Magnetic felsic intrusions associated with Canadian Archean gold deposits

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ABSTRACT
Felsic intrusions spatially and temporally associated with Archean Au deposits in the Superior Province of the Canadian Shield are magnetic, due to high magnetite content, in comparison to felsic igneous rocks in most of the Archean terrain. Examples are found in Au camps of Hemlo, Red Lake, Harker-Holloway, Mishibishu Lake, Wawa-Missanabie, Geraldton, Matachewan, and Bousquet–East Cadillac. These Archean intrusions are comparable with Phanerozoic magnetite-series plutons accompanying metallic mineralization and magnetite-rich intrusions hosting Au-rich porphyry deposits. The evidence shows a distinct tectonic setting for the gold mineralization involving the generation of the particular magmas. The association of the two indicates either the derivation of the ore constituents from the intrusions or the emplacement of the magmas along dilation zones which also provided fluid flow from depth. The identification of magnetite-rich felsic intrusions may aid in targeting favorable exploration areas for Archean Au deposits.

INTRODUCTION
Magnetite-series and ilmenite-series granitoids are recognized in Phanerozoic orogenic terrains (Ishihara, 1977, 1981). The magnetite-series intrusions are characterized by the occurrence of magnetite, generally in a range between 0.1 and 2 vol%, and they display magnetic anomalies. The ilmenite-series plutons contain less oxides, <0.1 vol%, and no magnetite (Ishihara, 1977). The difference is attributed to a difference in oxidation of the magmas; magnetite-series magmas have higher oxygen fugacity. Phanerozoic porphyry Cu deposits are exclusively hosted by magnetite-series intrusions, and base- and precious-metal mineralization may also accompany the intrusions (Ishihara, 1981). Ilmenite-series intrusions are generally barren, but some bear Sn and W mineralization, as in the Malaysian and Bolivian Sn belts (Ishihara, 1981).

Whereas felsic intrusive rocks, underlying large parts of Archean terrains, have generally low magnetic susceptibilities compared with surrounding mafic and ultramafic rocks, felsic intrusions associated with Archean Au mineralization are abnormally magnetic. This paper presents examples and discusses the significance of magnetic plutons to Archean Au mineralization.

MAGNETIC FELSIC INTRUSIONS IN THE CANADIAN ARCHEAN GOLD CAMPS
Hemlo
Au deposits occur in an intensely deformed part of an east-trending greenstone belt bounded by granitic rocks (Fig. 1); the Pukaskwa complex to the south, Cedar Lake pluton to the northeast, Heron Bay pluton to the southwest, and Gowan Lake pluton to the northwest (Fig. 2; Muir, 1982a, 1982b). Porphyritic felsic dikes are abundant near the ore zones and were probably derived from the Cedar Lake pluton (Corfu and Muir, 1986). The Au mineralization, which is bracketed by U-Pb zircon ages of dikes, was synchronous with the Cedar Lake pluton (Corfu and Muir, 1986). The Heron Bay and Cedar Lake plutons and the Pukaskwa complex have similar granodioritic compositions (Muir, 1982a, 1982b), but their magnetic susceptibilities are very different (Fig. 2). The Heron Bay pluton is nonmagnetic, similar to the Pukaskwa complex (Ontario Department of Mines–Geological Survey of Canada, 1963, Maps 2156G and 2167G). The Gowan Lake and Cedar Lake plutons display distinct magnetic anomalies. In particular, the Cedar Creek stock, a satellite of the Cedar Lake pluton, and the western margin of the Cedar Lake pluton show concentric magnetic anomalies (Fig. 2). They are located only ~300 m north of the Au mineralization.
Differences in oxidation conditions in the plutons are also reflected in their alteration; the margin of the Cedar Lake pluton displays hematitic alteration, and the Heron Bay pluton shows no signs of oxidized alteration. The oxidized nature of the magma of the Cedar Lake pluton is further confirmed by high Mg/Fe ratios in silicate minerals due to high $f_O_2$ (Cameron and Carrigan, 1987).

**Harker-Holloway**

Several east-trending Au-bearing zones are parallel to the Destor-Porcupine fault (Fig. 1). The McDermott deposit is being developed with reserves of 1.6 million tons at 0.263 oz/ton (Northern Miner [Toronto], May 5, 1986). Au-quartz veins occur in altered diorite and mafic volcanic rocks with abundant hematite (Workman, 1986), suggesting that the mineralization took place under oxidized conditions.

The Harker stock and a stock on the boundary between Harker and Garrison townships, which were intruded near the Destor-Porcupine fault, have exceptionally high magnetic susceptibilities, over $7.25 \times 10^3$ emu/cm$^3$, and they are prominent on the regional map covering 16 townships (Letros et al., 1983). Letros et al. (1983) called them "red magnetic syenites." Relatively unaltered samples indicate that they are magnetite-rich quartz monzonites with hematite and K-feldspar. The Garrison stock and a syenitic stock in the Michaud Township located farther away from the deposits are not magnetic (Ontario Department of Mines–Geological Survey of Canada, 1970, Map 295G; 1975, Map 20.140G).

**Wawa-Missanabie**

Supracrustal rocks in the belt were intruded by syntectonic tonalitic plutons and posttectonic granitic plutons and stocks. The Wawa area has several past producers within and near the Jubilee granodiorite stock, which is so magnetic as to attract hand magnets. Current producers in the Missanabie area (Renabie, Anglo-Dominion, and Canroes mines) are all located in the highly foliated Renabie pluton, which consists of quartz trondhjemite to granodiorite. The pluton contains abundant magnetite and exhibits distinct anomalies (Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2220G). Other foliated plutons with similar compositions, such as Marsh pluton (Bennett, 1978), are not magnetic (Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2219G) and are not known to accompany any significant mineralization.

Recent discoveries of economic Au deposits (Kremzar and Magino) are located near other magnetic intrusions in the area, the Finan granite stock, Kremzar diorite, and Magino granodiorite stocks (Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2193G). Less prominent but slightly magnetic intrusions in the area are the Ash Lake pluton (Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2220G) and Lachalsh Bay stock (Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2207G). Both are accompanied by Au showings.

**Mishibishu Lake**

Au mineralization occurs on the north shore of Mishibishu Lake near the contact between mafic volcanic rocks and clastic sedimentary rocks (Heather, 1985). The supracrustal rocks...
are intruded by several batholithic granites and stocks. The oval-shaped Mishibishu Lake stock consists of porphyritic monzonite (Bennett and Thurston, 1977). Abundant magnetite causes a prominent magnetic anomaly, noted by Bennett and Thurston (1977), and the rocks commonly exhibit hematite and K-feldspar alteration. The abundance of magnetite, the occurrence of primary titanite in plagioclase, and the lack of ilmenite implies high $O_2$ for the magmas (Noyes et al., 1983). The magnetic nature of the stock contrasts with surrounding nonmagnetic granitic plutons which are barren of Au (Fig. 3; Ontario Department of Mines–Geological Survey of Canada, 1963, Map 2176G).

**Table 1. Archean Gold Camps and Magnetite-Bearing Felsic Intrusions in Superior Province, Canada**

<table>
<thead>
<tr>
<th>Au*</th>
<th>Oxidized Plutons</th>
<th>Zircon Age x 10^6 yrs</th>
<th>Lithologies</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemlo</td>
<td>534 (1)</td>
<td>Cedar Creek stock</td>
<td>2690 (2)</td>
<td>Hb-bt gdite</td>
</tr>
<tr>
<td>Missabable</td>
<td>65 (8)</td>
<td>Renable pluton</td>
<td>2718 (17)</td>
<td>Q-drite (18)</td>
</tr>
<tr>
<td>Wawa</td>
<td>5 (14)</td>
<td>Mishibishu monzonite stock</td>
<td>2718 (17)</td>
<td>Drite, tdnite (18)</td>
</tr>
<tr>
<td>Red Lake</td>
<td>401 (1)</td>
<td>Dome stock</td>
<td>2718 (17)</td>
<td>Drite, tdnite, drite (18)</td>
</tr>
<tr>
<td>Kirkland Lake</td>
<td>720 (1)</td>
<td>&quot;Syenitic&quot; intrusive complex</td>
<td>P-x-mz, Hb-bt q-mz, q-sye</td>
<td>Mg, f-p, (38)</td>
</tr>
<tr>
<td>Harker-Halloway</td>
<td>&gt;13 (25)</td>
<td>Stock on Harker/Garrison Boundary</td>
<td></td>
<td>Mg, tit (26)</td>
</tr>
<tr>
<td>Beadmore-Geraldton</td>
<td>66 (1)</td>
<td>Coyle Lake stock</td>
<td>2690 (32)</td>
<td>Hb-gdite</td>
</tr>
<tr>
<td>Cameron Lake</td>
<td>&gt;8.7 (31)</td>
<td>Stephen Lake pluton</td>
<td>2690 (32)</td>
<td>Hb-gdite</td>
</tr>
<tr>
<td>Shebandowan</td>
<td></td>
<td>Moss Lake pluton</td>
<td>2683 (30)</td>
<td>Hb-bt gdite, locally p.</td>
</tr>
<tr>
<td>Bousquet-East Malartic</td>
<td>73 (1)</td>
<td>Moosha complex</td>
<td>2683 (30)</td>
<td>Fol. q-drite, q-drite, q-f-p</td>
</tr>
<tr>
<td>Lac Shortt</td>
<td>12 (36)</td>
<td>Intrusive complex</td>
<td></td>
<td>Sdy, drite</td>
</tr>
</tbody>
</table>


bt = biotite, drite = diorite, fol. = foliated, f-p = feldspar porphyry, gdite = granodiorite, gr-bt = green biotite, hb = hornblende, mg = magnetite, mgntic = aeromagnetic anomaly, mz = monzonite, p = porphyritic, px = pyroxene, q = quartz, q-f-p = quartz feldspar porphyry, q-mz = quartz monzonite, sdy = syenite, tit = titanite, tdnite = trondhjemite.

*Au produced plus reserve in metric tonnes.

**Red Lake**

The supracrustal rocks of the Red Lake greenstone belt are dated at 2992 to 2733 Ma, and they were intruded by several batholiths and stocks of granodioritic to monzonitic composition at 2700 and 2731 Ma (Andrews et al., 1986). Detailed zircon age determination of dikes suggests that the mineralization was synchronous with the intrusive activity (Andrews et al., 1986).

The central mining area, including the Dickinson and Campbell mines, is surrounded by the Trout Lake batholith to the east, the Dome and McKenzie stocks to the south, and the Hammel Lake batholith to the west. A southern Au zone, including the Madsen and Starratt-olson mines, is bounded by the Killala-Baird batholith and Faulkenham Lake stock to the west, the Dome stock to the north, and the Keg Lake stock to the east.

Iron formation and ultramafic intrusions obscure the magnetic nature of the felsic intrusions. However, the Dome, McKenzie, and Howey stocks, the southern part of the Little Vermillion Lake batholith, the Hammel Lake batholith, and the southern part of Trout Lake batholith display high total magnetic fields (Ontario Department of Mines-Geological Survey of Canada, 1960, Map 852G; Ontario Geological Survey, 1978, Map P1579). The Trout Lake
batholith near the border between Ange and Shaver and between Shaver and Ranger townships displays strong anomalies, over 1000 gammas above background. The petrographic descriptions of dikes and stocks by Horwood (1945, p. 41, 42, 45) and Ferguson (1965, p. 13) confirm high magnetic content of the intrusions.

**Beardmore-Geraldton**

This Au camp contains 18 past producers and is in an east-trending greenstone belt east of Lake Nipigon (Fig. 1). The supracrustal rocks were intruded by felsic plutons, stocks, and numerous porphyry sills, and the intrusions host a part of the ore in the camp. Au deposits in the northern camp occur near the contacts of felsic stocks: the Quebec Sturgeon mine in and near the Elmhirst Lake stock and Coyle Lake stock, the Mitto and Greenoaks showings in the Elmhirst Lake stock, and the Dik-Dik (Orphan) mine in and near the Kaby Lake stock. These stocks show prominent magnetic anomalies (Ontario Department of Mines–Geological Survey of Canada, 1974, Map 30,002G). Mackasey (1976) noted the magnetic character of the Coyle Lake stock. Mackasey (1976) and Mackasey and Wallace (1978) reported the occurrence of magnetite, titanite, and green pleochroic biotite in these stocks and in minor porphyry sills and dikes. Green biotite generally has high Fe\(^{3+}\) content relative to total Fe (Hayama, 1959).

**DISCUSSION**

Table 1 lists some Canadian Archean Au camps and the associated plutons. The compositions vary from tonalite to quartz syenite, and the margins of the intrusions commonly display foliation parallel to that in the host rocks. Their distribution along structural breaks and the deformation in and around the intrusions are taken as evidence for syntectonic to late tectonic emplacement of the intrusions (e.g., Colvine et al., 1984; Stott, 1985). All the intrusions contain primary magnetite, suggesting that their magmas were oxidized. These intrusions are analogous to Phanerozoic magnetite-bearing felsic plutons in Southeast Asia, Alaska, western North America, and Chile, which commonly accompany base- and precious-metal mineralization (Ishihara, 1977, 1981). The fertile nature of the intrusions is further demonstrated in southern Pacific porphyry copper belts (Mason and McDonald, 1978; Whalen et al., 1982), Chivas (1981) and Mason (1978) showed that the intrusions hosting porphyry deposits were crystallized from oxidized magmas and that the magmas were progressively more oxidized during the crystallization. Among porphyry Cu deposits, those rich in Au appear to be associated with even more highly oxidized intrusions. Sillitoe (1979) noted that the host intrusions for Au-rich porphyry Cu deposits contain abundant magnetite. This observation is confirmed in the Philippines (Sillitoe and Gappe, 1984) and South America (Sillitoe et al., 1982). The porphyry Au deposit at Porgera, Papua New Guinea, is also hosted in a highly magnetic dioritic complex. Pitcher (1983) suggested that Au-rich porphyry Cu deposits are hosted in M-type granitoids, which are intrinsically more oxidized than I-type.

In Archean greenstone belts, several workers have noted the spatial association of felsic intrusions with Au mineralization (e.g., Hodgson, 1983). The temporal association was recently pointed out from detailed zircon age data of pre-ore and crosscutting dikes (Colvine et al., 1985; Andrews et al., 1986). This study shows that the intrusions associated with Archean Au mineralization are all magnetic and oxidized in the magmatic stage, equivalent to Phanerozoic magnetite-series intrusions. The oxidized condition of the intrusions may be attributed to the intrinsically oxidized nature of the source magmas or vapor evolution from the magmas. If the magmas had high water content relative to Fe and if they were emplaced in dilation zones, preferential degassing of reduced gases, such as H\(_2\) and H\(_2\)S, may have caused the oxidation of the remaining magmas (e.g., Candela, 1986). The occurrence of the intrusions along tectonic breaks is consistent with both possibilities, but the moderately high content of Fe in the intrusions and the lack of reduced alteration near the intrusions may favor the intrinsically oxidized source magmas. In either case, the occurrence of magnetite-rich intrusions manifests a distinct tectonic setting involving the generation of particular magmas and the gold mineralization.

The association of the oxidized intrusions and the gold mineralization suggests that the intrusions are genetically related to the mineralization, or that the loci of the intrusions were the focus of the fluid flows. At present there is no strong evidence to negate the latter option, but I favor the derivation of ore fluids from or through the magma system on the basis of the evidence of the release of oxidized hydrothermal fluids from some of the intrusions (Hattori and Cameron, 1986; Cameron and Hattori, 1987). Felsic intrusions, which are oxidized either intrinsically or extrinsically, have the potential to be fertile for Au for the following reasons. (1) Oxidized magma can incorporate Au from source and surrounding rocks into melt by oxidizing Au to Au\(^{3+}\) and Au\(^{3+}\) and dissolving enclosing sulfides. (2) Oxidized magmas will not produce sulfide melts due to the high solubility of S (Carroll and Rutherford, 1985); therefore, Au would remain in the magmas. (3) Oxidized magmas will produce oxidized hydrothermal fluids. Au is more soluble in more oxidized fluids as ions or as chloride complexes. Au in thio complexes has maximum solubilities at \(f_{O_2}\) near the boundary between reduced and oxidized S species (Seward, 1973). Au, which partitioned into the fluid phase, would not precipitate immediately. Oxidized magmas thus efficiently extract Au, transport it to upper crustal levels, and concentrate it into hydrothermal fluids.

The above summary does not include the well-known Pearl Lake porphyry hosting the Hollinger-McIntyre deposits in Timmins, which does not display profound magnetic anomalies (Ontario Department of Mines–Geological Survey of Canada, 1970, Map 293G). When the mineralization takes place within a stock, intense alteration directly related to the mineralization destroys magnetite to form pyrite and hematite. However, pervasive hematitic alteration with anhydrite (e.g., Mason and Melnik, 1986) and anhydrite of magmatic-hydrothermal origin in the stock (Hattori and Cameron, 1986) indicate the oxidized nature of the magma. This is also the case at the Kirkland Lake Au camp. Intensive replacement of magnetite by hematite causes less prominent aeromagnetic anomalies (Ontario Department of Mines–Geological Survey of Canada, 1970, Map 289G), whereas relatively fresh hand specimens of the intrusions are strongly magnetic due to magmatic content up to 5 vol%. The occurrence of celestite in relatively fresh intrusions and barite in veins with magmatic signature indicate the oxidized nature of the magma. Thus, the two largest Archean Au camps in North America, Hollinger-McIntyre and Kirkland Lake, are hosted in and adjacent to felsic intrusions that crystallized from extremely oxidized magmas.

**CONCLUSIONS**

Felsic plutons spatially and commonly temporally associated with several major Archean Au deposits in the Abitibi greenstone belt are magnetic, equivalent to magnetite-series intrusions in Phanerozoic orogenic terrains as defined by Ishihara (1977). The fertile nature of oxidized plutons proven in Phanerozoic terrains is also characteristic of Archean terrains. The present study has an important implication for the exploration for Archean Au deposits; the identification of magnetite-rich intrusions and the recognition of oxidized magmatic hydrothermal alteration may assist in selecting the favorable areas.

**REFERENCES CITED**


—1962, Map 1169G, Caviar Lake: scale 1:50,000.


—1975, Aeromagnetic map 20,140G, 32D/5e: project: scale 1:125,000.


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