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Intrusion-Associated Gold Systems and Multistage Metallogenic Processes in the Neoarchean Abitibi Greenstone Belt

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Abstract: In gold-endowed greenstone belts, ore bodies generally correspond to orogenic gold systems (OGS) formed during the main deformation stage that led to craton stabilization (syntectonic period). Most OGS deposits postdate and locally overprint magmatic-hydrothermal systems, such as Au-Cu porphyry that mostly formed during the main magmatic stage (synvolcanic period) and polymetallic intrusion-related gold systems (IRGS) of the syntectonic period. Porphyries are associated with tonalite-dominated and sanukitoid plutons, whereas most IRGS are related to alkaline magmatism. As reviewed here, most intrusion-associated mineralization in the Abitibi greenstone belt is the result of complex and local multistage metallogenic processes. A new classification is proposed that includes (1) OGS and OGS-like deposits dominated by metamorphic and magmatic fluids, respectively; (2) porphyry and IRGS that may contain gold remobilized during subsequent deformation episodes; (3) porphyry and IRGS that are overprinted by OGS. Both OGS and OGS-like deposits are associated with crustal-scale faults and display similar gold-deposition mechanisms. The main difference is that magmatic fluid input may increase the oxidation state and CO_2 content of the mineralizing fluid for OGS-like deposits, while OGS are characterized by the circulation of reduced metamorphic fluids. For porphyry and IRGS, mineralizing fluids and metals have a magmatic origin. Porphyries are defined as base metal and gold-bearing deposits associated with large-volume intrusions, while IRGS are gold deposits that may display a polymetallic signature and that can be associated with small-volume syntectonic intrusions. Some porphyry, such as the Côté Gold deposit, demonstrate that magmatic systems can generate economically significant gold mineralization. In addition, many deposits display evidence of multistage processes and correspond to gold-bearing or gold-barren magmatic-hydrothermal systems overprinted by OGS or by gold-barren metamorphic fluids. In most cases, the source of gold remains debated. Whether magmatic activity was essential or marginal for fertilizing the upper crust during the Neoarchean remains a major topic for future research, and petrogenetic investigations may be paramount for distinguishing gold-endowed from barren greenstone belts.

Keywords: intrusion-related gold systems (IRGS), porphyry; magmatic-hydrothermal systems; multistage process; metallogenic model

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1. Introduction

The association between gold mineralization and small-volume felsic magmatism has long been recognized in Neoarchean supracrustal rocks, such as those of the Abitibi greenstone belt, Superior craton, Canada. Gold mineralization occurs in a variety of contexts, including orogenic gold systems (OGS), magmatic-hydrothermal systems, and Au-enriched volcanogenic massive sulfide (VMS) deposits. Most gold accumulated in greenstone belts is associated with OGS, which are structurally controlled deposits formed by the circulation of fluids produced by the metamorphic devolatilization of basalts and other rocks [1]. The spatial association between these systems and alkaline magmatism is well documented, although the genetic association with magmatism is controversial, e.g., the Canadian Malartic deposit, which was interpreted as a magmatic-hydrothermal system and re-interpreted as an OGS deposit [2,3]. This contribution reviews the main characteristics of the magmatic-hydrothermal and intrusion-hosted deposits of the Abitibi greenstone belt and aims to clarify the metallogenic models that best apply to Archean intrusion-associated mineralization.

This review focuses on metallogenic models because they are essential to exploration. Determining whether magmatic activity plays a marginal or essential role in Neoarchean mineralizing processes is required prior to integrating intrusive rocks into perspectivity models. In addition, magmatic fluid inputs tend to induce polymetallic signatures [4], which may form deposits having positive characteristics (e.g., that contain valuable by-products) or negative features (e.g., gold-bearing minerals with complex chemistries and that can induce recovery or environmental issues). Questioning the economic potential of magmatic fluids is also required to document the distribution of gold and base metals in magmatic systems and, by extension, in the Archean crust.

This review focuses on the Abitibi greenstone belt because it is a gold-endowed belt that contains several Au and Cu-Au porphyry deposits formed during the ~100 My magmatic phase that ends at ca. 2.70 Ga (see below) prior to the main deformation phase. In addition, the Abitibi belt contains pre- to syn-deformation (ca. 2.70–2.65 Ga, see below) magmatic-hydrothermal deposits, generally referred to as syenite-associated systems [4]. As this type of mineralization can be associated with alkaline and other types of magmas, the designation of intrusion-related gold systems (IRGS) is favored in this contribution. The IRGS are not to be mistaken for reduced intrusion-related gold systems (RIRGS), which are post-collisional polymetallic mineralization associated with reduced magmas and first recognized in a post-Archean collisional setting in western Canada [5]. The IRGS of the Abitibi belt tend to be associated with small-volume magma that rose along crustal-scale faults to reach the upper crust. As these faults also channelize metamorphic fluids, IRGS and OGS tend to be spatially associated. There is also a temporal association, as both systems formed during the syntectonic period (see below), with IRGS being generally older than OGS [4]. Some OGS may form within competent units, such as a felsic intrusion, to form intrusion-hosted deposits. In addition, OGS and IRGS may overprint each other. Multiple gold enrichment events are common and may even be a requirement for the genesis of large deposits [6]. A part of the gold mineralization of the Abitibi greenstone belt may thus correspond to multistage systems, as is discussed below. The amount of gold that magmatic and metamorphic fluids brought to an individual deposit, however, remains debated. The capacity of magmas to fertilize the upper crust during the Neoarchean remains a major research topic for the Abitibi and other greenstone belts.

2. Geological Setting

The Abitibi greenstone belt is located in the southern part of the Superior craton, Canada. There are several stages to the evolution of Archean greenstone belts such as the Abitibi belt, and these stages can be summarized as follows: (1) construction, characterized by the formation of a mafic crust; (2) maturation, with the development of tonalite-dominated magmatic systems (tonalite-trondhjemite-granodiorite—TTG—suites); (3) cratonization, including a succession of sedimentation and deformation events. An example of such evolution is proposed for the Chibougamau area, northeastern corner of the Abitibi greenstone belt [7]. The main geodynamic processes characterizing the construction, maturation, and cratonization stages are topics of considerable debate, as reviewed recently [8].

This contribution focuses on the magmatic evolution of greenstone belts and associated mineralizing systems. The main magmatic stages are (1) the synvolcanic period, characterized by large-volume tholeiitic magmatism and TTG suites (i.e., construction and maturation phases); (2) the syntectonic period, characterized by the onset of alkaline magmatism and other magmatic events (late maturation phase and cratonization); (3) the post-tectonic period, which includes anatexis melts. Magmatism in this latter period has a limited volume, and there are mostly two main magmatic stages to the evolution of late Archean (3.0–2.5 Ga) greenstone belts [9]. In the Abitibi belt, the oldest rocks of the synvolcanic period correspond to 2.79 Ga felsic volcanic units [10], a ~2.80 Ga tonalite intrusion [11] in the northeastern corner of the belt, and 2.74 Ga intrusive rocks [12] in the southwestern corner. The syntectonic period extends from 2690 to 2665 Ma in the southern part of the belt (Figure 1) and from 2701 to 2690 Ma in the Chibougamau area and the northern reaches [4,13,14]. An example of post-tectonic magmatism is the La Corne pluton, which includes a late intrusive phase dated at 2643 ± 4 Ma [15].

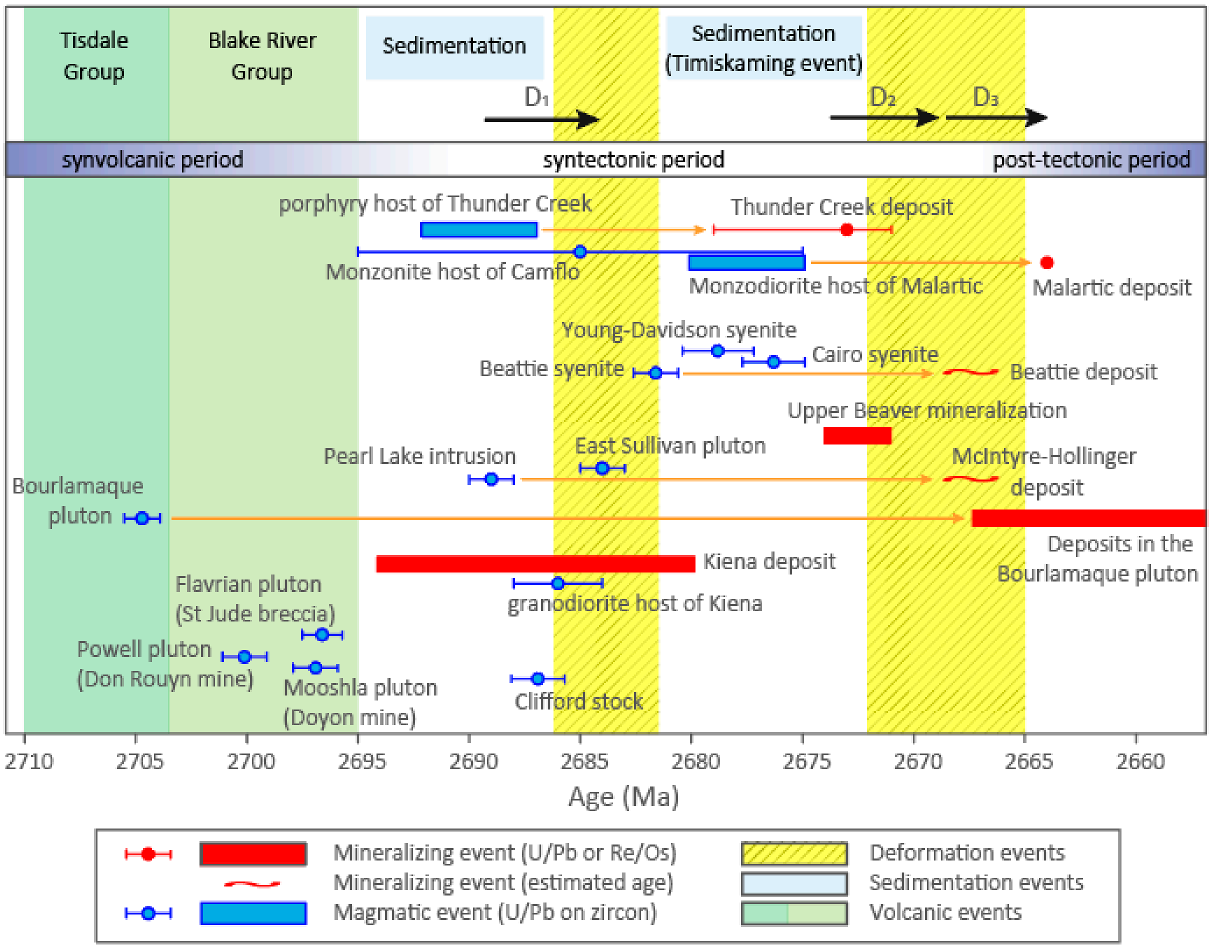

Figure 1. Diagram displaying the main chronological constraints available for late-synvolcanic and syntectonic mineralizing events (red) and mineralized intrusions (blue) described in the text and located in the southern part of the Abitibi greenstone belt. The data derive from multiple sources, as cited in the text and in Supplementary Material Tables S1–S3. The three main deformation events (D_1, D_2, and D_3) recognized in the Abitibi greenstone belt are from Robert [4]. The age of late volcanic events (Tisdale and Blake River groups) are from Thurston et al. [13].

The synvolcanic period is characterized by large-volume volcanic events and associated VMS systems. Voluminous magmatic systems, including subvolcanic intrusions, also formed during this period, and some are associated with porphyry-style mineralization. Porphyries are associated with TTG suites and coeval tonalite-trondhjemite-diorite (TTD) suites [16]. During the syntectonic period, the Timiskaming and other conglomerate-bearing basins formed after a compressional event (D_1) and prior to the main N–S compressional event (D_2) and its waning stage (D_3; Figure 1) [4]. Extensional and other processes favor the onset of alkaline magmatism and the related syenite-associated (or IRGS) style of mineralization [4]. In addition, a variety of mantle- and crustal-derived magmas formed during the syntectonic period, including sanukitoids, high-K calc-alkaline granitoids (HKCA), biotite-granite, and "enriched" TTG suites, which are K-richer than older TTG suites [17]. The genetic associations between IRGS and these types of magmas are discussed below. Post-tectonic intrusions, such as the La Corne pluton, are associated with Li-Mo mineralization [18], which will not be described further in this contribution.

3. Metallogenic Models

In this section, the main magmatic-hydrothermal and other intrusion-hosted gold deposits of the Abitibi greenstone belts are described (Table 1). This review relies on data compiled by the Ontario and Québec geological surveys, as well as references cited in the text and in Supplementary Material Tables S1–S3. The physical characteristics of the deposits are compiled and provided on an indicative basis (Table 2), as information available for well- and poorly documented deposits are difficult to compare. The deposits reviewed here correspond to small producers up to world-class deposits (Figure 2).

Table 1. Deposit and intrusion names, and location.

Deposit/Prospect	Intrusion	Area/Mining Camp (MC)
Lac Troilus	dykes	Opatica plutonic belt
Côté Gold	Chester intrusive complex	SW Abitibi greenstone belt
Central Camp	Chibougamau pluton	
MOP-II	unnamed intrusion	Chibougamau-Chapais MC
Dolodeau	Dolodeau stock	
Selbaie	Brouillan pluton	Selbaie MC
Douay	Douay syenite	NW Abitibi greenstone belt
Lac Shortt	unnamed intrusion	
Boyvinet	Boyvinet stock	Desmaraiville
Bachelor	O'Brien pluton	
Messegay	Launay	Taschereau
Don Rouyn	Flavrian-Powell intrusive complex	
St-Jude breccia	Flavrian-Powell intrusive complex	Rouyn Noranda MC
Silidor	Flavrian-Powell intrusive complex	
Doyon	Mooshla intrusive complex	Doyon-Bousquet-La Ronde MC
Clifford	Clifford stock	Blake River Group
Beattie	Beattie syenite	Porcupine-Destor fault zone
Wasamac	dykes	Francoeur-Wasa shear zone
Young-Davidson	Young-Davidson syenite	
Matachewan Consolidated	syenite stock	Matachewan
Cairo	Cairo stock	
Lake Shore	unnamed intrusion	
Macassa	unnamed intrusion	
Kirkland Lake deposit	Kirkland Lake intrusive complex	Kirkland Lake MC
Upper Beaver	unnamed intrusive suite	
Camflo-Malartic Hygrade	Camflo monzonite	Malartic MC
Canadian Malartic	dykes	
Kiena	dykes	
Several mineralization	Bourlamaque pluton	Val d'Or MC
East Sullivan	East Sullivan	
Hwy-44 property	unnamed intrusion	
Thunder Creek	unnamed intrusion	Timmins-Porcupine MC
McIntyre-Hollinger	Pearl Lake porphyry	
Golden (Canadian) Arrow	unnamed intrusion	Matheson
Kelore and Ross mines	unnamed intrusion	

3.1. Magmatic-Hydrothermal Systems: Porphyries

The Abitibi greenstone belt contains several predeformation magmatic-hydrothermal, porphyry-style mineralizations associated with intrusions of the synvolcanic period, i.e., TTG and TTD suites. The oldest of these systems is Côté Gold (Table 1), a world-class Au-Cu deposit (Figure 2) associated with the ca. 2.74 Ga Chester TTD suite [12,19]. The

Central Camp Cu-Au porphyry is also commonly cited as an example of Archean porphyry and is associated with the ca. 2.72 Ga Chibougamau TTD suite [20,21]. Older systems, such as the intensely deformed ca. 2.78 Ga Cu-Au Troilus porphyry [22], are located outside the Abitibi greenstone belt. The Troilus deposit displays characteristics generally attributed to porphyry systems, such as K-alteration, breccia, and disseminated mineralization [23].

The Côté Gold Au-Cu deposit, southwestern corner of the Abitibi belt (Figure 3), consists of disseminated sulfides and sheeted veins, and it displays evidence of K-alteration, i.e., biotite-bearing alteration assemblages [19,24]. Gold is centered on breccia bodies and is also contained in tonalite and diorite intrusive phases. The mineralization is coeval with the Chester intrusion, according to Re/Os dating on molybdenite, and the deposit is deformed and locally remobilized [25]. The Central Camp deposit displays less breccia, contains locally zoned mineralization, and consists mainly of sulfide-filled fractures [21]. This system has been compared with the deep and weakly mineralized parts of more recent porphyries [26]. A part of the mineralization is structurally controlled and associated with quartz veins, possibly because of remobilization during the syntectonic period. The age and chemistry of intermineral dykes was used to relate the Central Camp deposit to the Chibougamau pluton [27]. One of the mineralizing styles includes abundant magnetite, pointing to the presence of oxidized fluids, whereas K-feldspar alteration and fluid-inclusion studies point toward high-temperature and high-salinity fluids, respectively [21,28].

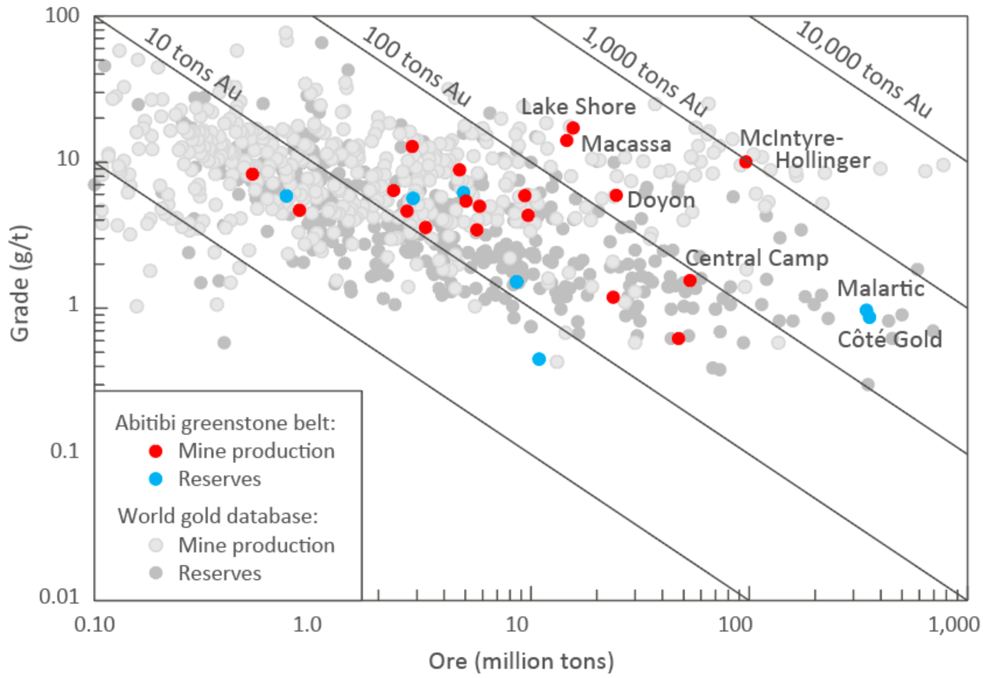

Figure 2. Magmatic-hydrothermal and other gold-bearing mineralizing systems displayed on a grade vs. tonnage diagram. The world gold database is from Gosselin and Dubé [29]. Production and reserve data for the deposits presented in the text (red and blue dots on the diagram) are compiled from the literature (Supplementary Material Table S2).

Table 2. Main physical characteristics of the deposits described in the text.

		Clifford	Côté Gold	Central Camp	Troilus	Kiena	Don Rouyn	Doyon	Selbaie	McIntyre-Hollinger	Golden Arrow	MOP-II	Bourlamaque	Lac Shortt	Bachelor	East Sullivan	Upper Beaver	Launay	Wasamac	Beattie	Boyvinet	Young-Davidson	Ross	Kelore	Matachewan Consolidated	Cairo	Lake Shore	Macassa	Douay	Hwy-44 property	Thunder Creek	Kirkland Lake deposit	Canadian Malartic	Silidor
Evidence for magmatic fluids [1]	K-alteration	√ [6]	√	√	√	√				√	√		√	√	√	√	√	√	√	√		√			√		√	√	√	√	√	√	√	
	Hematization	√					√			√	√			√	√		√	√		√	√	√	√	√	√	√	√	√	√	√		√	√	√
	Sulfate (barite, anhydrite)							√		√					√		√						√		√	√	√	√		√		√		
	Polymetallic signature					√			√								√		√	√	√	√	√		√			√		√	√	√	√	√
	Stable isotopes (O, S)	√								√	√				√	√				√		√	√		√	√	√	√		√	√	√	√	√
	Au-telluride association									√									√			√						√				√	√	
	Fluorite		√												√					√						√								
	Base metals (Cu-Mo)	√	√	√	√	√	√	√	√	√	√	√	√			√	√	√		√		√	√	√	√	√		√				√	√	
	Zoning [4]			√	√	√	√		√	√		√																						
Evidence for metamorphic fluids [2]	Fluid inclusions			√																	√													
	Stable isotopes (O, S) [5]										√									√		√												
Non-specific characteristics [3]	Structurally controlled			√	√		√			√		√	√	√	√			√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√
	Quartz-carbonate veins			√			√	√		√	√	√	√	√			√		√	√	√	√	√	√				√	√			√	√	√
	Invisible gold in sulfide																		√	√													√	
	Free gold			√	√												√		√	√	√							√			√	√	√	
Other characteristics	Disseminated sulfide	√	√	√	√	√	√	√		√	√	√	√		√	√	√	√	√	√	√	√		√	√	√			√	√	√		√	
	Silicification	√	√	√	√		√	√		√	√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Breccia	√	√	√	√	√	√	√		√	√	√			√	√	√	√	√	√	√		√	√				√	√			√		

[1] Magmatic fluids are generally oxidized, high-temperature, and high-salinity fluids with a complex chemistry, and they can induce, for example, K-alteration and hematization. [2] Metamorphic fluids are reduced, low-salinity, and CO_2-rich fluids with a characteristic P-T (2 kbar, 300–350 °C) [1]. [3] Characteristics that are frequent in OGS but that may also be displayed by an IRGS formed in a tectonically active area. [4] Zoning is generally concentric with a core and a peripheral zone displaying distinct ore and/or alteration minerals. [5] Isotopic values compiled from the literature are available in Supplementary Material Table S3. [6] Characteristics compiled from references cited in the text.

West of the Central Camp porphyry (Figure 3), the ca. 2.73 Ga Brouillan pluton is associated with the polymetallic mineralization of the Selbaie mine [30]. This mineralization consists of polymetallic veins and Au-bearing chalcopyrite stockwork, and it has been interpreted as an epithermal system [31]. This mineralization postdates nearby VMS and is deformed [31]. Another important volcanic center, renowned for its VMS deposits, is the Blake River Group (Figure 3), with its well-documented ca. 2.70 Ga Flavrian-Powell subvolcanic complex [32], intruded following a caldera collapse [33]. This pluton is associated with the Cu-Au-Mo Don Rouyn porphyry and the Cu-Mo St-Jude intrusive breccia [34,35]. The Don Rouyn deposit consists of disseminated sulfides and veinlets and displays a Cu-Au core associated with phyllic alteration and a chalcopyrite-hematite-bearing external zone. A part of the system is structurally controlled, possibly as a consequence of late remobilization [34]. Don Rouyn is likely a submarine porphyry and thus differs from post-Archean porphyries, which are generally subaerial [34]. The St-Jude intrusive breccia, which is also associated with a trondhjemitic intrusive phase of the Flavrian-Powell subvolcanic complex, displays a zoned chemical (hydrothermal alteration) and mineralization pattern [34,35]. As for the Selbaie mine, these porphyries tend to postdate VMS mineralization [34].

Additionally, in the Blake River Group, the Doyon-Bousquet-La Ronde camp is known for its OGS and Au-rich VMS. It also contains the Doyon Au±Cu deposit associated with the Mooshla TTD suite [36]. The Mooshla intrusion emplaced at shallow depth, and the Doyon system likely interacted with fluids already involved in VMS systems, whereas fluids exsolved from the intrusion may have contributed Au to seafloor mineralization [36]. Further west (Figure 3), the Clifford stock, and its Cu-Mo-Au porphyry mineralization, also intrudes into the Blake River Group but is a younger system (2686.9 ± 1.2 Ma; [37]), formed after Blake River–related magmatism and VMS mineralization [38]. This system displays shared characteristics with the deposits described above, such as breccia, disseminated sulfides, silicification, and K-feldspar alteration, and oxygen isotopes confirm that high-temperature fluids circulated in the mineralized area [38,39]. The Kiena mine, also in southern Abitibi (Figure 3), is another predeformation mineralization with an age similar to that of the Clifford stock. The Kiena Au deposit displays zoned alteration, stockwork, breccia, and intermineral dykes [40]. Cockade and other textures point toward a shallow-depth mineralizing process [40]. Kiena is a multistage system, with the mineralizing event predated by albitization and breccia and postdated by stockwork veining [40].

The deposits described in this section display several common features (Table 2). They correspond to gold and base metal mineralization, and examples of gold deposits having a polymetallic signature (Kiena, Selbaie) are rare. Breccia can be extensive, and zoned mineralization and alteration are common. Porphyry systems generally display K-alteration, i.e., K-feldspar associated with Fe-oxide (Central Camp, Clifford) or biotite (Côté-Gold, Kiena, St-Jude), whereas such alteration is lacking in systems interpreted as epithermal (e.g., Selbaie). The associated intrusions generally display evidence of a shallow depth of emplacement, e.g., miarolitic cavities, low-Al amphiboles, and open-fracture infilling. Post-mineralization deformation is common. These systems also display differences that may, in part, be attributed to the composition of the associated magma, i.e., diorite-tonalite or trondhjemite. Additionally, some of these systems formed within subaerial volcanoes (e.g., Central Camp), whereas others were submarine, such as these associated with the Blake River volcano, and magmatic fluids may have mixed with seawater-derived fluids. For these latter systems, links have been established between porphyry and VMS systems (e.g., Doyon deposit), whereas, in most cases, VMS predate the porphyry stage (e.g., Selbaie, Don Rouyn, Clifford).

3.2. Magmatic-Hydrothermal Systems: Porphyries Overprinted by OGS

In this section, several base metal deposits overprinted by gold mineralizing events are described. Most of these deposits are located along deformation zones in the southern part of the Abitibi greenstone belt (Figure 3). Mineralization is associated with high-Al TTG intrusions (Pearl Lake and nearby porphyries), a trondhjemite stock (Golden

Arrow), a quartz-feldspar porphyritic tonalite intrusion (MOP-II), and a tonalite-diorite pluton (Bourlamaque).

The giant McIntyre-Hollinger gold system (Figure 2) is part of the Pearl Lake Cu-Mo-Au porphyry (Table 1) [41]. Pearl Lake and the porphyries of Bristol Township and Carr Township correspond to the largest intrusions of the Porcupine gold camp [41]. These intrusions are related to base metal mineralization associated with K-alteration (biotite) and breccia that are intersected by auriferous veins [41]. The McIntyre-Hollinger deposit has been interpreted as a porphyry system modified by subsequent deformation [42]. The Au/Ag ratio is lower (1/6.5) in the internal Cu±Mo zone and peripheral Au zone (4.5/1), which may be interpreted as evidence for a thermally zoned hydrothermal system [43] but may also suggest a two-stage process. Gold mineralization is, indeed, structurally controlled and likely postdates the porphyry intrusions [38,44]. Hematization, the presence of anhydrite, and sulfur isotopes also suggest the presence of oxidized fluids (i.e., possible magmatic fluid input), but crosscutting relationships show that auriferous quartz-carbonate veins were introduced later and that the early magmatic event is gold barren [45]. The McIntyre-Hollinger Au system and nearby mineralization may correspond to early base metal mineralization (possibly porphyry-style) overprinted by OGS.

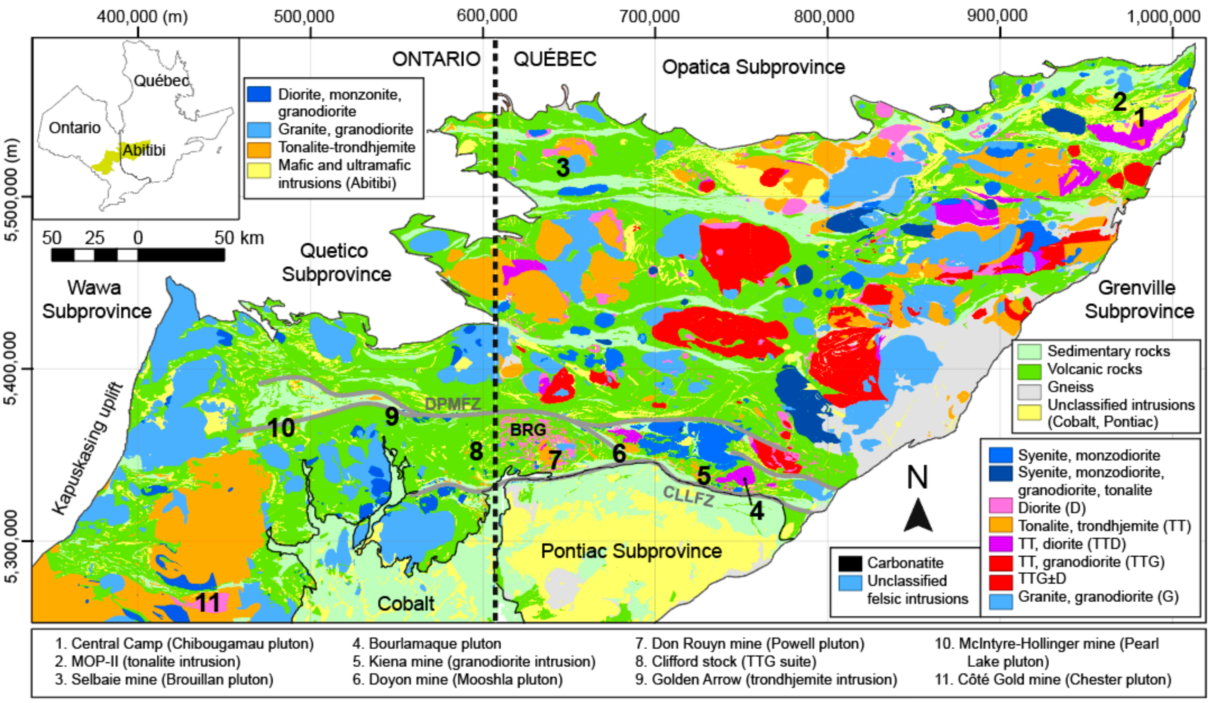

Figure 3. Geological map of the Abitibi greenstone belt showing the distribution of the main lithologies, as classified by Mathieu et al. [16] (see this article for details). The map is modified from the Ministère de l'Énergie et des Ressources Naturelles of Québec (MERN), the SIGÉOM data set, and the Ontario Geological Survey. The projection is UTM NAD83 Zone 17N. Numbers situate several intrusions described in the text. Destor–Porcupine–Manneville fault zone, DPMFZ; Cadillac–Larder Lake fault zone, CLLFZ; Blake River Group (BRG).

The Golden (Canadian) Arrow deposit, near Matheson (Figure 3), includes a shallowly emplaced trondhjemite. Seawater-derived fluids interacted with the intrusion, inducing Na-metasomatism. Then, low-temperature (220–250 °C) hypersaline fluid deposited galena within fractures [46]. The intrusion was then altered by oxidized, possibly magmatic, fluids, which induced K-feldspar alteration and hematization. Late-mineralizing events also formed auriferous quartz veins associated with carbonatization. Stable isotopes (oxygen, sulfur and carbon) point toward the presence of at least three distinct fluids [46]. Nearby deposits, such as the Kelore and Ross mines, are associated with syenite, and several lines of evidence (S isotopes, hematization) point toward the importance of magmatic fluids in the area [45]. Golden Arrow may be an early base metal mineralization overprinted by an OGS dominated by metamorphic and magmatic fluids (see below).

The MOP-II Au-Cu-Mo porphyry, Chibougamau area (Figure 3), is associated with a strongly deformed polyphased tonalite intrusion [47]. The main alteration is silicification, as well as sericitization, chloritization, carbonatization, and peripheral propylitic alteration. Zoning is also observed with Au at the core and peripheral Mo-Cu mineralization. Gold is located along the contact of the porphyritic dykes, and its distribution is controlled by fault zones. Alteration is extensive. The mineralizing style includes disseminated sulfides, breccia, and deformed quartz veins, and these features indicate that the mineralization is predeformation and likely corresponds to a porphyry system of the synvolcanic period [47]. Syntectonic deformation and fluid circulation are extensive, but these fluids may have been gold barren. A different situation is exhibited by the Bourlamaque pluton, located near the Cadillac–Larder Lake fault zone, which displays evidence (e.g., minor amounts of chalcopyrite, molybdenite, telluride, and weak K-metasomatism) of a weak porphyry system [48,49]. Gold mineralization at Bourlamaque is associated with quartz-carbonate-pyrite-tourmaline veins, is structurally controlled, and corresponds to an OGS [48,50]. The deposits described in this section thus correspond to OGS that overprint gold-bearing or gold-barren porphyries.

3.3. Magmatic-Hydrothermal Systems: IRGS or Syntectonic Porphyries?

In this section, several magmatic-hydrothermal systems of the syntectonic period are described. They correspond to the Bachelor Au Mine associated with the O'Brien stock, the Cu-Au $\pm$ Mo mineralization associated with the East Sullivan stock, as well as the Cu-Au-Mo Upper Beaver and the Au-REE Lac Shortt deposits (Figure 4, Table 1). Most of these systems are described as porphyry-style mineralization [51–53] but formed during the syntectonic period and may then correspond to IRGS, according to the classification adopted here. The mineralization can also be structurally controlled (Bachelor and Lac Shortt), as the circulation of gold-bearing fluids may be coeval with major deformation events [51,54].

The Lac Shortt deposit is related to a syenite-carbonatite system [55]. Nearby (Figure 4), the poorly documented Au-W-Ag Dolodeau mineralization is also spatially associated with a syenite-carbonatite complex [56,57]. The O'Brien stock comprises alkali-calcic to alkaline phases and is F-enriched, which explains the low temperature (650–700 °C) of its solidus [51]. The East Sullivan alkaline intrusion is also a polyphase pluton and displays anomalous F-contents [52]. The O'Brien and East Sullivan intrusions may correspond to sanukitoids [51,52]. The Upper Beaver complex also comprises a diversity of intrusive phases, such as monzonite, diorite, and granodiorite [53]. Despite the documentation available on these few examples, the distribution and metallogenic potential of carbonatite-bearing and sanukitoid magmatic systems in the Abitibi greenstone belt remain to be evaluated.

The intrusions described here are thus generally polyphase plutons that include C-rich phases (carbonatite and other alkaline magmas) or magmas having unusual chemistry (F-bearing sanukitoids). Most of these magmas may derive from a metasomatized mantle [41,58,59]. These are also oxidized magmas, as indicated by the lack of an Eu anomaly, the elevated Fe^{2+}/Fe^{3+} ratio, and the presence of magmatic magnetite, e.g., the East Sullivan intrusion [52]. Alkaline magmatism is also generally considered oxidized, as indicated by petrogenetic studies [60] and direct measurements of the fO_2 parameter using zircon chemistry [11]. Such magma exsolved oxidized fluids, as indicated by characteristic alteration minerals, such as sulfates, magnetite, and hematite [51,53]. Indeed, in Archean contexts, oxidized fluids are rare and are generally exclusively exsolved from magmas [45]. Stable isotope data (oxygen and carbon), which are available for East Sullivan (Table 2), confirm that these mineralizing systems are dominated by magmatic fluids [51].

Another important characteristic of magmatic-hydrothermal systems is the presence of high-temperature alkali alteration. The emblematic alteration is K-metasomatism and, to a lesser extent, Na-metasomatism. Potassic-feldspar alteration is particularly intense for carbonatite-bearing systems such as Lac Shortt, where fenetized rocks can be mistaken for syenite intrusive phases [54]. In the other systems, K-feldspar alteration is generally early. An additional five alteration styles are observed at Lac Shortt [54], and a diversity of alteration styles are reported at Upper Beaver and Bachelor [51,53]. Base metals, hydraulic breccia, and contact metamorphism (including a Ca-rich zone interpreted as a skarn for East Sullivan) are observed at East Sullivan and Upper Beaver [52,53]. These complex alteration patterns point to high-temperature and high-salinity (K-feldspar alteration), Cl-bearing (base metals) magmatic fluids that evolve by interacting with reduced host rocks and, possibly, by mixing with fluids circulating in the upper crust during the syntectonic period, e.g., meteoric water, metamorphic fluids.

The Au-Mo Messegay porphyry associated with the late- to post-tectonic Launay pluton may also belong to the group of mineralization described here. The Launay granite intrudes into an older tonalite and belongs to the Taschereau-Launay intrusive complex [61]. The Messegay occurrence consists of disseminated mineralization associated with four alteration types that include the alteration minerals magnetite, hematite, and microcline. A part of the ore is structurally controlled, and the Messegay mineralization displays characteristics of both porphyry and OGS [61].

Robert (2001) stipulates that one of the main characteristics of IRGS is their polymetallic signature. Such a signature is reported at Upper Beaver (Au-Ag-Hg-Te-Bi-Sb) [62]; however, it is not the defining characteristic of the deposits described in this section (Table 2). Their main feature is a correspondence to gold and, in places, to base metal mineralization related to syntectonic intrusions that display limited structural control and are associated with high-temperature and oxidized fluids. These deposits are commonly associated with K-feldspar, magnetite-, and hematite-bearing alteration assemblages.

3.4. Multistage Processes: IRGS Overprinted by OGS

This section refers to IRGS overprinted by OGS. The best examples are the Wasamac, Beattie, and Boyvinet mineralizations (Table 1), where pyrite has been studied in detail. These deposits are well documented because pyrite is an important marker of magmatic fluid input, e.g., Chibougamau area [63], and a tracer of metallogenic processes [64]. Additional deposits with more controversial metallogenic models are also presented in this section.

The Wasamac and Beattie deposits are located in and around syenite intrusions. The Beattie syenite has been studied in detail and consists of several intrusive phases [65]. The Boyvinet stock contains monzodiorite and monzonite intrusive phases, and these phases have the modal composition of syenite because of intense alkali metasomatism [66]. For these three systems, the early magmatic-hydrothermal event is characterized by K-feldspar alteration (Wasamac, Beattie) and Na-metasomatism for Boyvinet [66–68]. Early oxidizing fluids also induced hematization and are likely at the origin of the polymetallic signature observed at Wasamac (W-Pb-Bi-Te-Mo-Ag) and Beattie (Te-Hg-Mo-As-Au-Se-Ag-Sb) [67,69]. These deposits consist of disseminated sulfides and display lithological control, e.g., Beattie syenite [69].

These systems are overprinted by structurally controlled mineralization associated with sericitization, silicification, and carbonatization [66,67,69]. Albitization is also observed at Wasamac, which is attributable to the hydrolysis of K-feldspar by a reducing fluid [67]. Fluid inclusions point to metamorphic fluid–dominated systems [66]. These two-stage processes have mostly been deduced from pyrite chemistry and texture. Pyrite from the magmatic-hydrothermal stage (IRGS) are metal-rich, porous, and they contain invisible gold (Beattie) or Au-bearing telluride microinclusions (Wasamac) or display polymetallic signatures (Bi-Te-Cu-Ag-Sb; Boyvinet) [66,67,69]. The metamorphic fluid-stage (OGS) induced overgrowth of metal-poorer pyrites with W-Au-Ag (Wasamac) or As-Ni-Co-Se (Boyvinet) signatures and with visible gold fracture infilling [66,67,69].

Even if the intrusions observed in the field display evidence of autometasomatism, the early mineralizing stage may be associated with magmatic fluids derived from deep-seated alkaline intrusions [66,67]. The Boyvinet stock, for example, may have acted as a structural trap for such deeply derived magmatic fluids [66]. At Wasamac and Beattie, early pyrite contains invisible gold, suggesting that gold was introduced by the IRGS [67,69]. Whether the OGS brought additional gold to the system or only induced remobilization of early mineralization remains unknown. At Boyvinet, gold is most abundant in the later-stage pyrite [66], and the IRGS may have been less fertile than the OGS.

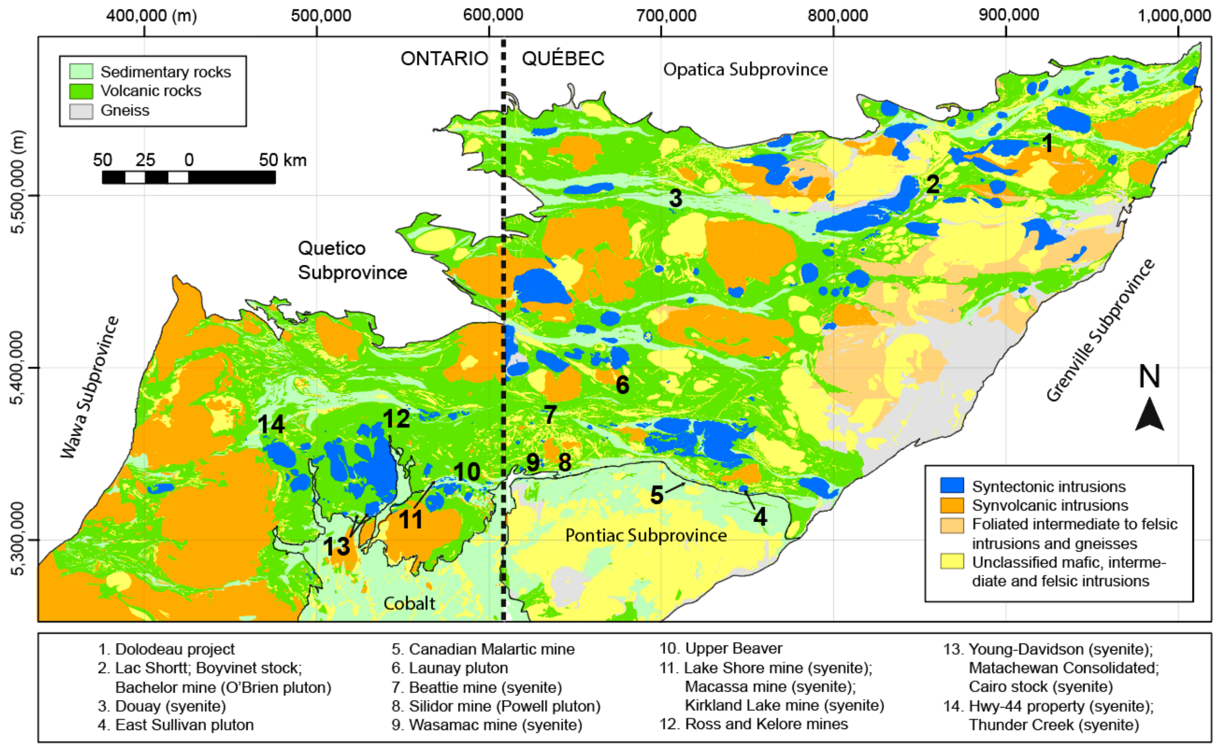

Figure 4. Geological map of the Abitibi greenstone belt displaying intrusions of the synvolcanic and syntectonic periods (modified from Mathieu et al. [16]). The map is modified from the MERN and Ontario Geological Survey data sets, and the projection is UTM NAD83 Zone 17N. Numbers locate intrusions and deposits described in the text.

The Abitibi greenstone belt contains several other multistage (IRGS overprinted by OGS) deposits. For example, the Young-Davidson Au deposit is associated with a syenite and displays several mineralizing styles, including disseminated pyrite and quartz veins (Table 2) [70,71]. A part of the gold is associated with K-feldspar alteration and telluride, and several pyrite generations are described [70]. In addition, oxygen and sulfur isotopes point toward magmatic and metamorphic fluid inputs [70], and Young-Davidson may correspond to a multistage system akin to these described in the previous section. Other interpretations have, however, been proposed for Young-Davidson, including a mixing of magmatic and metamorphic fluids [70,72]. The documentation of structurally controlled gold-bearing quartz veins led other authors to minimize the importance of the magmatic system and to suggest that the syenite is a structural trap for metamorphic fluids, i.e., an intrusion-hosted OGS model [71].

Within a few kilometers of the Young-Davidson mineralization (Matachewan area; Figure 4), several porphyry-style Cu-Mo-Au deposits are associated with small-volume syenite intrusions (e.g., Matachewan Consolidated) and with the larger-volume Cairo stock syenite. These mineralizations are associated with K-alteration, hematization, and barite (Table 2) formed by the circulation of oxidized magmatic fluids according to isotopic data [45,73]. At the Cairo stock, gold is associated with structurally controlled quartz veins [73], suggesting a multistage process. Nearby, the Macassa and Lake Shore deposits, both associated with syenite intrusions, may also result from multistage processes. At the Macassa mine, two distinct mineralizing styles are reported, and oxygen isotopes point toward magmatic fluid input [74,75]. Indeed, a part of the mineralization has a polymetallic signature, contains base metals (e.g., molybdenite-coated fractures), and is associated with K-alteration (K-feldspar, biotite) and sulfate, whereas native gold is found in chloritized shear zones associated with carbonatization and silicification [74,75]. The Macassa mine is a strongly structurally controlled deposit [76]. At Lake Shore, evidence is present for oxidized magmatic fluids (sulfate, hematization, sulfur isotopes) and for overprinting by quartz-carbonate auriferous veins associated with sericitization (Table 2) [77]. The Lake Shore deposit is strongly structurally controlled, and gold may be mostly associated with the second stage (OGS) mineralizing event [77].

The Young-Davidson, Matachewan Consolidated, and Cairo mineralizations, the world-class Macassa and Lake Shore deposits (Figure 2), and the Upper Beaver previously described deposit (Figure 4) belong to the well-endowed Kirkland Lake camp. This camp has a distinct metal signature (Te > Au, Mo, Pb, Ag, high Au/Ag, low As) and contains several structurally controlled deposits, demonstrating the importance of magmatic fluids and the successive deformation events in parts of the Abitibi belt [78]. Further north, the Timmins camp also contains IRGS overprinted by OGS, e.g., the Hwy-44 property (see next section). Still further to the north (Figure 4), the poorly studied Douay syenite also displays IRGS characteristics and a structurally controlled ore, and this syenite may be another example of multistage mineralization [79].

3.5. Intrusive Rocks and OGS

This section describes OGS deposits that display evidence of early (or coeval) magmatic fluid inputs. The Lake Shore deposit, described in the previous section, may belong to this category, as Hicks [77] proposed that gold was mostly introduced by the OGS. The Young-Davidson deposit (Section 3.4) may also correspond to an OGS having metamorphic and magmatic fluid inputs [70,72]. Some of the deposits described in this section (e.g., Malartic) also have controversial metallogenic models.

In the Timmins area (Figure 4, Table 1), porphyritic intrusions are closely related temporally to gold mineralization [80,81]. Some mineralization, such as that of the Hwy-44 property, is associated with a syenite intrusion, displays a polymetallic signature, and is dominated by magmatic fluids that induced K-feldspar alteration and hematization [82]. At the Hwy-44 property, however, gold grades are structurally controlled and uncorrelated to K-alteration. At the nearby Lake Shore Gold's Thunder Creek deposit (hereafter named Thunder Creek), some evidence for magmatic fluid input is documented (e.g., weak K-feldspar alteration, Cu-Bi-Au-enrichment); however, silicification is intense, and the deposit appears strongly overprinted by an OGS [82]. At Thunder Creek, pyrite chemistry suggests an early gold mineralizing event, and sulfur isotopes point toward the presence of oxidized magmatic fluids at Thunder Creek and Hwy-44 [82]. However, and in particular for the Thunder Creek deposit, the metamorphic overprint is extensive, and gold may have been mostly introduced by the OGS [82].

In the Kirkland Lake camp, the Kirkland Lake deposit (Figure 4) is another structurally controlled deposit that is spatially associated with an alkaline complex. The deposit displays early quartz-carbonate auriferous veins and evidence for a later event that introduced native gold and telluride [83]. Evidence for oxidizing fluids, such as sulfate, hematization, and sulfur isotopes (Table 2), is reported [45,84]. The deposit has been interpreted as an IRGS and compared with epithermal systems [78]; however, many authors argue that the mineralizing event postdates the outcropping alkaline complex [45,84] and that gold may have been introduced late in the evolution of the Abitibi greenstone belt [78]. The Kirkland Lake deposit may correspond to an OGS dominated by metamorphic and magmatic fluids derived from deep-seated alkaline magmas.

The world-class Canadian Malartic (Malartic here) deposit (Figure 2) also has a controversial metallogenic model. The deposit displays a polymetallic signature; telluride is reported, and K-alteration (K-feldspar, biotite), and stable isotopes (oxygen and sulfur) suggest magmatic fluid input (Table 2) [2]. The mineralization postdates the monzonite, granodiorite, and other outcropping intrusions [85], and it is suggested that magmatic fluids derived from deep-seated alkaline magmas [86]. Other authors note that the mineralizing style includes disseminated pyrite and quartz-carbonate veins and that most of the ore is structurally controlled. This suggests that gold was mostly introduced by the OGS that is superimposed on (or remobilized gold from) an early gold-bearing magmatic-hydrothermal system [3]. The nearby Camflo mine displays similar characteristics and is interpreted as an OGS having metamorphic fluids that mixed with deeply derived magmatic fluids [87].

Other deposits are spatially associated with intrusive rocks, but the mineralizing process was dominated by metamorphic fluids. These deposits may be classified as intrusion-hosted OGS, e.g., the mineralization spatially associated with the Bourlamaque pluton (Section 3.2). Another example is the Silidor deposit, located in a trondhjemite phase of the Powell pluton. The Silidor deposit is located next to the Don Rouyn porphyry and consists of gold-bearing quartz veins [88]. This structurally controlled system is associated with breccia and the alteration minerals carbonate, white mica, and fuchsite. Silidor is also associated with early hematization and contains Mo and W; its stable isotopes (oxygen and sulfur) point toward oxidizing conditions during the mineralizing event (Table 2) [88]. The presence of oxidizing fluids is surprising for this OGS that clearly formed away from, and later than, the nearby Don Rouyn porphyry.

4. Discussion

Many mineralizing systems in the Abitibi greenstone belt display evidence of inputs of both magmatic and metamorphic fluids. The metallogenic models that best apply to the gold-bearing systems observed in greenstone belt settings can be identified by discussing the characteristics of end-member models—magmatic-hydrothermal systems and OGS (Figure 5). Magmatic-hydrothermal systems correspond to hydrothermal systems dominated by magmatic fluids and are generally spatially and temporally associated with the causative intrusion (Figure 5). In greenstone belts, they correspond to porphyry (synvolcanic and possibly syntectonic periods) and IRGS and/or syenite-associated systems (syntectonic period). In the tentative classification proposed here, these systems belong to category A (Figure 6). A distinction between porphyry (A_1) and IRGS (A_2) is made following the conclusions proposed by the authors cited in the previous section:

1. Porphyry are base metal and gold-bearing deposits associated with large-volume plutons and can be characterized by zoned alteration and mineralization patterns;
2. IRGS are gold deposits that may display a polymetallic signature and that can be associated with small-volume alkaline or other intrusions of the syntectonic period.

Several deposits in the Abitibi greenstone belt belong to category A (Figure 6). Determining whether the Abitibi belt is particularly fertile for magmatic-hydrothermal systems, compared with other belts, is beyond the scope of this paper. It can be noted, however, that one of the largest deposits of the belt, the Côté Gold deposit (Figure 2), belongs to category A_1 and that porphyries may be significant exploration targets in greenstone belts.

The other end-member, OGS, is defined following the recommendations of Phillips and Powell [1] as a syntectonic gold system dominated by metamorphic fluids and formed during the main deformation stage (D_2 to D_3; Figure 1), i.e., category C_1 (Figure 6). Other interpretations, such as the continuum model [89], stipulate that OGS may be dominated by metamorphic, magmatic, and other fluids and that their distinctive characteristic is their association with crustal-scale faults and large-scale hydrothermal cells. This possibility is also considered here, and OGS-like deposits formed by the coeval circulation of metamorphic and magmatic fluids are referred to as category C_2 (Figure 6). The Abitibi greenstone belt contains many economically significant OGS, and only examples possibly associated with magmatism are reviewed here. Some systems, such as the intrusion-hosted Silidor deposit, display no genetic relationship with the host intrusion and may correspond to OGS of category C_1 (Figure 6). Silidor is, however, an unusual OGS; it displays evidence for oxidized fluid circulation, whereas OGS are generally characterized by the circulation of reduced metamorphic fluids [1,89].

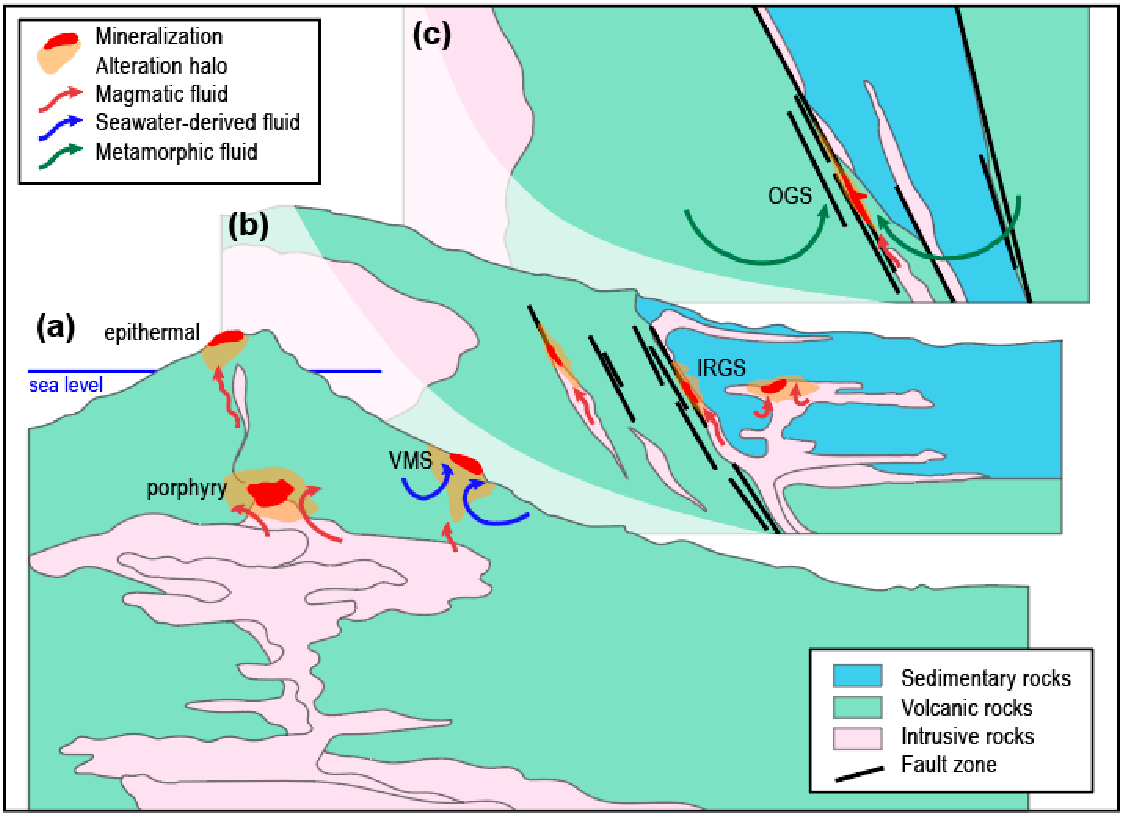

Figure 5. Schematic geological model showing the distribution of mineralizing systems of the synvolcanic period—volcanogenic massive sulfide (VMS), porphyry and epithermal systems—and of the syntectonic period — intrusion-related gold system (IRGS) and orogenic gold system (OGS). Three main stages of the evolution of the Abitibi greenstone belt are shown: (**a**) synvolcanic; (**b**) early syntectonic; (**c**) late syntectonic periods.

The Abitibi greenstone belt also contains many examples of deposits displaying characteristics of category A and C systems and that belong to category B (Figure 6). Categories A, B, and C may include a diversity of metallogenic processes, which are tentatively classified as follows:

Category A includes magmatic-hydrothermal deposits. The mineralization tends to be disseminated and not structurally controlled, as the association with active faults is a characteristic generally attributed to OGS. Some systems, however, are formed within tectonically active areas, and, consequently, a part of the mineralization is structurally controlled, e.g., Bachelor. Other deposits can be partially structurally controlled attributable to subsequent deformation that induces local remobilization of the mineralization, e.g., Central Camp. Contrary to category B, the systems of category A display no evidence for secondary, post-magmatic gold input. The mineralizing systems of category A demonstrate that TTG and TTD suites, as well as sanukitoids and other magmas, can generate gold-bearing mineralizing fluids. Much remains to be done to quantify the amount of gold and base metals transported by Archean magmatic systems, including a more systematic evaluation of volatile content and of the fO_2 parameter [11,60,90].

Category B may include two main mineralizing processes (Figure 6):

1 Deformed porphyry (B_1) or IRGS (B_2): gold-bearing magmatic-hydrothermal systems that were subsequently deformed and overprinted by an OGS or by gold-barren metamorphic fluids, e.g., Beattie and Douay syenites;

2 Multistage porphyry (B_1) or IRGS (B_2): gold-bearing or gold-barren magmatic-hydrothermal systems overprinted by an OGS, e.g., McIntyre-Hollinger, Malartic, and Lake Shore.

For category B systems, gold may be introduced by the magmatic-hydrothermal system, the OGS, or both. These deposits display evidence of magmatic and metamorphic fluid inputs (Table 2), and pyrite chemistry, for some systems (see Section 3.4), provides evidence for Au-bearing magmatic fluids. The question of the relative quantity of Au transported by magmatic vs. metamorphic fluids, however, remains open.

Category C includes OGS (C_1) and deposits that are similar to OGS (C_2) in terms of age (syn-D_2 event), location (association with crustal-scale faults), and gold-deposition mechanism, e.g., the fault-valve process [91]. For category C_1, felsic intrusions and other competent lithologies may act as structural traps for metamorphic fluids, and such deposits correspond to intrusion-hosted OGS. The main difference between systems of categories C_1 and C_2 is the nature of the mineralizing fluid, which may include a significant amount of fluid derived from deep-seated alkaline magmas for category C_2 systems, e.g., the Young-Davidson deposit [72] and the Kirkland Lake camp [78]. Evidence for oxidized fluids, such as stable isotopes and hematite- or sulfate-bearing alteration assemblages, may be a consequence of magmatic fluid inputs. Such fluids may also add CO_2 to the hydrothermal system, which is an essential buffer for optimal gold transportation [92]. Alkaline magmas are oxidized and CO_2-rich and may be the main source of magmatic fluids implicated in structurally controlled syntectonic mineralizing processes [66,67,72,78,86].

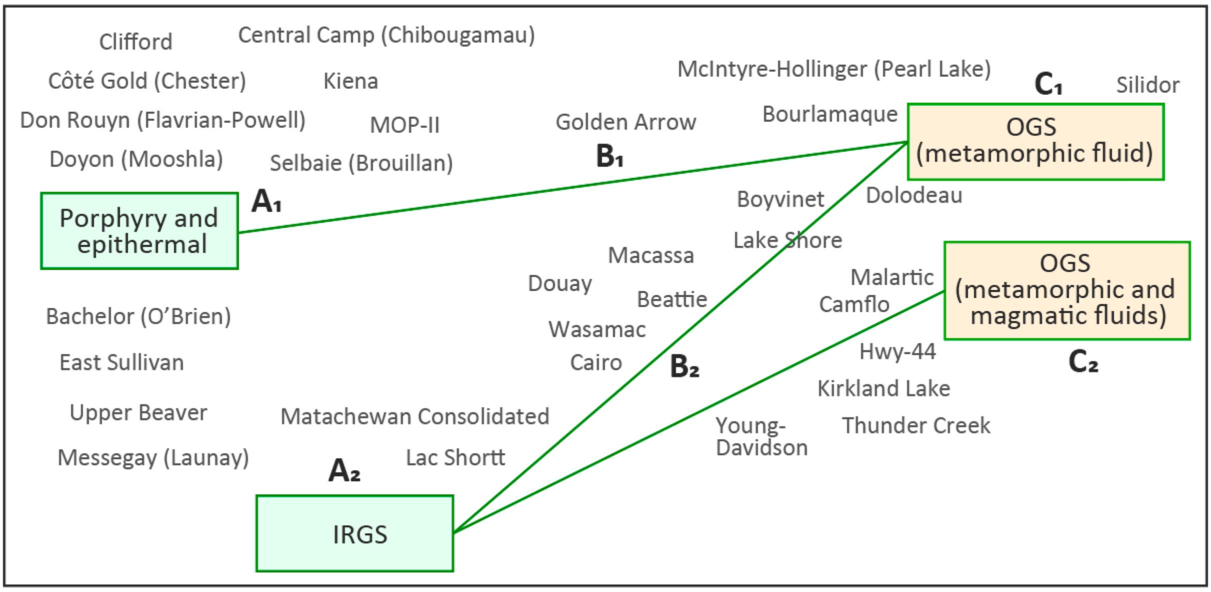

Figure 6. Organigram presenting a tentative classification of the mineralizing systems reviewed by this contribution. The deposits are magmatic-hydrothermal systems (category A), multistage systems (B), and OGS or equivalent (C). The deposits are tentatively distributed between categories A, B, and C on the basis of their physical characteristics, as described in Section 3.

The complex, locally multistage mineralizing systems of the Abitibi greenstone belt may be a consequence of sustained magmatic activity throughout the evolution of the belt. The circulation of magmatic fluids up to the latest deformation stages of the syntectonic period may be key to understanding the apparent complexity of the mineralizing systems reviewed here. The variety of metallogenic processes observed in the Abitibi belt may explain, in part, the heterogeneous distribution of mineralizing style and alteration type described along, for example, the Cadillac–Larder Lake fault zone [93]. However, a major question remains unanswered: were magmatic systems paramount for fertilizing the upper crust? Would the Abitibi greenstone belt be gold-endowed if the magmatic activity had been less voluminous and restricted to the synvolcanic and early syntectonic periods? Addressing such issues will require a profound understanding of gold and base metal distributions in Neoarchean magmatic systems. The fertility of the Archean mantle is also questioned, as the mantle is the source for most magmas of the syntectonic period and part of the TTD suites [16].

5. Conclusions

The Abitibi greenstone belt is a well-preserved gold-endowed belt that occupies a significant portion of the Superior craton, Canada. In the belt, auriferous mineralizing systems display a variety of characteristics that can be used to propose a tentative classification of the main metallogenic processes. Three main models are identified: (1) magmatic-hydrothermal systems; (2) multistage systems; (3) OGS. The magmatic–hydrothermal systems are base metal-bearing porphyries and polymetallic IRGS that include the syenite-associated systems described by Robert [4]. The OGS correspond to systems dominated by metamorphic fluids, and OGS-like systems are structurally controlled deposits dominated by metamorphic and magmatic fluids. The multistage systems correspond to porphyry and IRGS, both overprinted by OGS, and the relative amount of gold brought by the early and late mineralizing events remains undetermined. The importance of sustained magmatic activity in fertilizing the upper crust in the Abitibi belt also remains uncertain. This review, however, provides a new classification for auriferous mineralization that is spatially, temporally, and, in part, genetically related to magmatism in greenstone belt settings.

Supplementary Materials: The following are available online at https://www.mdpi.com/2075-163X/11/3/261/s1, Table S1: Main physical characteristics of the deposits described in the text (copy of Table 2), Table S2: Compilation of tonnage, grade, and geochronological data, Table S3: Compilation of isotopic data.

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