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THE FOGO PROCESS FROM A GEOLOGIST'S PERSPECTIVE: A DISCUSSION OF MODELS AND RESEARCH PROBLEMS

A. Kerr
Mineral Deposits Section

ABSTRACT

Fogo Island, located off the northeast coast of Newfoundland, is probably the best and most accessible place in the Province to explore the interior of a composite bimodal magma chamber. Intermittent field work on the Island since the early 1990s increasingly points to strong similarities between the Fogo Island intrusion and plutonic complexes of similar age in northeastern Maine (USA). This article examines key aspects of Fogo Island geology in the context of these influential studies, and discusses some potential research topics.

Fogo Island provides a tilted, vertical section through a tabular magma chamber that developed largely in sedimentary rocks. It may also preserve parts of the volcanic superstructure that originally sat above the magma chamber. The deeper section of the Fogo Island intrusion consists of layered mafic and intermediate rocks, whereas its upper section is dominated by coarse-grained granitoid rocks, with local areas of finer grained granite and quartz-feldspar porphyry. The boundary zone between these lower and upper sections is a complex region of interaction and hybridization, in part developed through the emplacement of hot mafic magmas into partially consolidated, cooler 'crystal mush' of granitoid composition. Similar features occur where mafic rocks are locally present at higher levels in the granitoid rocks, and widespread 'mixed rocks' where mafic enclaves are enveloped by a granitoid matrix for the most part record these processes. Other features described from the Maine intrusions, such as 'magmatic pipes' and 'magmatic pillow structures', are also present on Fogo Island. Collectively, this evidence indicates temporal coexistence of mafic and granitoid magmas through much of the lifespan of the Fogo Island magma chamber, and suggests that models developed for its counterparts in Maine are broadly applicable. Research opportunities abound on the Island, and these are by no means confined to the dominant plutonic rocks. Quantitative data such as geochemistry and geochronology are needed to assess and expand conceptual models presented here, but continued field studies are essential to validate the context of such work and constrain interpretation of results.

INTRODUCTION

Fogo Island is justly renowned for varied scenery, abundant wildlife, marine diversity, and its distinct cultural identity. The Island is also blessed with interesting geology, laid bare in exquisite detail along rugged yet accessible coastlines. I have long been interested in these spectacular outcrops and their problems. This interest was rekindled by research conducted on complex bimodal intrusions in northeastern Maine (USA) that are probably correlatives of the Fogo Island intrusion. This work supports a generalized model of a composite magma bimodal chamber initially proposed in an unpublished contract report (Kerr, 1994), and may help to explain some details unresolved at the time. In summary, Fogo Island provides a tilted section through a complex magma chamber that includes a lower mafic section, an upper granitic section, some spatially associated high-level intrusions and possibly coeval volcanic sequences. Following visits to the Maine intrusions in 2009, I returned with a strong conviction that models employed there could be applied to Fogo Island; this proved to be partially correct, but there remain many questions to ask through future research. The activities of the Shorefast Foundation since 2008 provided me an opportunity to resume intermittent field work, and to assist with public outreach and geotourism initiatives. In 2011, the Geological Association of Canada (Newfoundland and Labrador Section) sponsored a field trip to the Island. This article is in part derived from the field trip guidebook (Kerr, 2011).

This article has two objectives. The first is to outline models for the anatomy and development of composite bimodal magma chambers, in large part based upon Maine examples, and to highlight field evidence from Fogo Island supporting their application. The second is to draw attention to research opportunities and provide a starting point for such work, which will hopefully prompt others to ask questions that have not yet occurred to me.

GEOLOGICAL BACKGROUND

REGIONAL GEOLOGICAL SETTING

Fogo Island lies north of Gander and east of New World and Twillingate islands in Notre Dame Bay (Figure 1). The Island sits within the Exploits Subzone of the Dunnage Zone of the Appalachian Orogen, interpreted to comprise peri-Gondwanan volcanic arcs and continental basement accreted to Laurentia during the Silurian (Williams *et al*., 1988). In addition to Cambrian–Ordovician sequences, the Exploits Subzone also contains Silurian volcanic and sedimentary rocks, and abundant Silurian to Devonian plutonic rocks. The stratified rocks of western Fogo Island are assigned to the Silurian Botwood Group (defined by Williams, 1972) and include shallow-water clastic sedimentary rocks overlain by felsic pyroclastic and volcanic rocks. However, most of the Island is underlain by plutonic rocks that have given Late Silurian to Devonian Rb–Sr and U–Pb ages (Sandeman, 1985; Aydin, 1995). The southern part of the Island lies close to the trace of a composite fault zone termed the 'Dog Bay Line' (Williams *et al*., 1993; Currie, 1997). The boundary between the Exploits Subzone and the peri-Laurentian Notre Dame Subzone of the Dunnage Zone (the 'Red Indian Line') lies northwest of Fogo Island (Figure 1). Despite these major bounding structures, sedimentary rocks on Fogo Island are well preserved, and its plutonic rocks are largely undeformed, aside from synmagmatic effects. The *Fogo Island intrusion*, as it is termed here, is one of several bimodal Silurian–Devonian plutonic suites within the Exploits Subzone, but it is the only one exposed on the coast. Rocks equivalent to the Exploits Subzone and adjacent Gander Zone occur in southern New Brunswick, and also in the coastal regions of Maine, USA (Figure 1). In Maine, bimodal plutonic rocks of similar age and composition are termed the Coastal Maine Magmatic Province, and are superbly exposed on islands, notably Mount Desert Island, Vinalhaven Island and Isle au Haut (e.g., Hogan and Sinha, 1989). This long-distance connection is very important in the context of this article.

HISTORY OF INVESTIGATION

The biography of Fogo Island geology includes some well-known names. The first descriptions were by J.B. Jukes in 1842 and Alexander Murray in the late 1880s, but the first true geological maps were prepared by David M. Baird in 1958, and these remain the most useful for field work. Baird was assisted by a young student from St. John's named Harold ('Hank') Williams, who studied unusual mafic rocks in the Tilting area (Williams, 1957). R. Grant Cawthorn continued this initial work on the 'Tilting complex', through petrological and geochemical investigations (Cawthorn, 1978). Hamish Sandeman completed a thesis study in western Fogo Island, and first suggested temporal and genetic links between plutonic and volcanic rocks (Sandeman, 1985; *see* also Sandeman and Malpas, 1995). Regional work that focused on granites was completed in the 1990s (Kerr, 1994, 1997; Kerr *et al.*, 1994). The Tilting area received further attention from thesis studies by Saunders (1990) and Aydin (1995). The latter provides the only modern geochronological data from the Island.

In the mid-1990s, the Island was again mapped by the Geological Survey of Canada as part of a regional project (Currie, 1997a), but this map is less detailed than that of Baird (1958), and unit designations are interpretative, rather than purely descriptive. The differences between the maps of Baird (1958) and Currie (1997a) are partly unresolved, but some undoubtedly reflect the intrinsic difficulty of defining units and contacts within such complex and variable intrusive rocks (*see* also Figure 2). Currie (1997b, 2003) also discussed spatial relationships between granitic and mafic rocks in terms of a single sheet-like body with mafic rocks at its base, but suggested that this pattern recorded gravitational segregation of the two. Aside from my intermittent and somewhat casual field work, there have been no other investigations over the last 15 years. Figure 2 provides a simplified geological map of the Island, but representing the rocks in map form on *any* scale is problematic, especially for inland areas where existing maps disagree.

Although some well-known geologists have walked the shorelines and hills of Fogo Island, many aspects of its geology remain poorly understood. Why is this? I believe that in large part it reflects the absence of 'holistic' island-wide investigations in which interesting local topics (*e.g.*, the layered mafic rocks of the Tilting area) are viewed in a wider context. Secondly, the research emphasis has always been on the igneous rocks, and an interesting (and possibly closely related) story recounted by the stratigraphy on the west coast of the Island remains all but unread.

SOME ESSENTIAL FEATURES OF FOGO ISLAND GEOLOGY

Descriptions of rock units and their relationships are presented in a subsequent section, but some essential details are necessary as background for a summary of ideas drawn from analogous intrusions in northeastern Maine. Sedimentary and volcanic rocks of the Botwood Group occur on a mappable scale only in the northwestern and western parts of the Island. In the south and east of Fogo Island, plutonic rocks are largely of gabbroic to dioritic composition, and similar rocks also occur in the Tilting area, at its northeast corner (Figure 2). Central and northern Fogo Island are dominated by granitoid rocks, but the unit pattern is locally complex, with scattered areas of mafic rocks surrounded by

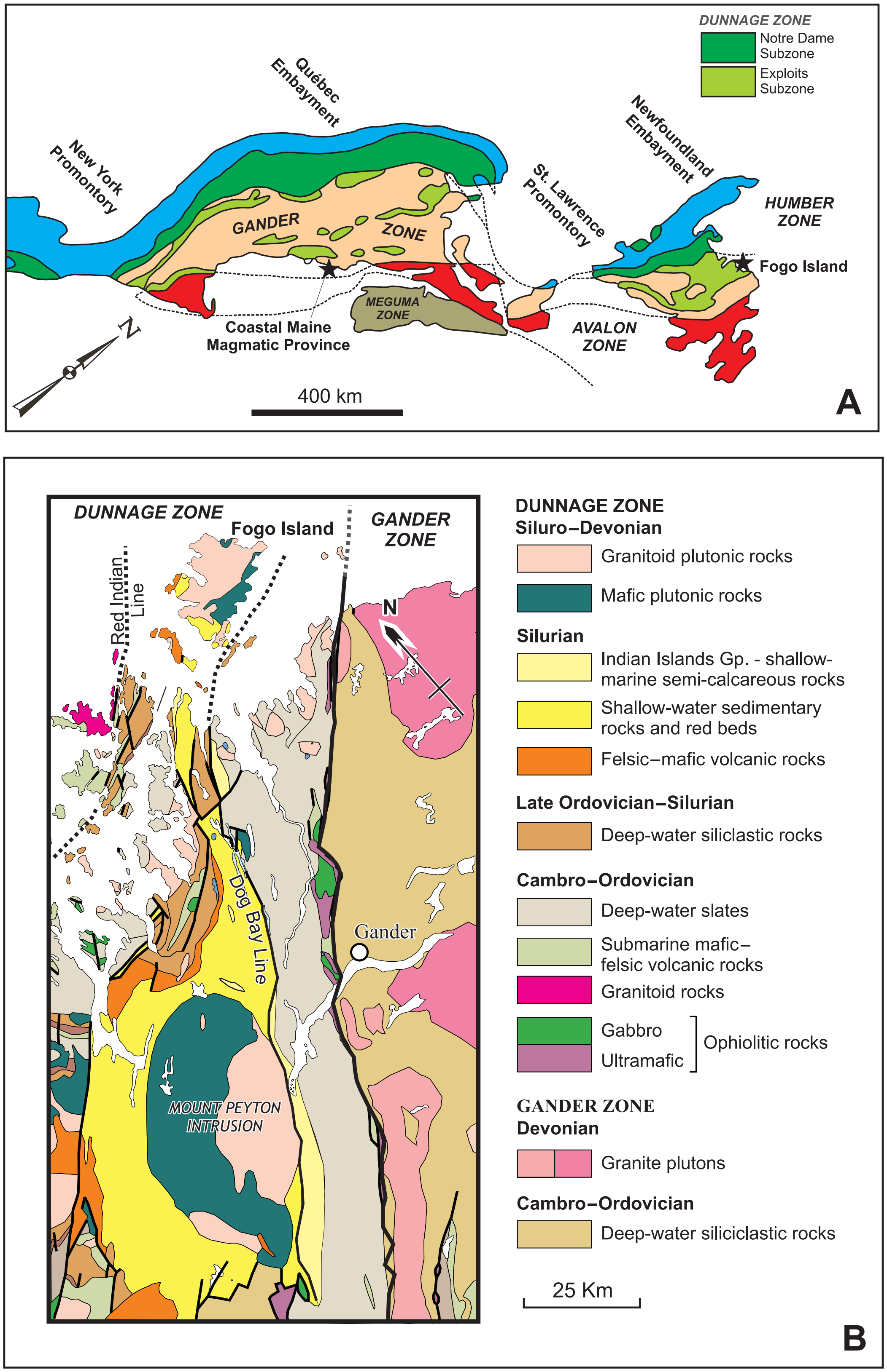


Figure 1. *A) Regional setting of Fogo Island and the Coastal Maine Magmatic Province in the context of the regional tectonic framework of the Appalachian Orogen; B) Regional geology of northeastern Newfoundland, including Fogo Island, after Colman-Sadd* et al.*, (1990).*

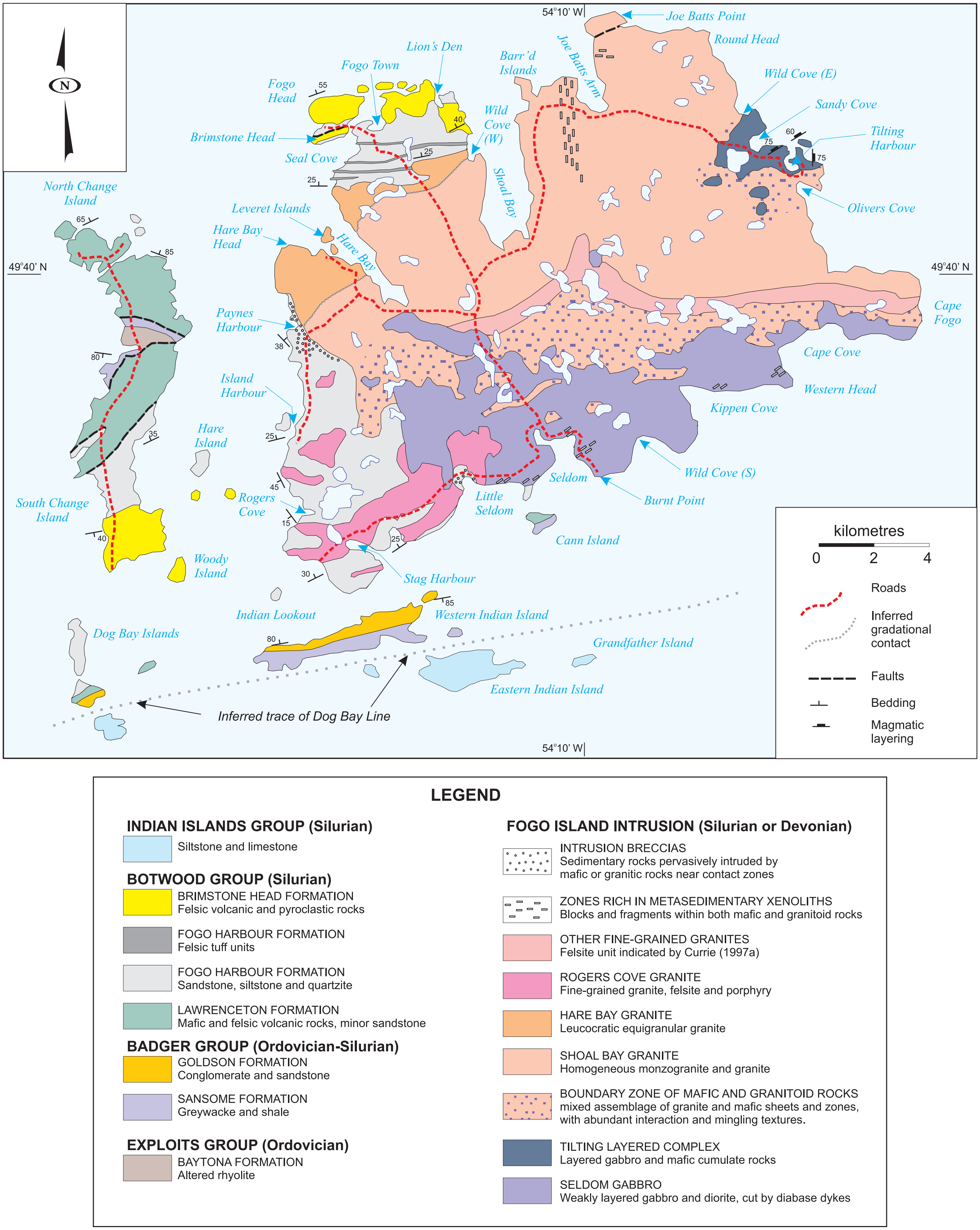


Figure 2. *Caption on opposite page.*

Figure 2. (opposite page) *Simplified geological map of Fogo Island. Drawn in part from earlier maps by Baird (1958) and Currie (1997a). Like all geological maps, this remains a work in progress, and resolution of differences between previous interpretations remains problematic. This applies particularly in some inland areas, where exposure is more limited. Baird (1958) indicated much of this area as granitic, whereas Currie (1997a) denoted it as part of his dioritic unit, but both authors noted the presence of both rock types. I opted to place much of this area as part of the complex transition zone between mafic and granitoid sections of the Fogo Island intrusion, based on information from coastal areas and roadside exposures. Similar comments apply to the east-west zone of fine-grained granite, north of this zone, which is derived exclusively from Currie (1997a). There are also contrasting interpretations of the geology on the Change Islands, but the interpretation of Currie (1997a) is adopted here. Note that the Little Fogo Islands, referred to in the text, are located 3 to 6 km north of Fogo Island, and are not shown in this map. Other features noted in the text, such as the intrusion breccia zones at Wild Cove (east) are too small to show on the scale of this map.*

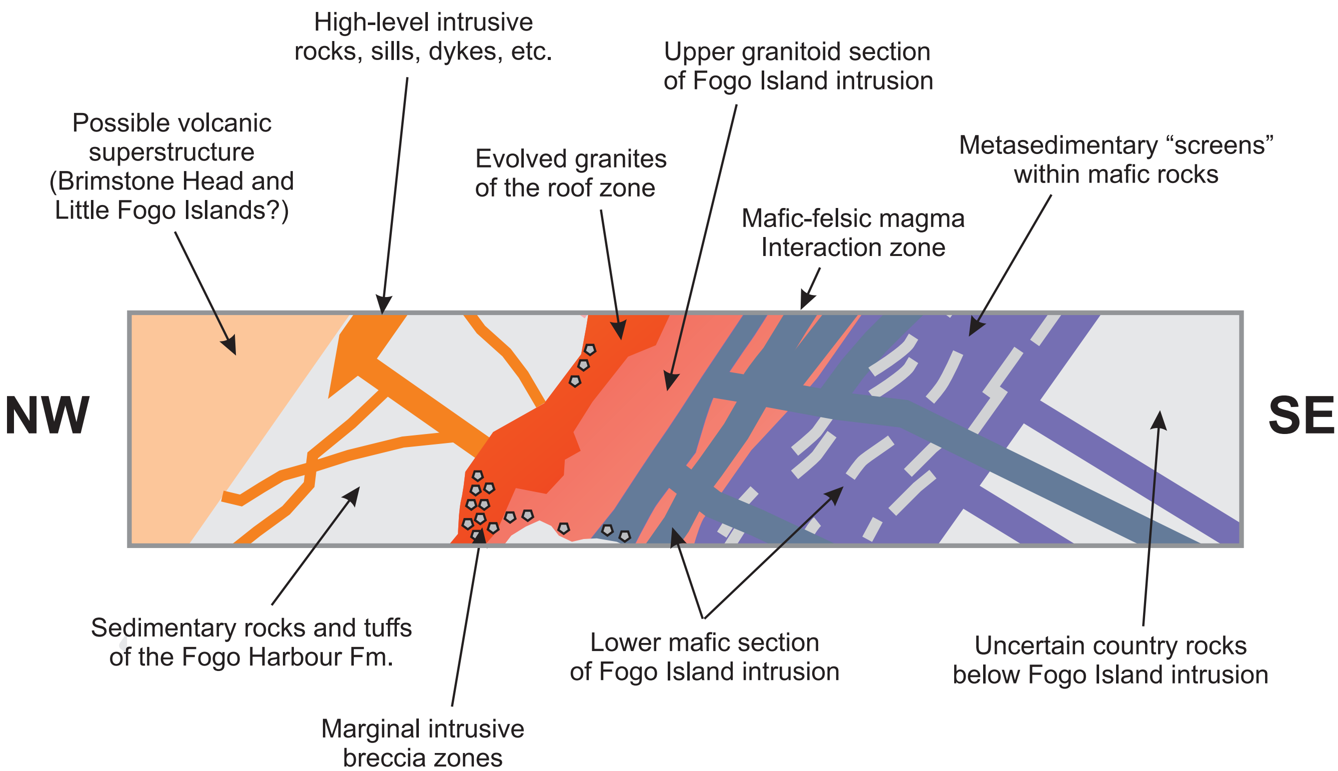


Figure 3. *A schematic cross-section across Fogo Island showing its regional interpretation as a tilted vertical section through a composite magma chamber, country rocks and possibly related volcanic superstructure. The amount of tilting is hard to establish, but is not as extreme as implied by this schematic view.*

granite. Most granitoid rocks are homogeneous and medium- to coarse-grained monzogranite and granite, but equigranular, silica-rich, leucocratic rocks occur mostly in the northwest, adjacent to the sedimentary rocks. Fine-grained granitic rocks also occur around the regional contact zone between mafic rocks and coarse-grained granitoid rocks. Where not obscured by fine-grained granites, the regional contact zone between mafic rocks and granitoid rocks is a complex zone in which both compositions are present, and show superficially chaotic distributions (Kerr, 1994). Baird (1958) indicated some of these areas simply as ‘intrusion breccias’, but Currie (1997a) placed some in a discrete ‘diorite’ unit. The relationships between mafic and granitoid rocks in this zone, and elsewhere in the intrusion, are critical in developing petrogenetic models.

In summary, Fogo Island is interpreted as a tilted vertical section through a composite bimodal magma chamber, its country rocks, and perhaps its associated volcanic products (Figure 3; Kerr, 1994). The mafic rocks form the lower

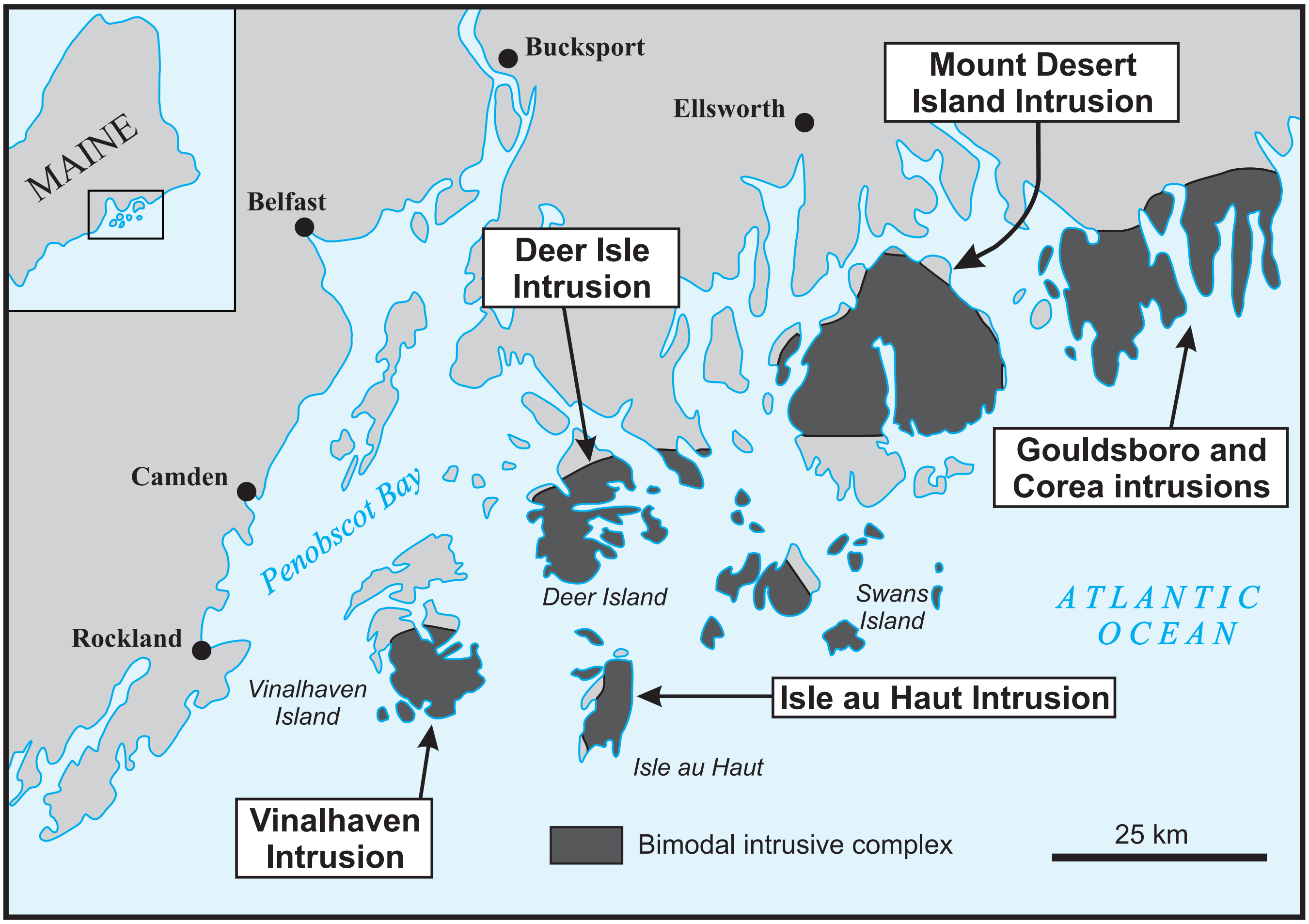


Figure 4. *Part of northeastern Maine, showing the locations of the Vinalhaven, Isle au Haut, Mount Desert Island, Deer Isle, Corea and Gouldsboro intrusions. Modified after Wiebe* et al. *(2000).*

section of the magma chamber, and the granitoid rocks form its upper section, with at least some of the high-level suites representing its roof facies. The felsic volcanic and pyroclastic rocks might be the extrusive counterpart of the magma chamber, but this remains difficult to verify. Currie (1997b) defined a similar geometric pattern, but his subsequent models for development of the 'batholith' differ from those offered in this article.

COASTAL MAINE INTRUSIONS AS COMPARATIVE MODELS

The Coastal Maine Magmatic Province (Hogan and Sinha, 1989) includes several bimodal intrusions (Figures 1 and 4) that have provided many interesting insights into the evolution of magma chambers. This section is largely derived from published sources (Chapman and Rhodes, 1992; Wiebe and Collins, 1998; Wiebe *et al.*, 1997, 2000, 2001, 2004, 2007; Hawkins and Wiebe, 2004, 2007; Lux *et al.*, 2007). The Vinalhaven intrusion (Figure 5) is here suggested as the closest analogue to Fogo Island. Other intrusions in Maine are also variably eroded and display a variety of levels within similar magma chambers; the Mount Desert Island, Isle au Haut, Gouldsboro and Corea intrusions (Figure 4) are also tilted vertical sections, and other intrusions dominated by homogeneous granites (*e.g.*, Deer Isle) are interpreted to be underlain by mafic rocks. Plate 1 illustrates some features that are key to the following discussion, mostly from examples on Vinalhaven Island.

Three fundamental concepts from studies of Vinalhaven and other composite intrusions are summarized by Wiebe and Collins (1998) and 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 mafic rocks because they solidify relatively quickly, but they are harder to separate within the granitoid rocks. The second is that heterogeneous mafic to intermediate rocks generally dominate the lower sections of magma chambers whereas more homogeneous granites typically occupy the upper sections. The third concept is that mafic and granitoid

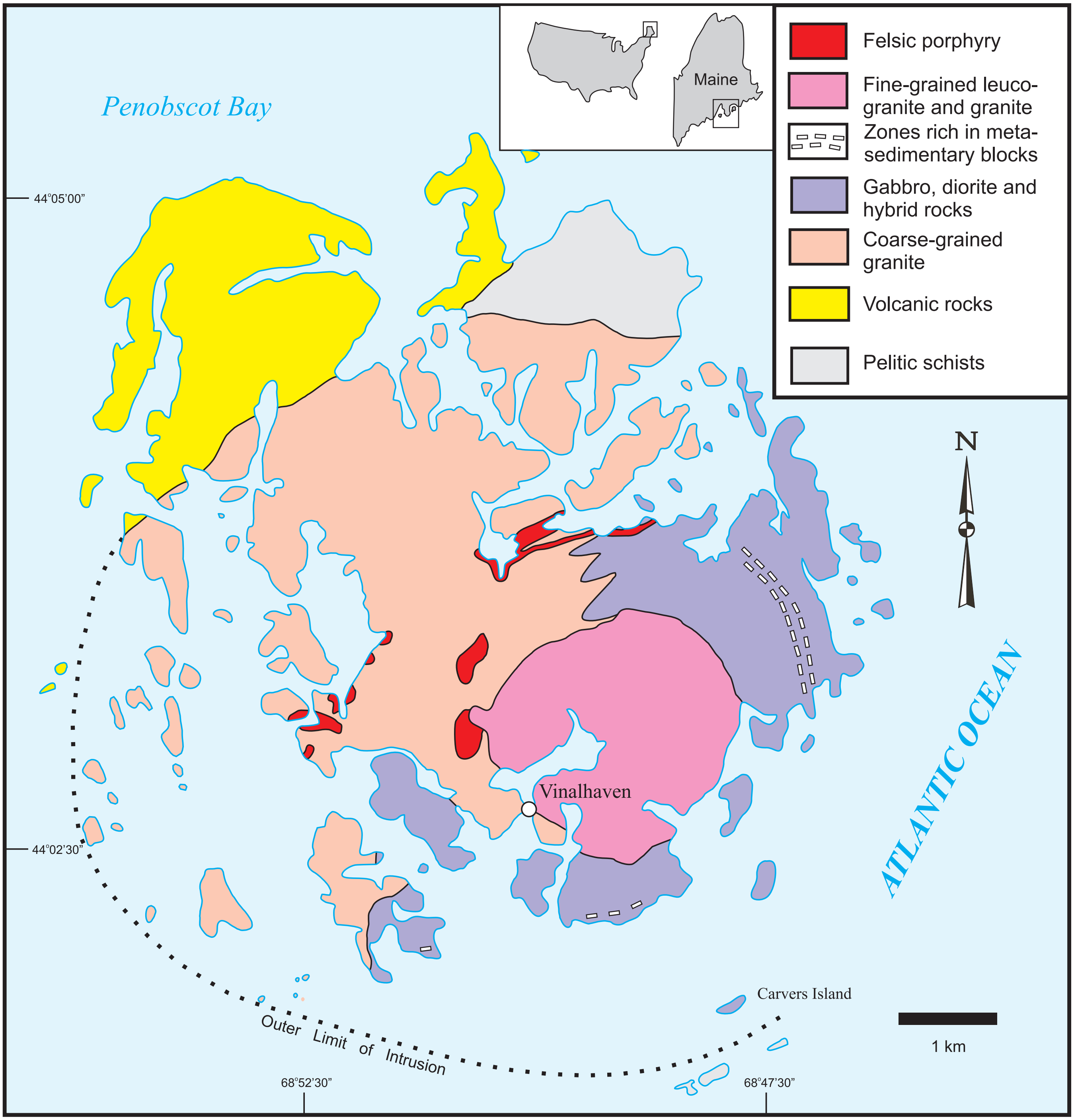


Figure 5. *Simplified geology of the Vinalhaven intrusion in coastal Maine. Adapted from Hawkins and Wiebe (2007).*

magmas coexist over the life span of the magma chamber. Specifically, mafic liquids were commonly emplaced into granitoid rocks that were at the time mush-like mixtures of accumulated crystals and residual liquids. Field relationships commonly show mafic rocks to be enveloped by felsic material (*e.g.*, Plate 1C, 1G), which would conventionally be interpreted to indicate that the latter is younger, but the true sequence of intrusion is opposite. The illusory time relationships result from the difference in solidus temperatures; the mafic liquid freezes quickly, but the granitoid ‘cumulates’ retain much greater mobility, and are less dense. It is suggested that mafic magma influxes were preferentially emplaced along the transient ‘floor’ where feldspar-dominated crystal mush sat below largely liquid granitoid magma (Chapman and Rhodes, 1992; Wiebe *et al.*, 1997, 2000). This location provides a natural density boundary

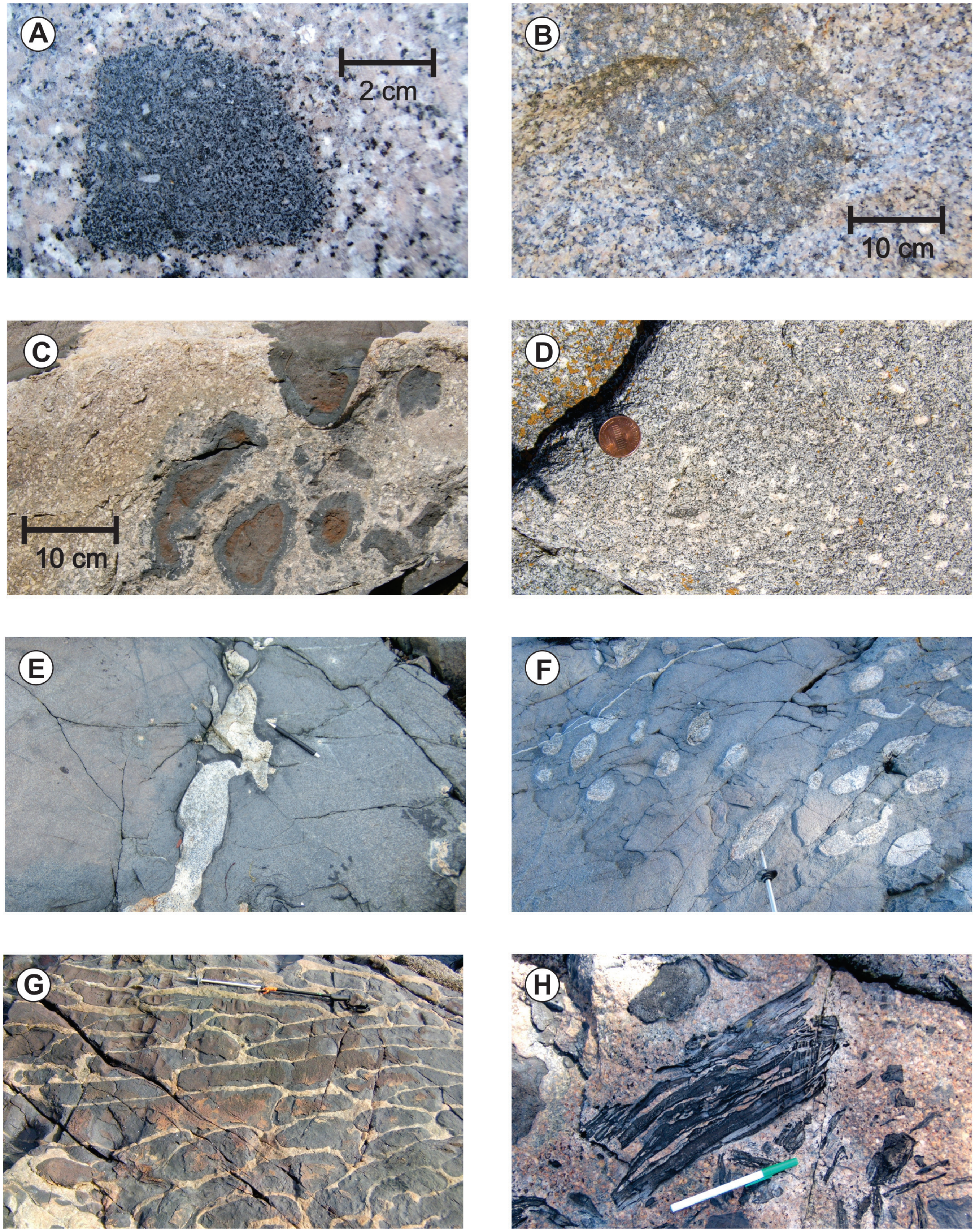


Plate 1. *Caption on opposite page.*

Plate 1. (opposite page) *Field relationships in the Vinalhaven intrusion, Maine. A) Fine-grained mafic enclave in homogeneous granite, about 4 cm across; B) Large enclave of intermediate composition in granite, containing K-feldspar phenocrysts (or xenocrysts); inclusion is about 20 cm across; C) Chilled lower section of a mafic sheet, showing pillow-like masses of fine-grained gabbro sinking into underlying granitoid material. Note chilling of mafic material; D) Homogeneous 'hybrid' diorite containing feldspar 'phenocrysts', likely derived as xenocrysts from associated granitoid magmas and crystal mush; E) 'Magmatic pipe' frozen in the process of ascending into a mafic sheet within granitoid rocks; F) Cross-sections of multiple magmatic pipes, which superficially resemble granitic inclusions on flat surfaces; G) Well-developed 'magmatic pillow structures' within a mafic zone, likely representing tube-like flow structures in cross-section; H) Metasedimentary xenoliths and blocks in granite. See text for discussion and elaboration.*

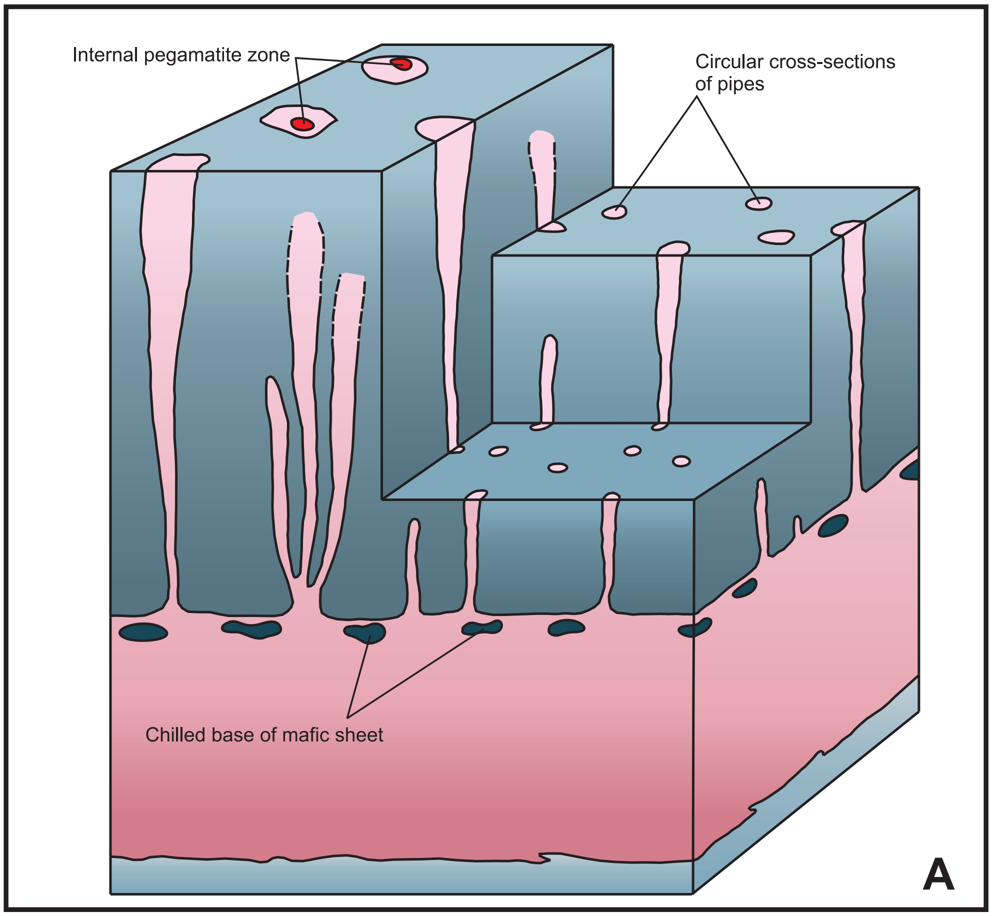
accompanied by an important change in physical properties. The boundary between lower mafic and upper granitoid sections of the magma chamber is thus a complex zone of interaction, and it likely migrates upward over its lifespan.

The Vinalhaven intrusion (Gates, 2001; Wiebe *et al.*, 2001, 2004, 2007; Figure 5) contains six main units, all of which have analogues on Fogo Island. The country rocks are pelitic schists, which have higher metamorphic grades compared to sedimentary rocks on Fogo Island, but similar compositions. Volcanic and pyroclastic rocks are well-preserved, and give similar U–Pb ages to the plutonic rocks of the Island (Hawkins and Wiebe, 2004; Hawkins *et al.*, 2009). The plutonic rocks are dominated by homogeneous granite, which typically contains rounded inclusions of more mafic composition (Plate 1A, 1B). A more complex zone of gabbro and diorite is interpreted to sit beneath the granite unit, and represents the lower section of the intrusion (Figure 5). Compositionally evolved equigranular granites and quartz-feldspar porphyries occupy the central region of the intrusion, and these intrude both mafic rocks and coarser grained granites.

Mafic and intermediate rocks consist of myriad individual sheet-like or lobe-like bodies, separated by thinner zones that, in part, resemble the upper granitoid rocks. In addition to gabbro and diorite, variably intermediate (diorite to monzonite) rocks are also present (*e.g.*, Plate 1D), and there are numerous zones of complicated and confusing 'mixed rocks', generally consisting of mafic zones within a matrix of granitoid composition. The lower contacts of individual mafic units are commonly chilled, and display loading structures that suggest that the denser mafic liquid 'collapsed' into underlying granitoid or intermediate material (*e.g.*, Plate 1C). These loading structures are morphological analogues of familiar sedimentary structures such as load-casts and ball-and-pillow structures.

Mafic and intermediate rocks also locally exhibit spectacular *magmatic pillow structures* (*e.g.*, Plate 1G). These are interpreted as analogues of subsea volcanic pillow lavas, in which erupting mafic magma is quenched by cold seawater. The temperature difference between mafic and felsic magmas is much less, but the same general principles apply. These features are interpreted as tube-like flow structures developed at the margins of lobate mafic 'flows' within the lower part of the magma chamber (Wiebe *et al.*, 1994). Similar features are also seen in dyke-like zones that transect granitic and mafic rocks; these might be conduit-like features through which mafic magmas were emplaced to higher levels in the chamber.

Vinalhaven Island is also well-known for its *magmatic pipes* (Plate 1E, 1F; Weibe *et al.*, 2000), which were described initially from nearby Isle au Haut (Chapman and Rhodes, 1992). Magmatic pipes are miniature diapirs that develop where dense mafic magma rests quasi-statically above more buoyant granitoid crystal mush. The latter rises upward into the mafic liquid, initially as pillar-like structures, which then become detached from their roots. Such pipes commonly develop above loading structures in the base of the mafic unit, and are, in part, a continuation of this process. The overall process resembles that seen in 'lava lamps', in which heated wax rises through oil. Such pipes may ascend to the top of the mafic unit, and collect there to form a more disorganized zone of texturally varied material. In other cases, 'frozen' pipes have crystallized as miniature closed systems, and contain internal residual pegmatites. However, most magmatic pipes are likely short-lived, because the granitoid material is variably assimilated by the mafic magma during their ascent. In this way, the composition of the mafic magma is changed through chemical mixing, and also by its retention of residual material from pipes, notably feldspar phenocrysts. The upper surfaces of mafic units tend to be complex zones of hybridization and mixing, in which chilled mafic inclusions and granitoid 'host rocks' exhibit chaotic patterns. Feldspar-porphyritic intermediate rocks (*e.g.*, Plate 1D) are common in such regions, and may represent the end-product of the development and disappearance of numerous pipes; only the most recently formed examples are actually preserved by solidification. Magmatic pipes are illustrated in Figure 6A, and the processes described above are summarized, in schematic form, in Figure 6B.



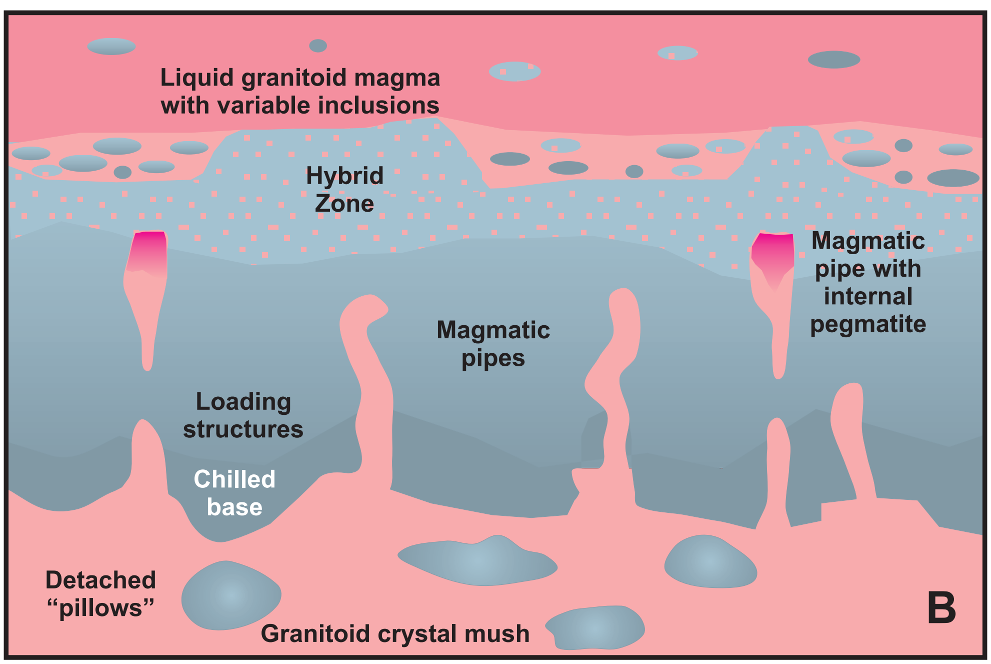


Figure 6. *A) Drawing of idealized magmatic pipes, as described by Chapman and Rhodes (1992) from Isle au Haut, Maine; adapted from their original figure. B) A schematic illustration of features commonly observed in mafic zones within the Vinalhaven intrusion and other intrusions in coastal Maine, and also within parts of the Fogo Island intrusion. Modified after Kerr (2011).*

Although granitoid rocks in the Vinalhaven intrusion are homogeneous, they preserve indirect evidence of interaction processes in rounded enclaves of fine- to medium-grained, variably porphyritic intermediate material (Plate 1A, 1B). A study of similar inclusions in the Mount Desert Island intrusion showed that they could be matched geochemically to ‘hybrid’ rocks within the mafic to intermediate sequence interpreted as the lower part of the magma chamber. It was suggested that such inclusions represent variably chilled samples of hybrid magmas, transported elsewhere within the magma chamber by convection currents (Wiebe *et al.*, 1997). The evidence from Maine supports the suggestion of Vernon (1984) that they are ultimately derived from coexisting mafic magmas, rather than representing samples of ‘restite’ from source regions of crustal melting (*e.g.*, Chappell and Stevens, 1988). The origins of various types of enclaves are also discussed extensively by Didier and Barbarin (1991).

Siliceous fine-grained granitic rocks and quartz-feldspar porphyries in the Vinalhaven intrusion could represent high-level magmas associated with the development of coeval volcanic sequences above the roof of the magma chamber, or residual liquids from granite crystallization. However, it has also been suggested that some could result from the mobilization of residual liquids in granitic crystal mush, or possibly re-melting of such material, in response to the emplacement of hot mafic magma batches at deeper levels (Wiebe *et al.,* 2004).

Vinalhaven Island also contains several zones that are rich in metasedimentary xenoliths, (*e.g.*, Plate 1H) and some of these were initially mapped as discrete country-rock units. Such fragment-rich zones are most common in the mafic and intermediate rocks, where they define several zones that are broadly conformable with the inferred magmatic stratigraphy. These zones may record periodic growth of the magma chamber due to the emplacement of mafic magmas near its base and consequent eruption of granitoid magmas (Hawkins and Wiebe, 2004). Such inflation is envisaged to be accommodated by collapse and foundering of the roof zone and the eventual accumulation of xenoliths near the transient floor of the magma chamber. The Mount Desert Island intrusion also contains a marginal zone of spectacular intrusion breccias (known as the ‘shatter zone’) that records the progressive disaggregation of the country rocks by granitoid magmas.

GEOLOGY OF FOGO ISLAND IN THE CONTEXT OF NEW MODELS

This section summarizes rock units and relationships on Fogo Island in the context of models based on the premises outlined above. Plates 2 to 13 illustrate features from outcrops on the Island, for comparison with those documented in Plate 1. The rock units on the island are logically divided into three groups, *i.e.*, sedimentary and volcanic rocks (Botwood Group), plutonic rocks (Fogo Island intrusion) and those of mixed character. The latter include true ‘intrusion breccias’ with angular or tabular fragments assigned to country rock units, but also heterogeneous rocks interpreted to form through magmatic interactions. The latter mostly form part of the Fogo Island intrusion. Note that in the following text, there are several references to three separate localities named *Wild Cove*; to avoid any confusion, these are accompanied by the geographic qualifiers ‘east’, ‘west’, and ‘south’ (Figure 2).

BOTWOOD GROUP

Fogo Harbour Formation

This formation includes all sedimentary rocks on Fogo Island south of Seal Cove (Figure 2), and some interbedded tuff units. In general, the formation is easily accessible and well-exposed, and there is good potential to define marker horizons and member-level subdivisions within it. It is dominated by thinly bedded grey to greenish siltstones, sandstones and crossbedded quartzites (Plate 2A, 2B). Soft-sediment deformation is common in thinly bedded units, and intraformational (slump-related?) breccias are also present. Other prominent primary features include sand dykes and current ripples (Plate 2E, 2F). Mudcracks reported by Baird (1958) are in some cases the bedding-surface expression of sand dykes (Plate 2F). The top of the formation, near the town of Fogo, is marked by spectacular matrix-supported volcanic conglomerates (Plate 2D), which mark the transition into the Brimstone Head Formation. These conglomerates have been interpreted as possible lahar deposits (P. Dean, pers. comm., 2012). Distinctive quartz and feldspar-rich units, slightly lower in the sequence, were variably interpreted as felsitic sills (Baird, 1958; Currie, 1997a) or as water-lain tuffs derived from explosive eruptions or ash flows (Sandeman, 1985). Based upon their conformable nature and the presence of similar but thinner tuff bands in sandstones that immediately underlie them (Plate 2C), I prefer the latter interpretation, although it may not apply to all examples. The exact age of the formation is unknown, and it is described as unfossiliferous (Baird, 1958). However, there is a distinctive bed with possible bioturbation and organic remains near the top of the sequence (Plate 2G) and possible poorly preserved shelly fossils (Plate 2H) occur within some coarse tuff-like rocks (debris-flows?). The tuff horizons in the upper part of the sequence offer potential for direct dating.

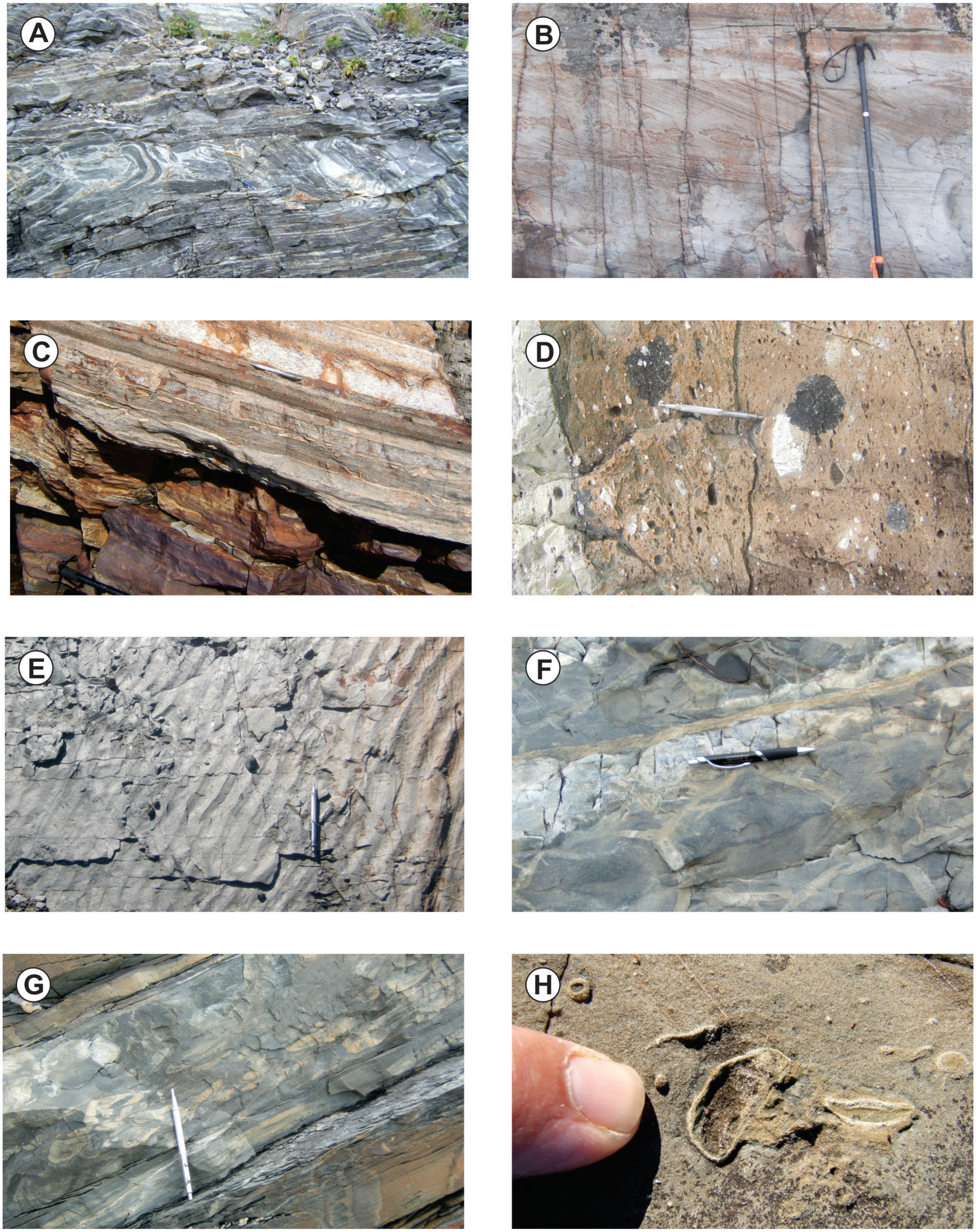


Plate 2. *Caption on opposite page.*

Plate 2. (opposite page) *Features of the Fogo Harbour Formation. A) Thin-bedded siltstones and mudstones with soft-sediment folding and possibly a 'slide zone' in the centre of the photo. The light areas are actually thin granite zones that are preferentially intruding the disturbed unit; B) Crossbedded quartzites; C) Conformable contact between siltstone (rusty material in lower part of photo) and a felsic tuff unit (white material at top. Note thin felsic tuff beds in transition zone, and sand dykes in underlying rocks); D) Matrix-supported volcanic conglomerate unit (a lahar?) in the upper part of the formation; E) Current ripples on a sandstone bedding plane; F) Polygonal patterns that superficially resemble dessication cracks, but may actually be the bedding plane expression of sand dykes; G) Calcareous sandstone bed showing possible bioturbation; H) Shelly fossils, as yet unidentified.*

Brimstone Head Formation (and other volcanic rocks)

The Brimstone Head Formation forms a semi-continuous belt across the rugged northwestern tip of the Island (Figure 2), and is interpreted to sit conformably above the Fogo Harbour Formation. Most of the formation consists of massive ignimbrites and pyroclastic breccias (Plate 3A, 3B, 3C). Many inland outcrops are featureless, black, obsidian-like rocks that contain tiny quartz phenocrysts and weak banding, and their origins are uncertain. At the base of the thick ignimbrite that forms Brimstone Head itself, there is a possible flow-banded rhyolite showing perlitic fracturing (Plate 3D), but there are few other reliable candidates for true extrusive rocks. Banding and eutaxitic fabrics are variably developed in many outcrops (Plate 3E, 3F) but their orientations are not always consistent. Sandeman and Malpas (1995) suggested cyclic units with welded bases and breccia-dominated upper sections, and Currie (1997a) refers to three or more such units. Poorly bedded, pale-green sedimentary rocks of ashy appearance resemble uppermost parts of the Fogo Harbour Formation, and have generally been mapped as part of that formation, but they could be lithologically similar units *within* the Brimstone Head Formation itself. There are unresolved structural complications in the area around Fogo Town, where contrasting outcrop patterns are indicated by the mapping of Baird (1958) and Currie (1997a). Unlike the Fogo Harbour Formation, which is widely intruded by fine-grained granitoid rocks, the ignimbrites of the Brimstone Head Formation contain few (if any) granitic dykes or veins.

The ignimbrite units in the Fogo Town area appear to dip moderately to the northwest, based on contacts and internal fabrics, but this attitude is not consistent with the near-vertical orientation of tube-like vesicles interpreted as gas-escape structures in related breccias (Plate 3C), which imply a much gentler local attitude. Also, the attitude of eutaxitic fabrics in some relatively well-preserved 'ignimbrites' varies widely within single outcrops, and there are places where bedding in sedimentary rocks seems to strike into massive ignimbrite. It remains possible that some of these supposedly extrusive rocks could be high-level intrusions or thick volcanic domes.

The extent of the Brimstone Head Formation is also a matter of possible debate. Baird (1958) did not define it beyond Fogo Island, but Currie (1997a) extended it to southern Change Islands. He also reassigned the 'North End formation' defined by Baird (1958) on Change Islands to the older Laurenceton Formation (supposedly beneath the Fogo Harbour Formation), and extended the Brimstone Head Formation to the Little Fogo Islands (north of the area shown in Figure 2). The Little Fogo Islands are described briefly by Baird (1958) and Eastler (1969); they contain spectacular felsic pyroclastic breccias (Plate 3G), possible mafic agglomerates, and red conglomerates and sandstones. The volcanic rocks are well-preserved and appear to have interacted with unconsolidated sediments, producing superb hyaloclastite textures where the two come into contact (Plate 3G, 3H). However, I have not yet seen the dark, featureless, aphanitic ignimbrites typical of Brimstone Head anywhere on the Little Fogo Islands.

FOGO ISLAND INTRUSION

As used here, the term *Fogo Island intrusion* includes all of the intrusive rocks of the Island, which are divided into mafic-intermediate varieties (Seldom gabbro and Tilting layered complex) and granitoid rocks (several named units). Numerous dykes and (sills ?) of mafic, granitic and intermediate composition cut the Fogo Harbour Formation near intrusive contacts, and also cut other named units within the intrusion. Note that the order of description employed below does not imply the sequence of intrusion.

Seldom Gabbro

Mafic rocks in southern and eastern Fogo Island (Figure 2) are here termed the Seldom gabbro, although many are probably diorites in strict petrological terms, because they contain hornblende and relatively sodic ($<An_{50}$) plagioclase, and some contain quartz. The contact between gabbro and structurally underlying Fogo Harbour Formation is exposed on the point at Little Seldom, and a contact zone dominated by intrusion breccia is exposed on the west side of Little Seldom Cove; however, these may not be the true basal contacts for the Fogo Island intrusion. Metasedimen-

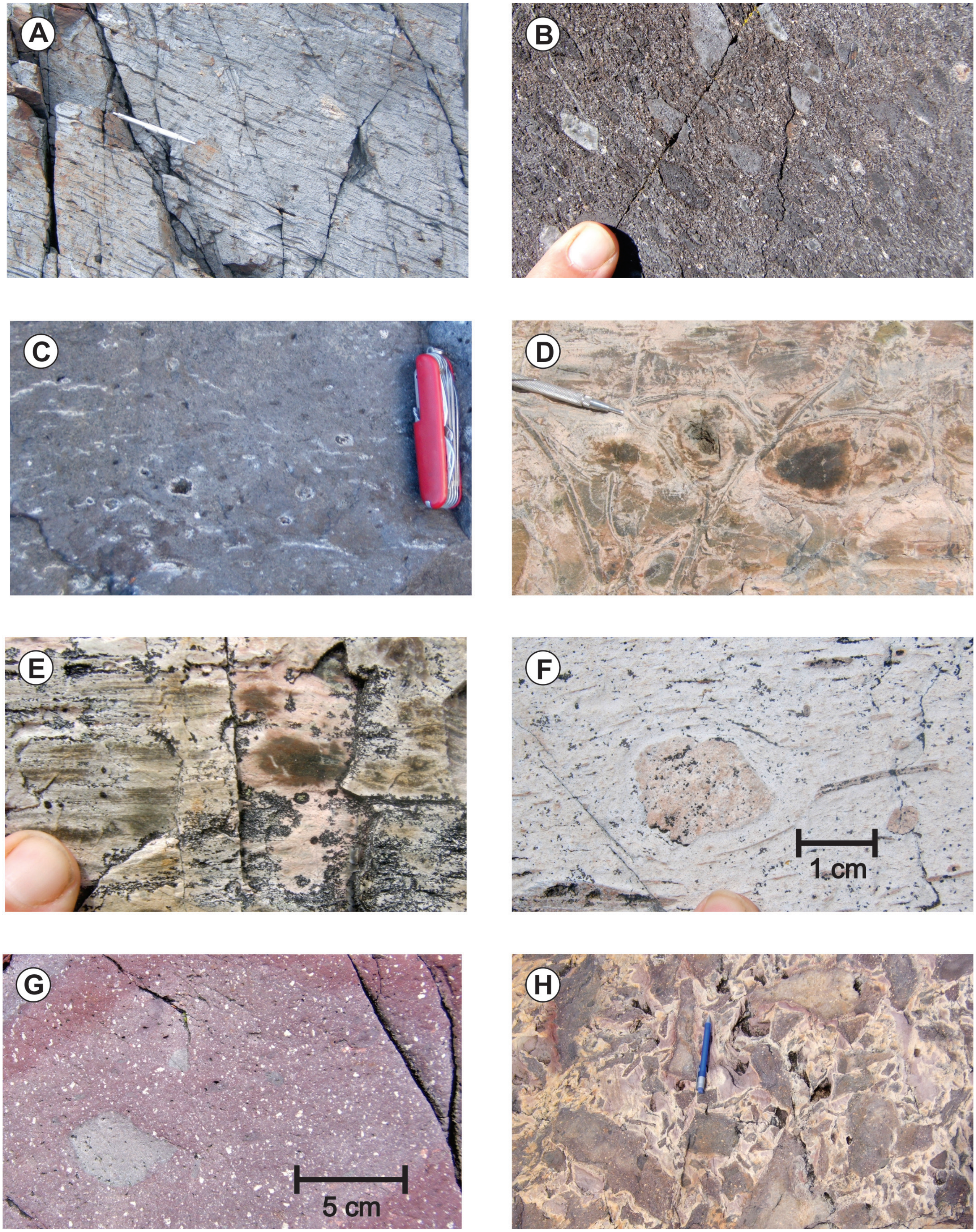


Plate 3. *Caption on opposite page.*

Plate 3. (opposite page) *Features of the Brimstone Head Formation and other volcanic rocks. A) Ignimbrite showing a strong eutaxitic fabric; B) Pyroclastic breccia in the upper part of an ignimbritic unit; C) Tube-like cavities interpreted as possible gas-escape structures in pyroclastic breccia; D) Pink glassy rock with altered fracture patterns, interpreted to have originally been a glassy rhyolite having perlitic fracturing; E) Fine-scale banding of uncertain origin, but possibly indicating an extrusive rock; F) Eutaxitic fabric wrapping around larger fragments in an ignimbrite; G) Part of a large rhyolitic volcanic block in a pyroclastic breccia from the Little Fogo Islands, note inclusions of grey rhyolite; H) 'Hyaloclastite' breccia thought to develop through interaction of felsic magma and unconsolidated sediment on the Little Fogo Islands.*

tary inclusions are common throughout the unit, suggesting that the Fogo Harbour Formation forms its regional country rocks.

Coastal exposures show that faint cumulate layering and/or magmatic fabrics are present in many outcrops, although such features are subtle (Plate 4A, 4B). The rocks are dominated by plagioclase and clinopyroxene, and minor interstitial quartz is commonly present. Hornblende and reddish biotite are present in variable amounts and include both primary igneous crystals and secondary material of variable appearance; many rocks are probably dioritic, with plagioclase compositions $<An_{50}$. In many cases, pyroxene is overgrown and mantled by green hornblende (Baird, 1958; A. Kerr, unpublished data).

The most complete section is along the east side of Seldom Harbour (Figure 2), where several subunits of relatively homogeneous gabbro and/or diorite are separated by zones rich in metasedimentary xenoliths. A similar xenolith-rich zone marks the possible base of the unit at Little Seldom, above a thin section of homogeneous material (Plate 4C). These fragment-charged zones resemble those in the lower part of the Vinalhaven intrusion in Maine, and are discussed in more detail in a later section, as they have more than one possible mode of origin. Although they have yet to be fully traced, I believe that they probably trend broadly east–west through southern Fogo Island, and possibly demarcate subunits that represent discrete influxes of mafic magma.

The lowermost portion of the Seldom gabbro, seen at Burnt Point and around Wild Cove (south) is cut by numerous diabase dykes (Plate 4D), some of which are composite (sheeted) or include discrete felsitic sections. In these outcrops, the host gabbro or diorite had solidified and cooled to the point of brittle fracturing during dyke emplacement. These mafic dykes are interpreted to be feeders that carried magma influxes to higher levels in the chamber following the solidification of lower sections.

The lower (southern) sections of the Seldom gabbro differ from equivalent rocks in the Vinalhaven intrusion in that there is little evidence for granitoid material separating units of mafic and intermediate rocks. The fragment-rich zones may indicate that mafic magma was in part emplaced directly into sedimentary country rocks, rather than into partially consolidated granitoid crystal mush. However, the interpreted upper section of the Seldom gabbro, which is best exposed between Cape Cove and Cape Fogo, is a composite zone in which gabbro–diorite and granodiorite to monzogranite are interlayered. An extensive region in the centre of the island is also assigned to this unit, because of conflicts in the map units of Baird (1958) and Currie (1997a). Individual mafic sheets exposed in coastal outcrops have chilled lower sections that exhibit loading structures and subsidence implying that they were emplaced into granitic crystal mush (Plate 4E, 4F). Magmatic pipes are also locally developed within the lower sections of individual mafic sheets, and the upper portions commonly include chaotic mixed rocks in which mafic enclaves are chilled against enveloping granitoid material (*see* later discussion). More homogeneous intermediate rocks containing K-feldspar phenocrysts are also widely developed (*e.g.*, Plate 4G), and these are interpreted as chemical and mechanical mixtures of mafic magma and granitoid cumulates – the 'phenocrysts' are likely *xenocrysts* in these rocks, although this is rarely apparent. In some cases, the mafic magma likely also contained pyroxene and/or amphibole phenocrysts (Plate 4H). Poorly-developed magmatic pillow structures are also locally present in this zone. Some mafic sheets have cleaner, more consistent planar contacts suggesting that they might have been emplaced at slightly later times into cooler, more solidified granitic country rocks. However, the widespread evidence for interaction between mafic magmas and granitoid mush or magma suggests that these contrasting magmas coexisted in space and time, as suggested for Vinahaven and other intrusions in coastal Maine.

Tilting Layered Complex

The Tilting layered complex (Figure 2) is the most extensively studied area of Fogo Island (Williams, 1957; Cawthorn, 1978; Saunders, 1990; Aydin, 1995). Despite such attention, there remain many questions about its internal relationships, and its relationship to surrounding granites and the compositionally similar Seldom gabbro. The Tilting area contains many spectacular outcrops, as illustrated by Plate 5.

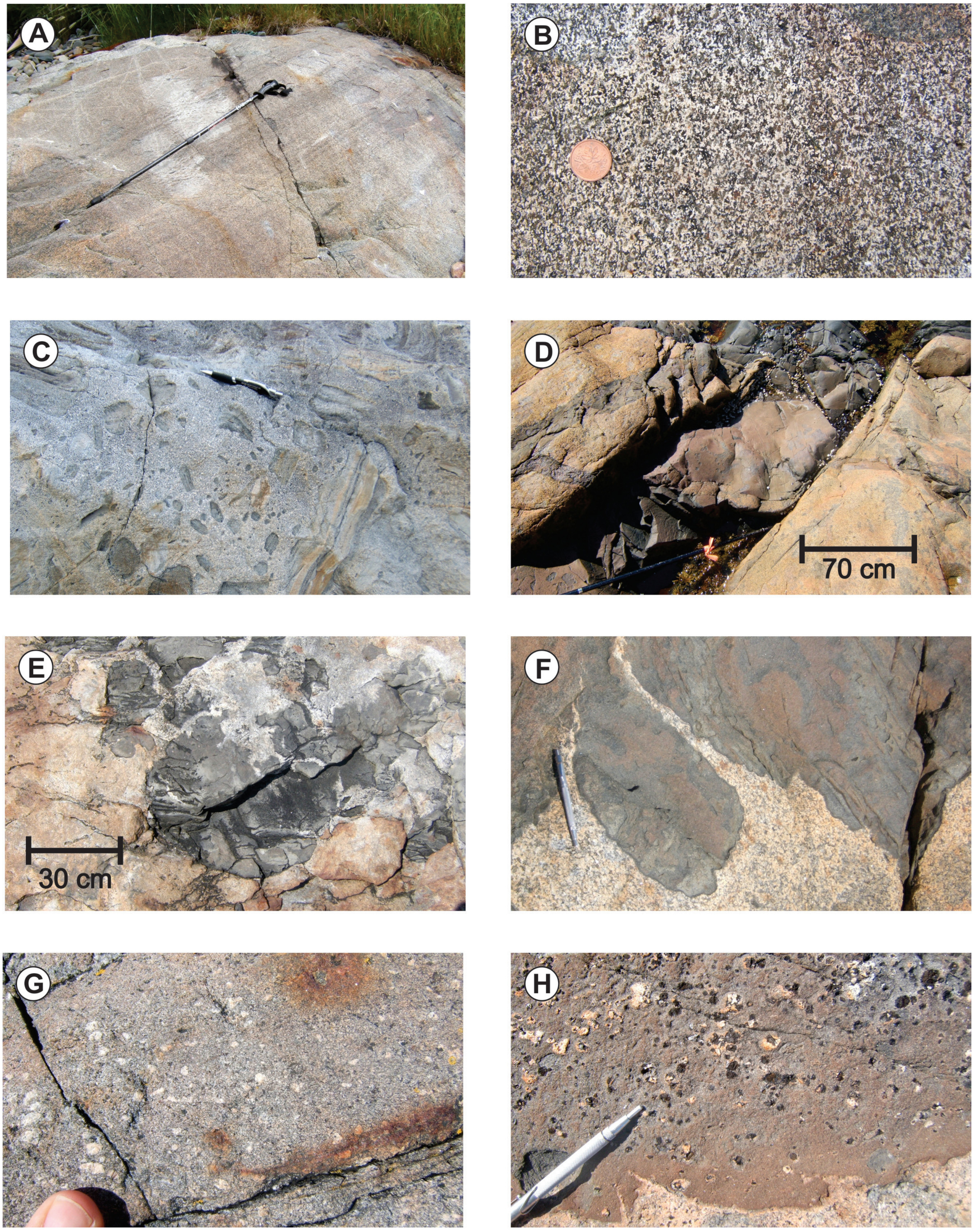


Plate 4. *Caption on opposite page.*

Plate 4. (opposite page) *Features of mafic and intermediate rocks, Seldom gabbro. A) Gently dipping cumulate layering in leucocratic gabbro or diorite; B) Typical medium-grained diorite, showing a weak magmatic fabric; C) Intrusion breccia with leucocratic matrix just above the base of the unit, containing blocks of Fogo Harbour Formation exhibiting variable contact metamorphism; D) Multiple generations of diabase dykes cutting leucocratic diorite near the inferred base of the unit at Wild Cove (south); E) Basal section of a mafic sheet in granitoid rocks in the transition zone at the top of the unit, showing chilling and loading structures; F) 'Load casts' in the base of a mafic sheet, note the thin (dark) chilled zone; G) Grey diorite containing K-feldspar 'phenocrysts', interpreted to be derived by mechanical mixing of mafic magma and granitic mush; H) Part of a mafic sheet showing true phenocrysts of pyroxene and admixed K-feldspar xenocrysts from the surrounding granitoid material.*

The Tilting layered complex is dominated by gabbro, norite and websterite (a clinopyroxene–orthopyroxene ultramafic rock), but it also includes dioritic rocks; it has a wider compositional range than the Seldom gabbro, but primary amphibole and biotite are similarly common (Cawthorn, 1978; Aydin, 1995; Aydin *et al.*, 1994). Primary igneous layering and magmatic fabrics (Plate 5A, 5B) dip at generally steep attitudes, and primary features such as trough layering (Plate 5B) and 'slump folding' (Plate 5D) are well preserved. At least five cyclic repetitions were defined by Cawthorn (1978). Each consists of basal websterite, passing upward into norite and gabbro, and 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. Xenolith-rich zones are also present within the complex, and resemble those described from the Seldom gabbro, although fragment orientations are steeply dipping. The entire complex is surrounded by granitic rocks (assigned to the Shoal Bay granite, *see* below) but the relationships with these rocks remain unclear. In the west, their mutual boundary is obscured by younger heterogeneous intrusion breccias (Aydin, 1995; *see* below). Younger intrusions of intermediate appearance disrupt the cumulate rocks in several areas (*e.g.*, Plate 5F). East of Tilting, the contact zone between steeply dipping layered gabbros and homogeneous granite is abrupt but no sense of intrusion is evident. The mafic rocks seem to dip southeastward underneath the granites, but this is difficult to verify.

The relationship between the Tilting layered complex and the Seldom gabbro is of much interest. One possibility is that the Tilting area is a 'window' through the upper granites into underlying mafic rocks that are laterally equivalent to the Seldom gabbro. The presence of other areas of mafic and intermediate rocks surrounded by granites south of Tilting and elsewhere in inland parts of Fogo Island (Baird, 1958; Figure 2) is consistent with this interpretation. At the other extreme, mafic rocks of the Seldom gabbro and Tilting layered complex could be temporally and spatially unrelated intrusions. In either interpretation, the present steeply dipping attitudes of layering in the Tilting area imply that originally subhorizontal cumulate zones must have foundered and collapsed soon after their development. There are no analogous layered rocks in the Vinalhaven intrusion, but they do occur elsewhere in Maine, notably within the Pleasant Bay intrusion (located east of the area in Figure 4). Wiebe and Collins (1998) discuss cumulate rocks in other composite intrusions, and suggest that the commonly steep attitudes of layering record the "collapse" of magma chamber floors during development.

Other Mafic and Intermediate Rocks

Mafic and intermediate rocks occur sporadically on Fogo Island in areas otherwise dominated by granitoid rocks. As discussed above, some of these could represent 'windows' through the granitoid rocks exposing underlying mafic sections of the intrusion. Coastal outcrops of such zones show that contact relationships of mafic and granitoid rocks are complex and chaotic, implying emplacement of mafic magmas into semi-consolidated granitoid rocks. Such zones are interpreted to record minor influxes of mafic magma into partially solidified granitoid rocks. Sheet-like mafic and intermediate zones within granite at Oliver's Cove (Figure 2) show chilled basal contacts with loading structures (Plate 6A), and also some of the best examples of magmatic pipes yet discovered on the Island (Plate 6B–6F). Some individual pipes contain internal pegmatitic zones, which have locally 'breached' contacts and leaked into the surrounding diorite (Plate 6D). Other pipes appear to have hydrated the surrounding magma, creating multiple sheath-like features that are defined by abundant hornblende and biotite (Plate 6B, 6C). Some of the latter resemble 'ladder dykes' described by Weinberg *et al.* (2001) and attributed to similar processes. In plan view, pipes are seen to be circular or lobate in cross-section (Plate 6E, 6F). There are also several other, more diffuse mafic zones in the Olivers Cove area, which are discussed in the subsequent section on rocks of mixed character.

Shoal Bay Granite

The Shoal Bay granite (named by Sandeman and Malpas, 1995) is the most widespread unit within the Fogo

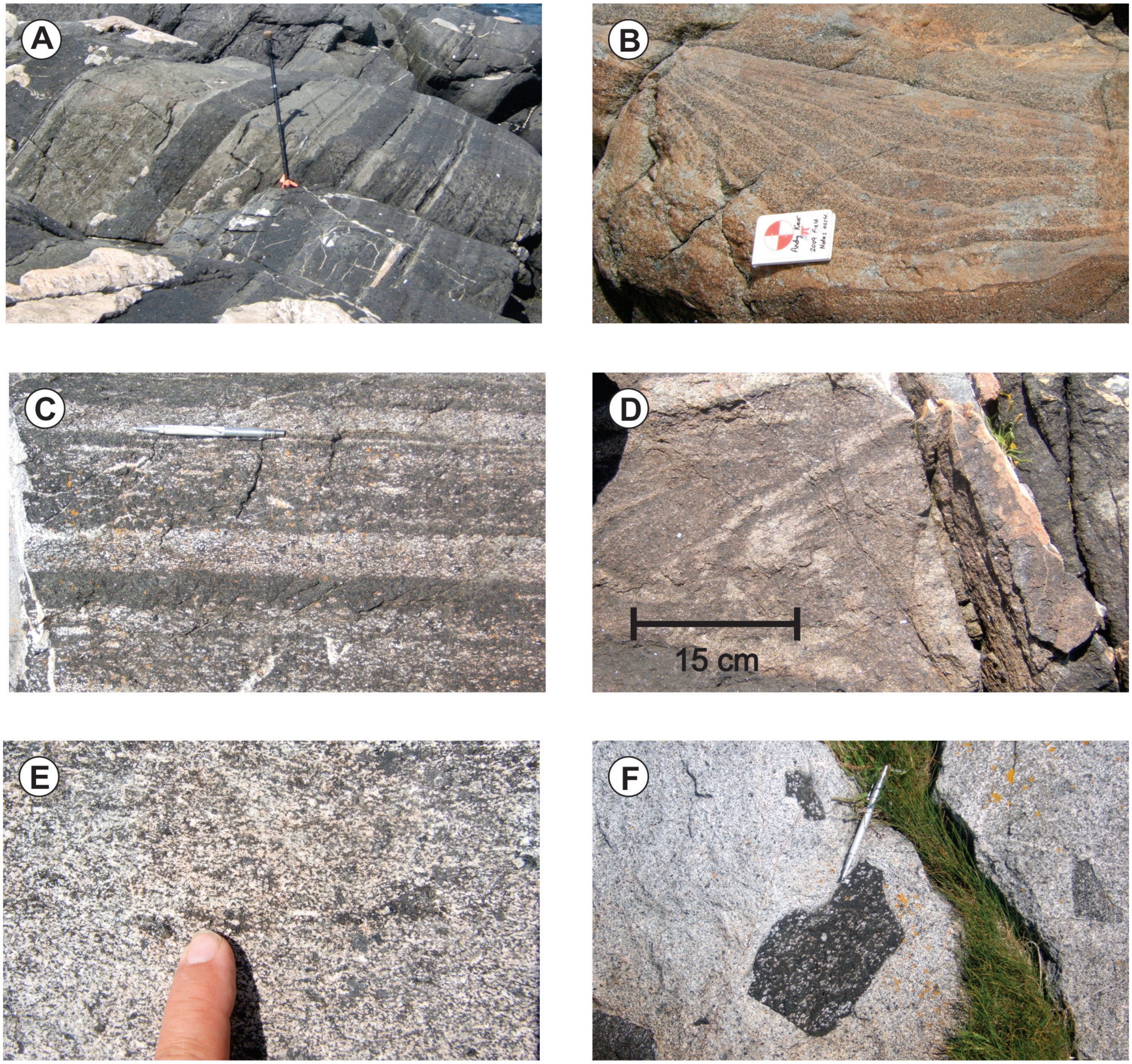


Plate 5. *Features of the Tilting layered complex. A) Rhythmically layered websterite and gabbro; note the steep dip of the layering; B) Possible channel structure in layered gabbro, in which layering dips steeply away from the viewer; C) Detail of fine-scale modal layering in gabbro defined by accumulation of plagioclase and ferromagnesian minerals; D) Part of a slump fold in layered gabbro; E) Weak magmatic fabric in massive, unlayered gabbro; F) Angular blocks of mafic cumulate rocks in younger pale-grey diorite intrusion.*

Island intrusion, extending from Deep Bay to north of Cape Fogo (Figure 2). It is a homogeneous, medium- to coarse-grained, white to beige or pink monzogranite to granite that typically contains both hornblende and biotite, and small K-feldspar phenocrysts (Plate 7A, 7B). Small rounded inclusions (enclaves) of mafic to intermediate composition (Plate 7A, 7C) are common, and vary in appearance. Many are round, aphanitic basaltic patches, but crystalline intermediate inclusions containing K-feldspar phenocrysts are also present. On the east side of Shoal Bay, there is an interesting 'double enclave' in which porphyritic intermediate material itself includes aphanitic basaltic material (Plate 7D). Hornfelsed metasedimentary xenoliths also occur locally in the Shoal Bay granite, and can form discrete intrusion breccia zones (*see* below), but these have far more restricted distributions than the igneous enclaves. The Shoal

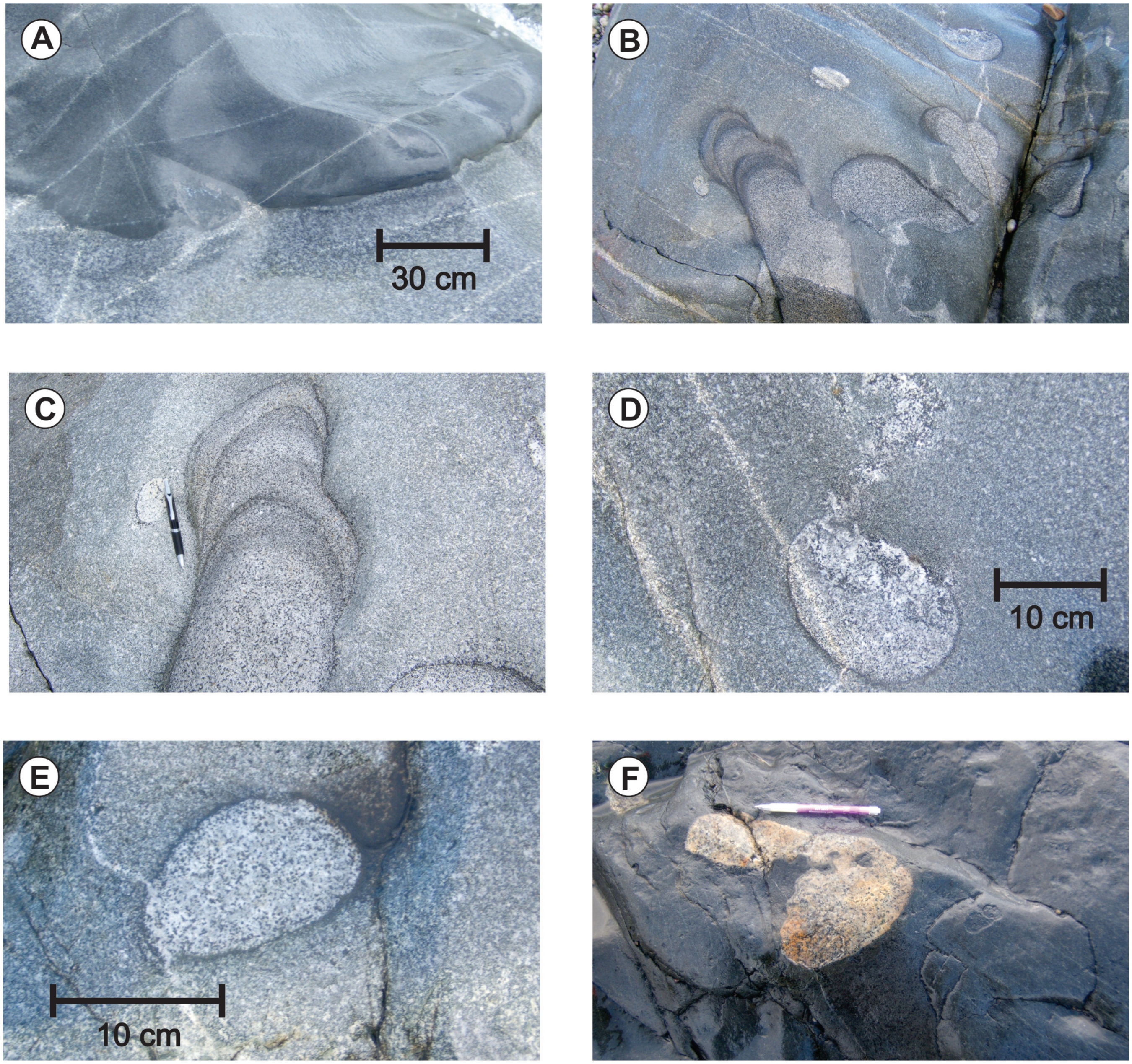


Plate 6. *Features suggesting interaction of mafic and granitoid magmas in the Olivers Cove area. A) Chilled basal contact of a mafic sheet, with loading structure in centre of photo, about 20 cm in height; B) Oblique and transverse cross-section through silicic 'magmatic pipes' developed within an intermediate sheet; C) Detailed view of 'magmatic pipe' showing a sheath of hydrous minerals developed in the surrounding intermediate rock; D) Cross-section through pipe, showing internal pegmatite zone 'leaking' during its final crystallization; E) Cross-section through a pipe, showing the sheath of hydrous minerals surrounding it; F) Cross-section through a larger lobate pipe, or perhaps one developed through coalescence of two individual pipes.*

Bay granite is generally monotonous, but it is cut by mafic and felsic dykes, some of which are discontinuous. Pegmatite zones are rare, but flat-lying aplitic sheets are common in many outcrops; these generally do not contain inclusions, and locally truncate inclusions in host granite.

The enclaves in the Shoal Bay granite are closely similar to those described from the Vinalhaven and Mount Desert Island intrusions (Wiebe *et al.*, 1997). The intermediate varieties closely resemble the K-feldspar porphyritic diorites and monzonites that occur within the boundary zone

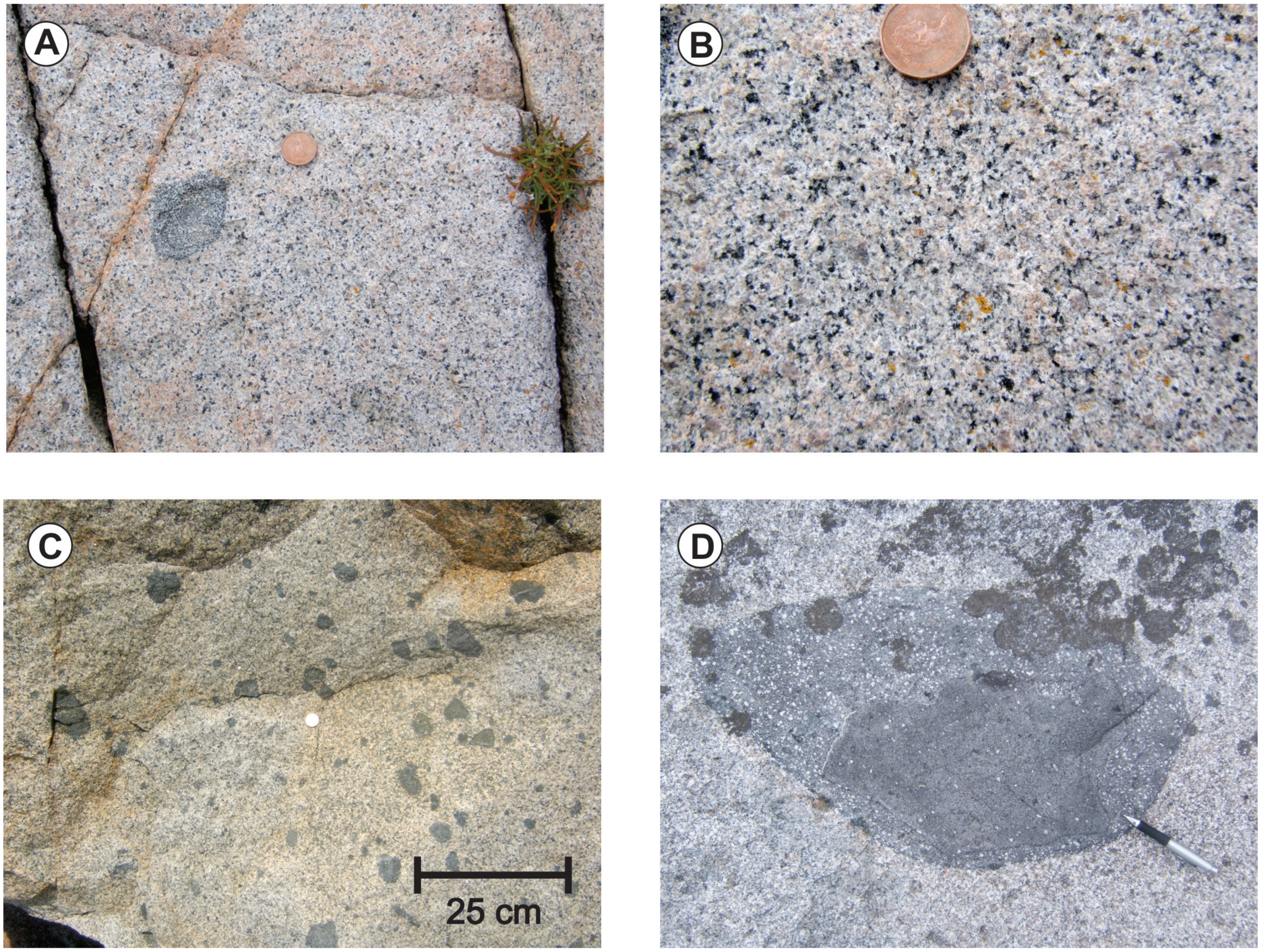


Plate 7. *Features of the Shoal Bay granite. A) Homogeneous, medium- to coarse-grained hornblende-biotite granite, typical of the unit, containing rounded intermediate enclave; B) Close-up view of granite, showing faintly K-feldspar porphyritic texture; C) Typical enclave-rich granite from the Barr'd Islands area; D) A rare 'double enclave' from Shoal Bay, in which an inner aphanitic mafic enclave is surrounded by a K-feldspar porphyritic diorite interpreted as a hybrid developed by mechanical mixing.*

between the Seldom gabbro and the Shoal Bay granite (*e.g.,* Plates 4G, 4H; *see* earlier discussion). Accordingly, enclaves are similarly interpreted as samples of mafic and hybrid magmas developed through chemical and physical interaction between mafic magmas and granitoid magmas or crystal mush at deeper levels in the Fogo Island intrusion.

Hare Bay Granite

The Hare Bay granite (microgranite of Sandeman and Malpas, 1995) stretches from Wild Cove (west) to the area west of Hare Bay (Figure 2). Sandeman and Malpas (1995) describe its contact with the Shoal Bay granite as generally gradational, and this is certainly near Wild Cove (west). The Hare Bay granite is typically orange or red, rich in K-feldspar, poor in mafic minerals and contains miarolitic cavities (Plate 8A). It generally does not contain inclusions. Granite veins cut the Fogo Harbour Formation near their mutual contact, and coarse quartz-feldspar patches occur in the granite (Plate 8B, 8C). The granite locally grades into aphanitic (subvolcanic?) felsites that exhibit features interpreted as spherulites (Sandeman, 1985; Plate 8D). Sandeman and Malpas (1995) suggested that it was the variably chilled high-level roof facies of the Shoal Bay granite, but Currie (1997a, 2003) contended that the Hare Bay granite was older than the Shoal Bay granite, and intruded by it. The distribution of the unit is consistent with an origin as a late, possibly residual magma related to the Shoal Bay granite, and contradictory intrusive relationships should be expected if this were so. From a geochemical perspective, the Hare Bay granite is more compositionally evolved than the Shoal Bay granite, has 'A-type' major- and minor-element characteristics, and is typically Zr-enriched (Sandeman and Malpas, 1995).

Rogers Cove Granite

Fine-grained granitoid rocks are also abundant in the southwestern part of Fogo Island, forming 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. These rocks are more varied in appearance than the Hare Bay granite, and include felsites and quartz-feldspar porphyries; however, the coarser grained varieties are similarly miarolitic and lecucocratic (Plate 8E). Larger bodies of such rocks in southwestern Fogo Island are exploited for road-construction material. These fine-grained granites and minor intrusions also have a close resemblance to pink, orange and red 'felsite dykes' that are widespread along the west coast of Fogo Island, on Change Islands and islands south and east of Change Islands (*see* below).

Other Fine-Grained Granite Units

Fine-grained 'felsitic' rocks that resemble parts of the Hare Bay and Rogers Cove granites also occur in the centre of Fogo Island, and are shown by the mapping of Currie (1997a) to extend eastward toward the Cape Fogo area as a semicontinuous belt (Figure 2). Minor bodies of such rocks occur elsewhere and generally intrude both mafic rocks and coarse-grained granites (*e.g.*, Plate 8F). The zone of fine-grained rocks indicated by Currie (1997a) across the centre of the Island was not indicated by Baird (1958) and has not been examined in inland areas, but where it is exposed north of Cape Fogo, it contains dark enclaves of uncertain origin and angular enclaves that resemble typical Shoal Bay granite (Plate 8G, 8H), suggesting that the fine-grained unit is actually younger, at least in this spot. Although it is possible that all of fine-grained granitoid rocks might be of the same age or origin, it is more likely that they form several discrete units that need not have identical contact relationships.

Dykes and Minor Intrusions

Dykes and minor intrusions are abundant in many parts of Fogo Island, and are mostly of mafic or felsic compositions; intermediate dioritic compositions are less common. Many such minor felsic intrusions in southwestern Fogo Island were assigned to the Rogers Cove granite of Sandeman (1985) and Sandeman and Malpas (1995). They clearly intrude the Fogo Harbour Formation, and are typically quartz- and/or feldspar-porphyritic (Plate 9A, 9B). Composite dykes, in which a felsic core is flanked by basaltic material, or vice-versa, are also very common along the west coast of the Island. In some cases, the felsic dykes contain numerous blobs of fine-grained mafic material that have 'amoeboid' shapes (Plate 9C). Such features suggest that mafic liquids were actually entrained within the felsic magma, and were rapidly chilled and frozen during ascent. Other composite dykes have discrete mafic and inclusion-free felsic portions suggesting that the same conduit was used by contrasting magmas at different times (Plate 9D). Although there may be temporal separation of mafic and felsic magmas within the confines of a single small intrusion, their local interaction as liquids indicates that they were synchronous on the longer time scale of magma chamber evolution.

Some grey, intermediate dykes observed on the west coast of the Island are feldspar-porphyritic and resemble the coarser grained diorites and monzonites that are developed in areas where mafic and felsic magmas appear to have interacted. These dykes are regarded as 'escaped hybrid magmas', which may better record the processes of mixing and hybridization than their trapped counterparts. The intermediate inclusions preserved within the Shoal Bay granite perhaps represent similar magmas that failed to 'escape' into surrounding country rocks.

'Mixed Rocks' Indicative of Magma Interaction

Mixed rocks are common in parts of the Fogo Island intrusion where both mafic rocks and granitoid rocks occur on an outcrop scale, such as in the area between Cape Cove and Cape Fogo (Figure 2). Other excellent examples occur in the area south and east of Tilting, around Oliver's Cove. They are likely also present in much of the central area that was indicated as granite by Baird (1958) but as diorite by Currie (1997a). Previous descriptions of the mafic rocks included some references to these rocks.

These rocks always include a mafic component, typically a fine-grained gabbro or diorite, and a granitoid component that generally resembles the Shoal Bay granite. Superficially, the mafic rocks are enclosed by the granitic material, in which they form rounded masses, with shapes that range from ragged and amoeboid to pillow-like or sausage-like (Plate 10A). Angular mafic fragments are rare in such zones, as are clearly defined granite veins within mafic fragments, but local examples of both can occur. Other common features include disrupted chilled margins on some, but not all, mafic enclaves (Plate 10B, 10C), and the local presence of paler grey intermediate inclusions that contain feldspar phenocrysts (Plate 10D).

These mixed rocks are all regarded as products of magma mingling processes that led to aborted or incomplete mixing. The hotter mafic magmas were emplaced into par-

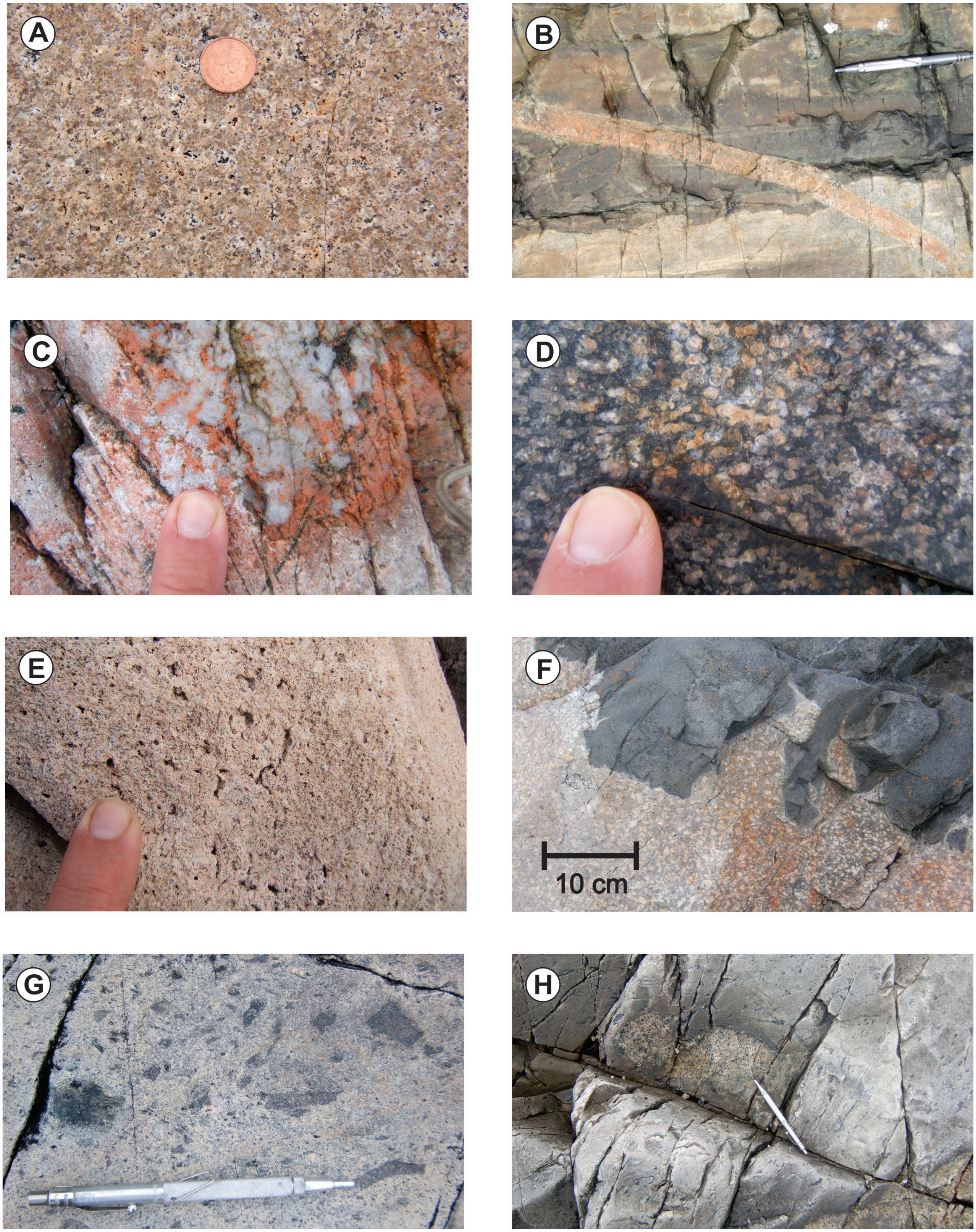


Plate 8. *Caption on opposite page.*

Plate 8. (opposite page) *Features of the Hare Bay granite, Rogers Cove granite and similar rocks. A) Typical equigranular, leucocratic Hare Bay granite, showing prominent miarolitic cavities; B) Granite vein cutting sedimentary rocks of the Fogo Harbour Formation close to their contact with the Hare Bay granite; C) Coarse quartz and K-feldspar pegmatite patch in the Hare Bay granite, close to its contact with sedimentary rocks; D) Spherulitic texture developed in glassy aphanitic rocks that appear to grade into fine-grained granite near Wild Cove (west); E) Rogers Cove granite, showing fine grain size and miarolitic cavities; F) Feldspar porphyry intruding mafic rocks of the Tilting layered complex, the lobate nature of the contact suggests that the country rocks were not entirely solidified at the time of intrusion; G) Grey, sugary fine-grained granite near Cape Fogo, containing angular inclusions of uncertain affinity; H) Xenolith of typical Shoal Bay granite in fine-grained granite unit near Cape Fogo.*

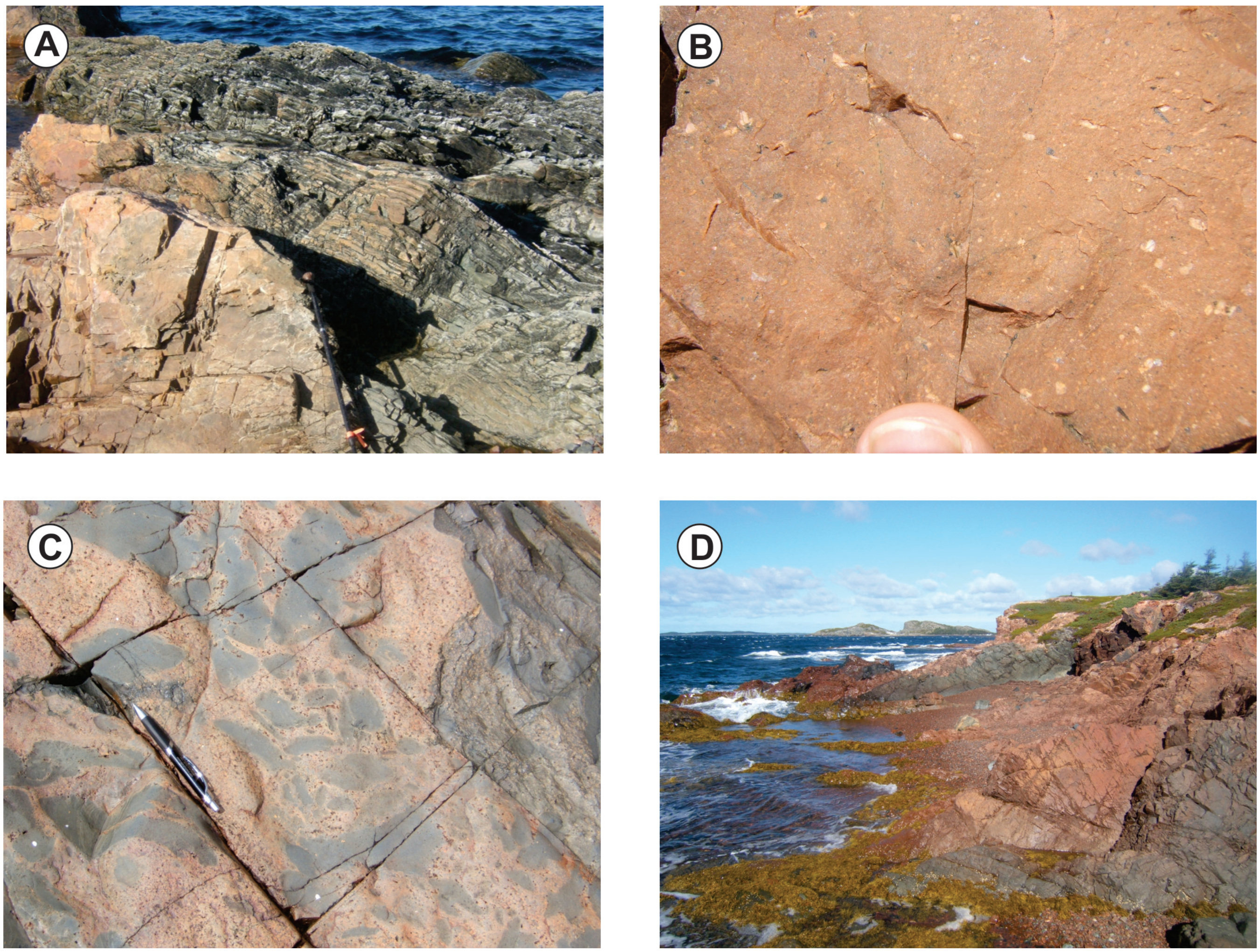


Plate 9. *Features of some minor intrusions that are probably linked to the Fogo Island intrusion. A) Pink quartz-feldspar porphyry dyke intruding thinly bedded siltstones of the Fogo Harbour Formation; B) Close-up view of quartz-feldspar porphyry, showing tiny phenocrysts of both minerals; C) Part of a composite dyke in which chilled irregular inclusions of basaltic composition are entrained within quartz-feldspar porphyry as a consequence of attempted magma mixing; D) Discrete 'sheeted' mafic (dark) and felsic (orange) dykes on the west coast of Fogo Island, south of Island Harbour.*

tially consolidated granitoid crystal mush, or came into direct contact with largely liquid granitoid magmas. The freezing of the mafic magma under such conditions limits the potential for actual mixing, and the apparent intrusive relationships do not record the sequence of emplacment. In some outcrops, generally rectiplanar mafic zones having

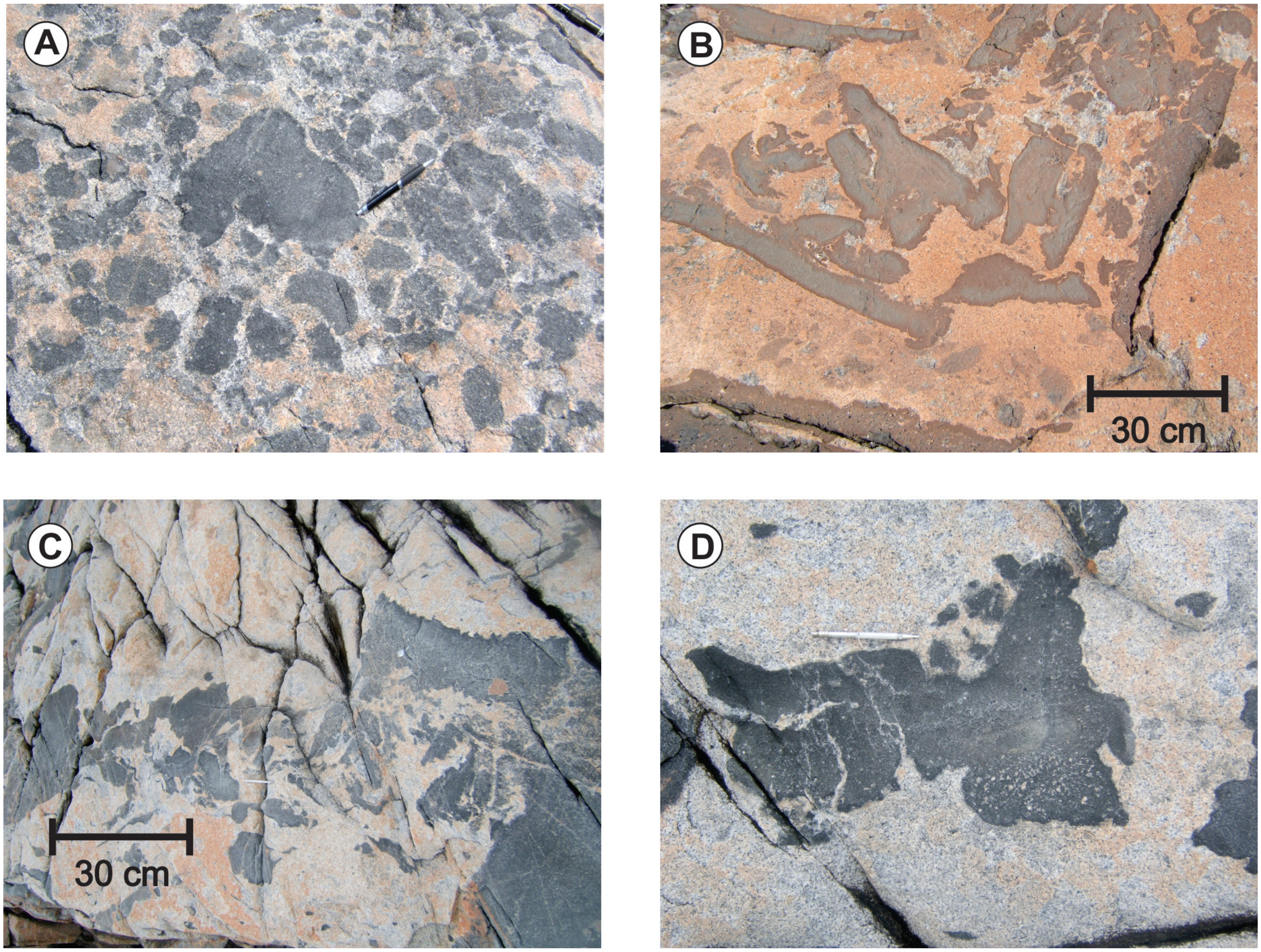


Plate 10. *Features of some 'mixed rocks' interpreted to record magma interaction and mingling. A) Granite littered with amoeboid and rounded blobs of chilled basaltic material, showing some local hybridization represented by grey areas; B) Broadly rectangular zones of mafic material floating in granite, probably representing a 'failed dyke', note prominent chill zones on the inclusions; C) A dyke or sheet of mafic composition cutting granitoid rocks, which has 'failed' and become dismembered in its central section, which collapsed into chilled inclusions of various shapes and sizes; D) Detail of chilled mafic inclusion from this zone, showing the local incorporation of K-feldspar 'phenocrysts' likely derived from surrounding crystal mush.*

chilled margins can be traced laterally into chaotic patches of mafic blobs within granite, suggesting that changes in wall-rock rheology influenced behaviour (Plate 10B, 10C). Multiple, discrete pillow-like masses within the granitoid matrix (Plate 10A) probably represent mafic magma influxes that disintegrated and collapsed where they entered more liquid-rich granitoid magma. The varied appearance of such rocks is interpreted to record a spectrum of situations in which mafic magma influxes variably failed to retain integrity. It is likely that variations in flow rate, relative viscosity, rheology and temperature differences all influenced the final results of such interactions, but exactly how and in what manner remains to be established.

INTRUSION BRECCIAS

If there is one rock type that visitors to Fogo Island always remember, it is 'intrusion breccia', in the broadest sense of the word, *i.e.*, complex rocks that are mixtures of more than one type of plutonic rock and/or country-rock material. Depending on the state of mind of the observer, these complex outcrops can be endlessly intriguing or completely frustrating. Baird (1958) depicted intrusion breccias *via* symbols superimposed upon units representing mafic or granitic rocks, but included mixed rocks developed through magmatic interaction (*see* above) in this category. Currie (1997a) attempted to define specific units of 'agmatite', but included most of the mixed magmatic rocks within his diorite unit. The most obvious examples of intrusion breccias are those that involve metasedimentary xenoliths, which occur at the margins or the Fogo Island intrusion, but also within it. An interesting zone of complex mixed rocks exposed at Wild Cove (east) is also interpreted as an intrusion breccia, rather than a product of magmatic interaction.

'Marginal' Intrusion Breccias containing Country-rock Fragments

Western Fogo Island preserves a spectacular zone in which the Fogo Harbour Formation is dissected on all scales by plutonic rocks; the latter are predominantly granitic in the north, but mafic and intermediate on the west side of Little Seldom Cove (Figure 2). Currie (1997a) indicated the northern part of this zone as a discrete unit, and it is superbly exposed along roadcuts and coastal outcrops (Figure 2). In this area, the Fogo Harbour Formation includes two contrasting sedimentary facies, *i.e.*, thinly bedded siltstone and mudstone, and more massive, thickly bedded sandstone and crossbedded quartzite. The thinly bedded rocks locally display complex and chaotic folding, but this appears to be of syn-depositional, soft-sediment origin (*see* also Plate 2A). Fine- to medium-grained granitic material invades these outcrops along bedding planes, creating 'sheeted' zones, within which individual granitic sills are linked by crosscutting veins (Plate 11A, 11B). In areas of chaotic folding, granite zones follow bedding planes around such structures, leaving the superficial impression that they might themselves be folded. However, detailed examination shows that the granite is actually discordant with respect to the soft-sediment structures, and disrupts them (Plate 11B). These zones of structural complexity seem to be preferred sites for forceful intrusion, presumably because they were weak. Individual granitic 'sills' range in thickness from a few centimetres to over a metre, and in many cases appear to have developed through progressive detachment of individual beds and layers from their roof zones (Plate 11C). These angular to tabular xenoliths appear to have settled within the granitic magma, in some cases accumulating at, or near, the base of the miniature sill. Along the western side of Little Seldom Cove, identical breccias are developed along the contact between the Seldom gabbro and sedimentary rocks (Plate 11D), indicating that this mode of intrusion and chamber development characterizes both the mafic and granitoid sections of the intrusion.

These marginal intrusion breccias are reminiscent in some respects of the so-called 'shatter zone' developed around the Mount Desert Island intrusion in Maine (Wiebe *et al.*, 1997). They also provide a small-scale illustration of the wider process by which the Fogo Island magma chamber may have developed within its sedimentary host rocks, and how stratigraphy and structure might control its geometry and evolution. In particular, the growth of sill-like subchambers through progressive dissection of their roof zones, and the accumulation of fragments toward their basal contacts, may provide an illustration of the wider geometry and structure inferred for the Seldom gabbro, which contains discrete xenolith-rich zones (discussed in the next section).

'Internal' Intrusion Breccias containing Country-rock Fragments

Zones that are rich in country-rock fragments and blocks are also present within interior portions of the Fogo Island intrusion, but their geographic distribution does not appear to be random. They occur in both mafic and granitoid rocks (Figure 2), and they have distinctive features in these settings.

An interesting fragment- and block-rich zone within the Shoal Bay granite occurs near Joe Batts Arm, adjacent to the new Fogo Island Inn (Plate 12A). Individual blocks range in size from a few centimetres to tens of metres, and mostly appear to be variably hornfelsed metasedimentary rocks, presumably from the Fogo Harbour Formation. The larger megablocks are dissected by granitic veins and pass laterally into granite littered with smaller angular blocks, indicating the progressive dissection of blocks through stoping (Plate 12B). The host granites contain smaller rounded inclusions that have igneous textures, as do most granites on the Island, but there is likely no connection between these and the huge xenolithic blocks. The blocks and matrix of the intrusion breccias are cut by mafic and felsic dykes. Currie (1997a) mapped this zone as a north–south-trending unit extending towards the centre of Fogo Island, roughly perpandicular to the regional strike of the Fogo Harbour Formation (Figure 2). Such a pattern suggests that it could represent the remnants of a 'country-rock wall' that might once have separated discrete subchambers during the evolution of the larger chamber. Scattered zones of similar angular metasedimentary fragments occur elsewhere in the Shoal Bay granite, but rarely at equivalent mappable scales.

The Seldom gabbro contains numerous zones that are rich in sedimentary fragments and blocks derived from the Fogo Harbour Formation. These have a wide size range but a generally tabular shape, and consistent orientations. To use analogous sedimentary terminology, such zones range from matrix-supported to clast-supported (Plate 12C; *see* also Plate 4c). In inland outcrops, some of the latter rocks are almost impossible to distinguish from bedded sedimentary rocks that show greater integrity. The sedimentary fragments vary from almost pristine siltstone and sandstone to spotted hornfels, and some are associated with pegmatite zones in the surrounding gabbro (Plate 12D), suggesting

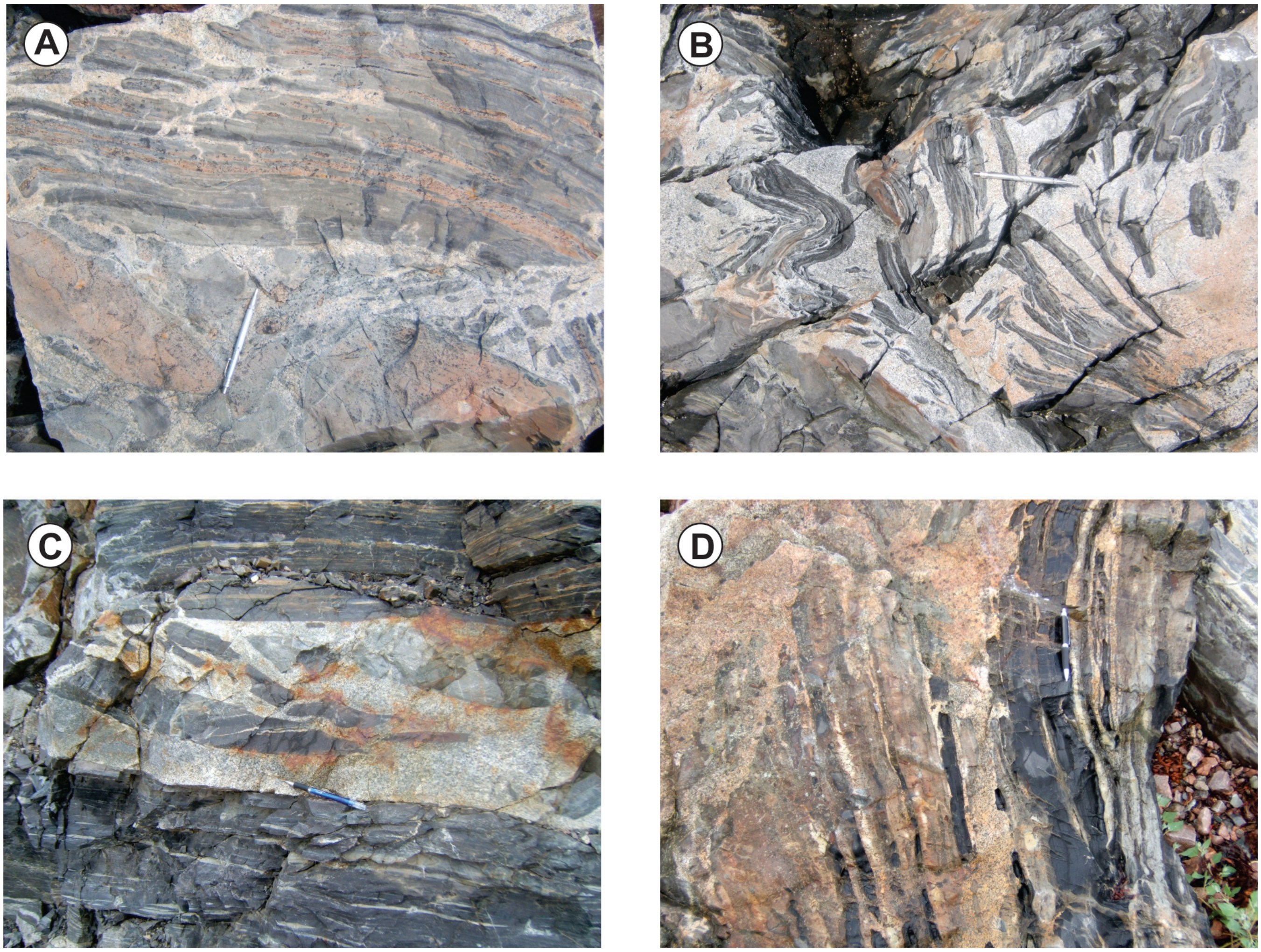


Plate 11. *Features of some marginal intrusion breccias from western Fogo Island. A)* In-situ *dissection of bedded sedimentary rocks by medium-grained granite; B) More advanced disruption of sedimentary rocks that contain fold structures of probable soft-sediment origin, which are preserved as folded xenoliths; C) A miniature granitic 'sill' in siltstones, showing the detachment of tabular xenoliths from the upper contact, and their accumulation toward the lower contact; D) Dissection of bedded sedimentary rocks by heterogeneous leucocratic material of intermediate composition near lower contact of the Seldom gabbro.*

dehydration and possibly local anatexis. Such features suggest that fragments had a wide range of 'residence times' within the magma, and accumulated at the bases of individual intrusive sheets, or at the transient floor of the magma chamber. As discussed previously, they resemble fragment-rich horizons defined in the lower section of the Vinalhaven intrusion. They could have formed through progressive dissection and destruction of roof zones in response to new influxes of magma (*cf.,* Hawkins and Wiebe, 2004), but could also represent variably dissected screens of country rocks separating sheet-like subchambers. The marginal breccias discussed in the preceding section provide small-scale examples of this exact process.

Intrusion Breccias at Wild Cove (East)

Interesting outcrops around Wild Cove (east) are also mixed rocks containing mafic and granitoid components, but appear distinct from superficially similar rocks attributed to magma interaction. The examples at Wild Cove (east) are interpreted as true intrusion breccias in which most fragments were solid rocks at the time of their disruption. The breccias cannot be represented at scale on Figure 2, but form a discrete zone along the boundary between the Tilting layered complex and the Shoal Bay granite. This was recognized by Aydin (1995), who included a variety of similarly heterogeneous rocks in the Tilting area as the "Wild

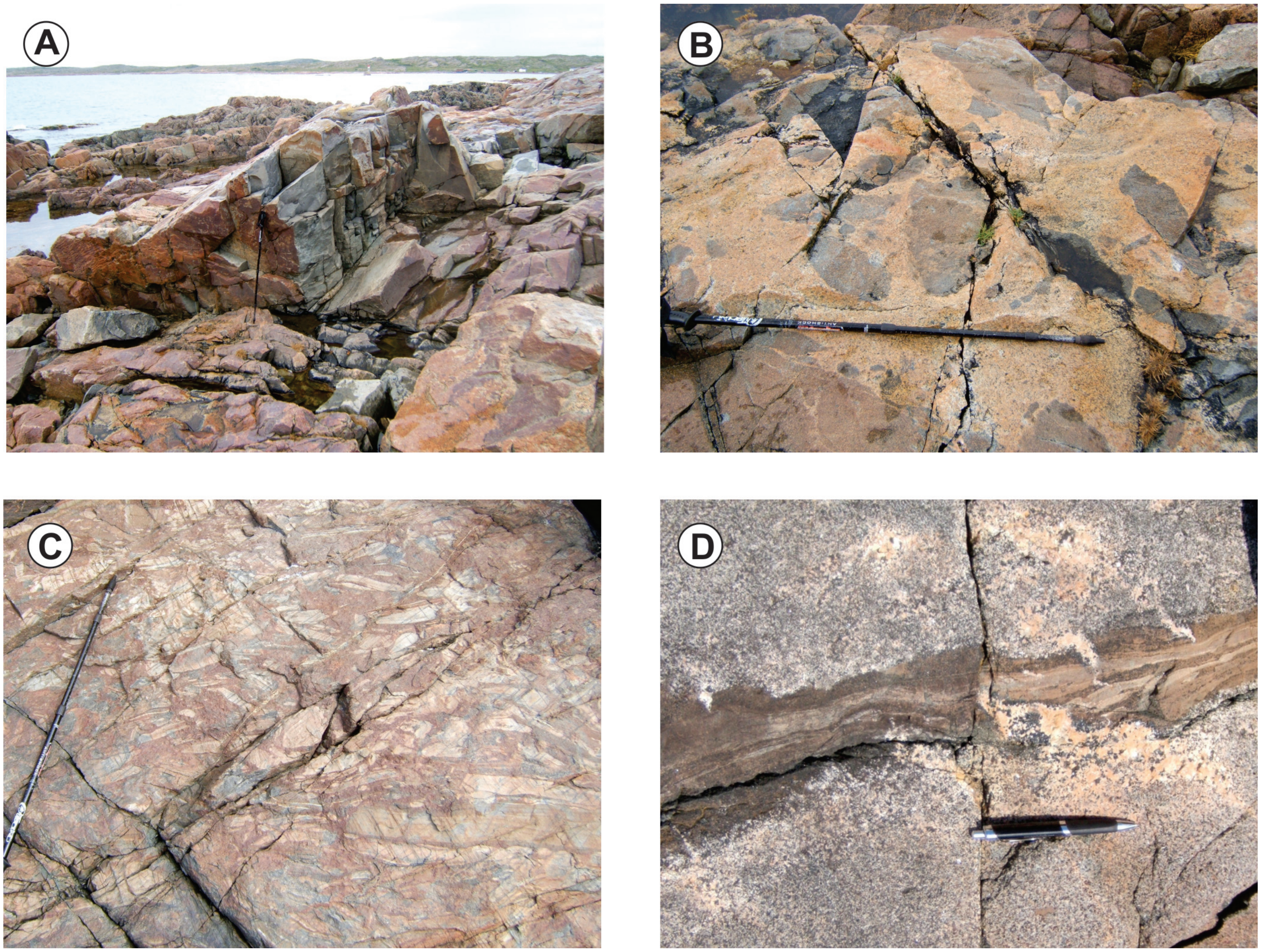


Plate 12. *Features of some internal intrusion breccias from Fogo Island. A) Large blocks of hornfelsed sedimentary rocks at Brown's Point, near the Fogo Island Inn – the sedimentary rocks typically have rusty weathering; B) Progressive stoping of large metasedimentary blocks by granite; C) Densely packed, 'clast-supported' intrusive breccia in the Seldom gabbro consisting of tabular sedimentary fragments in dark-weathering mafic matrix; D) Pegmatite development in gabbroic matrix within the Seldom gabbro, perhaps due to metamorphic dehydration of the larger metasedimentary fragment and addition of water to surrounding magma.*

Cove–Sandy Cove Suite"; however, some of these, notably near Olivers Cove, are more like the mixed rocks interpreted to develop through mingling and interaction (*see* above).

The Wild Cove (east) breccias are visually spectacular and include mafic to intermediate inclusions, ranging in size from a few centimetres to several metres, and ranging from fine-grained aphanitic material to coarse-grained, variably porphyritic, mafic rocks (Plate 13A, 13C). Some inclusions have 'internal structure' or cumulate layering, although most are structureless. Many of the rock types seen as inclusions in the breccia resemble those that occur within the Tilting layered complex, which adjoins it to the east, and probably also occurs at depth. The inclusions are mostly angular to subrounded or rounded in shape, but a few fine-grained mafic inclusions have ragged amoeboid shapes that are reminiscent of textures in breccias attributed to magma mingling (Plate 13D). To date, disrupted chilled margins have not been observed on these rarer inclusions. The mafic inclusions are surrounded by a medium-grained grey matrix of quartz-dioritic to granodioritic composition, poorer in K-feldspar than the typical Shoal Bay granite. Although discrete breccia zones cut the Shoal Bay granite on the point west of Wild Cove (east), inclusions of the granite have not been observed within the breccia zone itself, although they would be harder to recognize than those of mafic composition. The variety of and shapes of inclusions suggest that these intrusive breccias were developed through the disruption of solid, cooler rock types by a liquid magma. However, this magma might itself have entrained small amounts of

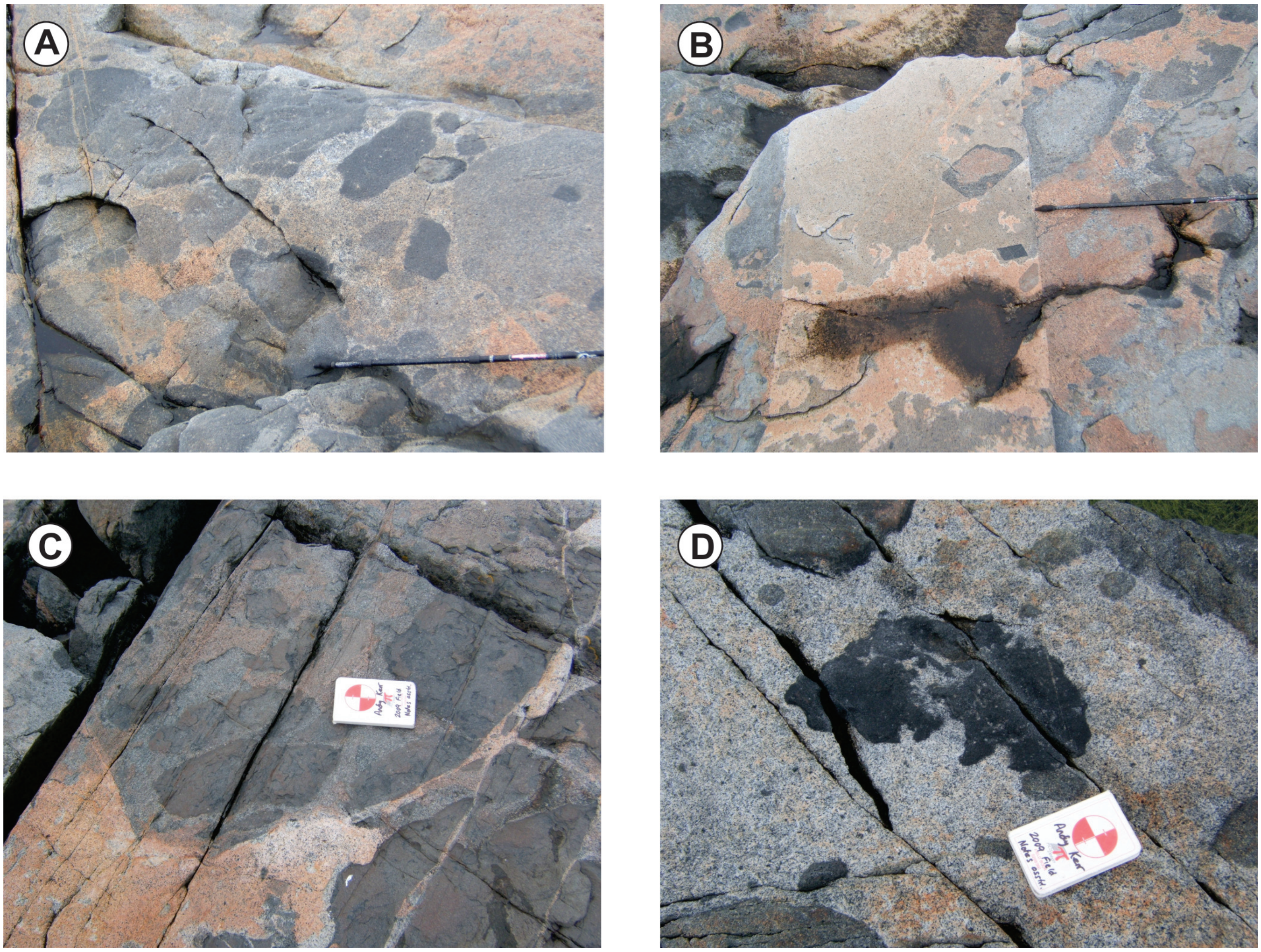


Plate 13. *Features of intrusion breccias at Wild Cove (east). A) Typical appearance, showing rounded to subangular inclusions of varied composition having sharp contacts. The fragment at upper left shows pre-existing compositional variation; B) Rectiplanar dyke cutting intrusive breccia and individual fragments within country rocks, but itself containing discrete fragments. Note that some of the apparent light and dark colour variation within the dyke is due to differential exfoliation of the weathered surface, and is not true compositional variation; C) Internal breccia texture within a large block, also indicative of multistage development for this zone; D) A rare aphanitic mafic inclusion with an irregular shape and possible chilling, suggesting that the invading intermediate magma contained at least small amounts of coexisting mafic magma.*

a coexisting mafic liquid, as suggested by the rarer amoeboid inclusions.

The breccia zone at Wild Cove (east) is demonstrably multiphase, because it contains rare blocks that have “internal” breccia textures of similar aspect (Plate 13C). It is also cut by at least two discrete rectiplanar dyke-like zones, up to 2 m wide, which have a slighter lighter-coloured matrix, and visibly truncate individual inclusions in their wall rocks. However, these dyke-like zones themselves contain a similar inclusion population (Plate 13B). This implies that intrusion breccias developed, solidified completely and cooled, before they were disrupted by subsequent pulses of fragment-charged magma that had a slightly different composition. This process occurred at least twice, and possibly many times.

The intrusion breccia at Wild Cove (east) is interpreted as a discrete younger influx of magma that disrupted crystallized rocks of the Fogo Island intrusion, notably the Tilting layered complex, which is interpreted to here sit beneath the Shoal Bay granite. The absolute age difference between inclusions and matrix is unknown, but they could be separated by millions of years. This point is very important in the context of geochronological data, because one of the dates obtained by Aydin (1995) is believed to represent the matrix of the intrusion breccia.

GEOCHRONOLOGICAL CONSTRAINTS

Geochronological data from Fogo Island are sparse, and in part ambiguous. Early K-Ar determinations suggested a Devonian age of 380 ± 16 Ma (Williams, 1964), but these likely represent cooling ages, and the exact rock types and locations remain unknown. Sandeman (1985) presented Rb–Sr isotopic data from granites, suggesting an age of 411 ± 13 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70484 ± 0.00018, but these appear to be an errorchron, rather than an isochron; exclusion of two samples provided a better fit suggesting an age of *ca.* 417 Ma.

U–Pb geochronological data presented by Aydin (1995), are difficult to interpret. A granite sample from an inland location on a disused road west of Tilting provided an age of 420 ± 2 Ma, but this is a lower intercept age as most of the zircon in the sample contains older inherited material; only one zircon fraction actually plotted on the concordia line. Titanite, from the same sample, gave a younger near-concordant age of about 408 Ma. The second age reported by Aydin (1995) represents her "Wild Cove–Sandy Cove Suite", which is, in part, equivalent to the intrusion breccias at Wild Cove (east). This gave a concordant zircon age of 408 ± 2 Ma. However, the sample location is on the east side of Sandy Cove (Figure 2), and the coordinates quoted actually lie offshore. The nearest outcrops belong to the Tilting layered complex, but these are cut by diffuse breccia zones that resemble the Wild Cove Zone. The 408 Ma age thus provides only a younger limit on the Fogo Island intrusion, and does not indicate the time of intrusion of mafic rocks such as the Seldom gabbro or Tilting layered complex.

Samarium-Neodymium (Sm–Nd) isotopic data for rocks from Fogo Island are reported by Fryer et al. (1992) and by Aydin (1995). A sample of the Shoal Bay granite (from near Joe Batts Arm) has an ε_{Nd} (CHUR) value of -1 calculated for an age of *ca.* 400 Ma (Fryer *et al.*, 1992), and three samples of granite gave values from -1 to +1.3 (Aydin, 1995). The Tilting layered complex gave a wide range of ε_{Nd} (CHUR) values from -0.1 to +5.1 (Aydin, 1995), and samples from the Wild Cove area also gave variable results, although it is not clear if the latter represent fragments, matrix or mixed material. Variation in Nd isotopic signatures is certainly indicative of magmas that have contrasting origins and sources within the intrusion, consistent with the other inferences for interaction of mafic and granitoid magmas.

DISCUSSION OF RESEARCH OPPORTUNITIES

Fogo Island presents many opportunities for geoscience research, and provides a superb natural laboratory for teaching igneous petrology and Earth Science in general. This article concludes with a brief listing of topics that could be considered in formulating such research. The most obvious possibilities are connected to the volcanic and plutonic rocks, but other aspects also deserve attention.

The sedimentary rocks of the Fogo Harbour Formation have never been studied from a sedimentological or stratigraphic perspective. I believe that there is potential to establish at least a local stratigraphy that would aid in understanding structural patterns and their relationship with the Fogo Island intrusion. My own limited field work in the last few years has also identified some possible fossil localities, which require specialized attention. The tuff units in the upper part of the formation represent potential targets for direct dating, although their relationships to the sedimentary rocks need to be clearly established.

With respect to igneous rocks, geochronology is the most obvious gap. Most of the plutonic rocks on the Island seem amenable to precise geochronology, but the probability of inheritance (*see* Aydin, 1995) suggests that methods capable of single or subgrain analyses (*e.g.*, the sensitive high-resolution ion microprobe, or SHRIMP) would be the best initial approach. Such work should logically include the Brimstone Head Formation, and other potentially correlative volcanic rocks, such as those of the Little Fogo Islands. Field evidence indicates that mafic and granitoid magmas coexisted as liquids on the time-scale of the magma chamber, even though local patterns may indicate one intruding the other. However, these latter observations in no way negate the wider temporal coexistence of two magma types. The lifespan of complex magma chambers is probably similar to or less than the uncertainty associated with dating such rocks (typically ± 2 Ma or so), so geochronology may not provide *absolute* proof of such models, although it could refute the concept. To document the evolution of any magma chamber requires highly precise methods, such as the 'chemical abrasion' technique coupled with thermal-ionization mass-spectrometry (TIMS), which can greatly reduce uncertainties imposed by lead loss. A study of the Vinalhaven intrusion summarized by Hawkins *et al.* (2009) provides an illustration of what might be accomplished on Fogo Island with such an approach.

There are two outstanding regional geology questions. The first is the timing relationship between formation of the Fogo Island intrusion and any penetrative deformation of the Fogo Harbour Formation. Folded xenoliths are present in marginal intrusion breccias, and also in internal breccias within the Seldom gabbro, but their origins are not entirely clear. I consider these to be soft-sediment structures (like those shown in Plate 11), but there are also regional folds of the Fogo Harbour Formation, and some of these (notably around Fogo Town) are relatively tight. The relationships between intrusive rocks and such structures are potentially important; specifically, does this deformation predate or postdate development of the magma chamber, or was it perhaps in part induced by its development? The second question concerns the relationship between the Fogo Harbour Formation and the Brimstone Head Formation, and is closely related. If the latter is equivalent to the Shoal Bay and/or Hare Bay granites, but the granites postdate deformation in the sedimentary rocks, there must also be stratigraphic and/or structural complications between the two formations. Alternatively, the Brimstone Head Formation could be older than the Fogo Island intrusion, whose true extrusive equivalent might be instead on the Little Fogo Islands, or elsewhere. The key location in terms of understanding these problems is the rather confusing area around Fogo Town, which is an obvious target for more detailed mapping. Filling gaps in our geochronological knowledge could also shed light on these questions, but it will not provide all of the answers.

Within the Fogo Island intrusion itself, there are numerous topics for investigation. An obvious question is the relationships between the Tilting layered complex to surrounding granites, and its possible links to other mafic to intermediate rocks of the Seldom gabbro. Previous studies of the Tilting area (*e.g.*, Cawthorn, 1978; Aydin, 1995) are somewhat introspective, and there is a need to consider these rocks in a wider context. Geophysical investigations might also provide insight into this problem and wider magma chamber anatomy. There is evidence from regional data of a positive gravity anomaly associated with Fogo Island (Weaver, 1967; Strong and Dickson, 1978), but this has not been assessed in detail. A more detailed gravity survey might answer a fundamental question, *i.e.*, are the dominant granites underlain by mafic rocks at depth, and can the thicknesses of the mafic and granitoid sections of the intrusion be constrained?

The parallels between Fogo Island and the composite bimodal intrusions of the coastal Maine area are a recurrent theme in this article, but it is reasonable to assume that such complex magma chambers would have distinct characteristics, reflecting local circumstances and conditions. Thus, the Fogo Island intrusion may differ from the Vinalhaven intrusion and other Maine examples in important respects, despite their wider affinity. A possible contrast lies in the intrusive environment of mafic and intermediate rocks in the lower part of the intrusions. The upper part of the Seldom gabbro, as exposed between Cape Cove and Cape Fogo, is strongly similar to Vinalhaven; multiple sheet-like influxes of mafic magma appear to have been emplaced into granitic crystal mush and (or) directly into liquid-state granitoid magma. However, the lower part of the Seldom gabbro largely lacks associated granitoid rocks, and may instead be constructed from sill-like mafic subchambers developed within sedimentary country rocks. The interaction between mafic and granitoid magmas on Fogo Island also seems to have been more ‘chaotic’ than in the Vinalhaven intrusion. For example, well-developed magmatic pipes, indicative of quasi-stable situations where mafic magma sits above crystal mush (Chapman and Rhodes, 1992) are less common on Fogo Island. Such contrasts could have a range of causes, including differences in the flow rates of mafic magma influxes, the relative temperatures and densities of the magmas, and the degree of solidification of granitoid crystal mush. In terms of understanding processes and controls, documenting subtle differences between the Fogo Island intrusion and its counterparts may be more informative than recounting general similarities. More detailed work is required to accomplish this goal. Finding additional magmatic pipe localities on Fogo Island is also important, because these miniature diapirs provide indications of the paleohorizontal at the time of emplacement, and would aid in geometric reconstructuion (*c.f.*, Wiebe and Collins, 1998).

The interpreted synchronicity between mafic magmas and granitoid magmas in the Fogo Island intrusion provides a framework for more detailed petrological and geochemical studies. Research completed within the Vinalhaven and Mount Desert Island intrusions (*e.g.*, Wiebe *et al.*, 1997, 2000, 2001, 2004) provides templates for investigations of this type. Possible topics include attempting to match inclusion populations with hybrid rocks developed in zones of interaction, and investigating physical and chemical mixing processes through trace-element and isotopic tracers. Fine-grained granites and quartz-feldspar porphyries, which have to date received limited attention, also represent an interesting topic for study; these may not all be roof zones or residual liquids. Alternative mechanisms such as melting or remobilization of granitoid cumulates by the thermal input from mafic magmas are well-documented for Vinalhaven (Wiebe *et al.*, 2004), and these processes may also apply on Fogo Island. It would also be interesting to attempt to link widespread and compositionally variable minor intrusions in the country rocks to processes in the interior of the Fogo Island magma chamber. Minor intrusions preserve a compositional record that may better document the evolution of liquid magmas than the equivalent plutonic rocks, many of which are mixtures of accumulated crystals and residual liquids. Minor intrusions may also preserve magma compositions that did not persist within the magma chamber itself, due to continued mixing and hybridization processes.

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Author's Note: The title of this article contains an oblique reference to the original 'Fogo Process', which was a film documentary project about community issues on the Island during the resettlement era of the 1960s. The fishing cooperative and several other community initiatives are viewed as outcomes of this ground-breaking project, which was initiated through Memorial University. A useful summary can be found at http://www.uoguelph.ca/~snowden/fogo.htm.

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