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U–Pb GEOCHRONOLOGICAL EVIDENCE FOR DEVONIAN DEFORMATION AND GOLD MINERALIZATION IN THE EASTERN DUNNAGE ZONE, NEWFOUNDLAND

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ABSTRACT

New U–Pb age determinations from the eastern Dunnage Zone provide evidence for periods of Early and Late Devonian deformation and also constrain the age of epithermal and mesothermal gold mineralization. Uranium–lead SHRIMP ages of 41l ± 5 and 381 ± 5 Ma from mafic dykes that intrude the Indian Islands Group indicate that unit to be no younger than ca. 406 Ma (compatible with fossil evidence for an Early Devonian minimum age) and to have been deformed in Early Devonian and Late Devonian times. Uranium–lead TIMS crystallization ages of 413 ± 2 and 411 ± 1.4 Ma from syntectonic, gneissic granodiorite and massive crosscutting granodiorite phases of the Long Island pluton respectively, bracket an Early Devonian episode of deformation. The Early Devonian deformation seems to have been focussed along the boundaries of the Dunnage Mélange and the northern and southern margins of the Silurian-deformed Botwood Group. The Late Devonian deformation is restricted to south of the Dog Bay Line and may mark a distal effect of the Acadian deformation in the Gander and Avalon zones to the east. The Dog Bay Line therefore marks an important contrast in age of deformation in the northeast Dunnage Zone.

At least some of the gold mineralization north of the Dog Bay Line appears to be associated with the Early Devonian plutonic rocks, however, the mesothermal gold mineralization south of the Dog Bay Line is at least, locally, Late Devonian or younger. The epithermal mineralization in this area is also likely to be Late Devonian or younger.

INTRODUCTION

The eastern Dunnage Zone of northeast Newfoundland contains a number of epithermal and mesothermal gold occurrences. These have been the subject of extensive exploration in recent years but little is known about their age. Some preliminary U–Pb dating was undertaken in 1993 in conjunction with regional mapping by the Geological Survey of Newfoundland and Labrador (O'Brien, 2003) to provide constraints on the age of deformation and gold mineralization. Additional samples were collected during a metallogenic study in 2004 (Squires, 2005) and preliminary ages reported by McNicoll (2005). The purpose of this paper is to present the final results for these samples and to discuss their regional tectonic and metallogenic implications.

REGIONAL GEOLOGY

Northeast Newfoundland is divided into the Dunnage, Gander and Avalon zones (Figure 1) that collectively represent the eastern side of the Lower Paleozoic Appalachian Orogen. The Dunnage Zone is divided by the Red Indian Line (Figure 2), which marks the fundamental Iapetan suture separating the peri-Laurentian Notre Dame Subzone to the west from the peri-Gondwanan Exploits Subzone to the east. The Exploits Subzone consists of Cambro-Ordovician magmatic arc-related sequences and is divided into two segments by the Dog Bay Line (a series of faults and shear zones, Williams *et al*., 1993). Both segments are overlain by sediment-dominated overstep sequences that range from Late Ordovician to Early Devonian. The sequential destruc-

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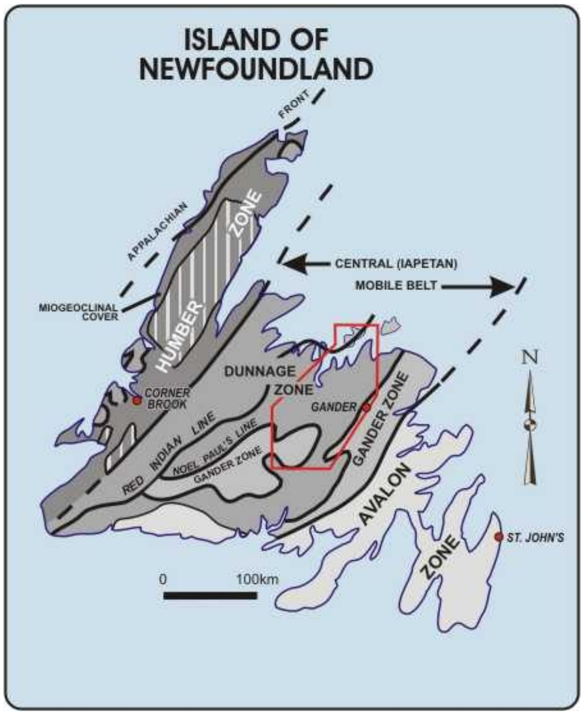

Figure 1. *Tectonic zones of Newfoundland. Location of the study area is outlined in red and shown in more detail in Figure 2.*

tion of these synorogenic overstep basins records the terminal closure of the Iapetus Ocean.

The position of the Dog Bay Line has been redefined by Dickson (*this volume*) and for the purposes of this paper, is defined as the faulted, northwestern boundary of the Indian Islands Group on Figure 2, where in its inland extent, it coincides with the Reach Fault.

North of the Dog Bay Line, the Exploits Subzone consists predominantly of lower to middle Ordovician volcanic and associated sedimentary rocks, including the Dunnage Mélange, and Exploits Group, which formed in island-arc and subduction-zone environments, overlain by a blanket of Upper Ordovician (Caradocian) black shale and chert. The Dunnage Mélange and its correlatives are a highly tectonized olistostromal unit of Middle Ordovician and older rocks that occur east and west of the Dog Bay Line (Williams *et al*., 1993). The mélange and the Caradoc shale are generally conformably overlain by a shallowing-upward sequence of turbidites and arc-derived conglomerates assigned to the Late Ordovician–Early Silurian Badger Group. This group is, in turn, conformably to disconformably overlain (Williams, 1993; Williams *et al*., 1993) by the Silurian Botwood Group, a series of mafic and felsic volcanic rocks overlain by grey sandstones and terrestrial red sandstones. The Botwood Group is locally unconformably overlain by the latest Silurian Stony Lake Formation volcanic rocks (423 +3/-2 Ma, Dunning *et al*., 1990).

In the Bay of Exploits, the Dunnage Mélange, Exploits, Badger and Botwood groups are intruded by the Long Island and Loon Bay granitic plutons (Figure 3). The Loon Bay pluton has been dated as Early Devonian (408 ± 2 Ma; Elliot *et al*., 1991) and correlated with the compositionally similar Long Island pluton, which, in turn, has been correlated with a dyke of unfoliated tonalite dated at 407 ± 3 Ma (Elliot *et al*., 1991). The Long Island pluton truncates regional folds and cleavage in the Badger Group (O'Brien, 2003). The Loon Bay pluton also crosscuts earlier fabric and metamorphic assemblages in the other Ordovician–Silurian sequences. On the Port Albert Peninsula, immediately west of the Dog Bay Line, Elliot *et al*. (1991) obtained a 422 ± 2 Ma crystallization age from a minor microgranitic intrusion belonging to a variably sheared and locally altered swarm of composite felsic–mafic dykes that intrude the Wigwam Formation of the Botwood Group. These Late Silurian intrusions are reported to crosscut minor structures related to several phases of regional ductile deformation but have been themselves deformed by folds and kink bands coeval with high-angle brittle faulting in their host rocks.

South of the Dog Bay Line, the sequence consists of Ordovician rocks, including parts of the Dunnage Mélange, Duder Group (described as mostly mélange by Currie, 1997) and Early to Late Ordovician Davidsville Group shales and arc-derived turbidites. These are conformably overlain by the Indian Islands Group, which consists of a shallowing-upward sequence of grey to red marine shales and calcareous siltstones (Williams *et al.*, 1993; Dickson *this volume*). On the basis of fossil evidence (Boyce *et al*., 1993) the Indian Islands Group ranges from Early Silurian (Llandovery) to latest Silurian–Early Devonian (Prídolí to Gedinnian), however, on the basis of recent work (Boyce and Dickson, *this volume*) the bulk of the unit is of Wenlock-Ludlow age. The distribution of the Indian Islands Group as shown on Figure 2 is after Dickson (*this volume*) who has redefined its extent from the earlier work of Williams *et al*. (1993).

An important plutonic feature of the area is the Mount Peyton Intrusive Suite, which forms an elliptical mass of gabbros and granites north of the Dog Bay Line (Figure 2). A gabbro phase of the suite has given a U–Pb zircon TIMS age of 424 ± 2 Ma (Dunning, 1992, 1994). O'Driscoll and Wilton (2005) have reported a number of LAM-ICP-MS ages from the Mount Peyton Intrusive Suite and some small plutons intrusive into the Indian Islands Group that have been interpreted by O'Driscoll and Wilton (*op. cit.*) to define a 430 to 424 Ma period of magmatism. On this basis, the Mount Peyton Intrusive Suite is no younger than Late Silurian and should predate the Indian Islands Group, given

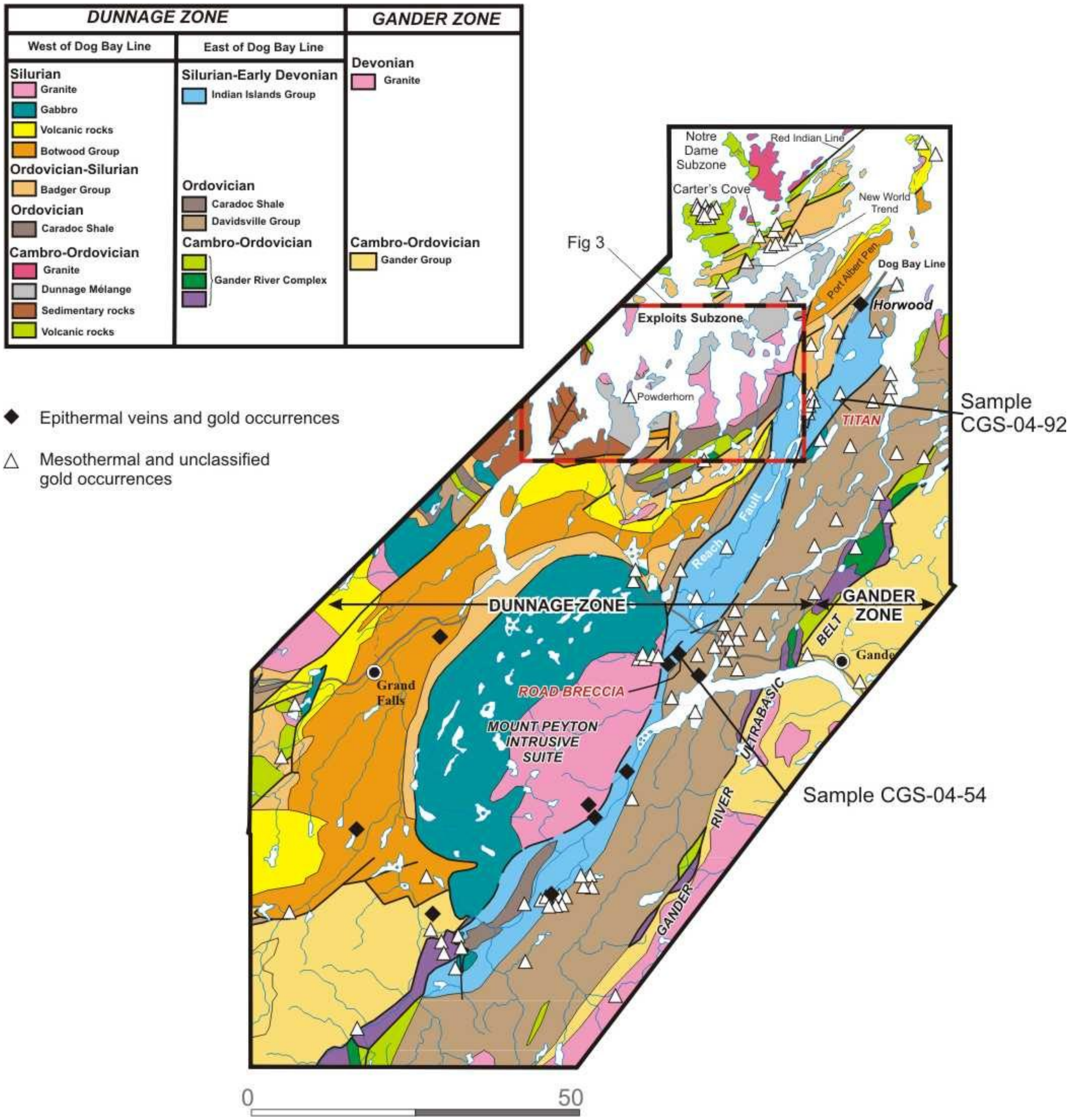

Figure 2. *Generalized geology of the northeast Dunnage and Gander zones, modified after Dickson* (this volume)*, and showing U–Pb geochronology sample sites and gold occurrences.*

that the latter is potentially as young as Early Devonian. However, this is contradicted by an apparent intrusive relationship between granite of the southwest Mount Peyton Intrusive Suite and the Indian Islands Group (Lake and Wilton, *this volume*), which suggests that parts of the Mount Peyton Intrusive Suite are younger than ca. 424 Ma.

AGE OF DEFORMATION

In the northeast Dunnage Zone, north of the Dog Bay Line, most stratified units display at least one phase of slaty cleavage and have been affected by low-grade metamorphism. The Silurian rocks of the Botwood Group experi-

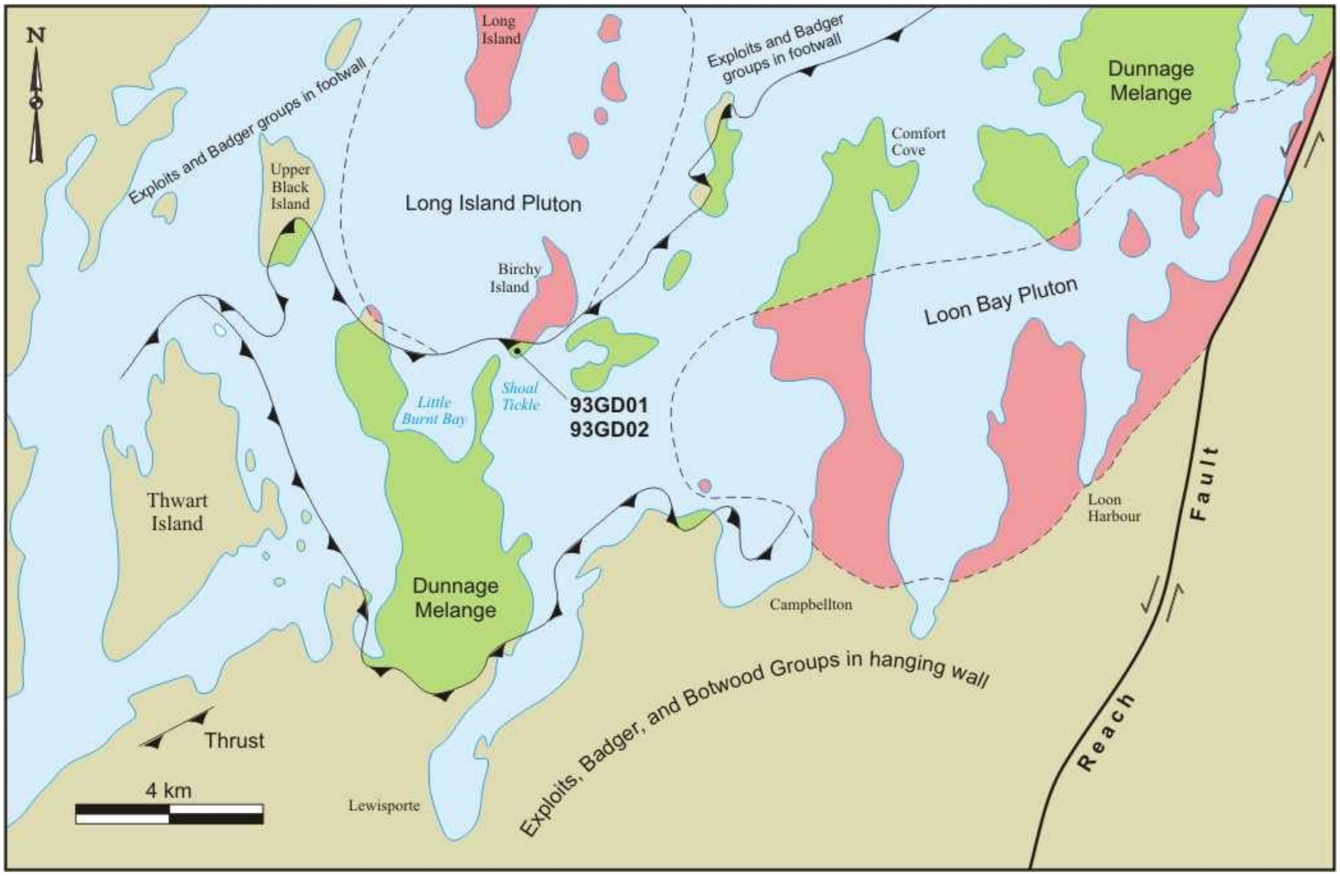

Figure 3. *Simplified geological map of the southern Bay of Exploits showing the location of the Long Island and Loon Bay plutons and the geochronology sample sites.*

enced regional deformation prior to intrusion of the 424 ± 2 Ma Mount Peyton Intrusive Suite and eruption of the 423 +3/-2 Ma Stony Lake Formation. Deformation was thus predominantly Mid- to Late Silurian and related to the Salinic Orogeny (Dunning *et al.*, 1990) of ca. 455 to 423 Ma range (van Staal, 2005). Evidence of a localized younger event on the north side of the Dog Bay Line is provided by the brittle-ductile deformation that affected the 422 ± 2 Ma Silurian minor intrusions of the Port Albert Peninsula (*see above*). South of the Dog Bay Line, the Indian Islands Group was not deformed until post-Prídolí to Gedinnian time.

The distinct difference in timing of deformation indicates a major tectonic break between the Botwood Group, which was being deformed in the mid-late Silurian (430 to 423 Ma) and the Indian Islands Group, which was still being deposited. The Dog Bay Line (Williams *et al.*, 1993) and Reach Fault (Dickson, *this volume*) are regarded as the sites of this break.

REGIONAL GOLD METALLOGENY

The northeast Dunnage Zone contains numerous epithermal and mesothermal gold occurrences (Figure 2; Squires, 2005; O'Driscoll and Wilton, 2005). Evans (1996) has described the mesothermal occurrences as having formed at shallower depths than normal for this type and to be transitional between epithermal and "true mesothermal" styles. The epithermal occurrences are low- to intermediate-sulphidation quartz-breccia vein systems. They are found mostly in the Botwood and Indian Islands groups and, as is typically the case with these systems (e.g., Hedenquist, 2000), were probably formed within 1 to 2 km of the earth's surface. The age of the epithermal systems must be Silurian or younger and they generally show close proximity to the Mount Peyton Plutonic Suite. A key question, therefore, is whether the mineralization is genetically related to the Silurian magmatism (e.g., O'Driscoll and Wilton, 2005) or younger events.

The mesothermal occurrences are generally late tectonic quartz-vein systems hosted by mafic dykes, metasedimentary rocks and, locally, felsic dykes and veins. Most of the occurrences seem to have formed in the late stages of regional deformation and are often spatially associated with shear zones. As is typical of mesothermal occurrences, they are inferred to have formed at deeper crustal levels than the epithermal systems. To date, there have been few constraints on their age in the northeastern Dunnage Zone. However, dating elsewhere in the Dunnage Zone (Evans, 2005 and references therein) has indicated mineralization ages between 437 Ma (Early Silurian) and 374 Ma (Late Devonian).

U–Pb GEOCHRONOLOGY SAMPLING

To constrain the age of deformation and gold mineralization, samples were collected from two mafic dykes in the Indian Islands Group; one (CGS-04-54) from the area of the Road Breccia epithermal gold occurrence, and the other (CGS-04-92) from the Titan mesothermal gold prospect in the northern part of the Indian Islands Group (Figure 2).

To shed further light on the timing of post-ca. 422 Ma deformation west of the Reach Fault and its relationship to Devonian plutonism, samples were collected from the southern, highly sheared margin of the Long Island pluton and its complexly deformed amphibolite-facies country rocks in the Bay of Exploits area (Figure 3). These rocks are well exposed in coastal sections near the Shoal Tickle of Little Burnt Bay (O'Brien, 2003). Two samples, one of a gneissic granodiorite (93GD01) and one of a crosscutting massive granodiorite (93GD02), were collected.

Sample location information (UTM coordinates) is provided below.

U–Pb ANALYTICAL METHODS

Heavy-mineral concentrates of samples CGS-04-54 and 92 were prepared using standard crushing, grinding, Wilfley table, and heavy liquid techniques. Mineral separates were sorted by magnetic susceptibility using a Frantz™ isodynamic separator. These samples did not yield much zircon and many of the grains were of only fair quality, containing abundant inclusions and fractures. As a result, *in situ* analyses of the zircons were performed on the SHRIMP II (Sensitive High Resolution Mass Spectrometer) at the Geological Survey of Canada.

SHRIMP analyses were conducted using analytical procedures described by Stern (1997), and using the standards and U–Pb calibration methods following Stern and Amelin (2003). Zircons from the Titan Prospect (CGS-04-92; z8429) and the Road Breccia Zone (CGS-04-54; z8430) gabbro samples were cast in 2.5 cm diameter epoxy mounts (GSC mount #355 for z8429 and GSC mount #350 for z8430) along with fragments of the GSC laboratory standard zircon (z6266, with $^{206}Pb/^{238}U$ age = 559 Ma). A laboratory zircon standard, Temora 2, was also analyzed on the two SHRIMP grain mounts (GSC mounts #355 and #350) with resulting dates of 415.3 ± 4.4 Ma (MSWD=1.4, n=12) and 417.8 ± 1.7 Ma (MSWD=1.0, n=12), respectively. The midsections of the zircons were exposed using 9, 6, and 1 µm diamond compound, and the internal features of the zircons were characterized with backscatter electrons (BSE) utilizing a Cambridge Instruments scanning electron microscope (SEM). Mount surfaces were evaporatively coated with 10 nm of high purity Au. Analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. The sputtered area used for analysis was ca. 25 µm in diameter and having a beam current of ca. 9 nA and 6 nA for z8429 and z8430, respectively. The count rates of ten isotopes of Zr^+, U^+, Th^+, and Pb^+ in zircon were sequentially measured over 7 scans with a single electron multiplier and a pulse-counting system with deadtime of 35 ns. Off-line data processing was accomplished using customized in-house software. The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in Table 1 incorporate a ± 1.0 % error in calibrating the standard zircon (*see* Stern and Amelin, 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the measured $^{204}Pb/^{206}Pb$ and compositions modelled after Cumming and Richards (1975). The $^{206}Pb/^{238}U$ ages for the analyses have been corrected for common Pb using both the 204- and 207-methods (Stern, 1997), but there is generally no significant difference in the results (Table 1). Isoplot v. 2.49 (Ludwig, 2001) was used to generate the U–Pb concordia diagrams where data are plotted with errors at the 2σ level (*see* e.g., Figures 5 and 8). Concordia ages (Ludwig, 1998) are calculated for the samples presented herein. These Concordia ages incorporate errors on the decay constants and include both an evaluation of concordance and an evaluation of equivalence of the data. The calculated Concordia ages and errors quoted in the text are at 2σ with decay-constant errors included.

Samples 93GD01 and 93GD02, collected for U–Pb TIMS dating, were processed and analyzed at Memorial University using the methods described in Dubé *et al.* (1996). Both samples yielded large amounts of simple euhedral prismatic zircon. The highest quality, clearest, euhedral grains were selected for analysis and some were abraded. Zircon fractions were washed in distilled HNO_3, doubly distilled H_2O, and then distilled acetone, prior to weighing on a microbalance and loading in Krogh-type TEFLON dissolution bombs. A mixed $^{205}Pb/^{235}U$ tracer was added in proportion to the sample weight, along with ca. 20 drops distilled HF and 1 drop HNO_3, then the bomb was sealed and placed in an oven at 210°C for 5 days. Ion exchange chemistry was

Table 1. Uranium–lead SHRIMP analytical data for samples CGS-04-54 (Road Breccia) and CGS-04-92 (Titan prospect)

Spot name	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb (ppb)	^{204}Pb/^{206}Pb	±^{204}Pb/^{206}Pb	f(206)^{204}	^{208}Pb/^{206}Pb	±^{208}Pb/^{206}Pb	^{207}Pb/^{235}U	±^{207}Pb/^{235}U	^{206}Pb/^{238}U	±^{206}Pb/^{238}U	Corr Coeff	^{207}Pb/^{206}Pb	±^{207}Pb/^{206}Pb	Ages (Ma)[1] ^{206}Pb/^{238}U	Ages (Ma)[1] ±^{206}Pb/^{238}U	Ages (Ma)[1] ^{207}PB/^{206}Pb	Ages (Ma)[1] ±^{207}Pb/^{206}Pb	Ages (Ma)[2] ^{206}Pb/^{238}U	Ages (Ma)[2] ±^{206}Pb/^{238}U
"Road Breccia Zone Gabbro Dyke: CGS-04-54 (z8430); UTM zone 21, NAD 27, 650494E - 5424541Nn ± 10m"																							
8430-4.1	164	79	0.496	11	9	0.000962	0.000217	0.0167	0.1399	0.0092	0.4553	0.0348	0.0657	0.0013	0.367	0.0503	0.0036	410	8	208	175	412	8
8430-5.1	79	44	0.582	6	4	0.000793	0.000432	0.0138	0.1863	0.0177	0.5022	0.0653	0.0660	0.0014	0.283	0.0552	0.0069	412	8	421	308	411	8
8430-7.1	110	51	0.482	7	11	0.001682	0.000339	0.0292	0.1395	0.0145	0.4210	0.0533	0.0650	0.0013	0.277	0.0470	0.0058	406	8	49	269	409	8
8430-8.1	73	31	0.434	5	6	0.001367	0.000415	0.0237	0.1408	0.0169	0.5472	0.0663	0.0661	0.0015	0.310	0.0601	0.0070	412	9	606	273	410	9
8430-12.1	91	37	0.424	6	6	0.001213	0.000382	0.0210	0.1419	0.0184	0.4895	0.0604	0.0663	0.0014	0.295	0.0536	0.0064	414	9	352	294	414	8
8430-11.1	175	83	0.488	12	8	0.000773	0.000238	0.0134	0.1573	0.0099	0.5209	0.0393	0.0665	0.0013	0.379	0.0568	0.0040	415	8	485	164	414	8
8430-10.1	76	38	0.516	5	7	0.001582	0.000578	0.0274	0.1767	0.0229	0.5614	0.0882	0.0669	0.0015	0.267	0.0609	0.0093	417	9	636	368	414	8
8430-11.2	124	70	0.578	9	9	0.001230	0.000310	0.0213	0.1781	0.0128	0.5167	0.0487	0.0665	0.0014	0.341	0.0563	0.0050	415	8	465	211	414	8
8430-12.2	130	76	0.603	9	7	0.000917	0.000258	0.0159	0.2012	0.0110	0.5148	0.0407	0.0654	0.0013	0.364	0.0571	0.0042	408	8	496	173	407	8
8430-8.2	76	42	0.568	5	11	0.002496	0.000452	0.0433	0.1554	0.0202	0.4169	0.0674	0.0646	0.0013	0.246	0.0468	0.0074	404	8	39	429	407	7
"Titan Prospect Gabbro Dyke: CGS-04-92 (z8429); UTM zone 21, NAD 27, 675730E - 5465523N ± 10m"																							
8429-7.1	106	38	0.373	6	9	0.001697	0.000307	0.0294	0.1076	0.0134	0.4228	0.0445	0.0585	0.0013	0.327	0.0524	0.0053	367	8	303	246	367	8
8429-20.1	94	38	0.420	6	11	0.002097	0.000362	0.0363	0.1308	0.0147	0.4863	0.0526	0.0605	0.0010	0.272	0.0584	0.0061	378	6	543	248	377	6
8429-40.1	95	61	0.663	6	5	0.001047	0.000262	0.0182	0.2101	0.0157	0.4932	0.0384	0.0610	0.0011	0.346	0.0587	0.0043	382	7	554	169	380	6
8429-54.1	181	90	0.515	11	11	0.001189	0.000353	0.0206	0.1542	0.0149	0.4499	0.0503	0.0612	0.0013	0.305	0.0533	0.0057	383	8	342	263	383	7
8429-18.1	119	84	0.734	8	13	0.001954	0.000305	0.0339	0.2018	0.0147	0.4148	0.0434	0.0614	0.0010	0.272	0.0490	0.0050	384	6	149	222	384	6
8429-51.1	119	85	0.737	8	4	0.000658	0.000379	0.0114	0.2301	0.0153	0.4830	0.0536	0.0616	0.0011	0.287	0.0569	0.0061	385	7	487	256	386	6
8429-41.1	71	34	0.494	5	7	0.001715	0.000352	0.0297	0.1460	0.0146	0.4405	0.0526	0.0623	0.0016	0.329	0.0513	0.0058	390	9	254	254	391	9
8429-52.1	96	44	0.475	6	5	0.001004	0.000377	0.0174	0.1328	0.0150	0.4455	0.0552	0.0648	0.0011	0.258	0.0498	0.0060	405	7	188	259	406	6
8429-47.1	92	45	0.509	6	6	0.001242	0.000457	0.0215	0.1567	0.0204	0.4984	0.0701	0.0651	0.0011	0.243	0.0556	0.0076	406	7	434	340	406	7
8429-56.1	155	94	0.626	11	8	0.000869	0.000183	0.0151	0.2030	0.0084	0.5208	0.0296	0.0653	0.0011	0.416	0.0579	0.0030	408	7	525	119	407	5
8429-42.1	86	36	0.432	6	5	0.001023	0.000302	0.0177	0.1447	0.0123	0.5500	0.0460	0.0656	0.0009	0.287	0.0608	0.0049	409	6	633	184	407	6
8429-5.1	72	34	0.486	5	4	0.000906	0.000350	0.0157	0.1690	0.0169	0.5634	0.0544	0.0661	0.0012	0.311	0.0619	0.0057	412	7	669	211	409	7
8429-8.1	105	60	0.586	7	5	0.000748	0.000206	0.0130	0.1900	0.0090	0.5086	0.0360	0.0662	0.0009	0.305	0.0557	0.0038	413	5	440	159	413	5
8429-49.1	144	63	0.449	10	1	0.000147	0.000113	0.0026	0.1498	0.0053	0.5396	0.0215	0.0665	0.0008	0.423	0.0588	0.0021	415	5	561	81	413	5
8429-1.1	94	47	0.517	7	3	0.000578	0.000216	0.0100	0.1604	0.0103	0.5396	0.0343	0.0667	0.0008	0.308	0.0587	0.0036	416	5	555	139	415	5
8429-2.1	93	40	0.437	6	5	0.000870	0.000205	0.0151	0.1312	0.0087	0.4850	0.0326	0.0670	0.0008	0.298	0.0525	0.0034	418	5	307	154	419	5
8429-46.1	106	48	0.468	8	7	0.001099	0.000307	0.0190	0.1511	0.0124	0.5634	0.0489	0.0681	0.0010	0.292	0.0600	0.0050	424	6	605	192	422	6
8429-12.1	187	84	0.465	13	6	0.000540	0.000158	0.0094	0.1451	0.0097	0.5260	0.0258	0.0681	0.0008	0.356	0.0561	0.0026	425	5	454	106	424	5
8429-50.1	309	62	0.206	22	8	0.000417	0.000073	0.0072	0.0539	0.0038	0.5390	0.0149	0.0750	0.0008	0.489	0.0521	0.0013	466	5	291	57	467	5
8429-14.1	178	98	0.566	14	4	0.000374	0.000152	0.0065	0.1787	0.0077	0.5764	0.0277	0.0753	0.0009	0.367	0.0555	0.0025	468	5	434	104	468	5
8429-19.1	402	103	0.265	30	6	0.000245	0.000077	0.0042	0.0869	0.0032	0.5976	0.0156	0.0753	0.0008	0.521	0.0576	0.0013	468	5	513	50	468	5
8429-39.1	260	199	0.792	22	7	0.000412	0.000074	0.0071	0.2470	0.0042	0.5841	0.0164	0.0756	0.0009	0.539	0.0560	0.0013	470	6	453	54	470	5
8429-55.1	214	114	0.551	22	4	0.000212	0.000076	0.0037	0.1679	0.0038	0.8188	0.0217	0.0955	0.0012	0.589	0.0622	0.0013	588	7	679	47	586	7

Notes (see Stern, 1997):

Uncertainties reported at 1σ (absolute) and are calculated by numerical propagation of all known sources of error

f206^{204} refers to mole fraction of total ^{206}Pb that is due to common Pb, calculated using the ^{204}Pb-method; common Pb composition used is the surface blank

[1] 204-corrected ages; [2] 207-corrected ages (Stern, 1997)

carried out using the procedure of Krogh (1973), with modified columns and reagent volumes scaled down to one tenth of those reported in 1973. The purified Pb and U were collected in a clean beaker in a single drop of ultrapure H_3PO_4.

Lead and uranium were loaded together on outgassed single Re filaments with silica gel and dilute H_3PO_4. Mass spectrometry was carried out using a multi-collector MAT 262. For most mineral fractions, Pb was measured in static mode with ^{204}Pb measured in the SEM in ion counting mode. The faraday cups are calibrated with NBS 981 and the ion counting system is calibrated against a faraday cup by measuring a known ratio. Small amounts of Pb are measured by peak jumping on the ion counter, with measurement times weighted according to the amounts of each mass present; U was measured by static double faraday collection. A series of datasets are measured in the temperature range 1400° to 1550°C for Pb and 1550 to 1640°C for U, and the best sets combined to produce a mean value for each ratio. The measured ratios are corrected for Pb and U fractionation of 0.1%/amu and 0.03%/amu respectively as determined from repeat measurements of NBS standards. The ratios are also corrected for laboratory procedure blanks (2 to 10 picograms - Pb, 1 picogram - U) and for common Pb above the laboratory blank, and with Pb of the composition predicted by the two-stage model of Stacey and Kramers (1975) for the age of the sample. Ages are calculated using the decay constants recommended by Jaffey *et al.* (1971).

The uncertainties on the isotopic ratios were calculated using an unpublished program and are reported at 2σ. Sources of uncertainty considered (at 2σ) include uncertainties on the isotopic ratio measurements by mass spectrometry, uncertainty on the Pb and U fractionation, assigned 50% uncertainty on the amount of the Pb and U blanks, and a 4% uncertainty on the isotopic composition of the Pb used to subtract the common Pb present above laboratory blank. These uncertainties are quadratically added to arrive at final 2σ uncertainties that are reported after the isotopic ratios in the data table. Ages calculated are the weighted average of the ^{207}Pb/^{206}Pb ages using ISOPLOT for these variably discordant data points and uncertainties are reported at the 95% confidence interval.

U–Pb SAMPLES AND RESULTS – SHRIMP DATING

ROAD BRECCIA ZONE (NTS 2D/14, UTM 650494E/ 5424541N, NAD 27, ZONE 21)

Sample CGS-04-54, a dark green, fine-grained gabbro, was collected from an east-southeast-trending gabbro dyke that intruded cleaved, vertically dipping and north-northeast-trending calcareous siltstones of the Indian Islands Group. The dyke postdates cleavage development in the host siltstones, but is fractured and cut by some thin quartz veins. A nearby, epithermal quartz-breccia vein containing anomalous gold values and termed the Road Breccia showing, strikes parallel to the dyke and also crosscuts bedding and cleavage in the host siltstones. Timing relationships between the vein and the gabbro dyke could not be determined.

A small number of zircons were retrieved from this sample, composed predominantly of well-faceted grains but also some rounded ones (Figure 4). A selection of well-faceted, euhedral zircons, most of which contain abundant inclusions, were put on a grain mount for SHRIMP analysis. Figure 5 presents representative back-scatter SEM images of zircons from this sample. All of the SHRIMP analyses from the gabbro overlap concordia and each other, defining a single age population (Figure 6). A Concordia age, utilizing all of the analyses (Table 2), is calculated to be 411 ± 5 Ma (MSWD of concordance and equivalence = 0.44; probability = 0.98; n=10). This Early Devonian date of 411 ± 5 Ma is interpreted as the crystallization age of the gabbro dyke.

TITAN PROSPECT (NTS 2E/7; UTM 675730E/ 5465523N, NAD 27, ZONE 21)

Sample CGS-04-92 was collected from a trench exposure of a coarse-grained, rusty carbonate-altered gabbro dyke that intrudes thin-bedded, Indian Islands Group sandstone (Plate 1). The gabbro is variably foliated and shares the same strong cleavage as the host sandstone. The deformation also postdates the carbonate alteration in the gabbro. The alteration and the dyke are cut by a series of quartz and carbonate veins, locally of oblique tension-gash nature (Plate 2), which developed in the late, brittle stages of deformation. The veins locally contain visible gold mineralization and appear to be of mesothermal style (Squires, 2005). The dyke was sampled to place a maximum age on the gold mineralization and alteration.

Some zircons were retrieved from sample CGS-04-92 and include a range of morphologies from well faceted to somewhat rounded. A selection of euhedral, prismatic to stubby prismatic zircon was placed on a SHRIMP grain mount to obtain a crystallization age for the gabbro (Figure 7). Most of the zircons in this rock contain abundant inclusions that are colourless to dark brown and elongate to round and equant. Figure 8 includes back-scatter SEM images of representative zircons from this sample with the ages of the grains highlighted (Table 1).

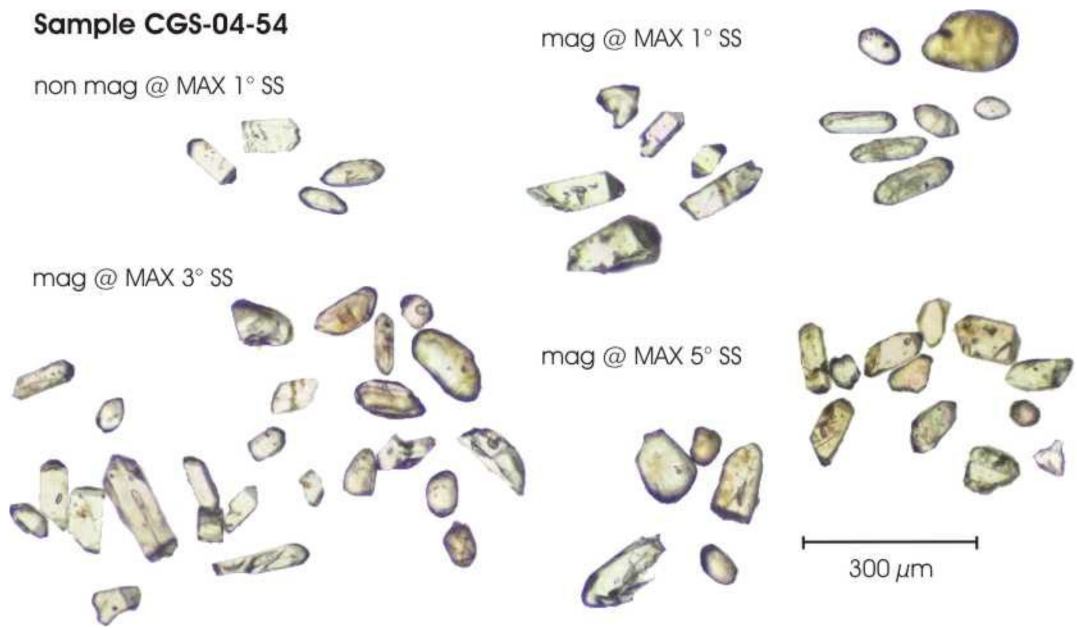

Figure 4. *Transmitted light photos of zircon retrieved from sample CGS-04-54, the Road Breccia Zone gabbro dyke.*

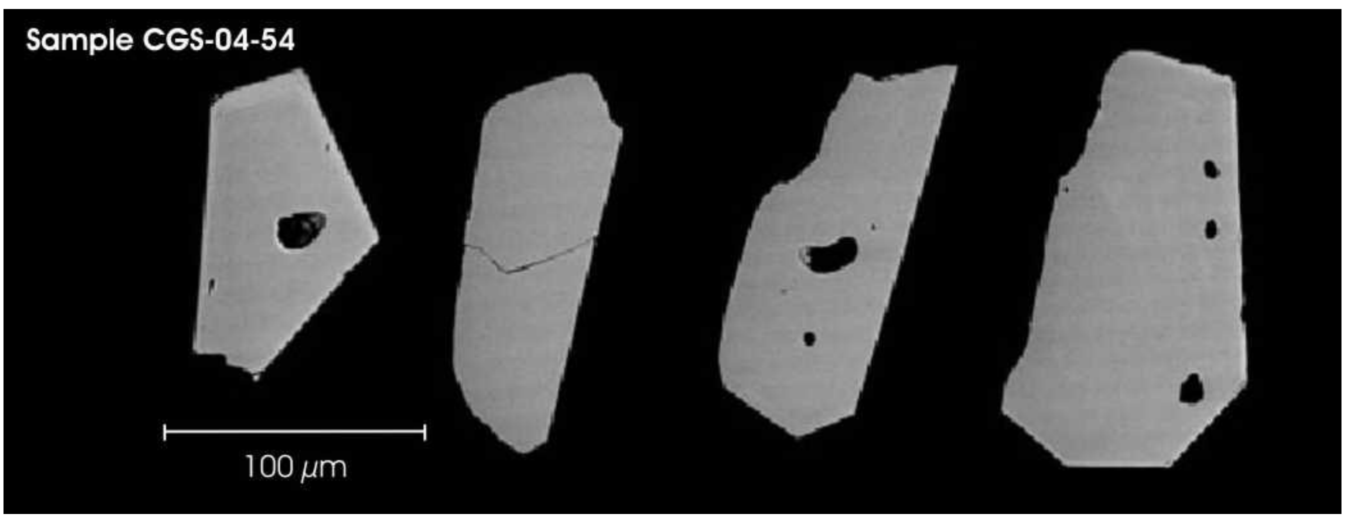

Figure 5. *Representative back-scatter SEM images of zircons from the Road Breccia Zone gabbro dyke.*

SHRIMP analyses from this sample define 4 age populations. Figure 9 presents a cumulative probability plot of the $^{206}Pb/^{238}U$ ages, which incorporate the ages and associated errors of the zircon analyses. Only data that are <5% discordant are included in the cumulative probability plots. A Concordia age (see Table 2) for the youngest zircon population of 381 ± 5 Ma (MSWD of concordance and equivalence = 0.65, probability =0.81; n=7) is interpreted to be the crystallization age of the gabbro. Older zircon populations in the gabbro have ages of ca. 414 Ma (n=11), ca. 469 Ma (n=4), and ca. 586 Ma (n=1) (see Table 2) and are interpreted to be inherited in origin, perhaps from the sandstone that this dyke has intruded. If all of the zircon in the gabbro is inherited, then 381 ± 5 Ma is a maximum age for the gabbro dyke.

U–Pb SAMPLES AND RESULTS – TIMS DATING

SAMPLE 93GD01 – GNEISSIC GRANODIORITE (NTS 2E/6, UTM 643650E/5468800N, NAD 27, ZONE 21)

A sample was collected from a finely banded gneissic phase of the Long Island pluton on southern Birchy Island

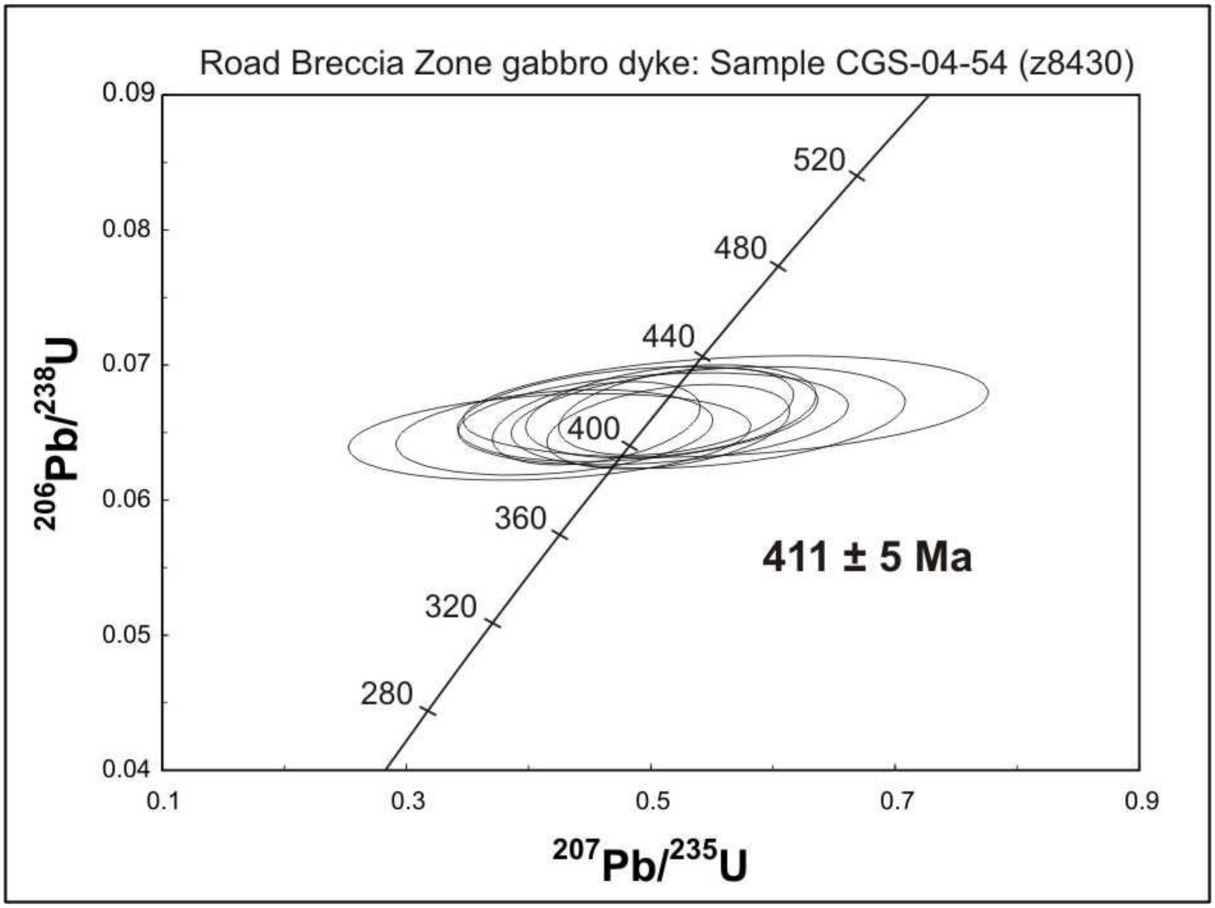

Figure 6. *Uranium–lead concordia diagram of SHRIMP analyses from the Road Breccia Zone gabbro dyke.*

(O'Brien, 2003) where the pluton concordantly intrudes psammites, amphibolites and pebbly pelites of the Dunnage Mélange. The unbroken parts of the mélange have been deformed and infolded with granodiorite veins or, in other localities, tectonically straightened and injected by dykes of granodioritic gneiss.

Four small fractions composed of 2 to 10 unabraded zircon grains were analysed. One analysis, Z4, contains an older inherited component and has a $^{207}Pb/^{206}Pb$ age of 511 Ma. Fractions Z1, Z2, and Z3 are closely spaced, with Z1 and Z2 essentially coincident (Figure 10), and all have $^{207}Pb/^{206}Pb$ ages of 413 Ma. The weighted average of these three analyses yields a date of 413 ± 2 Ma (95% confidence interval (CI), MSWD <0.001), calculated using ISOPLOT (Ludwig, 2001).

SAMPLE 93GD02 – MASSIVE GRANODIORITE (NTS 2E/6, UTM 643650E/5468800N, NAD 27, ZONE 21)

Massive, equigranular, coarse-grained hornblende granodiorite that cuts the tectonic fabric in the orthogneiss of 93GD01 (Plate 3) and the foliation in the country rock was sampled. This rock type is associated with moderately dipping sheets of megacrystic biotite granite present at the margins of the Long Island pluton and within the adjacent contact aureole.

Four fractions, each composed of ca. 20 to 50 clear euhedral zircons, were analyzed from this sample. Fractions Z1 and Z2 were abraded and are less discordant than Z3 and Z4 (Figure 10). All of the analyses are collinear, plotting on a line with a lower intercept at the origin within uncertainty. The $^{207}Pb/^{206}Pb$ ages of the analyses range from 411.7 to 409 Ma, overlapping within error. The weighted average of the $^{207}Pb/^{206}Pb$ ages yields a date of 411 ± 1.4 Ma (95% CI, MSWD = 1.09).

DISCUSSION

IMPLICATIONS FOR TIMING OF DEFORMATION

The development of the main slaty cleavage in the Indian Islands Group must have occurred after Indian Islands Group deposition and prior to intrusion of the ca. 411 Ma

Table 2. Uranium–lead TIMS zircon data for samples 93GD01 and 93GD02 from west of the Dog Bay Line

	Concentration			Measured		Corrected Atomic Ratios*								Age (Ma)		
Fraction	Weight (mg)	U (ppm)	Pb rad	total common Pb (pg)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
93GD01 GNEISSIC GRANODIORITE															
Z1 clr euh needles	0.022	516	32.2	13	3573	0.0800	0.06396	22	0.4853	16	0.05502	10	400	402	413.2
Z2 clr euh prisms	0.033	544	33.7	19	3819	0.0717	0.06394	22	0.4850	16	0.05502	10	400	402	413.0
Z3 clr euh prisms	0.031	554	34.5	25	2721	0.0930	0.06315	30	0.4791	22	0.05502	10	395	397	413.2
Z4 clr euh prisms	0.007	504	33.7	21	738	0.0886	0.06771	44	0.5370	36	0.05752	24	422	436	511.4
93GD02 GRANODIORITE															
Z1 clr euh abr	0.092	318	20.8	53	2252	0.1195	0.06481	30	0.4913	22	0.05498	12	405	406	411.4
Z2 stubby clr abr	0.092	396	25.4	25	5817	0.1092	0.06415	24	0.4859	18	0.05493	8	401	402	409.4
Z3 clr needles	0.229	485	29.8	194	2239	0.0983	0.06190	24	0.4693	18	0.05499	4	387	391	411.7
Z4 needles+flat prisms	0.253	511	30.9	196	2549	0.0933	0.06123	16	0.4636	12	0.05492	4	383	387	409.0

Notes: Z=zircon, clr=clear, euh=euhedral, abr=abraded.

* Atomic ratios corrected for fractionation, spike, laboratory blank of ca. 10 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 1 picogram U blank. 2σ uncertainties are reported after the ratios and refer to the final digits.

Plate 1. *General view of the Titan prospect showing the site for geochronology sample CGS-04-92 in foliated metagabbro. Foliation dips to right. Rusty brown carbonate alteration and quartz veins associated with gold mineralization are also visible.*

Plate 2. *Detail of foliated metagabbro dyke at Titan Prospect showing contact with Indian Islands Group slates and the crosscutting quartz and carbonate veins associated with mesothermal gold mineralization. The same foliation is developed in the slates and the metagabbro.*

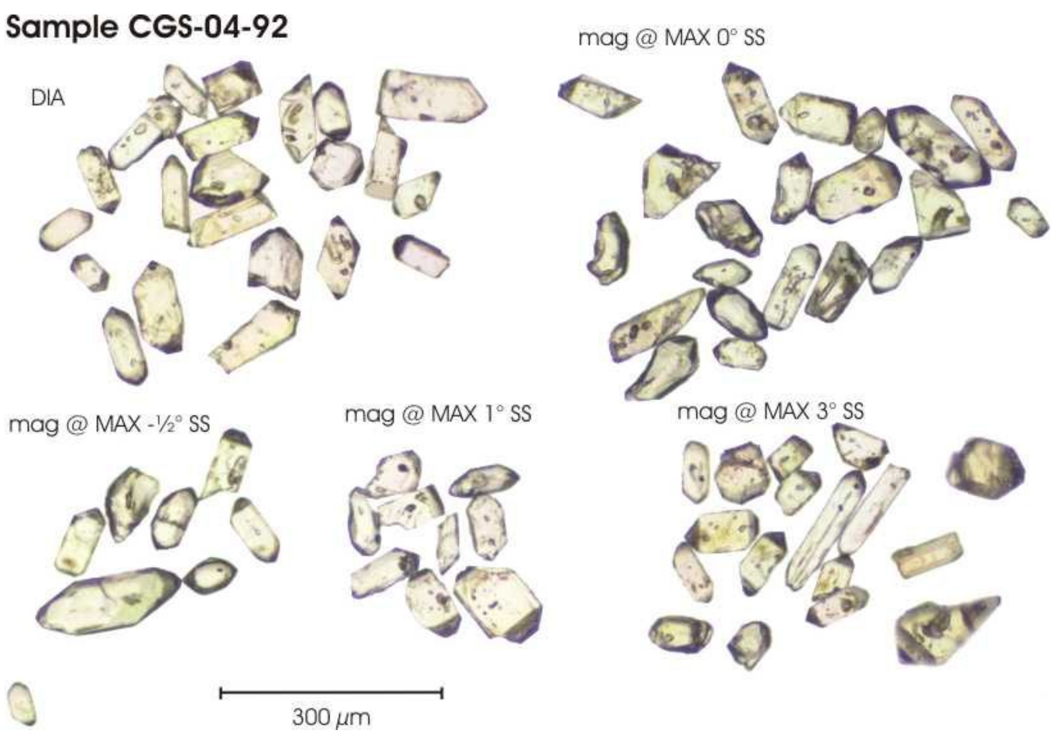

Figure 7. *Transmitted light photos of zircon from the Titan Prospect gabbro dyke, sample CGS-04-92, on the SHRIMP mount.*

Road Breccia gabbro dyke, i.e., in the Early Devonian. This is in agreement with the evidence from the Long Island pluton, where the two dated granitoid phases bracket deformation that occurred between 415 and 410 Ma and which overprints Salinic deformation in the country rocks. As the calculated ages of the two granodiorite samples overlap within uncertainty, they could have formed in a single tectonomagmatic event. The regional extent of this Early Devonian deformation is not fully established, but it may be related to reactivation of structures along the northern and southern boundaries of the Dunnage Mélange and the northern and (at least locally) southern margins of the Botwood Group.

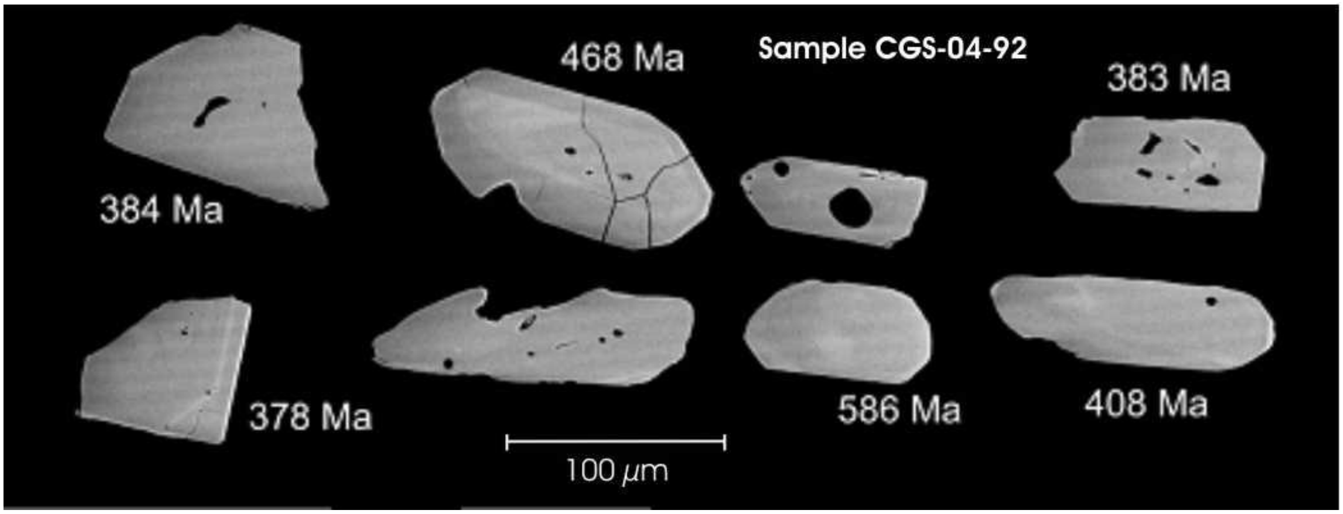

Figure 8. *Representative back-scatter SEM images of zircon from the Titan Prospect gabbro dyke.*

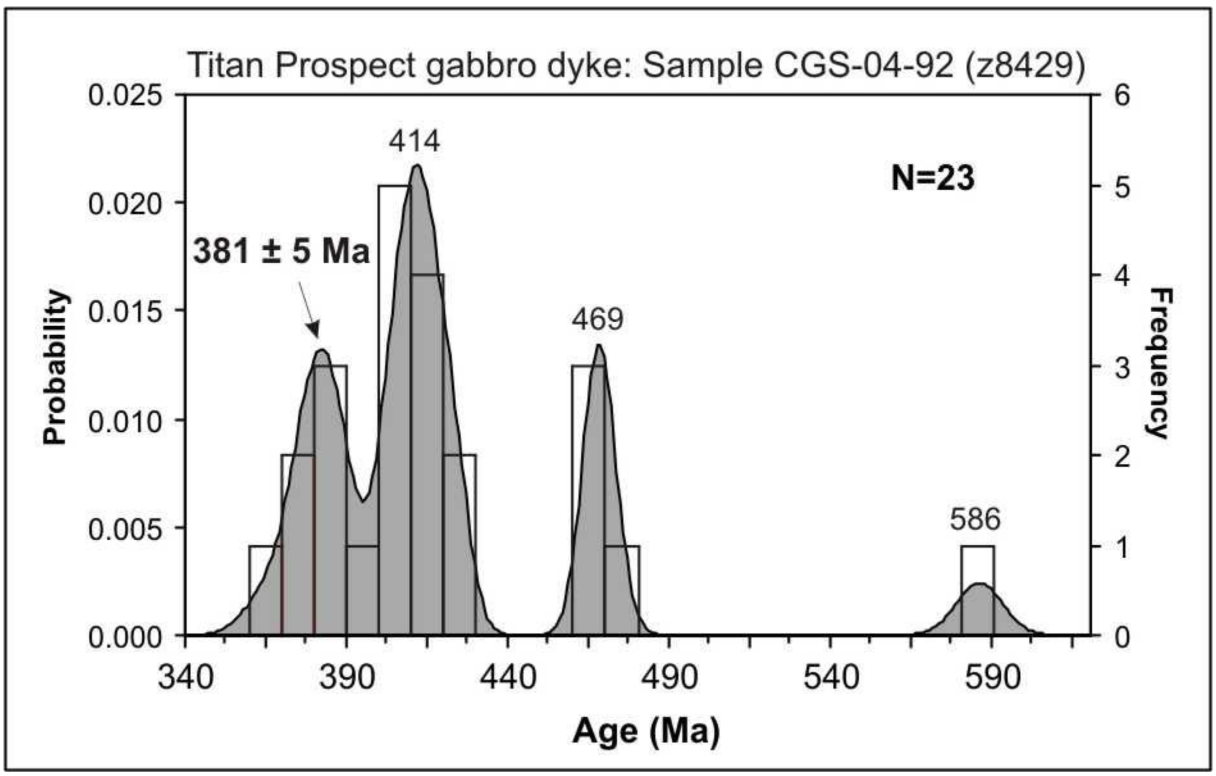

Figure 9. *Cumulative probability plot of SHRIMP analyses from the Titan Prospect gabbro dyke.*

In contrast, the results from the Titan metagabbro dyke indicate that the main development of foliation in the north-eastern part of the Indian Islands Group did not occur until after 381 ± 5 Ma, i.e., in the Late Devonian or younger. On this basis, two periods of deformation must have affected the Indian Islands Group. However, it is difficult to separate these in the field. Although the Indian Islands Group has been affected by polyphase deformation, the fabrics at both the Road Breccia and Titan locations seem to be early (S_1) fabrics. Clearly, though, they are not of the same age and pose a problem for structural correlation that can only be resolved through further work.

The post-381 Ma age of deformation in the Indian Islands Group is broadly comparable to the 400 to 385 Ma muscovite and biotite ^{40}Ar–^{39}Ar ages from the Gander Zone

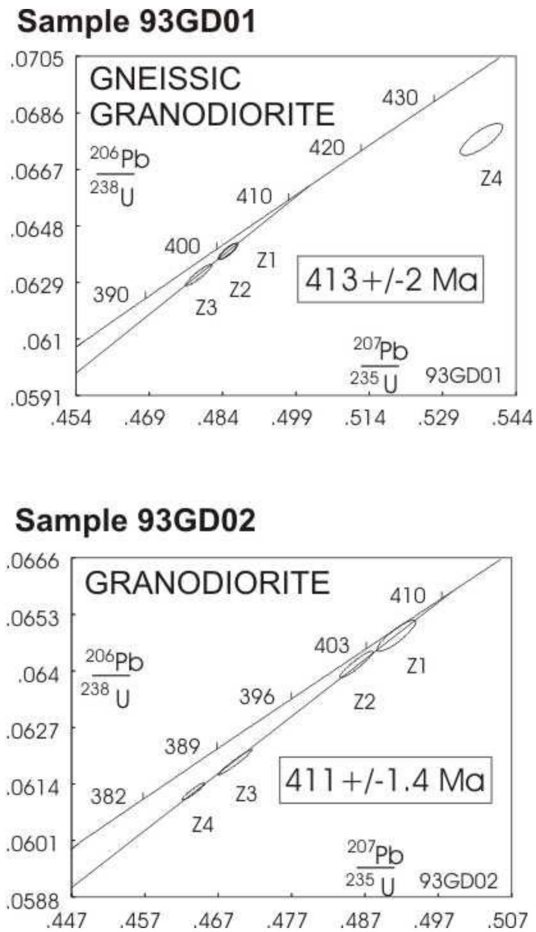

Figure 10. *Uranium–lead concordia diagrams for samples 93GD01 and 93GD02.*

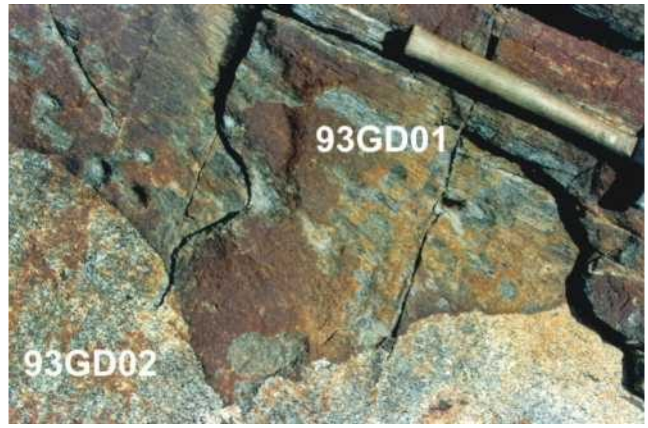

Plate 3. *Intrusive relationship between Sample 93GD01 and Sample 93GD02, as exposed near the Shoal Tickle of Little Burnt Bay.*

(O'Neill and Lux, 1989), and 390 to 370 Ma ^{40}Ar–^{39}Ar whole-rock metamorphic ages from the western Avalon Zone (Dallmeyer *et al*., 1983). These ages have been generally ascribed to the Acadian orogenic event, the upper age limit of which is otherwise provided by posttectonic granite batholiths of ca. 385 to 378 Ma in the Gander and Avalon zones (O'Neill *et al*., 1991; Kontak *et al*., 1988). Devonian deformation has also been recognized in southwest Newfoundland along the Dunnage–Gander zone boundary, where a complex series of structural events took place between 415 and 386 Ma (Dubé *et al*., 1996). The Reach Fault and Dog Bay Line therefore seem to mark the eastern limit of Salinic deformation in northeastern Newfoundland; the Indian Islands Group and other units to the east having been principally deformed in the Acadian Orogeny.

IMPLICATIONS FOR AGE OF THE INDIAN ISLANDS GROUP

The 411 ± 5 Ma date from the Road Breccia dyke indicates that the Indian Islands Group can be no younger than ca. 406 Ma, which using the age of the Silurian–Devonian boundary as 418 ± 2 Ma (Tucker *et al*., 1998; Okulitch, 2002), is consistent with the Silurian-possibly Early Devonian fossil evidence of Boyce *et al*. (1993), Boyce and Dickson (*this volume*).

IMPLICATIONS FOR THE AGE OF GOLD MINERALIZATION

The mesothermal mineralization at Titan is associated with late-tectonic quartz veining and pre- or syn-deformation carbonate alteration that must be Late Devonian or younger. Some of the mesothermal gold prospects north of the Dog Bay Line(Figure 2), notably those at the Port Albert, New World trend and Powderhouse Cove occurrences (Evans 1996), are, in part, associated with mineralized felsic dykes likely related to the Long Island and Loon Bay plutons. The unfoliated dykes intrude Silurian and Devonian deformation zones in which they crosscut penetrative fabrics but are locally affected by late fracturing and brittle shearing associated with gold mineralization. The mineralization is probably, therefore, Early Devonian. The Pond Island gold-bismuth showing (Evans, 1996), which is hosted by quartz-carbonate veins in Long Island granite, may be of similar age.

The epithermal mineralization cuts slaty cleavage in the Indian Islands Group, e.g., at the Road Breccia occurrence, and also at the Horwood breccia vein at Gander Bay (Figure 2; Squires, 2005) and must, therefore, be younger than Early Devonian. Since the epithermal systems occur in close proximity to the mesothermal ones, and given that epithermal systems generally form at higher, cooler crustal levels, it may also be reasonable to assume that they are younger than the mesothermal systems, i.e., also Late Devonian or younger.

There has been speculation (e.g., O'Driscoll and Wilton, 2005) that gabbro-granite intrusions, such as the Mount Peyton Intrusive Suite, may have driven hydrothermal systems to produce epithermal and mesothermal mineralization. Based on their (O'Driscoll and Wilton, *op. cit.*) interpreted 430 to 424 Ma (Early Silurian) ages for these plutons, and the evidence presented herein that mineralization is likely Early Devonian or younger, this does not seem likely. The possibility remains, however, that the southwest part of the Mount Peyton Intrusive Suite is younger than the reported ages (Lake and Wilton, *this volume*), thus leaving room for a genetic relationship. For the mesothermal mineralization in the Indian Islands Group, a more likely relationship is with the regional Acadian deformation and low-grade metamorphism of ca. 390 to 370 Ma.

The age of mesothermal gold mineralization elsewhere in Newfoundland is not well constrained but available evidence from the Baie Verte Peninsula indicates an age range from 437 to 374 Ma (Evans, 2005) and from the Cape Ray deposit in western Newfoundland (Dubé and Lauzière, 1997), a range of 415 to 386 Ma. These ages range from Early Silurian to Late Devonian and, as noted by Evans (2005), coincide with the range of the Salinic and Acadian orogenies. This report emphasizes the importance of Early and Late Devonian (or younger) mineralization ages. This has parallels with the results of Dubé and Lauzière, (1997) (*see above*) and also with the recent results of Kerr *et al.* (*this volume*) who report ^{40}Ar–^{39}Ar ages of 412.3 ± 2.3 and 413 ± 4.3 Ma for mafic dykes that bracket a period of Early Devonian gold mineralization in the White Bay area of northern Newfoundland. With respect to Late Devonian events, the Titan maximum age of 381 Ma is similar to the ca. 374 Ma age (Bédard *et al*., 1997) of the mesothermal Nugget Pond deposit on the Baie Verte Peninsula, and to the younger limit of ca. 386 Ma for gold mineralization at Cape Ray.

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