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NEW U-Pb DATES FROM SILURIAN ROCKS ON FOGO ISLAND: PRELIMINARY STRATIGRAPHIC AND TECTONIC IMPLICATIONS

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ABSTRACT

This short article reports on two chemical abrasion (CA-) ID-TIMS U–Pb zircon age determinations from volcanic and volcaniclastic rocks on Fogo Island, northeast Newfoundland. The study was initiated to test new ideas about stratigraphic and structural relationships based upon field mapping, and to ascertain the age of the Brimstone Head Formation, which is one of the youngest volcanic units recognized in east-central Newfoundland. A tuff horizon in the immediately underlying sedimentary Fogo Harbour Formation was also targeted. Although a precise age was obtained for a Brimstone Head Formation rhyolite, results for the tuff are complicated by clastic detritus. Nevertheless, the data provide useful preliminary constraints.

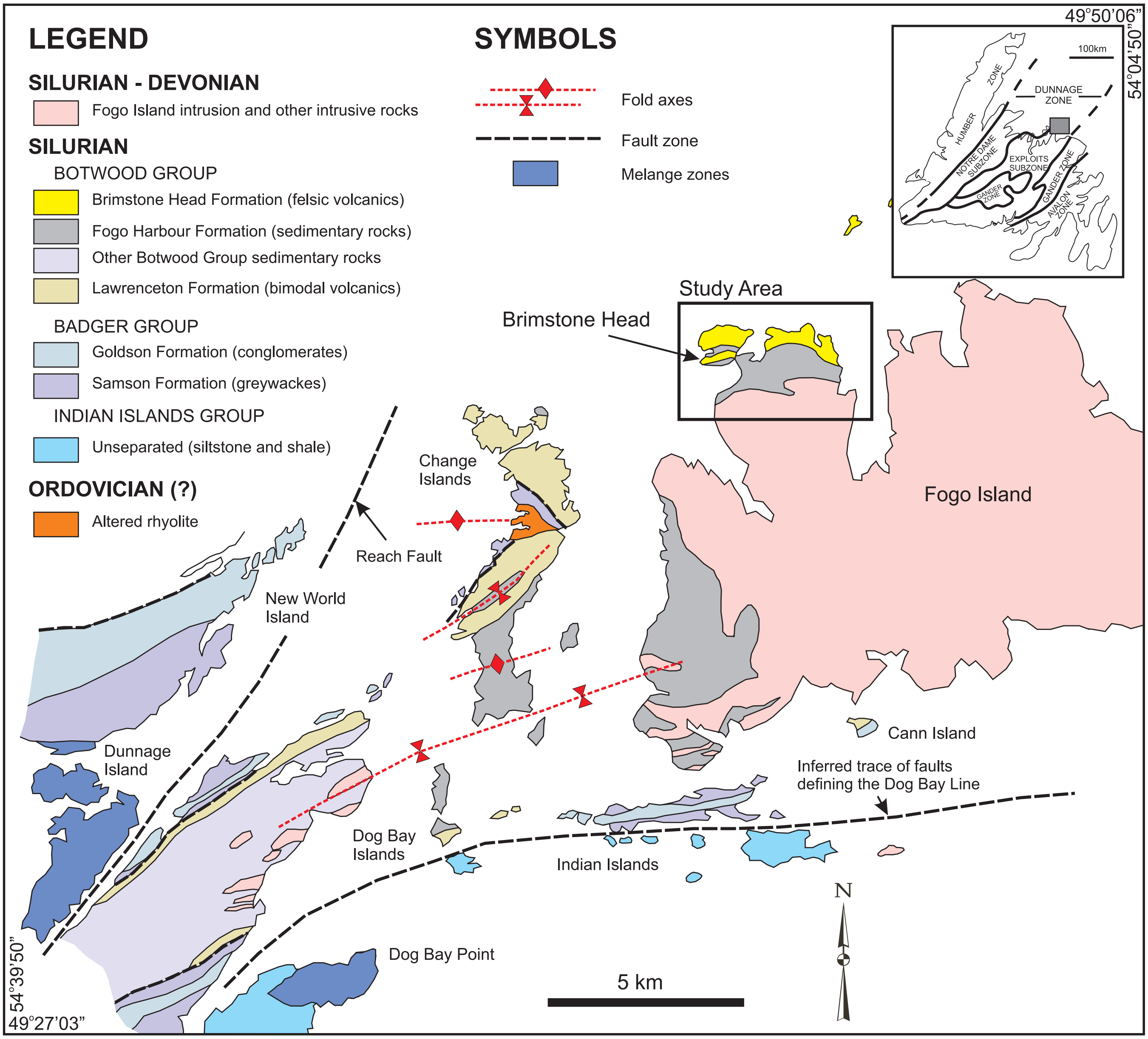
The basal rhyolitic unit of the Brimstone Head Formation, near the town of Fogo, yielded a relatively simple concordant U–Pb zircon age of 421.2 ± 0.6 Ma. This resembles ages from other Silurian volcanic rocks in eastern Notre Dame Bay, and is identical, within uncertainty, to a previously determined U–Pb zircon age from granite in eastern Fogo Island. The result lends support to earlier suggestions that the Brimstone Head Formation is at least, partially, an extrusive equivalent of the Fogo Island intrusion. It also indicates that penetrative deformation of the Brimstone Head Formation is latest Silurian or younger, likely recording Acadian events. A felsic tuff unit near the top of the Fogo Harbour Formation, which sits beneath the Brimstone Head Formation, yielded a mixed zircon population that includes Precambrian grains, implying that the rock includes a detrital component. The youngest analyzed zircon grains have a concordant U–Pb age of about 440 Ma, some 20 my older than the Brimstone Head Formation. This potential time gap is consistent with suggestions of a cryptic angular unconformity between the two formations, but the U–Pb data alone cannot prove this interpretation. Further investigative work, canvassing larger populations using microbeam geochronological techniques, is needed to better characterize the zircon age modes in the Fogo Harbour Formation tuff, and ascertain if there is indeed a discrete ca. *440 Ma (or younger) population of magmatic origin.*

INTRODUCTION

Fogo Island, located off the northeast coast of Newfoundland, is dominated by Silurian plutonic rocks that form a composite bimodal batholith of considerable complexity (Fogo Island intrusion; Baird, 1958; Currie, 2003; Kerr, 2013). Older sedimentary and volcanic rocks of presumed Silurian age are well exposed in coastal sections in western Fogo Island (Figures 1 and 2). The relationships between these formations, and their collective relationships to adjacent plutonic rocks, are discussed in two earlier reports (Kerr, 2013; Donaldson *et al.*, 2015). Western Fogo Island is also the site of ongoing undergraduate mapping projects sponsored by the universities of Cambridge and Oxford, in the UK, with in-kind support from the Shorefast Foundation. This short paper summarizes U–Pb zircon geochronological studies intended to test ideas discussed by Donaldson *et al.* (2015) following their mapping project in 2013. The new results are intriguing, but retain some ambiguity; they are consistent with but not fully diagnostic of a revised model for local stratigraphy. More work, including microdomain geochronology using laser-ablation inductively-coupled mass spectrometry (LA-ICPMS), will be aimed at resolving the remaining questions.

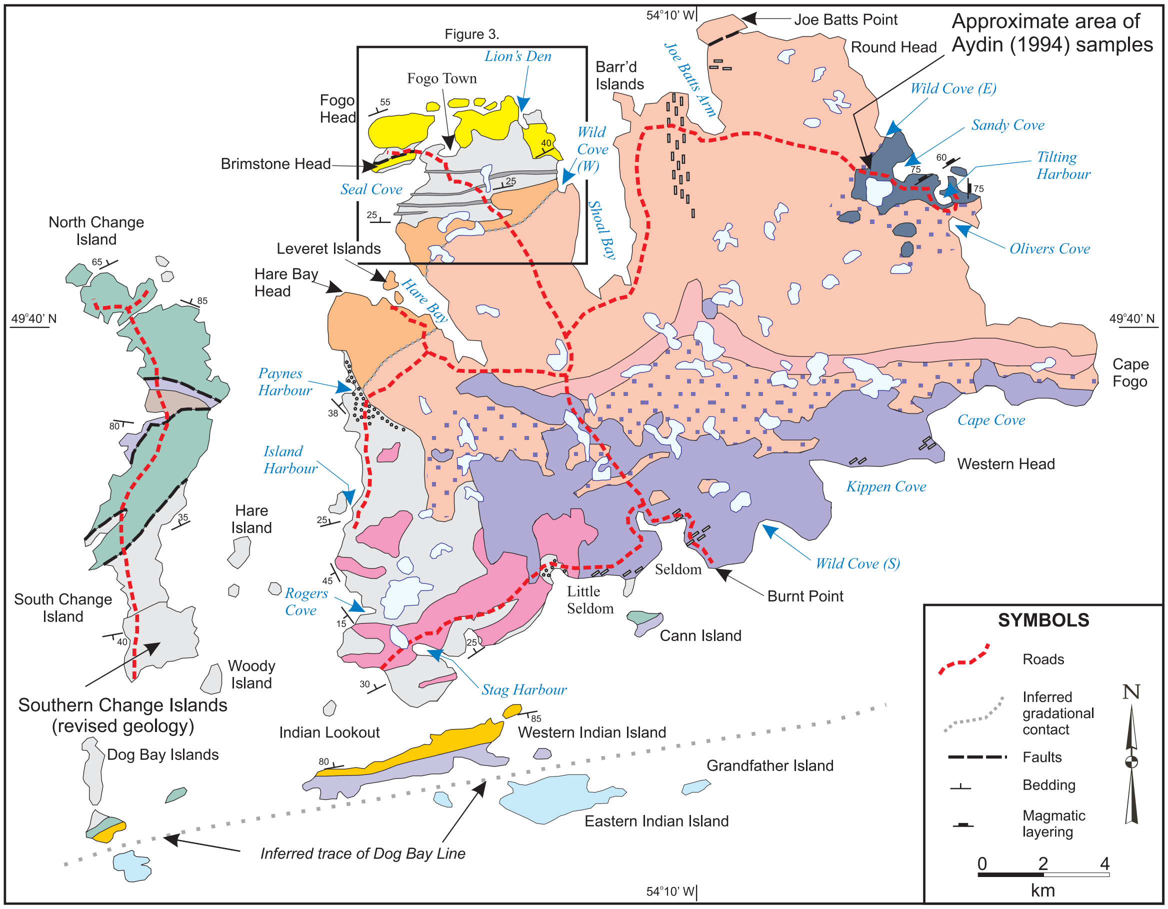
REGIONAL SETTING AND LOCAL GEOLOGICAL FRAMEWORK

Fogo Island is located in the Exploits Subzone of the Dunnage Zone (Figure 1, inset), which is part of the southeast (Gondwanan) margin of the late Precambrian to early Paleozoic Iapetus Ocean (Williams *et al.*, 1988). Northeast-



Figue 1. *Regional geological map of eastern Notre Dame Bay, modified after Williams* et al.*, 1995a, b, for use by Donaldson* et al. *(2015).*

ern Newfoundland is dominated by Late Ordovician and Silurian sedimentary and volcanic rocks, which are intruded by Silurian to Devonian plutonic rocks. Volcanic and volcaniclastic rocks interpreted as Cambrian–Ordovician arc sequences pass upward into mid-Ordovician black shales, which are in turn overlain by a shallowing-upward sequence of Late Ordovician to Early Silurian marine sedimentary rocks known as the Badger Group (Williams, 1972; Williams *et al.*, 1995a). The Badger Group is overlain by a younger sequence including subaerial volcanic rocks, themselves overlain by largely terrestrial sedimentary rocks, collectively termed the Botwood Group (Williams, 1972; Williams *et al.*, 1995b). The relationship between the Badger Group and the Botwood Group is interpreted as a broadly conformable transition (Williams, 1995a, b) or an angular unconformity (Currie, 1997a, b; van Staal *et al.*, 2014). On Change Islands, located just west of Fogo Island (Figures 1 and 2), steeply dipping greywackes of the Badger Group (Samson Formation) are locally overlain by subhorizontal pyroclastic breccias of the Botwood Group (Lawrenceton Formation), but minor faults obscure many contacts; the locality is interpreted as an unconformity (Currie, 1997b). Regional geochronological data are sparse; the Badger Group is considered to be older than 433 Ma on the basis of paleontological evidence and the youngest detrital zircons that it contains (Pollock *et al.*, 2007; Waldron *et al.*, 2012).



LEGEND

INDIAN ISLANDS GROUP (Silurian)

- 🟦 Siltstone and limestone

BOTWOOD GROUP (Silurian)

- 🟨 BRIMSTONE HEAD FORMATION
  Felsic volcanic and pyroclastic rocks

FOGO HARBOUR FORMATION

- ▩ Felsic tuff units
- ⬜ Sandstone, siltstone and quartzite

- 🟩 LAWRENCETON FORMATION
  Mafic and felsic volcanic rocks, minor sandstone

BADGER GROUP (Ordovician–Silurian)

- 🟧 GOLDSON FORMATION
  Conglomerate and sandstone
- 🟪 SANSOME FORMATION
  Greywacke and shale

EXPLOITS GROUP (Ordovician)

- 🟫 BAYTONA FORMATION
  Altered rhyolite

FOGO ISLAND INTRUSION (Silurian or Devonian)

- ⁘ INTRUSION BRECCIAS
  Sedimentary rocks pervasively intruded by mafic or granitic rocks near contact zones
- ▭ ZONES RICH IN METASEDIMENTARY XENOLITHS
  Blocks and fragments within both mafic and granitoid rocks
- ▨ OTHER FINE-GRAINED GRANITES
  Felsite unit indicated by Currie (1997a)
- 🟥 ROGERS COVE GRANITE
  Fine-grained granite, felsite and porphyry
- 🟧 HARE BAY GRANITE
  Leucocratic equigranular granite
- ▨ SHOAL BAY GRANITE
  Homogeneous monzogranite and granite
- ▦ BOUNDARY ZONE OF MAFIC AND GRANITOID ROCKS
  Mixed assemblage of granite and mafic sheets and zones; abundant interaction and mingling textures
- 🟦 TILTING LAYERED COMPLEX
  Layered gabbro and mafic cumulate rocks
- 🟪 SELDOM GABBRO
  Weakly layered gabbro and diorite, cut by diabase dykes

Figure 2. *Geological map of Fogo Island and Change Islands, modified after Kerr (2013) with many aspects of the geology derived from Baird (1958) and Currie (1997a, b), coupled with unpublished work.*

Volcanic rocks in the Lawrenceton Formation are dated elsewhere in the Notre Dame Bay area at 421 Ma and 418 Ma (van Staal *et al.*, 2014), and this age range is consistent with results from Silurian volcanic rocks elsewhere in the Exploits Subzone (Dunning *et al.*, 1990; McNicoll *et al.*, 2008). Donaldson *et al.* (2015) provide a more detailed review of regional relationships and associated problems.

On Fogo Island, sedimentary and volcanic rocks were at first assigned to the Fogo Group by Baird (1958), and considered to be Ordovician. Williams (1972) recognized that the volcanic rocks were subaerial rather than submarine, and reassigned all these rocks to his Botwood Group. The original formation-level names were retained for the sedimentary rocks (Fogo Harbour Formation) and the volcanic rocks (Brimstone Head Formation) restricted to Fogo Island. The sedimentary rocks were considered to correlate with those elsewhere in the Botwood Group, which are known as the Wigwam Formation (Williams, 1972). However, in contrast to the interpretation of Williams (*op.cit.*), the Wigwam Formation is dominated by red terrestrial clastic rocks, whereas the Fogo Harbour Formation seems to be of largely marine character. Also, sedimentary rocks elsewhere in the Botwood Group sit stratigraphically *above* the volcanic rocks of the Lawrenceton Formation, whereas the Fogo Harbour Formation sits *below* the volcanic rocks of the Brimstone Head Formation. The relationships suggested to Williams *et al*. (1995b) that the Brimstone Head Formation might include some of the youngest volcanic rocks in northeastern Newfoundland.

The Fogo Harbour and Brimstone Head formations are restricted to Fogo and Change islands. Sedimentary rocks on Change Islands (Figures 1 and 2) were initially placed in a separate formation by Baird (1958) but were correlated with the Fogo Harbour Formation by Currie (1997a, b), who also assigned a small area in southernmost Change Islands to the Brimstone Head Formation. Field work by the second author and by J.W. Botsford (personal communication, 2015) supports the correlation of the sedimentary rocks, but also suggests that these extend into and dominate southernmost Change Islands. The relationships of the Fogo Harbour and Brimstone Head formations to other parts of the Botwood Group, or to the older Badger Group, remain undefined and the contact between the Fogo Harbour Formation and the Brimstone Head Formation is exposed only in northwestern Fogo Island (Figures 1 and 2).

STRATIGRAPHIC PROBLEMS ON FOGO ISLAND

Since the mapping of Baird (1958), the Fogo Harbour and Brimstone Head formations have been viewed as a continuous conformable sequence that, aside from some local complications, dips and youngs consistently to the northwest. Prominent felsic units in the Fogo Harbour Formation were interpreted as concordant sills by Baird (1958) and Currie (1997a), but Sandeman (1985), Sandeman and Malpas (1995) and Kerr (2013) considered them to be conformable tuff horizons derived from major eruptive events. Coarse-grained volcaniclastic units near the top of the Fogo Harbour Formation were traditionally interpreted as part of a transition into the more ‘proximal’ volcanic centre represented by the Brimstone Head Formation. On the basis of geochemistry, the Brimstone Head Formation is interpreted as the extrusive equivalent of granitoid rocks elsewhere on Fogo Island (Sandeman and Malpas, 1995; Currie, 1997a, 2003), but this remains untested by geochronology. The Fogo Harbour Formation is cut by numerous mafic to felsic dykes that are generally correlated with the Fogo Island intrusion, but dykes of this type appear to be rare or absent in the Brimstone Head Formation (Donaldson *et al.*, 2015). There is a dearth of geochronological data from Fogo Island, aside from two ages from plutonic rocks near Sandy Cove, close to the community of Tilting (Figure 2). In this area, Aydin (1995) obtained an age of 420 ± 2 Ma from a ‘typical’ granite, and an age of 408 ± 2 Ma from a crosscutting diorite. Zircons from the granite are mostly older inherited grains, to the extent that the Silurian age is defined by only one fraction, and the exact locational context of the younger sample remains unclear. Kerr (2013) suggested that the younger age likely represents a minor intrusion that cuts both mafic and granitoid rocks of the Fogo Island intrusion; this is consistent with field evidence in the area west of Tilting (Kerr, 2013).

Kerr (2013) emphasized the importance of northwestern Fogo Island in understanding the regional stratigraphy and structure, and alluded to the possibility of a time gap between the Fogo Harbour and Brimstone Head formations. This suspicion was based on perceived inconsistencies in their contact relationships, and also on recognition that deformation in the Fogo Harbour Formation was more widespread and locally more intense than previously indicated. Detailed mapping of this area by Donaldson *et al.* (2015) argued against a conformable transition between the two formations, and they postulated that the base of the Brimstone Head Formation might be a cryptic angular unconformity. The key observations of Donaldson *et al.* (2015) are as follows:

1. The base of the Brimstone Head Formation is marked by a distinctive unit of quenched rhyolite or crystal tuff, which defines a complex map pattern consistent with a gently dipping to locally subhorizontal basal contact in many, but not all, areas.

2. The basal unit of the Brimstone Head Formation sits upon a number of different lithostratigraphic units interpreted to represent members of the uppermost Fogo Harbour Formation.

3. Sedimentary rocks belonging to the Fogo Harbour Formation are locally upside-down, and young away from their contact with the overlying Brimstone Head Formation, but the latter is upright, and its base is marked by the distinctive rhyolite unit.

The local structural inversion of the sedimentary rocks implies that the Fogo Harbour Formation underwent recumbent folding *prior to* the extrusion of the Brimstone Head Formation (Donaldson *et al.*, 2015). However, the Brimstone Head Formation is itself locally affected by penetrative deformation associated with high-angle reverse faults, indicating an important younger episode of deformation. Donaldson *et al.* (2015) outlined two models for testing, as discussed below.

The first interpretation is that the Fogo Harbour–Brimstone Head formational contact represents an unrecognized unconformity *within* the Botwood Group, situated higher in its stratigraphy than the basal unconformity documented on Change Islands (*see* above). In this interpretation, there would be two discrete Silurian or younger unconformities in this area. The second interpretation is that the Fogo Harbour Formation is *not* part of the Botwood Group, but is instead an older sequence, perhaps in part equivalent to the Badger Group. In this interpretation, the postulated unconformity on Fogo Island could be time-equivalent to the one on Change Islands. The present study was initiated in 2014 to test these two models and further explore their stratigraphic and tectonic implications.

GEOLOGY, ROCK TYPES AND SAMPLE LOCATIONS

This investigation has but one simple objective – to test the suggested interpretations of regional stratigraphy by dating rocks from the uppermost Fogo Harbour Formation and the lowermost Brimstone Head Formation. Donaldson *et al.* (2015) describe the local stratigraphy and illustrate both formations in detail, but the following account is limited to the units that were sampled for geochronology.

The Fogo Harbour Formation is best exposed south and west of the town of Fogo, where it consists of a north-dipping homoclinal sequence dominated by shallow-marine sandstones and siltstones, known as the Seal Cove section. This region appears to be simple from a structural perspective, but the area around the town of Fogo is significantly more complex, and contains several folds and faults (Figure 3). The Seal Cove section is punctuated by several white-weathering felsic units that were interpreted by Baird (1958) and Currie (1997a) as concordant intrusive sheets, perhaps related to the Fogo Island intrusion. However, Sandeman (1985) and Sandeman and Malpas (1995) suggested that these were conformable tuff units, and subsequent detailed examination (Kerr, 2013; Donaldson *et al.*, 2015) strongly supports this interpretation. These metre-scale tuff units, and thinner tuffaceous units that are now recognized elsewhere in this section, are interpreted to record various eruptive events that occurred during deposition of the Fogo Harbour Formation sediments. They are thus viable targets for geochronology, although it was deemed likely during sampling that detrital components could also be mixed with any magmatic zircon population present. Sample AKZ-14-01 was collected from an outcrop adjacent to the disused municipal dump site south of the town of Fogo, from a tuff unit that is approximately 2 m in thickness. This is one of the youngest fine-grained tuff units within the homoclinal part of the formation. The surrounding sedimentary rocks are variably crossbedded sandstones and siltstones, locally showing ripple marks. The sample location is at UTM coordinate 696215E/5509685N (NAD 1927 datum).

The Brimstone Head Formation underlies most of the hills around the town of Fogo, and is dominated by massive ignimbrites that show variable amounts of welding and contain strong eutaxitic fabrics that have variable orientations. The original textures are only locally well-preserved, but these suggest that many rocks are of fragmental pyroclastic origin; volcanic units of truly extrusive origin are difficult to verify in the field. Diffuse, grey, crosscutting zones that lack fragmental textures or eutaxitic fabrics are interpreted as synvolcanic dykes. The formation has a distinctive buff- or pink-weathering basal unit that has a brecciated texture suggestive of a rapidly-quenched rhyolite or ash-flow tuff; this was termed the *pseudorhyolite* by Donaldson *et al.* (2015). This unit is almost always present immediately above the Fogo Harbour–Brimstone Head formational contact. Sample AKZ-14-02 was collected on the south side of Brimstone Head, where the basal unit of the Brimstone Head Formation is in direct contact with greenish, poorly bedded volcaniclastic sandstones of the Fogo Harbour Formation (Figure 3). These latter sedimentary rocks sit above coarse- to very coarse-grained volcaniclastic debris-flows, which in turn sit above crossbedded sandstones that resemble the siliciclastic sequence that contains the tuff sample AKZ-14-01. The sample location is at UTM coordinate 694650E/5509920N (NAD 1927 datum). The vertical stratigraphic distance between samples AKZ-14-01 and AKZ-14-02 is estimated at less than 250 m. Sample locations are shown in Figure 3.

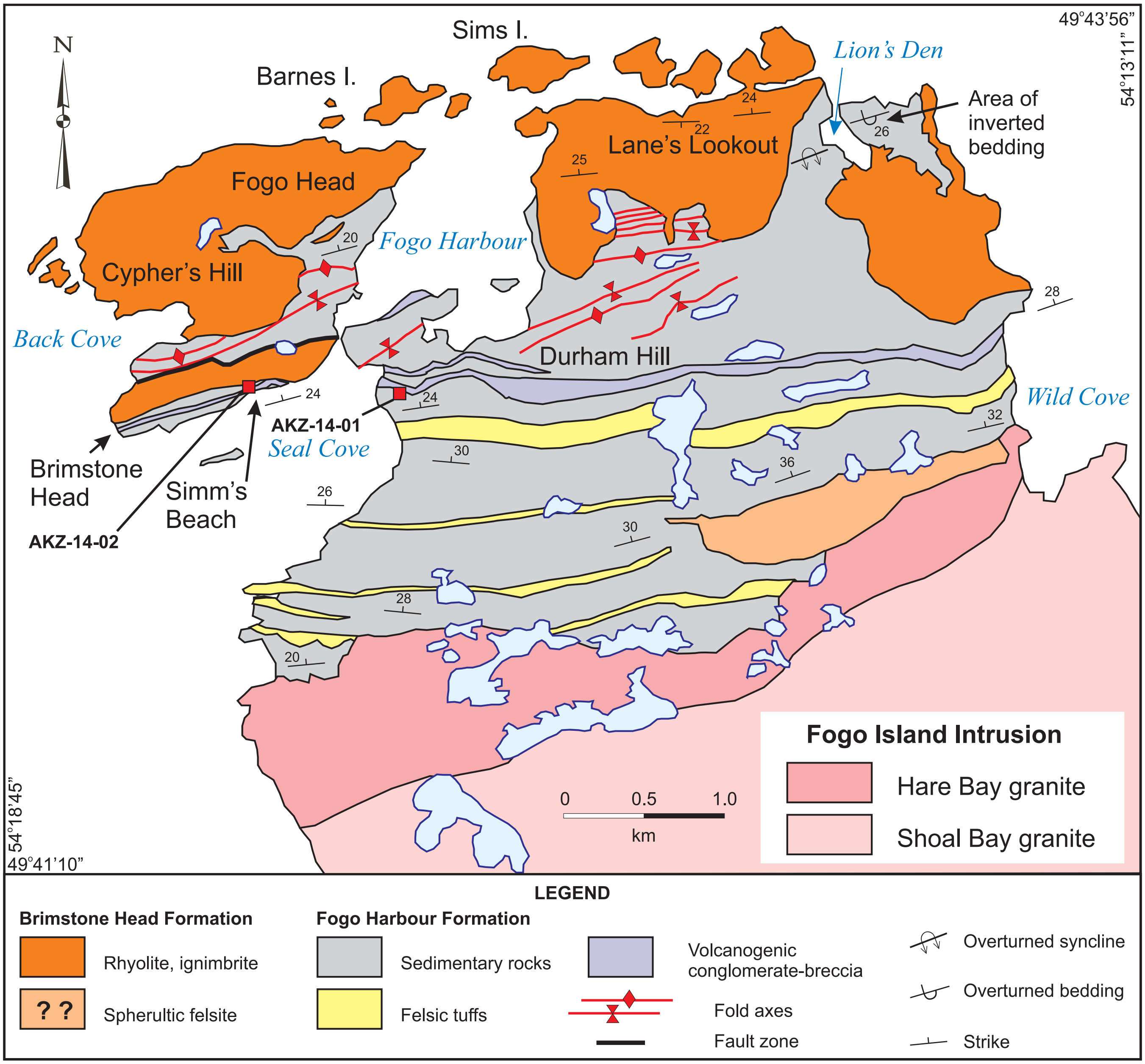


Figure 3. *Summary map of northwestern Fogo Island, modified after Donaldson* et al. *(2015), showing the locations of geochronology samples.*

U–Pb ZIRCON GEOCHRONOLOGY

Sample processing, preparation and U–Pb isotopic analysis of the two samples was completed at the Jack Satterly Geochronology Laboratory at the University of Toronto. The methods used in sample preparation, analysis and treatment of isotopic data correspond to those described by Kerr and Hamilton (2014). All zircon grains underwent a chemical abrasion pre-treatment before final analysis. The results for the two samples are listed in Table 1. Analytical errors presented in the table, in the concordia diagrams, and for ages presented in the text are all provided at the 2σ level of uncertainty.

Sample AKZ-14-02, from the Brimstone Head Formation, contained a relatively simple population of well-formed small zircon crystals of typical igneous appearance – mostly clear, colourless, short (2:1 to 3:1), well-terminated prisms, interpreted as a single generation of magmatic origin. Five fractions were analyzed, each comprising 3 zircon grains (Table 1). Measured U concentrations were consistent between fractions, falling between approximately

Table 1. Zircon U-Pb isotopic data for volcanic units, Fogo Island

Fraction	Description	Weight (mg)	U (ppm)	Pb^{T} (pg)	Pb$_{C}$ (pg)	Th/U	^{206}Pb/^{204}Pb	^{206}Pb/^{238}U	± 2σ	^{207}Pb/^{235}U	± 2σ	^{207}Pb/^{206}Pb	± 2σ	Ages (Ma) ^{206}Pb/^{238}U	± 2σ	^{207}Pb/^{235}U	± 2σ	^{207}Pb/^{206}Pb	± 2σ	Disc. (%)
AKZ-14-02 Brimstone Head Formation rhyolite																				
Z1	3 clr, cls, short pr, incl	2.8	299	58.2	0.6	0.458	6007	0.06754	0.00012	0.5137	0.0016	0.05517	0.00011	421.3	0.7	421.0	1.1	418.9	4.6	-0.6
Z2	3 clr, cls, short pr, incl, ck	2.4	261	42.7	3.1	0.367	901	0.06766	0.00014	0.5158	0.0067	0.05529	0.00066	422.0	0.8	422.4	4.5	424.1	26.8	0.5
Z3	3 clr, cls, short pr, incl	2.3	257	40.3	0.9	0.383	2968	0.06737	0.00012	0.5152	0.0025	0.05546	0.00022	420.3	0.7	422.0	1.7	431.0	9.0	2.6
Z4	3 clr, cls, short pr, ck	3.2	282	62.7	1.4	0.450	2758	0.06753	0.00012	0.5140	0.0025	0.05521	0.00022	421.3	0.7	421.2	1.6	420.6	8.9	-0.2
Z5	3 clr, cls, short pr	3.8	272	71.1	1.2	0.424	3845	0.06750	0.00012	0.5138	0.0019	0.05520	0.00016	421.1	0.7	421.0	1.3	420.5	6.5	-0.1
AKZ-14-01 Fogo Harbour Formation felsic tuff																				
Z1	3 clr, cls, sharp 2:1 pr, brkn	2.4	354	66.4	1.3	0.734	2966	0.07065	0.00013	0.5426	0.0024	0.05570	0.00020	440.1	0.8	440.1	1.6	440.4	8.1	0.1
Z2	3 clr, cls short pr, ck, brkn	1.0	348	27.0	0.8	0.585	1982	0.07297	0.00015	0.5662	0.0035	0.05627	0.00030	454.0	0.9	455.5	2.3	463.2	12.0	2.1
Z3	3 clr, cls, sm, el brkn pr	2.0	267	46.2	0.9	0.266	3254	0.08808	0.00016	0.7146	0.0029	0.05885	0.00019	544.1	0.9	547.5	1.7	561.4	7.0	3.2
Z4	3 clr, cls, el pr, minor rnd	3.1	259	144.5	1.0	0.316	8795	0.17472	0.00032	2.6113	0.0065	0.10839	0.00013	1038.1	1.8	1303.8	1.8	1772.6	2.2	44.8
Z5	3 clr, cls, subequant pr, ck	3.2	281	81.6	1.0	0.479	4911	0.08704	0.00016	0.7541	0.0024	0.06283	0.00014	538.0	0.9	570.6	1.4	702.6	4.7	24.4
Z6	3 clr, cls, 2:1 pr, minor rnd	2.0	221	109.9	2.0	0.574	3250	0.22995	0.00042	2.8392	0.0090	0.08955	0.00019	1334.2	2.2	1366.0	2.4	1415.9	4.1	6.4

Notes:

All analyzed fractions represent best available optical quality zircon, free of optical cores, inclusions and alteration.

Abbreviations: clr - clear; cls - colourless; pr - prisms; incl - minor inclusions; ck - minor cracks; brkn - some broken; sm - small; rnd - rounding.

Pb^{T} is total amount (in picograms) of Pb.

Pb$_{C}$ is total measured common Pb (in picograms) assuming the isotopic composition of laboratory blank: 206/204 - 18.221; 207/204 - 15.612; 208/204 - 39.360 (errors of 2%).

Pb/U atomic ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; 206Pb/204Pb is corrected for spike and fractionation.

Th/U is model value calculated from radiogenic 208Pb/206Pb ratio and 207Pb/206Pb age, assuming concordance.

Disc. (%) - per cent discordance for the given 207Pb/206Pb age.

Uranium decay constants are from Jaffey et al. (1971).

250-300 ppm, while model Th/U ratios were also tightly distributed between 0.38-0.46. All data plot on, or overlap concordia, with ^{206}Pb/^{238}U ages ranging narrowly between 420.3 to 422.0 Ma. Of these, three analyses cluster tightly (Z1, Z4, Z5), and a concordia age calculation (*e.g.*, Ludwig, 2003) based upon these three most precise results yields an age of 421.2 ± 0.6 Ma (Figure 4A). Thus, the Brimstone Head Formation provides an age consistent with its previous assignment as part of the Botwood Group (*see* later discussion).

Sample AKZ-14-01, from the Fogo Harbour Formation, has a more complex zircon population and age distribution. Zircon grain morphologies range from clear and colourless, short and elongate sharp prisms to slightly rounded, clear and cracked elongate grains, to well-rounded equivalents and strongly cracked varieties. A selection of six analyzed fractions (3 grains each) give relatively old and variably discordant results, including those with ^{206}Pb/^{238}U ages of 454 Ma, and model ^{207}Pb/^{206}Pb ages of approximately 544, 703, 1415 and 1775 Ma, implying that they consist of, or at least contain, older inherited material (Table 1; Figure 4B). This is also reflected in a wider range of Th/U ratios (0.32–0.73). Optically visible cores were not obvious in the older grains that were analyzed. The youngest analysis was determined on a fraction of three large, sharp prisms, which gave concordant results having a ^{206}Pb/^{238}U age of 440.1 ± 0.8 Ma (Figure 4B). At face value, the generally igneous morphology of zircon, combined with the youngest age from this fraction suggest that the results are inconsistent with previous assignment of these rocks to the Botwood Group, and imply that the Fogo Harbour Formation could be some 20 m.y. older than the Brimstone Head Formation. However, the zircon population is morphologically heterogeneous, and the few ages measured are scattered (Figure 4B); the older fractions likely comprise a detrital population, even though some individual grains are not obviously rounded. The most conservative conclusion from the results would be that the Fogo Harbour Formation cannot be older than 440 Ma, but a younger age cannot be excluded. More information is needed on the statistical distribution of zircon grain ages from this sample, and it is particularly important to

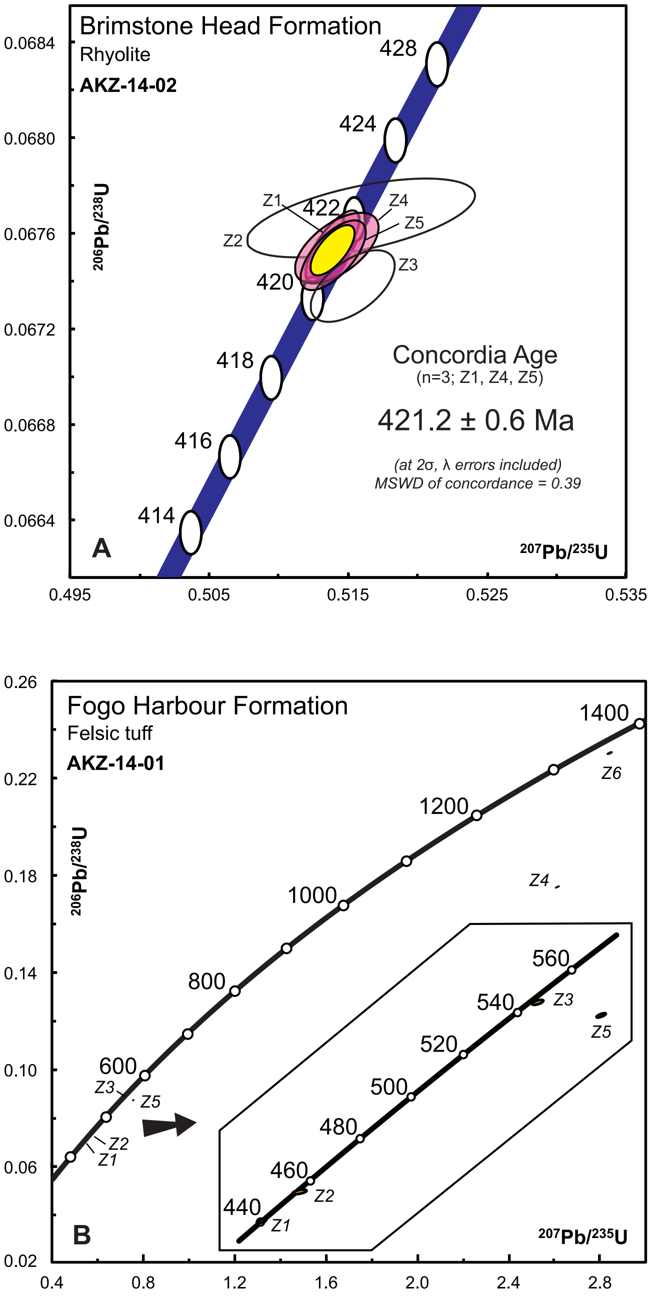


Figure 4. *U–Pb concordia diagrams. (A) Sample AKZ-14-02 – Brimstone Head Formation. Concordia Age calculation after Ludwig (2003), with decay constant errors included; (B) Sample AKZ-14-01 – Fogo Harbour Formation. Inset shows detail of younger interval of Concordia. Error ellipses and age calculations are shown at the 2σ level of uncertainty.*

ascertain if there is a significant population of latest Ordovician–earliest Silurian grains that record the eruptive event that generated the tuff. Such information, and also more insight into the provenance of inheritance (*i.e.*, inherited cores or discrete detrital grains), is more effectively explored *via in situ* microbeam analytical methods such as LA-ICPMS U–Pb geochronology.

DISCUSSION

The age obtained for the Brimstone Head Formation is relatively simple and unambiguous, showing that it crystallized at 421.2 ± 0.6 Ma. However, the Fogo Harbour Formation tuff contains zircons ranging in age from *ca.* 440 Ma (earliest Silurian) to *ca.* 1785 Ma (Paleoproterozoic).

The age of 421.2 ± 0.6 Ma obtained for the Brimstone Head Formation compares well with zircon ages obtained elsewhere from the volcanic rocks assigned to the Botwood Group. van Staal *et al.* (2014) report U–Pb SHRIMP ages of 412 ± 4 Ma and 418 ± 4 Ma from the Lawrenceton Formation elsewhere on the Island of Newfoundland, including its type area. Further afield, Dunning *et al.* (1990) reported a U–Pb zircon age of 423 ± 3 Ma from the Stony Lake volcanics in south-central Newfoundland, and McNicoll *et al.* (2008) reported a U–Pb SHRIMP age of 423 ± 3.5 Ma on zircon from rhyolitic rocks near Tally Pond in central Newfoundland. All of these units are considered to be broadly correlative with the Lawrenceton Formation, and they are within uncertainty of the new age reported here. However, there are still no geochronological data from the potentially important location of the Lawrenceton Formation on Change Islands, where it rests unconformably upon the Badger Group. This location is now of considerable interest in the context of this paper. Although these several U–Pb ages are indeed similar, none of the other dated locations listed above resemble the massive black and dark-grey ignimbrites exposed around Brimstone Head, based on descriptions and photographs.

The 421.2 ± 0.6 Ma age for the Brimstone Head Formation is also within uncertainty of the 420 ± 2 Ma U–Pb age reported by Aydin (1995) for a granite near Tilting (Shoal Bay granite of Kerr, 2013) and supports earlier inferences that the Brimstone Head Formation represents an extrusive equivalent of the Fogo Island intrusion. However, there are no other geochronological data presently available from the compositionally varied rocks of the Fogo Island intrusion, so such correlations must still be regarded as tentative. Finally, the age from the Brimstone Head Formation constrains the timing of penetrative deformation that affects it near reverse, and/or thrust, faults around the town of Fogo. These events must be latest Silurian or earliest Devonian. If there *is* an unconformity below the base of the Brimstone Head Formation, and it has a simpler structural history than the underlying Fogo Harbour Formation, as we suspect, these events are most likely of ‘Acadian’ age. An improved resolution of the age of the Fogo Harbour Formation will better constrain understanding of the deformational history of this area.

The data from the tuff near the top of the Fogo Harbour Formation are more difficult to interpret. The wide range of ages is consistent with an important component of detrital zircon, but the few analyses do not give any insight as to the *relative* importance of the different age groupings. Furthermore, there is not always a consistent or predictive physical difference between the zircon grains that gave Proterozoic ages and the grains that gave an age of ca. 440 Ma, aside from the fact that the youngest population was relatively large in grain size, and were sharply prismatic (however, some older populations were also sharply faceted). The only firm conclusion that can be drawn is that the Fogo Harbour Formation cannot be older than 440 Ma; it is possible, but not proven in this study, that this age might represent the actual time of tuff deposition. These results are consistent with field evidence that suggests a possible unconformity at the base of the Brimstone Head Formation (Donaldson *et al.*, 2015), but they are by no means diagnostic of this interpretation.

This question, and several others, can perhaps be resolved by further investigations using microdomain LA-ICPMS U–Pb geochronology. This would give more information on the nature of inherited older zircons, and perhaps discriminate between discrete older grains and composite grains that have older cores. It will also give information about the frequency of different age groupings, and ascertain if there is a discrete *ca.* 440 Ma population or, alternatively, whether grains with even younger magmatic ages are present. The wider question of the stratigraphic assignment of the Fogo Harbour Formation can also be addressed independently by this method, as there are published detrital zircon studies of the Badger Group and other parts of the Botwood Group (Pollock *et al.*, 2007; Waldron *et al.*, 2012). These two sequences have different detrital signatures, being respectively dominated by Paleozoic and Proterozoic zircon populations. Neoproterozoic zircons of "Gondwanan" affinity are present only in the upper BG. Ideally, this follow-up analytical work should be accompanied by more detailed investigation of the lithostratigraphy and sedimentology of the Fogo Harbour Formation, which to date has received limited attention.

CONCLUSIONS

Small-fraction, CA-ID-TIMS U–Pb zircon geochronological studies were carried out to test new stratigraphic and structural interpretations in northwestern Fogo Island. Felsic volcanic rocks of the Brimstone Head Formation gave a relatively simple concordant age of 421.2 ± 0.6 Ma, confirming that they likely belong to the Botwood Group, and are similar in age to the Lawrenceton Formation. The age is also identical to the one age presently available from the main phase of the granite in the Fogo Island intrusion, implying temporal and possibly genetic connections. The age also constrains the timing of localized penetrative deformation that affects the Brimstone Head Formation. The more complex U–Pb data from a felsic tuff in the uppermost Fogo Harbour Formation are less easily interpreted. The rock contains older zircons, likely of detrital origin, which yield model $^{207}Pb/^{206}Pb$ dates as old as Paleoproterozoic. The youngest zircon, at *ca*. 440 Ma, may represent the magmatic event that formed the tuff, but this cannot yet be proven. A conservative interpretation is that 440 Ma provides a maximum age constraint for deposition of the Fogo Harbour Formation. Such a result is consistent with the idea that there may be a time gap between the two formations, but it is not diagnostic. Further work aimed at resolving this problem will involve LA-ICPMS methods, which will better characterize the broader zircon population, and allow comparison with published data from the Badger Group and Botwood Group in the same general area.

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