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A Special Issue Devoted to Base Metal and Gold Metallogeny at Regional, Camp, and Deposit Scales in the Abitibi Greenstone Belt:

Preface

J. A. AYER,†

Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario, Canada P3E 6B5

P. C. THURSTON, AND B. LAFRANCE

Mineral Exploration Research Centre, Laurentian University, Sudbury, Ontario, Canada P3E 2C6

The Abitibi greenstone belt contains some of the world's largest Cu-Zn and Au deposits and significant amounts of Ni-Cu-PGE mineralization. Discoveries early in the 20th century were made by classic prospecting with subsequent discoveries commonly resulting from diamond drilling of targets identified by electromagnetic surveys. The next generation of deposits will be found at greater depth, based on geological and geophysical models, principally beneath the extensive overburden that covers most of the Abitibi greenstone belt. Thus, exploration will require improved knowledge of the geologic characteristics of the existing deposits, particularly the relationship between deposit- and regional-scale features, including the stratigraphic, plutonic, structural, and metamorphic architecture of the region, and will rely more heavily on expensive geophysical and geochemical techniques, verified by diamond drilling.

The papers in this Special Issue are part of the Discover Abitibi Initiative, a geoscience program funded by federal, provincial, and municipal governments in collaboration with the mining industry. Many of the results reported here are from projects funded by Phase II of the Discover Abitibi Initiative which commenced in 2003 and was focused on the Timmins-Kirkland Lake region (Fig. 1), a high mineral potential portion of the Abitibi greenstone belt that has been the source of exceptional mineral wealth. As part of the Discover Abitibi Initiative, the Greenstone Architecture Project was undertaken by the Mineral Exploration Research Center at Laurentian University to bridge the gap between academic and company information at the scale of individual deposits and the broad-based knowledge derived from government mapping. The project was designed as a multidisciplinary approach involving faculty, postdoctoral fellows, and graduate students in collaboration with geoscientists from the Ontario Geological Survey, the Geological Survey of Canada, consultants, and company geologists. As can be seen in the papers in this Special Issue, the program had both geological and geophysical components. The preliminary results of the Discover Abitibi Initiative and the Greenstone Architecture Project were released as a series of technical reports summarized in Ayer and Calhoun (2005) and Ayer et al. (2005). The more complete outcomes of a number of the projects are presented in this issue as well as results from other affiliated research projects.

Overview of the Special Issue

Regional papers

The first three papers are concerned with the regional tectonic and metallogenic significance of the Abitibi greenstone belt stratigraphy and its autochthonous construction as indicated by xenocrystic zircons in younger Abitibi units and feeder dike relationships. An unconformity-bounded Abitibi volcanic stratigraphy is postulated based on the presence of submarine disconformities and slow accumulation of iron formations which correlate with the timing of many Abitibi volcanogenic massive sulfide (VMS) deposits. The first reflection seismic imaging of Superior province supracrustal units allows upper crustal unit contacts and structures to be traced into the subsurface and provides the first view of major structures associated with epigenetic gold mineralization. Finally, a model for the older (>2.85 Ga) substrate and geodynamic origin of the juvenile (<2.75 Ga) crust in the Abitibi, with new evidence for isotopic inheritance indicating that the westernmost part of Abitibi interacted with older crust, may explain the relatively poor VMS endowment of the westernmost part of the subprovince.

The paper by Thurston et al. (2008) includes the first geochronologically constrained stratigraphic and/or lithotectonic map covering the entire breadth of the Abitibi greenstone belt from the Kapuskasing structural zone eastward to

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† Corresponding author: e-mail, john.ayer@ontario.ca

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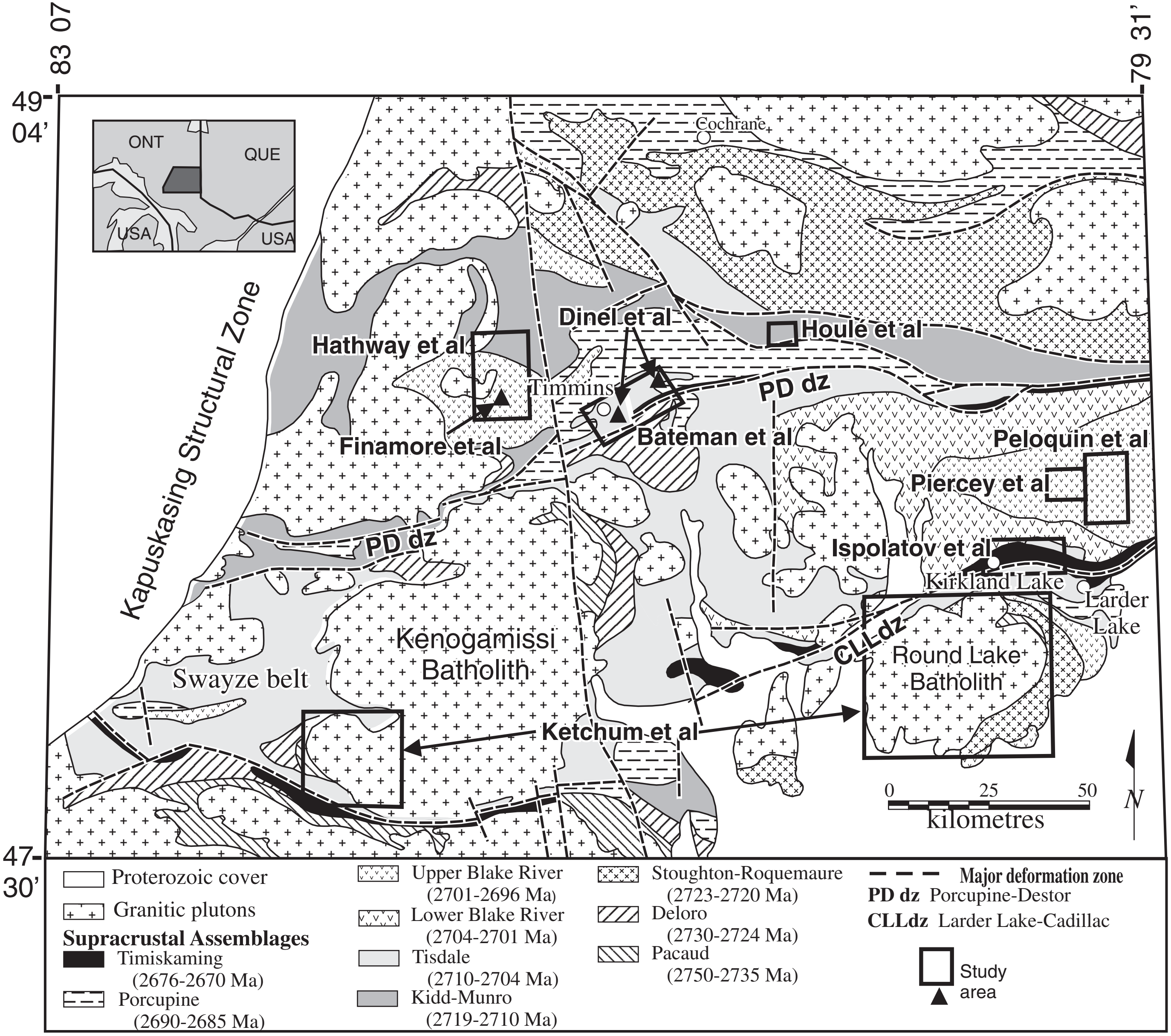

FIG. 1: Stratigraphy of the Ontario portion of the Abitibi greenstone belt (modified from Ayer et al., 2005) with the locations of the study areas of the papers in this issue.

the Grenville province. The paper expands the regional stratigraphic interpretation begun by Ayer et al. (2002, 2005; see Fig. 1) to other parts of the Abitibi greenstone belt in a collaborative effort between workers in Ontario and Quebec. In order to resolve the differing stratigraphic divisions and nomenclatures utilized on either side of the interprovincial border, an Abitibi greenstone belt-wide volcanic stratigraphy is erected subdividing the belt into seven volcanic episodes based on groupings of U-Pb zircon ages: (1) pre-2750 Ma, (2) 2750 to 2735 Ma, (3) 2734 to 2724 Ma, (4) 2723 to 2720 Ma, (5) 2719 to 2711 Ma, (6) 2710 to 2704 Ma, and (7) 2704 to 2695 Ma (Thurston et al., 2008). Many of the volcanic episodes are intercalated with and capped by relatively thin sedimentary interface zones dominated by chemical sedimentary rocks. Stratigraphic and geochronological analysis indicates discontinuous volcanic deposition with these sedimentary zones representing localized gaps of 2 to 27 m.y. between volcanic episodes. The gaps thus represent condensed sections consisting of up to 200 m of iron formation, chert breccia, heterolithic debris flows, sandstone, argillite, and conglomerate. The data support an autochthonous origin for the belt and suggest that the belt consists of a series of stratigraphic and/or lithotectonic units bounded by localized unconformities. This has fundamental implications for regional correlation and development of greenstone belts in general. The stratigraphic gaps are important as they are commonly correlative with the time of formation of Abitibi VMS deposits and thus the sedimentary interface zones represent important stratigraphic markers which can be used to help focus exploration.

Snyder et al. (2008) report on regional and high-resolution seismic reflection profiles focused on important metallogenic features such as the Porcupine-Destor deformation zone and the area of the Kidd Creek VMS deposit in the Timmins area. Past seismic surveys in the Abitibi subprovince funded by LITHOPROBE were designed to image large-scale features in the crust and upper mantle (e.g., Calvert and Ludden, 1999; Percival et al., 2004). In contrast to these earlier studies, Snyder et al. (2008) emphasize upper crustal seismic reflection profiles at higher resolution. The profiles reveal a number of prominent bands of reflectors within the upper 15 km of the crust. These reflectors define a series of folds or antiformal thrust stacks. The profiles have been integrated with structures and stratigraphy mapped at the surface (Ayer et al., 2005) confirming the presence of structural culminations in these locations. At depths greater than 10 km, the reflectors have generally shallower dips implying broad folding. Many of the upper crustal antiformal structures are continuous over strike lengths >50 km and the horizontal shortening appears to be more pronounced north of the Porcupine-Destor deformation zone. Major mesothermal gold deposits such as those at the Hollinger, McIntyre, and Dome mines in Timmins are located north of the Porcupine-Destor deformation zone on the northern, steeply dipping limbs of antiformal stacks, implying that the fold structures focused mineralizing fluids from the upper crust into the near surface. The Porcupine-Destor deformation zone is revealed in the high-resolution seismic sections to be a composite of early fault and fold structures and late transpressive fault arrays, consistent with the structural synthesis of the Timmins area presented here by Bateman et al. (2008).

Ketchum et al. (2008) report on a regional study of the Kenogamissi and the Round Lake plutonic complexes (Fig. 1). This geochemical, U-Pb geochronological, and Nd-Hf isotope study of plutonic and volcanic rocks provides evidence for the involvement of older crust in magma genesis near the Abitibi-Wawa subprovince boundary (Kapuskasing structural zone). Inherited zircons dated at ca. 2850 Ma occur both in 2747 Ma tonalite and 2700 Ma granodiorite of the Rice Lake batholith, part of the larger Kenogamissi plutonic complex. Igneous zircons from this batholith also display large intrasample variations in ^{176}Hf/^{177}Hf which are attributed to mixing of magmas derived from juvenile and older crustal sources. In contrast, tonalitic units dated at 2744 and 2715 Ma from the Round Lake plutonic complex, located 150 km east of the Kapuskasing structural zone, lack zircon inheritance and display less intrasample Hf isotope variability in zircons. The data suggest that the influence of older sialic crust on Abitibi volcanic and plutonic activity is restricted to an approximately 75-km-wide belt of Abitibi crust underlain by older Wawa crust from 2.75 Ga onward east of the Kapuskasing structural zone. This crustal geometry is consistent with development of the Abitibi subprovince at the edge of a proposed Wawa protocraton, perhaps as the result of rifting of this older continental block. An economic consequence of this tectonic model is that the contaminated Abitibi crust may have less potential to host VMS deposits than more juvenile crust, analogous to the Yilgarn craton in Australia where VMS deposits are restricted to the juvenile parts of the craton (e.g., Cassidy et al., 2005).

Base metal deposits

Five papers describe camp- and deposit-scale mapping and research on VMS and Ni-Cu mineralization (see Fig. 1 for project locations). Hathway et al. (2008) describe the Kamiskotia area, west of Timmins. This paper is complemented by a description of the Genex VMS deposit by Finamore (Hocker) et al. (2008). A paper by Péloquin et al. (2008) describes the Ben Nevis area of the Blake River Group. It is complemented by a paper by Piercey et al. (2008) that documents overprinting of porphyry Cu-Mo-Au–style mineralization on VMS mineralization in this group. The last paper is by Houlé et al. (2008) and examines the stratigraphy and architecture of komatiite-hosted Ni-Cu-(PGE)–bearing strata in Dundonald Township, east of Timmins.

The paper by Hathway et al. (2008) incorporates new mapping, geochronology, geochemistry, and stratigraphic interpretations of the Kamiskotia Volcanic Complex, which hosts several past-producing Cu-Zn VMS deposits formed during a restricted time interval. New U-Pb ages for this interval range from 2701.1 ± 1.4 to 2698.6 ± 1.3 Ma, indicating that the complex is correlative with the Blake River assemblage (2701–2697 Ma), rather than the Tisdale assemblage (2710–2703 Ma) as previously interpreted (Ayer et al., 2002). Similar in age and volcanology to the Noranda Formation, which hosts the VMS deposits of the Blake River Group in Quebec, the Kamiskotia Volcanic Complex consists largely of bimodal felsic and mafic lava flows and volcanic facies, which suggests that the VMS mineralization developed at or near the sea floor close to synvolcanic faults. New U-Pb ages of 2714.6 ± 1.2 and 2712.3 ± 2.8 Ma from the northeast-facing volcanic succession in the northern part of this study area indicate that it represents part of the Kidd-Munro assemblage (2719–2710 Ma). The rocks of the Kidd-Munro assemblage are coeval with the Kidd Volcanic Complex, which hosts the giant Kidd Creek VMS deposit ~30 km east of the study area. The lower part of the succession, in south-central Loveland Township, consists of high silica FIIIb rhyolites. These rocks are geochemically similar to ore-associated FIIIb rocks from Kidd Creek and are likely the most prospective part of this succession.

Finamore (Hocker) et al. (2008) present a new reconstruction of the volcanic environment of the Genex mine in the Kamiskotia area. The Kamiskotia Volcanic Complex is divided into Lower and Upper Kamiskotia strata separated by a 3.5-m.y. volcanic hiatus. The hiatus is interpreted as a submarine unconformity, in common with newly recognized unconformities throughout the greenstone belt (Thurston et al., 2008). The Genex and the other VMS deposits in the area occur within the Upper Kamiskotia strata and formed within a volcanic graben where synvolcanic mafic and intermediate sills and dikes with peperitic and locally pillowed contacts define a proximal volcanic vent area. The mineralization represents subsea-floor replacement sulfides localized within zones of higher primary permeability.

The paper by Péloquin et al. (2008) describes the relatively barren western part of the Blake River Group, which elsewhere hosts numerous VMS deposits in Québec. A new age of 2696.6 ± 1.3 Ma for the Ben Nevis Volcanic Complex overlaps the ages for the youngest formations of the Blake River Group in Québec (i.e., the Reneault-Dufresnoy Formation, 2696 ± 1.1 Ma, and the Bousquet Formation, 2698 ± 1 Ma). Similar to the Bousquet Formation, the Ben Nevis Volcanic Complex is not bimodal and, like both the Reneault-Dufresnoy and Bousquet Formations, pyroclastic rhyolites are common. The rhyolites of all these late-phase volcanic formations have greater LREE enrichment and more pronounced negative Nb anomalies than the older rhyolites of the Noranda or Misema–Duprat-Monbray Formations. The VMS deposits in the Reneault-Dufresnoy and Bousquet Formations are distinctly polymetallic (gold, silver, and base metal sulfides), as are the synvolcanic showings in the Ben Nevis Volcanic Complex. The similarity in age, lithological and geochemical character, and styles of synvolcanic mineralization suggests that the Ben Nevis Volcanic Complex was emplaced during late-stage volcanism that formed the Reneault-Dufresnoy and Bousquet Formations. Therefore, it remains unclear why this part of the Blake River Group is poorly endowed with VMS deposits.

Piercey et al. (2008) examine this question with a study on mineralizing events within the Ben Nevis Volcanic Complex and the Clifford Lake stock, where VMS-style mineralization is succeeded by porphyry-style Cu-Mo-Au mineralization. Semiconformable (epidode-quartz-pyrite) and pipelike (chlorite-quartz-chalcopyrite) alteration assemblages are recognized within the 2696 Ma volcanic complex. However, a younger Cu-Mo-Au mineralization appears to be spatially, temporally, and genetically related to the Clifford stock and associated dikes (U-Pb zircon ages of 2686.9 ± 1.2 and 2688.5 ± 2.3 Ma, respectively). An Re-Os age of 2682.4 ± 5 Ma on molybdenite from associated Cu-Mo-Au veins indicates the previously unrecognized porphyry-style Cu-Mo-Au mineralization event is associated with a suite of late adakitic intrusions in the Blake River Group. The key results of this study are that (1) intrusions which were previously thought to be synvolcanic can span an age range up to 10 m.y. younger than the volcanic rocks, (2) the abundance of younger intrusions in the western Blake River Group may explain the lack of VMS mineralization, and (3) the existence of porphyry-like intrusions of adakitic chemical affinity raises the possibility of porphyry-style Cu-Mo-Au mineralization in the Abitibi and possibly throughout the southern Superior province (see also Wyman et al., 2008).

Houlé et al. (2008) present new data on the volcanology, stratigraphy, and architecture of a volcanic and sedimentary succession of komatiitic flows and sills hosting Ni-Cu-(PGE) mineralization within the Kidd-Munro assemblage (2719–2711 Ma) in Dundonald Township. The stratigraphy comprises from base to top (1) pillowed and massive intermediate volcanic flows; (2) komatiite sills, argillites, and felsic volcaniclastic deposits overlain by komatiite flows, komatiitic sills, and pillowed intermediate volcanic flows; and (3) massive and pillowed mafic flows. The distribution and thickness of argillites and felsic volcaniclastic rocks define a synvolcanic graben in which the Dundonald South and Alexo Ni-Cu-PGE deposits occur. Sills and peperites in the lower komatiitic sequence at Dundonald Beach are products of a multigenerational emplacement history recording progressive lithification and related increases in the bulk density and rheology of the unconsolidated argillites, which ultimately permitted the eruption of lavas at Alexo. One of the significant new results of this work is that the nature of the near-surface rocks influences the localization of Ni-Cu-(PGE) deposits. In lava shields, the initial eruptions are typically most voluminous and, if erupted at sufficiently high flow rates, form channelized flows conducive to thermomechanical erosion of S-bearing footwall rocks. In subvolcanic-volcanic lava shields, however, channelized units may occur within the subvolcanic plumbing system and/or within overlying lavas.

Gold deposits

The final four papers examine epigenetic gold mineralization within the Timmins (>65 Moz Au) and Kirkland Lake-Larder Lake (>40 Moz Au) gold camps (see Fig. 1 for project locations). Bateman et al. (2008) and Ispolatov et al. (2008) present the results of structural mapping constrained by new U-Pb zircon dates and metallogenic research in the Timmins and Kirkland Lake areas, respectively. Dinel et al. (2008a) examine controls on gold mineralization at the Hoyle Pond gold mine in the Timmins area; Dinel et al. (2008b) document a new volcanic facies in the Timmins area and discuss its implications for gold mineralization.

Bateman et al. (2008) present new structural, geochronological, and geochemical data on the Porcupine gold camp in the Timmins area. This study more precisely defines the stratigraphy and the generations, timing, and effects of deformation. The stratigraphy is based on extensive use of new geochemistry to better define lithostratigraphic units and is used to demonstrate that regional uplift and extension produced a low-angle unconformity between the Tisdale (2710–2704 Ma) and Porcupine (2690–2685 Ma) assemblages, with excision of upper Tisdale stratigraphy during D_1. Structural synthesis demonstrates that D_2 resulted in thrusting and folding associated with early dip-slip movement in the Porcupine-Destor deformation zone, succeeded by D_3 in which sinistral strike-slip displacement along the Porcupine–Destor deformation resulted in opening of a transtensional half graben associated with unconformable deposition of Timiskaming sedimentary rocks (2676–2670 Ma). Right-lateral strike-slip movement (D_4) and intense constrictional strain (D_5) deformed the earlier dilatational jog that hosts Timiskaming assemblage rocks and acted as a compressional jog during right-lateral movement along the Porcupine-Destor deformation zone. An early gold mineralization is evident as clasts of ankerite veins within the Timiskaming conglomerate. However, the bulk of gold mineralization postdates Timiskaming sedimentation. Quartz-carbonate-tourmaline-gold veins (Hollinger-McIntyre, Hoyle Pond, Dome, Aunor–Delnite mines) developed largely as oblique slip and extensional vein arrays formed during late D_3 strike-slip faulting. Younger deposits (Pamour mine) are associated with faulting during D_4. Thus, the largest known Archean lode gold camp formed throughout protracted orogenesis consisting of a broadly transpressional regime, with unusually well developed early thrusting.

Ispolatov et al. (2008) present a new structural, geochronological, and metallogenic analysis of the Kirkland Lake-Larder Lake gold camp. The camp includes the giant

Kirkland Lake and world-class Kerr-Addison-Chesterville gold deposits, along with several smaller deposits and occurrences. These epigenetic gold deposits are associated with east-trending clastic and volcanic rocks of the Timiskaming assemblage, which unconformably overlie older volcanic assemblages to the north and are bounded by the Larder Lake-Cadillac deformation zone to the south. Three ductile deformation events (D_2, D_3, D_4) and two gold mineralization events postdate the deposition of the Timiskaming assemblage. The Upper Canada, McBean, and Anoki deposits formed during D_2, and, along with the Kerr-Addison-Chesterville, Omega, and Cheminis deposits, are probably related to a regionally extensive hydrothermal system associated with the development of the Larder Lake-Cadillac deformation zone and splays. Later sulfide-poor gold- and telluride-bearing quartz veins of the Kirkland Lake deposit were emplaced during D_4, synchronous with reverse-dextral movement along the ore-controlling brittle Kirkland Lake fault. The Kirkland Lake mineralization has a distinct metal signature (Te>Au, Mo, Pb, Ag, high Au/Ag, low As) which suggests that it probably represents a hydrothermal system linked to a deep magmatic (alkalic) fluid source unrelated to mineralization along the syn-D_2 Larder Lake-Cadillac deformation zone.

Dinel et al. (2008a) document the relationships between stratigraphy, structure, wall-rock alteration, and gold mineralization at the Hoyle Pond gold mine in the northeast part of the Porcupine Gold Camp. The mine is hosted in a homoclinal succession of ultramafic and mafic volcanic flows of the Hersey Lake and Central Formations (Tisdale assemblage). The bulk of the gold was emplaced at lithological contacts that were reactivated as D_4 shear zones during isoclinal folding and thrusting. The mineralization is characterized by free gold in quartz-carbonate (dolomite and ferroan-dolomite) filled shear and extension vein arrays. A broad carbonate alteration is overprinted by meter-scale alteration and mineralization consisting of an inner sericite alteration zone and an outer albite alteration zone consisting of albite, quartz, ferroan dolomite, and dolomite. Geochemical techniques are used to indicate that the deposit formed through mixing of reduced and oxidized fluids. Boron, arsenic, organic matter, and gold were likely derived from sedimentary rocks (Porcupine assemblage?) at depth and were transported in reduced fluids that mixed with oxidizing fluids containing Cr, K_2O, SiO_2, Na_2O, and CaO in structurally generated zones of high porosity within the volcanic rocks during orogenesis.

Dinel et al. (2008b) describe a newly recognized volcanic facies in the Pocupine gold camp, a spherulitic pillow-lobe tholeiitic dacite unit, which has been previously misidentified as pillow basalt. Trace elements indicate these rocks differ from typical pillow basalts. They also contain more abundant primary breccia and hyaloclastite, and the pillow lobes are contorted as a result of folding in a plastic state and are zoned, typically having a spherulite-rich core. The flows are exposed over a strike length of more than 10 km and are interpreted to have resulted from fissure eruptions. The resulting porous and permeable nature of the rocks may have helped to channelize hydrothermal gold-bearing solutions in the camp.

The multidisciplinary approach to mapping-based geoscientific research at regional, camp, and deposit scales represented by the papers in this issue has significantly advanced the understanding of metallogeneis of epigenetic gold, Cu-Zn VMS, and Ni-Cu-(PGE) deposits in the Abitibi greenstone belt. This work has (1) integrated structural mapping of the gold deposits with high precision U-Pb zircon geochronology, (2) integrated metallogenically important field relationships with geochronology, (3) integrated regional-scale, geochronologically constrained stratigraphic analysis with an updated interpretation of iron formations, and (4) provided new interpretations of high-resolution reflection seismic data with structural and stratigraphic control.

New collaborative mapping and research projects currently being undertaken in the Abitibi greenstone belt by the Geological Survey of Canada, the Ontario Geological Survey, and the Québec Geological Survey under the Target Geoscience Initiative III and Deep Search projects (see Ayer et al., 2007), and a new Phase of the Discover Abitibi Initiative, will continue to advance our understanding to help find additional metallic resources in the world's richest Archean greenstone belt.

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