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GEOLOGICAL RELATIONSHIPS IN NORTHWESTERN FOGO ISLAND AND THEIR IMPLICATIONS FOR THE TIMING OF OROGENIC EVENTS

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ABSTRACT

Sedimentary and volcanic rocks in northwestern Fogo Island are traditionally assigned to the Silurian Botwood Group, and are subdivided into the Fogo Harbour Formation (dominated by siliciclastic sedimentary rocks) and the Brimstone Head Formation (dominated by pyroclastic rocks). These two formations have long been considered to form a continuous, conformable, homoclinal sequence. Detailed mapping shows that the contact between the Fogo Harbour and Brimstone Head formations exhibits a complex geometry and that the volcanic rocks sit upon different lithostratigraphic units within the underlying sedimentary rocks in different places. New observations also indicate that sandstones sitting beneath the basal contact of the Brimstone Head Formation are locally downward-facing. These results suggest that the contact between the two formations is a cryptic angular unconformity across which there could be a significant time gap. It appears that the Fogo Harbour Formation experienced recumbent folding, uplift and erosion prior to the extrusion and deposition of the Brimstone Head Formation. The Brimstone Head and Fogo Harbour formations are juxtaposed locally by reverse faults associated with significant penetrative deformation.

The lowermost volcanic formation of the Botwood Group (the Lawrenceton Formation) has previously been reported to sit unconformably upon folded rocks of the older Badger Group on nearby Change Islands. The new information from Fogo Island suggests that there may also be a second unconformity within the sequence assigned as part of the Botwood Group, unless the Fogo Harbour Formation is actually an unrecognized part of the older Badger Group. In either interpretation, geochronological studies in northwestern Fogo Island could provide important constraints on the timing of Silurian and Devonian orogenic events in the Newfoundland Appalachians.

INTRODUCTION

Fogo Island, located in northeastern Newfoundland (Figure 1), was the subject of a recent article that focused on its mafic to granitic intrusive rocks, now interpreted as a composite magma chamber of late Silurian or early Devonian age (Kerr, 2013). However, western Fogo Island also reveals a section through sedimentary and volcanic rocks assigned to the Silurian Botwood Group (Williams *et al.*, 1995a, b; Currie, 1997a). The timing relationships between the deposition and deformation of these rocks, and the development of the adjacent Fogo Island intrusion remain uncertain, but are potentially important in terms of defining orogenic events in the Appalachian Belt (*e.g.*, van Staal *et al.*, 2014). This short report summarizes findings from field mapping projects completed in 2013 as part of the academic program at the University of Cambridge. An area centred on the town of Fogo (Figures 1 and 2) was mapped in detail to improve knowledge of local stratigraphy and structure, and to examine contact relationships between two formations assigned to the Botwood Group. The results prompt reconsideration of previous ideas about local stratigraphy and structure, and imply that the timing of important orogenic events could here be constrained by geochronology. The full details of reinterpretation require additional work and new problems remain for future resolution. This paper is intended as a summary of the key points and a discussion of new ideas that could be tested through future work.

GEOLOGY

REGIONAL SETTING

Fogo Island is located in northeastern Newfoundland, within the Exploits Subzone of the Dunnage Zone (Williams *et al.*, 1988). The Exploits Subzone largely represents island arcs and related sedimentary basins that formed on the southeast (Gondwanan) side of the Iapetus Ocean from late

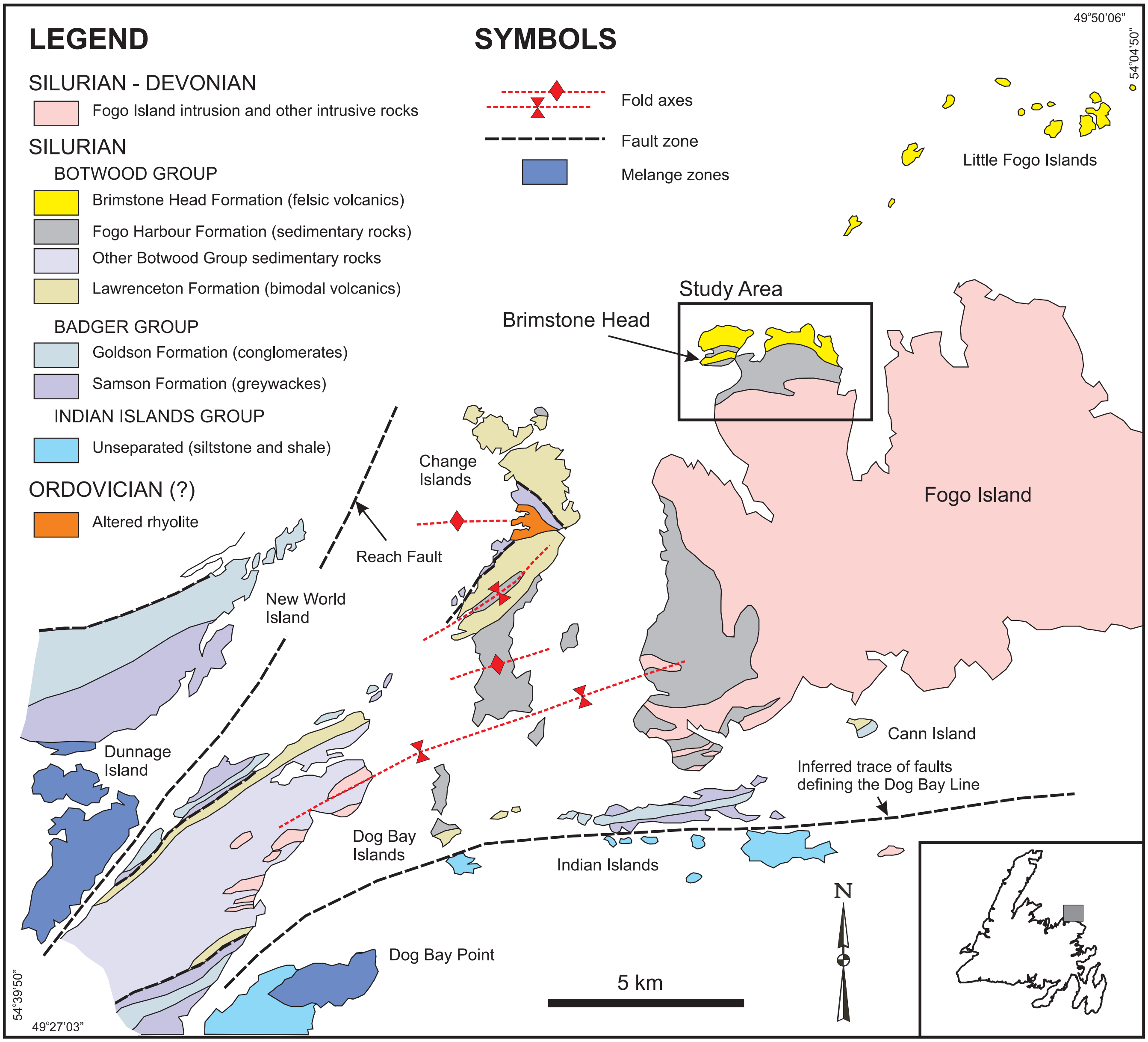

Figure 1. *Location of Fogo Island in northeastern Newfoundland and the general locations of Silurian sedimentary and volcanic sequences referenced in this paper; map adapted from Williams* et al. *(1995b) and Currie (1997a, b).*

Precambrian to Silurian times (Williams *et al.*, 1988). These arcs are inferred to have been built upon late Precambrian continental basement of the Ganderia block (van Staal, 2007; Zagorevski *et al.*, 2010). Current tectonic models propose the initial accretion of Iapetan arc systems to the leading edge of Ganderia, followed by the development of a long-lived arc (Victoria–Popelogan arc) above a southeast-dipping subduction zone, which generated a wide back-arc basin to the southeast (Exploits–Tetagouche basin). During mid-Ordovician times, the Victoria arc collided with its counterpart on the Laurentian margin of the Iapetus Ocean. The back-arc basin was then closed by northwest-directed subduction. For a summary of regional geology and current models, *see* Zagorevski *et al.* (2010) and van Staal *et al.* (2014). The Silurian sedimentary, volcanic and plutonic rocks exposed in the Fogo Island–Change Islands area are interpreted to have formed during these final stages of convergence and subduction, although some could represent magmatism that postdates final closure of the back-arc basin.

REGIONAL STRATIGRAPHY AND STRUCTURE

The stratigraphy of the region is portrayed schematically in Figure 3. Late Precambrian basement rocks and Cambrian–Ordovician arc volcanic sequences are the oldest

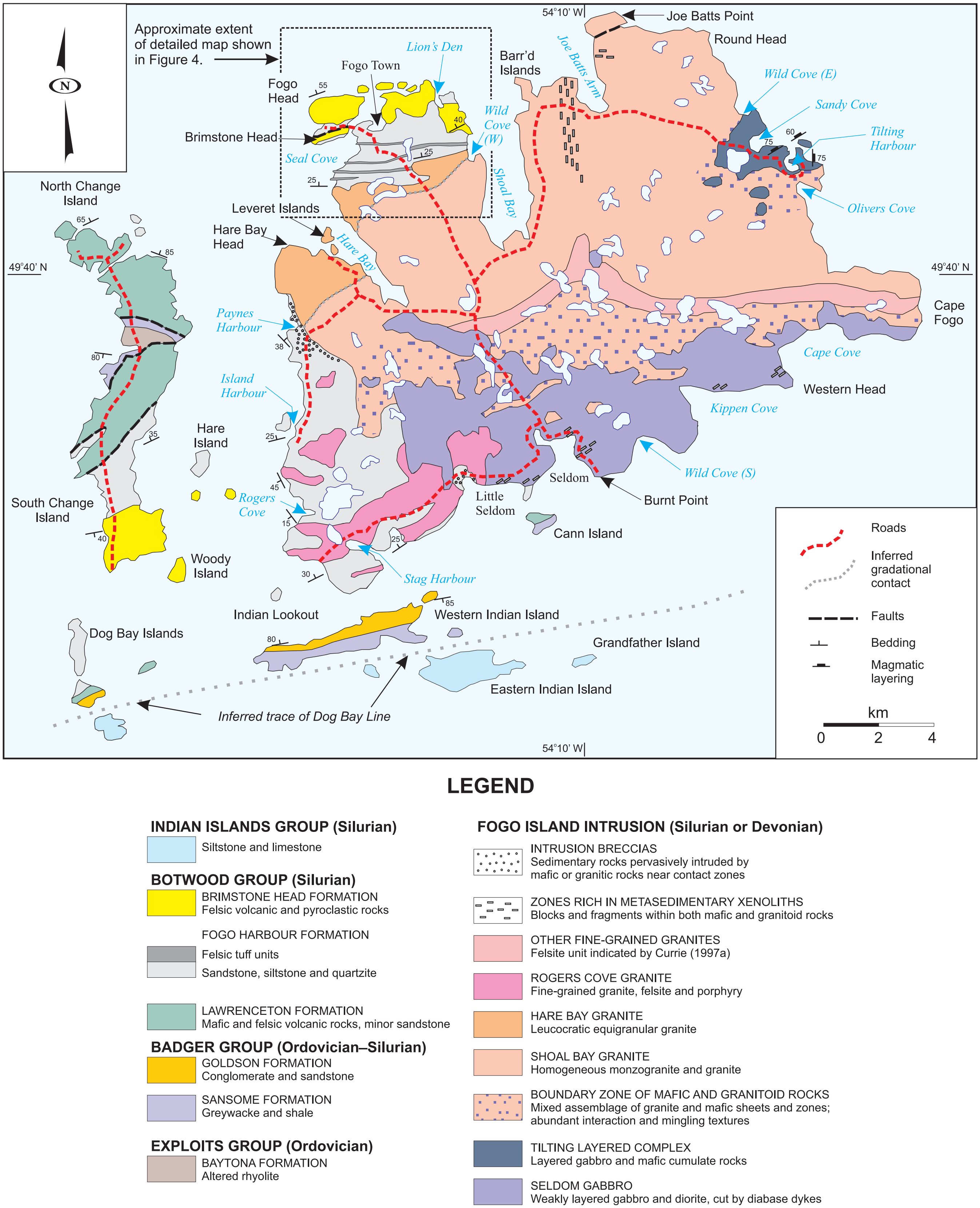

Figure 2. *Generalized geology of Fogo and the Change Islands, modified after Kerr (2013), showing the location of the area discussed in this report.*

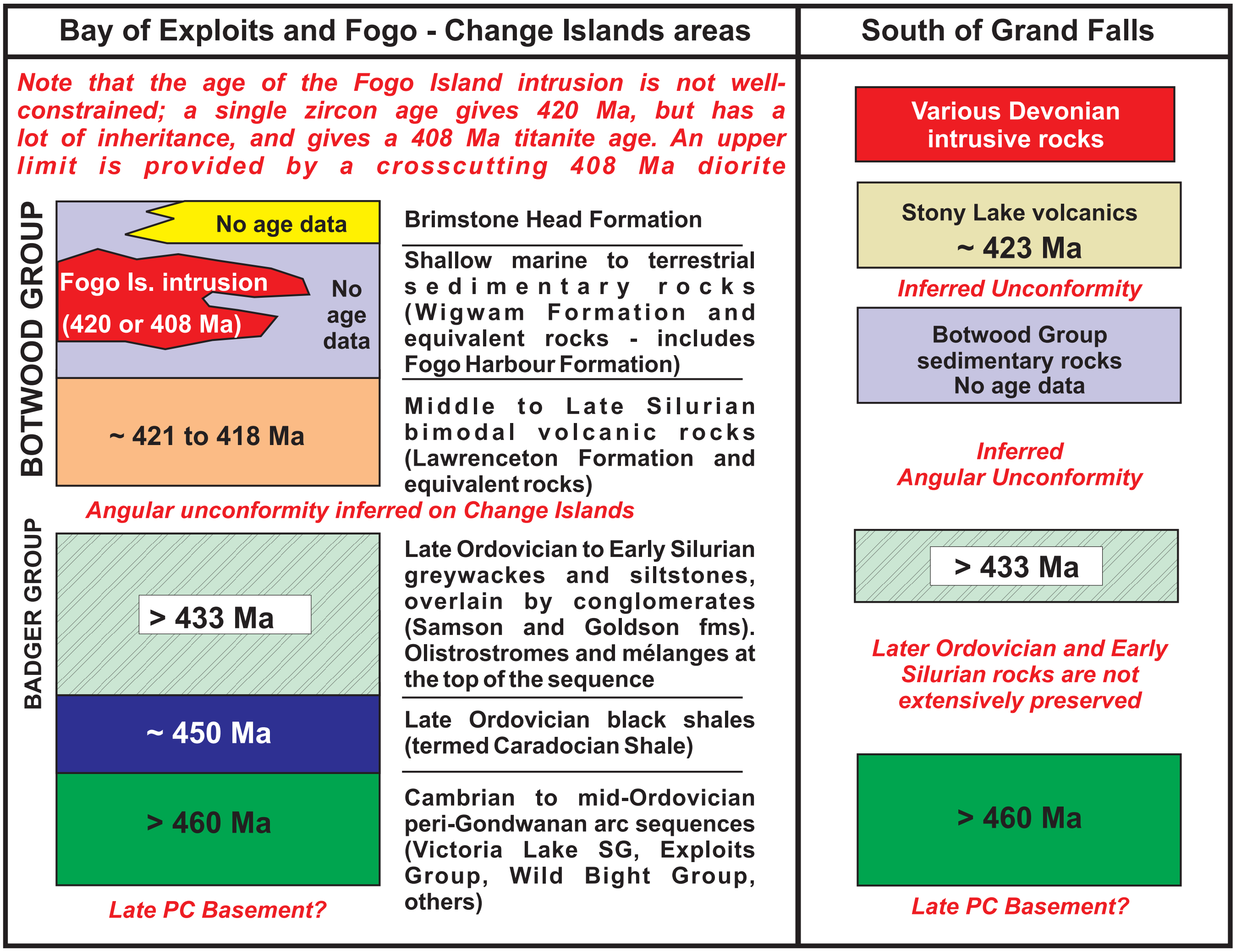

Figure 3. *Generalized stratigraphy of Ordovician and Silurian rocks in the eastern part of the Dunnage Zone (Exploits Subzone) in Newfoundland.* See *text for discussion.*

rocks in the Exploits Subzone, but are not exposed around Fogo Island. These arc rocks are overlain by regionally extensive black shales, and then by a shallowing-upward sedimentary sequence known as the Badger Group. This is interpreted to have been deposited within the back-arc basin, in part synchronously with its closure, and in part as a fore-arc accretionary prism (*e.g.*, van Staal *et al.*, 2014). The Badger Group includes two formations; the Samson Formation, dominated by shale and greywacke deposited in relatively deep water, is overlain by the Goldson Formation, dominated by conglomerate and also sedimentary mélanges (olistostromes). Calcareous shale, siltstone and limestone that occur in the southeast part of the Exploits Subzone are termed the Indian Islands Group (not indicated in Figure 3). Williams *et al.* (1995b) suggested that these were distal facies equivalents of the Badger Group, but it has also been suggested that they could in part be coeval with the Botwood Group. The debate about the stratigraphic and structural relationships of the Indian Islands Group is beyond the scope of this paper, but is reviewed in detail by Dickson (2006) and Dickson *et al.* (2007).

The Badger Group is succeeded by the Botwood Group, which consists of subaerial mafic to felsic volcanic rocks, overlain by shallow-water and terrestrial sedimentary rocks. These stratigraphic packages are termed the Lawrenceton Formation and Wigwam Formation, respectively. On Change Islands, there is good evidence that the Lawrenceton Formation sits unconformably upon the Badger Group (Currie, 1997a, b), but elsewhere the boundary is described as conformable (Williams *et al.*, 1995b). The Botwood Group is extensive, but its regional stratigraphy and facies anatomy are not well established. Van Staal *et al.* (2014) report U–Pb ages of 412 ± 4 Ma and 418 ± 4 Ma from the Lawrenceton Formation, which provide the best constraints upon its age. However, in south-central Newfoundland, the

"Stony Lake volcanics" are interpreted to sit unconformably upon Botwood Group sedimentary rocks (Anderson and Williams, 1970; Colman-Sadd *et al.*, 1990) and are dated at *ca.* 423 Ma (Dunning *et al.*, 1990). The volcanic rocks of western Fogo Island are also considered to sit above sedimentary rocks assigned to the Wigwam Formation (Williams *et al.*, 1995b; Currie, 1997a).

The principal deformational event in the Exploits Subzone is the Silurian Salinic Orogeny, interpreted to record the final closure of the Iapetus Ocean and its associated basins (*e.g.*, van Staal, 2005; van Staal *et al.*, 2014). The area was also affected by later deformation, generally ascribed to the Devonian Acadian Orogeny. The exact timing of these events, and the relationships between them, are not well understood, and may be time-transgressive across the Appalachian Orogen (*e.g.*, van Staal *et al.*, 2014). On the Change Islands, steeply dipping, cleaved greywackes of the Samson Formation are in contact with flat-lying pyroclastic rocks and redbeds of the Lawrenceton Formation. Although the contact is locally defined by minor faults, an angular unconformity is locally preserved (Currie, 1997b). This suggests that the Badger Group was folded and deformed *prior* to deposition of the Botwood Group, and likely defines the Salinic event(s). The volcanic rocks at this locality remain undated, but other ages from the formation imply that this deformation occurred before 421 Ma (van Staal *et al.*, 2014). The Botwood Group is tilted, and is affected by open to tight folds, but for the most part it is reported to be right-way-up; this deformation must be younger than 421 Ma, but is otherwise unconstrained. Karlstrom *et al.* (1982) proposed a complex tectonic history for eastern Notre Dame Bay, in which rocks of the Botwood Group are considered to be affected by thrusting.

The most prominent plutonic suites in the Exploits Subzone are bimodal assemblages that appear to be largely post-tectonic. These include the Mount Peyton intrusive suite (gabbro dated at 424 ± 2 Ma; Dickson *et al.*, 2007), the Fogo Island intrusion (for which sparse U–Pb data suggest an age of *ca.* 421 Ma; Aydin, 1995), and the Loon Bay granite (*ca.* 410 Ma; Elliot *et al.*, 1991). Some of these plutonic suites clearly intrude the Badger Group, and others intrude sedimentary rocks now assigned to the Botwood Group. However, their relationship to the deformation of the latter, or to volcanic rocks placed within the Botwood Group, is unclear. Van Staal *et al.* (2014) use the term "Fogo Suite" to refer to all of the Silurian volcanic and plutonic rocks in this region, but this terminology is very broad in the context of this study, and is avoided here.

SEDIMENTARY AND VOLCANIC ROCKS OF WESTERN FOGO ISLAND

General Patterns and Distribution of Units

The generalized geology of Fogo Island is shown in Figure 2 (Kerr, 2013; based in part on Baird, 1958; Currie, 1997a). The geology of the area discussed in this report is shown in simplified form in Figure 4. The discussion below is confined to the sedimentary and volcanic rocks, which occur mostly along the west coast, although they are present locally within the Fogo Island intrusion. Baird (1958) assigned the sedimentary and volcanic rocks to his "Fogo Group", assumed to be Ordovician in the absence of fossils. Williams (1972) recognized that the volcanic rocks were unlike those of known Ordovician sequences in Newfoundland and reassigned these rocks to the Silurian Botwood Group. This view has been retained (*e.g.*, Williams *et al.*, 1995a, b) but there are still no age constraints from paleontology or geochronology. The sedimentary rocks are termed the Fogo Harbour Formation and the volcanic rocks are termed the Brimstone Head Formation. The contact between these formations is seen only in the area around the town of Fogo (Figures 2 and 4), where the Brimstone Head Formation sits above the sedimentary rocks. In the south, the Fogo Harbour Formation is truncated by the Hare Bay granite, which is a high-level component of the Fogo Island intrusion. The bedding in the sedimentary rocks around the town of Fogo is moderate (20 to 35°) and consistently northwest-dipping; the beds appear to be right-way-up in most areas. Primary paleohorizontal indicators are rare in the Brimstone Head Formation, although marked fabrics are locally defined by flattened lapilli. These fabrics have varied orientations and cannot automatically be assumed to approximate bedding. It has previously been assumed that the volcanic rocks also dip to the northwest and conformably overlie the sedimentary rocks. However, the contact between the two formations has a complex geometry, which is not consistent with a simple dipping plane (Figure 4).

The Fogo Harbour Formation also occurs south of Hare Bay and extends to the area around Stag Harbour (Figure 2). In this southern tract, the sedimentary rocks are more extensively intruded by granites, felsite dykes and composite mafic–felsic dykes assigned to the Fogo Island intrusion. This southern tract is not discussed in this report, but further work is needed to evaluate its stratigraphy and structure in the light of our new findings.

The Little Fogo Islands (Figure 1) are also dominated by volcanic and pyroclastic rocks, but there are few descrip-

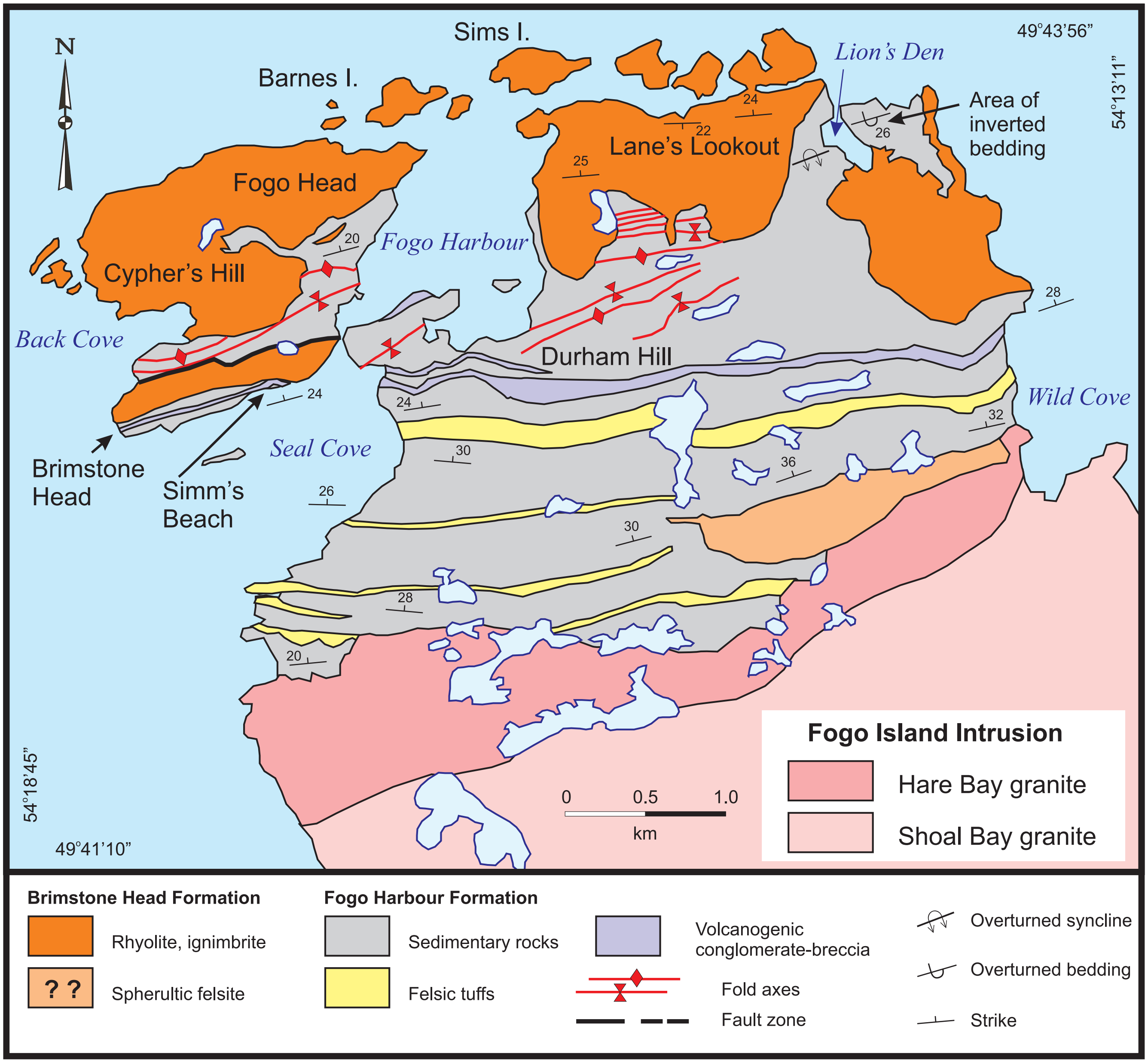

Figure 4. *Geological map of the area around the town of Fogo in northeastern Fogo Island, based on previous sources and new work in 2013.*

tions of these, aside from Eastler (1969). Baird (1958) correlated these small islands with volcanic rocks in northern Change Islands, now assigned to the Lawrenceton Formation, but Currie (1997a) grouped them as part of the Brimstone Head Formation, as indicated in Figure 1. Limited field work (A. Kerr, unpublished data, 2013) supports the interpretation of Baird (1958), which may have implications for regional structural configurations (*see* closing discussion).

There is limited previous information on regional structure and the sequence has generally been viewed as continuous, homoclinal and little-deformed. However, folds were noted near Brimstone Head (Baird, 1958) and Currie (1997a) indicated a fault in this area. The distributions of the Fogo Harbour and Brimstone Head formations near the town of Fogo suggest that there may be local fault-related repetition of the stratigraphic sequence, although Baird (1958) interpreted some sedimentary rocks to be interbedded with volcanic rocks as part of the Brimstone Head Formation.

Fogo Harbour Formation

In the study area, the Fogo Harbour Formation is best exposed on the shorelines of Seal Cove in the west and near

Wild Cove in the east, but also occurs in the valley between Brimstone Head and Fogo Head, and forms a tongue extending northward to a cove known as Lion's Den (Figure 4). The formation is dominated by well-bedded sandstones and siltstones, with minor pyroclastic and/or volcaniclastic rocks, conglomerate and chert. The sedimentary rocks were deposited in shallow water, based on current ripples, bidirectional crossbedding and other features, including possible desiccation cracks (Plate 1). The total exposed thickness in the study area approaches 2 km, but only part of this is preserved in the east. Note that these estimates do not include sedimentary rocks in the southern tract of the unit (Figures 1 and 2). For the most part, the sequence appears continuous and upright, aside from a key area near Lion's Den (discussed below). The sedimentary rocks appear to be unfossiliferous, although Kerr (2013) noted possible shelly fossils in southwestern Fogo Island. A sandstone bed at Seal Cove contains algal structures (oncolites) and some possible fossils exist north of Wild Cove (Plate 1). At this stage, the formation has not been subdivided into members, although this was one of the initial objectives of the study. However, there is some alternation of siltstone-dominated and sandstone-dominated sequences, which may be cyclic in nature.

Several white-weathering, massive units of pyroclastic and/or volcaniclastic origin occur within the formation and are best preserved in the Seal Cove section. These rocks contain broken feldspar crystals and rounded quartz eyes in a finer grained to amorphous matrix, and are locally heterogeneous. Baird (1958) and Currie (1997a) interpreted these to be intrusive sills, but others suggested a synsedimentary origin as airfall deposits or pyroclastic flows that entered coastal waters (Sandeman, 1985; Sandeman and Malpas, 1995; Kerr, 2013). Similar tuff-like rocks are interbedded on a fine scale within sandstones immediately below some of the thicker units (Plate 1), and all contacts examined to date are conformable, with no signs of contact metamorphism. It seems more likely that they are an integral part of the stratigraphic sequence and they provide potential marker horizons and boundaries for future member-level subdivisions of the formation.

In the uppermost part of the formation, several distinctive volcaniclastic units are best exposed around Simm's Beach, south of Brimstone Head, but can be traced eastward (Figure 4). These range in thickness from less than 1 m to several metres, and contain a wide variety of volcanic clasts and lesser sedimentary material. The degree of sorting varies and most outcrops contain scattered cobbles or boulders. The conglomerates are generally matrix-supported, and locally also contain broken sandstone beds, some of which are intact on a scale of metres (Plate 1). At Simm's Beach and near Wild Cove, these conglomeratic units are overlain by variable amounts of yellow to greenish sandstones and siltstones of volcaniclastic appearance and are interbedded with similar rocks. This mixed package is underlain by a thick (100 to 200 m at least) sequence of massive grey to beige crossbedded sandstones. This three-part marker sequence can be traced eastward through the town of Fogo and onto the hills south of Lane's Lookout (Figure 4). At Simm's Beach and elsewhere, thinner conglomeratic units are laterally discontinuous, but the thicker units provide valuable marker horizons and at least one can be traced across to the shore of Wild Cove (Figure 4).

In the Lion's Den area, well-bedded, massive, crossbedded sandstones are exposed to the north of the volcanic rocks of the Brimstone Head Formation (Figure 4), superficially suggesting a higher stratigraphic position. In the past, it was assumed that these were right-way-up, as are most parts of the Fogo Harbour Formation. Field work in 2013 included observations of truncation relationships in crossbedded units and other way-up structures (Plate 3), which indicate that these beds are actually upside-down. The full extent of structural inversion remains to be established, but this finding has important implications, as discussed subsequently.

Brimstone Head Formation

The Brimstone Head Formation is exposed around the town of Fogo and on the islands that protect Fogo Harbour (Figure 4). Although the general disposition of these rocks is readily established, understanding their features and origins is more difficult, as they are fine-grained, dark in colour and superficially appear glassy. Closer examination commonly reveals fiamme, *i.e.*, flattened fragments of pumice and other volcanic material (Plate 2). Tiny quartz phenocrysts are commonly present and more rarely there is evidence of complex flow-banding. The rocks were described as 'indurated tuffs' by Baird (1958), but they would be described today as rheoignimbrites. The attitudes defined by fiamme are highly variable, from subhorizontal to dips that locally exceed 75°. On the islands north of Fogo Harbour and adjacent shorelines, original fragmental textures are better preserved and fragments include flow-banded material (Plate 2). Diffuse grey, aphanitic, rhyolitic dykes are probably feeders to later eruptions. Wider (metre-scale) rectiplanar dykes of medium-grained grey porphyry cut multiple units (Plate 2) and should provide minimum ages for the formation. The thickness of the formation was previously suggested to be as much as 1000 m (Baird, 1958), but this assumes an attitude similar to that of the underlying Fogo Harbour Formation, which may not be correct. The overall map pattern of the formation (Figure 4) is more consistent with a gently dipping or subhorizontal attitude, in which the course of the basal contact is controlled by topography.

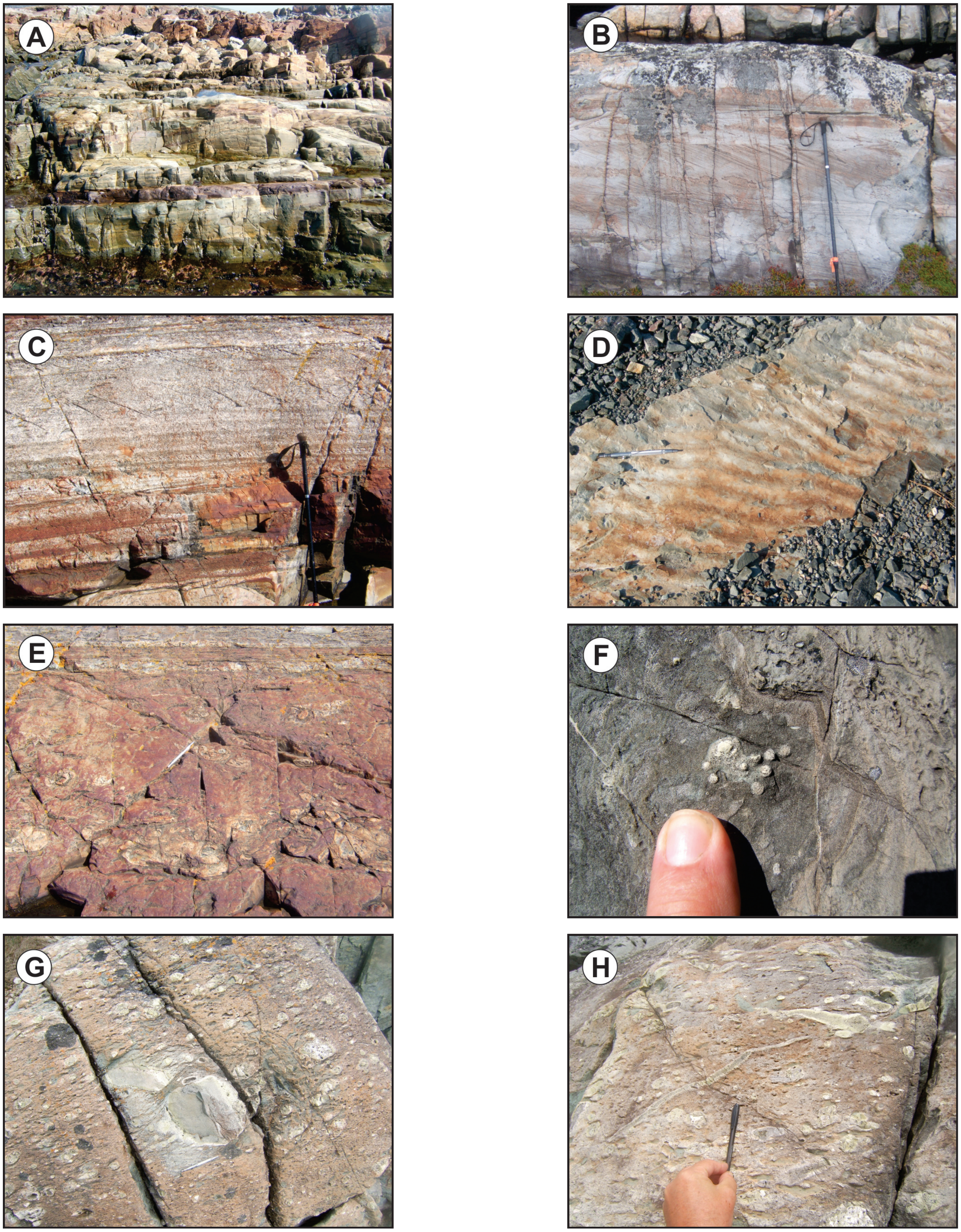

Plate 1. *Examples of rock types and features in the Fogo Harbour Formation. A) Typical well-bedded sandstones and siltstones, dipping away from the viewer; the red unit is one of very few such beds observed in the sequence, and is about 20 cm in thickness; B) Crossbedded sandstone unit; the hiking stick is about 1 m long; C) Well-bedded lower section of a white-weathering pyroclastic or volcaniclastic unit, suggesting synsedimentary origins; D) Well-preserved, centimetre-scale ripple marks on a bedding plane; E) Possible algal concretions (oncolites) in the lower section of a sandstone bed; F) Suspected organic remains, perhaps solitary corals or bryozoan features, in a grey, slightly calcareous sandstone unit; G) Distinctive matrix-supported volcaniclastic conglomerate unit, Simm's Beach area; note presence of larger cobbles and boulders; and H) Elongate clasts interpreted as broken sedimentary beds in conglomerate at Simm's Beach.*

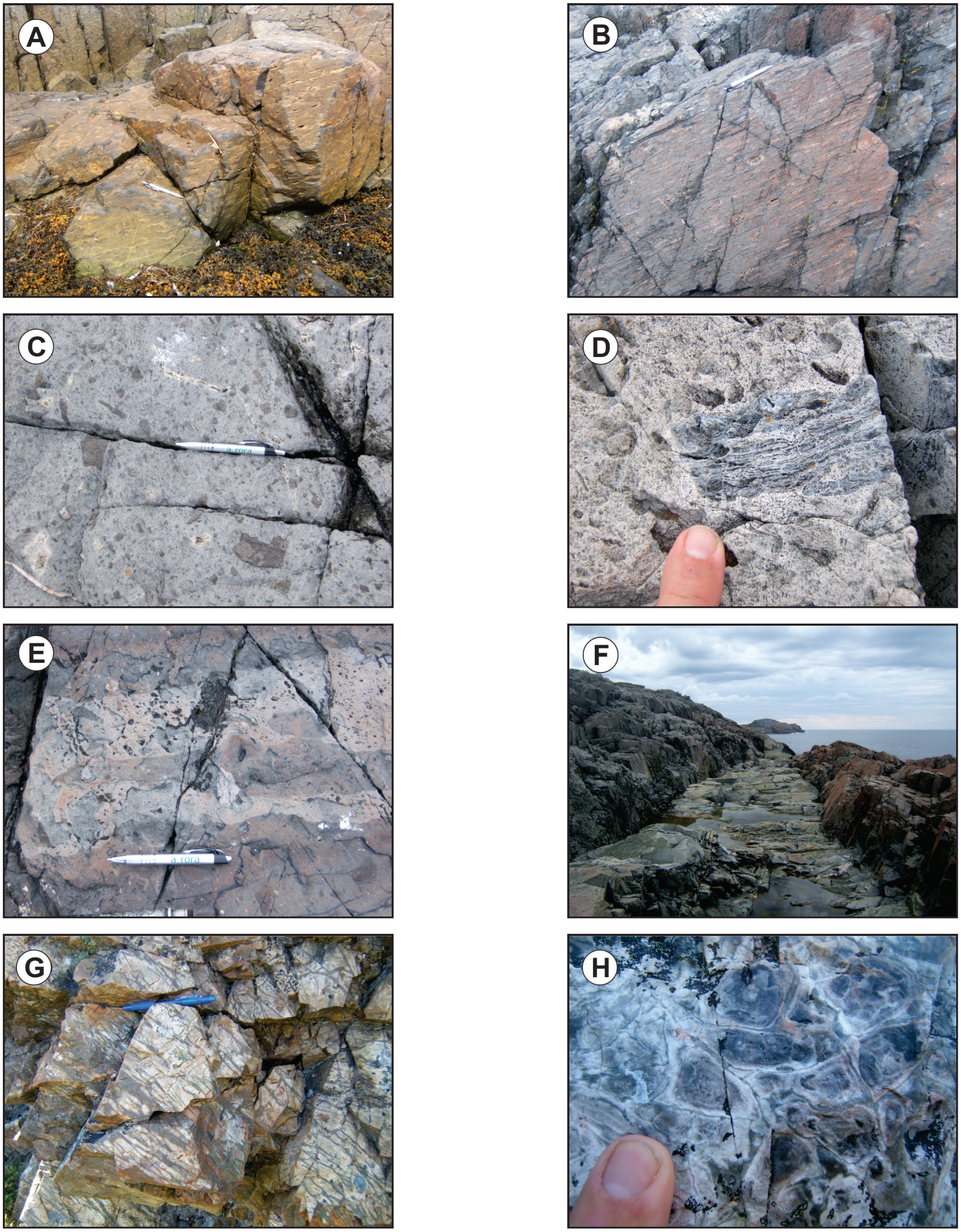

Plate 2. *Examples of rock types and features in the Brimstone Head Formation. A) Siliceous ignimbrites with gently dipping to flat-lying eutaxitic fabric and amygdules; B) Strong, dipping eutaxitic fabric defined by flattened pumice fragments (fiamme); C) Well-preserved, generally unwelded pyroclastic breccia containing pumice and rhyolite fragments; D) Detailed view of flow-banded grey rhyolite fragment in a pyroclastic breccia; E) Diffuse grey rhyolitic zone in breccia, possibly represents a synvolcanic dyke; note xenoliths of older volcanic rocks; F) Well-defined grey quartz-feldspar porphyry dyke cutting volcanic rocks; the dyke is about 3 m wide and can be traced for several hundred metres; G) Distinctive basal 'pseudorhyolite' unit of the Brimstone Head Formation; and H) Detailed view of the texture in the 'pseudorhyolite' unit, interpreted to record quenching-related fracturing and alteration.*

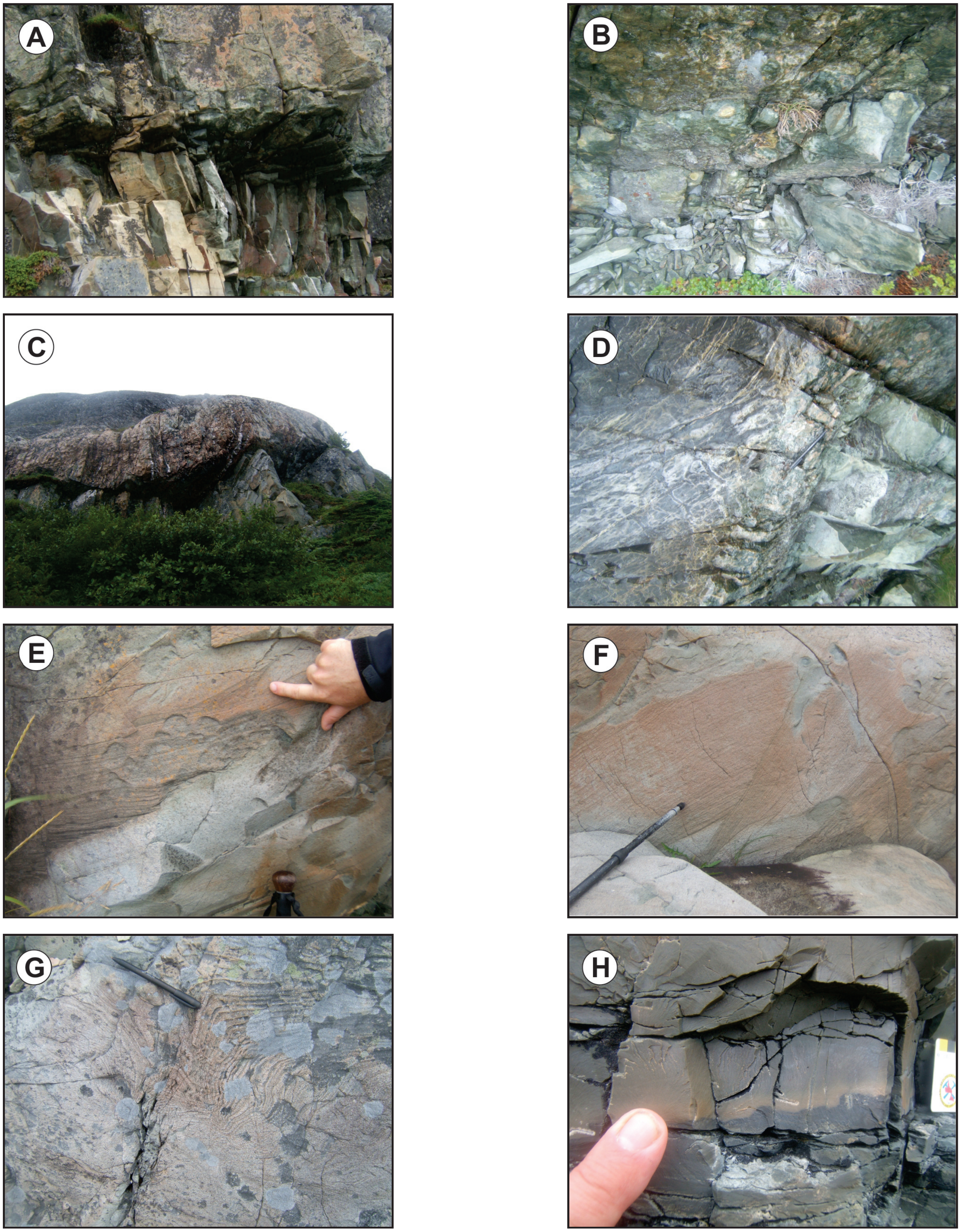

Plate 3. *Examples of rock types and relationships at or near the boundary between the Fogo Harbour and Brimstone Head formations. A) Sharp contact between greenish volcaniclastic sandstones (lower) and basal 'pseudorhyolite unit' (upper) near Simm's Beach; B) Contact between 'pseudorhyolite unit' (upper) and volcaniclastic conglomerate unit representing a lower stratigraphic unit in the Simm's Beach section; C) Formational contact south of Lane's Lookout, showing distinctive 'pseudorhyolite unit', which here contains numerous quartz veins; D) Steeply dipping contact between 'pseudorhyolite unit' (left) and poorly bedded sandstones (right), near Lion's Den; E) Upside-down sandstones in the Fogo Harbour Formation, showing two truncation surfaces; F) Detail of upside-down truncation surface in crossbedded sandstones; G) Convoluted bedding in sandstones, interpreted as an inverted fluid-escape structure; and H) Inverted grading and possible load casts in a cherty siltstone unit. Photos (E) to (H) all come from a small area on the northeast side of Lion's Den Cove.*

The formation has a distinctive basal unit that typically weathers beige or pink and is here termed the *pseudorhyolite*. This is a glassy rock that has an unusual texture (Plate 2) initially interpreted to record quenching-related perlitic fracturing and alteration of a rhyolite flow (Kerr, 2013). Subsequent petrographic work revealed broken crystals and other features that might be more consistent with a pyroclastic origin. Whatever its exact nature, this distinctive unit is invariably present at the basal contact and it assists in defining its position and three-dimensional geometry.

Granitoid Rocks

Granitic rocks in the south of the area (Hare Bay granite of Kerr, 2013) are dominated by fine- to medium-grained orange to red leucocratic granite that locally contains quartz and feldspar phenocrysts and is variably miarolitic. This unit was not examined in detail. Southeast of Seal Cove, the granite apparently truncates pyroclastic marker units within the Fogo Harbour Formation, implying that it is regionally discordant, even though observed contacts are locally conformable with bedding. Near the contacts, granitic dykes clearly cut across bedding on a local scale, but such dykes are rarely found in higher parts of the Fogo Harbour Formation. Currie (1997a, 2003) refers to an abundance of felsic dykes in the Brimstone Head Formation, but mapping reveals only diffuse grey rhyolitic dykes of probable synvolcanic timing and a few younger rectiplanar grey porphyry dykes. These dykes do not resemble the Hare Bay granite, nor do they resemble the abundant minor intrusions grouped with the Fogo Island Intrusion elsewhere, such as south of Island Harbour (Figure 2).

Peculiar and distinctive siliceous rocks that have devitrification textures and possible spherulites occur close to the contact between the Hare Bay granite and the Fogo Harbour Formation southwest of Wild Cove (Figure 4). The upper (northern) contact of the thickest unit dips beneath the sandstones. The southern contact against the granite appears to be sharp, although the sense of intrusion is not entirely clear. In the maps of Baird (1958) and Currie (1997a) these rocks are grouped with the Hare Bay granite, but they are here assigned to a separate unit, as suggested also by Sandeman (1985). This could be a subvolcanic intrusive unit linked to the Brimstone Head Formation, or a thick pyroclastic unit within the Fogo Harbour Formation. More work is required to better understand this interesting rock type and its contact relationships.

The Fogo Harbour – Brimstone Head Formational Boundary

The formational boundary exposed in the north of the area was a major focus for this study. The best exposures are south of Brimstone Head, in the vicinity of Simm's Beach, and in the area south of Lane's Lookout (Figure 4). New information from detailed work in these two areas and around Lion's Den indicates that this boundary is not a simple, planar, conformable contact. These new data are most consistent with interpretation of the contact as a cryptic angular unconformity.

At Simm's Beach, the 1- to 2-m-thick basal pseudorhyolite unit of the Brimstone Head Formation dips at roughly the same angle as the underlying bedded sedimentary rocks and the contact superficially appears as an abrupt conformable transition. This locality likely influenced the interpretation of Baird (1958). As noted previously, three discrete units of sedimentary rocks sit beneath the basal contact of the Brimstone Head Formation in this area. Detailed examination shows that yellow to green arenites and distinctive matrix-supported volcaniclastic conglomerates actually strike obliquely into the contact with the Brimstone Head Formation and that the latter sits upon different rock types in different areas (Plate 3). To date, the volcanic rocks have not been observed to sit upon the lowermost crossbedded sandstone package at Brimstone Head, but they are in contact elsewhere, such as at Lion's Den (*see* below). It could be argued that later faulting might have modified an originally conformable relationship south of Brimstone Head, but there is no evidence for motion on the contact itself.

South of Lane's Lookout, the Brimstone Head formation generally sits upon siltstones and sandstones, and its base is similarly marked by the pseudorhyolite unit. The topographic elevation of the contact varies widely, and its map pattern is very complex (Figure 4; Plate 3). The sedimentary rocks beneath the basal contact are generally poorly laminated, but in one area there appears to be an angular discordance of some 10–15°. Several tongues and outliers of volcanic rocks appear to form erosional remnants sitting upon dipping sandstones and siltstones to the south of the main belt of volcanic outcrops. In places, the basal contact of the Brimstone Head Formation is almost subhorizontal, but elsewhere it appears to be steep, and dips of up to 65° are recorded locally near Lion's Den. Most importantly, in the area around Lion's Den, new observations of sedimentary structures indicate that the sandstones are upside-down (Plate 3), but they still sit structurally beneath the ignimbrites and rhyolites, which form high rugged hills to the south. The volcanic rocks must be right-way-up, because the distinctive pseudorhyolite unit sits at their base, in its expected position.

The new observations suggest that there is an important time-gap between the Fogo Harbour and Brimstone Head formations, and that the latter at least locally sits subhorizontally upon the older sedimentary rocks. The contact itself must have some marked topography, based on elevation differences. This spatial evidence points, at the very least, to a significant disconformity. However, the recognition of structural inversion *beneath* the basal contact of the Brimstone Head Formation at Lion's Den indicates that the contact is more likely a significant angular unconformity. In essence, the Fogo Harbour Formation records deformational events and erosion that must *predate* the extrusion and deposition of the Brimstone Head Formation.

Structural Patterns – Preliminary Data

Field work completed since 2012 indicates that there are unrecognized structural problems in this area and possibly elsewhere on Fogo Island. The new recognition that parts of the Fogo Harbour Formation are overturned is just the latest unexpected chapter in an incomplete story, but preliminary discussion is merited here.

First, it appears that much of the Fogo Harbour Formation *is* a homoclinal, northwest-dipping, upright sequence, as initially proposed (Baird, 1958). To date, no signs of structural breaks or folds have been recognized in the section at Seal Cove, south of Brimstone Head (Figure 4). However, the north side of Brimstone Head is in part defined by a significant fault zone that was mapped by Currie (1997a) but not discussed. Baird (1958) also indicates some tight folds on the coast in this area, but these were not shown by Currie (1997a). This fault zone juxtaposes massive ignimbrites of the Brimstone Head Formation with schistose sedimentary rocks in which bedding is mostly eradicated. The deformed sedimentary rocks include schistose, flattened conglomerates and are probably the tectonized equivalents of the uppermost Fogo Harbour Formation (Plate 3). The attitude, associated penetrative deformation and inferred motion sense indicate that this structure is an important reverse or thrust fault that *postdates* the extrusion of the Brimstone Head Formation. Open to tight folds of the sedimentary rocks immediately north of Brimstone Head could be kinematically related to this fault zone, but could also be earlier structures (*see* below). A second zone of strong deformation with a similar orientation is present along the south shore of Back Cove (Figure 4) and may be a related structure, located structurally above the folds. The southern outcrop belt of the Brimstone Head Formation is not present on the east side of Fogo Harbour (Figure 4), which implies that it is excised by the fault zone. However, the position of this fault zone in the east of the area remains uncertain.

Very few folds were defined within the Fogo Harbour Formation by previous work, aside from those noted north of Brimstone Head by Baird (1958). The siliciclastic rocks are monotonous, so defining minor structures is not easy. The recognition of structural inversion in the crossbedded sandstones at Lion's Den provides strong evidence for tight or even isoclinal recumbent folding within the Fogo Harbour Formation, at least on a local scale. This style of folding is normally associated with the development of thrust faults, but no major structures of this type have yet been firmly identified. Variations in dip directions suggest that several small open folds exist south of Lane's Lookout, where sandstones are locally flat-lying or even south-dipping. In the narrow 'tongue' of sedimentary rocks that protrudes northward into the Brimstone Head Formation near here, metre-scale folds cannot be traced into the overlying volcanic rocks. This might reflect the differences in ductility and inherent 'foldability' between the two formations, but it is equally consistent with the idea that some folding predates extrusion of the Brimstone Head Formation.

In summary, there is much yet to be learned about the detailed structural patterns in this area, but preliminary observations indicate at least two periods of deformation. The oldest event affected the Fogo Harbour Formation and at least locally involved recumbent folding and perhaps thrusting. The overturning of sandstones near Lion's Den provides strong evidence for this style of deformation. These events predate the extrusion and/or deposition of the Brimstone Head Formation. The second (younger) event caused penetrative deformation in the Fogo Harbour Formation and juxtaposed it with the Brimstone Head Formation, so this must postdate development of the latter. It is more difficult to link individual folds to one or the other of these events, but there *must* have been some folding of the sedimentary rocks prior to the extrusion of the Brimstone Head Formation.

The intrusive relationship between dykes of the Hare Bay granite and sedimentary rocks of the Fogo Harbour Formation suggests that emplacement of the Fogo Island intrusion postdates both lithification and deformation of these sedimentary rocks. Kerr (2011, 2013) describes spectacular intrusion breccias north of Island Harbour, in which granites dissect tightly folded sedimentary rocks, but the structures were viewed as soft-sediment deformation. However, in the light of inferences from this study, this conclusion may now need some reconsideration; is it possible that some of these fold structures are of tectonic origin?

DISCUSSION

New detailed mapping in a relatively small area of Fogo Island provides insights that were not apparent on the more regional scale of previous investigations, which leads to reassessment of previous ideas. The information remains incomplete, as the project was brief in duration, but there is much to consider in terms of future work. The main conclusions are as follows:

1. The Fogo Harbour Formation seems to be a simple homoclinal upright sequence in much of its outcrop area but it has significant structural complexity in the north, where it is in contact with the younger Brimstone Head Formation. In at least one area, the sedimentary rocks are upside-down, indicating strong deformation, and recumbent folding.

2. The contact between the Fogo Harbour Formation and the Brimstone Head Formation is not a conformable transition but is more likely a cryptic angular unconformity. The most persuasive evidence for a significant time gap is the localized structural inversion of the Fogo Harbour Formation beneath the contact.

3. Assumptions about the attitude of the Brimstone Head Formation need reassessment. The patterns defined by fiamme in volcanic units do not necessarily indicate the paleohorizontal, and the outcrop pattern of volcanic rocks is more consistent with a gently dipping or sub-horizontal attitude. However, the contact between the two formations appears to have a complex three-dimensional topography and it is locally steep in attitude.

4. Both formations, and their mutual contact, are affected by later penetrative deformation in the area around Brimstone Head, and the sedimentary rocks are affected by folding that could also be later than both formations, although this is less certain. Folding following development of the Brimstone Head Formation provides one possible explanation for the topographic complexity of its basal contact.

5. Field relationships indicate that the Fogo Island intrusion is younger than the Fogo Harbour Formation and possibly also younger than its folding. However, there is no evidence that the granites cut the volcanic rocks of the Brimstone Head Formation, suggesting that the latter could be an extrusive equivalent, or a younger and genetically unrelated volcanic sequence.

These conclusions are presently based entirely upon field relationships, because there are essentially no geochronological data from any of these rocks, with the exception of results presented by Aydin (1995) for granite near Tilting. There is now a very strong case for geochronological investigations on Fogo Island and numerous candidate units could yield valuable age constraints. These are:

1. Synsedimentary volcanogenic units in the Fogo Harbour Formation. These are likely records of distant but massive eruptions; U–Pb ages from these rocks would directly constrain the age of the formation and perhaps also the duration of sedimentation if several such units could be dated with sufficient precision.

2. The Brimstone Head Formation. In conjunction with ages from the highest volcanogenic units in the Fogo Harbour Formation, U–Pb dates from these rocks would constrain the time gap represented by the postulated unconformity and should constrain the timing of deformation in the Fogo Harbour Formation. Equally, such data would provide a maximum age for later deformation that affected the Brimstone Head Formation.

3. The Fogo Island intrusion. The age range represented by this large and complex body remains undefined, and is obviously important in understanding the timing of these events, especially if it can be shown conclusively that it postdates early deformation of the Fogo Harbour Formation. Such information would also clarify its relationship with the Brimstone Head Formation, if the latter could be dated.

4. Volcanic rocks of Change Islands and the Little Fogo Islands. No attempt has yet been made to date volcanic rocks on Change Islands that appear to sit unconformably upon the folded and cleaved rocks of the Badger Group. As discussed below, the correlation of the volcanic rocks on the Little Fogo Islands may be important in understanding the regional structural configuration.

CONCLUDING SPECULATIONS

The key finding of new detailed work is that there could be a significant and previously unrecognized angular unconformity on Fogo Island. The final section of the paper discusses the potential implications of this conclusion.

If existing regional stratigraphic assignments are accepted at face value, the proposed unconformity sits *within* the Silurian Botwood Group, which may require that volcanic rocks of the Brimstone Head Formation now be reassigned. If this interpretation is correct, there are two unconformities in the Fogo Island – Change Islands area, because the base of the Botwood Group upon the Badger Group is itself an angular unconformity (Currie, 1997a, b). This would indicate that the Silurian Salinic Orogeny was two-stage, and that the Botwood Group (minus the Brimstone Head Formation) represents the intervening time period. All of these units were then subsequently affected by the later deformation recorded on the north side of Brimstone Head. The previous interpretation is shown schematically in Figure 5A and the new interpretation is shown in Figure 5B. Note that the Little Fogo Islands are viewed as equivalent to the Lawrenceton Formation in Figure 5B, rather than equivalent to the Brimstone Head Formation, with the implication that older rocks were thrust southward over the Fogo Har-

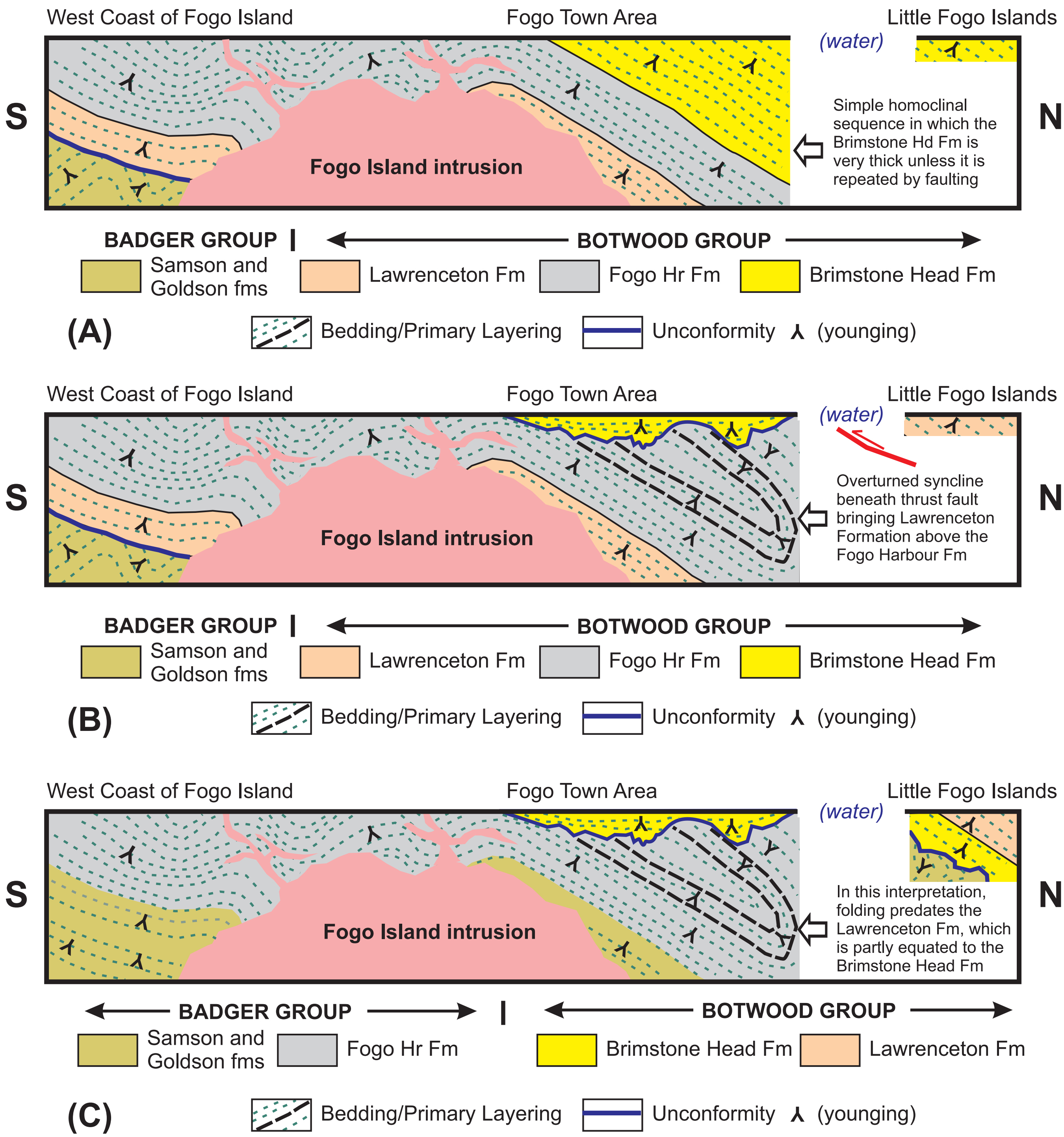

Figure 5. *Schematic cross-sections indicating possible interpretations of regional relationships in the Fogo Island – Change Islands area. A) Previous interpretation, in which the basal formation of the Botwood Group (Lawrenceton Formation) sits unconformably on the Badger Group and the western Fogo Island Botwood Group sequence is continuous; B) Revised interpretation in which the base of the Brimstone Head Formation represents a second angular unconformity above folded rocks of the Fogo Harbour Formation; and C) An alternative interpretation in which the sedimentary rocks of the Fogo Harbour Formation are reassigned as part of the older Badger Group.* See *text for discussion.*

bour Formation. This provides a possible explanation for the overturning of sedimentary rocks at Lion's Den, *i.e.*, they sit within the footwall syncline of a regional thrust. This suggestion is also broadly consistent with regional models proposed some years ago by Karlstrom *et al.* (1982).

However, there is another possibility that cannot be dismissed, as shown schematically in Figure 5C. The Fogo Harbour Formation occurs only on islands and it is physically isolated from all other rocks assigned to the Botwood Group, except the Brimstone Head Formation. Its contacts with the Lawrenceton Formation on the Change Islands are inferred to be faults (Currie, 1997b) and there are no contacts between it and the Badger Group. Thus, the assignment of these rocks to the Botwood Group is by inference and may be incorrect. It remains possible that the Fogo Harbour Formation is actually part of the Badger Group, which more obviously exhibits strong deformation similar to that implied here for northwestern Fogo Island. If this interpretation is correct, there need only be one unconformity and the Brimstone Head Formation could be a time-equivalent of the Lawrenceton Formation. The potential for constraining the timing of orogenic events remains just as strong if this interpretation is correct.

In conclusion, there is much to be learned on Fogo Island and adjacent regions beyond the intricacies of the composite bimodal magma chamber documented by previous work (Currie, 2003; Kerr, 2011, 2013). It is perhaps fitting that Brimstone Head, which already holds some mythical status as one of the proposed corners of the Flat Earth, and was immortalized in the poetry of Al Pittman, might ultimately prove also to be an important locality in understanding Appalachian tectonics.

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