the east side of the cove, located at 712935E/5508775N. The outcrops located on the shoreline enroute are amazingly complex, and we must avoid getting sidetracked. This area was placed in the diorite unit by Currie (1997) whereas Baird (1958) simply designated it as a zone of intrusive breccia. *Be attentive for breaking waves at this spot if the seas are rough. Be equally cautious of breaking bones on the very uneven outcrop surfaces.*

The point consists of a granite-like rock that contains numerous mafic inclusions, many of which have complex shapes and local chilled contacts against their matrix, which is here actually more quartz-dioritic than granitic. This locality is actually included within the granite unit by both Baird and Currie, but in reality all such boundaries are arbitrary placements. This outcrop is a total mess, with a light-coloured matrix littered with dark mafic blobs. Chilling is not obvious on all of these, but they are generally very fine-grained. There are some more continuous and homogeneous zones of fine-grained mafic material, but these are surrounded by inclusion-rich zones into which they appear to grade. In one part of the outcrop, an inclusion-rich zone has a broadly rectiplanar geometry that is strongly reminiscent of a dyke. If it was a dyke, it appears that this it simply could not keep itself together as a coherent body, and simply collapsed or disintegrated into much smaller blobs.

The outcrop is interpreted to record the *attempted* emplacement of a mafic magma into a partially liquid granitic crystal mush - as in the previous stop, the timing relationship is the reverse of what it may appear to be at first sight. In this case, perhaps the volume and flow rate of the mafic liquid was insufficient to form a sheet-like zone like those seen earlier, and we just ended up with this mess instead. Alternatively, perhaps the mafic magma was heading upwards in a dyke-like conduit through more solidified granitoid material, and then encountered the less consolidated material above, such that it never actually made it to a point where it could be emplaced into the granitic magma chamber. In such an interpretation, this outcrop is analogous to a "peperite", like those formed when hot lava is emplaced into unconsolidated sediments. But my favourite fanciful interpretation is that such zones might connect to something akin to a mafic lava fountain within the granitic magma, from which frozen blobs of diabase rained back down. All these volcanic analogues are fully appropriate in understanding some of these features. As mentioned earlier, the Vinalhaven Island Intrusion contains superb pillow-lava like rocks that actually formed deep within a magma chamber. If you can have a magmatic pillow lava, why not a magmatic lava fountain?

In contrast to Olivers Cove, where a good argument can be made for at least localized mixing and hybridization, this outcrop is better interpreted as a zone of attempted mixing that ended up instead largely as mingling. Mafic and felsic magmas are not truly immiscible liquids, but their contrasting temperatures, viscosities and solidus characteristics simply do not favour homogenization under most circumstances. Given time, they can mix and mate, but they tend to dislike one another intensely upon first meeting! In contrast, the more quiescent, "organized" interaction provided by the emplacement of sheet-like magma flows and development of magmatic pipes seems more likely to result in the production of hybrid magmas, perhaps through a selective contamination processes. The most important point that these two stops is the compelling evidence for the coexistence of mafic and felsic magmas in both space and time. Not to mention compelling evidence of the complexities of the processes involved!

Stop 2.7: Layered Rocks and Ultramafic Cumulates of the Tilting Layered Complex

From the previous stop, follow the coastal trail to the west. In places the trail can be tricky to spot, but it is better to stay back from the shoreline outcrops and related boulder fields, or it will take longer. The outcrops are mostly granites with scattered mafic zones, including some groups of large diabase pillows, but there is no time for detailed examination. After about 15 minutes of walking, a prominent jet-black outcrop will appear, which marks one of the ultramafic zones in the Tilting Complex. This stop begins just before this, at 712660E/5509640N, with the best exposures close to the water, and in a large outcrop just inland from this. *As in all areas here, be attentive for breaking waves if sea conditions are rough.*

The granite passes abruptly into layered mafic rocks at this point, and all previous accounts state that the granite is younger, but - as demonstrated by previous stops - such things cannot always be taken at face value on Fogo Island. There is a very nice area where trough-like features are developed, defined by mafic mineral accumulations. The layering dips steeply south in this area, in contrast to inferences from the Olivers Cove area, and it also youngs in that direction. The larger outcrop just inland from the trough-layered zone actually contains multiple cross-bedded zones with a herringbone pattern, but these are not immediately evident due to the lichen. The attitude of the layering actually varies considerably in these outcrops. In general, the dip of layering in the Tilting Layered Complex is steeper than indications of paleohorizontal seen elsewhere in the Fogo Island Intrusion, so perhaps it should have been called the Tilted Layered Complex. The well-layered rocks are underlain (to the north) by massive pyroxene-rich ultramafic cumulate rocks (websterites, with both ortho- and clinopyroxenes), which make up the prominent black outcrops. These are very spectacular on a sunny day due to the numerous well-developed crystal surfaces. Interestingly, one of the topics addressed in Hank Williams' 1957 B.Sc. Thesis was the applicability of the new "cumulate theory" developed by Wager and Brown in the Skaergaard area of east Greenland to the origins of such rocks, as opposed to other explanations then in vogue. Hank concluded that Wager and Brown's ideas provided the best explanation for the rocks of the Tilting area, and this interpretation has certainly not changed.

From this stop, the coastal trail continues all the way to Tilting, but this is a somewhat longer route. There are interesting things to see on the way; the granite dykes cutting the layered rocks will be obvious, but can geologists spot two other fanciful features dubbed the "Devil's Rocking Chair" and the "Devil's Heart ?" Rest assured that both do have sensible geological explanations. The quickest route back is to leave the trail about 100 m beyond the websterites, and head directly for the houses across a small marsh. *Participants without rubber boots may find negotiating the wetter sections a bit of a challenge, but you have been warned.*

Stop 2.8: Cyclic Cumulate Rocks of the Tilting Layered Complex near the Squish Studio

From the road in Tilting, return to the vehicles at the Ball Park or Oliver's Cove. Drive west through the village, and turn right by the church, along the west side of the harbour, and park by the museum, just before the sharp right-hand bend. The trail from here (Turpins Trail) leads directly to the studio site, and the outcrops of interest are on the point just beyond the studio. They are easily visible because of the obvious layering. The Squish Studio is a widely-photographed site and - if you stand in right place - looks uncannily like a white monoclinic crystal perched upon the rocky landscape. *Be attentive for breaking waves near the point.*

These outcrops provide some of the best examples of cyclic magmatic layering in the Tilting Complex. The layering dips steeply towards the northwest here, and parts of at least two cycles are visible, although later intrusive dykes of broadly intermediate composition (escaped hybrids?), obscure some of the relationships, as do the ubiquitous felsic sheets and veins. The cyclic units have mafic cumulates at their base (although not as spectacular as the websterites at previous stops) which pass up into well-layered rocks within which there discrete mafic cumulate units, and eventually into leucocratic plagioclase-rich rocks that have locally pegmatitic textures. These locally contain large amphibole crystals and are obvious candidates for geochronological studies. The uppermost leucocratic unit in a cycle is overlain abruptly by further mafic cumulates.

The Tilting Complex contains several cycles of layering, which likely represent discrete magma influxes, and it is reasonable to expect that there would have been interactions between new magma and partially crystallized cumulates. Such features are documented within largely mafic layered rocks in the coastal Maine plutons, most notably in the Pleasant Bay Intrusion, which has multiple layered units and virtually no granitic rocks (Wiebe et al., 2000). Aydin et al. (1994) make reference to "finger structures" at the bases of some cyclic units, and I suspect that these are magmatic pipes akin to those visited earlier today, although the exact locations remain to be determined. On a wider scale, the exact relationship and meaning of the Tilting Layered Complex in the context of the Fogo Island Intrusion remain a mystery. The previous research work on the Tilting Complex has largely addressed its "internal" features and development, but there is a need to look at it in a much wider framework.

Stop 2.9: Gabbro with Delicate Xenoliths, Sandy Cove Beach (optional stop)

Sandy Cove beach is justifiably famous as an idyllic place for a picnic on a hot summer day, or for a fireside party on a clear night. In a province that is not well-endowed with sandy beaches, this one is truly a sheltered gem. The fine white sand presumably comes from granites elsewhere on the north coast, because most of the rocks exposed in this area are distinctly mafic. From the previous stop, return to the main road in Tilting at the church, and then drive west for 1.4 km, and park by the roadside just past the Knights of Columbus picnic park, by the sign that warns of restrictions on dogs. From here, walk northward to the beach across the grassy area to a large outcrop almost surrounded by the sand, located at 710220E/5514140N. *There are no significant hazards at this locality, although it is possible that windblown sand could get into the eyes.*

Although the Tilting area is best known for its mafic cumulate rocks, it also includes more homogeneous mafic rocks, which resemble those seen in the Seldom Gabbro. This particular outcrop contains many xenoliths of metasedimentary origin, presumably derived from the Fogo Harbour Formation. These are well-aligned, and have tabular shapes, and some are sheet-like remnants of single thin beds. This outcrop is very reminiscent of xenolith-rich zones seen earlier in the Seldom area, in which such fabrics were suggested as manifestations of flow. However, these xenoliths are amazingly delicate, and I have problems understanding their survival within a dynamic magma chamber. Note that the fabric defined by the xenoliths here is steep vertical, as is typical for much of the Tilting Complex.

Stop 2.10: The Totally Wild Breccias of Wild Cove

From Sandy Cove Beach drive a short distance to the west and park where "Farm Road" joins the highway, just before the "Thank you for visiting scenic Tilting" sign. From here, a trail runs parallel to the road for a short distance, and then heads northward through one of the few patches of boreal forest that exist on northern Fogo Island. The trail is a very pretty walk through forest and wetlands, emerging in open barrens above Wild Cove. The walk to Wild Cove takes about 20 minutes; after the second patch of woodland, cut directly across to the shoreline, where the first outcrops are at 709725E/5511380N. *Wild Cove is aptly named; it is important to stay clear of the areas affected by breaking waves at all times. Be careful also of the uneven surfaces and loose boulders along the shore.*

Note that this trail is part of a loop, leading to the point northwest of Sandy Cove and then back to Sandy Cove beach and the previous stop. If an independent excursion provides time, this is a very pleasant and geologically interesting hike. However, the descriptions provided below apply only to the first section, which is dominated by intrusive breccias.

The entire shoreline at Wild Cove consists of spectacular intrusive breccias, to which the matrix appears of quartz diorite to granodiorite composition, rather than granite like that of the Shoal Bay Granite, which lies to the west and south. These rocks correspond to the "Sandy Cove - Wild Cove Suite" of Aydin (1995) and were placed in the "diorite" unit by Currie (1997). Baird (1958) simply designated them as intrusive breccias. As in the case of the Olivers Cove area, the positioning of any boundary between these units is arbitrary and subjective. Note that there are numerous examples of "false inclusions" produced by the local erosion of lighter weathered surfaces. But there are also lots of real inclusions, most of which are enclaves rather than xenoliths.

The Wild Cove breccias are more complex and intimidating than other such zones, because they include a wide variety of inclusion types. There are medium to coarse-grained mafic plutonic rocks that in places closely resemble those seen within the Tilting layered complex. Layered blocks are not common, but they are present locally. There is also a complete range of fine- to medium-grained mafic enclaves, and also diabase-like enclaves that may be chilled. The shapes of most of the inclusions here are fairly angular, and those that show internal structure must have been included as solid material. The fine-grained mafic rocks tend to have more blobby or amoebic shapes, but I have only rarely seen clear chilled margins. There are also some angular xenoliths of hornfelsed metasedimentary rocks, but these are uncommon. An important feature of some larger blocks is that they themselves contain discrete enclaves, showing that they were formed in a slightly earlier cycle, solidified, and then "reworked" following invasion by another pulse of magma. The matrix locally has a blotchy mottled appearance, perhaps resulting from variable contamination by assimilated material. Some mafic inclusions contain feldspar phenocrysts, which are not present in the matrix. These could record the crystallization history of the parent magmas, but could equally represent mechanical mixing with granitic mush that occurred prior to their solidification and inclusion in this breccia. In contrast to earlier stops that record unsuccessful or partially successful mixing of mafic and felsic magmas in liquid or partly liquid states, the Wild Cove breccias seem *largely* to result from the disruption of largely solid materials of varied origin by a younger pulse of liquid magma. There are, however, no constraints on the absolute time difference, and these features remain consistent with the long-term spatial and temporal coexistence of mafic and felsic magmas

The second part of the stop is about 200 m to the east, at 709880E/5511350. Here, a dyke-like feature provides an important insight, but note that this can be difficult to spot in late afternoon or evening light. Look for a rectiplanar light-coloured zone cutting through the outcrop. Along its margins, the inclusions in the breccia are truncated. The interior of the dyke, however, is filled with another complex intrusive breccia - though you may need to look carefully here to distinguish true inclusions from false inclusions. This locality illustrates that whatever processes created these zones were long-lived on a large scale and episodic on a local scale; the breccias had stabilized and solidified, and then the whole process started again. The blocks with internal breccia textures in parts of the outcrop further attest to a still earlier cycle in this process.

If time permits, it is worth walking another 350 m or so to the east, to the point opposite Sandy Cove and Tilting. The point is a spectacular intrusive breccia in which large blocks the size of cars are progressively stoped and broken into smaller pieces. In this particular spot, the fragment population is relatively homogeneous, so it perhaps illustrates the initial stages of formation. However, some blocks here appear to contain internal breccia structure, attesting to the repeated and cyclic nature of these processes. Amoeboid and possibly chilled diabase enclaves suggest that the matrix itself carried entrained globules of mafic magma as it destroyed and fragmented earlier-crystallized rocks. From this point, the trail will eventually lead back to Sandy Cove beach. If this route is followed, look out for "the snakes". These are some very peculiar and elongated sinuous enclaves of compositionally banded material that have long puzzled me.

Stop 2.11: Xenolith Breccias at the Fogo Island Inn Site, near Brown's Point, Barr'd Islands

The final stop for today is yet another intrusive breccia, located at the site of the new Fogo Island Inn, under construction at the time of the field trip. From the trails at Wild Cove or Sandy Cove, drive west through Joe Batts Arm into Barr'd Islands, and take the construction site access road, located shortly before the prominent brick church located on a side road. All of the shoreline outcrops beneath the Inn are essentially similar, but the best area for examination is at the west end of the site, at 709870E/5511350N. *Be attentive for breaking waves if sea conditions are rough.*

These outcrops are part of an extensive breccia zone between Joe Batts Arm and Barr'd Islands. Currie (1997) suggested that this zone continued southward into the interior of the island, and that it might represent a vertical wall between subchambers. The blocks in this zone range from the size of houses to just a few cm across, with all sizes in between. They are almost all pale grey variably hornfelsed metasedimentary rocks, probably derived from the Fogo Harbour Formation. The tabular xenoliths suggestive of in-situ dissection of bedded rocks or gravitational accumulation of xenoliths seem to be absent here. Instead, the progressive destruction and fragmentation of large blocks can be demonstrated, beggining with a network of granitic dykes, and ending with a chaotic mess. The zone is cut by elsewhere by diabase dykes containing plagioclase phenocrysts, and also by the ubiquitous felsite dykes.

Interestingly, there are also parallels to these rocks in the coastal Maine plutons, most notably in the Mount Desert Island Intrusion. The main granitic unit here is almost entirely surrounded by a feature termed the “shatter zone”, in which the country rocks are dismembered by granitic magma in a similar manner. This makes an excellent stop at which to end the day, and a great place from which to watch the sunset. The site of the Fogo Island Inn is particularly emblematic of the harsh but beautiful northern coast of the island, and enjoys spectacular views of the Little Fogo Islands.

DAY THREE

HIGH-LEVEL GRANITES AND VOLCANIC ROCKS OF THE FOGO TOWN AREA

After a day and a half of wandering around the deeper regions of the Fogo Island magma chamber, the itinerary for Day Three visits the uppermost section of the intrusion, and possibly related volcanic and pyroclastic rocks. The majority of these stops are in the area around Fogo Town, and are accessible through hiking trails. Some of these excursions involve steep climbs on trails, notably at Fogo Head and Brimstone Head, but these are mostly for the sake of views, and are optional out-and-back (or up-and-down) excursions.

The volcanic and pyroclastic rocks of the Brimstone Head Formation are best examined in coastal exposures, because their original features and textures and commonly very cryptic in weathered inland locations. The islands in Fogo harbour contain beautiful exposures, as do some sections on the northwest side of Shoal Bay. From a brief excursion in 2011, the Little Fogo Islands also seem to have spectacular rock types and relationships in clean, superbly-exposed outcrops. The Brimstone Head Formation has never been studied in detail, but it has great potential for such research. Because the coastline here is steep, ee are restricted largely to inland outcrops.

It should be noted that some localities to be visited today are reputedly in dangerous proximity to the edge of the Flat Earth. Although to date there have been no injuries or fatalities that are directly related to this mythical feature, the warning on the Brimstone Head Trail ("One false step could be your last") should be taken seriously, because this locality - and others - are surrounded by steep and potentially dangerous cliffs.

Stop 3.1: Hare Bay Granite (or differentiated facies of the Shoal Bay Granite)

This stop may be omitted, as the Hare Bay Granite was visited on Day One in coastal exposures at Deep Bay. These outcrops are natural surfaces on the east side of the road between Fogo Town and Fogo Central, at the UTM location 698750E/5507925N. The outcrops are just south of the ponds used locally as swimming spot. *The outcrops are just on the other side of the ditch, but be warned that said ditch is likely to be wet in places. Or wet everywhere.*

This particular outcrop sits within the Shoal Bay Granite as mapped by Baird and by Currie, but has many of the characteristics of the Hare Bay Granite. It is a mediun-grained, equigranular, orange to brick-red granite, virtually devoid of mafic minerals, and contains miarolitic cavities.

Stop 3.2: Felsic Igneous Rocks in the Fogo Harbour Formation - Ash-flow tuffs or Satellite Sills ?

This locality is easy to find, as it is a large aggregate and gravel quarry on the east side of the road, 1.5 km south of the junction by the rock garden in Fogo Town. The outcrops are very distinctive and easy to locate because many of them are very rusty. *Be wary of rough surfaces and loose blocks, and also broken glass, wrecked cars and some other assorted debris.*

This locality features two groups of rocks. On the south side of the pit are well-bedded, laminated siltstones and sandstones of the Fogo Harbour Formation, which dip towards the north. Cross-bedding is visible in these outcrops. The prominent rusty ridge within the pit is a different rock type that sits stratigraphically above the sandstones and siltstones; the best place to see these is in outcrops by the side of the rough road that leads to the upper bench in the pit, where the rusting is least intense. This is a white to pale grey, siliceous rock that contains small quartz phenocrysts best seen on fresh surfaces with a hand lens. The rusting, due to sulphides, does not seem to be an inherent feature of this rock type, but rather is on fracture surfaces, possibly part of a subvertical faulted zone that transects the pit.

There are several such units within the sedimentary rocks of the Fogo Harbour Formation between the upper contact of the Hare Bay Granite and the base of the Brimstone Head Formation. These were originally mapped as felsitic sills by Baird (1958) but were suggested by Sandeman and Malpas (1995) to be tuffaceous pyroclastic rocks. Currie (1997) preferred the sill interpretation and cited the presence of contact metamorphism as evidence for such an origin. These particular outcrops do not provide any information that illuminates this debate, and the coastal outcrops on nearby Seal Cove are likely a better place to examine contact relationships in detail. It is, of course, entirely possible that both tuffs and subvolcanic sills exist within this area,

Stop 3.3: Pyroclastic Breccias of the Brimstone Head Formation, Fogo Head Trail

Two trail networks provide access to the volcanic, pyroclastic and sedimentary rocks of the Brimstone Head Formation. The longer of these, around Lion's Den, is very scenic but has only one or two interesting outcrops. The Fogo Head trail provides better material for geologists, and also some wonderful panoramic views. The starting point for the trail is on the north side of Fogo Harbour, almost at the end of the road, where a small viewpoint with some fake cannons has been constructed. To access the road on the north side of the harbour turn right at the main junction just past the large Anglican church. Hike westwards along the trail, over the first hill and down into the valley beyond, where there is a small beach. The outcrops of interest are located on the northwest side of the beach, at 695590E/5511445N. *The outcrops are rough and sharp, and behave in a brittle and dangerous manner should you try to hammer them. Please do not do so.*

These outcrops appear black and featureless at first sight, but the more time spent here, the more features will be seen. Good surfaces clearly show that they contain fragments of a wide size range and are thus pyroclastic rocks, rather than true rhyolitic flows (these latter seem to be very rare on Fogo Island). However, most of the fragments are probably pieces of glassy volcanic lava derived from explosive eruptions. There is one particularly large fragment that shows this mode of origin best, and it can be identified because of the large lithophysae or gas escape structures that it contains. The entire outcrop contains gas-escape structures, suggesting that it was deposited very quickly in a hot state. In cross-section on relatively flat surfaces the lithophysae appear as circular structures, because they have a tubular shape. Examination of relatively vertical outcrop surfaces will show them in long section, where they form pale streaks. For some reason, the largest and most spectacular lithophysae seem to have formed within larger rhyolite blocks.

The outcrop is cut by greyish rhyolite dykes and also by pale-coloured zones of bleaching, which may be confused easily in some areas. The dykes can be distinguished by their sharp contacts, but in detail these are lobate and complex. It is possible that these breccias were still hot when the dykes were emplaced, perhaps as feeders to continued eruptions. The bleached zones are presumably related to discharge of hydrothermal fluids, and some of them exhibit brecciation textures that could result from gas or steam expansion.

Stop 3.4: Fogo Head Viewpoint

From the previous stop, walk uphill over the outcrops, rejoin the trail, and labour up the steep hill and steps to the first viewpoint on Fogo Head. There is not much to see on the way, although some of the outcrops in the trail reveal fragmental textures. The outcrops on the summit are the glassy, obsidian-like, black material that is characteristic of many of the ignimbrite (welded tuff) units in the formation, but few original features can be seen. The views make up for the poor outcrops. The Little Fogo Islands, spread out on the northeast horizon, are likely also part of this volcanic belt, and can be imagined as a more "drowned" version of the rugged landscape around Fogo Town. In the other direction, the community of Change Islands is visible clearly; there are also volcanic rocks in this area, but these are basaltic to intermediate in composition. The idea that these might be equivalent to the mafic plutonic rocks of the Fogo Island magma chamber has been considered, but there is no proof of this, and they could be significantly older. The high barren island beyond Change Islands to the northwest is Bacalao Island, which sits off Twillingate (not visible). This consists of Cambrian-aged trondjemite and tonalite of the Twillingate Intrusion, and actually sits on the other side of the Red Indian Line (junction between peri-Laurentian and peri-Gondwanan terranes in the Central Mobile Belt of Newfoundland. The land in the far distance is the coast of the Baie Verte Peninsula. If time permits, there is a second viewpoint a short distance along the trail that has very good views of local outcrops. A headland visible from this spot shows a prominent transition from black rocks to paler grey rocks. These will not be visited, but the paler unit is a discrete ignimbrite (welded tuff) that has locally well-developed eutaxitic textures defined by intensely flattened fragments.

Stop 3.5: Ignimbrites (welded ash-flow tuffs) at Back Cove

From the previous stop, return to the trailhead, and drive back into Fogo. Alternatively, it is possible to continue on the trail, which descends to the road leading to this stop, but it will take longer. In Fogo Town, turn right, and follow the road leading to Brimstone Head, but swing right at the small Catholic Cemetery to reach Back Cove. Park above the small beach, where there are several outcrops. The best location is around 694660E/5510550N, on the beach. Good outcrops are also present on and below a trail leading from the cove on its north side (look for the flight of wooden steps). *This is a protected location, but some outcrop surfaces may be sharp.*

The outcrops around the trail are uninformative on weathered surfaces. However, the fresh and glass-like broken surfaces show gently-dipping eutaxitic fabrics. These can also be seen on larger surfaces in the shoreline outcrops, where the flattened fragments are more readily discerned. It appears that much of the Brimstone Head Formation, including the head itself, consists of these pyroclastic flows, products of Silurian nuée ardente eruptions. Such eruptions are perhaps the most dangerous manifestations of volcanism, as exemplified by the famous destructive eruption that completely destroyed St. Pierre (Martinique) in April 1902.

Stop 3.6: Sedimentary rocks within ? (below?) the Brimstone Head Formation

From the previous stop, return along the road to the junction by the cemetery, and turn right on the road to Brimstone Head Park, which is just a short distance down this road and has ample parking. From the parking area, set out on the trail to Brimstone Head, but turn right at the start of the boardwalk to follow a well-defined trail that leads after a few minutes walk to an old well, near the coast underneath the north face of Brimstone Head. From the well descend into a small protected cove that exposes some well-bedded sedimentary rocks. Geological maps imply that these sit below the Brimstone Head Formation, which certainly looms large above, but there are some uncertainties about this relationship. *The outcrop surfaces in the cove are steep, so be careful.*

The rocks in the cove are green to grey, well-bedded sandstones and siltstones of the Fogo Harbour Formation, which here define a tight syncline in which a sequence of relatively thickly-bedded rocks is overlain by thinly-bedded green siltstones. The syncline can be traced readily by following a prominent bedding plane that displays well-developed ripple marks. Other bedding planes display lumpy (nodular?) patterns that are equally distinctive. The axis to this fold plunges to the west. On the north side of the cove, the sedimentary rocks include some white-weathering units that appear to contain coarse-grained volcanic detritus, and locally resemble volcaniclastic tuffs. The ash-flow tuffs that form Brimstone Head (see next stop) would appear to dip through or below the location of these outcrops, and it is really not clear if they sit stratigraphically below or above them. However, there could be faults through this area that complicate geometric relationships. Examination of outcrops in and around Fogo Town, and the differing map patterns portrayed by Baird (1958) and Currie (1997) shows that some ash-flow tuffs are indicated as sedimentary rocks or vice-versa, and these can appear superficially similar in less-than-ideal exposures. There is clearly room for more detailed work in this area to better understand these relationships.

Stop 3.7: Brimstone Head

The final stop for Day Three is on Brimstone Head itself, which is a steep but rewarding climb from the cove. Return to the well, and follow a side trail up a small valley towards the stairway visible on the head. This rejoins the main Brimstone Head trail, which ascends the steep eastern slope to the summit. Those who do not wish to partake in the ascent can return on either trail to the parking area. *Brimstone Head is surrounded by steep and dangerous cliffs, not to mention the mythical edge of the Flat Earth.*

Brimstone Head consists of massive ignimbrites (ash-flow tuffs). The best exposures of these are on the steep climb, where north-dipping eutaxitic fabrics and flattened fragments are visible on several surfaces, dipping down towards the folded sedimentary rocks of the previous stop. On the summit, there is little to see geologically, but the numerous sharp stones of obsidian-like material provide a clear clue to the derivation of the name for this locality.

Needless to say, the panoramic views from this spot are spectacular on a clear day, and are worth examining closely, because the Flat Earth Society claims that one of the four corners of the Flat Earth can be seen from here under the right conditions. The other three mythical corners are located on the island of Hydra in Greece (another beautiful but rocky location), Papua New Guinea and in the Bermuda Triangle. The direct distance from Fogo Island in Newfoundland, to the only other Fogo Island in the world (located in the Cape Verde Islands off the coast of Africa) is 4,479 km. I have often wondered if the likely similarity between the ancient volcanic landscapes of the Fogo town area and the modern volcanic landscapes of Cape Verde might have had a role to play in the naming of our Fogo Island. However, such a theory is impossible to prove in an objective way, and in this respect may resemble some of the geological ideas expressed in this guide.

REFERENCES

Aydin, N. S.
1995: Petrology of the composite mafic-felsic rocks of the Fogo Island batholith: A window to mafic magma chamber processes and the role of mantle in the petrogenesis of granitoid rocks. Unpublished Ph.D. Thesis, Department of Earth Sciences, Memorial University of Newfoundland.

Aydin, N. S., Malpas, J., and Jenner, G.
1994: Physical characteristics of the Tilting layered suite, Fogo Island, Newfoundland. South African Journal of Geology, 97, 496-506.

Baird, D. M.
1958: Fogo Island map-area, Newfoundland. Geological Survey of Canada, Memoir 301.

Cawthorn, R. G.
1978: The petrology of the Tilting Harbour igneous complex, Fogo Island, Newfoundland. Canadian Journal of Earth Sciences, 16, 526-539.

Chapman, M., and Rhodes, J. M.
1992: Composite layering in the Isle au Haut igneous complex, Maine: Evidence for periodic invasion of a mafic magma into an evolving magma reservoir. Journal of Volcanology and Geothermal Research, 51, 41-60.

Currie, K. L.
1997: Fogo map-area, Newfoundland. Geological Survey of Canada Open File 3466, 1:50,000 scale map with marginal notes.

Currie, K. L.
2003: Emplacement of the Fogo Island batholith, Newfoundland. Atlantic Geology, 39, 79-96.

Dickson, W. L.
2006: The Silurian Indian Islands Group and its relationships to adjacent units. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 2006-1, 1-25.

Eastler, T. E.
1969: Silurian geology of Change Islands and eastern Notre Dame Bay, Newfoundland. American Association of Petroleum Geologists, Memoir 12, 425-432.

Elliot, C. G., Dunning, G. R., and Williams, P. F.
1991: New U-Pb zircon age constraints on the timing of deformation in north central Newfoundland and implications for early Paleozoic Appalachian orogenesis. Geological Society of America Bulletin, 103, 125-135.

Fryer, B. J,, Kerr, A., Jenner, G. A., and Longstaffe, F. J.

1992: Probing the crust with plutons: regional isotopic geochemistry of granitoid plutonic suites across Newfoundland. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Report 92-1, 118-139.

Gates, O.
2001: Bedrock geology of North Haven and Vinalhaven Islands. Maine Geological Survey, Department of Conservation, State of Maine, Open File 01-373, report and map.

Hawkins, D. P, and Wiebe, R. A.
2004: Discrete stoping events in granite plutons: A signature of eruptions from silicic magma chambers? Geology, 32, 1021-1024.

Hawkins, D. P., and Wiebe, R. A.
2007: Construction of the subvolcanic Vinalhaven Intrusive Complex, coastal Maine. 20th Annual Keck Symposium, proceedings - http://keck.wooster.edu/publications.

Hawkins, D. P., Brown, N., Wiebe, R. A., Klemetti, E., and Wobus, R.
2009: Documenting the timescale of pluton construction: U-Pb geochronology of the subvolcanic Vinalhaven Intrusion and associated volcanic rocks. Geological Society of America, Abstracts with Programs, 41-7, 148.

Hodge, D. S., Abbey, D. A., Harbin, M. A., Patterson, J. L., Ring, M. J., and Sweeney, J. P.
1982: Gravity studies of subsurface mass distributions of granitic rocks in Maine and New Hampshire. American Journal of Science, 282, 1289-1324.

Hogan, J. P., and Sinha, A. K.
1989: Compositional variation of plutonism in the coastal Maine magmatic province: mode of origin and tectonic setting. In R. D. Tucker and R. G. Marvinney (eds), Studies of Maine Geology, volume 4, Maine Geological Survey, Department of Conservation, State of Maine, 1-33.

Hughes, C. J.
1972: Note on the variability of granophyric texture. Geological Society of America Bulletin, 83, 2419-2422.

Kerr, A.
1994: An integrated lithogeochemical database for the granitoid plutonic suites of Newfoundland: Part A - An overview of geology, geochemistry, petrogenesis and mineral potential. Unpublished contract report NC 1.1.3, submitted to the Geological Survey of Canada as part of the Canada-Newfoundland Agreement on Mineral Development.

Kerr, A.
1997: Space-time-composition relationships among Appalachian-cycle plutonic suites in Newfoundland. Geological Society of America Memoir 191, 193-221.

Kerr, A., Hayes, J. P., Colman-Sadd, S. P., Dickson, W. L., and Butler, A. J.

1994: An integrated lithogeochemical database for the granotoid plutonic suites of Newfoundland. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Open File 2377.

Lux, D. R., Hooks, B., Gibson, D., and Hogan, J. P.
2007: Magma interactions in the Deer Isle granite complex, Maine: Field and textural evidence. Canadian Mineralogist, 45, 131-146.

Sandeman, H. A.
1985: Geology, petrology and geochemistry of the Fogo Island granites, northeast Newfoundland. Unpublished B.Sc. Thesis, Department of Geology, Memorial University of Newfoundland.

Sandeman, H. A., and Malpas, J. G.
1995: Epizonal I- and A-type granites and associated ash-flow tuffs, Fogo Island, northeast Newfoundland. Canadian Journal of Earth Sciences, 32, 1835-1844.

Strong, D. F., and Dickson, W. L.
1978: Geochemistry of Paleozoic granitoid plutons from contrasting tectonic zones of northeast Newfoundland. Canadian Journal of Earth Sciences, 15, 134-146.

Whalen, J. B., Currie, K. L., and Chappell, B. W.
1987: A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology, 95, 407-419,

Whalen, J. B., McNicoll, V., van Staal, C. R., Lissenberg, C. J., Jenner, G. A., Longstaffe, F. J., and van Breemen, O.
2006: Spatial, temporal and geochemical characteristics of Silurian collision-zone magmatism, Newfoundland Applachians: An example of a rapidly-evolving magmatic system related to slab break-off. Lithos, 89, 377-404.

Wiebe, R. A.
1974: Coexisting basic and intermediate magmas, Ingonish, Cape Breton Island. Journal of Geology, 82, 74-87.

Wiebe, R. A., Smith, D., Sturm, M., King, E. M., and Seckler, M. S.
1997: Enclaves in the Cadillac Mountain Granite (coastal Maine): Samples of hybrid magma from the base of the chamber. Journal of Petrology, 38, 393-423.

Wiebe, R. A., Snyder, D., and Hawkins, D. P.
2000: Correlating volcanic and plutonic perceptions of silicic magma chamber processes: Evidence from coastal Maine plutons. Geological Society of America Field Forum, September 14-18, 2000, Guidebook.

Wiebe, R. A., Frey, H., and Hawkins, D. P.

2001: Basaltic pillow mounds in the Vinalhaven Intrusion, Maine. Journal of Volcanology and Geothermal Research, 107, 171-184.

Wiebe, R. A., Manon, M. R., Hawkins, D. P., and McDonough, W. F.
2004: Late-stage mafic injection and thermal rejuvenation of the Vinalhaven Granite, coastal Maine. Journal of Petrology, 45, 2133-2153.

Wiebe, R. A., Jellinek, M., Markley, M. J., Hawkins, D. P., and Snyder, D.
2007: Steep schlieren and associated enclaves in the Vinalhaven Granite, Maine: possible indicators for granite rheology. Contributions to Mineralogy and Petrology, 153, 121-138.

Williams, H.
1957: Petrology of the Tilting Igneous Complex, Fogo district, Newfoundland. Province of Newfoundland, Department of Mines and Resources, Report 13 (also M.Sc. Thesis, Memorial University).

Williams, H.
1964: Notes on the orogenic history and isotopic ages of Botwood map-area, northeastern Newfoundland. Geological Survey of Canada, Paper 64-17, 22-29.

Williams, H.
1972: Stratigraphy of the Botwood map-area, northeastern Newfoundland. Geological Survey of Canada, Open File 113.

Williams, H.
1979: Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, 16, 792-807.

Williams, H., Colman-Sadd, S. P., and Swinden, S.
1988: Tectonostratigraphic divisions of central Newfoundland. Geological Survey of Canada, Paper 88-1B, 91-98.

Williams, H., Currie, K. L., and Piasecki, M. A. J.
1993: The Dog Bay Line, a Silurian terrane boundary in northeast Newfoundland. Canadian Journal of Earth Sciences, 29, 2481-2494