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Blake River Group evolution: characteristics of the subaqueous Misema and New Senator calderas

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ABSTRACT

The Misema and New Senator calderas are instrumental in understanding the evolution of the Blake River Group in the Abitibi greenstone belt and the formation of volcanic massive sulfide deposits. The 40-80 km in diameter, E-W trending Misema caldera is a coalescence of at least two large mafic shield volcanoes that formed prior to 2702.9±4.1 Ma (ca. 2703 Ma) based on the Cléricy gabbro complex. The margin of the Misema caldera displays a 10-15 km wide inner and outer ring zone, in which numerous mafic ring dyke structures (e.g. Montsabrais) and subaqueous pyroclastic deposits are observed. The mafic ring dyke complexes are considered deeper level expressions of summit calderas related to a shield volcano phase and the pyroclastic debris may either be associated with the summit volcanoes and/or a product of Misema caldera collapse. The Montsabrais tonalite, with an age of 2696.3±1.3 Ma, shows that the Noranda caldera age volcanism and plutonism influenced older caldera structures. Claude Pilote (PhD, UQAC) is conducting detailed volcanic facies studies around the Mobrun area on the subaqueous pyroclastic deposits and effusive mafic-felsic sequence.

The 15-30 km in diameter New Senator caldera is a NW-SE trending structure characterized as a bimodal mafic-felsic tholeiitic to calc-alkaline sequence. The basal segment of the caldera next to the Glenwood rhyolite in the Noranda area proper is part of the PhD thesis of Lyndsay Moore (PhD, UQAC). The gabbro sills have been reinterpreted to represent ponded magma or magma lakes, which are common in mafic summit calderas. These subaqueous magma lakes are massive units with a change in grain size from coarse- to fine-grained and a hyaloclastite top. Felsic lava flow units increase up-section. The Kiwanis (Noranda) pluton, a high-level synvolcanic magma chamber, intrudes the felsic rocks, and is in turn cross-cut by basaltic dykes and sills. This pluton is polyphase, as indicated by the ages 2697.5 ± 1.6 Ma and 2702.1± 2.0 Ma. The former is synchronous with Noranda caldera evolution, whereas the latter characterizes New Senator evolution. The volcanic features, such as flows, domes, high-level intrusions (as well as dykes-sill complexes), and their highly variable ages show that a simple stratigraphy is not possible in Archean volcanic arc terranes. Instead, calderas are complex volcanic structures that require detailed facies mapping to establish a volcanic evolution.

1. INTRODUCTION

The DIVEX study is an outgrowth of research conducted by the senior author on the Normetal (Lafrance *et al.*, 2000; Mueller *et al.,* in press), Hunter Mine (Chown *et al.*, 2000; Mueller and Mortensen, 2002), and Misema calderas (Mueller *et al.*, 2007) of the Abitibi greenstone belt, as well as an excellent study by Hudak *et al.* (2003) on the 2735 Ma Sturgeon Lake caldera, Wabigoon Subprovince. Divex support (18,000$ for 2007) partially funded Claude Pilote's and Lyndsay Moore's (UQAC, PhD candidates) detailed studies on the physical volcanology of the Misema and New Senator calderas of the Archean Blake River Group (BRG). The historic Noranda caldera of de Rosen-Spence (1976) with most of VMS-deposits is not the focus of this study, but its structures are significant in that they affect the two previous caldera-forming events. The intersections between Noranda caldera structures with the previous two caldera fault systems are prime exploration targets as they are first order pathways for hydrothermal fluids (e.g. carbonate alteration) and VMS mineralization. The initial provocative and ingenious model proposed by Pearson (2005), Daigneault and Pearson (2006), and Pearson and Daigneault (2006, submitted) into three caldera events has merit. The Blake River Group has been re-interpreted as a caldera cluster or nested caldera system, and is best categorized as a *meganested caldera complex* (Figure 1), whereby the oldest and largest Misema caldera comparable in size to the Toba megacaldera. The interpretation put forth by Vital Pearson of CONSOREM (Consortium de Recherche en Exploration Minérale) is a new take on an 'old déjà vu mining camp' many thought had passed its prime. The inferred ages of the various caldera-forming events (*see section results*) may change but the overall sequence of caldera events remains intact and has thus far been substantiated by volcanic facies mapping of our UQAC study group. In addition, carbonate alteration initially thought to be a minor component in the Blake River Group and absent in the central mining camp of Noranda, Quebec (e.g. Hannington *et al.*, 2003), is major hydrothermal alteration mineral assemblage.

2. CALDERA LITERATURE REVIEW

The aim of this study in 2006-2007 was two fold: (1) evaluate the felsic volcanic complex of the Mobrun area as well as focus on the subaqueous pyroclastic rocks inferred to be of Misema caldera age, and (2) study the volcanic evolution of the basal portion of the New Senator caldera with special emphasis on the gabbro sills.

Currently, the doctoral thesis of *Claude Pilote* is focused on the area around Mobrun in the northeastern sector of the Misema caldera of the Blake River Group, concentrating on subaqueous pyroclastic deposits and their proximity to assumed eruption vents, as well as the related mafic-felsic Misema volcanic successions in that sector. Spatial relationships of volcanic vents and deposits are significant because synvolcanic fault systems, such as caldera margin faults, discern favourable sites for volcanic massive sulfide (VMS) deposits. The doctoral thesis of *Lyndsay Moore* will concentrate on the basal segment of the New Senator caldera, whereby emphasis is placed on the mafic sills that have been reinterpreted as thick ponded magma units. The new interpretation of certain gabbro-diorite sills as ponded magma could help target new exploration sites (see Schmincke, 2004). Both studies are intimately related to massive sulfide exploration, and the Misema, as well as the New Senator caldera, are prime candidates for any new exploration program. The geochemistry, petrography, and isotope studies compliment the field-based volcanic facies studies (collaboration with Drs. N. Banerjee and B. Wing). Both PhD studies are focussed on a specific problem but are integrated in the regional volcanic facies mapping program in the Mobrun and southern Noranda areas conducted by the UQAC research group headed by Wulf Mueller. Calderas are collapse structures, 2-100 km in diameter and derived from (1) violent explosions, (2) continual effusive evacuation of high-level magma chambers, and/or (3) lateral migration of magma (Tilling and Dvorak, 1993; Lipman, 2000). The pre-caldera structure is a stratovolcano, a composite volcano, or a shield volcano. Different types of calderas are a function of the collapse mechanism and depth of magma chamber, whereby piston, trapdoor, piecemeal, down sag, and funnel calderas have been recognized (Walker, 1984; Roche *et al.*, 2000). Subsidence mechanisms control eruptions and the topography of the caldera moat, and with it, intra-caldera depositional sites from small-scale volcanism, such as felsic flows (de Rosen-Spence *et al.*, 1980), fountaining eruptions (Mueller and White, 1992), or hydroclastic fragmentation processes (Mueller *et al.*, 1994), but also, the locus of synvolcanic faults systems, hydrothermal fluids, and possible volcanic massive sulfide (VMS) sites. Ohmoto (1978) recognized early on that silicic submarine calderas were key sites for volcanic-hosted massive sulfides. The Archean calderas from the Rouyn-Noranda (de Rosen-Spence, 1976), Hunter Mine (Mueller and Mortensen, 2002), Normetal (Lafrance *et al.*, 2000), and Sturgeon Lake areas (Hudak *et al.*, 2003) are first order hydrothermal VMS loci (Mueller *et al.* 2004, in press).

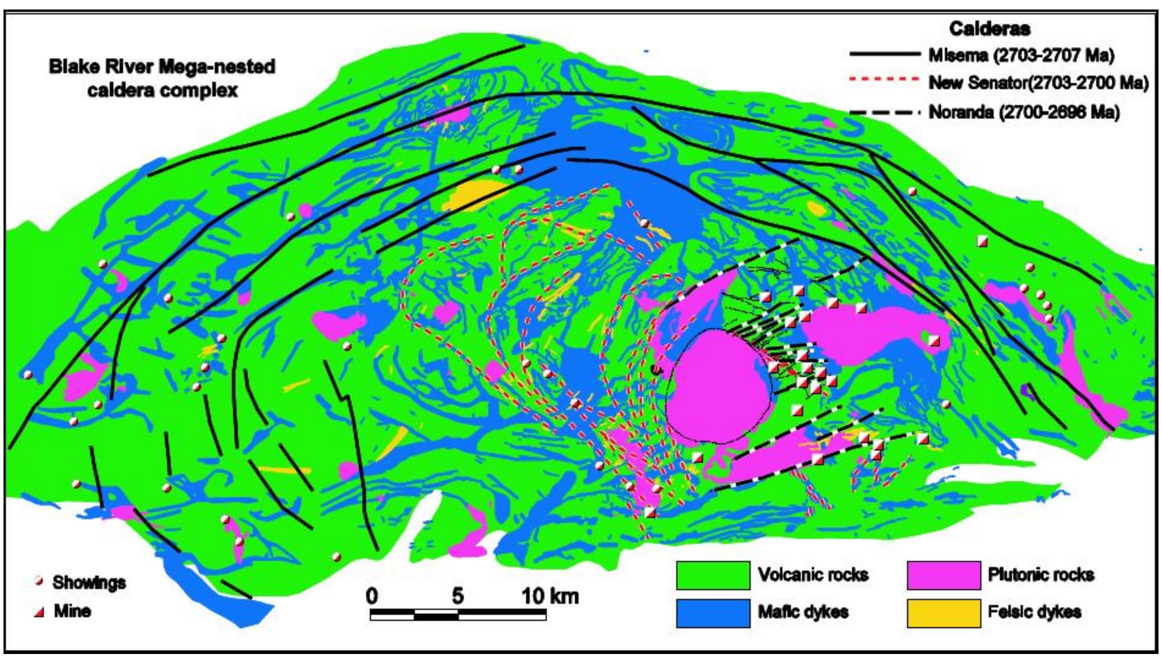

Figure 1: Geology of the Archean Blake River meganested caldera complex with mafic dyke swarms and ring faults that outline the 2703-2707 Misema Caldera (early caldera event). The New Senator (2) and Noranda (3) calderas are part of the second and third caldera-forming events, respectively (Pearson, 2005).

The 3000 km2 subaqueous Blake River meganested caldera complex (Figure 1) is a world class metallotect with respect to both hydrothermal Cu-Zn massive sulfides and gold-rich massive sulfides (Hannington *et al.*, 1999). The Blake River Group is subdivided into the Misema and Noranda subgroups (Goodwin, 1977), which now defines the Blake River caldera complex. The former subgroup is composed predominantly of tholeiitic basaltic to andesitic volcanic rocks and the latter contains both tholeiitic and calc-alkaline rocks. Pearson (2005) and Daigneault and Pearson (2006) recognized three major caldera-forming events in the Blake River Group, which include the E-W striking, 40x80 km, 2703-2707 Ma Misema megacaldera (upper age to be determined, work 2007 in progress Mueller-Friedman-Mortensen); the 2700-2703 Ma, NW-striking, 15x30 km, New Senator caldera (age determinations 2007 in progress Mueller-Friedman-Mortensen); and the classic ENE-striking, 15x20k km, Noranda caldera (2696-2700 Ma; Mueller *et al.*, 2007). The caldera complex is comparable in geometry to the overlapping Las Cañadas caldera (Marti and Gudmundsson, 2000) and the nested calderas in the Campi Flegrei field, Naples (Orsi *et al.*, 1996), but also strikingly similar in structure to Olympus Mons on Mars.

3. RESULTS

3.1. Misema caldera results

Misema caldera results: The 80-40 km Misema megacaldera structure is defined by a double ring fault structure, which is assumed to be the locus of the inward and outward dipping faults respectively (see experiments and documentation, Acocella, *et al.*, 2000; Roche *et al.*, 2000; Geshi *et al.*, 2002). As is usual for arc (e.g. Ambrym, Vanuatu) or oceanic island (e.g. Tenerife, Canary Islands) volcanoes an initial shield forming phase develops. The Blake River Group is no exception and is constructed of at least two shield volcanoes, which formed the base of the Misema caldera. Synvolcanic mafic dykes of gabbroic and dioritic composition intruded along major ring structures and define the structural caldera margin. It was the organization of these diorites and gabbros into a coherent pattern that lead Pearson (2005) to define the Misema caldera with a shield volcano rift zone geometry. In addition, Mueller *et al.* (2007) identified numerous 5-10 km circular mafic ring dyke structures within the inner and outer fault zone (Figure 1). These circular to ellipsoidal structures (e.g. Montsabrias and Dragfold-Duparquet) are composed coarse-grained gabbros (Figure 2a), mafic massive and pillowed lava flows (Figure 2b), and subaqueous fragmental debris (Figure 2c) or pyroclastic deposits (Figure 2d,e,f). Mueller *et al.* (2007) inferred these structures to be consistent with summit calderas on mafic shield volcanoes. They are similar in size and geometry to those on the summit of Mauna Loa (McCarter *et al.*, 2006) and Kilauea. The Montsabrais shield building phase, representative of one of these mafic ring dyke complexes, was initially documented by Dimroth *et al.* (1982). An age of 2702.9±4.1 Ma for a gabbro complex (Mueller *et al.*, 2007) in the Mobrun area yields a first order estimate of this older shield building phase of the Misema caldera. The 2696 Ma Cléricy pluton (Mortensen, 1993), which intruded the Cléricy gabbro complex, and a polyphase tonalite in the heart of the Montsabrais mafic ring complex with an age of 2696.3±1.3 Ma (Mueller *et al.*, 2007) shows that Noranda caldera plutonism and felsic volcanism affected previous calderas.

Mafic lava flows, locally cross-cut by mafic aphanitic feeder dykes (Figure 2b), are predominantly pillowed with minor pillow breccia and hyaloclastites, and compare favourably to the construction of seamounts (Corcoran, 2000). Jevis south subaqueous pyroclastic deposits are either directly associated with the interpreted summit calderas of the shield volcano phase or developed contemporaneously with Misema caldera formation. Numerous explosive eruptions were identified as indicated by the pyroclastic units in the two volcanic events (Figure 3). Subaqueous pyroclastic deposits were first recognized by Fiske and Matsuda (1964) in Japan, and the observed fining-upward sequences in the study area correspond to doubly-graded beds, which represent deposition from a submarine explosive event (Fiske and Matsuda, 1964). The Misema caldera has three distinct mappable pyroclastic units (sampled again for age determinations), whereby thus far only the Dalembert Tuff (Tassé *et al.*, 1978), an Archean analogue to the Japanese deposits, has been considered in detail. The Jévis South and Kino North deposits of the Mobrun area (Pilote *et al.*, 2007) were mentioned by Trudel (1978), and referred to as the 'Fiskite de Clléricy' (after Dick Fiske). The studied pyroclastic deposits of Jévis South and Kino North deposits in the Mobrun area are bounded by pillowed flows, autoclastic felsic subaqueous breccias and black shale suggesting emplacement below storm-wave base (>200 m). The tephra is 80-100 m-thick and contain several 5-50 m fining-upward sequences, which are divided into three divisions: A) a 2-25 m-thick, massive lapilli tuff breccia, B) a 1-10 m-thick, normal to inverse graded, lapilli tuff, C1) a 0,5-15 m-thick, stratified and surge-type crossbedded, coarse-grained tuff to fine lapilli division and C2) a 0,1-35 m coarse- to fine-grained tuff with parallel laminations and ripples. This tripartite division compares to primary subaqueous felsic fountain deposits in the Archean Hunter Mine Group (Mueller and White, 1992), where division A represents laminar mass flow to high density current deposition, division B indicates turbulent, unsteady density current deposits, subdivison C1 subdivision is consistent highly turbulent density currents with local scouring caused by traction currents, and C2 subdivision corresponds to low density currents and suspension deposition. The high to low vesicular pyroclasts (pumice), as well as liberated euhedral and broken crystal support an explosive origin.

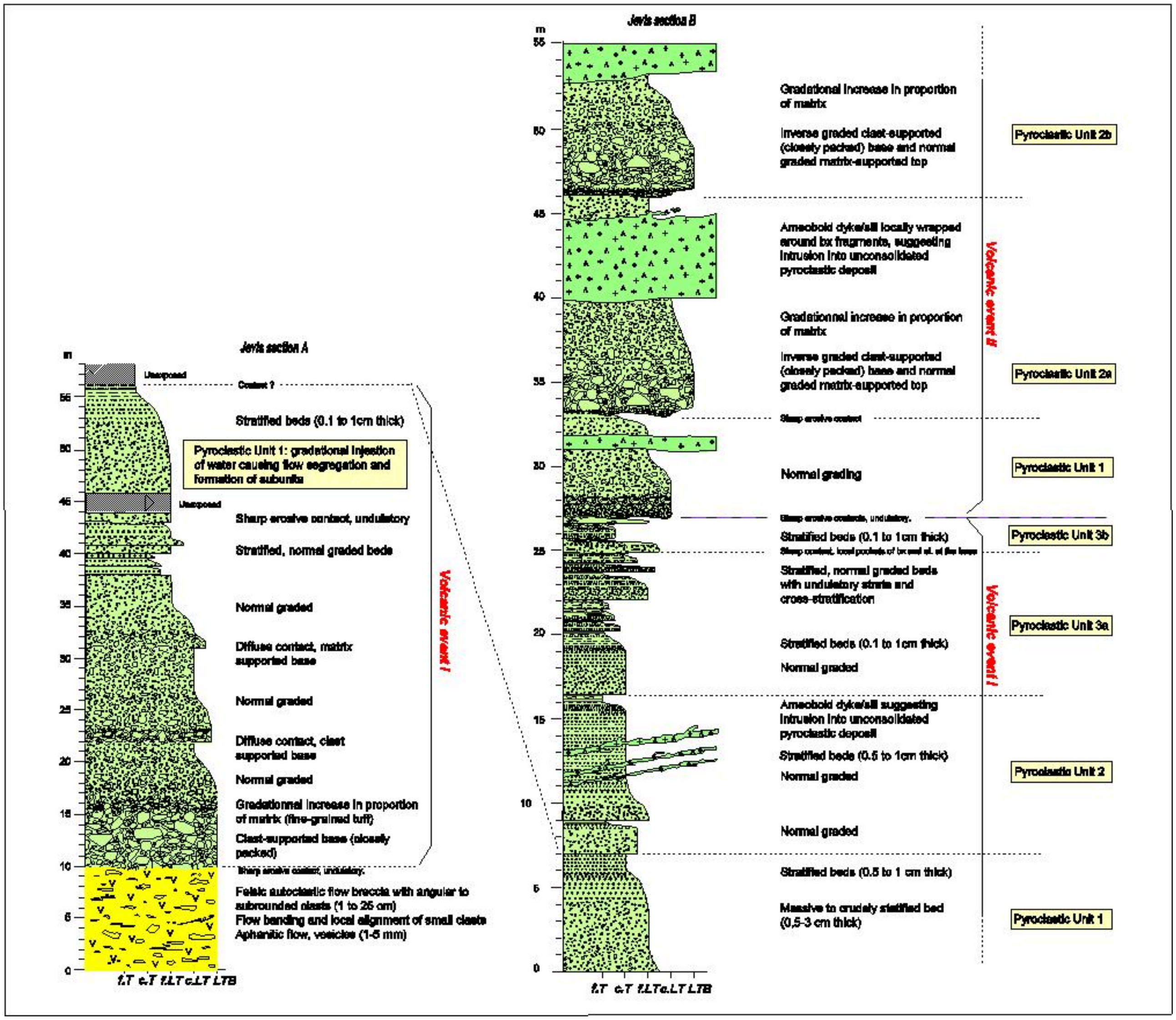

Figure 3: ***Misema caldera subaqueous pyroclastic deposits overlying felsic flow breccias. The pyroclastic units represent distinct eruption events. Note fining-upward sequences in pyroclastic units with massive, graded beds and stratified beds indicative of sediment gravity flow and traction current processes and laminated tuff suggesting suspension deposition (modified from Mueller et al., 2006; Pilote et al., 2007).***

3.2. Continuation of Misema Project

Claude Pilote (PhD) with BSc honours students will focus on the felsic flow-dome-hyaloclastite complexes of the Mobrun area after the pyroclastic deposits have been mapped. Emphasis is placed on the immediate mine area and the mafic-felsic volcanism of Noranda caldera age. Late rifting affected the Misema caldera and shows that caldera volcanism may straddle 8-13 m.y. Discerning between subaqueous Misema and Noranda volcanic activity will be challenging, but selected U-Pb zircon age determinations will help solve the problem.

3.3. New Senator caldera results

The newly identified New Senator caldera (Pearson, 2005) is a 15x30 km NW-SE trending structure with an E-W stratification at the base. The caldera is a complex nested structure within the heart of the Blake River Group that post dates the Misema megacaldera. From an exploration point of view, the New Senator caldera may well host the well-known Horne Mine rather than the Noranda caldera (Daigneault and Pearson, 2006). Generally, the largest massive sulfide deposits are located at the caldera wall or margin (Mueller *et al.*, in press), so that the E-W striking Horne Mine and adjacent chaotic collapse breccias may well be the expression of the New Senator caldera margin, while the Quemont deposit and its ENE-striking breccias may represent the margin of the Rouyn-Noranda caldera.

The basal segment of the New Senator caldera is mafic dominated sequence with numerous basaltic dykes and sills intruding the mafic massive to pillowed basalt flows with minor felsic aphanitic massive to brecciated flows with stratified volcaniclastic deposits (Figure 4a). A series of 5-30 m-thick massive mafic sills the caldera are exposed at the base of the caldera. Daigneault and Pearson (2006) and Lyndsay Moore (PhD-UQAC in progress) have inferred these 'sills' to be part of a subaqueous magma lake during the early stages of caldera evolution based on detailed volcanic facies mapping. The massive sills display asymmetric cooling patterns with the grain-size decreasing toward the top of the chilled margins that also locally display 10-200cm thick hyaloclastite cooling contacts (Figure 4b, c) and V-shaped vapour phase segregation pipes. Pillowed flow units are minor in these massive ponded magmas. If the flow tops are not identified, the massive gabbros can be easily mistaken for sills.

A rigorous sampling program has been conducted for age determinations and geochemical composition of volcanic rocks of the New Senator caldera. A small, tonalitic polyphase pluton at Kiwanis (Figure 4d; Noranda; Plage Kiwanis) Lake in the city of Rouyn-Noranda intrudes felsic aphanitic massive to brecciated lava flows. It is in turn cross-cut by fine-grained basaltic sills and dykes (Figure 4e). The polyphase nature of this high-level pluton is corroborated by ages of 2697.5 ± 1.6 Ma and 2702.1 ± 2.0 Ma, with the former consistent with Noranda caldera activity, and the latter representative of inferred New Senator evolution. The 2702 Ma age indicates that felsic and mafic flows intruded by this pluton must be older, and that the Misema caldera must be even older, as suggested by the 2702.9 Ma of the Cléricy gabbro complex. The 2697.5 Ma age of the western segment of this polyphase pluton shows the complexity of high-level magma chambers as well as continued use of magma conduits over protracted periods. These results support the notion that calderas evolve over 8-13 m.y. A similar history is recorded for the island Tenerife and Valles caldera.

3.4. Continuation of New Senator Project

The New Senator caldera volcanic facies mapping project by Lyndsay Moore (PhD) commenced in 2007, so that more questions than answers arise at this stage of the study. Continued detailed mapping of selected areas at the base of the New Senator (project incorporates, but terminates at the Glenwood rhyolite). The Glenwood rhyolite needs a modern volcanic facies study because new areas have been sampled to chronicle the evoulution of the New Senator caldera in its new context and it is possible that Noranda caldera volcanism may have overprinted and affected New Senator caldera synvolcanic systems.

4. DISCUSSION AND CONCLUSIONS

Preliminary observations from the combined study areas, in addition with the newly obtained age determinations, show that the initial division by Pearson (2005) into three caldera forming events: the Misema, New Senator and Noranda calderas; is well founded and seems to be a valid. The mafic dominated Misema caldera is a large-scale structure characterized by numerous gabbros, which intrude the annular synvolcanic faults (Figure 1). An age of 2702.9±4.1 Ma for the Cléricy gabbro complex is the first indication that the Misema caldera and associated shield building phase is part of an older event. Numerous other sill-like gabbro intrusions have been sampled to support this hypothesis. The 5-10 km in diameter mafic ring dyke complexes between the 10-15 km wide inner and outer rings of the Misema caldera are considered primary structures not related to deformation, but rather a deeper level expression of mafic summit calderas associated with rifting as noted for the oceanic Islands of Hawaii and Tenerife.

The subaqueous pyroclastic deposits at this Blake River stage have no Archean analogue thus far but can be compared to subaqueous arc volcanism in Japan and with calderas along the oceanic Izu-Bonin arc. The tripartite division of these deposits with andesitic pumice supports a primary deposition, but in which water was ingested at different stages into the flow during transport. The Montsabrais tonalite in the heart of the Montsabrais mafic ring dyke complex with an age of 2696.3±1.3 Ma is indicative of Noranda caldera activity and is supported by similar ages of felsic volcanic rocks in the Mobrun area.

The New Senator caldera shows the change from mafic to bimodal mafic-felsic volcanism, which is evidenced by primitive tholeiitic lavas evolving to more evolved calc-alkaline lavas. There is a definite increase in felsic rocks, but these are difficult to date as all flows thus far recognized are aphanitic. Several samples of assumed New Senator felsic volcanism have been taken. The principal results from our studies 2006-2007 concerns the previously interpreted mafic gabbro-dioritic sills and the polyphase high-level tonalitic pluton or magma chambers feeding the various volcanic flows. The Kiwanis (Noranda) pluton displays a polyphase history from 2702.1± 2.0 to 2697.5 ± 1.6 Ma showing that Archean magma chambers below calderas evolve over at least over 3 m.y. The high-level plutons in the Blake River Group appear to be more complex than initially perceived, and a polyphase magma history is required to explain the three caldera forming events.

The sills in the New Senator caldera are prominent at the base and numerous ones have thin to thick well-developed hyaloclastite chilled margins. Many of the circular structures were considered pillow rims, but upon close inspection, a network of fractures during cooling developed in the upper segments of the gabbro and facilitated water ingestion and thermal granulation. The tops of the ponded magma interacted with seawater and hot magma possibly vaporized seawater causing vapour phase streaming the formation of lobate (pillow-type) hyaloclastite structures and in-situ hyaloclastite brecciation in the shape of large V’s. Circulation of seawater along synvolcanic faults and dykes is omnipresent as is indicated by the hyaloclastites. Abundant seawater floor alteration in the form of silicification is a distinct characteristic.

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