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The magnetic signature of Neoarchean alkaline intrusions and their related gold deposits: Significance and exploration implications

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ABSTRACT

Exploration for Neoarchean intrusion-related gold deposits in the Abitibi greenstone belt of the Superior Craton, Canada, is of increasing interest as the two most recent Abitibi gold mines are intrusion-related. Late-Archean alkaline intrusions in the Abitibi Subprovince are separated into three groups based on their geophysical and geochemical signatures: (1) large, heterogeneous, unmineralized plutons; (2) small magnetite rich-syenites with magmatic gold, which is often remobilized along fault arrays; (3) small magnetite poor-quartz-syenites to alkali granites with magnetite-rich halos and magmatic gold mineralization. The positive, aeromagnetic high centred signature of some gold-bearing intrusions is related to the high content in magnetite of the more ferromagnesian intrusions resulting from their magmatic evolution. Intrusions with an annular shape record a lower Fe_2O_{3t} content in their less magnetite-rich cores and gold mineralization occurs within their magnetite-rich metasomatized host-rocks. If the aeromagnetic signature has an annular-shape, the lower-magnetic zones in the magnetic aureole are the more favourable zones. For those with a positive magnetic signature, the intrusion itself is the target.

1. Introduction

Phanerozoic alkaline intrusion-related gold deposits have been recognized worldwide (e.g. Cripple Creek, Colorado and Ladolam, Papua New Guinea; Jébrak and Marcoux, 2015). Similar Neoarchean deposits are now recognized in greenstone belts such as in the Yilgarn Craton of Western Australia and the Abitibi greenstone belt of the Superior Craton (Robert, 2001; Duuring et al., 2007; Beakhouse, 2011). In the latter, the two most recently opened or re-started gold mines in the Quebec part of the Abitibi, Canadian Malartic and Lac Bachelor, are intrusion-related (Fayol et al., 2013; Helt et al., 2014).

About one hundred late, calc-alkaline to alkaline intrusions are distinguished in Ontario and Quebec on geological surveys maps. The 2685 to 2670 Ma plutons (Legault and Lalonde, 2009) are clearly different from 2697 Ma and older TTG intrusions and from Al-rich leucogranite (S-type) intrusions which formed by melting a crustal component after 2665 Ma (Goutier and Melançon, 2010). Abitibi calc-alkaline to alkaline intrusions belong to the sanukitoid *sensu lato* clan of Laurent et al. (2014). Most of the intrusions are located along or near major brittle-ductile shear zones or 'faults' including the Cadillac Larder Lake Fault zone and the Destor Porcupine Fault zone in the southern Abitibi, and Lennox Creek-Harricana, Casa Berardi and Detour Lake in the northern Abitibi. All these faults are marked by Temiskaming-type basins that contain detrital sediments and/or volcanic rocks (Daigneault and Archambault, 1990; Thurston et al., 2008). The plutons vary from less than 500 m to 10 km in diameter (Legault and Lalonde, 2009) and display large differences in composition from truly alkaline syenite, to carbonatite to felsic monzodiorite (Kontak, 2012; Helt et al., 2014; Nadeau et al., 2014; Bigot and Jébrak, 2015). Many of these intrusions contain gold mineralization, which is explained either by a genetic connection or by a late rheological control (Robert, 2001).

These gold-related late intrusions have been long known to have a distinctive magnetic signature, commensurate with their oxidic character (Hattori, 1987). A geophysical approach is therefore useful to constrain better the redox state of intrusions and their associated mineralization, and to provide efficient exploration tools (c.f. Clark and Schmidt, 2001). In this paper, we propose a classification of these late intrusions emphasizing their magnetic character, their major element geochemistry and their metallogenic potential. The petrological and geodynamical interpretation of these intrusions from trace element geochemistry will be discussed in a companion paper.

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2. Methods

The study used the Geological Survey of Canada high-resolution TGI3 aeromagnetic Abitibi data compilation (Keating et al., 2010). This is a compilation of datasets from Quebec (MERN), Ontario (OGS) and Geological Survey of Canada (GSC). The surveys were flown at a mean flight altitude of 120 m with a maximum line spacing of 200 m; data were gridded at a 50 m interval. To enhance the aeromagnetic images, the residual aeromagnetic total field grid was processed using Oasis montaj software. The residual total field grid was generated by removing the International Geomagnetic Reference Field and data were reduced to the pole (Keating et al., 2010). The long wavelength component due to deepest sources was removed using a Butterworth filter, keeping the short wavelengths arising from shallow, approximately less than 5 km, source bodies (calculated from the slope of the radially averaged power spectrum using the method of Spector and Grant, 1970). This method generates detailed images of the residual magnetic field reflecting variations in magnetism in and around the plutons. Removal of the long wavelength component was necessary to allow observation of the smallest intrusions and to image the magnetic zoning around and within these stocks. However, even with this treatment, considering that regional data with up to 200 m line spacing is used, the study focused on intrusions of at least 0.25 km^2 and dikes are excluded.

Profiles of the filtered grid were generated over 31 alkaline intrusions widely distributed within the Abitibi Subprovince in Quebec and Ontario (Fig. 1). Studied intrusions represent about 30% of recognised alkaline intrusions in the Subprovince. Their shape and size, surface dimension and area, of intrusions were calculated using the image analysis software ImageJ (Schneider et al., 2012) based on contours drawn in Oasis Montaj. From these enhanced aeromagnetic images and profiles, field work at Lac Bachelor and from reviews of previous studies, correlations between lithology, mineralization, shape, size, and magnetic susceptibility led to a classification of plutons associated with gold mineralization.

A magnetic susceptibility survey was carried out in the Bachelor Mine (Fig. 1A) from the O'Brien intrusion to the outer mineralized zone using a Georadis KT-10 Magnetic Susceptibility Meter to correlate aeromagnetic responses of the intrusions and host rocks to field exposures. For the other intrusions, we use data from Bigot (2012) and published datasets (Ontario Geological Survey, 2001).

A compilation of 163 geochemical rock analysis of 18 intrusions from geological surveys (OGS, MERN), companies and academic studies (Bigot, 2012; Martin, 2012; Fayol et al., 2013) was used to correlate the magnetic response and the lithological properties of the intrusions. Data sources can be found in the associated data repository.

3. Results

3.1. Aeromagnetic signatures of late intrusions

All intrusions display a generally regular concentric aeromagnetic signature. Three main signatures were distinguished (Table 1): fourteen intrusions present an "annular" signature, 10 a "composite" signature and 7 a "positive" signature. These three types are exemplified respectively by the O'Brien, the Beattie and the Otto intrusions (Fig. 2). As our measurements have been made on about 30% of the known late alkaline intrusions in the Abitibi (estimation made from geological maps in the public domain–MERN, OGS–and a recent study by Lafrance (2012) on these intrusions), the results are representative and clearly indicate that these three types of aeromagnetic signatures are commonly observed.

The annular type O'Brien intrusion, associated with le Lac Bachelor gold mine, is a quartz-syenite intruding intermediate tuffs, andesites, basalts and minor felsic volcanic rocks (Lauzière, 1989; Fayol et al., 2013). The intrusion shows a low magnetic response, however the host rocks are highly magnetic (Fig. 2A). Gold mineralization is mainly within the magnetite-rich halo to the intrusion and is particularly abundant in zones where hematite partly replaces magnetite. Consequently, the ore zones correspond to a lower magnetic response compared to the overall highly magnetized halo. Magnetic susceptibilities measured in the mine (Fig. 3) show that the highest value corresponds to magnetite alteration of the tuff around the intrusion. The quartz-syenite itself is weakly magnetic and where hematite alteration is present, the magnetic susceptibility drops to less than $1 \cdot 10^{-3}$ SI.

The "positive" type Beattie syenite (Fig. 2B) has the opposite magnetic signature due to its high magnetic susceptibility magnetite-rich core (Fig. 3). The edges and sheared syenite are hematite-carbonate-pyrite-(Au) rich which correlates with lower measured magnetic susceptibilities (Bigot, 2012). The syenite is hosted by basalts to the north and Timiskaming sedimentary rock to the south. The intrusion has a high, positive anomaly and the host rocks are less magnetic.

The composite type Otto stock (Fig. 2C) is a multi-kilometric polyphase syenitic stock in the Kirkland Lake area (Smith and Sutcliffe, 1988; Berger, 2006). The stock is hosted by mafic and intermediate volcanics and is not mineralized, however many mineralized syenite dikes are known in the area. Its magnetic signature is characterized by highly magnetic, narrow edges and variations of the magnetic response due to lithological heterogeneities within the Otto stock. The aeromagnetic response correlates with the measured variations of the magnetic susceptibility of each lithology (Fig. 3). This stock is a typical example of the "composite" magnetic signatures that characterize intrusions with surface area greater than 9 km^2.

In the Kirkland Lake area, the Königsberger ratio is often greater than 1 (Ontario Geological Survey, 2001; Dentith and Mudge, 2014) which means that the remanent magmatism has a greater influence than the induced magmatism on the aeromagnetic signal. However, in these three examples, there is a strong correlation between the aeromagnetic signal and the magnetic susceptibility measured on rock samples. Therefore, the variations of the aeromagnetic signal are interpreted to be the result of variations in induced magnetism where remanent magmatism may parallel the present day magnetic field.

The distinction between the previous three categories is more distinct on magnetic profiles. "Annular" intrusions are small, less than 3 km^2 in surface area and about 1 km in average diameter (Fig. 4A). The 100–700 nT magnetic field variation between the edges and core of the intrusion is larger than for other intrusion types. The "positive" intrusions are also small, with an average surface area of 1.4 km^2 (Fig. 4B). The variation between edges and core is less, reaching a maximum of 200 nT.

Finally, the "composite" category of ten intrusions appears more heterogeneous than the two others categories (Fig. 4C). All of these intrusions are large (9–69 km^2 surface area), and amongst the largest alkaline intrusions of the Abitibi greenstone belt. Except for two intrusions (Otto, Lebel) which have very highly magnetized borders, the magnetic field variation is not that significant, with a maximum of 200 nT. However, since the intrusions are very large and heterogeneous, their magnetic susceptibility fluctuates; edges are nevertheless always more magnetic by ca. 100 nT than the core. In addition to lithological heterogeneities, the Otto stock is cut by the north trending Amikougami Fault, the east and west sides of the intrusion may not be at the same erosional level due to normal fault displacements (Berger, 2006). However, no interpretation of the vertical distribution of magnetite or oxidation

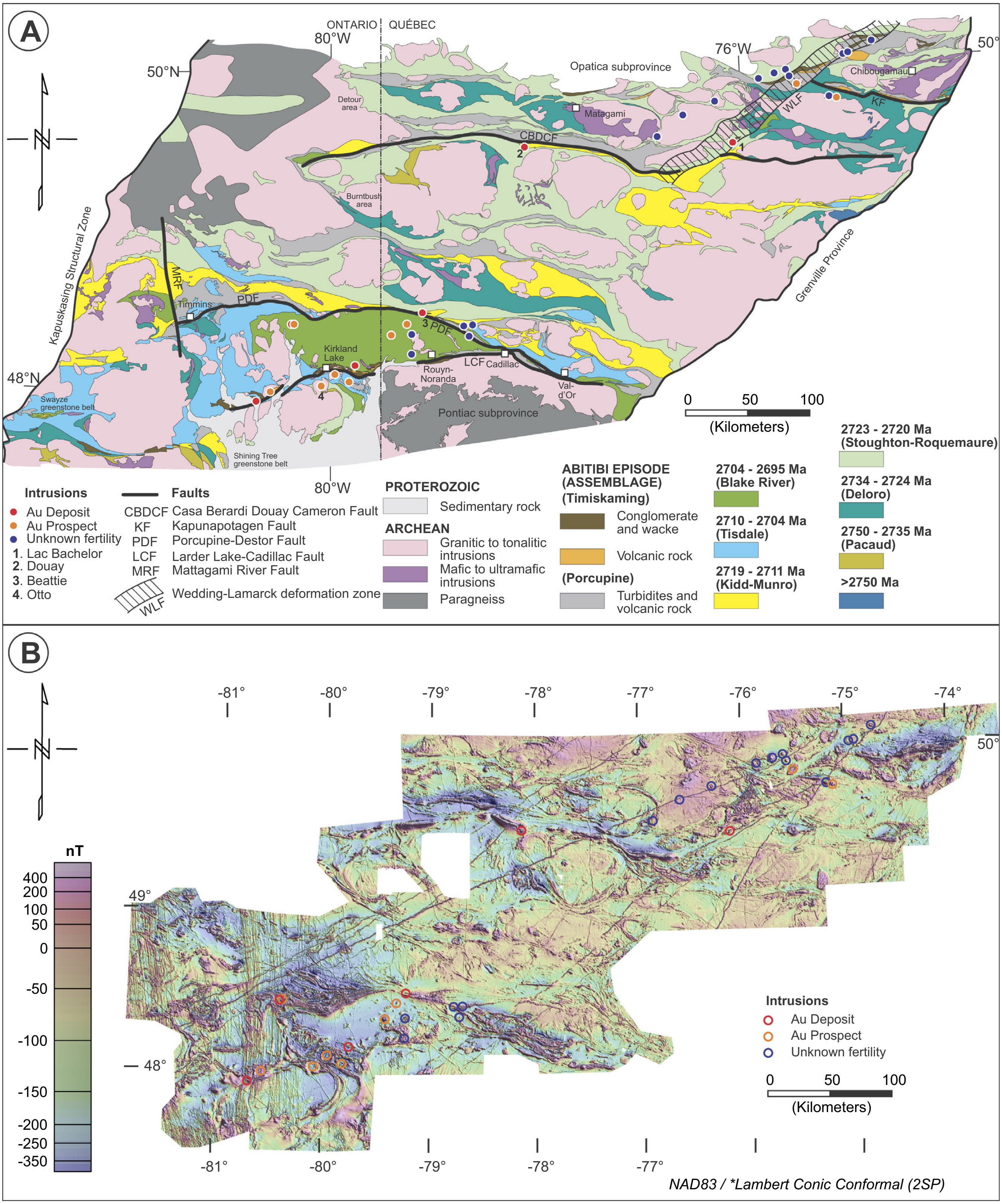

Fig. 1. (A) Location of the 31 alkaline intrusions studied on the Abitibi geology map (modified from Thurston et al., 2008). (B) Shaded residual total field Abitibi aeromagnetic image (derived from the GSC dataset described by Keating et al., 2010).

Table 1
Intrusion characteristics; Shape: C = Circular, O = Oval, E = Elongated; Magnetic Signature: A = Annular, P = Positive, C = Composite.

Intrusion	X	Y	Filtered residual magnetic field (mean at center)	Area km^2	AR (length/width)	Shape	Magnetic signature	Host rocks	Fault/deformation corridor	Age	References
	NAD83-Lambert Conic Conformal										
Rageot	1494665.88	1388563.32	−20.11	1.80	4.01	E	A	Sediments	Wedding-Lamarck		SIGEOM – MM89-03
Jumeau E	1484414.26	1376165.68	−5.67	18.19	1.20	C	C	Sediments/mafic volcanics	Wedding-Lamarck		SIGEOM
Jumeau W	1481360.26	1374226.28	−15.36	9.17	1.16	C	C	Sediments/mafic volcanics	Wedding-Lamarck		SIGEOM
Gilbert	1439955.80	1352867.05	3.91	0.27	3.28	E	A	Mafic volcanics	Wedding-Lamarck/Dussault		SIGEOM
Daine	1432753.04	1348482.48	−19.50	23.44	1.62	O	C	Mafic volcanics	Wedding-Lamarck/Dussault		SIGEOM
Gisèle	1443540.79	1348884.98	45.01	2.84	1.15	C	P	Sediments	Wedding-Lamarck/Dussault		SIGEOM
Saussure	1449874.59	1344826.29	−9.08	33.89	2.32	O	C	Sediments	Wedding-Lamarck/Dussault/Kapunapotagen		SIGEOM
Branssat	1422961.6	1342145.51	−10.99	22.35	1.12	C	C	Mafic volcanics	Wedding-Lamarck/Dussault		SIGEOM
Jean-Luc	1474437.85	1341556.11	−8.87	0.38	3.13	E	A	Mafic volcanics	Kapunapotagen		SIGEOM
Dolodau	1479799.11	1341800.88	−35.20	0.34	1.31	C	A	Mafic volcanics/granodiorite	Kapunapotagen	2677 Ma	Tilton and Bell (1994)
Inconnue	1397995.55	1318076.09	−12.63	0.75	1.56	O	A	Diorite			SIGEOM
Ailly	1380068.34	1303267.81	29.20	0.83	1.52	O	P	Granite-granodiorite			SIGEOM
O'Brien	1418964.18	1291868.84	−44.00	0.59	2.39	O	A	Mafic volcanics	Wedding-Lamarck/Opawica		Buro (1984), Lauzière (1989) and Fayol et al. (2013)
Berthiaume	1366076.90	1284221.88	12.57	30.67	1.59	O	C	Granite-granodiorite		2687.9 ± 1.2 Ma	Goutier (2005)
Douay	1279007.88	1253788.06	−67.40	1.74	4.25	E	A	Mafic volcanics/sediments	Casa-Berardi	2676 + 6/−5 Ma	Davis et al. (2000)
Lac Matissard	1272163.21	1125200.41	40.71	0.94	1.59	O	P	Mafic volcanics	Porcupine-Destor		
Beattie	1232473.44	1123534.07	90.16	2.08	4.95	E	P	Sediments/mafic volcanics	Porcupine-Destor/Beattie/Donchester	2681.6 ± 1 Ma	Mueller et al. (1996), Bourdeau (2013) and Bigot and Jébrak (2015)
Ruisseau Gaumont	1266278.28	1123030.13	35.53	1.16	3.72	E	P	Sediments/mafic volcanics	Porcupine-Destor		SIGEOM
Lac Imau NE	1271650.97	1116890.08	23.46	1.29	1.19	C	A	Sediments/mafic volcanics	Porcupine-Destor/Parfouru		SIGEOM
Lac Duparquet	1227032.32	1114871.94	145.23	1.23	1.24	C	P	Intermediate volcanics/gabbro			SIGEOM
Lac Nora	1235818.55	1106304.22	−34.33	2.13	1.60	O	A	Intermediate-mafic volcanics			SIGEOM
Lac Tarsac	1221868.3	1102439.48	−78.92	2.28	1.86	O	A	Intermediate volcanics			SIGEOM
Golden Arrow E	1149730.89	1096286.08	−403.77	0.77	1.91	O	A	Intermediate-mafic volcanics	Porcupine-Destor/Arrow		Cherry (1983) and Cameron and Hattori (1987)
Golden Arrow W	1148066.12	1095818.52	−313.96	0.88	1.37	C	A	Intermediate-mafic volcanics	Porcupine-Destor/Arrow		OGS
Aldermac	1238949.7	1092744.95	−75.43	3.01	2.18	O	A	Intermediate volcanics	Larder Lake-Cadillac		SIGEOM
Upper Beaver	1202418.04	1076783.28	−170.37	0.46	1.31	C	A	Mafic volcanics	Larder Lake-Cadillac		Kontak et al. (2008)
Lebel	1190049.62	1067370.91	43.72	27.57	1.91	O	C	Sediments/mafic volcanics	Larder Lake-Cadillac	2673 ± 2 Ma	Cruden and Launeau (1994) and Wilkinson et al. (1999)
McElroy	1201005.74	1064555.89	−58.00	16.99	1.23	C	C	Mafic volcanics	Larder Lake-Cadillac		Abrahams (1950)
Otto	1182602.35	1057196.38	25.81 52.26 −4.04	68.84	1.29	C	C	Mafic volcanics	Larder Lake-Cadillac	2671 ± 8 Ma 2680 ± 1 Ma 2679 ± 1 Ma	Corfu et al. (1989), Othman et al. (1990), Corfu et al. (1991) and Berger (2006)
Cairo	1148580.30	1044925.06	−5.74	65.10	1.63	O	C	Sediments/mafic volcanics	Larder Lake-Cadillac	2676 ± 1.7 Ma	Lovell (1967) and Berger (2006)
Young Davidson	1140418.6	1036000.46	59.15	0.83	2.88	O	P	Mafic volcanics/sediments	Larder Lake-Cadillac	2678.8 ± 1.6 Ma	Martin (2012), Naderi (2013) and Zhang et al. (2014)

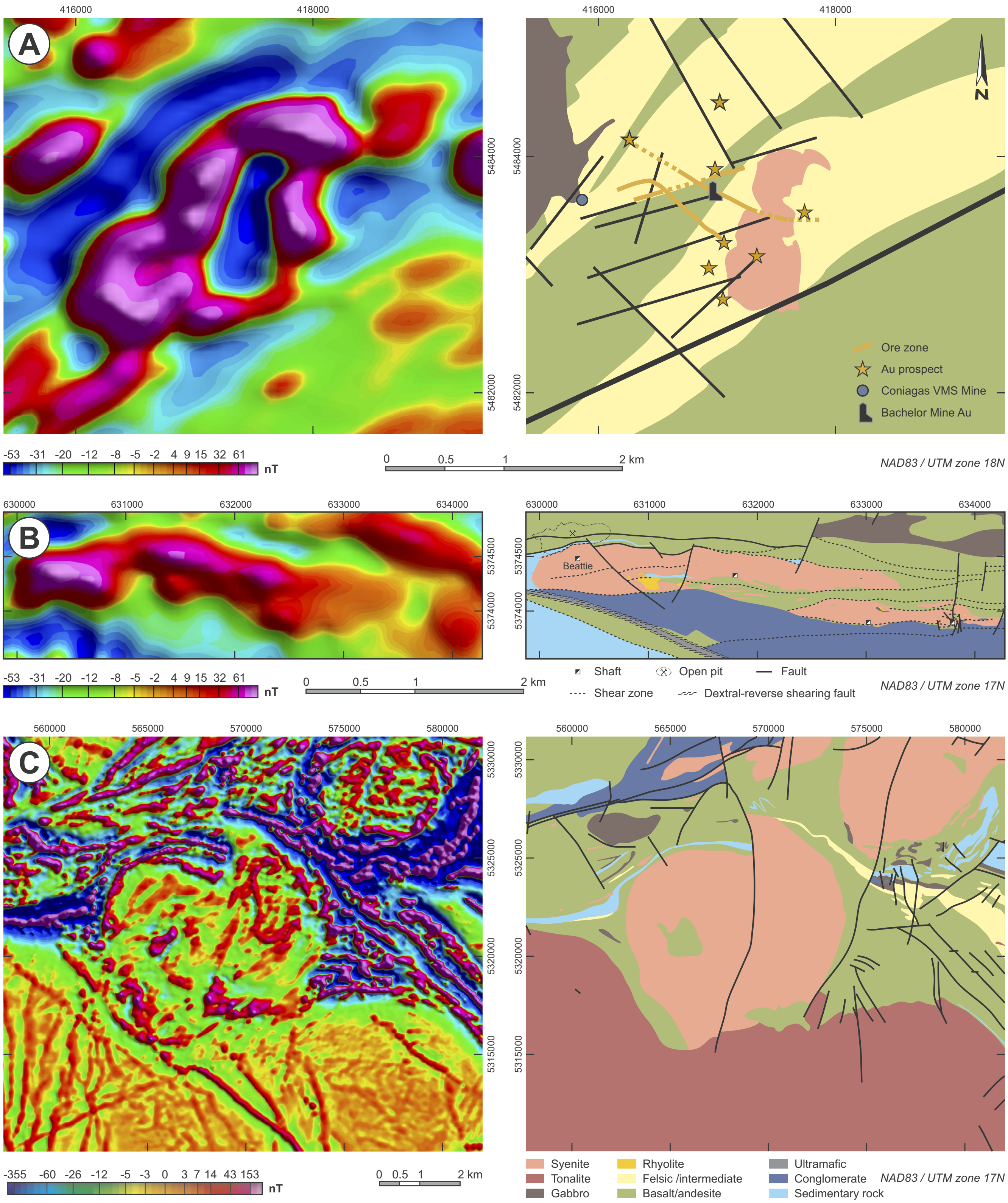

Fig. 2. Three magnetic signatures types. (A) "Annular", (B) "positive" – central magnetic high, (C) "composite" exemplified respectively by the O'Brien, Beattie and Otto intrusions.

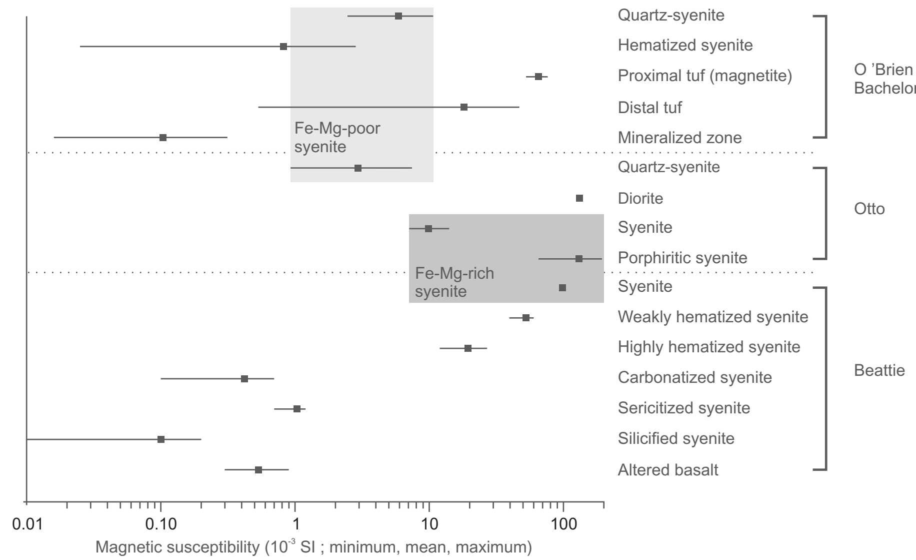

Fig. 3. Magnetic susceptibilities of the O'Brien, Otto and Beattie intrusions, related mineralized zones and host-rocks showing the correlation between lithology, alteration and magnetic susceptibility values.

state can be made because of the presence of several alkaline phases (porphyritic-, quartz-, mafic-syenites and hornblendite) in the main syenite body (Smith and Sutcliffe, 1988; Berger, 2006) and because of displacement along the Amikougami fault.

3.2. Geochemistry vs. magnetic signature

Plutons are characterized as either granite, syenite or monzonite based on their geochemistry (Fig. 5), and a clear geochemical distinction between the "positive" and "annular" intrusions is recognized. A "positive" magnetic signature characterizes the intermediate group ($55 < SiO_2 < 70\%$, $6 < Na_2O + K_2O < 13$) of magnetite-rich intrusions which also contain amphibole.

Plutons with an "annular-like" magnetic response are either alkali-silica rich granitic intrusions ($SiO_2 > 60\%$, $Na_2O + K_2O > 7.5\%$) or more mafic intrusions ($SiO_2 < 60\%$). These two end members display very different metallogenic potential: the alkali-silica rich granitic intrusions are frequently associated with Au-(Cu) mineralization in the wall-rock (e.g. O'Brien, Golden Arrow), whereas the more mafic ones (e.g. Lac Imau, Aldermac) have no known mineralization. Several polyphased intrusions (e.g. Douay, Lac Nora, Lac Tarsac) encompass both lithologies and significant gold concentration can occur (e.g. Douay). The alkali-silica rich granitic intrusions are the only "annular-like" intrusions with known economic gold concentrations (e.g. O'Brien, Golden Arrow). They are silica-rich ($SiO_2 > 60\%$) in comparison to the ferromagnesian intrusions, where silica is either a primary component or as secondary quartz. For instance, field observations made for the O'Brien stock at the Lac Bachelor gold mine show that the high silica content of the intrusion is partly due to a post-solidus silicification that is expressed by a quartz veinlet stockwork associated with gold mineralization (Fayol, 2016). Those silicified intrusions commonly have an annular magnetic signature with low magnetic values in their core (e.g. O'Brien, Golden Arrow; Figs. 3 and 4).

Larger intrusions with "composite" magnetic signatures have heterogeneous geochemical compositions with variations similar to the "annular" intrusions. However, these heterogeneities are present in the intrusions itself where lithologies vary from mafic to more silica-alkali-rich (e.g. Otto, Cairo, and Lebel).

Harker diagrams (Fig. 6) show linear trends for TiO_2, MgO, FeO, CaO, Na_2O and Al_2O_3, indicating a progressive increase in sodic plagioclase toward a syenitic composition, and a decrease of ferromagnesian minerals. The TiO_2 content provides a clear distinction between more mafic "annular" intrusions where $TiO_2 > 0.6\%$, "positive" ones (0.3–0.6% TiO_2) and silica-rich end members of the "annular" group where $TiO_2 < 0.3\%$. The diffuse distribution of K_2O reflects the post-solidus potassic alteration. There is a continuum from Fe-Mg-Ti-rich to less ferromagnesian and more silica-rich intrusions. The major element diagrams therefore demonstrate that the alkali-silica rich granitic intrusions appear to be the final product of a differentiation process of a unique parental magma beginning with mafic syenites.

The "positive" magnetic response is a very distinctive pattern for magnetite-rich syenites and quartz-monzonite that are commonly mineralized in their core (e.g. Beattie, Young-Davidson). The "annular" signature is distinctive of both ferromagnesian rich intrusions and felsic ones, outside of the "positive" intrusions geochemical composition range. However, silica rich ones usually have a more contrasting signature with low magnetic values at their core and higher ones at the edges (e.g.; Golden Arrow, O'Brien).

3.3. Mineralization vs. size and magnetic signature

Two groups are defined from size analyses of the intrusions presented in Fig. 7, viz. intrusions smaller than 3 km^2 and intrusions bigger than 9 km^2. They are separated by a gap between 3 and 9 km^2 without any known intrusions. Their shape is described using the aspect ratio, i.e. the ratio between the longest diameter of the intrusion and its shorter one (Table 1). Based on the previous study of Legault and Lalonde (2009), three categories are defined: circular ($1 < AR < 1.5$), oval ($1.5 < AR < 3$) and elongate ($AR > 3$). All the largest intrusions have a circular or slightly oval shape. The smallest intrusions (less than 3 km^2) have shapes varying from circular to elongate without distinction between "annular" and "positive" types (Table 1).

Among the three types of magnetic signatures obtained in this study, "annular" and "positive" patterns highlight plutons most prospective for gold mineralization as several host gold deposits. In comparison larger intrusions with a "composite" profile are only Au prospects with no economic gold concentration known to date (Fig. 7).

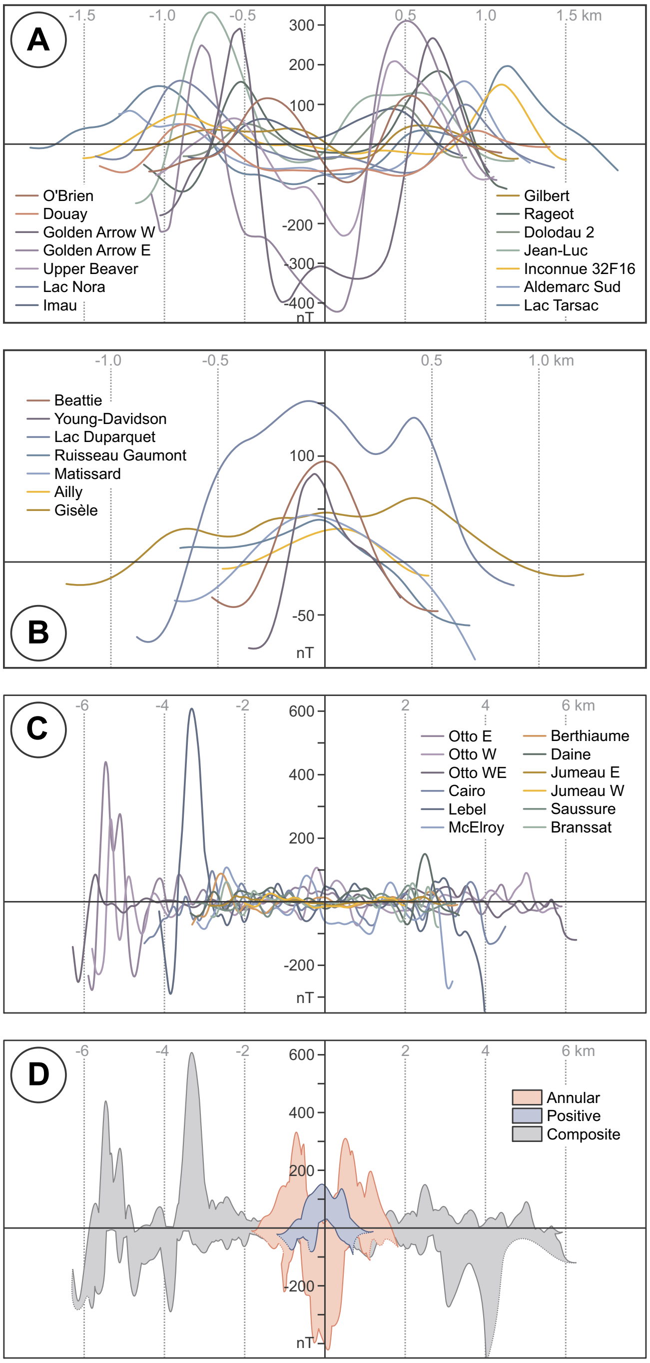

Fig. 4. Aeromagnetic profiles of the intrusions. (A) "Annular", (B) "positive", (C) "composite", (D) synthesis of all three types.

Of the fourteen intrusions with "annular" magnetic signatures, four have known economic or sub-economic intrusion-related mineralization (e.g. Douay, O'Brien, Golden Arrow West, Upper Beaver; McNeil and Kerrich, 1986; Lauzière, 1989; Robert et al., 1997; Robert, 2001; Kontak et al., 2008; Fayol et al., 2013). Most of the gold is hosted in highly metasomatized (magnetite, hematite, K-feldspar, pyrite) host rocks at the syenite edges. The Upper Beaver deposit is a different system; it is more typical of Au-Cu porphyry-style deposit with mineralization both in the host rocks and a vein system in the syenite (Kontak et al., 2008). For all these deposits the gold mineralization is mainly situated in the highly magnetic halo around the low-magnetic intrusion on enhanced geophysical images. Those mineralized system are characterized by low magnetic value at center of the intrusions. This might be correlated to their higher silica and lower ferro-magnesian content. This could reflect silicification process that occurred on mineralized system. Three other intrusions (Golden Arrow East, Dolodau and Lac Tarsac) are gold prospects. Less siliceous, ferro-magnesian-rich intrusions have no recognized gold occurrences, unless (such as for Douay) they comprise polyphase more felsic phases.

For the seven intrusions with a "positive" magnetic signature, two have known economic or sub-economic mineralization (e.g. Beattie, Young-Davidson). In these deposits, the mineralization is mainly in the magnetite-rich ± hematite, K-feldspar, carbonate, pyrite alteration zone of the syenite. Gold mineralizing fluids are inferred to be magmatic as temperature estimates performed at Young-Davidson are too high for metamorphic fluids alone and the magmatic input seems essential (Naderi, 2013). A secondary contribution of metamorphic fluids associated with remobilization or as an input of juvenile gold is possible (Martin, 2012; Naderi, 2013; Bigot and Jébrak, 2015). Those mineralized syenite have a high-magnetic response on enhanced aeromagnetic images. As shown in K_2O vs. SiO_2 diagram (Fig. 6), strong potassic alteration can occur. The Lac Duparquet intrusion is a prospect.

The style of mineralization associated with larger intrusions where a genetic link has been inferred between large stocks and mineralized smaller plugs and dikes (Beakhouse, 2011), such as in the Kirkland Lake area (Rowins et al., 1993), is more difficult to determine. In the Matachewan area, the Cairo stock hosts a few mineralized veins associated with late faults in altered syenite (Berger, 2006). A genetic link is suggested with the Young-Davidson syenite which is interpreted as a distal dike (Lovell, 1967). However, no economic gold concentration is known in those large, composite intrusions and only some minor prospect are recognized.

In conclusion, small intrusions, less than 3 km^2, are highly prospective with 50% of them hosting gold occurrences (19%) and deposits (29%). The gold mineralization is associated with either (1) extensive metasomatism of the host rocks around the intrusion due to magmatic fluids (Fayol, 2016); (2) metasomatized syenite due to magmatic-metamorphic fluid mixing (Naderi, 2013; Bigot and Jébrak, 2015). These two styles of mineralization correspond to (1) "annular" and (2) "positive" patterns respectively. Considering the proportion of deposits and prospects both types are equally prospective.

4. Discussion

Lithology and hydrothermal process, due to presence of magnetite and other paramagnetic minerals, are known to influence the magnetic properties of rocks. In this section we propose a review of known effects, previous assumptions related to those parameters and their application to Neoarchean intrusions in the literature. Afterward a synthesis of this study results and their consequences in term of intrusion genesis and gold setting is proposed.

The link between magnetite-series intrusions, oxidized hydrothermal fluids and gold mineralization has long been recognized in the Abitibi Subprovince (Cameron and Hattori, 1987; Hattori, 1987; Rowins et al., 1991). The magnetite content of the intrusions is controlled by the Fe content and the oxidation state of the magma (Ishihara, 1977). Beakhouse (2007, 2011) considers that magnetite is the more abundant ferromagnetic mineral in intermediate to felsic plutons and therefore proposes the use of magnetic susceptibility as a proxy for fO_2. The late-Archean alkaline intrusions with known gold mineralization portray relatively high magnetic susceptibility related to their Fe_2O_{3t} content. Where

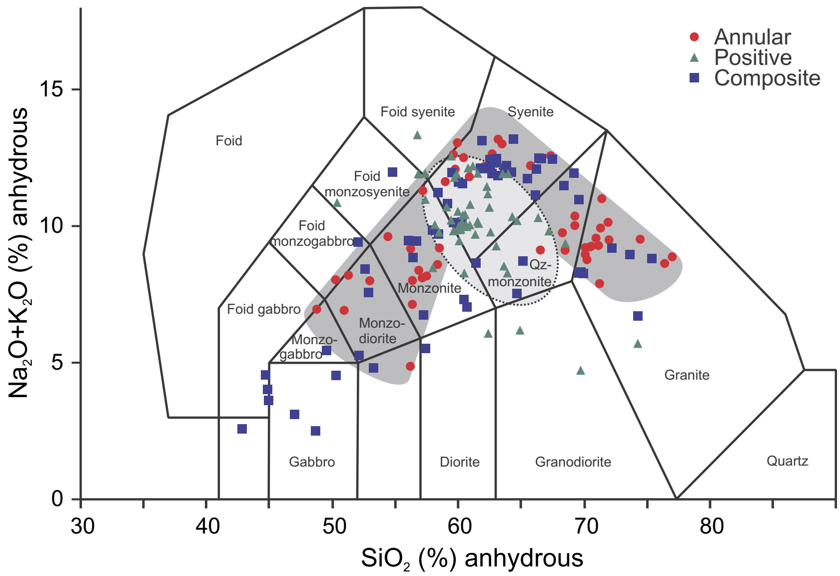

Fig. 5. Geochemistry of the intrusions highlighting alkali vs. silica-rich fields (Middlemost, 1985). The "positive" intrusions have homogeneous syenitic compositions, whereas "composite" and "annular" intrusions fall into both syenite to granite and more mafic monzonites to gabbro groups.

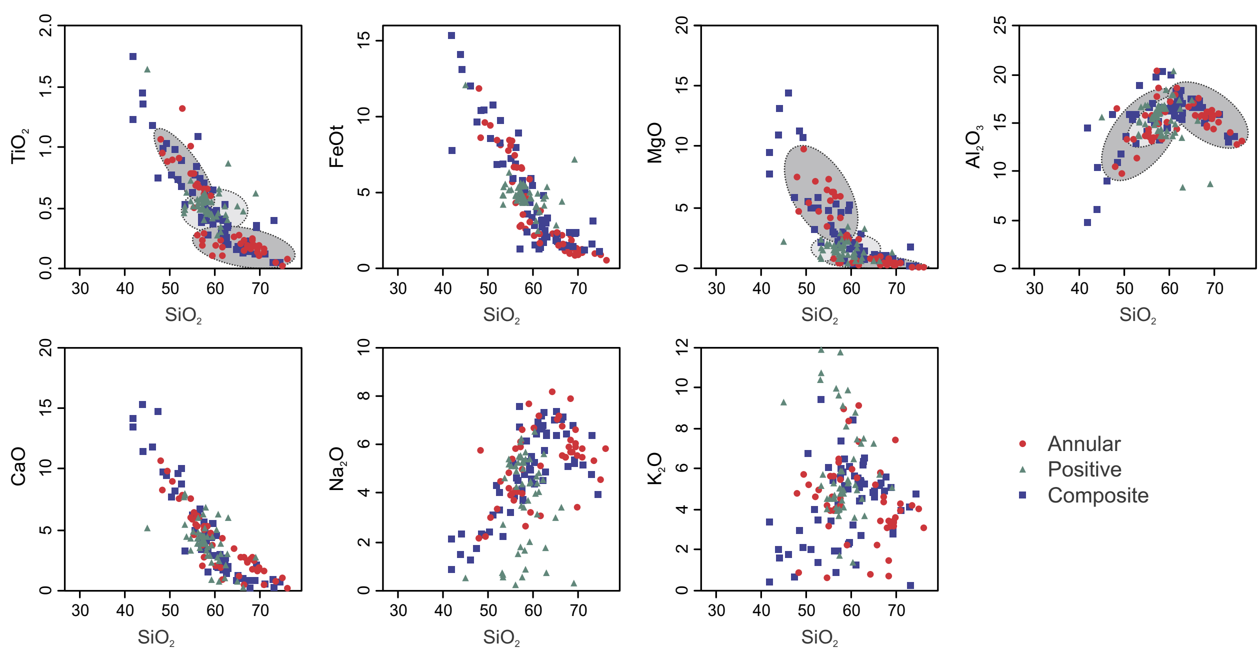

Fig. 6. Harker diagram showing almost linear evolutionary trends for TiO_2, MgO, FeO, CaO, Na_2O and Al_2O_3 with differentiation (SiO_2 increase) whereas K_2O has a more diffuse distribution.

the oxidation state of the magma is over the fayalite-magnetite-quartz buffer, magnetite crystallization occurs.

Hydrothermal alteration appears to be a key component in the interpretation of the magnetic signature of mineralized systems (Clark, 1997, 2014; Gunn and Dentith, 1997). The early alteration stage of potassic alteration (K-feldspar) is usually magnetite-producing or, at least, magnetite remains stable (Beane and Bodnar, 1995; Arancibia and Clark, 1996). Magnetite and K-feldspar crystallisation are produced by biotite and/or amphibole iron oxidation (Liang et al., 2009). In oxidized-alkaline systems such as the Abitibi alkaline-related gold deposits, potassic alteration is abundant but the magnetite-hematite transition is the key to gold precipitation (Cameron and Hattori, 1987; Robert, 2001; Martin, 2012; Fayol et al., 2013; Bigot and Jébrak, 2015). The oxidized character of the magmatic fluids allowed incorporation of Au and S in the melt which avoids early precipitation of the sulfide. To precipitate gold and pyrite, a reduction of sulfate to sulfide is required (Cameron and Hattori, 1987; Mungall, 2002; Pokrovski and Dubrovinsky, 2011; Sun et al., 2015). The intrusion of the magma into ferromagnesian volcanic rocks—such as tholeiitic basalt, andesite and tuff—and circulation of associated fluids remobilized Fe from those host rocks which created a magnetite halo around the intrusion. This reaction between fluids and host rocks changes the oxidation state of the fluids, allowing pyrite and hematite to precipitate. A high-magnetic response is expected for the magnetite-rich zone whereas the phyllic and propylitic alteration zones are magnetite-destructive, with crystallization of pyrite and hematite and are therefore less magnetic. In

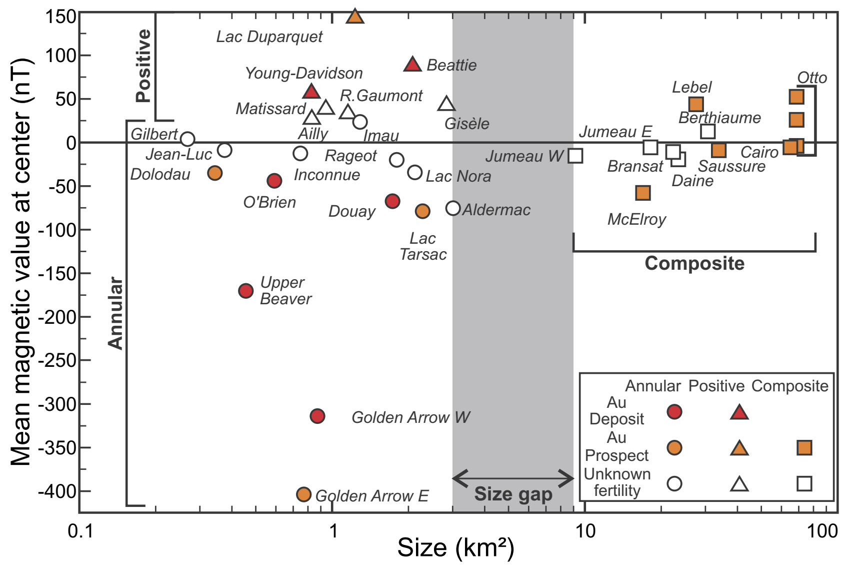

Fig. 7. Distribution of the three types of magnetic signatures *vs.* intrusion size and relationship to gold mineralization.

several deposits in Abitibi (e.g. O'Brien, Douay, Beattie, Young-Davidson, Golden Arrow), gold mineralization is frequently associated with pyrite-hematite-rich zones, and therefore should be located in zone of lower magnetic susceptibility resulting in a low aeromagnetic response.

As shown, in Section 3.1, in the Abitibi, there is a strong correlation between aeromagnetic signatures and magnetic susceptibilities of intrusions, mineralization and surrounding rocks measured in the field. Measurements and interpretations for the Kirkland Lake rocks presented on Dentith and Mudge (2014) also illustrate this correlation.

Late alkaline plutons are common along major structural discontinuities in Archean greenstone belts. In the Abitibi subprovince, they are usually of limited surface area (<10 km^2), although the largest ones may attain 100 km^2. They display rounded to elliptical shape. Their compositions vary from gabbro to granite, with large variations in alkali related both to primary signature and late potassic mobility. However, they do form a distinct assemblage (sanukitoid *s.l.*; Laurent et al., 2014) suggesting formation by fractionation of the same type of magmatic reservoir. Numerous gold deposits have been associated with such magmatism, including the large Canadian Malartic gold deposit. In fact, Canadian Malartic is now recognized as a complex system developed in two main stages (De Souza et al., 2015): (1) an early gold mineralization event related to "syn-Timiskaming" porphyritic intrusions and characterized by potassic alteration, stockworks and a complex metallic assemblage of Au + Te + W + Bi ± Ag ± Mo ± Pb; (2) a syn-deformation gold mineralization which consists of either remobilization of the first gold concentration or mineralization associated with a super imposed hydrothermal system. This is consistent with the model described for intrusion-related gold deposits that have a positive, central high, magnetic signature, such as Beattie and Young-Davidson.

Three distinct types of aeromagnetic signatures are widely distributed in the belt (Fig. 8):

- A positive, central high magnetic signature, corresponding to small meta-aluminous syenitic intrusions with a high ferro-magnesian content; gold is directly associated with these intrusions but may also be mobilized along crosscutting shear zones and within quartz veins, involving metamorphic fluids.

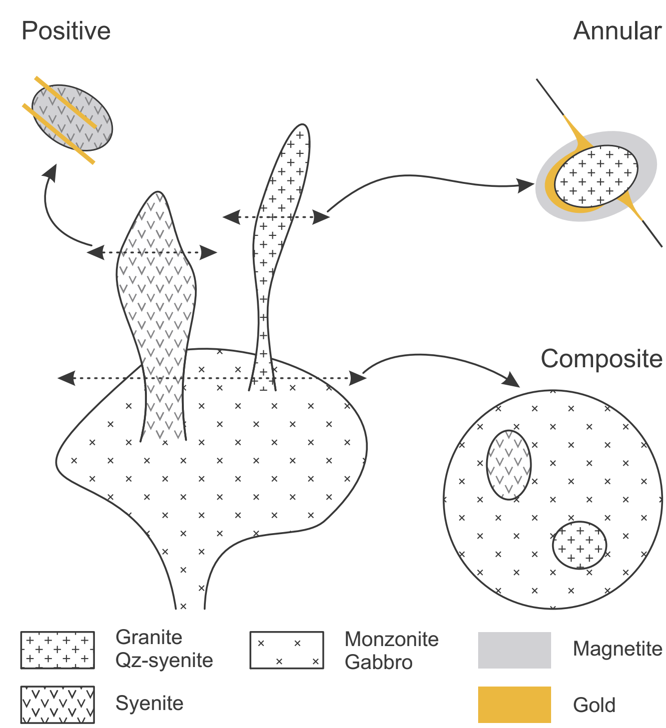

Fig. 8. The three intrusions type probable relationships and related gold settings.

- An annular signature, corresponding to (1) small meta-aluminous granitic intrusions with a low ferro-magnesian content; gold is both disseminated and within veins associated with a magnetite/hematite halo where, in the Lac Bachelor deposit, gold is related to a late magmatic-hydrothermal event and (2) more mafic intrusions, possibly magnetite-poor for which there is no recognized mineralization.
- A composite signature, reflecting lithological heterogeneities of large intrusions; gold does not seem to be directly associated with these intrusions.

As summarized by Sillitoe (2010), Phanerozoic Cu-(Au) porphyry deposits are related to small intrusions which are the expression of the late magmatic evolution of a large unmineralized parental batholith. Geochemical compositions of late-Archean intrusions show that these stocks may represent three differentiation stages of the same parental magma. Therefore, we can attempt to draw a parallel between Phanerozoic porphyry deposits and late-Archean intrusion related gold deposits where the large, heterogeneous, unmineralized intrusions would be equivalent to Phanerozoic parental batholiths. Small, more felsic, mineralized intrusions—"positive-" and "annular-like"—would be the equivalent of Phanerozoic mineralized porphyries. However, further research is needed to see how far this comparison can go and how knowledge on Phanerozoic Cu-(Au) porphyry deposits can help us to understand better late-Archean intrusion related gold deposits.

5. Conclusion

Regional aeromagnetic surveys are shown to be a powerful tool to explore for late-Archean intrusion-related gold deposits seeking (1) "annular" (2) "positive" patterns. In both cases, the focused should be on small intrusions, less than 3 km^2, located near crustal structures. In the case of "annular" magnetic signature, the favorable zones are in the highly-magnetic aureole around the intrusion and more specifically the lower-magnetic zones indicative of hematite and pyrite metasomatism (e.g. O'Brien). Identification of the more prospective "annular" signature can be made by preferentially targeting intrusions having the lowest magnetic values at core and, if geochemistry is available, $SiO_2 > 60\%$ and $TiO_2 < 0.3\%$. In the case of "positive" magnetic signatures, the intrusion itself is the target. However, remobilization at the edges can occur if the intrusion edges are faulted or sheared (e.g. Beattie). "Composite" ones are not considered to be highly prospective, as there is no known associated gold deposit. However, smaller intrusions in their vicinity could be prospective (e.g.: Young Davidson, Kirkland Lake).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2016.07.009.

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