Current Research (2008) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 08-1, pages 173-192

GEOLOGICAL AND METALLOGENIC IMPLICATIONS OF U-Pb ZIRCON GEOCHRONOLOGICAL DATA FROM THE TALLY POND AREA, CENTRAL NEWFOUNDLAND

V. McNicoll, G.C. Squires[1], A. Kerr[2] and P. J. Moore[3]
Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8

ABSTRACT

The volcanic rocks of the Tally Pond area are the most economically important part of the Victoria Lake supergroup, and host the productive Duck Pond and Boundary VMS deposits, as well as numerous other prospects. This report summarizes new U–Pb geochronological data that add to our understanding of this structurally complex area, but which also raise some new questions and complications.

Geochronological results indicate that the volcanic rocks in this area include sequences of Precambrian (~565 Ma), Cambrian (~515 to 509 Ma) and Silurian (~422 Ma) age, and that previously identified Precambrian volcanic rocks (Sandy Brook group) are likely of regional extent. The Cambrian volcanic rocks (Tally Pond Group) appear to be the most abundant, but it remains difficult to delineate the precise extent of each package within this poorly exposed area. Polymetallic VMS mineralization is present in both Precambrian and Cambrian volcanic sequences, but the largest known deposits are hosted by the latter. However, at least three interesting VMS prospects are suspected to be hosted by Precambrian volcanic sequences, suggesting that these rocks have wider potential for discovery. The Silurian volcanic rocks lie in the easternmost part of the study area, and likely correlate with the adjacent Stony Lake group. These rocks are likely of subaerial character, and thus have little potential for VMS mineralization.

New age determinations from the Duck Pond mine area reveal that the Duck Pond and Boundary VMS deposits are coeval, possibly representing structurally displaced portions of a much larger mineralizing system developed at ~509 Ma. The unaltered volcanic rocks that structurally overlie the ore horizon yield slightly older (514–513 Ma) ages, suggesting that an important fault separating mineralized and unmineralized sequences may have originally been a thrust, despite later normal motions. Hypabyssal intrusive rocks in the Duck Pond area appear to be essentially synvolcanic in timing, and thus do not provide useful constraints on the timing of fault motions. Late Precambrian inheritance in some Cambrian volcanic rocks suggests that the younger island arc developed upon late Precambrian crust, rather than in a purely intra-oceanic setting.

INTRODUCTION

The official opening of the Duck Pond mine in May 2007 brought over thirty years of mineral exploration in the Tally Pond area to fruition. This area lies within the Exploits Subzone of the Dunnage Zone (Williams *et al.*, 1988; Figure 1), rather than the Notre Dame Subzone of the Dunnage Zone, which has traditionally been the main focus of exploration for VMS deposits. The host rocks to the Duck Pond deposit form part of the Victoria Lake supergroup, which is now the focus of systematic exploration, and also part of the area investigated by the Geological Survey of Canada as part of the Targeted Geoscience Initiative (TGI) Red Indian Line project (*e.g.*, Rogers and van Staal, 2002; Zagorevski *et al.*, 2003; Rogers *et al.*, 2006). The metallogeny of the Victoria Lake supergroup was investigated previously (Kean and Evans, 2002; Moore, 2003; Squires and Moore, 2004) and is ongoing (*e.g.*, Hinchey, 2007, *this volume*). Uranium–lead zircon geochronology is an important aspect of both regional mapping and mineral deposit studies.

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[1] Messina Minerals Inc., P.O. Box 1, Millertown, NL, AOH 1V0
[2] Mineral Deposits Section, Geological Survey, Department of Natural Resources, P.O. Box 8700, St. John's, NL, A1B 4J6
[3] Royal Roads Corporation, Suite E-130, Prince Charles Place, 120 Torbay Road, St. John's, NL, A1A 2G8

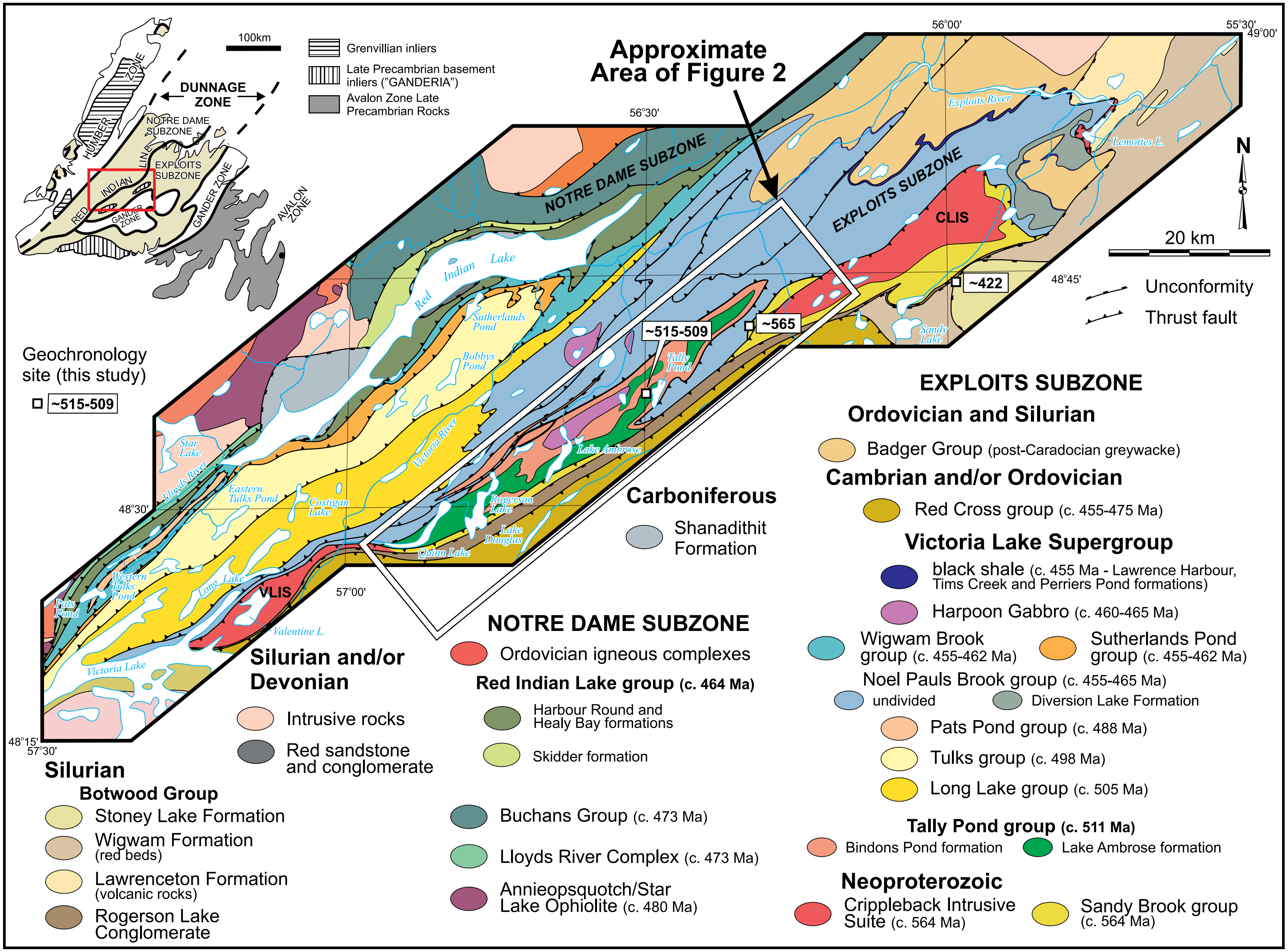


Figure 1. *Location and generalized geology of the area surrounding Red Indian Lake, including rocks of the Victoria Lake supergroup. CLIS - Crippleback Lake intrusive suite; VLIS - Valentine Lake intrusive suite. Geochronological results from this study are indicated, but others are omitted for the sake of clarity; geological map from a compilation by N. Rogers based, in part, on GSC mapping.*

This paper reviews important new U–Pb geochronological data from rocks that are closely associated with the mineralization at the Duck Pond mine, and elsewhere in the Tally Pond area. Squires and Moore (2004) provided an initial discussion of some of these results that has been referenced elsewhere (*e.g.*, Rogers *et al.*, 2006). This report now provides the complete data, additional unpublished ages, and more detailed discussion of all results. In summary, the new dates constrain the timing of VMS mineralization at Duck Pond, and demonstrate that late Precambrian volcanic rocks previously identified in the area also host VMS mineralization. The results also demonstrate that some volcanic rocks previously thought of as Cambrian are in fact Silurian. Inherited zircon populations in the younger volcanic rocks demonstrate that late Precambrian suites likely formed an older substrate to Cambrian volcanic rocks, and suggest that the latter did not develop in a truly ensimatic environment.

REGIONAL GEOLOGICAL AND METALLOGENIC FRAMEWORK

The Victoria Lake Group (Figure 1) was defined initially by Kean (1977) and Kean *et al.* (1981), and subsequently informally assigned supergroup status by Evans and Kean (2002). It is presently defined as including all pre-Caradocian (*i.e.*, >450 Ma) rocks located between the Red Indian Line and the Silurian Rogerson Lake Conglomerate (Figure 1). The Victoria Lake supergroup is traditionally divided into two large volcanic packages (the Tally Pond volcanic belt and Tulks volcanic belt; Kean and Jayasinghe, 1980), that sit within a wider area dominated by volcaniclastic sedimentary rocks (Figure 1). The area also includes intrusive rocks, ranging in composition from granite to gabbro, and not all of these are reliably dated. However, at least two granitoid suites are late Precambrian (565–563 Ma; Evans *et al.*, 1990), and are probably fault-bounded inliers of older basement, considered to represent part of the crustal block termed "Ganderia" by van Staal *et al.*, (1998) and Rogers *et al.* (2006). It has long been suspected that the Victoria Lake supergroup is a composite entity, but poor exposure and a paucity of geochronological data prevented further subdivision of the volcanic belts. Recently, Rogers and van Staal (2002) suggested a revised framework on the basis of existing geochronological data and new U–Pb results (*e.g.*, Zagorevski *et al.*, 2003); however, some of the data upon which this is based remain unpublished.

As part of this process, the Tally Pond volcanic belt was redefined at a group level, and assigned a Cambrian age (after Dunning *et al.*, 1991). The sedimentary rocks that adjoin the Tally Pond group were assigned to the newly defined Noel Paul's Brook and Wigwam Brook groups, and considered to be of Arenig to Caradocian age (~490 to 450 Ma). Other subdivisions of the Victoria Lake supergroup are not discussed here, and readers are referred to Rogers and van Staal (2002) for detailed information. This paper uses "Tally Pond group" in the same sense as these workers, *i.e.*, to include rocks of Cambrian age. Figure 1 also illustrates the probable extent of Precambrian rocks that are now assigned to the Sandy Brook group (see discussion below), and also indicates the other subdivisions of the Victoria Lake supergroup and adjacent areas proposed by Rogers and van Staal (2002).

There has long been a suspicion that the Tally Pond area might contain rocks older than Cambrian. A U–Pb zircon laser-ablation pilot study yielded a late Precambrian age (~572 Ma) for a mafic dyke that apparently cut felsic volcanic rocks (Wilton *et al.*, 2003). Rogers *et al.* (2006) subsequently obtained a ~563 Ma age directly from felsic volcanic rocks in the same general area (Figures 1 and 2). They redefined these rocks, and suggested correlatives defined by geochemical data, as the Sandy Brook group (broadly equivalent to the Sandy Lake sequence of previous workers). However, the precise extent of these older rocks versus their younger counterparts in the Tally Pond group remains problematic, due to poor outcrop and some overlap in their geochemical signatures.

The regional metallogeny of the Victoria Lake supergroup has been discussed elsewhere (Kean and Evans, 1988; Evans and Kean, 2002; Hinchey, 2007), and mineralization in the Tally Pond area was reviewed by Kean (1985), and more recently by Moore (2003) and Squires and Moore (2004). The economically important Duck Pond deposits are known to be associated regionally with felsic volcanic rocks of Late Cambrian age (Evans *et al.*, 1990; Dunning *et al.*, 1991; Squires and Moore, 2004; Rogers *et al.*, 2006; Figure 2). In the western part of the Tally Pond group, a similar Late Cambrian age was obtained from felsic volcanic rocks (Dunning *et al.*, 1991), implying that VMS mineralization at the nearby Lemarchant prospect is also of this age (Figure 2). However, northeast of the Duck Pond deposit, polymetallic mineralization at the Burnt Pond prospect is hosted by felsic volcanic rocks, that are along strike from the late Precambrian rhyolites of the Sandy Brook group (Rogers *et al.*, 2006; Figure 2).

Geochronological studies summarized here were initiated in 2002 and 2003 to examine the Duck Pond deposit footwall and hanging-wall volcanic sequences in more detail, and to establish if the host rocks to the Burnt Pond prospect are also of Precambrian age.

GEOLOGY AND MINERALIZATION

The volcanic and sedimentary rocks of the Tally Pond area are mostly covered by surficial deposits, and map pat-

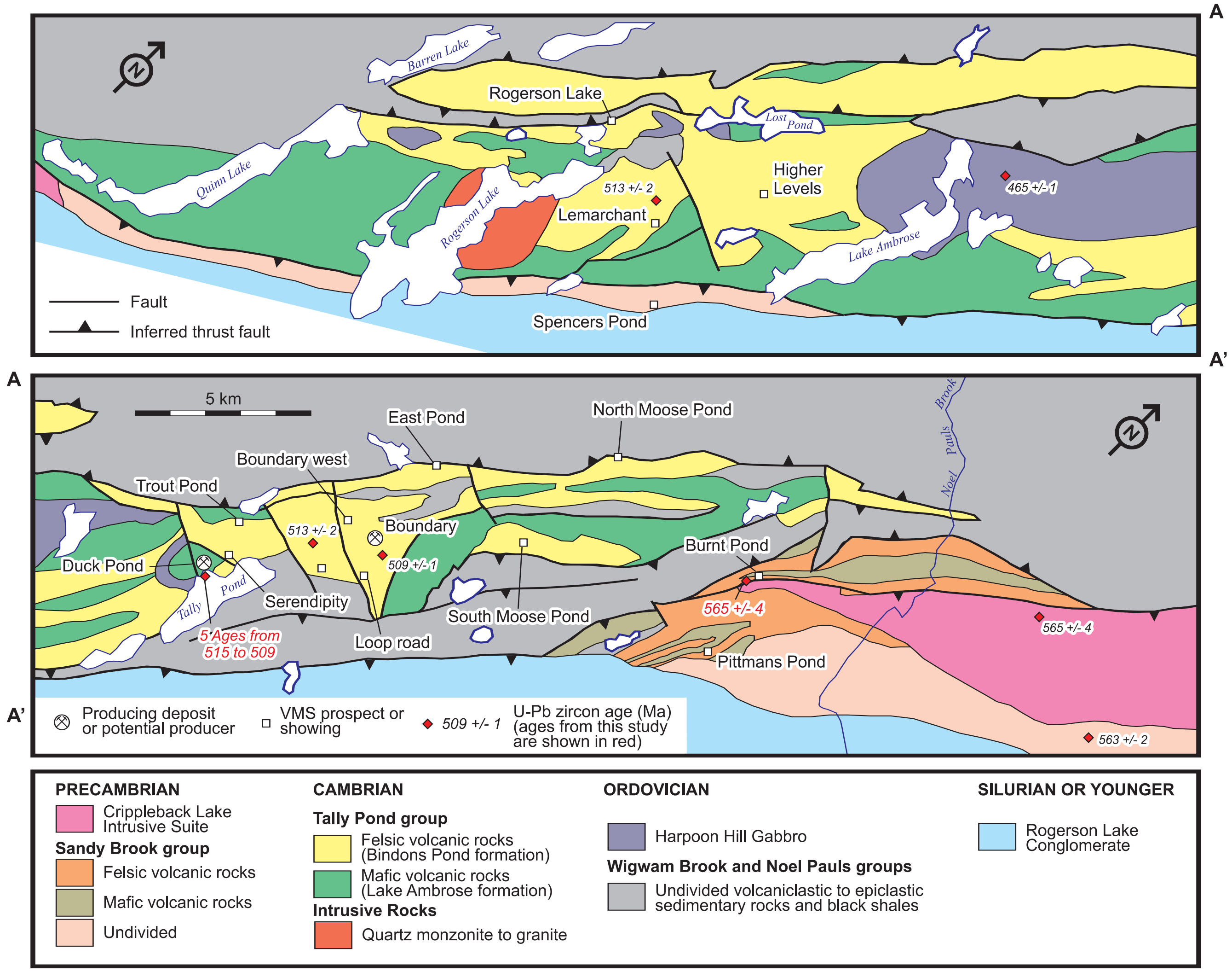


Figure 2. *The geology of the Tally Pond area, showing all pertinent geochronological data and the locations of VMS deposits and prospects discussed in this report; modified after Squires and Hinchey (2006), and Rogers* et al. *(2005a and b, 2006).*

terns are not well-constrained. Figure 2 is a combination of the 1:100 000 scale compilation of Squires and Hinchey (2006), in part, from industry data, and more generalized maps by Rogers *et al.* (2005a and b, 2006), notably at the northeastern and southwestern ends of the map area. The stratigraphic terminology below follows Rogers *et al.* (2006).

SANDY BROOK GROUP

The Sandy Brook group lies along the southeast edge of the Victoria Lake supergroup in the Tally Pond area, mostly south of the ca. 563 Ma Crippleback Lake intrusive suite (Figure 2). A thin belt of Sandy Brook group is postulated between Lake Ambrose and Quinn Lake (Figure 2), on the basis of geochemical correlations (Squires and Hinchey, 2006; Rogers *et al.*, 2005b). The Sandy Brook group is unconformably overlain by the Rogerson Lake Conglomerate to the south, and is in presumed tectonic contact with the younger Tally Pond group to the north. The Sandy Brook group consists of pillowed to massive basalts, mafic tuffs, andesitic flows, siliceous quartz-porphyritic rhyolites and subvolcanic intrusive rocks of similar compositions. It is a bimodal assemblage with evolved, REE-enriched felsic rocks, and has Nd between -3.2 and -5.2 at t=560 Ma, suggesting that even older continental crust contributed to the magmas. The basalts include two groups corresponding to island-arc tholeiite (± depleted-arc tholeiite) and continental-arc calcalkaline basalt (Rogers *et al.*, 2006).

THE BURNT POND Zn–Pb–Ag–Au PROSPECT

The most important VMS prospect within the Sandy Brook group is at Burnt Pond, some 12 km northeast of Tally Pond (Figure 2; described by Moore, 2003; Squires and Moore, 2004). Mineralization is hosted within complex metavolcanic rocks, adjacent to deformed granitoid rocks correlated with the Crippleback Lake intrusive suite. This was initially discovered and drilled by Noranda Exploration in the 1970s and 1980s, but results at the time suggested that grades were subeconomic; however recent exploration work suggests better grades along strike, up to 0.8% Cu, 24% Pb, 26% Zn, 791 g/t Ag and 1.6 g/t Au over 0.37 m (Moore, 2003). The host quartz-phyric felsic tuffs and lesser sedimentary rocks are separated from a hanging-wall sedimentary sequence by a fault zone, and the host rocks are deformed and overturned (Squires and Moore, 2004). A mafic sill within the host sequence appears little-deformed by comparison with the adjacent rocks, although its contact relationships are uncertain due to shearing in the wall rocks. The absence of sulphides in the mafic sill could be taken as an indication that it postdates the mineralization, but it could also have been inserted tectonically. A sample from this mafic sill yielded the late Precambrian laser-ablation ICP-MS U–Pb age obtained by Wilton *et al.* (2003) but, because of the uncertainty in relationships, this did not necessarily indicate an older age for the felsic rocks. However, it raised the possibility that the host rocks to mineralization are substantially older than those at the Duck Pond or Boundary deposits (see below). The felsic tuff that actually contains the mineralized zone was thus sampled for U–Pb geochronology; the location of the sample analyzed in this study is indicated in Figure 2.

TALLY POND GROUP

The Tally Pond group is a bimodal volcanic assemblage. The Lake Ambrose formation, defined by Rogers *et al.* (2006), corresponds to the "Lake Ambrose basalts" of Dunning *et al.* (1991) and the unnamed mafic volcanic rocks of earlier workers (Kean, 1977; Kean and Jayasinghe, 1980). It comprises massive to locally pillowed tholeiitic basalt, associated with tuff, pillow breccia, andesites and minor sedimentary rocks. The formation is generally unmineralized and not altered. Previously unnamed felsic rocks were termed the Bindons Pond formation by Rogers *et al.* (2006), and comprise aphyric to massive or flow-banded dacite, rhyolite, felsic tuff, breccia, volcaniclastic sedimentary rocks and quartz-feldspar porphyry. The Bindons Pond formation is hydrothermally altered on a wide scale, and it hosts sulphide mineralization. The locations of import ant prospects, including the recent LeMarchant discovery, by Paragon Minerals, are shown in Figure 2. Rogers *et al.* (2006) suggest that the Bindons Pond formation stratigraphically overlies the Lake Ambrose formation, although this is difficult to prove. The complex map pattern (Figure 2) implies structural repetition, or that more than one felsic formation is present, and exploration drilling shows that mafic and felsic rocks are intercalated on all scales. At the Duck Pond deposit, unmineralized mafic and felsic rocks sit structurally above the mineralized felsic sequence (Squires *et al.*, 1991, 2001; see later discussion). Mafic volcanic rocks of the Tally Pond group are broadly arc-related tholeiites; both mafic and felsic sequences partly overlap, in composition, the rocks of the Sandy Brook group (Rogers *et al.*, 2006). However, the Tally Pond group has ϵ_{Nd} of 1.8 to 3.1 at t=511 Ma, and thus had more primitive sources than the Sandy Brook group (Rogers *et al.*, 2006).

DUCK POND AND BOUNDARY Cu–Zn–Ag–Au DEPOSITS

The Duck Pond and Boundary deposits contain combined reserves of about 4.1 Mt at ~3.3% Cu, 5.7% Zn, 0.9% Pb, 59 g/t Ag and 0.9 g/t Au (Aur Resources, 2007). The near-surface Boundary Deposit was discovered in 1980, and the much larger Duck Pond Deposit was discovered 5 years later; most of the reserves and resources are at Duck Pond, which commenced production (from underground) in early 2007. The Boundary Deposit is scheduled to be mined as an open-pit operation in the last year of production.

The Duck Pond Deposit is described in detail elsewhere (Squires *et al.*, 1991, 2001; Moore, 2003; Squires and Moore, 2004), and is merely summarized here, using a SW–NE cross-section through the deposit (Figure 3, after Squires and Moore, 2004) that illustrates essential geological relationships. There are at least three discrete sulphide lenses, but these are thought to have originally formed a single body, prior to disruption by faults. The ore is hosted by altered felsic volcanic, pyroclastic and volcaniclastic rocks that are termed the Mineralized Block. These rocks are juxtaposed against an upper panel of unmineralized rocks, termed the Upper Block, by a prominent fault zone. Although displacements across it suggest normal motion, this fault is known as the Duck Pond thrust (Squires *et al.*, 1991, 2001). The fault zone is discordant with the stratigraphy, and includes tectonic lozenges of graphitic sedimentary rocks that are correlated with a thin sequence of incompetent graphitic sedimentary rocks northeast of the ore zones (Figure 3). This sedimentary interval appears to be conformable above altered felsic rocks on a local scale in the northeastern part of the deposit, and it locally hosts exhalative-style mineralization and ore-bearing debris flows (the Serendipity showing; Figure 3). The presence of graphitic lozenges within the Duck Pond thrust suggests that these rocks have been dragged to the southwest, indicating at least a latest normal motion. Splays of the Duck Pond thrust also disrupt the ore zones, with a similar normal sense of motion. The youngest rocks that are affected by the fault are subhorizontal gabbro sills that intrude the volcanic rocks of the Upper Block (Figure 3). These rocks have distinct "within-plate" geochemical signatures (Squires and Moore, 2004) and are correlated with the Harpoon Hill gabbro (Figure 2),

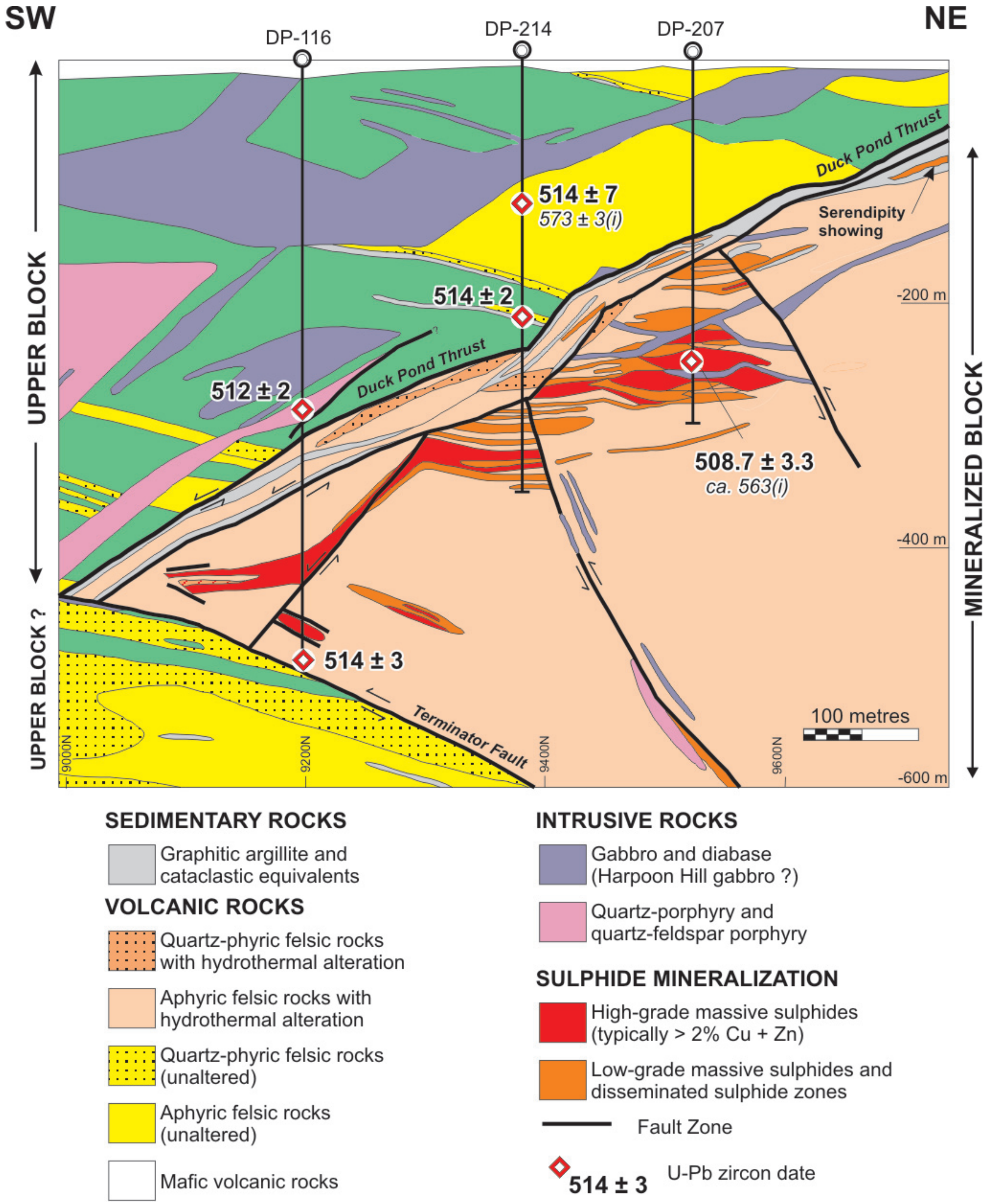


Figure 3. *Simplified cross-section through the Duck Pond Deposit (Line 9600 east) showing some of the essential geological relationships and geochronological data discussed in this report; modified after Squires and Moore (2004). Ages shown in italics followed by (i) indicate those defined by inherited zircons.*

which was dated at 465 ± 1 Ma (Pollock, 2004; see later discussion). Small-scale motion indicators within the Duck Pond thrust indicate both reverse and normal motion, and a study based on examination of drill core suggested that there was probably an early episode of reverse motion (T. Calon, personal communication to GS, 1987). These observations form the basis for the present interpretation that the structure originated as a thrust, but was subsequently reactivated as a normal fault (Squires *et al.*, 1991, 2001).

The massive sulphide zones at Duck Pond locally exhibit spectacular banding that superficially resembles bedding, but these ores are not viewed as truly exhalative in origin. Squires *et al.* (1991, 2001) suggest that sulphides replaced pre-existing, unconsolidated material in a subseafloor environment, and, in places, faithfully mimicked primary features. The venting of mineralizing fluids onto the seafloor is suggested by the debris-flow mineralization in rocks stratigraphically above the main ore lenses (the Serendipity showing; Figure 3). The argillaceous sedimentary rocks may have formed a less permeable "seal" that trapped much of the fluid and promoted replacement of more permeable units at depth (Squires *et al.*, 2001). However, the mineralization is not epigenetic, as any time gap between host-rock deposition and pervasive replacement is geologically insignificant. A well-defined alteration pipe has not been identified to date in the immediate footwall to the deposit, but there is a zone of intense chloritic alteration located to the northwest (not in the plane of Figure 3) that may represent a structurally offset hydrothermal conduit system.

The Boundary Deposit comprises three subcropping lenses of massive sulphide mineralization. Both the mineralization and associated felsic volcanic host rocks are identical to counterparts at the main Duck Pond Deposit. The sulphide zones at Boundary are associated with intense chloritic alteration in their immediate footwall rocks (Squires *et al.*, 2001; Moore, 2003; Squires and Moore, 2004). Squires *et al.* (1991, 2001) suggested that the Boundary sulphide mineralization and associated alteration is a structurally disrupted portion of the same broad mineralizing system that hosts the main Duck Pond Deposit. Although the later normal displacements of sulphide zones observed at Duck Pond are relatively small, earlier disruptions by thrusting may have involved more significant motions.

Geochronological studies reported in this paper were initiated to test ideas about the age of mineralization at Duck Pond, to test age relationships between the unmineralized Upper Block and the underlying mineralized block, and to test postulated Duck Pond–Boundary correlations. The locations of samples are indicated in Figures 1 and 2, and individual results are placed in context in Figure 3.

RHYOLITIC ROCKS OF THE PATCH VALLEY AREA

The recognition that there could be Precambrian volcanic rocks in the Burnt Pond area raises questions about the nature, age and affinity of felsic volcanic rocks that lie to the east of these (Figure 1). In map sheet NTS 2D/11, these rocks were included within the "Tally Pond formation" by Colman-Sadd and Russell (1988) and have generally been considered to be of Cambrian age; they were denoted as such by Kean and Evans (2002). These rocks are bounded to the east by fresh rhyolitic rocks of the Stony Lake group (Colman-Sadd and Russell, 1988), for which a precise Silurian age of 423 +3/-2 Ma was later obtained by Dunning *et al.* (1990). Field examination of outcrops in the area known as Patch Valley, in the northwestern corner of map sheet NTS 2D/11, indicate that these rocks are rhyolites similar in appearance to those at Miguel Hill, within the Stony Lake group, and they are dissimilar to typical Tally Pond group felsic rocks. A geochronological sample was collected to resolve this question. The sample location lies outside the area depicted in Figure 2, but it is indicated in Figure 1. Note that the location shown on a previous summary map (Squires and Moore, 2004) is about 1 km west of the actual location, which lies about 500 m east of the boundary between map sheets NTS 12A/09 and 2D/11. The coordinates are listed in Table 1.

U-Pb ZIRCON GEOCHRONOLOGY

PREVIOUS RESULTS AND STUDY METHODS

Several previous geochronological studies are relevant in the context of these new data; most localities and results are indicated in Figure 2. Dunning (1986) initially obtained identical 513 ± 2 Ma U-Pb zircon ages from felsic volcanic rocks near the Boundary Deposit, and near the LeMarchant prospect, establishing the presence of Cambrian arc rocks in Iapetus (Dunning *et al.*, 1991). Subsequently, Pollock (2004) obtained a slightly younger U-Pb TIMS age of 509 ± 1 Ma from altered felsic rocks sitting conformably above the Boundary Deposit, which indicate the timing of mineralization; this age was later reported by Rogers *et al.* (2006). As discussed previously, Rogers *et al.* (2006) confirmed a Precambrian age (563 ± 2 Ma) for felsic volcanic rocks of their Sandy Brook group about 8 km to the east of the Burnt Pond prospect. Granitic rocks of the Crippleback Lake and Valentine Lake intrusive suites were dated at 563 ± 2 Ma and 565 ± 4 Ma, respectively (Evans *et al.*, 1990; Figure 1), but the full data for these remain unpublished. The dated locality for the Valentine Lake intrusive suite lies outside the area depicted in Figure 2. Wilton *et al.* (2003) obtained a 572 ± 4 Ma age from a mafic sill at Burnt Pond, using the laser-ablation ICP–MS method. The youngest age from the Tally Pond

Table 1. U-Pb isotopic data for samples analyzed using TIMS techniques

							Isotopic Ratios[6]								Ages (Ma)[8]						
Fraction[1]	Description[2]	Wt. ug	U ppm	Pb[3] ppm	206Pb[4] 204Pb	Pb[5] pg	208Pb 206Pb	207Pb 235U	±1SE Abs	206Pb 238U	±1SE Abs	Corr.[7] Coeff.	207Pb 206Pb	±1SE Abs	206Pb 238U	±2SE	207Pb 235U	±2SE	207Pb 206Pb	±2SE	% Disc
Burnt Pond Prospect																					
Z7886; Felsic Tuff, Burnt Pond prospect (Drillhole EO-90-01, 164.6 to 169.6 metres)																					
A1 (7)	Co,Clr,rIn,Eu,Pr,Dia	29	216	21	918	38	0.21	0.73510	0.00167	0.09051	0.00010	0.753	0.05891	0.00010	558.5	1.1	559.5	1.9	563.6	7.0	0.9
A2 (9)	Co,Clr,rIn,Eu,Pr,Dia	26	203	21	782	39	0.26	0.73540	0.00186	0.09061	0.00010	0.730	0.05886	0.00011	559.1	1.2	559.7	2.2	562.1	8.2	0.6
A3 (35)	Co,Alt,rIn,Eu,Pr,Dia	28	245	24	477	83	0.24	0.72397	0.00282	0.08896	0.00012	0.707	0.05902	0.00018	549.4	1.4	553.0	3.3	567.9	13.4	3.4
A4 (24)	Co,Clr,rIn,Eu,Pr,Dia	28	170	17	828	33	0.24	0.73438	0.00170	0.09028	0.00010	0.725	0.05900	0.00010	557.2	1.1	559.1	2.0	566.9	7.4	1.8
Duck Pond Deposit: Upper Block																					
Z7827; Quartz-phyric dacitic lapilli tuff, Duck Pond deposit (Drillhole DP-99-214A, 211.2 to 216.0 metres)																					
A1 (22)	Co,Clr,cIn,Eu,Pr,Dia	23	238	21	2204	13	0.16	0.66389	0.00100	0.08296	0.00008	0.768	0.05804	0.00006	513.8	0.9	517.0	1.2	531.1	4.3	3.4
B1 (22)	Co,Clr,rFr,cIn,Eu,Pr,M1°	18	212	18	2492	8	0.16	0.62528	0.00096	0.07889	0.00008	0.784	0.05749	0.00006	489.5	0.9	493.2	1.2	510.2	4.4	4.2
C1 (23)	Co,Clr,rFr,cIn,Eu,St,Osc,M3°	21	145	13	2429	6	0.18	0.64828	0.00092	0.08160	0.00008	0.874	0.05762	0.00004	505.7	0.9	507.4	1.1	515.3	3.3	1.9
C2 (25)	Co,Clr,cIn,Eu,St,Osc,M3°	17	232	20	2757	7	0.18	0.64370	0.00091	0.08111	0.00008	0.832	0.05756	0.00005	502.7	1.0	504.6	1.1	513.1	3.5	2.1
C3 (27)	Co,Clr,fFr,cIn,Eu,St,Osc,M3°	15	349	30	3577	7	0.18	0.65150	0.00086	0.08210	0.00008	0.881	0.05755	0.00004	508.7	0.9	509.4	1.1	512.7	2.9	0.8
Z7646; Porphyry within Duck Pond thrust (Drillhole DP-87-116, 277.1 to 293.1 metres)																					
A1 (39)	Co,Clr,fFr,fdIn,Eu,St,M0°,90	26	148	13	637	32	0.16	0.64325	0.00303	0.08114	0.00032	0.889	0.05750	0.00012	502.9	3.8	504.3	3.7	511	10	1.6
A2 (30)	Co,Clr,fFr,fdIn,Eu,St,M0°,100	27	152	13	1890	11	0.16	0.64621	0.00141	0.08139	0.00014	0.817	0.05759	0.00007	504.4	1.7	506.1	1.7	514	6	2.0
B1 (35)	Co,Clr,fFr,fdIn,Eu,St,M1°,95	31	158	13	2912	8	0.16	0.64452	0.00425	0.08118	0.00053	0.982	0.05758	0.00007	503.2	6.3	505.1	5.2	514	5	2.2
B2 (25)	Co,Clr,rFr,fdIn,Eu,St,M1°,95	27	120	10	2268	7	0.16	0.64628	0.00105	0.08153	0.00010	0.810	0.05749	0.00006	505.2	1.1	506.2	1.3	511	4	1.1
B3 (38)	Co,Clr,rFr,fdIn,Eu,St,M1°,80	27	114	10	2971	2	0.17	0.65490	0.00117	0.08258	0.00012	0.702	0.05752	0.00007	511.5	1.4	511.5	1.4	511	6	0.0
Duck Pond Deposit: Mineralized Block																					
Z7828; Quartz-phyric dacitic lapilli tuff, mineralized, Duck Pond Deposit (Drillhole DP-88-168, 244.6 to 257.5 metres). NOTE: Also investigated using SHRIMP Method																					
A1 (17)	Z,Co,Clr,fFr,fIn,Pr,M0°	16	241	23	1842	12	0.21	0.71180	0.00107	0.08796	0.00009	0.819	0.05869	0.00005	543.4	1.0	545.8	1.3	555.7	3.9	2.3
A2 (17)	Z,Co,Clr,fFr,nIn,Pr,M0°	16	196	18	2196	8	0.20	0.68801	0.00100	0.08532	0.00008	0.828	0.05849	0.00005	527.8	0.9	531.6	1.2	548.0	3.8	3.8
A3 (13)	Z,Co,Clr,fFr,nIn,Pr,M0°	19	271	26	2064	14	0.21	0.71708	0.00103	0.08841	0.00008	0.844	0.05883	0.00005	546.1	1.0	548.9	1.2	560.7	3.6	2.7
A4 (14)	Z,Co,Clr,fFr,nIn,Pr,M0°	17	178	17	1765	9	0.20	0.69110	0.00104	0.08590	0.00008	0.826	0.05835	0.00005	531.2	0.9	533.5	1.3	542.9	4.0	2.2
Z7826; Quartz porphyritic dacite dyke, mineralized, Duck Pond deposit (Drillhole DP-87-111A, 485.0 to 493.9 metres)																					
A1 (17)	Co,Clr,fFr,cIn,Eu,St,M1°	18	233	21	2676	8	0.19	0.65966	0.00089	0.08315	0.00008	0.866	0.05754	0.00004	514.9	0.9	514.4	1.1	512.3	3.1	-0.5
A2 (19)	Co,Clr,fFr,cIn,Eu,St,M1°	22	273	24	2010	15	0.21	0.63288	0.00092	0.08011	0.00007	0.838	0.05730	0.00005	496.8	0.9	497.9	1.1	503.0	3.7	1.3
B2 (17)	Co,Clr,rFr,cIn,Eu,St,M3°	24	271	24	1058	32	0.18	0.64832	0.00131	0.08159	0.00008	0.768	0.05763	0.00008	505.6	1.0	507.4	1.6	515.6	6.2	2.0
B3 (5)	Co,Clr,rFr,fIn,Eu,St,M3°	1	1906	169	731	14	0.18	0.66007	0.00166	0.08293	0.00009	0.712	0.05772	0.00011	513.6	1.0	514.7	2.0	519.3	8.4	1.1
Patch Valley Rhyolites																					
Z7612; Rhyolite, Patch Valley area (Sample PJM-02-012; UTM zone 21;574159E; 5396983N). NOTE: Also investigated using SHRIMP method.																					
A1 (26)	Co,Clr,cIn,El,Eu,M1°	29	95	7	2095	6	0.17	0.51562	0.00102	0.06775	0.00010	0.729	0.05520	0.00007	422.6	1.2	422.2	1.4	420	6	-0.6
A2 (25)	Co,Clr,fIn,El,Eu,M1°	13	65	4	1022	1	0.14	0.51155	0.00188	0.06717	0.00014	0.516	0.05524	0.00017	419.1	1.6	419.5	2.5	422	14	0.7
B1 (14)	Co,Clr,Eu,Pr,M1°	36	112	9	5693	2	0.13	0.69871	0.00092	0.07687	0.00008	0.846	0.06592	0.00005	477.4	1.0	538.0	1.1	804	3	42.1
C1 (30)	Co,Clr,fIn,Eu,St,M1°	44	154	23	134	508	0.17	1.59606	0.02320	0.14059	0.00050	0.690	0.08234	0.00102	848.0	5.7	968.7	18.1	1254	48	34.5
D1 (20	Co,Clr,fIn,El,Eu,Osc,M3°	38	137	10	4704	3	0.14	0.51394	0.00078	0.06753	0.00008	0.881	0.05519	0.00004	421.3	1.0	421.1	1.0	420	3	-0.3
D2 (28)	Co,Clr,El,Eu,Osc,M3°	26	206	14	7388	3	0.14	0.51465	0.00093	0.06735	0.00011	0.875	0.05542	0.00005	420.2	1.4	421.6	1.3	429	4	2.2

Notes:

[1] All zircon fractions are abraded following the method of Krogh (1982). Number in bracket refers to the number of grains in the analysis.

[2] Zircon descriptions: Co=Colourless, Clr=Clear, fFr=Few Fractures, rFr=Rare Fractures, cIn=Clear Inclusions, fIn=Few Inclusions, nIn=Numerous Inclusions, rIn=Rare Inclusions, Eu=Euhedral, Pr=Prismatic, St=Stubby Prism, Osc=Oscillatory zoning, Dia=Diamagnetic, M0°=Magnetic @ 1.8A, 0°SS.

[3] Radiogenic Pb

[4] Measured ratio, corrected for spike and fractionation

[5] Total common Pb in analysis corrected for fractionation and spike

[6] Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from <0.1- 0.1 pg for U and 2-5 pg for Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey-Kramers compositions

[7] Correlation Coefficient

[8] Corrected for blank and common Pb, errors quoted are 2 sigma in Ma

area, prior to this study, was 465 ± 1 Ma, from the large Harpoon Hill gabbro pluton (Pollock, 2004; Figure 2). Most previous data from the area were obtained using multigrain TIMS methods, but our study involves a combination of TIMS and microdomain SHRIMP analyses. The latter were employed in cases where zircon yields were inadequate for TIMS, and/or to better resolve issues related to inheritance.

With the exception of the rhyolite sample from Patch Valley, all samples for this study consisted of split diamond-drill core, sampled with the kind permission of Aur Resources in the Duck Pond area. The sample from the Burnt Pond area was collected from drill core archived by the Department of Natural Resources, originally acquired by Noranda. The UTM coordinates and/or depths of core intervals for all samples are provided in the data tables. All geochronological research, including preparation, was completed at the GSC geochronology laboratory in Ottawa, Ontario, Canada. Processing, analysis and data treatment are discussed in contract reports (McNicoll, 2003, 2004). U–Pb TIMS analytical methods utilized in this study are described by Parrish *et al.* (1987) with the treatment of analytical errors after Roddick (1980) and regression analysis modified after York (1969). Uranium–lead SHRIMP II analyses followed procedures described by Stern (1997) and Stern and Amelin (2003). Concordia ages (Ludwig, 1998) are caculated for some of the samples presented herein. The analytical results are shown in Uranium–lead concordia diagrams in Figure 4 (TIMS analyses) and Figure 5 (SHRIMP analyses), with 2σ errors displayed. The TIMS data are presented in Table 1, and the SHRIMP data are presented in Table 2.

RESULTS

Felsic Volcanic Host Rocks to the Burnt Pond Prospect

The analyzed sample (z7886) came from drillhole EO-90-01 (drilled by Noranda Exploration) within the zone of sulphide mineralization. This drillhole is on the same section as drillhole BP-2001-03, where Wilton *et al.* (2003) obtained their 572 ± 4 Ma laser ablation age from a mafic sill. The sample is a quartz crystal tuff, locally grading into a rhyolitic breccia; from a lithological perspective, it is very similar to samples dated from the Tally Pond group (see below). The sample contained only a small amount of zircon, but the euhedral, prismatic grains were of high quality and four multigrain fractions were analysed using TIMS methods. The euhedral, prismatic morphology of the grains argues against a xenocrystic origin. The upper intercept of a linear regression of these anlyses (MSWD=0.36, anchored at the origin) is 565 ± 4 Ma, indicating crystallization during the late Precambrian (Figure 4).

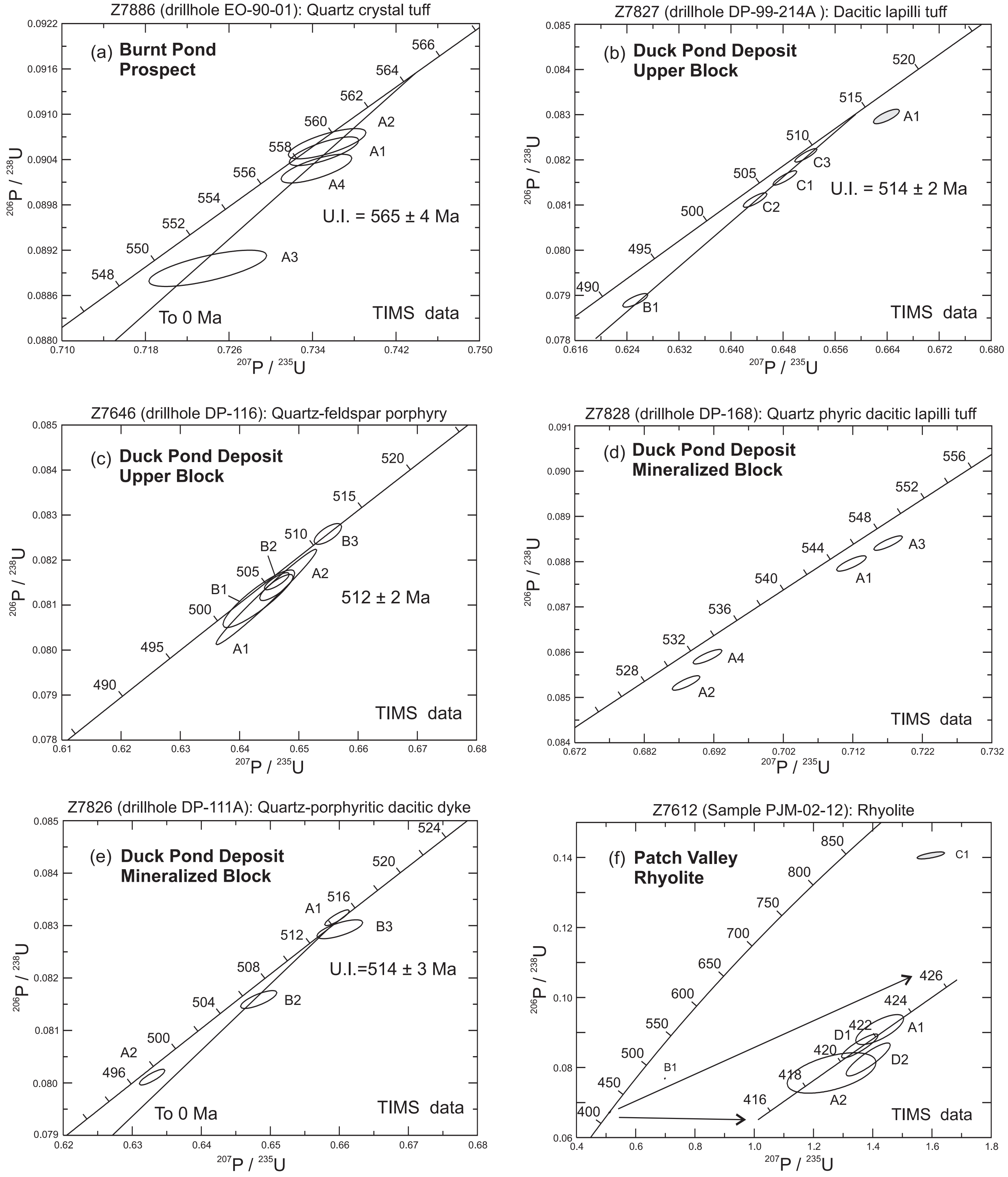
Duck Pond Deposit: Upper Block Samples

Three samples were analyzed from the Tally Pond group in the "Upper Block" at the Duck Pond Deposit, with the objective of understanding its original relationship to the structurally underlying "Mineralized Block", and perhaps constrain the age of displacements on the Duck Pond thrust (Figure 3).

The first sample (z7528) came from drillhole DP-214, located slightly more than 100 m above the composite Duck Pond thrust (Figure 3). It is an unaltered, unmineralized felsic extrusive rock interpreted as a porphyritic dacitic flow (Squires and Moore, 2004). It provided a small amount of zircon, and the morphology of grains was highly varied. Such patterns indicate complex origins, and the zircons were thus investigated using the SHRIMP technique. The SHRIMP analyses revealed two distinct age populations (Figure 5). Most of the grains are late Precambrian, giving a weighted average ^{206}Pb/^{238}U age of 573 ± 4 Ma (MSWD=0.28, n=8). The remaining grains have an average ^{206}Pb/^{238}U age of 514 ± 7 Ma (MSWD=0.87, n=3). This latter age resembles previous results from Tally Pond group felsic rocks, but it does not necessarily date crystallization of this rock. The felsic extrusive rocks in the Duck Pond-Boundary area are notoriously deficient in zircon, and it is possible that all the grains are xenocrysts. Nevertheless, 514 ± 7 Ma is a maximum age for this sample, and the ca. 573 Ma fraction has to represent inherited material.

The second sample (z7827) was analyzed in an effort to resolve the ambiguity of the 514 ± Ma age from z7528. It came from drillhole DP-214A, at a depth of ~ 213 m, much closer to the Duck Pond thrust (Figure 3). Unlike the first sample, it is a submarine pyroclastic rock – specifically, a quartz-porphyritic dacitic lapilli tuff within a sequence of mafic rocks. The sample provided a better yield of zircons with euhedral morphology, including broken crystal tips. The grains were amenable to TIMS methods (Figure 4). Of the five multigrain fractions, discordant fraction A1 likely contains an inherited component. A linear regression of the remaining fractions defines a lower intercept of 89 Ma, with an upper intercept of 515 +6/-3 Ma (MSWD=1.06). A linear regression excluding fraction B1, which is the most discordant analysis and has a different morphology than the other 3 fractions, has an upper intercept age of 514 ± 2 Ma (MSWD=0.77, anchored at the origin). This age of 514 ± 2 Ma is interpreted to record the crystallization age of the sample, and it supports the result obtained from the rare Cambrian zircons in the first sample.

The third sample (z7646) came from drillhole DP-116 at a depth of ~285 m, and is a quartz-feldspar porphyry that


Z7886 (drillhole EO-90-01): Quartz crystal tuff

Z7827 (drillhole DP-99-214A): Dacitic lapilli tuff

Z7646 (drillhole DP-116): Quartz-feldspar porphyry

Z7828 (drillhole DP-168): Quartz phyric dacitic lapilli tuff

Z7826 (drillhole DP-111A): Quartz-porphyritic dacitic dyke

Z7612 (Sample PJM-02-12): Rhyolite

Figure 4. *U-Pb concordia diagrams for samples analyzed using TIMS techniques. (a) felsic tuff, Burnt Pond prospect; (b) dacitic tuff, Duck Pond Deposit, Upper Block; (c) quartz-feldspar porphyry, Duck Pond Deposit, Upper Block; (d) mineralized felsic tuff, Duck Pond Deposit, Mineralized Block; (e) Mineralized quartz-porphyritic dacitic dyke, Duck Pond Deposit, Mineralized Block; (f) rhyolite, Patch Valley area. For discussion of individual samples, see text.*

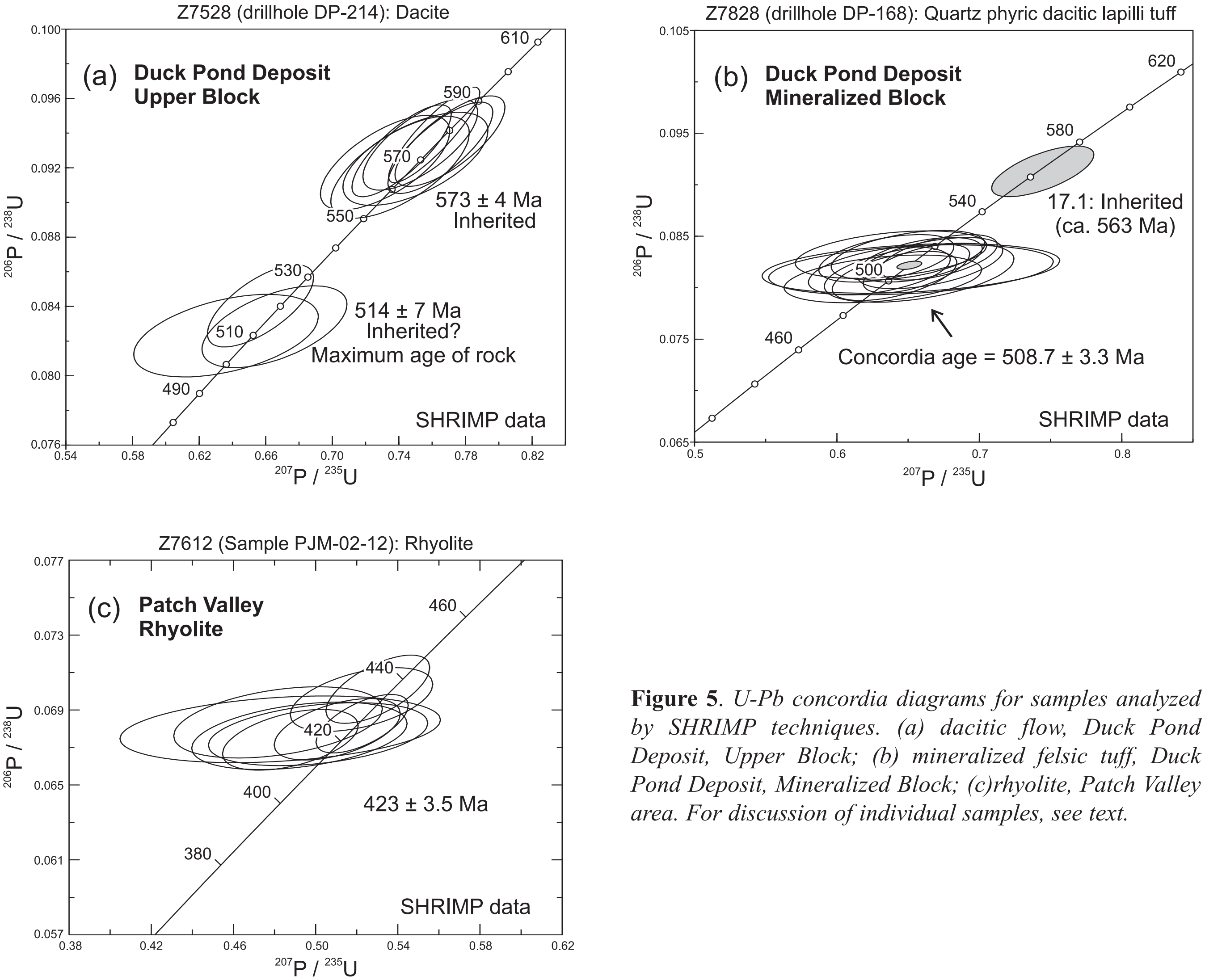


Figure 5. *U-Pb concordia diagrams for samples analyzed by SHRIMP techniques. (a) dacitic flow, Duck Pond Deposit, Upper Block; (b) mineralized felsic tuff, Duck Pond Deposit, Mineralized Block; (c)rhyolite, Patch Valley area. For discussion of individual samples, see text.*

appears to be discordant with the lithostratigraphy of the Upper Block (Figure 3). This unit is affected by a splay of the Duck Pond thrust at its northeast end, but lacks the strong deformation seen in adjacent felsic flows and tuffs. The sample contained abundant zircon, mostly of well-faceted, prismatic morphology. One fraction was concordant, but the remainder show minor Pb loss. A weighted average of the ^{207}Pb/^{206}Pb ages is 512 ±2 Ma (MSWD=0.4, n=5), which is interpreted to record the crystallization of the rock (Figure 4). The slightly younger age compared to the first two samples is consistent with the geological relationships inferred from drilling (Figure 3), but the ages do overlap within respective errors.

In an attempt to better constrain motions on the Duck Pond thrust, two attempts were made to date the gabbroic rocks that cut the lithostratigraphy of the Upper Block (Figure 3). A sample from the upper part of drillhole DP-116 (Figure 3) failed to yield any zircon, but a sample collected from drillhole DP-97 (not shown in Figure 3) yielded just 5 zircons, of which three appeared to be of xenocrystic origin. The two faceted grains recovered were very small and were not analyzed (McNicoll, 2003)

Duck Pond and Boundary Deposits: Mineralized Block Samples

The rhyolites and dacites that host replacement-style sulphide ores at Duck Pond were likely glassy at the time of their formation, as evidenced by relict textures suggesting perlitic fracturing and devitrification (Squires *et al.*, 2001), and they are depleted in zirconium. This is not a good combination of features for U–Pb geochronological studies, and it is thus not surprising that the two samples collected initially from the immediate footwall sequences to the Duck Pond and Boundary sulphide lenses were devoid of zircon (McNicoll, 2003). Due to this problem, an attempt was made to instead analyze a rock of pyroclastic origin, and

Table 2. U-Pb isotopic data for samples analyzed using SHRIMP techniques

																	Ages (Ma) ± 1σ[1]				Ages (Ma) ± 1σ[2]	
Spot name	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	^{204}Pb (ppb)	^{204}Pb/^{206}Pb	f206	^{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	^{206}Pb/^{238}U	±^{206}Pb/^{238}U	^{207}Pb/^{206}Pb	±^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	±^{206}Pb/^{238}U
Duck Pond Deposit: Upper Block																						
Z7528; Rhyolite, Duck Pond deposit (Drillhole DP-99-214, 126.0 to 150.0 metres)																						
7528-11.1	229	145	0.654	21	3	0.00016	0.00278	0.2069	0.0056	0.6367	0.0225	0.08226	0.00098	0.450	0.05614	0.00179	509.6	5.9	457.8	72.2	510.4	5.8
7528-18.1	243	97	0.412	21	2	0.00012	0.00200	0.1286	0.0045	0.6656	0.0177	0.08278	0.00097	0.548	0.05831	0.00131	512.7	5.8	541.6	49.7	512.2	5.8
7528-1.1	357	310	0.895	34	3	0.00012	0.00210	0.2764	0.0028	0.6572	0.0130	0.08399	0.00097	0.678	0.05675	0.00083	519.9	5.8	482.0	32.6	520.5	5.8
7528-9.1	433	294	0.700	44	5	0.00014	0.00238	0.2187	0.0025	0.7407	0.0169	0.09201	0.00121	0.668	0.05839	0.00100	567.4	7.1	544.5	37.9	567.8	7.2
7528-21.1	403	211	0.541	39	4	0.00013	0.00217	0.1687	0.0025	0.7319	0.0158	0.09228	0.00112	0.658	0.05752	0.00094	569.0	6.6	511.5	36.5	570.0	6.6
7528-6.1	328	182	0.575	32	1	0.00002	0.00043	0.1822	0.0028	0.7499	0.0177	0.09249	0.00110	0.605	0.05881	0.00111	570.2	6.5	560.0	41.8	570.4	6.5
7528-15.1	375	261	0.719	39	0	0.00000	0.00008	0.2285	0.0023	0.7650	0.0128	0.09314	0.00108	0.771	0.05957	0.00064	574.1	6.4	588.0	23.5	573.8	6.3
7528-4.1	589	405	0.712	60	3	0.00007	0.00122	0.2239	0.0018	0.7417	0.0121	0.09296	0.00109	0.791	0.05787	0.00058	573.0	6.4	524.9	22.3	573.9	6.4
7528-16.1	440	298	0.699	45	3	0.00008	0.00130	0.2208	0.0022	0.7530	0.0140	0.09333	0.00108	0.709	0.05851	0.00077	575.2	6.4	549.1	29.2	575.7	6.4
7528-19.1	1144	1299	1.174	132	57	0.00062	0.01075	0.3688	0.0020	0.7705	0.0135	0.09352	0.00107	0.742	0.05975	0.00070	576.3	6.3	594.6	25.8	575.9	6.3
7528-13.1	359	246	0.707	37	0	0.00001	0.00017	0.2225	0.0029	0.7612	0.0112	0.09388	0.00113	0.881	0.05881	0.00041	578.5	6.7	560.0	15.3	578.8	6.7
Duck Pond Deposit: Mineralized Block																						
Z7828; Dacitic lapilli tuff, mineralized, Duck Pond Deposit (Drillhole DP-88-168, 244.6 to 257.5 metres). NOTE: Also investigated by TIMS method																						
7878-1.1	161	54	0.344	13	2	0.00022	0.00377	0.1103	0.0072	0.6582	0.0271	0.08139	0.00118	0.463	0.05865	0.00216	504.4	7.0	554.2	82.5	503.6	7.0
7878-3.1	291	185	0.656	26	1	0.00007	0.00119	0.2050	0.0033	0.6563	0.0152	0.08178	0.00096	0.610	0.05820	0.00107	506.8	5.8	537.4	40.9	506.3	5.7
7878-4.1	212	103	0.502	18	3	0.00017	0.00289	0.1588	0.0040	0.6660	0.0209	0.08232	0.00102	0.506	0.05867	0.00160	509.9	6.1	555.0	60.5	509.2	6.1
7878-7.1	160	72	0.463	14	2	0.00020	0.00354	0.1469	0.0087	0.6526	0.0407	0.08167	0.00099	0.314	0.05795	0.00346	506.1	5.9	527.9	136.6	505.7	5.6
7878-8.1	136	45	0.340	11	3	0.00028	0.00490	0.1071	0.0088	0.6526	0.0425	0.08181	0.00099	0.306	0.05786	0.00362	506.9	5.9	524.3	143.3	506.6	5.6
7878-5.1	186	69	0.386	16	8	0.00056	0.00974	0.1139	0.0052	0.6386	0.0274	0.08316	0.00095	0.382	0.05570	0.00223	514.9	5.6	440.5	91.5	516.0	5.6
7878-10.1	268	149	0.574	24	3	0.00015	0.00261	0.1798	0.0037	0.6592	0.0177	0.08265	0.00089	0.508	0.05784	0.00135	511.9	5.3	523.8	51.9	511.7	5.3
7878-13.1	220	99	0.467	18	2	0.00015	0.00252	0.1487	0.0051	0.6411	0.0178	0.08109	0.00098	0.541	0.05734	0.00135	502.6	5.9	504.7	52.7	502.6	5.8
7878-14.1	186	86	0.479	16	3	0.00024	0.00423	0.1522	0.0043	0.6352	0.0193	0.08279	0.00094	0.484	0.05565	0.00149	512.8	5.6	438.3	60.9	513.9	5.6
7878-16.1	194	92	0.492	16	3	0.00025	0.00431	0.1515	0.0043	0.6303	0.0203	0.08157	0.00095	0.471	0.05605	0.00161	505.5	5.6	454.3	64.9	506.2	5.6
7878-22.1	170	58	0.350	14	4	0.00033	0.00576	0.1084	0.0045	0.6506	0.0220	0.08309	0.00099	0.466	0.05679	0.00171	514.6	5.9	483.4	67.9	515.0	5.9
7878-49.1	325	216	0.687	30	1	0.00004	0.00064	0.2263	0.0036	0.6721	0.0167	0.08289	0.00091	0.548	0.05881	0.00123	513.3	5.4	560.0	46.3	512.6	5.4
7878-61.1	120	48	0.411	10	3	0.00033	0.00580	0.1263	0.0075	0.6329	0.0282	0.08079	0.00095	0.380	0.05682	0.00236	500.8	5.7	484.5	94.6	501.0	5.6
7878-17.1	395	286	0.749	40	5	0.00015	0.00260	0.2310	0.0028	0.7449	0.0146	0.09128	0.00101	0.658	0.05918	0.00088	563.1	6.0	573.8	32.8	562.9	6.0
Patch Valley Rhyolite																						
Z7612; Rhyolite, Patch Valley area (Sample PJM-02-012; UTM zone 21; 574159E; 5396983N). NOTE: Also investigated by TIMS method																						
7612-2.1	182	97	0.548	13	1	0.00009	0.00162	0.1717	0.0041	0.4927	0.0157	0.06633	0.00082	0.492	0.05388	0.00150	414.0	4.9	366.0	63.9	414.6	4.9
7612-38.1	234	70	0.309	16	3	0.00023	0.00394	0.0951	0.0039	0.4877	0.0165	0.06741	0.00081	0.472	0.05247	0.00158	420.5	4.9	306.0	70.3	421.9	4.9
7612-17.1	121	85	0.729	9	3	0.00035	0.00614	0.2278	0.0072	0.4921	0.0262	0.06762	0.00090	0.361	0.05278	0.00264	421.8	5.4	319.3	117.7	423.0	5.3
7612-35.1	139	35	0.259	9	2	0.00021	0.00364	0.0798	0.0064	0.5012	0.0267	0.06771	0.00084	0.351	0.05368	0.00270	422.4	5.1	357.7	117.7	423.1	5.0
7612-15.1	248	133	0.554	18	2	0.00014	0.00243	0.1695	0.0038	0.5105	0.0154	0.06797	0.00082	0.510	0.05448	0.00142	423.9	4.9	390.8	59.7	424.3	4.9
7612-3.1	93	42	0.463	6	2	0.00041	0.00702	0.1353	0.0100	0.4828	0.0390	0.06797	0.00089	0.287	0.05151	0.00402	423.9	5.4	263.8	189.9	425.8	5.1
7612-26.1	394	176	0.463	28	1	0.00003	0.00057	0.1432	0.0025	0.5226	0.0112	0.06827	0.00078	0.622	0.05552	0.00094	425.7	4.7	433.3	38.0	425.6	4.7
7612-55.1	152	83	0.566	11	2	0.00026	0.00449	0.1812	0.0073	0.4817	0.0254	0.06834	0.00095	0.643	0.05112	0.00251	426.1	5.8	246.5	117.3	428.2	5.7
7612-24.1	336	133	0.409	24	2	0.00008	0.00137	0.1268	0.0039	0.5223	0.0174	0.06956	0.00085	0.480	0.05446	0.00160	433.5	5.1	390.1	67.4	434.0	5.1
7612-33.1	437	403	0.951	36	2	0.00007	0.00127	0.2932	0.0034	0.5303	0.0126	0.07011	0.00091	0.384	0.05485	0.00101	436.8	5.5	406.2	41.9	437.2	5.5

Notes:

Uncertainties reported at one sigma and are calculated by numerical propagation of all known sources of error (Stern, 1997).

f206 refers to mole fraction of total ^{206}Pb that is due to common Pb based on ^{204}Pb; data have been corrected for common Pb according to procedures outlined in Stern (1997)

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

obtain a maximum age from a hypabyssal intrusive rock that was affected by alteration and mineralization.

A quartz-phyric dacitic lapilli tuff (z7828) was sampled from drillhole DP-168, at a depth of ~250 m, where it represents weakly mineralized felsic host rocks within the main Duck Pond orebody (Figure 3). The interval is considered to represent part of the host sequence that escaped pervasive replacement by sulphides. It contained a modest amount of zircon, with consistent subhedral to euhedral morphology. However, the TIMS analyses of four multigrain fractions are variably discordant and an age cannot be calculated (Figure 4). The causes of discordancy could include inheritance or lead loss, or (more likely) both effects. The sample was thus also investigated using SHRIMP techniques. Most of the SHRIMP data are concordant; a concordia age is calculated to be 508.7 ± 3.3 Ma (MSWD of concordance and equivalence = 0.56, probability = 0.96), which is interpreted as the crystallization age of the host rock (Figure 5). Although this tuff was locally replaced by the sulphides, this process occurred whilst it remained unconsolidated, and the result is considered to indicate the timing of mineralization (after Squires *et al.*, 2001). A single SHRIMP analysis gave an age of ca. 563 Ma, indicating inheritance in this sample; the TIMS data (Figure 4) suggest that this is quite significant in the wider population of grains.

A second sample (z7826) came from drillhole DP-111A, at a depth of about 490 m, within the Mineralized Block, but very close to a second fault (the Terminator fault) beneath which unmineralized rocks equated with the Upper Block occur (Figure 3). This is a quartz-porphyritic dacitic dyke that contains disseminated sulphide mineralization (Squires and Moore, 2004), and which cuts mineralized felsic wall rocks. The sample contained moderate amounts of zircon that have a stubby prismatic morphology, and were amenable to TIMS analysis. Two fractions are nearly concordant at ca. 514 Ma, but the other fractions show variable discordance, suggestive of Pb loss (Figure 4). A linear regression including analyses A1, B3 and B2 that is anchored at the origin has an upper intercept age of 514 ± 3 Ma (MSWD=1.47). This provides a maximum age for the sulphide mineralization, but is within the wider error envelope of the SHRIMP age from the tuff within the orebody.

Patch Valley Rhyolite

The outcrop sample of rhyolite from this area contained abundant high-quality zircon, of varied but generally prismatic morphology. Two multigrain fractions (B1, C1) are highly discordant, suggesting that they contain significant inherited components, older than the late Precambrian material identified in other samples. The remaining fractions plot on or very close to concordia (Figure 4). A weighted average of the ^{206}Pb/^{208}U ages of the most concordant analyses yields an age of 422 ± 1 Ma. Some of the zircons contained obvious cores, and therefore this sample was also investigated using SHRIMP. The SHRIMP data define a cluster of mostly concordant analyses, with a weighted average ^{206}Pb/^{207}U age of 423 ± 3.5 Ma (Figure 5). The two oldest SHRIMP analyses were excluded from this calculation as they are interpreted to contain inherited components (Table 2). Combining both data sets, an age of 422 ± 2 Ma is suggested as the crystallization age for the rock. The age confirms that the rhyolites at this location are of Silurian age, and cannot be assigned to either the Tally Pond group or the Sandy Brook group.

DISCUSSION

The results summarized in this report support three main findings. In conjunction with previous work, they confirm that the volcanic rocks of the Tally Pond area include late Precambrian (~565 Ma), Cambrian (~514–509 Ma) and Silurian (~422 Ma) sequences. As most of these ages come from rocks associated with VMS mineralization, they suggest that both Precambrian and Cambrian sequences have potential for polymetallic Cu–Zn–Ag–Au deposits. Patterns of zircon inheritance provide a link between Precambrian and Cambrian volcanic rocks, which may be important in understanding paleogeographic and tectonic reconstructions for the Newfoundland Appalachians. The new results, and relevant previous data, are summarized in Figure 6, which is used below as a framework for further discussion.

PRECAMBRIAN VOLCANISM AND VMS MINERALIZATION

The 565 ± 4 Ma age from the Burnt Pond locality is identical within error to the 563 ± 2 Ma age obtained by Rogers *et al.* (2006) from felsic rocks some 12 km to the northeast (Figure 2), and indicates that late Precambrian volcanic rocks are regionally important. These ages also correspond closely to those from the Valentine Lake and Crippleback Lake intrusive suites (563 ± 2 Ma and 565 ± 4 Ma, respectively; Evans *et al.*, 1990). Late Precambrian crust is clearly widespread within the Exploits Subzone of the Dunnage Zone, and includes both volcanic and plutonic suites. The age also shows that the VMS mineralization at Burnt Pond formed during the Precambrian, even though the style of mineralization is similar to that seen within the Cambrian Tally Pond group (see below). The Pittmans Pond prospect, located some 3 km south of the Burnt Pond prospect (Figure 2), is likely also of late Precambrian age, as it is hosted by equivalent rocks. Based on the correlations suggested by Rogers *et al.* (2006) and Squires and Hinchey (2006), it is suspected that the Spencer's Pond prospect, located southwest of Lake Ambrose (Figure 2, description by Squires and

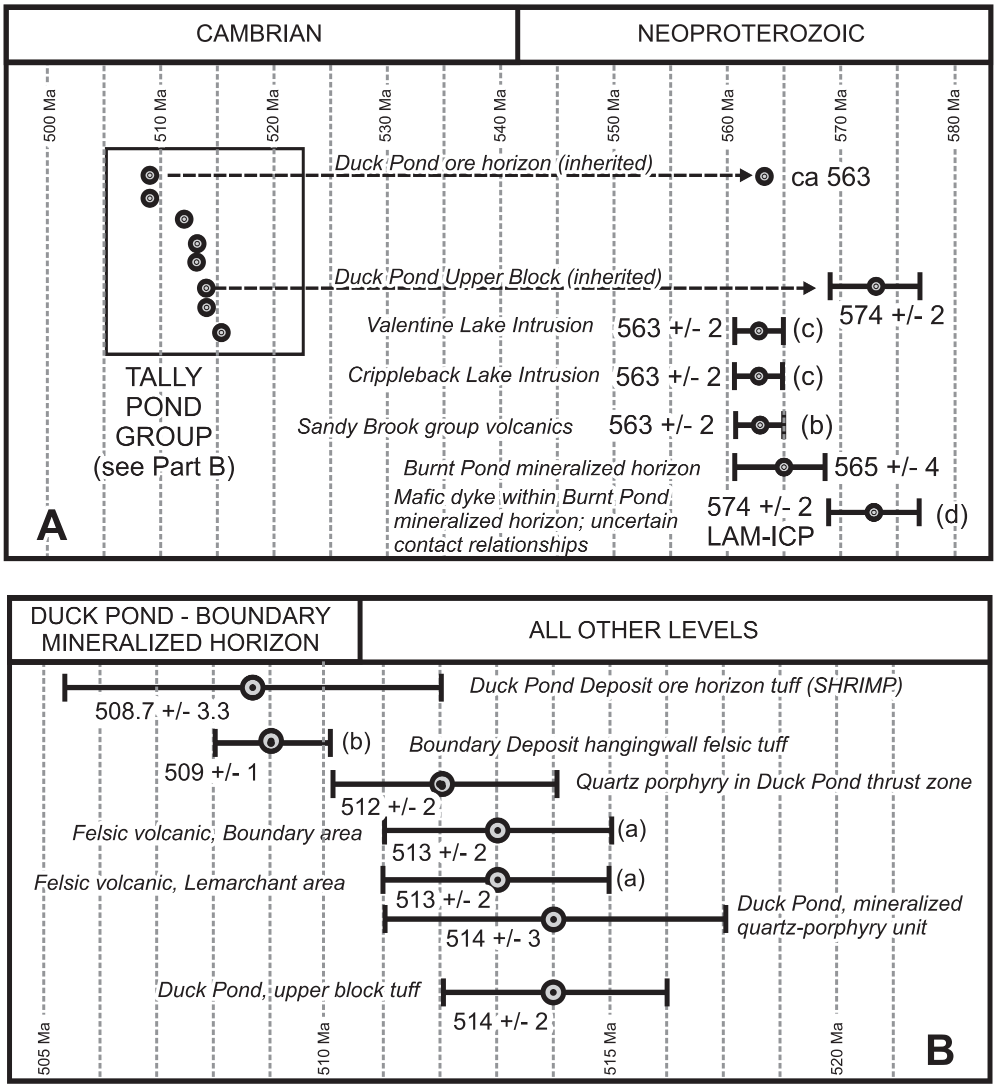


Figure 6. *Summary of U-Pb ages discussed in this report and previous age determinations from rocks within and around the Tally Pond volcanic belt. Note that the Silurian rhyolite from the Patch Valley area, and the imprecise age from sample z7528, are omitted from the figure for clarity. Sources for previous determinations: (a) Dunning* et al., *1991; (b) Rogers* et al., *2006; (c) Evans* et al., *1990; (d) Wilton* et al., *2003.*

Moore, 2004) is also late Precambrian, although this remains to be proven by geochronology.

The distinction and delineation of late Precambrian and Cambrian volcanic sequences within the belt remains a significant problem, for it is impossible to date every rock. However, trace-element geochemistry and Nd isotope signatures have been suggested as tools for their separation (Rogers *et al.*, 2006), and largely define the distribution shown in Figure 2. Although geochemical differences are discernable, the volcanic rocks of the Sandy Brook and Tally Pond groups do partly overlap in composition, and these methods are difficult to apply on a sample level. It thus remains possible that other rocks presently included within the Tally Pond group could be of Precambrian age.

THE AGE OF THE DUCK POND AND BOUNDARY DEPOSITS

Volcanism in the Tally Pond group was known to be of Late Cambrian (~513 Ma) age on the basis of previous data (Dunning *et al.*, 1991; Rogers *et al.*, 2006). However, the new geochronological results provide further constraints, and may also indicate age differences between barren and mineralized sequences (Figure 6). Crystallization ages of extrusive, pyroclastic and intrusive rocks from the Tally Pond group range from 515 Ma to 509 Ma, and the error envelopes for many samples overlap (Figure 6), but there appear to be two subpopulations amongst these samples.

The felsic pyroclastic host rocks to the VMS mineralization at the Duck Pond and Boundary sulphide deposits have the youngest ages (509 ± 3 Ma and 509 ± 1 Ma, respectively; latter age from Rogers *et al.*, 2006). The ages indicate that these VMS deposits are coeval, and may represent the same mineralizing system (but not necessarily the same orebody), that was disrupted by subsequent motions along important faults. In contrast, the oldest ages (ca. 514 Ma) come from unmineralized volcanic rocks in the structurally overlying Upper Block. The errors for these ages and those for the mineralized rocks do overlap at their younger and older extremes, respectively, but the overlap is limited to 1 Ma or less, with the exception of the less precise SHRIMP determination from sample z7528. This pattern suggests that the samples from the Upper Block are probably older, which supports the idea that the fault separating the Upper Block and the Mineralized Block was originally a thrust, as suggested previously on the basis of regional geology and kinematic indications (Squires *et al.*, 1991, 2001). The term Duck Pond thrust, first coined in the late 1980s, appears to be an appropriate label for this important structure.

Interpretation of the ages from hypabyssal intrusive rocks is more complicated. The mineralized dacitic dyke-like unit from the footwall of the Duck Pond Deposit has an age that is older than the ca. 509 Ma age from the mineralized felsic tuffs, although the errors do overlap at their outer limits. It is also within error of the ages obtained from the Upper Block. It clearly provides a maximum age for the mineralization, and also suggests that the aphyric felsic volcanic rocks that it intrudes are somewhat older than the mineralized horizon, which is consistent with their location in the stratigraphy (Figure 3). The age is also closely similar to ages previously obtained by Dunning *et al.* (1991) from felsic volcanic rocks elsewhere within the Tally Pond group.

The 512 ± 2 Ma age obtained from the crosscutting quartz porphyry dyke in the Upper Block is also consistent with its contact relationships, as its country rocks are dated at ca. 514 Ma. As the dyke is affected by the Duck Pond thrust, the 512 Ma age provides a maximum limit for motions on this structure, but this constraint is not very informative, because it is so close to the age obtained for the host rocks to mineralization (Figure 6). The Duck Pond thrust also cuts late gabbroic sills within the Upper Block; although attempts to date these rocks were unsuccessful, they are believed to correlate with the Harpoon Hill gabbro, which was dated at 465 ±1 Ma in another location (Pollock, 2004). If this is correct, it implies that motions on the fault are Late Ordovician or post-Ordovician in timing.

It remains possible that the Duck Pond thrust had a long and complex history, in which it started out as a synvolcanic extensional fault, which was then converted to a thrust during compressional orogenesis, and finally reverted to normal motions at some later stage. Models for VMS mineralization (*e.g.*, Franklin *et al.*, 2005) commonly suggest that synvolcanic fault systems focus hydrothermal discharge.

SILURIAN VOLCANIC ROCKS AND THEIR SIGNIFICANCE

The 422 ± 2 Ma age from the rhyolite in Patch Valley argues against previous assignment of these rocks to the "Tally Pond formation" by Colman-Sadd and Russell (1988). The age suggests that subaerial felsic volcanic rocks of the Stony Lake group are more widespread in this area than previously supposed, and implies that the Tally Pond group (as presently defined) occurs only to the northwest of the Precambrian Sandy Brook group. Rogers *et al.* (2005a) indicate that the Sandy Brook group is bounded to the southeast by Silurian sedimentary rocks in the largely unexposed northeastern corner of map sheet NTS 12A/09, which continues into the area of the Patch Valley sample. The presence of dated rhyolites in the adjacent map sheet suggests that both sedimentary and volcanic rocks of Silurian age are present throughout, but the poor outcrop precludes delineation of these two components.

THE TECTONIC SETTING OF THE TALLY POND GROUP

Previous geochronological results from the Cambrian Tally Pond group (Evans *et al.*, 1990; Dunning *et al.*, 1991) provided no hint of an older crustal component, and it was concluded that these rocks formed in an intra-oceanic or "ensimatic" island arc within Iapetus (Dunning *et al.*, 1991). Such a conclusion is broadly consistent with the largely tholeiitic geochemistry of mafic volcanic rocks. Data from the Boundary Deposit (Pollock, 2004) also did not reveal inherited zircon. The new results demonstrate that inherited zircons are present in three samples from the Tally Pond group, and the SHRIMP analyses from two of these directly constrain the age of the older substrate from which these were derived. Rhyolite from the unmineralized Upper Block contains inherited 573 ± 4 Ma zircons, and the host rocks to mineralization at Duck Pond contained a single dated ca. 563 Ma zircon. The TIMS data for this latter sample (Figure 4) suggest that inheritance is more widespread than the single SHRIMP analysis indicates. There is also an indication of inheritance in the TIMS data from the dacitic tuff in the Upper Block (sample z7827). The ages of these inherited zircons in SHRIMP analyses resemble those from the Precambrian volcanic rocks dated in this study and by Rogers *et al.* (2006), and those from nearby late Precambrian plutonic suites (Evans *et al.*, 1990). As pointed out initially by Squires and Moore (2004), these inheritance patterns confirm that the Cambrian island arc represented by the Tally

Pond group was built upon older substrate of late Precambrian plutonic and volcanic rocks, rather than being juxtaposed against them by later faulting. Rogers *et al.* (2006) suggested that trace-element patterns and Nd isotope variations within the Tally Pond group volcanic rocks were consistent with this conclusion.

Neodymium isotope data from the Precambrian rocks in this area (Kerr *et al.*, 1995; Rogers *et al.*, 2006) suggest that this late Precambrian crust also included older continental material, and is, in part, distinct from rocks of equivalent age in the "type" Avalon Zone. Such input is also suggested by the radiogenic Pb compositions of sulphide minerals at Duck Pond (Pollock and Wilton, 2004), and by the generally more radiogenic Pb compositions of VMS deposits within the Exploits Subzone compared to their counterparts in the Notre Dame Subzone (Swinden and Thorpe, 1984).

There are indications also of inheritance in the data from the Silurian Patch Valley rhyolite, for which two multigrain fractions had highly discordant analyses. This inference was not quantified further with the SHRIMP, but it implies the presence of Mesoproterozoic or Paleoproterozoic zircons, rather than the Neoproterozoic xenocrystic material identified in the Tally Pond group samples.

CONCLUSIONS

Uranium–lead geochronological data summarized in this report improve our understanding of the economically important volcano-sedimentary rocks of the Tally Pond area, and provide more precise age constraints on base-metal deposits within them. The ~565 Ma age from mineralized felsic rocks at Burnt Pond confirms the regional extent of Precambrian volcanism, and indicates that these rocks have potential for VMS mineralization. Several other prospects in the belt, previously viewed as Cambrian, could also be hosted by these older volcanic sequences. New data from the Cambrian host rocks to the Duck Pond Cu–Zn–Ag–Au Deposit suggest that the mineralized horizon is one of the youngest components of this sequence (~509 Ma), and that it is coeval with the nearby Boundary Deposit. This supports the idea that the two deposits are structurally disrupted segments of a much larger mineralizing system developed at this time. Given the structural complexity of the area, it is certainly possible that other sulphide orebodies remain to be discovered in the subsurface.

The unmineralized and unaltered volcanic rocks of the Upper Block at Duck Pond are slightly older (~514 Ma) than the structurally underlying ore horizon (~509 Ma), although there is some overlap in errors on these ages. The important fault zone that separates mineralized and unmineralized rocks may originally have been a thrust, even though the latest motions upon it are normal. Motions that disrupted the composite Duck Pond–Boundary VMS system were perhaps associated with the period of thrusting, but the exact timing of this event remains unconstrained. The hypabyssal felsic intrusive rocks in the mine area appear to be synvolcanic, and thus do not provide clear timing constraints upon fault motions. However, the truncation of late gabbroic sills implies that motions postdate ca. 465 Ma, if the sills correlate with the dated Harpoon Hill gabbro.

Finally, the late Precambrian Sandy Brook group and the Cambrian Tally Pond group are linked by patterns of zircon inheritance. The 565 to 563 Ma xenocrystic zircons in some of the Cambrian volcanic rocks suggest that they were formed upon an older "continental" substrate, and do not represent an intra-oceanic arc.

The ca. 422 Ma age from a rhyolite located in the northeastern part of the Tally Pond area suggests that rocks in this area that were previously assigned to the "Tally Pond formation" are, instead, part of the adjacent Stony Lake group. It now seems likely that the Cambrian Tally Pond group is restricted to areas northwest of the Precambrian rocks of the Sandy Brook group.

ACKNOWLEDGMENTS

The work summarized in this article was conducted at the GSC geochronology laboratory. The staff of the GSC geochronology laboratory are thanked for their assistance with sample processing and analysis. This article was reviewed carefully by Neil Rogers, who is thanked for constructive criticism and advice that significantly improved its contents.

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