Precise U-Pb geochronology of the Matagami mining camp, Abitibi Greenstone Belt, Quebec: stratigraphic constraints and implications for VMS exploration

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Abstract
The Matagami mining camp in the northern Abitibi greenstone belt of Canada contains 19 known Archean volcanogenic massive sulfide (VMS) deposits, eleven of which have collectively produced 46.5 Mt of zinc-rich ore to date. The VMS deposits occur in three NW-SE to WNW-ESE oriented trends called the North Flank, the South Flank, and the West Camp which are composed of a felsic to mafic volcanic sequence cut by mafic to intermediate, synvolcanic sills and dikes. In order to clarify stratigraphic relationships between the South Flank and the West Camp, and to constrain the temporal evolution of volcanic activity, six new high-precision U-Pb zircon ages have been obtained. These data show that the total duration of felsic volcanism in the South Flank was no more than 2.5 m.y., with the rhyolites extruded in the following order: Watson Rhyolite (2725.9 ± 0.8 Ma), Bracemac Rhyolite (2725.8 ± 0.7 Ma), Dumagami Rhyolite at the Persévérance Mine (2725.4 ± 0.7 Ma), Dumagami Rhyolite in the Orchan West VMS deposit area (2724.9 ± 0.7 Ma). A hiatus in effusive volcanism is represented by the Key Tuffite, an important marker horizon in the camp. The hiatus probably lasted on the order of 0.5 m.y. Significantly, the rhyolite from the footwall of the Caber VMS deposit in the West Camp has an age of 2725.9 ± 1.2 Ma, identical to that of the Watson Rhyolite on the South Flank.

Introduction
Since October 1963, the Matagami mining camp in the Archean Abitibi greenstone belt in Canada has produced 46.5 Mt of ore at average grades of 8.2% Zn, 0.56% Cu, 20.9 g/t Ag and 0.4 g/t Au (Adair, 2009). The Persévérance mine opened in July 2008 with resources of 5.12 Mt of ore at average grades of 15.8% Zn, 1.2% Cu, 29 g/t Ag and 0.4 g/t Au (Xstrata plc, 2008). Renewed interest in the area and associated intense exploration resulted in the recent discovery and delineation of the Bracemac and McLeod deposits, which are currently being prepared for mining by Xstrata Zinc and Donner Metals. Production is expected to start in 2013 at Bracemac-McLeod (Xstrata plc, 2010).

The VMS deposits in the Matagami mining camp occur in three NW-SE to WNW-ESE oriented trends called the North Flank, the South Flank, and the West Camp (Fig. 2). Each trend is generally composed of a felsic to mafic volcanic sequence intruded by mafic to intermediate, synvolcanic sills and dikes. The geology of the Matagami mining camp is most clearly understood in the South Flank, where the majority of VMS deposits have been found to date, principally but not exclusively along a stratigraphic marker horizon known as the Key Tuffite. The Key Tuffite is located just above a very thick and laterally extensive submarine rhyolite. Despite the presence of the Key Tuffite, or its interpreted equivalent, throughout the Matagami mining camp, extending the South Flank stratigraphy to other areas, notably to the “West Camp” (Fig. 2), has proven to be problematic, because such areas are less well known, and in some cases more intensely deformed. Therefore, relationships and correlations between the different parts of the Matagami mining camp require clarification.

One strategy to better understand the temporal evolution of volcanism and to correlate volcanic units between the different areas is to examine the combined geochemistry and high-precision geochronology of felsic volcanic rocks. Prior to our study, the U-Pb ages of volcanism and intrusions in the Matagami area were determined by Mortensen (1993) as part of an Abitibi-
wide geochronology study, but the age of several key felsic units remained unknown, with the actual time-stratigraphic context of the Matagami mining camp itself being poorly constrained.

In this paper, we present six new high-precision U-Pb dates from various felsic volcanic units from the South Flank and West Camp at Matagami. At a regional scale, this allows us to demonstrate a stratigraphic correlation between the productive South Flank and the prospective West Camp. Within the South Flank, we show that the sampled felsic volcanism was of short duration. The volcanic hiatus during which the Key Tuffite was emplaced, and most of the VMS deposits formed, was even shorter.

Geologic setting

The Matagami mining camp is located in the northern part of the Abitibi greenstone belt (Fig. 1), which is part of the Archean Superior Province in Quebec, Canada. Some 19 Zn-rich volcanogenic massive sulfide (VMS) deposits are currently known in the camp (Fig. 2), of which ten have been mined out, one is currently in production (Persévérance), and another will begin production soon (Bracemac-McLeod). The VMS deposits are hosted by mafic to felsic, subalkaline volcanic rocks emplaced in a submarine environment. Many VMS deposits consist of concordant sulfide lenses underlain by sulfide stringers and a discordant chlorite ±talc-magnetite alteration pipe (Lavallières et al., 1994). The felsic volcanic rocks and the spatially associated VMS deposits occur in three trends, oriented NW-SE to WNW-ENE, that subcrop below significant glacial till. The first two trends are called the North Flank and the South Flank (Piché et al., 1993), and they are located on the sides of the Bell River Complex, a layered mafic intrusion which is considered to be synvolcanic (e.g., Mortensen, 1993; Maier et al., 1996). The third trend is known as the “West Camp” and contains the Phelps Dodge, Caber and Caber North deposits, plus other occurrences (e.g., Masson, 2000; Fig. 2). Volcanic rocks generally dip at medium to high angles toward the SW in the South Flank (Fig. 3), and are subvertical in the other two trends. The stratigraphic facing direction is to the northeast in the West Camp, to the north in the North Flank and toward the southwest in the South Flank. An exception is the Persévérence Mine area where the strata are nearly subhorizontal (Fig. 3). Stratigraphic relationships between these three areas require clarification and this is among the objectives of the current geochronological study.

South Flank geology

The largest portion of the ore tonnage extracted to date has been from the South Flank, principally from the Mattagami Lake mine. Historically, Sharpe (1968) assigned the volcanic rocks of the South Flank (and the larger Matagami area) to two stratigraphic units: the felsic-dominated Watson Group at the base and the mafic-dominated Wabassee Group at the top. These groups contain several felsic volcanic units (Table 1) which can be differentiated from each other based on their stratigraphic position and geochemical signature (e.g., Table 2). Details and discussion of the geochemical variations in the felsic rocks from the Matagami mining camp will be published elsewhere.

Watson Group

In the South Flank, the Watson Dacite, which consists of lobate and massive lavas in outcrop, occurs at the base of the Watson Group. The dacite forms at least half of the volume of the group. This is overlain by the Watson Rhyolite, which mainly consists of coherent lavas. The rhyolite is typically quartz-phyric and spherulitic, with variable proportions of amygdules. In outcrop, this rhyolite displays lobes with very thin hyaloclastite margins. The rhyolite, which is up to 500 m thick, is found everywhere on the South Flank (over a lateral distance of at least 19 km), indicating that the volcanic event that produced the Watson Rhyolite had a large volume. Submarine rhyolites of this volume are uncommon, but examples of Miocene subaerial rhyolite flows of this magnitude have been documented for example in the Snake River Plain, USA (Brannen et al., 2008). Voluminous rhyolite flows are generally less viscous than other rhyolites, and may be emplaced at high temperatures (e.g., Barrie, 1995). Another possible explanation for the inferred low viscosities of some rhyolites in the Abitibi greenstone belt is the suggested presence of dissolved depolymerizing agents in the melt (e.g., Moulton et al., 2008, 2011), although the presence of abundant amygdules in the Watson Rhyolite argues against the latter idea.

The Watson Rhyolite is stratigraphically overlain by a 0.3 m to 12 m thick volcanioclastic-exhalative horizon known as the Key Tuffite (Jenney, 1961; Davidson, 1977; Liaghat and MacLean, 1992) which is present throughout the South Flank. The vast majority of the VMS lenses of the South Flank are located at the stratigraphic level of the Key Tuffite, which therefore serves as an important exploration guide (Lavallières et al., 1994). The discordant portion of these mineralized bodies is located within the uppermost part of the Watson Rhyolite.

Wabassee Group

The Wabassee Group on the South Flank consists mostly of basalts and andesites, with volumetrically minor felsic rocks and a number of volcanioclastic-exhalative intervals that are less laterally continuous than the Key Tuffite. Some of these horizons are nevertheless associated with VMS lenses, for example in the Bracemac-McLeod area, which has been intensely explored recently (Adair, 2009). In this area, the base of the Wabassee Group consists of the Bracemac Rhyolite, a relatively thin (up to 70 m thick), quartz-phyric, and mostly coherent (massive) rhyolite sitting directly upsection from the Key Tuffite (Fig. 3A, B). Both the Watson Rhyolite and the Bracemac Rhyolite were
spherulitic, and lobate to massive. At this locality, the rhyolite is quartz-phyric, highly in this area.

Rhyolite thins and the base of the Wabassee Group consists of mafic to intermediate volcanic rocks. Higher geochronology in the Orchan West area (Fig. 4, Table 1).

The Dumagami Rhyolite was sampled for U-Pb geochronology in cross-section 29725E, above the Equinox lens (Fig. 3C, D; Table 1). At this locality, the rhyolite is quartz-phyric, highly spherulitic, and lobate to massive.

Still further to the northwest, in the Persévérance Mine area, the Dumagami Rhyolite directly overlies the Key Tuffite, without intercalated mafic or intermediate volcanic rocks (Fig. 3C, D). Three distinct ore lenses are mined at Persévérance: Persévérance-main, Persévérance-West and Equinox. These ore lenses are present within chlorite pipes, with little concordant lens-type mineralization (Arnold, 2006). The Dumagami Rhyolite in the Persévérance area (informally called “Dumagami-P” Rhyolite herein) is quartz-phyric and often strongly spherulitic. Relative to other known thicknesses of the Dumagami Rhyolite in the South Flank, it is unusually thick and may be filling a local graben (Arnold, 2006). Geochemical data (e.g., Table 2: Ti/Zr ratio) indicates that the Dumagami-P is different from the Dumagami Rhyolite elsewhere in the Matagami mining camp, including on the North Flank. This geochemical difference, combined with the position of the Dumagami-P directly overlying the Key Tuffite (without intervening mafic to intermediate volcanic rocks), suggests that the Dumagami-P may be a distinct stratigraphic unit, possibly older than the Dumagami Rhyolite present elsewhere. The Dumagami-P Rhyolite was sampled for U-Pb geochronology just above the Key Tuffite in cross-section 29725E, above the Equinox lens (Fig. 3C, D; Table 1).

West Camp geology

The stratigraphy of the West Camp is not well established due to the following factors: fewer drill holes, less outcrop, a greater degree of deformation, and a larger proportion of intrusive rocks in many areas relative to the South Flank. Watson-like rhyolites and dacites can be identified in the West Camp on a geochemical basis; other rhyolites with different geochemical signatures also occur. To compare the West Camp with the South Flank volcanic stratigraphy, we have sampled two Watson-like rhyolites for U-Pb geochronology; one at the Caber VMS deposit and one to the SE of the McIvor Pluton (Fig. 5).

The Caber deposit consists of a relatively small, but Zn-rich massive sulfide lens (0.48 Mt at 11.7% Zn, 0.97% Cu, 14.4 g/t Ag and 0.23 g/t Au; Masson, 2000) that occurs at the top of a Watson-like rhyolite (Fig. 5A, B, Table 2: see the first three geochemical ratios). Laterally, the Caber mineralization grades into an interval containing chert-pyrite sphalerite (a “tuffite”) which has been proposed to be correlative with the Key Tuffite (Masson, 2000). The footwall rhyolite at Caber is typically quartz-phyric, spherulitic, and commonly amygdulate-rich. Chlorite alteration is present, increasing in intensity with proximity to mineralization. The VMS lens is overlain by mafic to intermediate volcanic rocks, and semi-concordant mafic to intermediate dikes have extensively inflated the volcanic sequence and invaded the mineralized zone. Towards the NE, the McIvor Pluton occurs on the other side of an important fault zone named McIvor Fault Zone.

The second U-Pb sample from the West Camp comes from a Watson-like rhyolite located near the McIvor Pluton, 7 km southeast of Caber (Figs. 2, 5C, D, Table 2). Based upon map patterns and geochemistry, this appears to be the same rhyolite as that at Caber, but the new U-Pb dating suggests otherwise (see below). In this area, the stratigraphy is subvertical, and mafic to intermediate intrusions again thicken the volcanic succession. The rhyolite is a weakly spherulitic, quartz-phyric, mostly coherent rock.

U-Pb geochronology

Previous U-Pb dating

In his regional eastern Abitibi geochronological study, Mortensen (1993) obtained an age of 2724.5 ± 1.8 Ma for the Watson Rhyolite from an outcrop location on the South Flank (Fig. 2). A rhyolite from the North Flank was dated at 2723.1 ±0.8/-0.7 Ma by the same author; however, it is unclear exactly which rhyolite was dated on the North Flank, as no geochemical analysis is available for the dated sample (Fig. 2). On the basis of the 2σ age envelope, Mortensen (1993) therefore concluded that volcanism in the Matagami area occurred between 2726.3 and 2722.4 Ma. In the same study, a granophyre from the Bell River Complex gave a crystallization age of 2724.6 ±2.5/-1.9 Ma (Fig. 2), and the complex was interpreted to be a synvolcanic intrusion.

Samples selected for this study

Drill core samples for the current U-Pb geochronology study were collected from geological cross-sections typically containing the Key Tuffite and/or VMS deposits, so that the relationship between the dated rocks and mineralization is unambiguous. In each selected cross-section, several drill holes were examined in order to select the least altered rocks based on visual examination of the cores. High Ishikawa alteration index
values and low sodium contents suggest that some of the selected rocks have nevertheless suffered significant VMS-related hydrothermal alteration (Table 2). The rhyolites sampled in drill cores are massive rocks which preserve, at least in part, pre-alteration volcanic textures such as spherules and phenocrysts and were verified to have the typical geochemical signatures of each targeted felsic unit using ratios of immobile elements (Table 2). When present, dikes were excluded from the sampled core intervals, and the samples did not contain inclusions of other rock types.

Analytical techniques

U-Pb ID-TIMS (isotope dilution thermal ionization mass spectrometry) was performed at the Geological Survey of Canada in Ottawa. Analytical methods utilized in this study are modified after Parrish et al. (1987). Heavy mineral concentrates were prepared by standard crushing, grinding, Wilfley table, and heavy liquid techniques. Mineral separates were sorted by magnetic susceptibility using a Frantz isodynamic separator and were handpicked using a binocular microscope. All of the analyses are of single zircons, unless otherwise noted, which have been very strongly air abraded using the method of Krogh (1982) or chemically abraded following the techniques of Mattinson (2005). Chemically abraded grains were annealed for 48 hours at 1000°C, followed by leaching with HF for varying lengths of time as noted in Table 3. Details of zircon morphology, quality, and abrasion technique are summarized in Table 3. Procedural Pb blanks for analyses in this study are generally 1 pg or less. Treatment of analytical errors follows Roddick (1987). U-Pb ID-TIMS analytical results are presented in Table 3, where errors on the ages are reported at the 2σ level, and displayed in the concordia plots (Fig. 6). Errors calculated for ages presented in the text are also reported at the 2σ level of uncertainty.

Results and interpretation: South Flank

Watson Rhyolite; MC-08-37 (Geological Survey of Canada geostratigraphical laboratory number 9627): The Watson Rhyolite from the McLeod area contains abundant high quality zircons. Those that were selected for analysis contained low U (all analyses but one are <26 ppm U). Six single-grain analyses overlap each other and range from 0.8-0.3 percent discordant (Table 3, Fig. 6A). A weighted average of the 206Pb/207Pb ages of all of these near concordant analyses is 2725.9 ± 0.8 Ma (mean standard of weighted deviates, MSWD = 0.90; probability of fit = 48%). This age of 2725.9 ± 0.8 Ma is taken to be the crystallization age of the Watson Rhyolite in the McLeod area and, by extension, on the entire South Flank.

Bracemac Rhyolite; MC-08-43 (9624): The sample from the Bracemac Rhyolite contains a fair number of small, well faceted zircons. Many of the zircons contain abundant fractures and inclusions (Table 3). Six single grains were analyzed from the rhyolite. Three of the grains were physically (air) abraded, yielding results that are 1.6 to 0.5 percent discordant, while three were chemically leached for six hours, and gave results that are concordant to only 0.5 percent discordant. A linear regression with lower intercept at the origin and containing all of the analyses has an upper intercept at 2725.8 ± 0.7 Ma (MSWD = 0.91; probability of fit = 46%; Fig. 6B). The date of 2725.8 ± 0.7 Ma is taken to be the crystallization age of the Bracemac Rhyolite.

Dumagami-P Rhyolite; EQ-00-41 (9625): The Dumagami Rhyolite sample from the Perséverance mine (Dumagami-P) contains a small number of fair to good quality zircons. Six single grains were analyzed, each showing very low U contents, ranging from 40 – 12 ppm (Table 3). All of the analyses overlap and range between only 0.7 to 0.2 percent discordant (Fig. 6C). The chemically abraded analysis A6-1 overlaps the others but is slightly more discordant. A weighted average of the 206Pb/207Pb ages of all of these near-concordant analyses is 2725.4 ± 0.7 Ma (MSWD = 0.62; probability of fit = 64%), which is taken to be the age of the Dumagami-P Rhyolite.

Dumagami Rhyolite; OR-01-32 (9913): The Dumagami Rhyolite from the Orchan West area contains a small number of fair quality zircons. Analyses for five single grains overlap and are nearly concordant (Fig. 6D). A weighted average of the 206Pb/207Pb ages of these analyses is 2724.9 ± 0.7 Ma (MSWD = 0.95; probability of fit = 44%). A sixth analysis, A2, is slightly older at ca. 2734 Ma and is interpreted to be an inherited grain. The date of 2724.9 ± 0.7 Ma is taken to be the crystallization age of the Dumagami Rhyolite at Orchan West.

Results and interpretation: West Camp

Watson-like rhyolite; NCB-98-38 (9912): The sample of quartz-phryic, massive rhyolite collected from the Caber area contains high quality, well faceted zircons. The grains that were analyzed contained low U (<35 ppm). Three single-grain analyses overlap each other and concordia, and a fourth analysis is more discordant (1.3%) (Fig. 6E). A weighted average of the 206Pb/207Pb ages of these analyses is 2726.2 ± 1.2 Ma (MSWD = 1.1; probability of fit = 33%). A weighted average including only the three most concordant analyses (0.4-0.3% discordant) is 2725.9 ± 1.2 Ma (MSWD = 0.86; probability of fit = 42%). This age of 2725.9 ± 1.2 Ma is taken to be the best interpretation for the crystallization age of the rhyolite and is the same as that presented above for the Watson Rhyolite on the South Flank (Fig. 7).

ranging in morphology from stubby prismatic to elongate. Six zircon analyses range from being 0.5 to 0.1 percent discordant. Chemically abraded analyses A12-1 and C16-1 overlap the other analyses but are slightly more concordant (Fig. 6F, Table 3). A weighted average of all six analyses is 2723.4 ± 0.7 Ma (MSWD = 0.70; probability of fit = 62%), which is taken to represent the crystallization age of this rhyolite.

Discussion

**South Flank**

On the South Flank, the four ages and their associated errors overlap significantly. However, the progression of ages (represented by the squares on Fig. 7) yields a temporal evolutionary sequence for the South Flank volcanism that corresponds to that observed from stratigraphic relationships: the Watson Rhyolite is the oldest, followed by the Bracemac, the Dumagami-P, and the Dumagami rhyolites.

More interesting is the duration of volcanism. The maximum duration of felsic volcanism in the South Flank was from 2726.7 Ma (maximum age of the Watson Rhyolite) to 2724.2 Ma (minimum age of the Dumagami Rhyolite at Orchan West), i.e. a maximum duration of 2.5 m.y. Since all known VMS deposits in this area were likely formed between the eruption of the Watson Rhyolite and the Dumagami Rhyolite, the mineralization therefore occurred, together with the deposition of associated tuffites, within 2.5 m.y. or less.

The Key Tuffite represents a period of quiescence in the effusive volcanism, during which most of the VMS deposits of the South Flank were formed. The period of deposition of the Key Tuffite, and the more or less contemporaneous VMS deposits, is constrained by the ages of three rhyolites: the Watson (directly below the tuffite), the Bracemac (directly above) and the Dumagami-P (also directly above). Assuming the age of the Watson Rhyolite at McLeod applies throughout the South Flank, at Persévérence, the Key Tuffite deposition period lasted a maximum of 2.0 m.y. (this value is obtained by taking the difference between the maximum age for the Watson Rhyolite, 2726.7 Ma and the minimum age for the Dumagami-P Rhyolite, 2724.7 Ma). It is more likely, however, that the period of time for the Key Tuffite deposition was on the order of 0.5 m.y. or less (between 2725.9 Ma for the Watson Rhyolite and 2725.4 Ma for the Dumagami-P Rhyolite). Clearly, the volcanic hiatus between the Watson Group and the Wabassee Group was brief. For comparison, Barrie et al. (1999) calculated based on a numerical model that the giant Kidd Creek VMS deposit was formed within about 0.65 m.y. Based on their numerical modeling work on the synvolcanic Bell River Complex at Matagami, Carr et al. (2008) found that hydrothermal venting lasted about 135 000 years. Elsewhere in the Abitibi greenstone belt, Thurston et al. (2008) have identified depositional gaps marked by sedimentary interface zones lasting between 2 and 27 m.y., i.e. longer than the estimated depositional gap for the Matagami mining camp.

The Dumagami-P Rhyolite at Persévérence and the Dumagami Rhyolite in the Orchan West area are different chemically and are in different stratigraphic positions, as explained above. The U-Pb ages and associated errors for these felsic units overlap, but the Orchan West rocks may be slightly younger. This supports the idea that the Dumagami-P Rhyolite could be a distinct stratigraphic unit.

While there is an intimate association between sulfide mineralization and the Key Tuffite, evidence from the South Flank VMS deposits show that mineralizing hydrothermal activity occurred both contemporaneously with the Key Tuffite and following its deposition. At Persévérence for example, the Key Tuffite is mostly devoid of mineralization (Arnold, 2006) and tuffite fragments are included in the massive sulfides, suggesting that at least a part of the mineralization here postdated the Key Tuffite, but predated the deposition of the Dumagami-P Rhyolite. In another example, the Bracemac-McLeod VMS deposit exhibits the development of sulfide mineralization in lenses both at the Key Tuffite level and at two horizons upsection within the Wabassee Group. All three horizons can be linked by relatively continuous footwall alteration, suggesting that hydrothermal activity persisted over a period of time that exceeded the deposition of the Key Tuffite and the Bracemac Rhyolite in this area.

**West Camp**

Correlations between the South Flank and the West Camp have been based on the occurrence of geochemically similar rhyolites (e.g., Watson Rhyolite in the South Flank and a Watson-like rhyolite in the West Camp) overlain by tuffite intervals. The high-precision age determinations presented herein for the Watson Rhyolite, just below the McLeod massive sulfide lens in the South Flank, and a Watson-like rhyolite, just below the Caber sulfide lens in the West Camp, yield identical ages (Fig. 7). This supports the South Flank-West Camp correlation and reinforces the exploration potential of the West Camp. In addition, this correlation increases the total extent and volume of the Watson Rhyolite in the Matagami area. These results demonstrate the high potential for unraveling stratigraphic relationships within a study area using high-precision U-Pb ages.

At the 2σ level of uncertainty, the geochronological results suggest that the Watson-like rhyolite near the McIvor pluton is younger than the Watson-like rhyolite at the Caber VMS deposit by at least 0.6 m.y. (minimum age of 2724.7 Ma for Caber minus maximum age of 2724.1 Ma for McIvor). So, although the two Watson-like rhyolites dated in the West Camp share the same geochemistry, they have distinct ages. There are two possible explanations for this result: (1) two temporally distinct Watson-type effusive events occurred at Matagami; or (2) the dated sample represents not an extrusive rhyolite but instead a small tonalitic intrusion (or endogenous dome) with a rhyolitic texture.
and a Watson-like chemistry. More work will be needed to identify the correct hypothesis.

**Link between Archean volcanism, magmatism and VMS deposits at Matagami**

Most VMS deposits in the Matagami mining camp are situated stratigraphically on top or near the top of the Watson Rhyolite, and geographically not far from the synvolcanic Bell River Complex. This is clearly not a Watson Rhyolite, and geographically not far from the VMS deposit. More work will be needed to identify the correct hypothesis. And a Watson-like chemistry. More work will be needed to identify the correct hypothesis.

**Conclusions**

This paper presents six new high-precision U-Pb ages for the Matagami mining camp, allowing a better understanding of the temporal evolution of volcanic activity and more confident stratigraphic correlations between different parts of the camp. Specifically, this study has shown or confirmed that:

1. Geochronological data supports a distinction between the "typical" Dumagami Rhyolite, found above a package of mafic to intermediate volcanic rocks, and a slightly older Dumagami-P Rhyolite in the Persévérence mine area, in direct contact with the Key Tuffite.

2. The duration of felsic volcanism in the South Flank was no more than 2.5 m.y., with the rhyolites extruded in the following order: Watson, Bracemac, Dumagami-P, and Dumagami.

3. The Key Tuffite and the VMS deposits emplaced along this marker interval by exhalative processes were formed within a time period shorter than 2.0 m.y. – possibly on the order of 0.5 m.y. or less – i.e. between the crystallization of the Watson Rhyolite and that of the Dumagami-P Rhyolite. The volcanic hiatus and hydrothermal activity therefore lasted a relatively short period of geological time.

4. The West Camp and the South Flank can now be more confidently correlated based on the fact that the same age was obtained for the Watson Rhyolite on the South Flank (2725.9 ± 0.8 Ma) and a geochronologically identical rhyolite in the footwall of the Caber VMS deposit in the West Camp (2725.9 ± 1.2 Ma). This correlation confirms a strong exploration potential for the West Camp.

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### Table 1. Location, context and results for the new U-Pb samples.

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>Area</th>
<th>Diamond drill hole</th>
<th>Sampled interval</th>
<th>GSC lab number</th>
<th>U-Pb age (Ma)</th>
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<td><strong>South Flank</strong></td>
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<td>Dumagami-P Rhyolite</td>
<td>Persévérence mine,</td>
<td>EQ-00-41</td>
<td>117.9-130.5 m</td>
<td>z9625</td>
<td>2725.4 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Équinoxe lens</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>West Camp</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Watson-like rhyolite</td>
<td>Caber deposit</td>
<td>NCB-98-38</td>
<td>287-292.2 m</td>
<td>z9912</td>
<td>2725.9 ± 1.2</td>
</tr>
<tr>
<td>Watson-like rhyolite or tonalite</td>
<td>SE of McIvor pluton</td>
<td>1214-98-02</td>
<td>244-268.9 m*</td>
<td>z9626</td>
<td>2723.4 ± 0.7</td>
</tr>
</tbody>
</table>

* Minus one dike and some more altered sections

### Table 2. Geochemical analyses of the geochronological samples, performed at INRS-ETE.

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>Watson McLeod</th>
<th>Bracemac McLeod</th>
<th>Dumagami-P Persévérence EQ-00-41</th>
<th>Dumagami Orchan West OR-01-32</th>
<th>Watson-like Caber NCB-98-38</th>
<th>Watson-like McIvor area 1214-98-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site DDH</td>
<td>MC-08-37</td>
<td>MC-08-43</td>
<td>EQ-00-41</td>
<td>OR-01-32</td>
<td>NCB-98-38</td>
<td>1214-98-02</td>
</tr>
<tr>
<td><strong>Major oxides by fusion ICP-AES (%)</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>SiO₂</td>
<td>78.0</td>
<td>74.8</td>
<td>68.4</td>
<td>70.7</td>
<td>70.0</td>
<td>77.2</td>
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<tr>
<td>TiO₂</td>
<td>0.26</td>
<td>0.23</td>
<td>0.70</td>
<td>0.73</td>
<td>0.31</td>
<td>0.27</td>
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<tr>
<td>Al₂O₃</td>
<td>10.13</td>
<td>9.89</td>
<td>10.70</td>
<td>11.5</td>
<td>10.4</td>
<td>9.59</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.29</td>
<td>7.15</td>
<td>6.18</td>
<td>7.12</td>
<td>8.26</td>
<td>5.46</td>
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<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.07</td>
<td>0.04</td>
<td>0.14</td>
<td>0.09</td>
<td>0.02</td>
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<tr>
<td>MgO</td>
<td>4.76</td>
<td>0.91</td>
<td>9.20</td>
<td>1.05</td>
<td>7.01</td>
<td>4.51</td>
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<tr>
<td>CaO</td>
<td>0.12</td>
<td>0.64</td>
<td>0.12</td>
<td>3.78</td>
<td>0.15</td>
<td>&lt; 0.09</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.59</td>
<td>4.09</td>
<td>&lt; 0.07</td>
<td>3.78</td>
<td>0.05</td>
<td>&lt; 0.07</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.59</td>
<td>0.29</td>
<td>0.26</td>
<td>0.06</td>
<td>0.81</td>
<td>1.36</td>
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<tr>
<td>P₂O₅</td>
<td>&lt; 0.02</td>
<td>0.01</td>
<td>0.10</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
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<tr>
<td>LOI</td>
<td>2.9</td>
<td>1.5</td>
<td>4.5</td>
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<td>Total</td>
<td>103</td>
<td>99</td>
<td>100</td>
<td>101</td>
<td>101</td>
<td>101</td>
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<tr>
<td><em><em>Ratios</em> and alteration indices</em>*</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ti/Zr (ppm/ppm)</td>
<td>2.7</td>
<td>3.3</td>
<td>9.0</td>
<td>14.5</td>
<td>2.9</td>
<td>2.9</td>
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<tr>
<td>Al₂O₃/TiO₂ (%)</td>
<td>40</td>
<td>43</td>
<td>15</td>
<td>16</td>
<td>34</td>
<td>36</td>
</tr>
<tr>
<td>Zr/Y (ppm/ppm)</td>
<td>4.1</td>
<td>2.6</td>
<td>3.6</td>
<td>2.7</td>
<td>3.4</td>
<td>3.9</td>
</tr>
<tr>
<td>La/Lu (ppm/ppm)</td>
<td>12</td>
<td>18</td>
<td>20</td>
<td>19</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>La/Sm (ppm/ppm)</td>
<td>2.1</td>
<td>2.2</td>
<td>2.2</td>
<td>2.6</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Gd/Lu (ppm/ppm)</td>
<td>7.9</td>
<td>10.9</td>
<td>10.8</td>
<td>8.1</td>
<td>9.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Ishikawa AI** (0-100)</td>
<td>90</td>
<td>20</td>
<td>99</td>
<td>13</td>
<td>97</td>
<td>100</td>
</tr>
<tr>
<td>CCPI*** (0-100)</td>
<td>77</td>
<td>59</td>
<td>94</td>
<td>62</td>
<td>90</td>
<td>83</td>
</tr>
</tbody>
</table>

* Trace elements by fusion ICP-MS.
** Alteration index from Ishikawa (1976).
*** Chlorite-carbonate-pyrite index (Large et al., 2001).
Table 3. Geochronology results: U-Pb ID-TIMS analytical data.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (Z; 1)</td>
<td>Co,Er,Ur,Pr,Fr, Fr</td>
<td>2.5</td>
<td>23</td>
<td>14</td>
<td>1491</td>
<td>1.3</td>
<td>0.18</td>
<td>13.53607</td>
<td>0.02075</td>
<td>0.52194</td>
<td>0.00072</td>
</tr>
<tr>
<td>B1 (Z; 1)</td>
<td>Co,Er,Ur,Pr,Fr, Fr</td>
<td>6.8</td>
<td>14</td>
<td>9</td>
<td>2615</td>
<td>1.2</td>
<td>0.15</td>
<td>13.56866</td>
<td>0.01804</td>
<td>0.52310</td>
<td>0.00060</td>
</tr>
<tr>
<td>A2 (Z; 1)</td>
<td>Co,Er,Ur,Pr,Fr, Fr</td>
<td>2.6</td>
<td>26</td>
<td>16</td>
<td>2313</td>
<td>0.9</td>
<td>0.17</td>
<td>13.59495</td>
<td>0.02126</td>
<td>0.52867</td>
<td>0.00079</td>
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<tr>
<td>B2 (Z; 1)</td>
<td>Co,Er,Ur,Pr,Fr, Fr</td>
<td>3.7</td>
<td>11</td>
<td>7</td>
<td>1899</td>
<td>0.7</td>
<td>0.18</td>
<td>13.55329</td>
<td>0.02255</td>
<td>0.52537</td>
<td>0.00076</td>
</tr>
</tbody>
</table>

Notes:
- Z: zircon.
- Number in bracket refers to the number of grains in the analysis. CA = chemically abraded following the method of Mattinson (2005); all other grains were physically abraded (Krogh, 1982).
- Fraction description: Co=Colourless, Br=light brown, Cl=Clear, Eu=Euhedral, Fr=Prismatic, St=Stubby prismatic, El=Elongate, Tip=Tip, Frag=Fragment, rFr =Rare Fractures, fFr=Few Fractures, Z=zircon. Number in bracket refers to the number of grains in the analysis.
- CA = chemically abraded following the method of Mattinson (2005); all other grains were physically abraded (Krogh, 1982).
- 204Pb, 206Pb, 207Pb, 208Pb: measured in parts per billion (ppb) with uncertainties at 1σ.
- 206Pb/238U: measured in parts per million (ppm) with uncertainties at 1σ.
- 207Pb/235U: measured in parts per billion (ppb) with uncertainties at 1σ.
- 208Pb/206Pb: measured in parts per million (ppm) with uncertainties at 1σ.
- Ages (Ma): calculated ages in million years (Ma) corrected for the effects of common Pb.

(a) MC-08-37 (Z627): Watson Rhyolite (drill hole MC-08-37; depth 870.5-877.0 m)
- A1: Co,Er,Ur,Pr,Fr, Fr
- B1: Co,Er,Ur,Pr,Fr, Fr
- A2: Co,Er,Ur,Pr,Fr, Fr
- B2: Co,Er,Ur,Pr,Fr, Fr
- B3: Co,Er,Ur,Pr,Fr, Fr
- B4: Co,Er,Ur,Pr,Fr, Fr

(b) MC-08-43 (Z624): Bracemac Rhyolite (drill hole MC-08-43; depth 716.2-728.7 m)
- A1: Co,Er,Ur,Pr,Fr,Fr,CA6
- B1: Co,Er,Ur,Pr,Fr,Fr,CA6
- A2: Co,Er,Ur,Pr,Fr,Fr,CA6
- B2: Co,Er,Ur,Pr,Fr,Fr,CA6
- A3: Co,Er,Ur,Pr,Fr,Fr,CA6
- B3: Co,Er,Ur,Pr,Fr,Fr,CA6

(c) EQ-00-41 (Z625): Dumagami-P Rhyolite (drill hole EQ-00-41; depth 117.9-130.5 m)
- A1: Co,Er,Ur,Pr,Fr,Fr,CA6
- B1: Co,Er,Ur,Pr,Fr,Fr,CA6
- A2: Co,Er,Ur,Pr,Fr,Fr,CA6
- B2: Co,Er,Ur,Pr,Fr,Fr,CA6
- A3: Co,Er,Ur,Pr,Fr,Fr,CA6
- B3: Co,Er,Ur,Pr,Fr,Fr,CA6

(d) OR-01-32 (Z9913): Dumagami-P Rhyolite (drill hole OR-01-32; depth 756.0-768 m)
- A1: Co,Er,Ur,Pr,Fr,Fr,CA6
- B1: Co,Er,Ur,Pr,Fr,Fr,CA6
- A2: Co,Er,Ur,Pr,Fr,Fr,CA6
- B2: Co,Er,Ur,Pr,Fr,Fr,CA6
- A3: Co,Er,Ur,Pr,Fr,Fr,CA6
- B3: Co,Er,Ur,Pr,Fr,Fr,CA6

(e) NCB-98-38 (Z9912): Watson-like rhyolite at Caber (drill hole NCB-98-38; depth 287.0-292.8 m)
- A1: Co,Er,Ur,Pr,Fr,Fr,CA6
- B1: Co,Er,Ur,Pr,Fr,Fr,CA6
- A2: Co,Er,Ur,Pr,Fr,Fr,CA6
- B2: Co,Er,Ur,Pr,Fr,Fr,CA6
- A3: Co,Er,Ur,Pr,Fr,Fr,CA6
- B3: Co,Er,Ur,Pr,Fr,Fr,CA6

(f) 1214-98-2 (Z625): Watson-like rhyolite (drill hole 1214-98-2; depth 244-268.9 m)
- A1: Co,Er,Ur,Pr,Fr,Fr,CA6
- B1: Co,Er,Ur,Pr,Fr,Fr,CA6
- A2: Co,Er,Ur,Pr,Fr,Fr,CA6
- B2: Co,Er,Ur,Pr,Fr,Fr,CA6

Notes:
- Correlation Coefficient: correlation coefficient corrected for the effects of common Pb.
- Ages (Ma): calculated ages in million years (Ma) corrected for the effects of common Pb.
- Errors quoted are 1σ.
- All other grains were physically abraded (Krogh, 1982).
FIGURES

Figure 1. (a) Location of the Abitibi greenstone belt in eastern Canada. (b) Simplified geological map of the Abitibi greenstone belt showing the location of Matagami.

Figure 2. Simplified geological map of the Matagami area, modified from Roy and Allard (2006), with locations of the VMS deposits (square symbols). The location of samples dated by U-Pb methods reported by Mortensen (1993) are shown (circles) according to the reported longitude/latitude coordinates. However, the sample from the Bell River Complex was placed north-east of Matagami rather than at the reported coordinate (which is not in the Bell River Complex). The location of more detailed maps is illustrated except for Figure 5A which was too small to display (refer to the Caber deposit symbol for location). Grid on all maps is UTM Nad 83, zone 18.

Figure 3. Location of U-Pb geochronological samples from the South Flank. A and B. Surface geology and vertical cross-section at the McLeod VMS deposit, where the Watson and Bracemac rhyolites have been sampled. C and D. Surface geology and vertical cross-section through the Equinox lens at the Persévérance mine, where the Dumagami-P Rhyolite has been sampled just above the Key Tuffite. At McLeod, the Bracemac Rhyolite is capped by the Bracemac Tuffite and the rest of the Wabassee Group consists of mafic to intermediate lava flows. The volcanic rocks are cut by numerous mafic to felsic intrusions. In the Persévérance area, note the lack of mafic to intermediate lavas between the Watson Rhyolite and the Dumagami-P Rhyolite. Drill holes shown on both sections are projected horizontally by up to 50 m.

Figure 4. Geological map (a) and vertical cross-section (b) through the Orchan West area of the South Flank, showing the location of the U-Pb sample in the Dumagami Rhyolite. Drill holes on the section are projected horizontally by up to 50 m.

Figure 5. Geological maps and vertical cross-sections of two sectors from the West Camp: A and B through the Caber VMS deposit, showing the location of the U-Pb sample in a Watson-like rhyolite; C and D through the volcanic rocks SE near the McIvor Pluton, showing the location of the other U-Pb sample in a Watson-like rhyolite. Drill holes shown on both sections are projected horizontally by up to 50 m.

Figure 6. U-Pb concordia diagrams for the six dated rhyolite samples. See text for discussion.

Figure 7. Compilation of new U-Pb results (squares) for the South Flank and the West Camp. Also shown is Mortensen’s (1993) U-Pb age for the Watson Rhyolite (circle). See text for discussion.
Ross et al., Fig. 1
VMS deposit
Mined VMS deposit
Location of Mortensen's (1993) U-Pb samples

Faults
VMS deposit
Proterozoic diabase
Sedimentary rocks
Intermediate to felsic intrusions
Mafic to intermediate intrusions
Mafic to intermediate volcanic rocks
Felsic volcanic rocks

2724.5 ± 1.8 Ma
2723.1 ± 0.8/0.7 Ma
2724.6 ± 2.5/1.9 Ma

Ross et al., Fig. 2
McLeod deposit

Volcanic rocks
- Wabassee Group
  - Mafic rocks
  - Dumagami-P Rhyolite
  - Bracemac Rhyolite
- Watson Group
  - Watson Rhyolite
  - Watson Dacite

Intrusive rocks
- Mafic to intermediate
- Felsic to intermediate

Tuffite, alteration and mineralization
- Tuffite
- Massive sulfides
- Intense chlorite alteration

Section 13300E (Fig. 3b)

Section 29725E (Fig. 3d)

Ross et al., Fig. 3
**Orchan West deposit**

- **Wabassee Group**
  - Mafic to intermediate volcanic rocks
  - Dumagami Rhyolite

- **Watson Group**
  - Watson Rhyolite

**Geochronology sample**

**Massive sulfides**

- Overburden

**Section E-W (Fig. 4b)**

**WATSON**

**DUMAGAMI**

**OR-01-32**

**Orchan West Section**

Ross et al., Fig. 4
Ross et al., Fig. 5
South Flank

(a) Watson Rhyolite at McLeod

(b) Bracemac Rhyolite at McLeod

(c) Dumagami-P Rhyolite at Persévance

(d) Dumagami Rhyolite in Orchan West area

West Camp

(e) Watson-like rhyolite at Caber

(f) Watson-like rhyolite in McIvor sector

Ross et al., Fig. 6
Watson Rhyolite (Mortensen)

Watson Rhyolite at McLeod

Bracemac Rhyolite at McLeod

Dumagami-P Rhyolite at Persévéranse

Dumagami Rhyolite at Orchan West

Watson-like rhyolite at Caber

Watson-like rhyolite at McIvor

Ross et al., Fig. 7