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U-Pb DETRITAL ZIRCON GEOCHRONOLOGICAL CONSTRAINTS ON THE EARLY SILURIAN COLLISION OF GANDERIA AND LAURENTIA ALONG THE DOG BAY LINE: THE TERMINAL IAPETAN SUTURE IN THE NEWFOUNDLAND APPALACHIANS

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ABSTRACT. The Dog Bay Line is a major Silurian terrane boundary in the Exploits Subzone of the Newfoundland Appalachians. Late Ordovician-Early Silurian rocks northwest of the Dog Bay Line, the Badger and Botwood groups, contain detritus sourced exclusively from Laurentia. These rocks were deposited upon peri-Gondwanan volcanic arc terranes that were accreted to Laurentia in the Middle Ordovician. The Davidsville and Indian Islands groups southeast of the Dog Bay Line have stratigraphic links to peri-Gondwanan terranes and were deposited during the Late Ordovician-Early Silurian upon the peri-Gondwanan margin of Iapetus and were then accreted to Laurentia in the Early Silurian.

A change from Paleozoic-dominated (Badger Group) to Meso- and Neoproterozoic-dominated (Botwood Group) detritus in sequences northwest of the Dog Bay Line is attributed to the Middle Ordovician collision and exhumation of peri-Laurentian arc terranes of the Notre Dame Subzone with Laurentia. Unroofing and erosion of these accreted arc terranes re-exposed Laurentian basement and deposited detritus from the latter into the Botwood Group. Salinic orogenesis resulting from the collision of Ganderia with Laurentia resulted in obduction and erosion of the accreted Victoria and Exploits arcs and deposition of the detritus into a forearc basin on Laurentia.

The absence of zircons in the 510 to 550 Ma and 1520 to 1600 Ma age range northwest of the Dog Bay Line and no 1600 to 1700 Ma zircons southeast of the Dog Bay Line suggests the presence of a Silurian arm of the Iapetus Ocean (Tetagouche-Exploits basin) that separated Laurentia from peri-Gondwanan microcontinents of Ganderia and Avalonia. The change in Late Ordovician deep marine turbidites to Early Silurian stable-shelf rocks and non-marine, subaerial sediments east of the Dog Bay Line parallels that on the Laurentian margin and indicates the destruction and subsequent closure of Iapetus. The upper sequences of the Botwood Group (Rogerson Lake Formation) contain 700 to 800 Ma zircons that are atypical of Laurentia, but are common in peri-Gondwanan terranes, and suggest that the youngest rocks of the Botwood Group may post-date closure of the Dog Bay Line and transgress the suture as an overlap sequence.

The presence of Silurian orogenesis on both the Laurentian and peri-Gondwanan margins of Iapetus is consistent with the closure of the Tetagouche-Exploits basin and Iapetus Ocean by the Late Silurian. Laurentia and the Ganderian microcontinent were involved in a continent-continent collision suggesting that rocks along the Dog Bay Line represent the last known occurrence of Iapetus in the Newfoundland Appalachians.

INTRODUCTION

The Wilson cycle of opening and subsequent closure of ocean basins is a significant fundamental process in interpreting the evolution and paleogeography of the Earth. The age of final break-up of the Neoproterozoic supercontinent of Rodinia and opening of the Iapetus Ocean is well constrained to the late Neoproterozoic-Early Cambrian (Williams and Hiscott, 1987; Kamo and others, 1989; Cawood and others 2001; Waldron and van Staal, 2001). However, due to the lack of necessary rock

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sequences as a result of the destruction of oceanic crust by subduction processes, the timing of ultimate closure of Iapetus is not well documented and has been suggested as Middle Ordovician (Chandler and others, 1987; Buchan and Hodych, 1992), Silurian (Williams and others, 1993; Currie, 1995) or Devonian (Dewey and Kidd, 1974; McKerrow and Cocks, 1977; McKerrow, 1988). The timing and nature of closure of the Iapetus Ocean are of fundamental importance in understanding the history of Paleozoic accretion and collisional orogenesis in the Appalachian Orogen.

The Ordovician-Silurian tectonic history of the Newfoundland Appalachians is characterized by the formation and eventual destruction of numerous subduction and associated accretionary complexes in the Iapetus Ocean (Colman-Sadd and others, 1992; van Staal and others, 1998). In Newfoundland these rocks are preserved as ophiolite sequences that were synchronously obducted onto the Laurentian and Gondwanan margins in the Early Ordovician. These events (Taconic and Penobscot orogenies) have been traditionally viewed as the climax of orogenic activity in Newfoundland (Church and Stevens, 1971; Dewey and Bird, 1971; Williams, 1979, 1984; Colman-Sadd and others, 1992). Discrete Silurian deformational, magmatic and metamorphic events, however, are documented throughout the Dunnage Zone of Newfoundland (Dunning and others, 1990; O'Brien and others, 1991; Cawood and others, 1994), where they record the accretion of peri-Gondwanan island arc terranes with composite Laurentia (van Staal, 1994; van Staal and others, 1998) and indicate the occurrence of a climactic continent-continent Silurian collision in the Newfoundland Appalachians.

A critical question in Appalachian geology is the timing and nature of accretion of the Ganderian microcontinent to Laurentia and associated destruction and closure of Iapetus in the Late Ordovician-Early Silurian. Widespread occurrences of clastic-sediment-dominated sequences deposited in forearc basins across Newfoundland are viewed as products of uplift and erosion that were deposited contemporaneously with the closure of Iapetus. Resolving the age and nature of the source detritus in these sequences is essential in determining the temporal and spatial relationships between the timing of terrane accretion relative to orogenesis. We purport that Late Ordovician and Silurian sedimentary sequences on opposing sides of the Dog Bay Line, a major Silurian terrane boundary in northeast Newfoundland, were formed from erosion of two distinct geological terranes separated by an ocean basin and consequently the Dog Bay Line represents the terminal Iapetan suture.

Previous studies on the nature and location of Iapetan suture(s) in Newfoundland were conducted mainly using paleomagnetic (Buchan and Hodych, 1992), faunal (McKerrow and Cocks, 1977) and stratigraphic (Williams and others, 1993) data. For the present study we utilize U-Pb geochronological data that was acquired from individual detrital zircons using a laser-ablation microprobe (LAM) joined to an inductively coupled plasma-mass spectrometer (ICP-MS) at Memorial University of Newfoundland (MUN). The data from rocks along the Dog Bay Line are used to determine the maximum limit for the age of deposition and sediment provenance components of these rocks and to ascertain the Ordovician-Silurian tectonic evolution and ultimate termination of Iapetus in the Newfoundland Appalachians.

Regional Geology

The island of Newfoundland (fig. 1) lies at the northeastern terminus of the Appalachian Orogen (Williams, 1979, 1984). The orogen in Newfoundland is considered to be a two-sided symmetrical system (Williams, 1964) in which relicts of the early Paleozoic Iapetus Ocean (Dunnage Zone) are bounded to the west by the Laurentian craton (Grenville Province) with its Late Neoproterozoic to Early Ordovician passive margin sequence (Humber Zone) and to the east by accreted microcontinental terranes, the Gander and Avalon zones. The Gander Zone consists of Cambrian and

Lower Ordovician clastic rock sequences deposited on Early Cambrian, Neoproterozoic, Mesoproterozoic and Archean basement rocks (van Staal and others, 1996). The Avalon Zone is characterized by mainly Neoproterozoic (750 – 550 Ma) arc-related, generally low-grade volcanic-sedimentary successions and associated plutonic rocks, overlain by an early Paleozoic platformal cover sequence. Both zones are considered to have formed near or at the northern margin of Gondwana (O'Brien and others, 1996; van Staal and others, 1996; Fortey and Cocks, 2003) and accreted to the active Laurentian margin in the Silurian (Gander) and Devonian (Avalon) (van Staal and others, 1998). The Dunnage Zone is distinguished by its lower Paleozoic, dominantly mafic, volcanic rocks, ophiolitic suites and mélanges. Sedimentary rocks include graywacke, slate, chert, epiclastic volcanic rocks and minor limestone, all deposited in a marine environment. The rocks are mainly Middle Cambrian to Middle Ordovician in age (Williams, 1979; Williams and others, 1988; Williams, 1995 and references therein).

The Dunnage Zone has been divided into two major subzones based on the marked differences in Lower to Middle Ordovician stratigraphic, faunal, geochemical, geophysical and isotopic characteristics (Williams and others, 1988). The divisions are the Notre Dame Subzone in the west, with an Arenig, Laurentian low-latitude fauna, and the Exploits Subzone in the east, with an Arenig, high-latitude peri-Gondwanan fauna. The Notre Dame Subzone displays evidence of Early to Middle Ordovician orogenesis (Taconic orogeny) due to its accretion onto the Laurentian craton (Waldron and van Staal, 2001). As a result, the Ordovician marine volcanic and sedimentary rocks are characteristically unconformably overlain by Silurian continental volcanic rocks and redbeds. In contrast, the Exploits Subzone interacted with the Gander Zone during the Early Ordovician Penobscot orogeny, while still at high southerly latitudes near the Gondwanan margin (Colman-Sadd and others, 1992; van Staal and others, 1996), and its rocks generally display a continuous record of Ordovician to Silurian sedimentation. The two subzones are separated by an extensive fault system, the Red Indian Line, which is a major suture traceable across Newfoundland. The two subzones developed on opposing sides of the Iapetus Ocean (van Staal and others, 1998; Hall and others, 1998; van der Velden and others, 2004). The western part of the Exploits Subzone was juxtaposed with the Notre Dame Subzone by the Caradoc (Williams and others, 1988; McNicoll and others, 2001).

Late Ordovician to Early Silurian siliciclastic sequences are present across the northern Appalachians and generally define a coarsening-upward change from marine to subaerial-continental deposition. These rocks are interpreted to mark the onset of syntectonic sedimentation and were deposited as clastic wedges in arc-trench gap and forearc basins separated by emergent landmasses related to the Late Ordovician collision of peri-Gondwanan elements with the Laurentian margin (Williams, 1995; van Staal and others, 1998). These rocks everywhere overlie rocks of older zones; however, they do not necessarily follow the early Paleozoic zonation of the orogen. In the Exploits Subzone, the Middle Ordovician to Lower Silurian marine sequences were locally deposited unconformably upon Penobscot ophiolites, suggesting the existence of a middle Paleozoic ocean basin (Williams and O'Brien, 1991; Colman-Sadd and others, 1992; Williams and others, 1993; van Staal, 1994). Previous workers (Kusky and others, 1987; McKerrow, 1988; Scotese and McKerrow, 1990) also speculated on the presence in Newfoundland of a Silurian oceanic arm of the Iapetus Ocean that did not close until the Late Silurian or Early Devonian.

LOCAL GEOLOGICAL SETTING

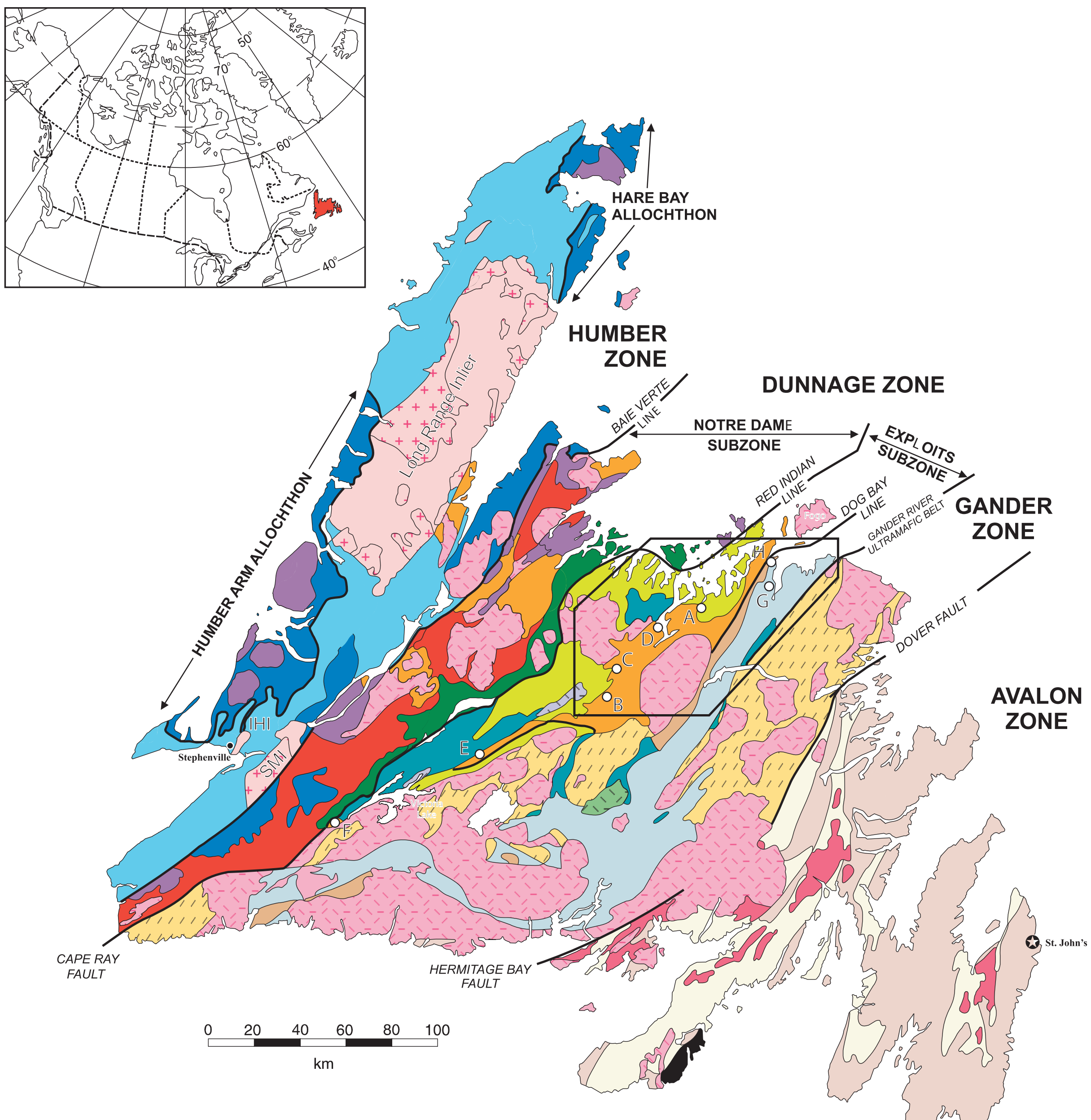
The Dog Bay Line (fig. 2) is a major Silurian terrane boundary that lies within the Exploits Subzone of the Dunnage Zone (Williams and others, 1993). The Exploits Subzone comprises Early to Middle Ordovician volcanic rocks, mélanges, and Caradocian shales that are conformably overlain by Late Ordovician to Early Silurian turbidites and Early to Late Silurian volcanic rocks and redbeds. Late Ordovician to Silurian rocks west of the Dog Bay Line are assigned to the Middle Paleozoic Badger and Botwood groups, which lie adjacent to each other. The Badger and Botwood groups represent the largest single area of early to middle Paleozoic rocks in the Newfoundland Appalachians, extending for over 300 km from the northeast coast at Fogo Island southwestward to Victoria Lake. These two groups are bounded to the northwest by steep faults that separate them from adjacent Ordovician rocks but, in the south, they locally unconformably overlie Neoproterozoic to Lower Ordovician rocks of the Victoria Lake Supergroup (Evans and Kean, 2002; Valverde-Vaquero and van Staal, 2002). Their southeastern boundary, which follows the trace of the Dog Bay Line southwestward from northeastern Newfoundland to Victoria Lake, is everywhere faulted. Conformable stratigraphic relationships with Ordovician rocks are locally also present in the north (Williams, 1967; Karlstrom and others, 1982).

The Badger Group consists of an Upper Ordovician to Lower Silurian marine turbidite sequence that comprises an upward-coarsening unit of basal graywackes containing siltstone and conglomerate interbeds, a middle unit of conglomerate and an upper unit of graywackes and siltstone (Williams, 1993). This sequence is overlain by the Botwood Group (Williams, 1972), an extensive, thick sequence of sub-aerial hematite-rich volcanic rocks (Lawrenceton Formation) overlain by fluviatile red and gray cross-bedded sandstones of the Wigwam Formation (Williams and others, 1993). Polymictic conglomerate, the Rogerson Lake Formation, which forms the upper part of the Botwood Group (Williams and others, 1995), occurs along the western margin of the group. Interfingering of Badger and Botwood group lithologies indicates that the Badger-Botwood contact is regionally conformable; although in places the contact is modified by faults or local erosional disconformities (Williams, 1993; Williams and others, 1993).

The Botwood Group is mainly Lower Silurian. Early late Llandovery fossils were obtained from the Lawrenceton Formation (Eastler, 1969; van der Pluijm and others, 1987). The age of the Wigwam Formation is constrained to the Wenlock as it is intruded by composite mafic to felsic dikes that have that yielded a U-Pb zircon age of 422 ± 3 Ma age (Elliot and others, 1991). The tightly folded Botwood Group is unconformably overlain by the flat-lying Upper Silurian (423 ± 3 Ma, Dunning and others, 1990) Stony Lake felsic volcanics (Anderson and Williams, 1970). Berry and Boucot (1970) reported an early Ludlovian monograptus graptolite from redbeds, suggesting that the upper parts of the Botwood Group may post date Early Silurian deformation.

East of the Dog Bay Line, rocks of the Indian Islands Group comprise a Silurian shallow marine shale and limestone sequence (Charles Cove Formation) that passes upwards into subaerial red beds of the Big Indian Pond Formation (Williams, 1993; Currie, 1995). These rocks conformably overlie Caradocian black shale and Middle to Late Ordovician marine limestone, shale and sandstone and turbiditic conglomerate of the Davidsville Group that are continuous eastwards to the Dunnage-Gander Zone boundary (GRUB Line). The Dog Bay Line lies within a complex shear zone marked by mélange of mafic volcanic rocks and gabbros in disrupted dark shales that varies from 100 to 1000 m in width (Williams, 1993; Williams and others, 1993).

Silurian strata across the Dog Bay Line display marked contrasts (fig. 3). The thick turbiditic sequences similar to the Badger Group and subaerial volcanic rocks akin to the Botwood Group west of the Dog Bay Line are absent from the Indian Islands Group east of the line and marine calcareous rocks are absent west of the line. Ordovician rocks and faunas, however, are generally considered to be continuous across the Dog Bay Line, although there are also minor, but significant lithological differences, mainly the absence of Middle Ordovician mafic volcanic rocks east of the Dog Bay Line. The



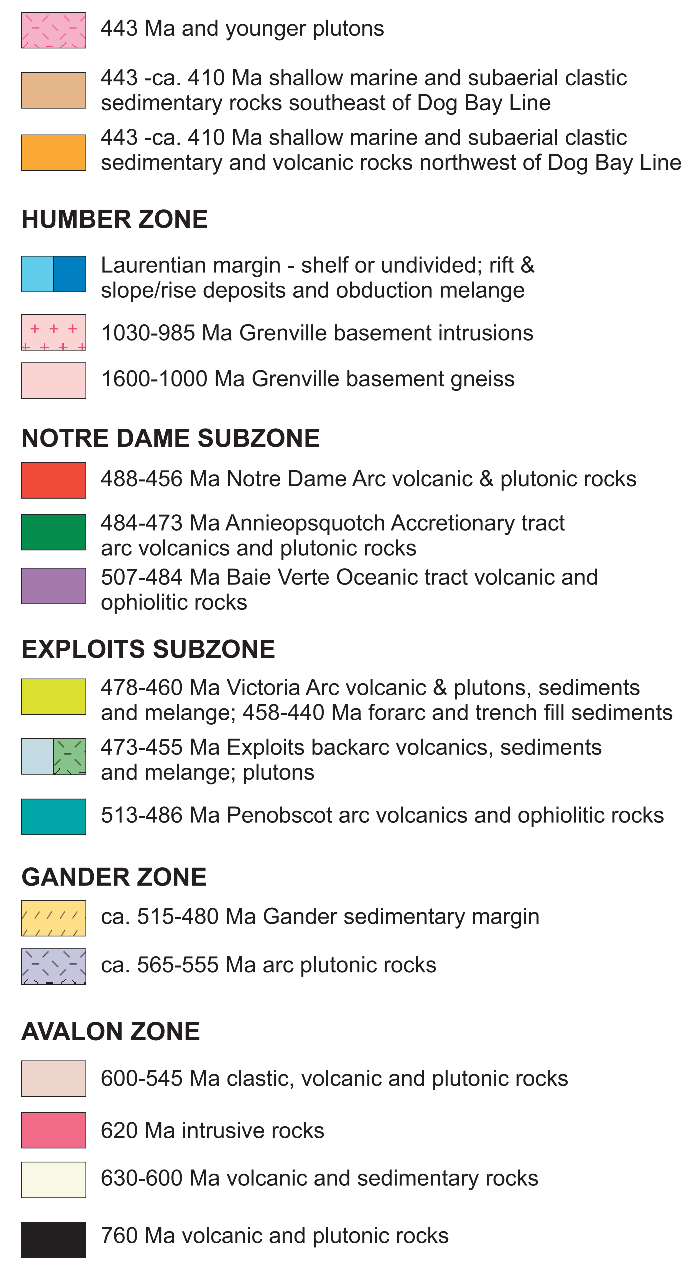
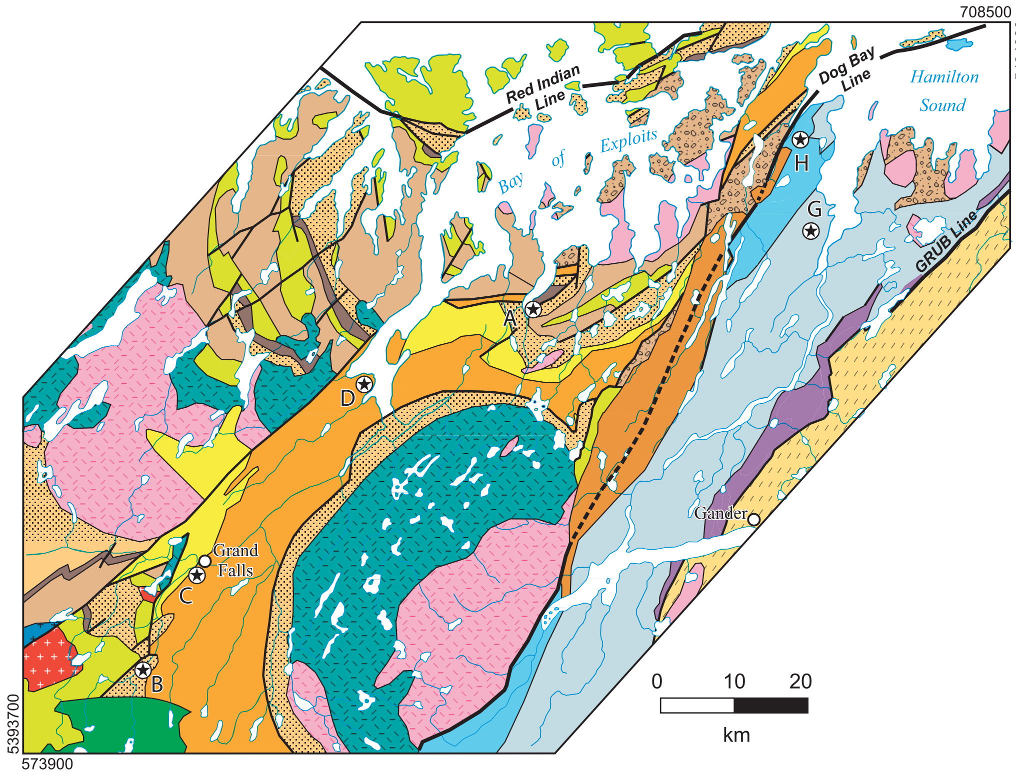


Fig. 1

Simplified geological map of Newfoundland by age and tectonic elements (after van Staal and others, 1998). The area of figure 2 is outlined; detrital zircon sample locations are indicated. SMI: Steel Mountain Inlier; IHI: Indian Head Inlier.



SILURIAN-DEVONIAN

felsic intrusive rocks

Ten Mile Lake Fm.
red shale, siltstone, sandstone

SILURIAN

Stony Lake volcanics
rhyolite, tuff, agglomerate

Mt Peyton Intrusive Suite
felsic/mafic intrusive rocks

Botwood Group
Wigwam Fm.
sandstone, conglomerate
Lawrenceton Fm.
subaerial volcanic rocks

Indian Islands Group
shale, sandstone, limestone

LATE ORDOVICIAN-EARLY SILURIAN

Badger Group
graywacke, conglomerate

Davidsville Group
graywacke, conglomerate,
shale, limestone

CAMBRIAN-ORDOVICIAN

Exploits Subzone
black shale, siltstone
sedimentary/volcanic rocks
melange

Gander Group
quartz graywacke, psammite,
semipelite, paragneiss

Gander River Complex
gabbro, trondhjemite, diabase,
mafic volcanic rocks

NEOPROTEROZOIC

quartz monzonite, gabbro

Fig. 2
Geology of the Dog Bay Line area in northeast Newfoundland.

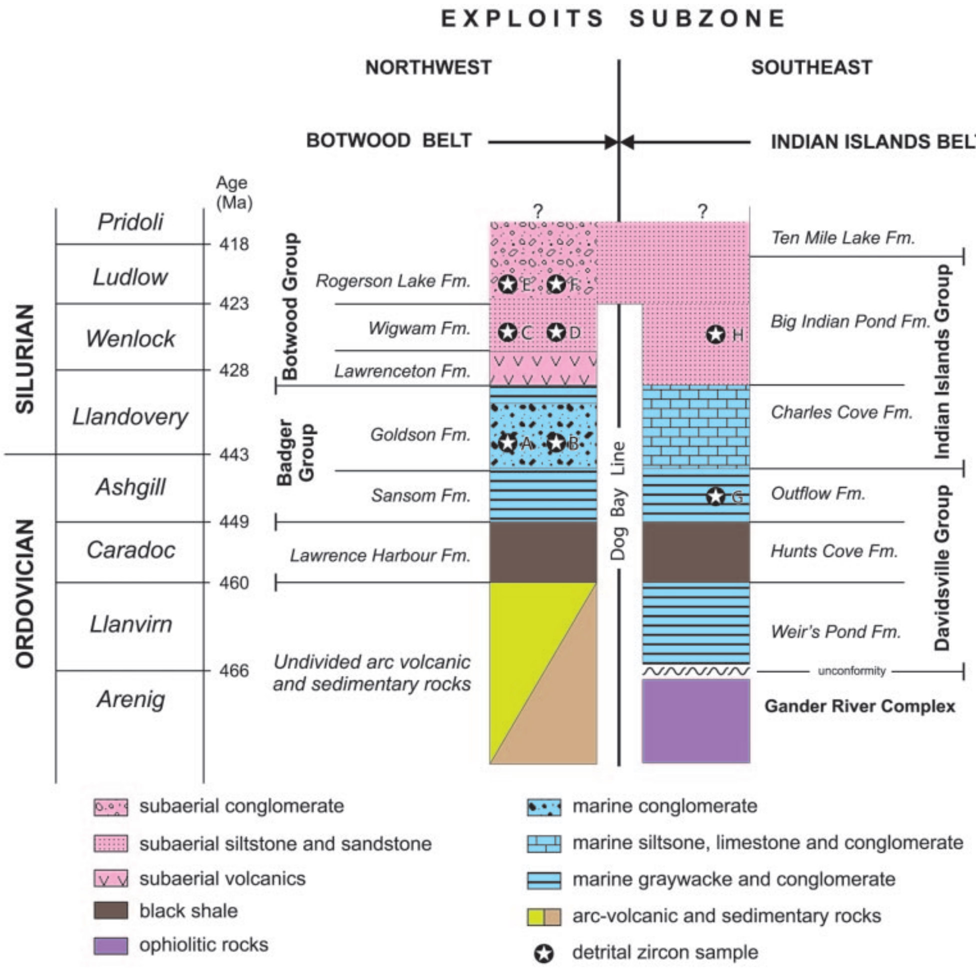


Fig. 3. Stratigraphic section across the Dog Bay Line in the Exploits Subzone.

youngest redbeds and conglomerates of the Botwood Group (Rogerson Lake Formation) may correlate with the upper parts of the Indian Islands Group or with a sequence of Late Silurian redbeds, the Ten Mile Lake Formation (Currie, 1995). The latter conformably overlies Wenlock, or younger, strata of the Indian Islands Group and transgress the Dog Bay Line as an overlap sequence.

ANALYTICAL METHODS

Zircons were processed at the Radiogenic Isotope Laboratory at MUN using a Wilfley™ table, Frantz™ isodynamic separator and heavy liquids. The zircon crystals (fig. 4) were individually hand-picked from mineral concentrates in alcohol under a binocular microscope and mounted with epoxy in 2.5 cm diameter grain mounts. The crystals were polished to expose even surfaces at the cores of the grains in order to remove the outer surfaces which are typically enriched in uranium (Krogh, 1982).

LAM-ICP-MS analyses within selected zircon crystals were performed using a VG PlasmaQuad 2S+ mass spectrometer coupled to an in-house custom-built, Q-switched 266 nm Nd:YAG ultraviolet laser. The method is described in detail by Košler and

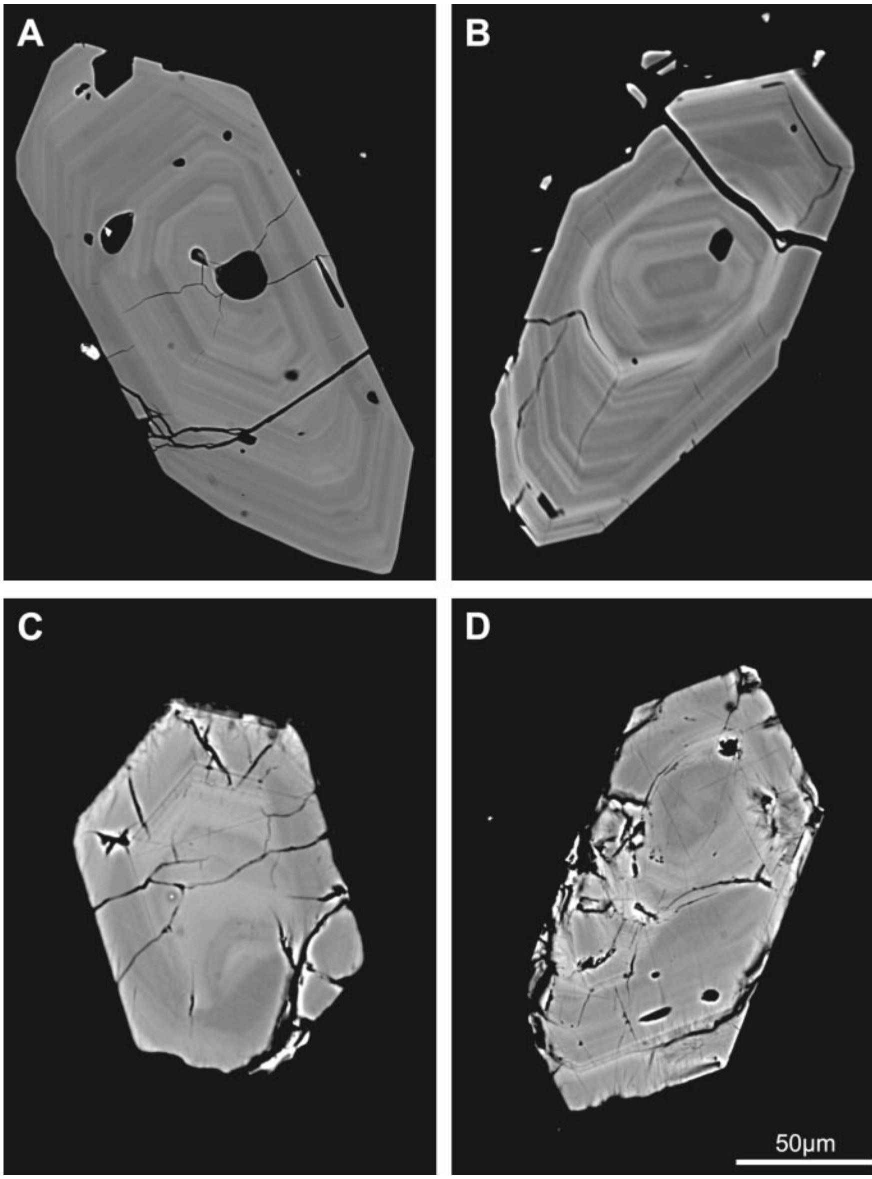


Fig. 4. Back-scatter electron scanning electron microscope images taken with a beam current of 10 nA and accelerating voltage of 25 kV of typical zircons from the Badger Group (A and B) and Botwood Group (C and D).

others (2002) with minor modifications by Cox and others (2003). During ablation, the sample was mounted on a computer-driven motorized stage on the microscope and moved beneath the stationary laser to produce a rectangular pit of variable sizes, usually in the range of 20 to 40 μm, in order to match zircon crystal size. The depth of the pit varied from ca. 10 to 50 μm depending on line length and ablation time. The U, Th and Pb isotopic ratios in the zircons were acquired for ca. 200 s, along with a

Tl/Bi/Np tracer solution that was nebulized simultaneously with the laser ablated solid sample.

Raw data were corrected for electron multiplier dead time (20 ns) and downloaded to a PC for processing using an in-house spreadsheet-utility program (LAMdate). The $^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios were calculated and blank corrected for each analysis. Aspiration of the Tl/Bi/Np tracer solution allowed for a real-time instrument mass bias correction using the known isotopic ratios of the tracer solution measured while the sample was ablated; this technique is largely independent of matrix effects that can variably influence measured isotopic ratios and hence the resulting ages. The high instrumental Hg background prohibited accurate measurement of ^{204}Pb. Nonetheless the amount and composition of common-Pb present in zircons analyzed represents an insignificant amount relative to the content of radiogenic Pb; hence, no common Pb correction was applied to the data. Most LAM analyses are accurate enough to solve most problems of provenance without applying a common Pb correction (for example, Cox and others, 2003; Murphy and others, 2004).

Accuracy and reproducibility of U-Pb analysis in the MUN laboratory are routinely monitored by measurements of natural in-house zircon standards of known TIMS U-Pb age. To monitor the efficiency of mass bias and laser-induced fractionation, the 295 ± 1 Ma (Ketchum and others, 2001) pegmatitic gem zircon 02123 was analyzed before and after every five unknowns. Residual laser-induced fractionation was typically less than 0.05%/amu based on repeat measurements of the $^{206}Pb/^{238}U$ ratio of the reference standard. Age determinations were calculated using the ^{238}U (1.55125×10^{-10} a^{-1}) and ^{235}U (9.8485×10^{-10} a^{-1}) decay constants and the present day $^{238}U/^{235}U$ ratio of 137.88 (Jaffey and others, 1971). Final ages and Concordia diagrams were produced using the Isoplot/Ex macro (Ludwig, 1999) in conjunction with the LAMdate spreadsheet program (Košler and others, 2002).

For analyses that are concordant or overlap the Concordia curve (at 1σ errors) the concordia age is reported because it makes optimal use of all radiogenic U/Pb and Pb/Pb ratios simultaneously and therefore is more precise than any single U-Pb or Pb-Pb age. For positively discordant analyses the low ^{207}Pb count rates in young (<1500 Ma) zircons precludes the use of $^{207}Pb/^{206}Pb$ ages and accordingly the more precise $^{206}Pb/^{238}U$ ages are preferred. The $^{206}Pb/^{238}U$ ages are also favored for slightly reversely discordant analyses. In discordant zircons older than 1.5 Ga, the $^{207}Pb/^{206}Pb$ ages are reported because they contain higher amounts of ^{207}Pb and therefore have smaller uncertainties.

U-Pb GEOCHRONOLOGY

Single U-Pb ages from detrital zircon grains were obtained from eight samples from Late Ordovician and Silurian sequences on both sides of the Dog Bay Line in Newfoundland (fig. 3). Six samples were collected from the Laurentian margin northwest of the Dog Bay Line, two samples from each of: 1) the Goldson Formation of the Badger Group, part of the Ordovician basal marine sequence; 2) the overlying Early Silurian terrigenous Wigwam Formation of the Botwood Group; and 3) the overlying Early (to Late?) Silurian Rogerson Lake Formation.

Samples from southeast of the Dog Bay Line were collected from the basal marine Davidsville Group (Dunnage Zone) and the overlying terrigenous Indian Islands Group. Location of the dated samples is shown in figures 1 and 2 and table 1. The data are listed in table 1 and plotted on concordia diagrams (fig. 5) and Gaussian cumulative probability curves (fig. 6).

Goldson Formation, Badger Group.—The Goldson Formation is a thick bedded, coarse-grained, polymict pebble to boulder conglomerate that contains subangular to well-rounded clasts of granite, jasper, metatonalite, chert, sheared siltstone and mafic

TABLE 1

U-Pb isotopic data of LAM ICP-MS analysis of detrital zircons

	CONCORDIA COLUMNS									*AGES and 1σ absolute error (Ma)*						*Reported Age*	
analysis	**$^{207}Pb/^{235}U$**	**±2σ**	**$^{206}Pb/^{238}U$**	**±2σ**	**$^{207}Pb/^{206}Pb$**	**±2σ**	**±2σ $^{207}Pb/^{235}U$**	**±2σ $^{206}Pb/^{238}U$**	**±2σ $^{207}Pb/^{206}Pb$**	**$^{207}Pb/^{235}U$**	**1σ**	**$^{206}Pb/^{238}U$**	**1σ**	**$^{207}Pb/^{206}Pb$**	**1σ**	**(Ma)**	**1σ**
Badger Group - Goldson Formation																	
A. Lewisporte E 642453 N 5453672 (Zone 21, NAD 1927)																	
1	9.8517	0.7821	0.0784	0.03	0.1853	0.0054	15.88	14.75	5.88	2421	73.2	2201.7	137.6	2645.6	48.8	***2645***	***±49***
2	2.4452	0.2807	0.076	0.018	0.0828	0.0061	22.96	15.68	14.72	1256	82.7	1331.1	94.3	1198.5	145.2	***1331***	***±94***
3	2.5898	0.1724	0.2215	0.0148	0.0912	0.0033	13.31	13.37	7.26	1297.8	48.8	1290	18.2	1450.4	69.1	***1290***	***±18***
4	1.8415	0.1058	0.0821	0.0059	0.0787	0.0043	11.79	6.64	11.02	1060.4	38.8	1059.9	32.4	1097	110.3	***1059***	***±32***
5	0.5727	0.0271	0.0793	0.002	0.0562	0.0026	9.47	5.13	9.24	459.8	17.5	492.1	12.1	461	102.4	***492***	***±12***
6	0.5872	0.0578	0.0773	0.0048	0.0571	0.0046	19.69	12.34	16.04	469.1	37	486.6	28.9	421.7	179	***486***	***±29***
7	0.6078	0.0317	0.0779	0.0033	0.596	0.003	10.44	8.41	10.13	482.2	20	483.5	19.6	587.4	109.9	***483***	***±18***
8	0.6139	0.0336	0.2293	0.0029	0.0618	0.0028	10.93	7.6	9.02	486	21.1	479.7	17.6	594.5	97.7	***479***	***±18***
9	0.603	0.04	0.0772	0.0033	0.0607	0.003	13.25	8.88	10.92	479.2	25.3	464.9	19.9	556.2	119.1	***479***	***±19***
10	0.5951	0.0255	0.0722	0.0018	0.0604	0.0028	8.57	4.54	9.13	474.1	16.2	479.2	10.5	546.1	99.8	***479***	***±11***
11	0.5965	0.0242	0.0771	0.0021	0.588	0.0026	8.12	5.48	8.9	475	15.4	478.7	12.6	487.1	98.2	***478***	***±12***
B. Stony Lake Road E 585100 N 5404089																	
1	1.7297	0.1434	0.1731	0.0058	0.0724	0.0048	16.58	6.75	13.25	1019.6	53.3	1029.1	32.1	995.9	134.7	***1027***	***±27***
2	0.6148	0.0227	0.0786	0.0023	0.0563	0.0017	7.37	5.75	6.13	486.6	14.3	488	13.5	465.5	67.9	***487***	***±10***
3	0.6125	0.029	0.0786	0.0017	0.0587	0.0026	9.48	4.25	8.7	485.1	18.3	488	10	557.7	94.8	***487***	***±9***
4	0.6069	0.0563	0.0782	0.0022	0.0575	0.0052	18.54	5.55	18.03	481.6	35.5	485.5	13	510.5	198.2	***485***	***±12***
6	0.6307	0.0257	0.0763	0.0024	0.0586	0.0025	8.14	6.42	8.69	496.6	6	473.9	14.7	552.5	94.8	***484***	***±11***
5	0.6227	0.0305	0.0767	0.0024	0.0576	0.0028	9.8	6.22	9.63	491.6	19.1	476.2	14.3	516	105.8	***482***	***±12***
7	0.6218	0.0451	0.0762	0.0036	0.0575	0.005	14.51	9.51	17.25	491	28.2	473.4	21.7	512.4	189.5	***480***	***±17***
8	0.6176	0.0336	0.0766	0.0022	0.0587	0.0033	10.86	5.7	11.14	488.4	21.1	476.6	13.1	555	121.5	***479***	***±11***
9	0.608	0.0988	0.0735	0.0178	0.058	0.0135	32.5	48.41	46.71	482.3	62.4	457.4	106.9	528.3	511.8	***476***	***±56***
10	0.6648	0.0255	0.0744	0.0021	0.064	0.0023	7.67	5.69	7.05	517.5	15.6	462.4	12.7	471	74.6	***462***	***±13***
11	0.5727	0.0296	0.0734	0.0024	0.0569	0.0023	10.34	6.67	8.15	459.8	19.1	456.7	14.7	487.6	89.9	***458***	***±12***
12	0.5735	0.0317	0.0723	0.0024	0.0572	0.0025	11.05	6.76	8.61	460.3	20.4	449.8	14.7	498.9	94.8	***453***	***±12***
13	0.5377	0.0313	0.0706	0.0021	0.0549	0.0027	11.61	5.91	9.68	436.9	20.7	440	12.6	408.1	108.2	***439***	***±11***

Table 1

(*Continued*)

analysis	CONCORDIA COLUMNS $^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	±2σ $^{207}Pb/^{235}U$	±2σ $^{206}Pb/^{238}U$	±2σ $^{207}Pb/^{206}Pb$	AGES and 1σ absolute error (Ma) $^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	Reported Age (Ma)	1σ
Botwood Group - Wigwam Formation																	
*C. **Grand Falls*** E 601836 N 5427391																	
1	11.0418	0.5148	0.468	0.0202	0.1799	0.0068	9.32	8.62	7.57	2526.7	43.4	2474.6	88.6	2651.5	62.8	***2516***	*±39*
2	4.1148	0.1387	0.2983	0.0079	0.1023	0.0021	6.74	5.31	4.05	1657.3	27.5	1682.9	39.3	1666.8	37.5	***1666***	*±22*
3	4.1367	0.0984	0.2945	0.0094	0.1077	0.0021	4.76	6.37	3.96	1661.6	19.4	1664.1	46.7	1761.6	36.2	***1662***	*±18*
4	3.1945	0.2587	0.2697	0.0059	0.0942	0.0022	16.19	4.4	4.64	1455.8	62.6	1539	30.1	1512.5	43.8	***1512***	*±44*
5	3.0259	0.0716	0.248	0.0059	0.0892	0.0016	4.73	4.79	3.52	1414.2	18.1	1428.2	30.7	1408.3	33.7	***1428***	*±31*
6	2.5957	0.2217	0.2357	0.0087	0.0828	0.0075	17.08	7.38	18.04	1299.4	62.6	1369.3	45.5	1263.6	176.2	***1341***	*±37*
7	2.3293	0.0818	0.2152	0.0056	0.0797	0.0027	7.03	5.18	6.7	1221.3	25	1256.4	29.6	1190.3	66.2	***1236***	*±19*
8	2.1338	0.0588	0.2063	0.005	0.0763	0.0023	5.51	4.8	5.91	1159.8	19	1209	26.5	1102.9	59	***1209***	*±27*
9	2.2314	0.1284	0.2027	0.008	0.0813	0.0026	11.51	7.91	6.46	1190.9	40.4	1189.8	43	1228.2	63.4	***1190***	*±29*
10	1.9218	0.0561	0.1885	0.0039	0.0753	0.002	5.84	4.12	5.42	1088.7	19.5	1113.1	21.1	1076	54.4	***1100***	*±14*
11	1.8817	0.0647	0.1827	0.0047	0.0776	0.002	6.88	5.14	5.03	1074.7	22.8	1081.9	25.6	1137.7	50	***1078***	*±17*
12	1.8225	0.0692	0.1832	0.0062	0.077	0.0022	7.59	6.75	5.67	1053.6	24.9	1084.4	33.7	1122.2	56.5	***1064***	*±20*
13	1.7691	0.0539	0.172	0.005	0.0746	0.0027	6.09	5.76	7.19	1034.2	19.8	1023.2	27.3	1057	72.4	***1030***	*±16*
14	1.6753	0.0682	0.1727	0.0046	0.0732	0.0028	8.14	5.31	7.68	999.2	25.9	1027.1	25.2	1018.2	77.8	***1013***	*±18*
*D. **Botwood*** E 620313 N 5444592																	
1	14.2267	0.4192	0.5119	0.017	0.2031	0.0037	5.89	6.65	3.63	2764.9	28	2664.6	72.6	2851.3	29.5	***2751***	*±26*
2	4.4312	0.4054	0.3136	0.0222	0.1019	0.0091	18.3	14.17	17.77	1718.2	75.8	1758.6	109	1658.2	164.6	***1731***	*±62*
3	4.1667	0.1576	0.2897	0.0138	0.1019	0.0022	7.56	9.53	4.22	1667.5	31	1640.1	69	1658.8	39.1	***1663***	*±28*
4	3.307	0.1312	0.2777	0.0113	0.0859	0.0018	7.94	8.16	4.23	1482.7	30.9	1579.7	57.2	1335.3	40.9	***1504***	*±27*
5	2.676	0.0748	0.2356	0.0055	0.082	0.0019	5.59	4.68	4.66	1321.9	20.7	1363.7	28.8	1245.2	45.7	***1336***	*±17*
6	2.2887	0.0788	0.2103	0.0061	0.0788	0.0012	6.89	5.83	2.96	1208.8	24.3	1230.5	32.7	1167.2	29.4	***1217***	*±19*
7	1.7924	0.0796	0.1826	0.0073	0.073	0.0021	8.88	8.02	5.67	1042.7	28.9	1080.9	39.9	1015.2	57.4	***1056***	*±23*
8	0.658	0.02	0.0824	0.0022	0.0575	0.0016	6.09	5.3	5.62	513.4	12.3	510.4	13	510.3	61.7	***512***	*±9*

TABLE 1

(*Continued*)

	CONCORDIA COLUMNS						±2σ	±2σ	±2σ	*AGES and 1σ absolute error (Ma)*						*Reported Age*	
analysis	$^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	(Ma)	1σ
Botwood Group - Rogerson Lake Formation																	
E. Rogerson Lake E 515102 N 5367912																	
1	1.6061	0.1367	0.1667	0.0075	0.0844	0.0053	17.03	8.95	12.52	972.6	53.3	994.0	41.2	1301.2	121.6	***986***	***±33***
2	0.6717	0.0466	0.0883	0.0037	0.0613	0.0015	13.87	8.32	4.85	521.8	28.3	545.5	21.7	651.1	52.0	***537***	***±17***
3	0.6981	0.0465	0.0842	0.0042	0.0585	0.0017	13.32	9.89	5.65	537.7	27.8	521.1	24.8	549.9	61.6	***528***	***±19***
4	0.5361	0.0371	0.0835	0.0029	0.0578	0.0014	13.84	6.96	4.83	435.8	24.5	517.2	17.3	522.5	53.0	***517***	***±17***
5	0.6297	0.0380	0.0832	0.0024	0.0585	0.0013	12.08	5.73	4.52	495.9	23.7	515.2	14.2	549.8	49.4	***510***	***±12***
6	0.5540	0.0296	0.0818	0.0021	0.0554	0.0012	10.69	5.22	4.18	447.6	19.3	506.6	12.7	429.8	46.6	***507***	***±13***
7	0.6211	0.0396	0.0803	0.0033	0.0577	0.0009	12.74	8.24	3.26	490.5	24.8	497.6	19.7	517.7	35.7	***495***	***±15***
8	0.6095	0.0308	0.0792	0.0026	0.0566	0.0010	10.11	6.61	3.46	483.2	19.4	491.6	15.6	475.2	38.3	***488***	***±12***
9	0.6004	0.0363	0.0800	0.0034	0.0562	0.0016	12.08	8.52	5.70	477.5	23.0	495.8	20.3	458.6	63.2	***488***	***±15***
10	0.6150	0.0334	0.0785	0.0030	0.0583	0.0009	10.85	7.62	3.07	486.7	21.0	487.1	17.9	542.6	33.6	***487***	***±14***
11	0.5905	0.0298	0.0789	0.0024	0.0584	0.0011	10.11	6.07	3.85	471.2	19.0	489.5	14.3	544.2	42.1	***483***	***±11***
12	0.5769	0.0243	0.0767	0.0019	0.0574	0.0008	8.44	4.92	2.72	462.4	15.7	476.6	11.3	506.6	29.9	***479***	***±9***
13	0.4984	0.0349	0.0769	0.0024	0.0547	0.0011	14.00	6.29	4.05	410.6	23.6	477.3	14.5	401.5	45.4	***477***	***±14***
14	0.5339	0.0394	0.0779	0.0029	0.0581	0.0014	14.77	7.38	4.83	434.4	26.1	483.8	17.2	531.8	52.9	***468***	***±14***
F. Burgeo Road E 445025 N 5336483																	
1	3.4427	0.1799	0.2595	0.0128	0.0948	0.0010	10.45	9.90	2.15	1514.2	41.1	1487.0	65.8	1523.6	20.3	***1523***	***±20***
2	3.3023	0.2905	0.2560	0.0149	0.0988	0.0017	17.59	11.68	3.37	1481.6	68.6	1469.4	76.7	1601.1	31.4	***1491***	***±66***
3	2.3701	0.1155	0.2129	0.0096	0.0787	0.0008	9.75	9.00	2.03	1233.6	34.8	1244.2	50.9	1164.8	20.1	***1218***	***±22***
4	1.7175	0.0658	0.1707	0.0059	0.0699	0.0006	7.66	6.97	1.58	1015.1	24.6	1016.1	32.7	925.4	16.2	***1013***	***±17***
5	1.6469	0.1701	0.1680	0.0157	0.0703	0.0013	20.66	18.64	3.61	988.4	65.3	1001.2	86.4	937.8	37.0	***963***	***±41***
6	1.4917	0.1924	0.1525	0.0113	0.0778	0.0015	25.79	14.79	3.86	927.0	78.4	915.1	63.1	1140.7	38.3	***897***	***±51***
7	1.3917	0.0670	0.1467	0.0060	0.0668	0.0007	9.63	8.19	2.08	885.4	28.5	882.7	33.8	833.0	21.7	***889***	***±25***
8	1.2001	0.1042	0.1390	0.0073	0.0682	0.0018	17.37	10.52	5.29	800.6	48.1	838.9	41.4	875.9	54.7	***839***	***±41***
9	1.1447	0.1027	0.1250	0.0109	0.0688	0.0014	17.94	17.49	3.95	774.7	48.6	759.3	62.6	891.3	40.8	***802***	***±34***
10	1.1473	0.0659	0.1187	0.0048	0.0671	0.0007	11.48	8.06	2.18	776.0	31.1	723.3	27.6	841.2	22.7	***723***	***±28***
11	1.0330	0.0948	0.1144	0.0071	0.0642	0.0012	18.35	12.38	3.88	720.4	47.3	698.2	41.0	748.1	41.0	***698***	***±41***
12	0.7248	0.0741	0.0994	0.0058	0.0604	0.0016	20.44	11.71	5.41	553.5	43.6	610.8	34.1	619.2	58.4	***611***	***±34***
13	0.7817	0.0281	0.0953	0.0035	0.0606	0.0007	7.18	7.38	2.36	586.5	16.0	586.6	20.7	624.2	25.5	***586***	***±14***
14	0.8759	0.0475	0.0940	0.0038	0.0634	0.0007	10.84	8.00	2.36	638.7	25.7	578.9	22.2	722.0	25.1	***579***	***±22***
15	0.7203	0.0525	0.0912	0.0043	0.0601	0.0010	14.57	9.44	3.21	550.8	31.0	562.8	25.4	606.4	34.8	***572***	***±24***
16	0.7089	0.0395	0.0898	0.0033	0.0572	0.0009	11.13	7.29	2.99	544.1	23.4	554.3	19.4	501.0	32.9	***554***	***±19***
17	0.6231	0.0351	0.0860	0.0025	0.0584	0.0010	11.28	5.92	3.47	491.8	22.0	531.9	15.1	545.0	37.9	***532***	***±15***
18	0.6889	0.0324	0.0848	0.0032	0.0592	0.0007	9.40	7.59	2.35	532.1	19.5	525.0	19.1	576.1	25.5	***527***	***±19***

TABLE 1

(*Continued*)

analysis	CONCORDIA COLUMNS $^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	±2σ $^{207}Pb/^{235}U$	±2σ $^{206}Pb/^{238}U$	±2σ $^{207}Pb/^{206}Pb$	AGES and 1σ absolute error (Ma) $^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	Reported Age (Ma)	1σ
F. Burgeo Road E 445025 N 5336483																	
19	0.5988	0.0714	0.0787	0.0057	0.0587	0.0009	23.85	14.47	2.96	476.4	45.3	488.2	34.0	554.5	32.3	***510***	***±24***
20	0.5943	0.0321	0.0816	0.0025	0.0569	0.0006	10.79	6.05	2.06	473.6	20.4	505.6	14.7	486.5	22.7	***506***	***±15***
21	0.5086	0.0387	0.0806	0.0020	0.0582	0.0012	15.21	5.05	4.21	417.5	26.0	499.9	12.2	538.5	46.1	***500***	***±12***
22	0.6550	0.0286	0.0804	0.0029	0.0578	0.0009	8.74	7.24	2.98	511.5	17.6	498.3	17.4	520.5	32.7	***498***	***±17***
23	0.5115	0.0828	0.0794	0.0068	0.0553	0.0011	32.36	17.16	3.83	419.5	55.6	492.4	40.7	424.5	42.7	***492***	***±40***
24	0.6472	0.0273	0.0793	0.0031	0.0577	0.0004	8.44	7.89	1.47	506.8	16.8	492.2	18.7	518.5	16.2	***492***	***±19***
25	0.6276	0.0220	0.0789	0.0016	0.0589	0.0008	7.00	4.15	2.56	494.6	13.7	489.3	9.8	564.8	27.9	***489***	***±10***
26	0.5729	0.0267	0.0786	0.0021	0.0558	0.0008	9.32	5.25	3.01	459.9	17.2	487.6	12.3	444.9	33.5	***488***	***±12***
27	0.6252	0.0250	0.0786	0.0021	0.0563	0.0006	8.00	5.34	1.96	493.1	15.6	487.8	12.5	464.1	21.7	***484***	***±12***
28	0.4929	0.0385	0.0780	0.0020	0.0595	0.0012	15.64	5.25	4.04	406.9	26.2	484.0	12.2	584.1	43.8	***484***	***±12***
29	0.5826	0.0351	0.0766	0.0029	0.0555	0.0008	12.07	7.65	3.01	466.2	22.6	475.7	17.5	434.3	33.5	***483***	***±16***
30	0.5270	0.0475	0.0729	0.0033	0.0565	0.0007	18.03	9.10	2.39	429.8	31.6	453.5	19.9	473.5	26.4	***482***	***±13***
31	0.6381	0.0319	0.0773	0.0027	0.0598	0.0013	10.01	6.99	4.23	501.1	19.8	479.7	16.2	596.0	45.8	***480***	***±16***
32	0.6075	0.0270	0.0770	0.0017	0.0584	0.0012	8.90	4.49	4.24	482.0	17.1	478.4	10.3	544.0	46.4	***478***	***±10***
33	0.6126	0.0235	0.0767	0.0024	0.0565	0.0008	7.68	6.38	2.93	485.2	14.8	476.7	14.7	473.0	32.4	***477***	***±15***
34	0.6084	0.0129	0.0765	0.0012	0.0574	0.0004	4.25	3.19	1.31	482.6	8.2	475.3	7.3	505.3	14.4	***475***	***±7***
35	0.5838	0.0299	0.0764	0.0028	0.0554	0.0006	10.25	7.24	2.16	466.9	19.2	474.6	16.6	426.6	24.1	***475***	***±17***
36	0.5500	0.0394	0.0764	0.0023	0.0572	0.0009	14.32	6.05	3.20	445.0	25.8	474.6	13.8	499.9	35.2	***475***	***±14***
37	0.3891	0.0627	0.0755	0.0030	0.0564	0.0014	32.23	7.82	5.11	333.7	45.8	469.2	17.7	467.5	56.6	***469***	***±18***
38	0.5351	0.0244	0.0751	0.0018	0.0593	0.0009	9.10	4.70	2.99	435.2	16.1	466.7	10.6	577.4	32.5	***467***	***±11***
39	0.5220	0.0323	0.0750	0.0016	0.0545	0.0007	12.37	4.15	2.75	426.5	21.5	465.9	9.3	393.5	30.8	***466***	***±9***
40	0.5175	0.0534	0.0710	0.0038	0.0584	0.0010	20.65	10.84	3.26	423.5	35.7	441.9	23.1	545.8	35.7	***463***	***±16***
41	0.6093	0.0222	0.0757	0.0016	0.0591	0.0006	7.29	4.15	2.01	483.1	14.0	470.3	9.4	570.8	21.9	***462***	***±8***
42	0.5774	0.0245	0.0739	0.0022	0.0561	0.0008	8.47	6.06	2.87	462.8	15.7	459.4	13.4	458.1	31.8	***459***	***±13***
43	0.4650	0.0323	0.0735	0.0020	0.0549	0.0009	13.91	5.57	3.14	387.7	22.4	457.3	12.3	408.5	35.1	***457***	***±12***
44	0.5490	0.0499	0.0726	0.0029	0.0563	0.0012	18.17	7.99	4.24	444.3	32.7	451.8	17.4	463.1	47.0	***456***	***±14***
45	0.4138	0.0401	0.0723	0.0028	0.0546	0.0012	19.36	7.76	4.35	351.6	28.8	450.0	16.9	397.4	48.7	***450***	***±17***
46	0.5218	0.0426	0.0723	0.0032	0.0563	0.0009	16.35	8.95	3.21	426.4	28.5	449.9	19.5	466.2	35.6	***450***	***±19***
47	0.5330	0.0263	0.0722	0.0023	0.0560	0.0005	9.88	6.24	1.96	433.8	17.4	449.5	13.5	452.9	21.8	***449***	***±14***
48	0.5573	0.0215	0.0710	0.0022	0.0561	0.0006	7.73	6.27	2.05	449.8	14.1	442.1	13.4	455.7	22.7	***442***	***±13***

TABLE 1

(Continued)

analysis	CONCORDIA COLUMNS $^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	±2σ $^{207}Pb/^{235}U$	±2σ $^{206}Pb/^{238}U$	±2σ $^{207}Pb/^{206}Pb$	AGES and 1σ absolute error (Ma) $^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	Reported Age (Ma)	1σ
G. Davidsville Group - Outflow Formation E 682949 N 5466368																	
1	13.7494	0.4103	0.5573	0.0163	0.2149	0.0176	5.97	5.85	16.38	2732.6	28.2	2855.6	67.4	2943	132.3	***2750***	***±26***
2	3.2918	0.1968	0.2666	0.0121	0.0968	0.0048	11.96	9.08	9.95	1479.1	46.6	1523.5	61.6	1562.6	93.3	***1495***	***±37***
3	1.5869	0.1877	0.1612	0.0205	0.0727	0.0033	23.66	25.48	9.2	965.1	73.7	963.7	114	1005.7	93.3	***965***	***±62***
4	1.3579	0.1075	0.1473	0.0073	0.073	0.0048	15.83	9.89	13.11	871	46.3	885.9	40.9	1012.9	132.8	***879***	***±31***
5	0.6315	0.0249	0.0818	0.0026	0.0581	0.0012	7.9	6.37	4.17	497	15.5	506.7	15.5	531.7	45.6	***502***	***±11***
6	0.6194	0.0533	0.08	0.0041	0.0602	0.0052	17.23	10.29	17.22	489.5	33.4	496.1	24.6	611	186	***494***	***±20***
7	0.584	0.032	0.0794	0.0018	0.0563	0.0031	10.94	4.48	10.98	467	20.5	492.4	10.6	462.4	121.7	***487***	***±9***
8	0.6022	0.033	0.0792	0.0028	0.0557	0.0036	10.96	7.13	13.04	478.6	20.9	491.4	16.9	441.6	145	***486***	***±13***
9	0.6045	0.0448	0.0771	0.003	0.0577	0.0039	14.83	7.77	13.36	480.1	28.4	478.7	17.9	519.7	146.6	***479***	***±15***
10	0.5991	0.0292	0.0763	0.0027	0.0597	0.0028	9.76	7.07	9.39	476.7	18.6	474.2	16.2	591.6	101.8	***475***	***±12***
11	0.5726	0.0472	0.0769	0.0028	0.0563	0.0052	16.48	7.2	18.61	459.7	30.5	477.7	16.6	464.2	206.2	***474***	***±15***
12	0.5831	0.0468	0.0767	0.0036	0.0576	0.0044	16.06	9.28	15.19	466.4	30	476.2	20.3	512.7	166.9	***473***	***±18***
13	0.5886	0.0219	0.0763	0.0024	0.058	0.0017	7.44	6.3	5.89	470	14	474.3	14.4	531	64.5	***472***	***±10***
14	0.5824	0.058	0.075	0.0032	0.0582	0.0026	8.86	8.58	8.78	466	16.5	466	19.3	538.3	96	***466***	***±17***
15	0.555	0.0309	0.0722	0.0024	0.057	0.0035	11.12	6.58	12.13	448.3	20.1	449.2	14.3	490.2	133.7	***449***	***±12***
16	0.5319	0.0484	0.0726	0.0049	0.0545	0.0027	18.19	13.58	9.74	433.1	32.1	451.6	29.6	390.4	109.3	***443***	***±22***
H. Indian Islands Group - Big Indian Pond Formation E676942 N 5475812																	
1	4.1698	0.2768	0.2803	0.0108	0.1134	0.0057	13.28	7.7	10.07	1668.1	54.4	1593	54.3	1854.5	91	***1854***	***±91***
2	4.961	0.5727	0.331	0.0449	0.1098	0.0053	23.09	27.13	9.64	1812.7	97.6	1843.2	217.4	1796	87.8	***1818***	***±88***
3	3.3583	0.1914	0.2574	0.0145	0.1001	0.0057	11.4	11.28	11.37	1494.7	44.6	1476.8	74.5	1626.5	105.7	***1490***	***±38***
4	2.81	0.08	0.2346	0.0058	0.087	0.0019	5.69	4.96	4.41	1358.2	21.3	1358.3	30.4	1360.6	42.5	***1358***	***±17***
5	2.0134	0.0858	0.1985	0.0054	0.0742	0.0026	8.52	5.43	6.93	1120	28.9	1167.4	29	1047.4	69.9	***1143***	***±20***
6	2.0291	0.0888	0.1924	0.0066	0.0809	0.0017	8.76	6.87	4.13	1125.3	29.8	1134.2	35.7	1218.1	40.6	***1129***	***±23***
7	1.8783	0.0543	0.1837	0.0048	0.0745	0.0016	5.78	5.19	4.41	1073.5	19.2	1086.9	26	1053.9	44.4	***1078***	***±15***
8	0.9072	0.1083	0.1072	0.0044	0.0664	0.0054	23.88	8.25	16.13	655.6	57.7	656.5	25.8	820.4	168.4	***656***	***±24***
9	0.7786	0.0248	0.0955	0.0019	0.0622	0.0021	6.37	3.95	6.67	584.7	14.2	588	11.1	680.3	71.1	***587***	***±9***
10	0.5929	0.0281	0.0784	0.0021	0.0556	0.0023	9.48	5.48	8.39	472.7	17.9	486.5	12.8	437.9	93.3	***482***	***±10***
11	0.5987	0.0366	0.0772	0.0027	0.0591	0.0033	12.24	1.07	11.31	476.4	23.3	479.2	16.2	569.3	123.1	***478***	***±13***
12	0.5302	0.0153	0.0697	0.0015	0.0573	0.0016	5.78	4.42	5.68	431.9	10.2	434.3	9.3	503.5	62.5	***433***	***±7***

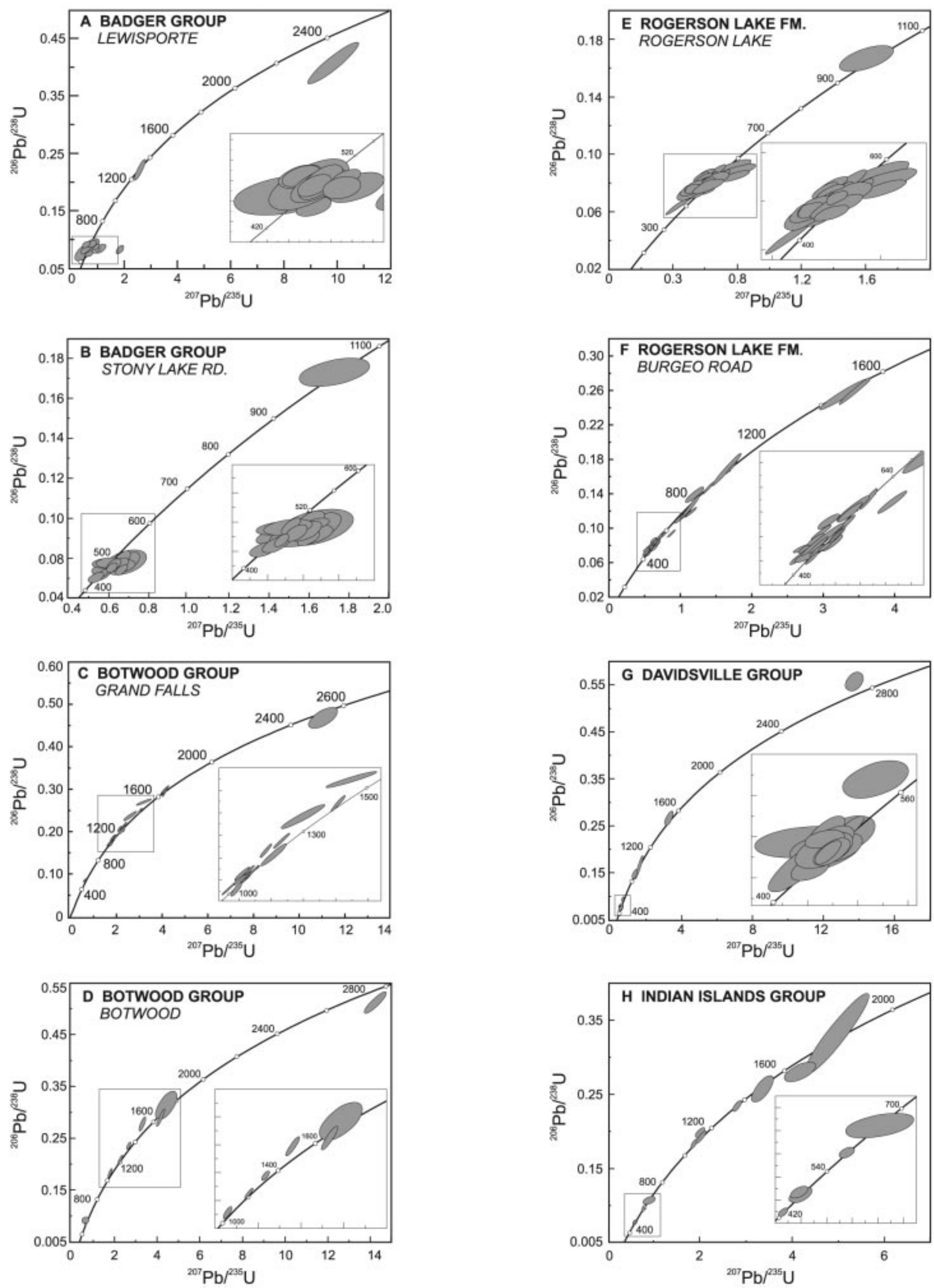


Fig. 5. U-Pb Concordia diagrams of dated samples; error ellipses are 1σ.

and felsic volcanic rocks. The Goldson Formation conformably overlies thick-bedded graywackes of the Sansom Formation, the basal unit of the Badger Group, which in turn conformably overlies Caradocian black shale in the Exploits Subzone. In the Dog Bay area, the Goldson Formation is conformably overlain by subaerial volcanic flows

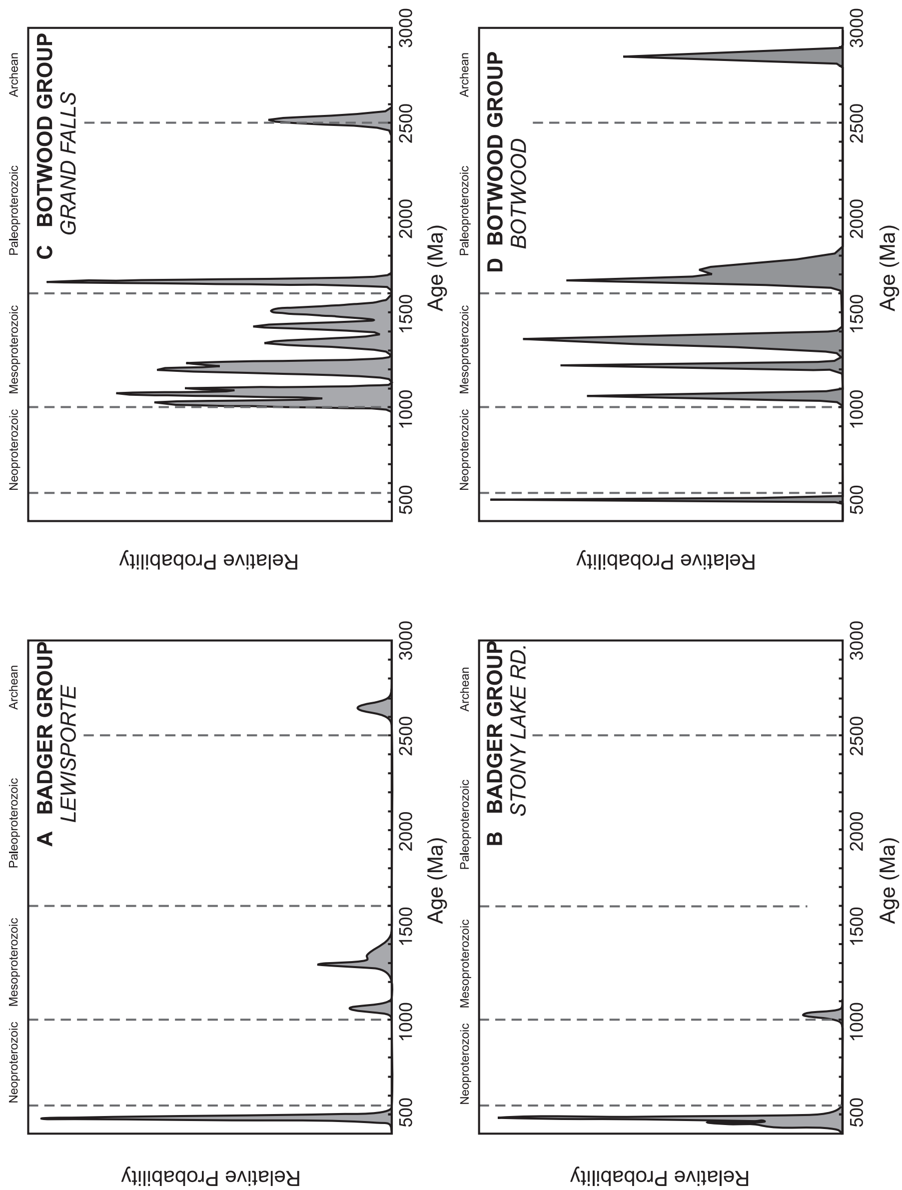


Fig. 6. Gaussian cumulative probability curves for analyzed samples. Only those analyses within ±15% discordance are plotted; ^{207}Pb/^{206}Pb ages are used for zircons older than 1.5 Ga.

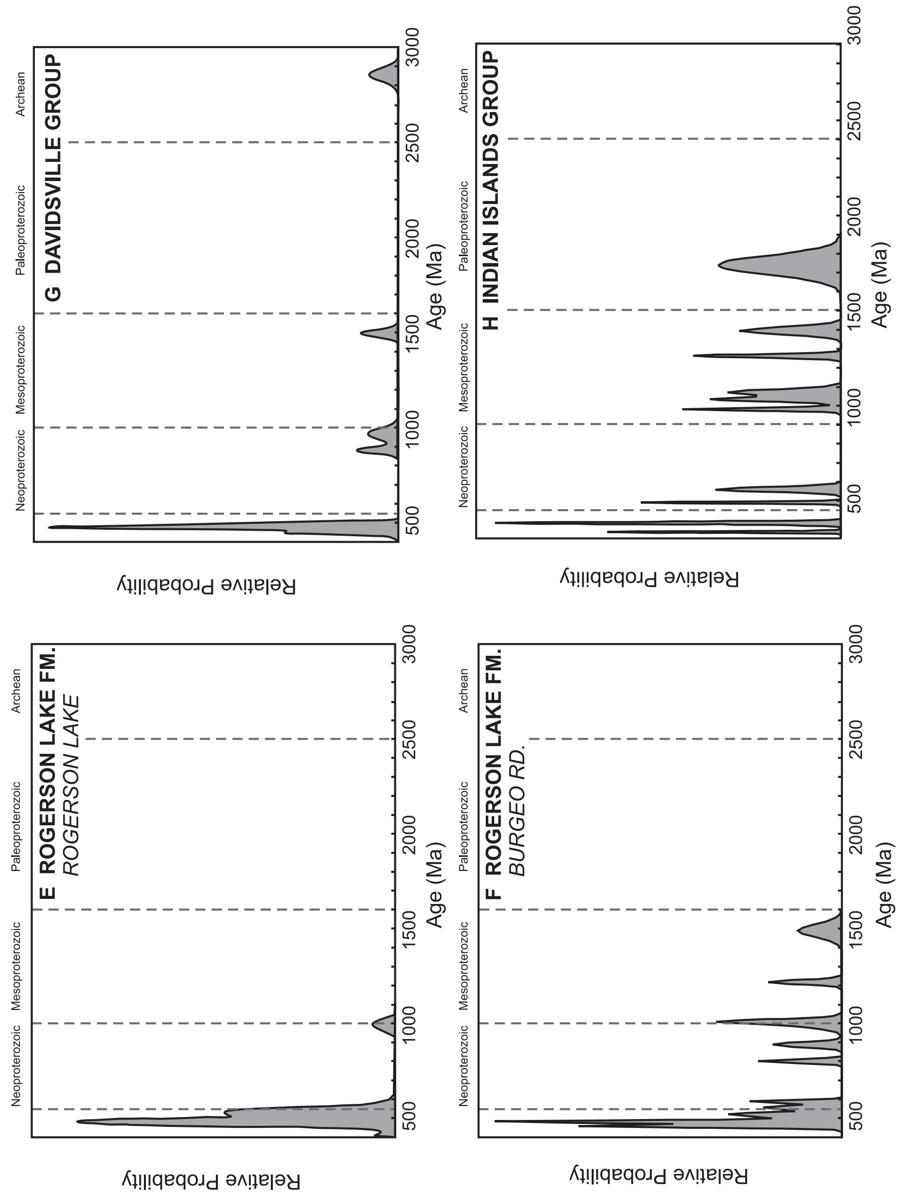


Fig. 6. Continued

and red sandstone of the Botwood Group. Fossil bearing strata assigned to the Goldson Formation have an age range that extends from the middle Ashgill to the early Llandovery (O'Brien, 2003).

The analyzed sampled (A) was collected from the east shore of Burnt Bay in the town of Lewisporte. This sample yielded abundant zircons that varied from clear, round anhedral grains with minor fractures, to clear, elongate prisms that contained abundant fractures. Both morphologies contained inclusions that appeared to be mainly feldspar. Simple oscillatory zoning was visible in back-scattered electron (BSE) images from some grains (fig. 4). Laser ablation analysis produced near concordant data (fig. 5A) with ages that range from 2645 Ma to 478 Ma. The dominant grouping of ages (fig. 6A) is in the Cambrian and Ordovician (509 Ma – 464 Ma) and a minor grouping of ages in the Mesoproterozoic (1331, 1290, and 1059 Ma). The oldest population was obtained from a single zircon grain that has an Archean age of 2645 Ma.

Goldson Formation, Badger Group.—This gray pebble conglomerate sample (B) was collected from an isolated outcrop alongside Stony Lake Road approximately 25 km south of the town of Grand Falls. Zircon grains were dominantly euhedral prismatic 0.02 mm long crystals, with a lesser amount of smaller rounded and broken grains. Some of the euhedral crystals contain unknown mineral inclusions. The detrital zircon ages define two populations on Concordia (fig. 5B). The dominant population (fig. 6B) is Ordovician and comprises ages that vary between 487 and 439 Ma. The oldest age is Proterozoic from a single zircon grain that has a concordant age of 1027 ± 27 Ma.

Wigwam Formation, Botwood Group.—The Wigwam Formation is a 2.5 to 3.5 km thick unit of medium- to coarse-grained, cross-bedded red and green sandstone that conformably overlies subaerial volcanic rocks of the Lawrenceton Formation. Two coarse-grained red sandstone samples (C and D) were collected from: (1) the south shore of the Exploits River in the town of Grand Falls; and (2) a roadside outcrop in the town of Botwood. Both samples contained abundant detrital zircons that exhibited a variety of morphologies from anhedral to euhedral, well faceted, clear, slightly colored crystals that were fractured and fragmented. Some of the grains contained inclusions, but no crystal zonation was observed in any of the grains imaged. Both samples were analyzed separately but are discussed together because they contain comparable age spectra.

Analytical results for the zircon grains (figs. 5C and 5D) cluster in the Late Archean (ca. 2750 – 2500 Ma) and the Paleoproterozoic (between 1730 and 1660 Ma). The largest population (figs. 6C and 6D) of zircons clusters in the Mesoproterozoic between 1512 and 1013 Ma, whereas a single detrital zircon yielded a Cambrian age of 512 Ma.

Rogerson Lake Formation, Botwood Group.—The Rogerson Lake Formation constitutes part of the southwest extension of the Botwood Group (Williams and others, 1995). It comprises red to purple conglomerate of pebble-sized clasts of sandstone, siltstone, rhyolite, basalt, granite and shale set in a medium-grained sandy matrix. The presence of numerous red sandstone clasts in the conglomerate suggests that parts of the underlying Wigwam Formation may have been recycled and cannibalized into the Rogerson Lake Formation. The formation unconformably overlies Middle Ordovician and older volcanic and Neoproterozoic intrusive rocks of the Exploits Subzone.

This sample (E) was collected from the type area of the formation along the southern shore of Rogerson Lake. The conglomerate varies from gray to red, with pebble-sized clasts in a matrix of gray to red sandy material. The matrix consists of quartz, feldspar, muscovite and chlorite with hematite and carbonate cement. The varied clast population includes subrounded to rounded clasts of red siltstone, sandstone, shale and limestone; mafic flows and porphyritic rhyolite clasts are abundant.

U-Pb data (fig. 5E) for detrital zircons define a single group that yield a restricted age (fig. 6E) ranging from the late Neoproterozoic (ca. 545 Ma) to the Middle Ordovician (ca. 468 Ma). Although comprising a single grain, a minor early Neoproterozoic component is recognized with an age of 986 ± 33 Ma.

Rogerson Lake Formation, Botwood Group.—The conglomerate consists of strongly deformed, coarse-grained, polymictic red pebble clasts of dominantly felsic volcanics with minor jasper, gray and red sandstone, black shale, limestone, quartz porphyry and granite. The rock is in tectonic contact with felsic volcanic rocks of the Victoria Lake Supergroup (Williams and others, 1995). The presence of red sandstone clasts suggests that Early Silurian redbeds of the Wigwam Formation may have been recycled into this unit. This unit has been correlated (Zagorevski and van Staal, 2002) with the Rogerson Lake Formation, but the rare limestone interbeds are atypical of Botwood Group lithologies.

The analyzed sample (F) was collected from a roadside outcrop on the Burgeo highway in southwest Newfoundland. Two zircon populations were recognized (fig. 6F); a subhedral, clear, colorless group and a collection of clear, pale red zircons. The data show that no age differences are apparent between the two groups. The distribution of data points on Concordia (fig. 5F) show prominent clusters in the Mesoproterozoic (1523 – 1218 Ma), late Mesoproterozoic to early Neoproterozoic (1013 – 897 Ma), and Neoproterozoic (802 – 698 Ma). The majority of zircons have latest Neoproterozoic to Cambrian ages between 579 and 495 Ma and Ordovician ages ca. 490 to 440 Ma.

Outflow Formation, Davidsville Group.—The Outflow Formation (Currie and Williams, 1995) constitutes the medial formation of the Davidsville Group. The unit comprises fine- to coarse-grained turbiditic sandstone, locally containing shale intraclasts, interbedded with gray to black siltstone and slate; minor conglomerate beds are locally present at the base of the formation. The age of the Outflow Formation is not directly known since it is unfossiliferous. Its age, however, is constrained between the late Arenig and late Llanvirn by peri-Gondwanan trilobites and shelly fauna from sandstones and brachiopods, cephalopods and trilobites in limestone of the underlying Weir's Pond Formation (McKerrow and Cocks, 1976; Boyce and others, 1988) and by the Llandovery age of the overlying Indian Islands Group.

This sample (G) of coarse-grained, green sandstone was taken from a roadside outcrop on the eastern shore of Gander Bay and contains zircons that are euhedral, elongate grains with minor inclusions and fractures. A smaller proportion of anhedral, sub-rounded grains with abundant fractures are also present. Dated zircons (fig. 5G) range in age from 2750 ± 26 Ma to 443 ± 22 Ma. The data (fig. 6G) show distinct groups in the Archean (2750 Ma), the Mesoproterozoic (ca. 1495 Ma), the early Neoproterozoic between 965 ± 62 Ma and 879 ± 31 Ma and the Late Cambrian-Ordovician between 502 ± 11 Ma and 443 ± 22 Ma.

Big Indian Pond Formation, Indian Islands Group.—The Big Indian Pond Formation is the uppermost unit of the Indian Islands Group (Williams and others, 1993). It consists mainly of subaerial red sandstone and siltstone that are disconformable upon Ordovician shales and mélange of the Davidsville Group. The age of the Indian Islands Group is constrained by Wenlock brachiopods and shelly faunas (Wu, ms, 1979) and Ludlow graptolites (Berry and Boucot, 1970; Williams, 1972). The Indian Islands Group is conformably overlain by gently dipping red shale, siltstone and sandstone of the Ten Mile Lake Formation (Currie, 1995) that contains Pridolian to Lochkovian bivalve faunas (Boyce and others, 1993).

The sample (H) of fine-grained, silty, red sandstone was collected from a roadside outcrop in the community of Horwood. It yielded numerous zircons that varied from

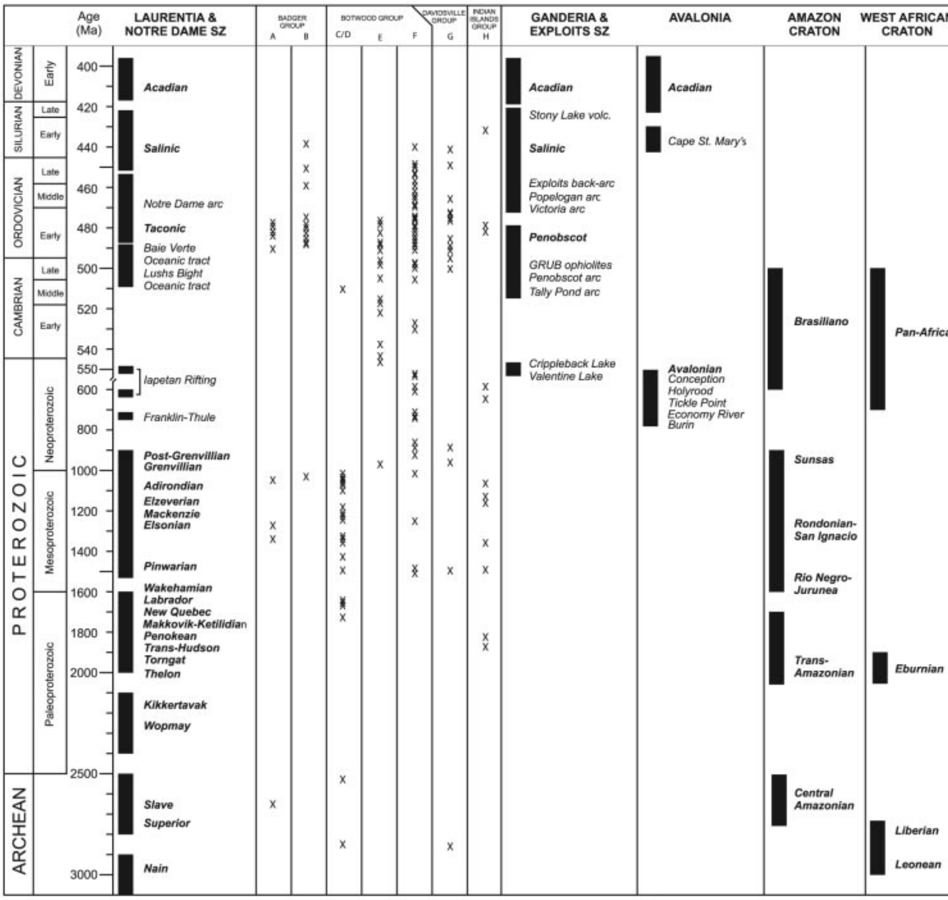


Fig. 7. Comparison chart of detrital zircon ages from Late Ordovician-Silurian sequences from northeast Newfoundland and ages of magmatic, metamorphic and orogenic events in Laurentia and Gondwana.

clear and colorless to slightly cloudy, elongate, euhedral crystals to rounded zircons with abundant fractures.

The zircon grains, representing the entire range of crystal morphologies, yielded a wide range of ages (figs. 5H and 6H) that cluster in the Paleoproterozoic (ca. 1850 Ma), Mesoproterozoic (1358 ± 17 Ma), late Mesoproterozoic (between 1167 ± 29 Ma and 1078 ± 15 Ma) and Neoproterozoic to Silurian (650 – 430 Ma).

DETRITAL PROVENANCE

The new U-Pb age data (fig. 7) for detrital zircons from Late Ordovician to Early Silurian rocks of central and northeastern Newfoundland denote a varied provenance including Paleozoic accreted volcanic arcs, Proterozoic orogenic belts and Archean cratonic sources that can be matched with specific source terranes from the Laurentian hinterland, the tectonically active Laurentian margin and peri-Gondwanan microcontinents.

Northwest of the Dog Bay Line

The oldest rocks sampled from the Badger Group northwest of the Dog Bay Line (samples A and B; fig. 6) are dominated by zircons that have Paleozoic ages of between

510 and 440 Ma; the majority of these grains are Late Cambrian to Tremadocian and have ages that cluster at ca. 510 to 480 Ma. These ages correspond well with the ages of arc/backarc volcanic sequences in either the Notre Dame Subzone or the Exploits Subzone. The Notre Dame Subzone contains a collection of Upper Cambrian to Tremadoc supra-subduction-zone ophiolites (Bay of Islands - 485 ± 5 Ma, Lushs Bight - ca. 495 Ma, Betts Cove - 488 +3.1/-1.8 Ma, Annieopsquotch - 481+4/-1.9 Ma) and ensimatic volcanic-plutonic complexes (Twillingate-Sleepy Cove-Moreton's Harbour, Little Port) termed the Baie Verte oceanic tract. Geochronological and geochemical evidence indicate that volcanic activity occurred from before 507 Ma (Little Port Complex) and continued for ca. 40 m.y. to about 468 Ma (Dunning and Krogh, 1985, 1991; Jenner and others, 1991; Elliot and others, 1991). These sequences were intruded by a series of Ordovician tonalitic plutonic rocks, termed the Notre Dame arc, between 490 and 455 Ma (Dubé and others, 1996; Whalen and others, 1997; Swinden and others, 1997).

The Early and Middle Ordovician magmatic arc and ophiolite sequences in the underlying rocks of the Victoria Lake Supergroup, and Wild Bight and Exploits groups of the Exploits Subzone have a similar age range (515 – 455 Ma, van Staal and others, 1998 and references therein) as those in the adjacent western Notre Dame Subzone, with which they were juxtaposed by the middle to late Caradoc (ca. 455 Ma, McNicoll and others, 2001). Two periods of Early to Middle Ordovician volcanism are recorded in the rocks of the western Exploits Subzone (Evans and others, 1990; O'Brien and others, 1997; MacLachlan and Dunning, 1998; Rogers and van Staal, 2002; Zagorevski and others, 2003). Cambrian-Tremadoc (ca. 515 – 486 Ma) volcanic-plutonic arc rocks, locally with an ophiolitic base (the Penobscot/Exploits arc) and a late Arenig-Caradoc (479 – 455 Ma) volcanic sequence that records the formation of a kinematically unrelated rifted arc complex, the Victoria arc-Exploits backarc system (van Staal and others, 1998). Mafic and felsic volcanism continued at least until the early Caradoc.

Previous workers (Dean, 1978; Nelson, 1981; Arnott, 1983) dominantly favored a Notre Dame Subzone provenance for the detritus in Silurian rocks of the Badger Group based on clast composition and paleocurrents. Helwig (ms, 1967), however, speculated that both the Notre Dame and the western Exploits subzones may have shed detritus into the Badger Group. The zircon data alone cannot establish if the detritus were derived from either subzone, but the Exploits Subzone contains no record of a major Late Ordovician unconformity as the Middle Ordovician volcanic succession is conformable upwards into the marine Badger and terrigenous Botwood groups in the Early Silurian. The detritus were most likely derived from the Notre Dame Subzone as its Early Ordovician rocks are overlain by Early Silurian subaerial volcanic rocks and related redbeds with significant unconformity (Williams and others, 1988).

In contrast to the underlying Badger Group, the samples from the Wigwam Formation of the Botwood Group (Samples C and D, fig. 6) are dominated by zircons of early Neoproterozoic (900 Ma) and late Mesoproterozoic (1030 and 1250 Ma) age; detritus younger than 1000 Ma is typically absent. A reasonable potential provenance for these zircons is the Long Range Inlier of western Newfoundland (fig. 1) which constitutes part of the Grenville Province (Owen and Erdmer, 1990; Heaman and others, 2002; Gower and Krogh, 2002).

The Long Range Inlier is the largest exposure of Laurentian basement inside the Appalachian Orogen and comprises Proterozoic high-grade quartz-feldspar gneisses and granites. Basement gneisses of the Long Range Inlier in the area of Western Brook Pond are dated at 1250 Ma (Erdmer, 1986) and 1466 ± 10 Ma (Heaman and others, 2002). Gneissic basement rocks sampled from the eastern edge of the Long Range Inlier near Cat Arm Road, however, are older and yield early Mesoproterozoic ages of 1530 ± 8 Ma and 1631 ± 2 Ma (Heaman and others, 2002). These Mesoproterozoic rocks are intruded by a belt of granitoid plutons, both in the Long Range Inlier and the adjacent Grenville Province in southern Labrador and Québec that were emplaced during two distinct episodes that span a ca. 60 Ma period between 1032 and 985 Ma (Gower and Loveridge, 1987; Schärer and Gower, 1988). Early Grenvillian granitoid intrusions were emplaced during the period 1032 to 1022 Ma whereas Late Grenvillian granitoid bodies were emplaced in the period 999 to 985 Ma and post-date Grenvillian high-grade metamorphism (Heaman and others, 2002; Gower and Krogh, 2002).

Another potential source for the Mesoproterozoic and Neoproterozoic zircons is the Steel Mountain and Indian Head inliers exposed in southwest Newfoundland (fig. 1). Felsic granulite gneiss of the Disappointment Hill complex in the Steel Mountain Inlier yielded an upper intercept U-Pb zircon age of 1498 + 9/-8 Ma and a foliated gabbro related to Steel Mountain anorthositic rocks has an upper intercept age of 1254 ± 14 Ma (Currie and others, 1992). Several granitic gneiss units of the Indian Head Inlier from the Stephenville area contain hornblende and biotite that yielded undisturbed $^{40}Ar/^{39}Ar$ spectra with ages of 880 and 825 Ma, respectively (Dallmeyer, 1978).

The Proterozoic ages of detrital zircons in the Botwood Group therefore cover the same age range within the limits of uncertainty as those in the Laurentian basement inliers in western Newfoundland. However, the various Paleoproterozoic and Mesoproterozoic (1750 – 990 Ma) ages also correspond with the ages of magmatism, deformation and metamorphism in southern Labrador. There rocks occur that formed during the Grenvillian (1080 – 985 Ma), Adirondian (1180 – 1080 Ma), Elzevirian (1230 – 1180 Ma), Middle Elsonian (1350 – 1290 Ma), Pinwarian (1520 – 1460 Ma), Trans-Labrador (1654 – 1646 Ma) and Pre-Labradorian (>1710 Ma) orogenic events (Connelly and Heaman, 1993; Tucker and Gower, 1994; Gower and Krogh, 2002). The zircon data alone do not discriminate between first generation detrital zircons derived directly from the above protosources and second-generation reworked zircons. The latter, however, cannot be precluded as Nd and Pb isotopes (Whalen and others, 1997), and Mesoproterozoic and Paleoproterozoic xenocrystic zircon data (Dunning and others, 1989), indicate that the Notre Dame arc formed by partial melting of Middle Proterozoic or older crust or sediments derived from such crust.

The oldest zircons in the rocks northwest of the Dog Bay Line are three Archean grains sampled from the Badger and Botwood groups. The 2850 to 2650 Ma zircons ages correspond in age with rocks of the Makkovik Province of central Labrador; granodioritic gneiss from the Aillik Domain yielded zircons of 2813 +16/-13 Ma with 2648 Ma fractions (Ketchum and others, 2002). Archean rocks are also present in the Nain Province of northern Labrador. In the Hopedale block, a suite of granitic intrusions was emplaced at ca. 2850 Ma (Loveridge and others, 1987) whereas zircons related to high-grade metamorphism at ca. 2700 Ma are present in the Saglek block (Bridgwater and Schiøtte, 1991).

The two conglomerate samples from the Rogerson Lake Formation (samples E and F) contain a dominant Paleozoic (ca. 570 – 480 Ma) and minor Neoproterozoic (ca. 560 – 550 Ma) zircon population. The Paleozoic ages are found in vestiges of arc/backarc sequences from both the Notre Dame and Exploits subzones, whereas the late Neoproterozoic ages correspond with Neoproterozoic arc plutonic rocks preserved in the Victoria Lake Supergroup in the Exploits Subzone of central Newfoundland. Two of these plutons, the Valentine Lake and Crippleback Lake quartz monzonites have been dated by U-Pb zircon at 563 ± 2 Ma and 565 +4/-3 Ma, respectively (Evans and others, 1990). It is also possible that these detrital zircons were derived from the Iapetan rift related volcanics of the Humber Zone, the 550.5 +3/-2 Ma Skinner Cove Formation (Cawood and others, 2001) and 555 +3/-5 Ma Lady Slipper pluton (Cawood and others, 1996), since Early Silurian deformed rocks occur as far west as the Humber Zone (Castonguay and Tremblay, 2003). However, it is more likely that these zircons were derived from erosional unloading and unroofing of the Victoria and Exploits arc/backarc sequences in the western Exploits Subzone that are unconformably overlain by the Rogerson Lake Formation since these rocks contain zircons within the range 540 to 510 Ma, which are absent in the Humber Zone and Notre Dame Subzone.

The detrital zircons of ca. 725 Ma age from the Rogerson Lake Formation (sample F) are not correlatable with any known rocks in the ophiolitic or arc volcanic sequences of the Notre Dame or Exploits subzones. Nor do they correspond with any currently exposed rocks in the Laurentian basement of the Humber zone. These ages, however, may be related to the earliest stages of Rodinian break-up; during the Neoproterozoic Laurentia was situated in the core of the supercontinent Rodinia (Hoffman, 1991). Ages between 760 and 700 Ma have been reported for rift-related mafic dikes and rhyolites in the central and southern Appalachians (Goldberg and others, 1986; Su and others, 1994; Tollo and Hutson, 1996), and late Neoproterozoic rift-related intrusive rocks are present along all the margins of Laurentia (Hoffman, 1988, 1989) including the southwestern and northern Canadian Shield. One of these swarms, the Franklin igneous event in Nunavut, has been dated by U-Pb geochronology at 723 +4/-2 Ma (Heaman and others, 1992). This intrusive igneous event may be related to a widespread episode of extension, break-up and rifting along northwestern Laurentia and may in part be linked to a series of protracted or repeated large-scale intrusive events, including the Long Range dikes, that span over 200 Ma and document the final breakup of Rodinia.

Alternatively, these zircons may be Gondwanan-related and derived from the Ganderian basement rocks of the Victoria arc sequences or from Avalonian zircons recycled from the Gander Zone. In the Avalon Zone of Newfoundland, rocks of the Burin Group record an episode of rifting at 763 ± 2 Ma (Krogh and others, 1988); similar ages are found in the Flemish Cap Granodiorite (751 Ma, Mandville, 1989) and the Economy River orthogneiss (734 ± 2 Ma) in the Cobequid Highlands of Nova Scotia (Doig and others, 1991). For this interpretation to be viable, however, it requires that sedimentation in the upper sequences of the Botwood Group post-dates the Ganderia-Laurentia collision.

Southeast of Dog Bay Line

Rocks from the opposing southeast side of the Dog Bay Line show a wide age spectrum with well defined Cambrian-Ordovician (520 – 440 Ma), Neoproterozoic-Late Mesoproterozoic (713 – 580 Ma and 890 – 1160 Ma), Mesoproterozoic (1350 – 1800 Ma) and Archean (2650 – 2850 Ma) age assemblages. The Ordovician clastic sedimentary rocks of the Davidsville Group are dominated by Late Cambrian-Early Ordovician zircons that are similar to the depositional age of the strata. Although it is possible that these zircons were derived from the Victoria and Penobscot arc volcanic rocks of the western Exploits Subzone, it is more likely that the zircons were sourced from Upper Cambrian ophiolitic Penobscot backarc rocks of the eastern Exploits Subzone (Colman-Sadd and others, 1992; Jenner and Swinden, 1993; van Staal and others, 1998). The latter include the Pipestone Pond, Coy Pond and Gander River complexes that comprise small bodies of mafic-ultramafic plutonic and volcanic rocks interpreted as incomplete ophiolite suites. Conglomerates of the Davidsville Group unconformably overlie and contain clasts of ultramafic rocks and tonalites of the Gander River Complex. O'Neill (1991) suggests that the Gander River Complex formed the principal source of detritus in the overlying Davidsville Group. Formation of ophiolite complexes in the Exploits Subzone partially overlaps formation of the Tremadoc arc volcanic rocks of the Victoria Lake, Exploits and Wild Bight groups and is constrained by a 493 +2.5/-1.9 Ma age from the Pipestone Pond Complex and a 489 Ma age from the Coy Pond Complex (Dunning and Krogh, 1985).

Detritus derived from the Gander Zone sedimentary rocks and their rarely exposed Neoproterozoic to Early Cambrian basement, however, are equally possible as a source. Stratigraphic and intrusive relationships and the presence of detrital titanite indicate that the Gander Zone clastic sedimentary rocks were deposited during the Early Cambrian to early Arenig (O'Neill, 1991; Colman-Sadd and others, 1992), whereas its inferred basement in southern Newfoundland has yielded ages between 700 and 495 Ma (Dunning and O'Brien, 1989; O'Brien and others, 1991). Petrographic analysis of the Davidsville Group (O'Neill, 1991) indicates that its source terrain was, in part, a continental block that included sedimentary graywackes and arenites and granitoid plutons. Fossils and zircons in Gander Zone cover rocks of New Brunswick, which are lithologically undistinguishable from those in Newfoundland (van Staal and others, 1996) provide tighter time constraints: ~514 to 480 Ma for the clastic cover rocks (Pickerill and Fyffe, 1999; van Staal and others, 2002). The youngest known basement rocks that unconformably underlie clastic rocks of the Gander cover are arc volcanic rocks of the New River belt with a U-Pb zircon age of 514 ± 2 Ma (Johnson, 2001; McLeod and others, 2003). Ordovician granitic rocks are abundant throughout the Gander Zone in Newfoundland and elsewhere. One pluton, the 474 +6/-3 Ma Partridgeberry Hills Granite intrudes both Gander and Dunnage Zone rocks (Colman-Sadd and others, 1992).

Mesoproterozoic (ca. 1550 Ma) and Neoproterozoic (ca. 710 – 580 Ma) zircons from the Davidsville and Indian Island groups are the first evidence for a Gondwanan-derived detrital component in the Ordovician and Silurian rocks in the Exploits Subzone. Similar age spectra are found in the underlying Early Cambrian strata of the Gander Group (O'Neill, 1991). 1520 to 1600 Ma orogenic and magmatic events are noticeably absent from Laurentia and characteristic of Gondwana. Within the peri-Gondwanan terranes, late Neoproterozoic tectonomagmatic and depositional events span more than 200 Ma between the end of the ca. 1000 Ma orogenesis and the onset of Appalachian orogenesis. In the Newfoundland Avalon Zone magmatic, deformational, and metamorphic events (O'Brien and others, 1996) are recognized at 760 Ma (Burin Group), 685 to 670 Ma (Tickle Point Formation; Furby's Cove Intrusive Suite), 635 to 590 Ma (Holyrood Intrusive Suite; Love Cove Group) and 590 to 565 Ma (Conception Group). Rock of these ages occur also in Laurentia, although temporally equivalent sedimentary sequences on the Laurentian margin do not contain zircons of these ages and therefore it is more likely that the ca. 800 to 600 Ma zircons were derived from peri-Gondwanan terranes.

The presence of ca. 710 to 580 Ma Neoproterozoic zircons in Silurian rocks southeast of the Dog Bay Line and their absence in temporally equivalent sedimentary sequences on the Laurentian margin imply that they were not derived from Laurentia and suggest their derivation from a peri-Gondwanan terrane, either Ganderia or Avalon or some combination of both terranes. The exact mode of transport however, is uncertain and there are at least three possible interpretations that could explain the data: 1) The zircons are first-generation detrital grains, derived directly from igneous protosources in the Avalon Zone and deposited directly onto the Exploits Subzone; 2) The zircons are xenocrysts inherited from basement in the Ordovician Gander Zone igneous rocks that were subsequently exposed, eroded and deposited into the Indian Islands and Davidsville groups; 3) The zircons are second-generation Avalonian zircons that were recycled from sedimentary rocks in the Gander Zone. On the basis of zircon morphology each of these situations is possible as the zircons ranged from euhedral well-faceted crystals to well rounded grains that contain abundant fractures. The first situation, however, is not likely because even though Gander and Avalon have similar arc-dominated Neoproterozoic basement rocks, they have very distinct magmatic, depositional and tectonic histories (O'Brien and others, 1996) and were therefore most likely tectonically decoupled and widely separated in the early Paleozoic. The second situation is also dubious as the zircons are all near-concordant and show no evidence of overgrowths and/or Pb loss that would be expected if the zircons were subjected to the high temperatures of partial melting. The third situation is easily envisaged as single detrital zircon and titanite U-Pb ages from clastic rocks of the Gander Group contain late Neoproterozoic to Early Cambrian components (O'Neill, 1991). Therefore, we consider Ganderia to be the most likely source of this detritus.

The coexistence of significant amounts of Neoproterozoic, Mesoproterozoic, and Archean zircons in all of the Late Ordovician to Early Silurian sequences from both sides of the Dog Bay Line appears to preclude their use in determining sediment provenance. Early Cambrian (540 – 510 Ma) igneous rocks do not occur in Laurentia and are extremely rare in Avalonia, but they are diagnostic for Ganderia. Detritus within the range 540 to 510 Ma is present in samples from southeast of the Dog Bay Line (O'Neill, 1991) and consequently the 900 to 1800 Ma and >2500 Ma zircons from the south east of the Dog Bay Line are more readily explained as being derived from a Gondwanan source rather than Laurentia. These ages correspond to the Pan-African (500 – 750 Ma), Eburnian (1900 – 2200 Ma) and Liberian (>2500 Ma) orogenic events (fig. 7) of the West African craton (Nance and Murphy, 1996). This part of Gondwana, however, contains no record of an early Neoproterozoic to Mesoproterozoic orogenic event thereby negating a West African provenance. A more plausible provenance for the Davidsville and Indian Island groups is the Amazonian craton. The Amazonian craton comprises a cratonic collage that was assembled through a complex orogenic history involving the Sunsas/Aguapei (900 – 1100 Ma), Rondonian/San Ignacio (1450 – 1250 Ma), Jurena/Rio Negro (1750 – 1500 Ma), Trans-Amazonian (2200 – 1900 Ma) and Archean orogens (3200 – 2600 Ma) in South America (Teixeira and others, 1989). The Brasiliano (ca. 500 – 600 Ma) orogenic cycle resulted in the collision of the Amazonian craton with other Paleoproterozoic and older cratons to form the South American nucleus of Gondwana (Ramos, 1988; van Staal and others, 1996). The absence of ca. 1650 Ma zircons southeast of the Dog Bay Line also supports an Amazonian provenance as Amazonia lacks any magmatic activity between 1700 to 1600 Ma.

DISCUSSION: THE LATE ORDOVICIAN-EARLY SILURIAN TECTONIC EVOLUTION OF THE NORTHEASTERN NEWFOUNDLAND APPALACHIANS

Contrasts between the range and distribution of detrital zircon ages from rocks on opposing sides of the Dog Bay Line impose important constraints on the paleotectonic relationships between each clastic sequence, namely their sediment sources, depositional and tectonic histories. The new zircon data from the Badger and Botwood groups, northwest of the Dog Bay Line, cover a broad range of ages that collectively display similar ages that are present in varying proportions in each unit. The detrital ages are dominated by Iapetan, Grenvillian, Pinwarian, and Makkovikian orogenic sources that are characteristic of Laurentia. In contrast, the Davidsville and Indian Islands groups southeast of the Dog Bay Line have stratigraphic links to, and contain detritus from, peri-Gondwanan terranes which were accreted to Laurentia in the Early Silurian.

Taconic Obduction of the Notre Dame Subzone and Penobscot Obduction of the Exploits Subzone (480 – 455 Ma)

The abundance of Iapetan arc and associated intrusive zircons in the Badger Group is attributed to the accretion of the Notre Dame Subzone with Laurentia and indicate that juxtaposition of the Exploits and Notre Dame subzones and closure along the Red Indian Line was complete by the Ashgill. Dismembered volcanic arc and ophiolitic rocks derived from Baie Verte oceanic tract and Notre Dame arc were obducted, exhumed and eroded in the Ashgill-Llandovery (Tremblay and others, 1997) and redeposited as syntectonic, north younging, upward-coarsening sequences of graywackes and conglomerates (Badger Group) into the adjacent oceanic trench. The volcanic and ophiolitic rocks may also have been exposed due to a Late Ordovician regression that is possibly related to continental glaciation in Laurentia (McCann and Kennedy, 1974).

During the Llanvirn-Caradoc, the opposing eastern side of the Dog Bay Line was situated along the relatively stable, passive Gander margin of peri-Gondwana. The Davidsville Group contains detritus from and unconformably overlies obducted Penobscot ophilolites of the Gander River Complex. The absence of ca. 900 to 510 Ma and 1500 to 1600 Ma age zircons in the basal sequence (Badger Group) west of the Dog Bay Line and the presence of significant Neoproterozoic detritus in the Indian Islands Group suggests a sediment trap consistent with the presence of a Late Ordovician-Early Silurian seaway, the Tetagouche-Exploits back-arc basin (Iapetus II of van der Pluijm and van Staal, 1988), which separated the Gander margin from Laurentia and its accreted arc terranes (Williams and others, 1993; van Staal, 1994; Currie, 1995; van Staal and others, 1998).

Opening and Width of the Tetagouche-Exploits Basin (472 – 455 Ma)

The Late Ordovician-Early Silurian Tetagouche-Exploits basin situated along the Dog Bay Line (fig. 8A) has been interpreted to relate to either a marine succession of separate fault-bounded pull apart basins (Watson, ms, 1981; Arnott, 1983; Arnott and others, 1985; Kusky and others, 1987), a single depositional basin (Karlstrom and others, 1982; Reusch, ms, 1983; van der Pluijm, 1986; Lafrance and Williams, 1992) or series of basins controlled by thrust imbrication (Pickering and others, 1988). The detrital zircon data, however, suggest the presence of more than one depositional basin, as Ashgill-Wenlock rocks northwest of the Dog Bay Line contain detritus derived exclusively from Laurentia and zircons southeast of the line have no Laurentian affinities. Sedimentological and paleocurrent data support the idea of several distinct depositional basins located on opposite sides of the Tetagouche-Exploits basin. Late Ordovician sequences northwest of the Dog Bay Line contain northwest-younging, west-derived debris (Watson, ms, 1981; Arnott, 1983; Pickering, 1987); strata southeast of the line indicate deposition with an easterly provenance (Pajari and others, 1979).

The width of the Tetagouche-Exploits back-arc basin separating these depositional basins is constrained by faunal and geochronological data to about 1000 km (van Staal and others, 1998). Similar Arenig to Llanvirn faunas are present on both sides of the Dog Bay Line (Neuman, 1984; Williams and O'Brien, 1991) and pelagic larvae of animals such as brachiopods are thought to be capable of traversing oceans of such width, but not further (Fortey and Cocks, 2003), which suggest that this seaway was not a wide ocean basin. The transition from arc-related to non-arc magmatism in the Exploits Subzone (Swinden and others, 1990) is confined to the late Arenig-early Llanvirn. The earliest refractory and transitional arc-tholeiites generated during the initial stages of backarc basin formation are present in the Wild Bight Group (471 ± 4 Ma; MacLachlan and Dunning, 1998), Exploits Group (470 Ma; O'Brien and others, 1997) and Baie d'Espoir Group (468 ± 2 Ma; Colman-Sadd and others, 1992). The cessation of spreading and back-arc volcanism was complete by the Caradoc with a hiatus in magmatism and extensive black shale deposition across the entire Exploits Subzone. An average seafloor spreading rate of between 5.0 –7.5 cm a^{-1} over this ca. 15 Ma time span would produce an ocean basin in the range of 750 to 1125 km. An ocean basin wider than this width would also imply relatively high rates of convergence to close this basin by the Late Silurian.

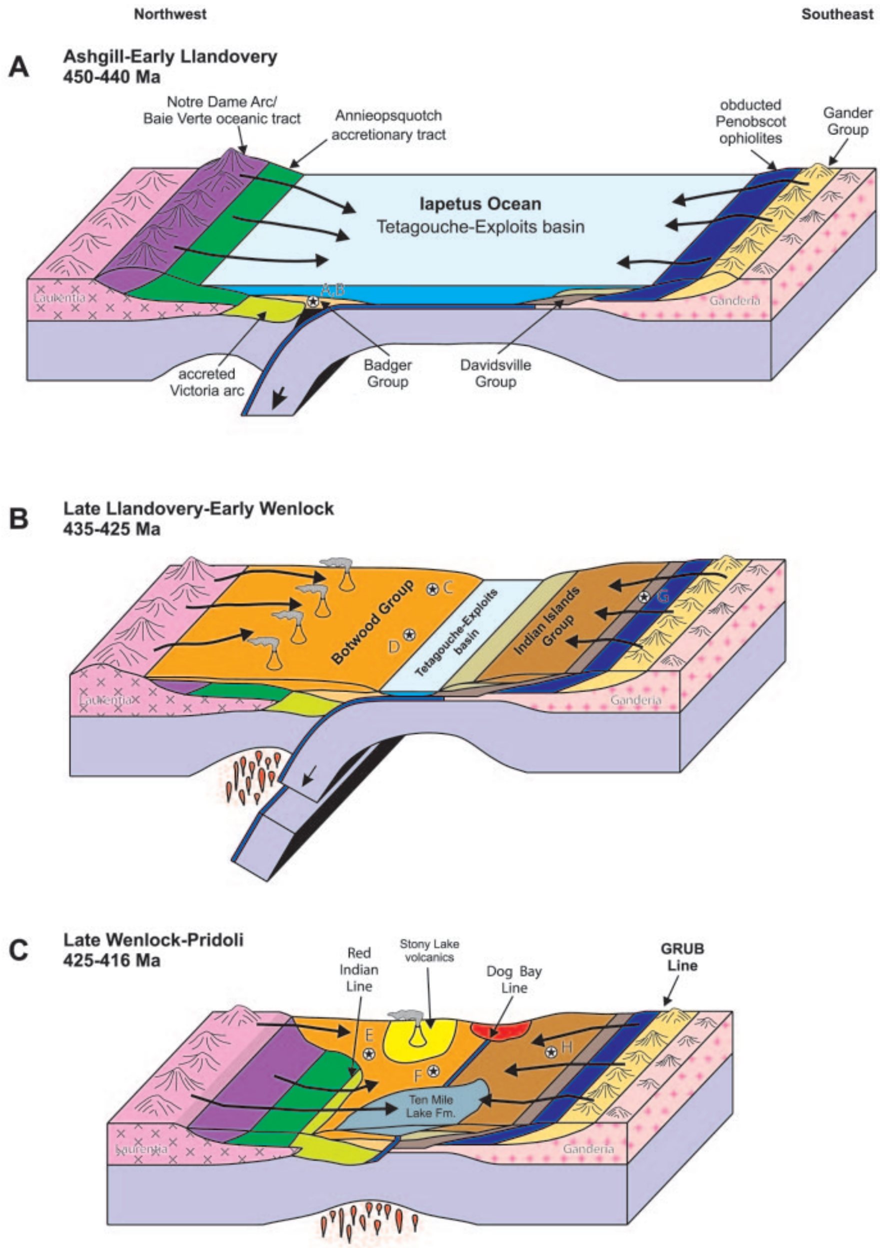


Fig. 8. Late Ordovician-Late Silurian collision tectonic evolution of the Newfoundland Appalachians as proposed from detrital zircon data. The Dog Bay Line lies along the Ganderia-Laurentia collision zone and represents the terminal Iapetan suture in the Newfoundland Appalachians. Arrows indicate zircon sources and potential transport directions. Cartoon is drawn to emphasize stratigraphic and structural relationships and no scale is implied.

Initiation of Subduction and Closure of the Tetagouche-Exploits Basin (455 – 425 Ma)

Closure of the Tetagouche-Exploits backarc basin (fig. 8B) was initiated in the Late Ordovician and is recorded in the transition from deep marine (Badger Group) to subaerial terrigenous sedimentation in the Botwood Group, and a change in depositional setting from an arc-trench to an overlying forearc basin. In contrast to the Paleozoic-dominated Badger Group, zircons in redbeds of the Early Silurian Wigwam Formation of the Botwood Group cluster in the early Neoproterozoic to Mesoproterozoic range, defined by Gower and Krogh (2002) and Heaman and others (2002) as characteristic for the Grenville Province. These data suggest that the Laurentian basement must have been more elevated than the accreted Iapetan terranes. Such a situation could possibly be related to erosional unroofing of the obducted Baie Verte oceanic tract and Notre Dame arc sequences in the hinterland thereby exposing the underlying and uplifted Laurentian basement.

Regression on the Laurentian margin is synchronous with a change from deep-water turbidites (Gander Group) to overlying shallow-water, stable-shelf sedimentary rocks of the Davidsville Group on the Gander margin. Oceanic lithosphere of the Tetagouche-Exploits basin was destroyed by oblique northwest directed subduction beneath the Laurentian margin. Late Ordovician-Early Silurian ophiolites from this basin are not preserved in Newfoundland; however, the Pine Falls and Noggin Cove formations (Johnston and others, 1994) comprise non-arc oceanic back-arc basalts (E- or T-MORB) and gabbros that are situated immediately along the eastern side of the Dog Bay Line.

Collision of Ganderia and Laurentia and Salinic Orogenesis (425 – 418 Ma)

Closure of the Tetagouche-Exploits backarc basin (fig. 8C) was complete by the Late Silurian (ca. 423 Ma) at which time the Indian Islands Group was juxtaposed against the Botwood Group across the Dog Bay Line. Late Silurian date for closure is also supported by paleomagnetic data that indicate a similar paleomagnetic inclination for the Indian Islands and Botwood groups in the Late Silurian (Smethurst and McEnroe, 2002). Deposition of conglomerates on the Laurentian margin which occurred synchronously and continued after closure was dominated by Paleozoic zircons derived from both the Notre Dame and Exploits subzones, indicating major uplift and erosional unroofing of the Victoria and Exploits arcs.

These data suggest that the conglomerates of the Rogerson Lake Formation sampled from the Burgeo highway may represent the youngest rocks of the Botwood Group that transgress the Dog Bay Line as an overlap sequence. A similar sequence, the Late Silurian Ten Mile Lake Formation is reported (Currie, 1995) to uncomfortably overly the Dog Bay Line southwest of Dog Bay. This interpretation is supported by the presence of limestone clasts in the Rogerson Lake Formation that are atypical of Botwood Group lithologies and may have been derived from the Indian Islands Group.

Ocean closure along the Dog Bay Line was coincident with Silurian orogenesis (Dunning and others, 1990) involving magmatism, metamorphism, deformation, and the shedding of coarse clastic material from uplifted sequences related to the collision of the Ganderian microcontinent with Laurentia. Structural data recorded in the rocks of the Botwood Group (Arnott, 1983; Reusch, ms, 1983; van der Pluijm, 1986, 1987; Lafrance and Williams, 1992) suggest that synsedimentary sedimentation in the forearc basin was controlled by both southeast- and northwest-directed thrusting and related folding with high rates of uplift necessary to sustain conglomerate deposition. Both thrust faults and folds are cut by the Mount Peyton Intrusive Suite (Williams and others, 1988), which has been reported to have yielded Late Silurian magmatic zircons (G. R. Dunning, unpublished data, 1994). The age of deformation is further supported by the undeformed Stony Lake volcanics (423 ± 3 Ma, Dunning and others, 1990) which unconformably overlies and contain clasts of Botwood Group sedimentary rocks. Uplift and subaerial, arc-related magmatism (Whalen, 1989) in the Dunnage Zone was in all probability attributable to west or northwestward-directed subduction of oceanic crust of the Tetagouche-Exploits basin beneath the Laurentian margin. The

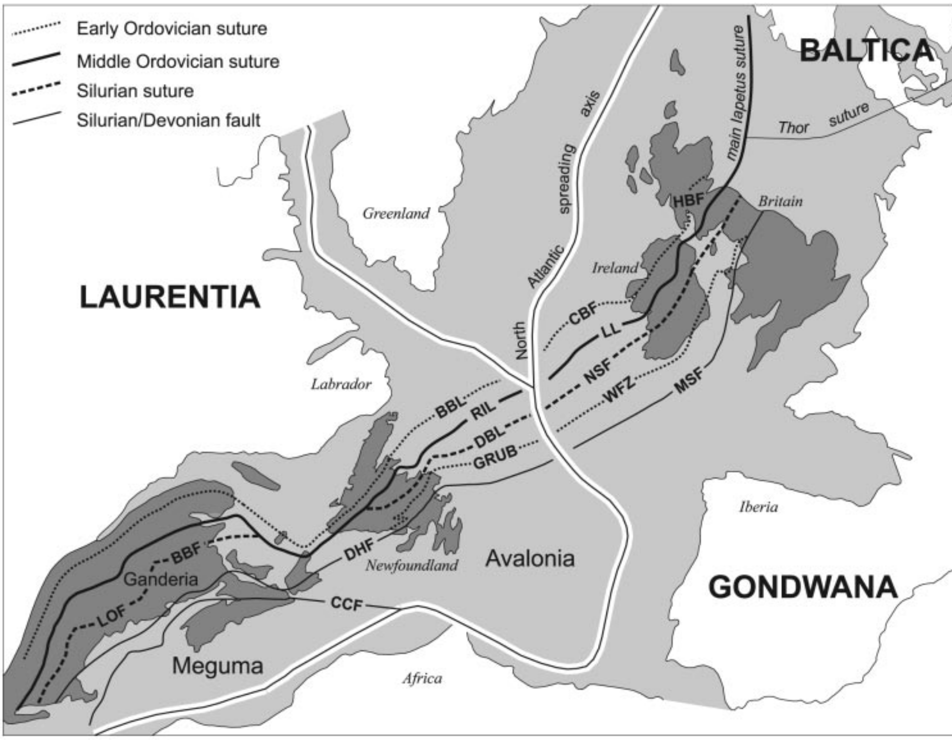


Fig. 9. Map of the northern Appalachians and Irish/British Caledonides of the restored North Atlantic region showing the position of Iapetus Ocean suture zones (after Valverde-Vaquero and others, 2006). BBF: Bamford Brook Fault; BBL: Baie Verte-Brompton Line; CBF: Clew Bay Fault; CCF: Cobequid-Chedabucto Fault; DBL: Dog Bay Line; DHF: Dover-Hermitage Fault; GRUB: Gander River Ultramafic Belt; HBF: Highland Boundary Fault; LL: Leadhills Line; LOF: Liberty-Orrington Fault; MSF: Menai Strait Fault; NSF: Navan-Silvermines Fault; RIL: Red Indian Line; WFZ: Wicklow Fault Zone.

voluminous Early Silurian non-arc magmatic suites (Kerr, 1997) in the Dunnage Zone are interpreted to represent syncollisional to postcollisional mantle-derived magmatism related to slab breakoff and underplating and mantle upwelling of hot asthenospheric material under the lower crust following the closure of Iapetus (van Staal and de Roo, 1995; van Staal and others, 1998).

Correlatives of the Dog Bay Line in the Northern Appalachians and British and Irish Caledonides

The orogenic model proposed herein for the northeast Exploits Subzone based on detrital zircon data allows for the reconstruction of the tectonic history of the Appalachians in Newfoundland and correlation with the Caledonides of Ireland and Great Britain and the northern Appalachians of Maritime Canada and New England.

Continuation of the Dog Bay Line across the Atlantic to the northeast (fig. 9) relies on the broad parallels between the tectonic framework of the Newfoundland Appalachians and the Caledonides of Ireland and Great Britain (Williams, 1978). The Llanvirn volcanic rocks of the Grangegeeth Terrane, within the Navan-Silvermines fault system in eastern Ireland are characteristic of arc-related volcanism (Owen and others, 1992) and may correlate with the Middle-Late Ordovician rocks of the Victoria arc of the Exploits Subzone located west of the Dog Bay Line in Newfoundland (Valverde-Vaquero and others, 2006). Sedimentary rocks in the Grangegeeth Terrane contain Llanvirn graptolites that have high-latitude Gondwanan affinities but mixed Laurentian-Baltic brachiopods in the Cardoc (Harper and Parkes, 1989). The adjacent Bellowstown Terrane contains different within-plate mafic and felsic volcanic rocks (Winchester and van Staal, 1995) and is characterized by Anglo-Welsh faunas during the Caradoc that are closely related to those of the Lakesman Terrane in the Lake District of England (van Staal and others, 1998). Llanvirn faunas in the Bellowstown Terrane are similar to those in the Exploits Subzone of Newfoundland, which led van Staal and others (1998) to propose that the Bellowstown Terrane formed near the outboard margin of Ganderia. These data suggest that the Navan-Silvermines fault is the equivalent to the Dog Bay Line in Newfoundland and represents the Silurian Ganderia-Laurentia suture in Ireland and Great Britain.

Extension of the Dog Bay Line to the southwest is interrupted by the Gulf of St. Lawrence; however, correlative rocks in a similar tectonic setting occur in Maritime Canada and New England. Equivalents of the Badger and Botwood groups are present in Late Ordovician forearc siliciclastic turbidites and Early Silurian redbeds, basalt and rhyolite of the Gaspé-Aroostook belt that extends from western New England into northern New Brunswick and adjacent Québec. The Fredericton belt exposed in central New Brunswick and adjacent New England comprises a thick sequence of Llandovery to Ludlow marine, locally slightly calcareous turbidites that nowhere are interlayered with volcanic rocks and are interpreted as a foredeep basin (van Staal and de Roo, 1995). Correlative rocks of the Indian Islands Group occur in a similar tectonic setting in Newfoundland. This suggests that the boundary between the Gaspé-Aroostook and Fredericton belts, the Bamford Brook Fault in New Brunswick and the Codyville (Ludman and others, 1993) and Liberty-Orrington faults (Tucker and others, 2001) in adjacent Maine, represents the terminal suture of the Salinic collision between Laurentia and Ganderia. Geochronological constraints on the Early Silurian (West and others, 1992, 2003) age of structures indicate that closure of the Iapetus Ocean was approximately coeval along the entire margin of the northern Appalachians in New Brunswick, Maine and Newfoundland.

CONCLUSIONS

The Dog Bay Line records the Early Silurian collision of Ganderia and Laurentia and the final closing of the Iapetus Ocean in Newfoundland. U-Pb analysis of detrital zircons from overlap sequences deposited on the Laurentian margin show an overall age range from Archean to Early Paleozoic with a distinct absence of 510 to 550 Ma and 1520 to 1600 Ma ages. These ages are consistent with detritus in clastic sequences northwest of the Dog Bay Line being derived from the Nain craton, Grenville, and Appalachian orogens of the Laurentian hinterland. Ages of detrital zircons from the opposing Ganderian margin, southeast of the Dog Bay Line, contain different age spectra than zircons from the Laurentian margin and are interpreted to be derived from the Ganderian microcontinent and Amazonian craton of Gondwana. These data, although specific to the closure of Iapetus along the Dog Bay Line in Newfoundland, suggest the presence of an Early Silurian arm of the Iapetus Ocean (Tetagouche-Exploits basin) that separated Laurentia from peri-Gondwanan microcontinents of Ganderia and Avalonia. The idea of a Late Ordovician-Early Silurian backarc basin along the peri-Gondwanan margin of Iapetus was proposed for rocks in New Brunswick (van Staal, 1987, 1994; van der Pluijm and van Staal, 1988; Rogers and van Staal, 2003), the south coast of Newfoundland (Valverde-Vaquero and others, 2000) and northeastern Newfoundland (Swinden and others, 1990; Williams and others, 1993; Currie, 1995; O'Brien and others, 1997; MacLachlan and Dunning, 1998).

Closure of the Tetagouche-Exploits basin (and Iapetus Ocean) in the Early Silurian was coeval with major episodes of deformation, metamorphism, plutonism, uplift and erosion related to Silurian orogenesis, the Salinic orogeny, that is recognized throughout the Newfoundland Appalachians in Notre Dame Bay (van der Pluijm, 1986, 1987; Elliott and others, 1991; Lafrance and Williams, 1992) and the south coast of Newfoundland (Dunning and others, 1990; O'Brien and others, 1991), in New England (West and others, 1992; Hepburn and others, 1995), and New Brunswick (Ruitenberg, 1967). Laurentia and the Ganderian microcontinent were involved in a continent-continent collision suggesting that sedimentary sequences along the Dog Bay Line represent the youngest rocks formed in Iapetus and indicate that the Iapetus Ocean between Laurentia and Ganderia was fully closed by the Late Silurian. These data have broader implications for the evolution of the peri-Gondwanan margin of the northern Appalachians as generally coeval tectonic processes were active along the entire northern peri-Gondwanan margin of Iapetus.

The closure of Iapetus involved a complex and protracted collisional history of numerous micro-continents, volcanic arcs and back-arc basins that were accreted to Laurentia between the Early Ordovician and Late Silurian. The notion of a single suture zone in a complex orogen such as the Appalachians is unrealistic as several temporal and spatial distinct suture zones are present (fig. 9). The Early Ordovician (Taconic) Baie Verte Line marks the boundary between the continental margin of Laurentia (Humber Zone) and Iapetan oceanic rocks (Dunnage Zone), while the Early Ordovician (Penobscot) GRUB Line defines the contact between the vestiges of Iapetus and Ganderia (Gander Zone). The Middle Ordovician Red Indian Line is considered the main Iapetan suture zone in that it separates peri-Laurentian (Notre Dame Subzone) and peri-Gondwanan (Exploits Subzone) oceanic elements. The Dog Bay Line is a younger feature in the Appalachians and delineates the terminal Iapetan suture in Newfoundland as it marks the Early Silurian (Salinic) collisional zone between Ganderia and Laurentia.

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