

## The Éléonore Gold Mine: Exploration, Discovery and Understanding of an Emerging Gold District in Eeyou Istchee James Bay, Superior Province, Northern Québec, Canada

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### ABSTRACT

*The Eeyou Istchee James Bay municipality was always considered less prolific for major gold discoveries than the Abitibi region mainly because of the scarcity of greenstone belts and presence of high-grade metamorphism. Conceptual models, including potential for porphyry systems, and influence of metamorphic gradients on hydrothermal fluid circulation were tested by Virginia Gold Mines near a Cu-Ag-Au-Mo showing hosted by the Ell Lake diorite and discovered by Noranda in 1964. A trail of mineralized boulders, including one that provided a grab sample at 22.9 g/t Au, was identified in 2002, and followed up-ice to the source area, leading to the discovery of the Roberto deposit in 2004.*

*The property was acquired by Goldcorp Inc. in 2006, production started in October 2014 and commercial production was achieved on April 1, 2015. In June 2016, the Éléonore mine had mineral reserves of 4.57 Moz (23.44 Mt at 6.07 g/t Au), measured and indicated gold mineral resources of 0.93 Moz (5.14 Mt at 5.66 g/t Au) and inferred mineral resources of 2.35 Moz (9.73 Mt at 7.52 g/t Au).*

*Mainly hosted by <2675Ma sedimentary rocks, the deposit is located 1.5 km south of the interpreted tectonometamorphic contact between the Opinaca (paragneiss to migmatite) and La Grande subprovinces (volcano-sedimentary belts and syn- to late-tectonic intrusions). A multidisciplinary approach is presented here to decipher stratigraphic relationships as well as structural, metamorphic and magmatic events relative to the establishment of the distinct geological setting and hydrothermal footprint. This approach is based on extensive detailed surface and underground mapping, core logging, lithochemistry, 3D modelling, and U-Pb geochronology. These have led to the identification of ore zones characterized by a diversity of mineralization styles including: i) stockwork of quartz, dravite veinlets with microcline, phlogopite replacement zones with pyrrhotite, arsenopyrite, and löllingite (5050 and 5010 zones); ii) quartz, actinolite, diopside, hedenbergite, muscovite, schorl, arsenopyrite-löllingite-pyrrhotite veins, hydrothermal breccia and amphibolite-biotite schist (6000, 7000, 8000 and hangingwall zones); and iii) more atypical metamorphosed high-grade ore in paragneissic rocks (e.g. 494 zone) and lower grade replacement zones and pegmatite dykes (North zone). A common metallic signature of the various ore zones including Au-As-B-Sb ( $\pm$ Bi-W-Te-Sn-Mo-Se) was identified as well as lithochemical proxy for the hydrothermal system. The ubiquitous presence of gold-rich löllingite inclusions within arsenopyrite overgrowths, as well as pyrrhotite, actinolite, diopside, hedenbergite, biotite and microcline, and post-ore deformation indicate that the bulk of gold mineralization has recorded prograde metamorphism and coeval deformation followed by retrograde metamorphism.*

*Gold mineralization in the Éléonore mine and adjacent properties (Cheechoo and Éléonore South) suggests that the Opinaca/La Grande tectonometamorphic contact and in particular the ~5 km area, located immediately to the south of the contact, is a promising area. Gold mineralization locally occurs in 2620-2600 Ma pegmatite dykes and within or in the vicinity of a 2612 Ma reduced granodiorite/tonalite intrusion. The Éléonore mine area records i) long-lived Au-bearing hydrothermal activity associated with regional metamorphism, coeval deformation, reduced magmatism (~2612 Ma Cheechoo granodiorite/tonalite), and injection of numerous leucogranite and pegmatite veins and dykes, coeval with ii) polyphase deformation recorded by sedimentary rocks next to a major tectonic contact with a migmatitic domain. In this context, gold mineralization share analogies with hypozonal orogenic gold deposits as well as reduced intrusion-related gold systems.*

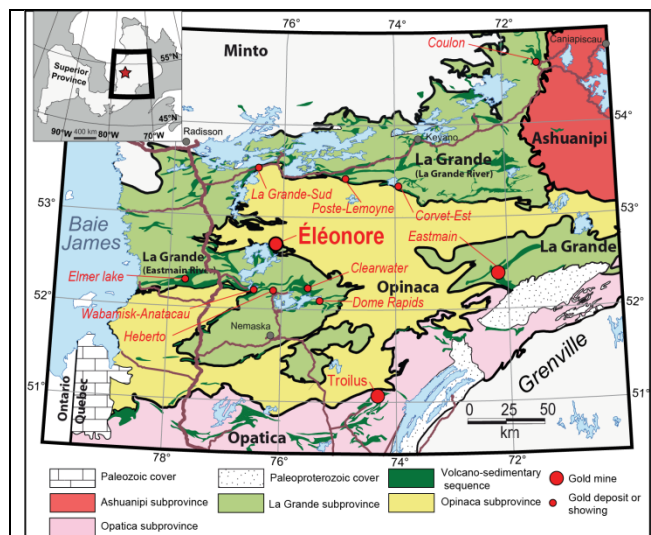
*The discovery of the Roberto deposit was the result of standard field exploration methodology including a combination of systematic prospecting around historical showings, sampling of erratic boulders, glacial flow directions to track sources of gold-bearing ones, extensive geophysical (magnetic, induced polarization surveys) and geochemical surveys (soil and lake sediments), mechanical stripping with channel sampling, and drilling, all of which were essential in the discovery and for the development of the Éléonore mine.*

## INTRODUCTION

The Éléonore mine (Roberto gold deposit) is located in the Eeyou Istchee James Bay municipality, northern Québec (Figure 1). This vast area is part of the Superior Province (Figure 1) of the Canadian Shield (Card and Ciesielski, 1986; Percival, 2007). Acquired by Goldcorp Inc. in 2006, commercial production was achieved on April 1, 2015. As of June 30, 2016, the Éléonore mine had mineral reserves of 4.57 Moz (23.44Mt at 6.07 g/t Au), measured and indicated mineral resources of 0.93 Moz (5.14Mt at 5.66 g/t Au) and inferred mineral resources of 2.35 Moz (9.73Mt at 7.52 g/t Au) (Goldcorp, 2016). From 2015 to the end of 2016, the mine produced 523,800 oz. of gold and 2017 production is projected to be 315,000 oz. ( $\pm 5\%$ ) (Goldcorp, 2017). The deposit, the first world-class gold deposit in the region, is located within the Superior Province, ~1.5 km south of the interpreted tectonometamorphic contact between the Opinaca and the La Grande subprovinces.

Several other gold showings, deposits and properties such as Eastmain mine, La Grande Sud, Corvet-Est, Poste Lemoyne and Wabamisk are also located in the vicinity of the contact between the Opinaca and La Grande subprovinces (Figure 1). The Troilus mine is located near the structural contact between the Opinaca Subprovince and the Frotet-Evans greenstone belt within the Opinaca Subprovince (Figure 1). The Troilus mine is interpreted as an Archean analogue of porphyry deposit (Poulsen et al., 2000) or a product of two separated structurally-controlled episodes of hydrothermal mineralization (Goodman et al., 2005). The Eau Claire gold deposit (Clearwater property, Eastmain Resources) has measured and indicated resources of 951,000 oz. (7.22 Mt at 4.1 g/t Au) and inferred resources of 633,000 oz. (5.07 Mt at 3.9 g/t Au) (SRK, 2015). Located in the Lower Eastmain greenstone belt, the deposit is hosted by amphibolite facies rocks and located in a kilometric-scale  $F_2$  fold near a  $D_2$  shear zone. A network of east-striking, south-dipping quartz-tourmaline-carbonate veins and amphibolite-tourmaline-rich schists are the two main types of mineralization (Cadieux, 2000; Tremblay, 2006; SRK, 2015).

Gold deposits in metamorphosed and deformed terranes are hosted within a wide range of host rocks, at various crustal levels and typically in association with major structures (Colvine, 1989; Groves et al., 1990; Poulsen et al., 2000; Goldfarb et al., 2005; Robert et al., 2005; Dubé and Gosselin, 2007). Some are hosted by amphibolite or granulite facies metamorphic rocks (Couture and Guha, 1990; Barnicoat et al., 1991; Groves, 1993; Neumayr et al., 1993; Poulsen et al., 2000; Goldfarb et al., 2005). Some world-class Canadian gold deposits (e.g. Hemlo, Lupin, Musselwhite) belong to this group and remain relatively controversial (Dubé et al., 2015). Understanding such deposits could considerably increase exploration targeting efficiency and lead to potential discoveries in highly metamorphosed Archean terranes elsewhere in the Superior province and abroad (Dubé et al., 2015; Goldfarb, 2016).



**Figure 1:** Location of the Éléonore mine in North America and in Eeyou Istchee James Bay municipality (map from Goutier (2015) based on Système d'information géominère of Québec (SIGEOM) data).

This paper presents a brief historical perspective of gold exploration in the area and regional mapping program conducted by the Geological Survey of Canada and the Ministère de l'Énergie et des Ressources naturelles du Québec (MERN) during the last 120 years. The discovery history of the Roberto deposit in 2004, by Virginia Gold Mines Inc. (now Osisko Gold Royalties), is then briefly reviewed with particular emphasis on exploration methods and regional exploration strategy. The regional setting of the deposit is presented in order to provide a framework for the description of the deposit-scale geological setting. The geology of selected adjacent showings is summarized and implications for exploration at the scale of the Eeyou Istchee James Bay municipality are highlighted.

## REGIONAL MAPPING AND EXPLORATION

The first geological map of the James Bay area was made by Albert Peter Low, geologist for the Geological Survey of Canada (Low, 1896). Traces of gold associated with pyrite within chlorite schist were found at the mouth of the Wabamisk River (Low, 1896), near the current Reservoir deposit and Bear Island showing (Eastmain Resources). Early gold exploration mainly focused on the Eastmain River greenstone belt (Gauthier and Larocque, 1998). Dome Mines Ltd. explored the Eastmain River area in 1935 and 1936 and discovered the Dome Rapids showing (McCrea, 1936). The Geological Survey of Canada conducted geological mapping (Shaw, 1942). In 1964, Noranda conducted an electromagnetic (EM) survey, trenching, portable diamond drilling and geological mapping. Three holes were performed to investigate two copper showings on the property. Due to limited extent of copper mineralization at depth, the claims were dropped after the 1964 exploration program. In 1969, PCE Exploration re-evaluated the Ell Lake showing with a combination of EM and magnetic surveys, geochemistry, and diamond drilling. At the end of the 1970s, the Ministère des Richesses naturelles du Québec (now MERN) produced 1:100 000 geological maps in the Eastmain River area (Remick, 1977;

Franconi, 1978). In 1975, a geochemical survey of lake sediments was undertaken by Société de Développement de la Baie-James from the Québec government (Gleeson, 1976), reanalyzed later (1996, 2010) by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and instrumental neutron activation (Beaumier, 1990; Beaumier and Kirouac, 1994). The arsenic content in lake sediments outlined Au-As mineralization closely associated with high-metamorphic gradients (Davenport et al., 1997; Gauthier et al., 2007). With the discovery in Ontario of the Hemlo (Wawa Subprovince) and Musselwhite (North Caribou Terrane) deposits in the 1980s, targeting higher-grade metamorphic rocks become more attractive (Gauthier, 2000). In 1994, Gouvernement du Québec started a 1:50 000 mapping program in the Middle-North (50<sup>th</sup> and 55<sup>th</sup>; Chartrand et al. (1995)), leading to the identification of more than 200 gold occurrences, mainly in the James Bay area (Chartrand, 1994). After 1997, MERN conducted mapping programs in the Eastmain River of the La Grande Subprovince (Simard and Gosselin, 1999; Moukhsil, 2000; Moukhsil et al., 2003). From 2006 to 2008, 1:250 000 and 1:50 000 geological mapping and compilation of the Opinaca reservoir area were carried out by the Ministère des Ressources naturelles et de la Faune (Bandyayera and Fliszár, 2007; Bandyayera et al., 2010).

## REGIONAL SETTING

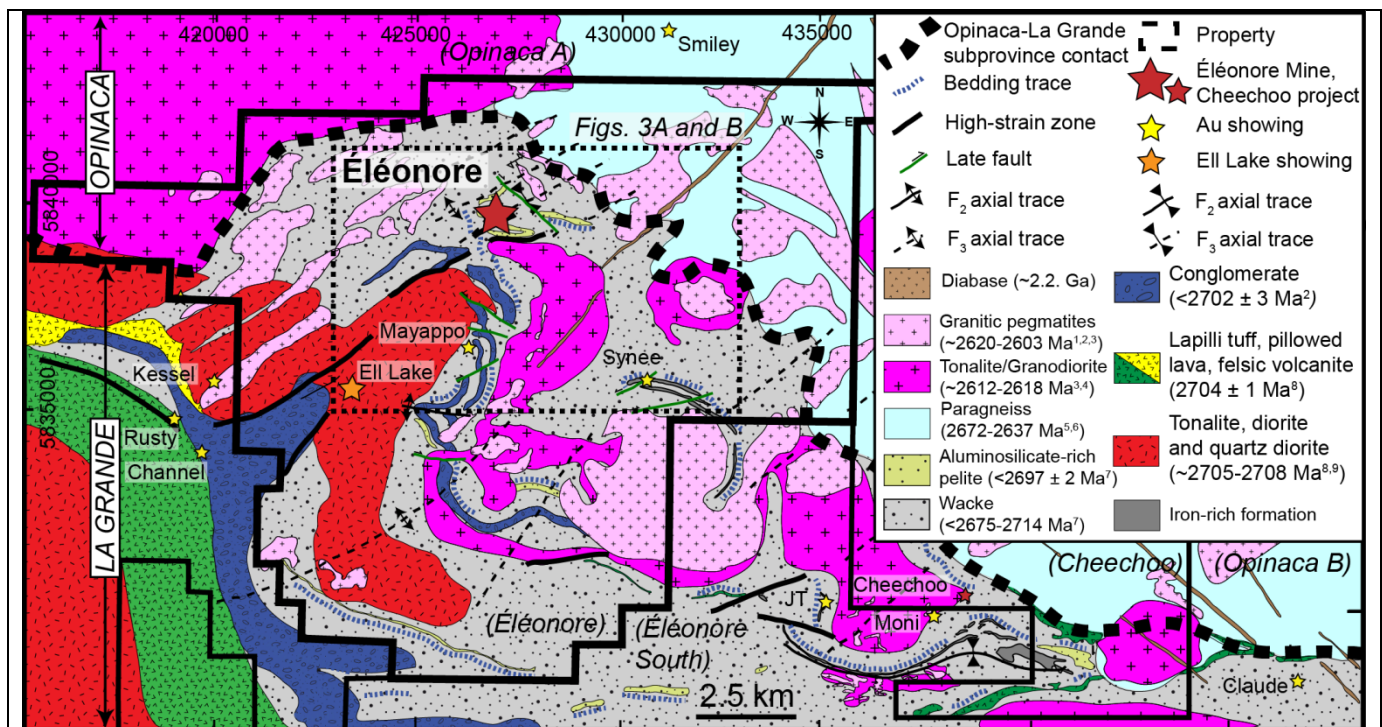
The Eeyou Istchee James Bay municipality is a vast area of about 335,000 km<sup>2</sup> including the La Grande and the Opinaca subprovinces, the northern part of the Opatica Subprovince, the Nemiscau Subprovince, and small parts of the Ashuanipi and Minto subprovinces (Figure 1). The Opinaca Subprovince is characterized by paragneiss and migmatites intruded by syn- to post-tectonic intrusions (Simard and Gosselin, 1999; Bandyayera and Fliszár, 2007; Morfin et al., 2013). These tonalitic to granitic intrusions and associated pegmatite dykes, have a S-type peraluminous composition suggesting a derivation from partial melting of metasedimentary rocks (Moukhsil et al., 2003; Morfin et al., 2014). The Opinaca Subprovince has been interpreted as an injection complex (accumulation of anatexitic melt in the lower crust as defined by (Weinberg and Searle, 1998), where episodic partial melting and associated intrusion of numerous leucogranite dykes and veins occurred between 2671 and 2637 Ma coeval with the main phase of deformation (D<sub>2</sub>) in the Opinaca (David et al., 2010; Morfin et al., 2013). A long-lived tectono-metamorphic event was initiated early (2671 and 2637 Ma) in the highly metamorphosed rocks located in the center of the Opinaca Subprovince (Morfin et al., 2013) and later within the surrounding La Grande Subprovince supracrustal rocks at 2620–2600 Ma (Dubé et al., 2011). Evidence of retrogression (hydration of orthopyroxene into biotite and/or amphibole) is restricted to D<sub>3</sub> shear zones (Simard and Gosselin, 1999; Morfin et al., 2013). In the Opinaca, the latter are locally truncated by younger granitic and tonalite intrusions (Morfin et al., 2013) associated with the Vieux Comptoir granitic suite with younger phase dated at 2618–2614 Ma (David and Parent, 1997; Goutier et al., 1999).

Relics of reworked Paleo- to Mesoproterozoic basement, preserved within Meso- to Neoproterozoic volcano-sedimentary sequences with syn- to late-tectonic intrusions, belong to the La Grande

Subprovince. The La Grande Subprovince is separated into a northern La Grande River and a southern Eastmain River domain (Gauthier and Larocque, 1998). The Eastmain River domain (Figure 1) has been mapped and studied by the Geological Survey of Canada (Low, 1896), the MERN (Remick, 1977; Franconi, 1978; Simard and Gosselin, 1999; Moukhsil, 2000; Moukhsil et al., 2003). The Middle and Low Eastmain greenstone belt (Eastmain domain of La Grande Subprovince) is defined by four volcanic cycles from 2752 to 2703 Ma generating komatiitic to rhyolitic lavas and tuffs with local calc-alkaline affinities (Moukhsil et al., 2003). Conglomerate and turbiditic wacke containing local iron-rich formations overlie volcanic sequences (Franconi, 1978; Moukhsil et al., 2003), a feature present at the Éléonore property (Ravenelle et al., 2010).

The Éléonore property straddles the contact zone between the Opinaca Subprovince and the Eastmain River domain of the La Grande Subprovince (Figure 2). The contact between these two distinct domains is locally hidden by tonalite and granodiorite intrusions (Hocq, 1994). The boundary is defined by a gradual evolution from greenschist to upper amphibolite and granulite metamorphic rocks (Gauthier et al., 2007; Bandyayera et al., 2010), by a discontinuity on a regional aeromagnetic survey (Bandyayera et al., 2010), and the appearance of orthopyroxene and diatexite or melt volume in the paragneissic rocks.

The Low Formation (La Grande Subprovince) hosts the Roberto deposit. It consists of turbiditic rocks deposited during or after <2714–2675 Ma (Ravenelle et al., 2010; Ravenelle, 2013). The Low Formation includes <2702 Ma heterolithic conglomerate dominated by rounded diorite clasts (Ravenelle et al., 2010), and <2714–2675 Ma wacke and arenitic lenses (Bandyayera and Fliszár, 2007; Bandyayera et al., 2010). It is unconformably deposited on pillowed basalt lavas and lapilli tuffs of the ca. 2704 Ma Kasak Formation (Bandyayera and Fliszár, 2007). The Opinaca and Ell Lake plutons belong to a group of older intrusions, respectively, at 2708.9 ± 0.9 Ma (Bandyayera and Fliszár, 2007) and 2705.6 ± 1.9 Ma (J. David, unpublished report for Virginia Gold Mines Inc., 2005). In the vicinity of the mine, syn- to late-tectonic tonalite and granodiorite (ca. 2612 Ma) and pegmatite dykes (2620–2603 Ma; (Dubé et al., 2011)) intruded the La Grande Subprovince supracrustal rocks (Ravenelle et al., 2010; Fontaine et al., 2015). One of those intrusions is the Cheechoo granodiorite/tonalite, located southeast of the Éléonore mine (Figure 2). Mainly composed of feldspar phenocrysts in a matrix of quartz and feldspar, the intrusion also contains various proportions of albite, microcline, biotite, and traces of pyrrhotite, arsenopyrite, diopside and actinolite, depending on the intensity of alteration and mineralization. The intrusion is emplaced within sedimentary rocks and locally cut by pegmatite dykes and lamprophyres dykes. The Cheechoo granodiorite/tonalite hosts gold mineralization (Sirios Inc, 2016; Azimut, 2017). Younger rocks in the area consist of diabase dykes (Figures 2) oriented northeast or northwest which are, respectively associated with the Senneterre swarm dated at 2221–2216 Ma (Buchan et al., 1993) and Mistassini swarm dated at 2515–2503 Ma (Hamilton, 2009; W. Davis, unpublished data, 2014).



**Figure 2:** Simplified geological map of the Éléonore property and adjacent properties. Compiled from Bandyayera and Fliszár, 2007; Ravenelle et al., 2010; Ravenelle, 2013, and unpublished companies reports (Azimut Exploration Inc., Beaufield Inc., Goldcorp Mine Éléonore et Sirios Inc). Éléonore: 100% Goldcorp; Éléonore South: Goldcorp, Eastmain Resources and Azimut Exploration joint venture; Cheechoo: Sirios Resources; Opinaca A and B: Hecla, Everton and Azimut. Selected blocks and grabs are sampled during 2001–2003 exploration program of STG/Virginia Gold Mines (L'Heureux, 2001; Costa and Ouellette, 2003). 1: (Dubé et al., 2011); 2: (Ravenelle et al., 2010); 3: (Fontaine et al., 2015); 4: (Goutier et al., 2000); 5: (David et al., 2010); 6: (Morfin et al., 2013); 7: (V. McNicoll, unpublished data); 8: (Bandyayera and Fliszár, 2007); 9 (J. David, unpublished data, 2005).

## DISCOVERY HISTORY

After the Moyen-Nord mapping program and between the 50<sup>th</sup> and 55<sup>th</sup> parallels by the Québec government launched in 1994 (Chartrand, 1994), Virginia Gold Mines started its greenfield exploration program in 1995 along Transtaïga road and along Eastmain river, but only in 2001 in the northern part of Opinaca reservoir area (Figures 3A and B). M. Gauthier and J-F Ouellette explored the area with a seaplane when the Opinaca reservoir level was low, permitting access to old showings such as Ell Lake. Based on metamorphic gradient maps (Gauthier et al., 2007), specific areas were selected in conjunction with arsenic content in lake sediments (Gleeson, 1976) in order to identify new target areas. Virginia Gold Mines undertook a systematic grab sampling program near the Ell Lake showing between 2001 and 2003 (L'Heureux, 2001; Costa and Ouellette, 2003). A high-grade 2 m<sup>3</sup> erratic sub-angular boulder containing 22.9 g/t Au, 148 ppm Cu, 18 ppm Sb, 9 ppm Bi and 2 ppm Ag, was found in 2002 (Costa and Ouellette, 2003). This boulder was described as a quartzo-feldspathic paragneissic rock and/or a biotite schist enriched in phyllosilicates and aluminosilicate minerals containing 6% pyrrhotite, 1% pyrite and 1% arsenopyrite (Costa and Ouellette, 2003). An analogy with the Hemlo deposit in terms of gold grade, alteration assemblage and texture was highlighted (P. Archer, pers. comm. to B. Dubé, 2003).

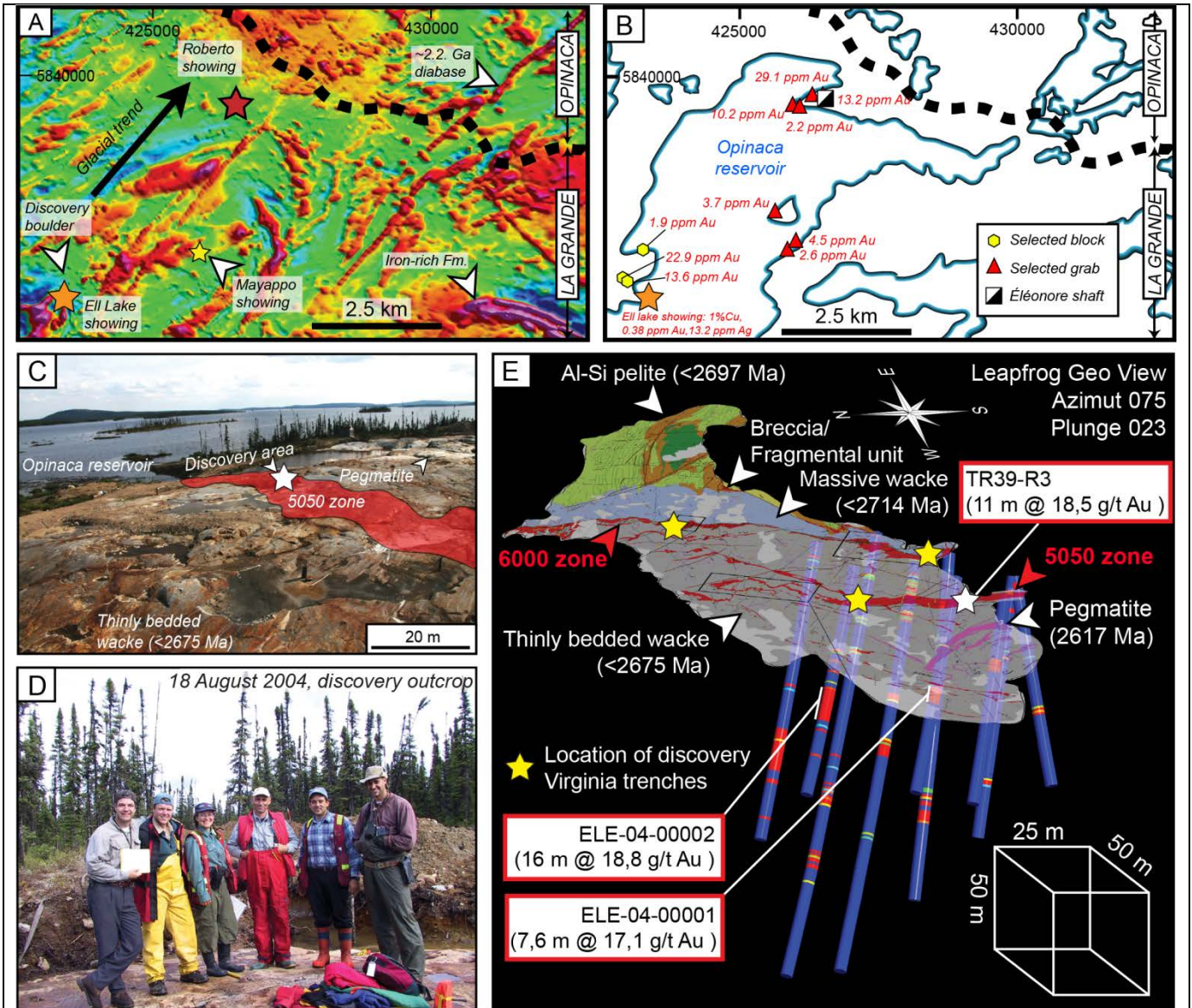
The summer 2003 and winter 2004 programs were designed to locate the source of this boulder (Ouellette and Cayer, 2004). Following the glacial dispersion trend (Figure 3A), ground magnetic, EMH (Horizontal Electromagnetic) and IP (Induced Polarization) surveys on 200 m spaced lines and soil geochemical MMI (Mobile Metal Ions) surveys led to the definition of new targets including some in the northwest shore of the Opinaca reservoir (Ouellette and Cayer, 2004; Cayer and Ouellette, 2005). Additional exploration included channel sampling and drilling, airborne geophysics, MMI soil geochemical, EMH, ground magnetic and IP surveys (Ouellette and Cayer, 2004; Cayer and Ouellette, 2005).

Extensive stripping and geological mapping helped in further outlining the deposit, its geological and structural characteristics, and its footprint (Figure 3E). On August 18<sup>th</sup> 2004, trench results were confirmed (Figure 3D) including TR-04-39-R3; 11 m @ 18.5 g/t Au (Figure 3E) and a few months later, the first drill hole intercepted the 5050 zone (former Roberto showing) at about 50 m depth (ELE-04-0001; 7.6 m @ 17.1 g/t Au; (Figure 3E). In 2005, 247 drill holes were completed in the 5050 zone area with additional soil geochemical sampling to delineate mineralized envelopes (Cayer and Ouellette, 2005; Savard and Ouellette, 2005). Goldcorp acquired the property from Virginia Gold Mines in March 2006. In the summer 2007, Goldcorp decided to strip an



area of 100 m x 400 m (Figure 3E) and enlarge the discovery trenches of Virginia Gold Mines. This outcrop was mapped by J-F. Ravenelle (PhD student at INRS-ETE at this time) in order to better constrain the complex setting and geometry of the mineralized zones and define timing relationships between gold mineralization and deformation (Figure 3C; (Ravenelle et al., 2010)). The interpretation still impacts planning of current mine

development. Ravenelle's (2013) study of the Roberto deposit focussed on detailed structural analysis of the large stripped Roberto outcrop and other surface exposures, structural analysis of drill core, U-Pb geochronology, petrographic analysis of alteration, ore and metamorphic assemblages, and 3-D geological modelling.



**Figure 3:** Selected discovery features of the Roberto deposit area, northern Québec. A: Geophysical image of total magnetic intensity; B: Selected samples that led to the discovery of the Roberto showing; C: Aerial view of the discovery area with the attitude of the 5050 zone and a large pegmatite dyke in its immediate footwall; D: Virginia Gold Mines and Services Techniques Géonordic inc. Team: Jean-Francois Ouellette, Francois Huot, Mélanie Tremblay, Paul Archer, Alain Cayer and Michel Chapdelaine (photo courtesy of Benoît Dubé); E: Roberto outcrop 3D view with location of Virginia discovery trenches and drill holes, and ore zones. Surface geology from (Ravenelle et al., 2010; Ravenelle, 2013). Al-Si: Aluminosilicate-bearing.

## GEOLOGY OF THE ÉLÉONORE MINE

The Éléonore mine is mainly hosted by a heterogeneous sedimentary sequence of the Low Formation (Figure 4). The sequence is composed of massive wacke, thinly bedded wacke, heterolithic conglomerate, arenite and aluminosilicate-bearing pelite (Figures 4 and 5). These sedimentary rocks are metamorphosed to amphibolite facies and evolve into paragneiss towards the Opinaca-La Grande contact (Figure 4). These sedimentary units are intruded by deformed and altered <2674 Ma diorite and <2668 Ma feldspar-phyrlic dioritic dykes (Figure 4; V. McNicoll, unpublished data) as well as syn- to late-tectonic  $2612 \pm 1$  Ma granodiorite/tonalite (Figure. 2) (Fontaine et al., 2015), and 2620–2603 Ma pegmatite dykes (Ravenelle et al., 2010; Dubé et al., 2011; Ravenelle, 2013; Fontaine et al., 2015). The 2620–2603 Ma pegmatite dykes are abundant near the contact between the two distinct sedimentary packages (Figure 5A), or intermingled with surrounding paragneiss.

The sedimentary rocks are affected by polyphase deformation (Ravenelle et al., 2010; Fontaine et al., 2015). The hanging-wall sedimentary package has recorded  $F_1$  folds illustrated by repetition of the aluminosilicate-bearing pelite with fold closures in the hanging wall of the ore zones (Ravenelle et al., 2010). The axial plane of these  $F_1$  folds is sub-parallel to an interpreted unconformity and/or  $D_1$  fault based on U-Pb detritic geochronology (Figures 4 and 5). The kilometre-scale  $F_3$  fold geometry is characterized by refolded smaller scale  $F_2$  folds with a steeply dipping roughly west-trending axial planar  $S_2$  foliation (Figures 4). The latter is well displayed by alignments of aluminosilicate and/or biotite and associated with steeply north- to south-plunging  $L_2$  lineation collinear with  $F_2$  fold axis in the main ore shoot area (Figure 5A; Ravenelle et al., 2010). Isoclinal and/or parasitic asymmetric  $F_2$  folds are locally non-cylindrical and disharmonic and commonly present in the deposit area (Fontaine et al., 2015). The <2714–2697 Ma sedimentary sequence located in the hanging-wall of the ore zones is folded by  $F_2$  and transposed by the main  $S_2$  foliation (Figures 4 and 5). Particularly, on the northern part of the mine area, the main foliation ( $S_2$ ) is affected by an  $S_3$  foliation, axial planar to  $F_3$  open folds (Ravenelle et al., 2010; Ravenelle, 2013; Fontaine et al., 2015). Some pegmatite dykes postdate  $D_2$  and some are affected by  $D_2$ . All pegmatite dykes are deformed by  $D_3$  (Figure 4).

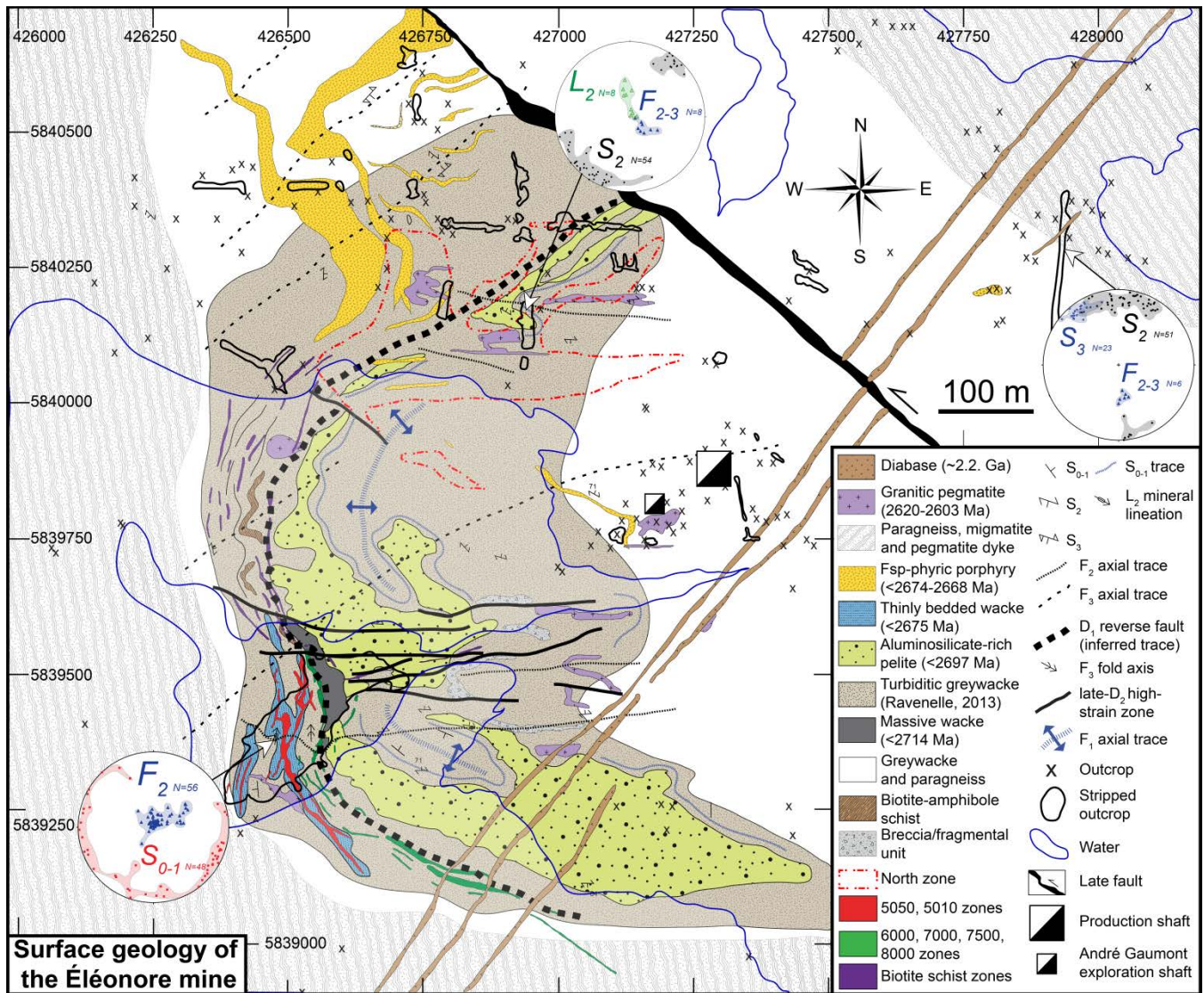
The steep metamorphic gradient in the area (Gauthier et al., 2007; Ravenelle et al., 2010) is well illustrated by the appearance of diatexites, ~1,500 m northeast of the production shaft (Figure 4). Locally, paragneiss is also present at depth and in the immediate footwall of the deposit (Ravenelle, 2013; Fontaine et al., 2015). Aluminosilicate-bearing pelite records a prograde amphibolite metamorphic facies as illustrated by sillimanite and microcline growth coeval with muscovite breakdown at upper amphibolite metamorphic grade (Ravenelle, 2013). At depth, increasing abundance of quartz-feldspathic veinlets associated with biotite, and amphibole-rich selvages are ubiquitous in association with leucogranite dykes and veins and pegmatitic leucogranite of the felsic injection complex described by Morfin et al. (2013). The presence of greenschist facies assemblages, overprinting prograde amphibolite facies

assemblage suggests a late retrogression event (Ravenelle et al., 2010).

A relatively large asymmetric hydrothermal footprint is associated with the ore zones. A proximal potassium- and magnesium-bearing metasomatic alteration halo (0–75 m; 270 ppb Au) is surrounded by an intermediate (75–100 m) and/or distal calcium-bearing alteration halo ( $\leq 100$ –250 m; 110 ppb Au). The distal calcium-bearing metasomatism is defined by replacement bands (Figure 6A) or pervasive alteration zones (Figure 6B) containing calcium-rich minerals (actinolite, diopside) in association with feldspar (20–60%), and a minor amount of coarse grained biotite, garnet and quartz (Ravenelle, 2013). The abundance of actinolite and/or diopside and schorl (iron-rich tourmaline) increases in the intermediate alteration halo (100–75 m from ore zones). The abundance and thickness of replacement zones, veinlets and veins (actinolite and/or biotite and/or diopside and hedenbergite) strongly increases towards the ore zones ( $\leq 75$  m). At the proximity of the ore zones, the deformation intensity commonly increases sharply, especially at depth, and, centimetre-scale porphyroblasts of actinolite and phlogopite are more common (Fontaine et al., 2015).

Various styles of mineralization have been documented from surface, underground mapping and drill holes (Ravenelle et al., 2010; Fontaine et al., 2015), i) a stockwork of quartz-dravite (magnesian tourmaline) veinlets with microcline, phlogopite replacement zones and associated pyrrhotite, arsenopyrite, and löllingite (5010 and 5050 zones) is mainly hosted in the <2675 Ma thinly bedded wacke (Figure 6C) and its metamorphosed equivalent at depth (Figure 6D), ii) quartz veins and breccias with various proportions of muscovite, actinolite, diopside, hedenbergite, schorl, arsenopyrite, löllingite ( $\text{FeAs}_2$ ) and pyrrhotite (Figures 6E and F), silica flooding, quartz vein and breccia and amphibolite-biotite schist with disseminated arsenopyrite-löllingite-pyrrhotite, at or close to the contact between the <2675 Ma and <2714–2697 Ma sedimentary package (6000, 7000, 7500, 8000 and hanging-wall zones), iii) more atypical high-grade ore zones in paragneiss containing various amount of arsenopyrite-löllingite-pyrrhotite in highly deformed quartz±feldspar veins and associated leucogranite dykes (494 zone), and iv) lower grade metasomatic zones with amphibole-diopside ±pyrrhotite veins and locally gold-bearing pegmatite dykes mainly in the North zone. The North zone (1.3 g/t Au over 200 m in drill hole ELE-11-00735) is characterized by: i) quartz-feldspar veinlets with disseminations of fine-grained arsenopyrite, ii) pervasive calc-silicate alteration (Figure 6B) and iii) hydrothermal quartz breccia and veins containing calcium-bearing mineral assemblage (grossular, diopside, carbonate, actinolite and epidote) with disseminated pyrrhotite and arsenopyrite. Hanging-wall zones show a combination of 6000 and 7000 zones (former Roberto East zones) attribute with local dismembered quartz veins, and/or silicified zones containing visible gold. Gold mineralization occurs within east-west trending, with north- or south-dipping discontinuous panels including replacement zones and dismembered quartz with visible gold, calcium-bearing assemblage and potassic, silica-rich hydrothermal breccia.

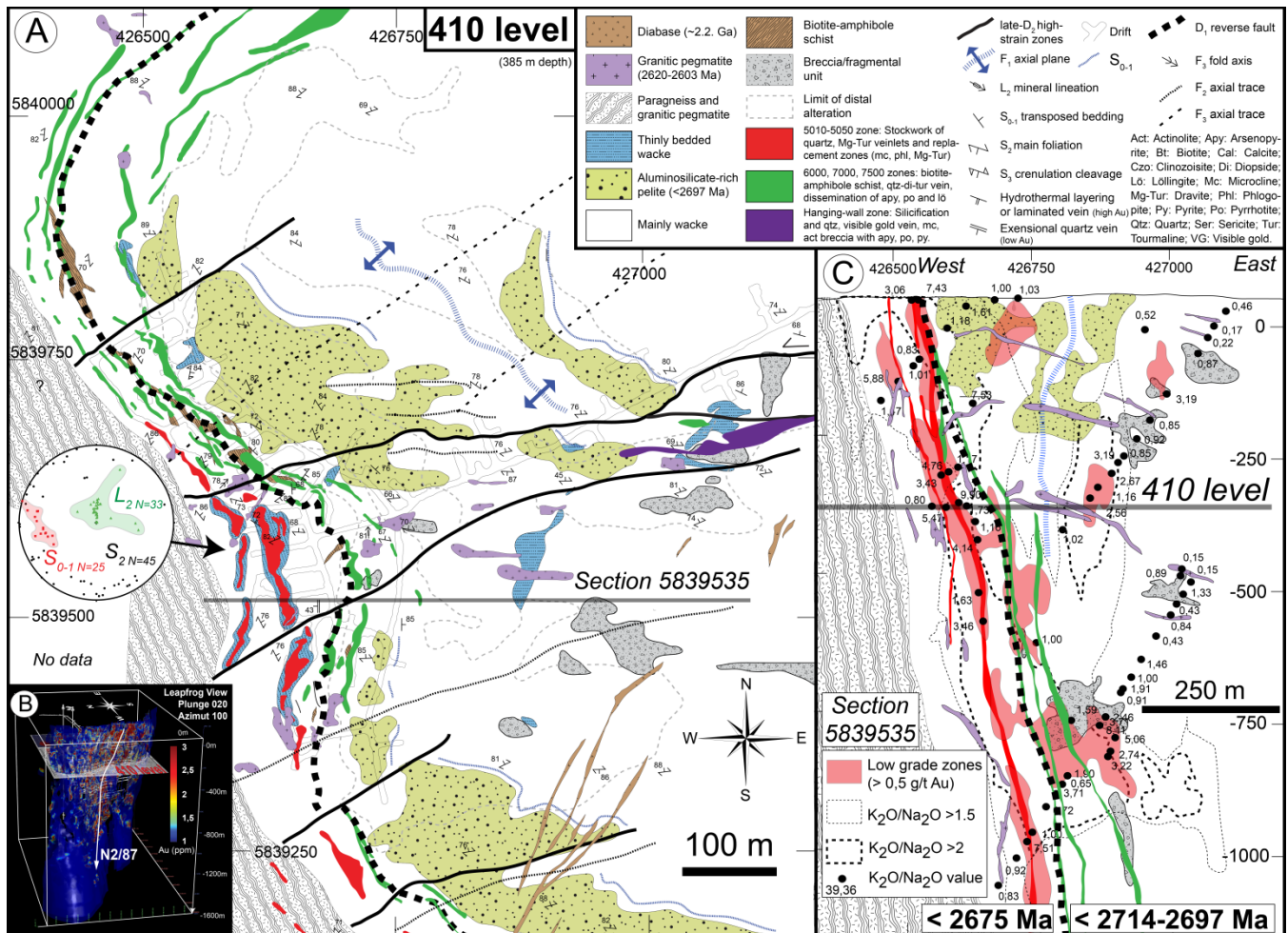




**Figure 4:** Geological map of the Éléonore mine surface geology with selected structural features. Compiled from drill holes descriptions and 3D modelling (50 m depth), stripped outcrops and previous geological maps from (Ravenelle et al., 2010; Ravenelle, 2013). Structural data including stereonet plots illustrate various generations of structures spatially associated with the hydrothermal system of the Éléonore mine. The Éléonore mine area is strongly influenced by the interplay of  $D_2$  and  $D_3$  folding events that control the final geometry of auriferous zones.

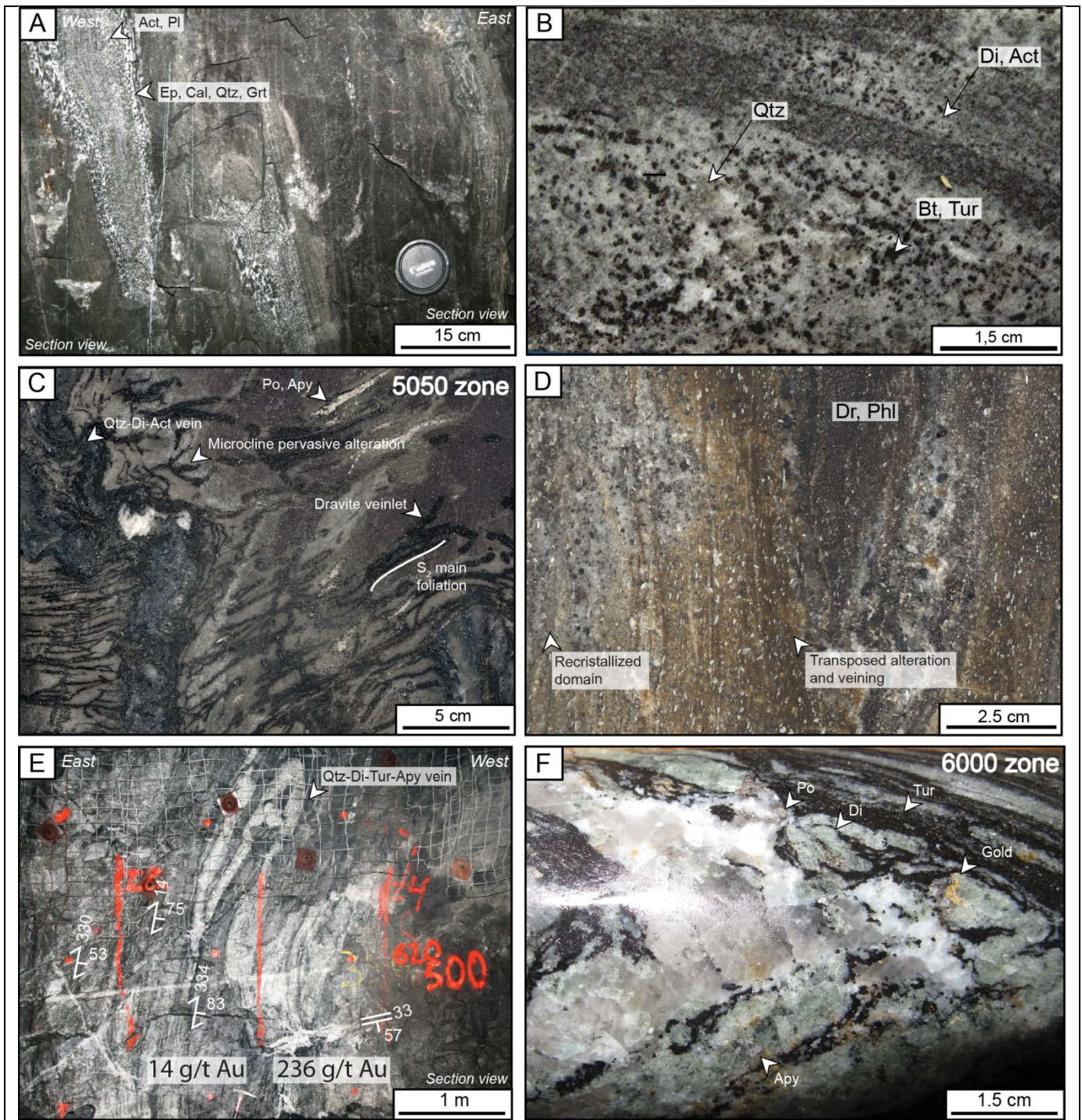
High-grade gold mineralization (>15 g/t Au) mainly formed east- or west-dipping discontinuous planar panels (Figure 5C). The main ore shoot is located within the hinge zone of a curvilinear  $F_2$  fold, illustrated by  $F_2$  fold axis in the Roberto showing (Figure 4). Underground, all zones are locally transposed into the east- or northwest-trending  $S_2$  main foliation and affected by late- $D_2$  steeply north- or south-dipping high-strain zones (Figures 4 and 5A).

At surface, Zone 6000 is strongly deformed and transposed by  $D_2$  structures (Ravenelle et al., 2010). A late dextral reactivation along an interpreted pre-existing  $D_1$  structure is recorded at the contact of the 6000 zone and the massive wacke as illustrated by the presence of sigmoidal quartz veins within a massive tourmaline-rich unit (Ravenelle, 2013). The north limb of the kilometre-scale  $F_2$  fold is more complex and disturbed by the presence of a <2674 Ma dioritic intrusion. The latter is strongly deformed by  $F_2$  and  $F_3$  folds and is located in the structural footwall of the aluminosilicate-bearing pelite (Figure 4).



**Figure 5:** 410 level geological map and 5839535 section map of the Roberto deposit. A: Geological map of the 410 level, the first developed underground level of the Éléonore Mine; B: 3D view of concentration (ppm) of gold; C: Transversal 5839535 section. 6000 zone is located within a D<sub>1</sub> reverse fault, juxtaposing an older sedimentary sequence (<2714–2697 Ma) and the youngest one (<2675 Ma). The footwall of the zones is characterized by paragneiss, migmatite and pegmatites which commonly cut across ore bodies in depth. The K<sub>2</sub>O/Na<sub>2</sub>O illustrates, at least in part, the transformation of sodic plagioclase into microcline during pervasive alteration associated with the emplacement of the auriferous system.





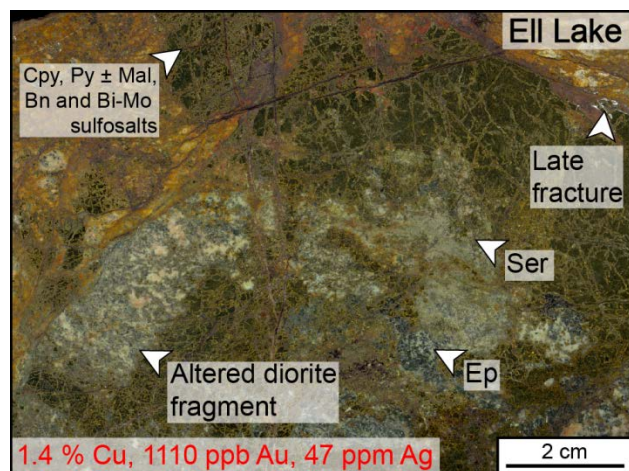
**Figure 6:** Selected alteration and mineralization features of the Roberto deposit. A: Underground photograph of distal metasomatic replacement bands with zonation of mineral assemblage and recrystallized texture (200 ppb Au) B: Core photograph of pervasive calc-silicate alteration (actinolite, diopside) combined with quartz, biotite and/or tourmaline in the core of the alteration halo (1-2 g/t Au) C: Grab photograph of stockwork of dravite veinlet and associated microcline pervasive alteration in vein selvages from 5050 zone (25 g/t Au); D: Grab photograph of strongly recrystallized and deformed 5050 zone (80 g/t Au) at 800 m depth with transposed alteration (microcline, phlogopite and dravite) and veining (quartz and dravite) with disseminated coarse arsenopyrite-löllingite-pyrrhotite composite grains; E: Underground photograph of the south wall of the isoclinally folded high-grade East-Roberto zone (at 600 m depth); F: Core photograph of quartz, actinolite and/or diopside, schorl (iron-rich tourmaline), arsenopyrite, pyrrhotite and visible gold in a laminated vein from the 6000 zone.



## GEOLOGY OF OTHER SHOWINGS

### Ell Lake Showing (Goldcorp)

The Ell Lake Cu-Ag-Au-Mo showing is hosted by the Ell Lake diorite/quartz diorite (Bandyayera and Fliszár, 2007; Bécu et al., 2008) close to a northeast-trending late-D<sub>2</sub> to D<sub>3</sub> high-strain zone (Figure 2). The intrusion has been dated at 2705 ±1.9 Ma (J. David, unpublished report for Virginia Gold Mines Inc., 2005). The intrusion has dioritic, quartz-dioritic and tonalitic compositions, and calc-alkaline to alkaline affinities (Bécu et al., 2008). It contains plagioclase, biotite and hornblende phenocrysts locally aligned along the main northeast-trending foliation. The foliation is strongly developed close to the mineralized area (Bécu et al., 2008). The mineralization is composed of variable amounts of chalcopyrite with minor amount of pyrite, magnetite, molybdenite, electrum and bismuth sulfosalts and tellurides (Figure 7). A propylitic alteration containing chlorite, epidote, sodic plagioclase and carbonates is also present (Bécu et al., 2008). Presence of K-feldspar dykes and heterogeneous compositions of the intrusion suggest multiple magmatic pulses in the area (Bécu et al., 2008). Several quartz-tourmaline veins and breccias are also present. The showing was originally interpreted as a potential porphyry system associated with dioritic magmatism (L'Heureux, 2001) but complex structural and textural evidence suggest a structurally-controlled type of mineralization associated with sericitization and epidotization.



**Figure 7:** Grab photograph of a mineralized sample from the Ell Lake Cu-Ag-Au-Mo showing. Ell Lake mineralization is composed of chalcopyrite, pyrite, malachite and bornite and Bi-Mo sulfosalts associated with sericite (Ser) and epidote (Ep) (7.05% Cu, 5.6 g/t Au, 33.1 g/t Ag average content based on 5 selected samples; Bécu et al., 2008).

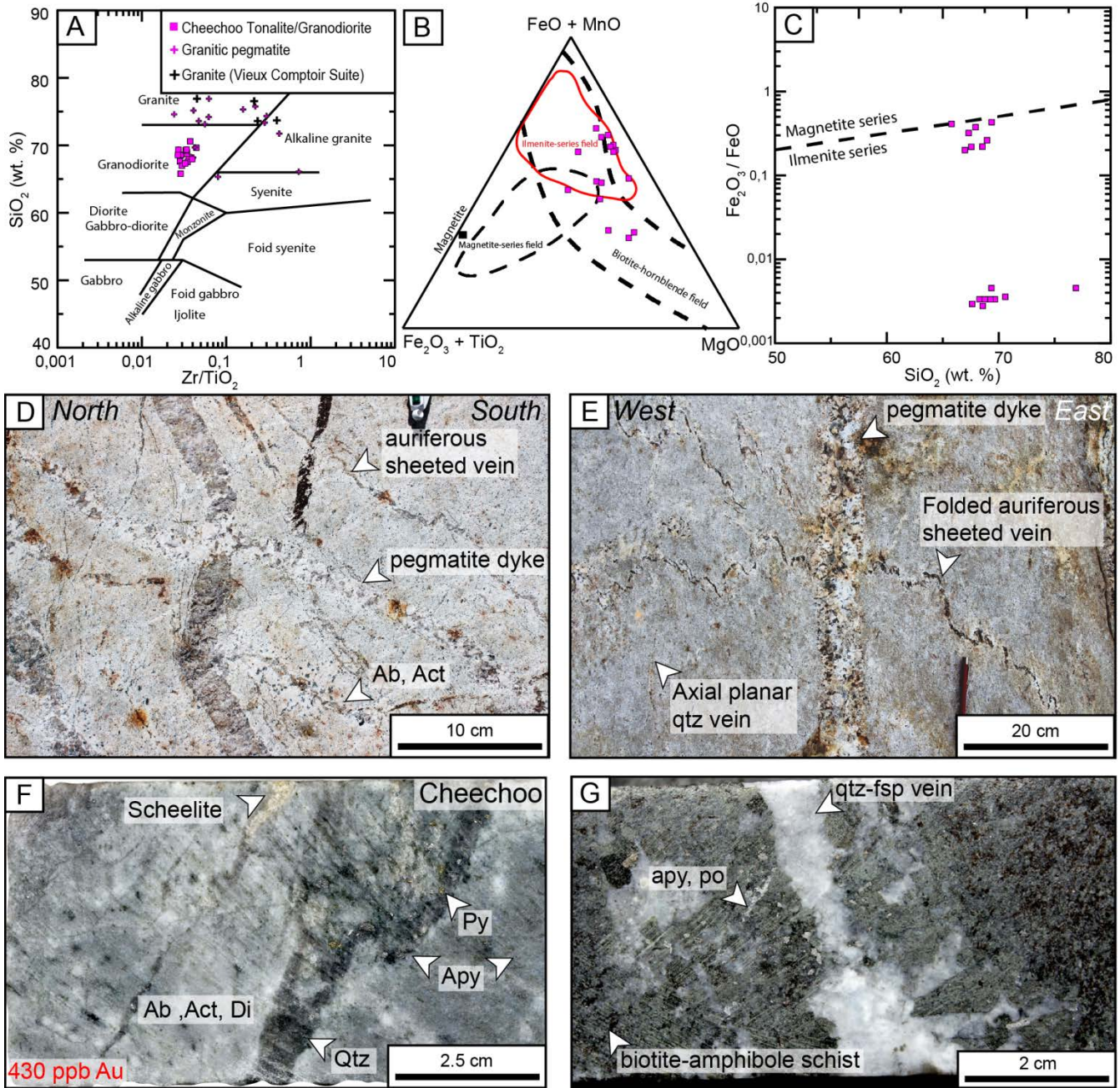
### Cheechoo Property (Sirios Resources)

Sirios Resources acquired the Cheechoo project in autumn 2004 just after the announcement of the Roberto showing discovery. From 2005 to 2011, Golden Valley Mines, the operator project, conducted various exploration program including EMH and aeromagnetic surveys, ground magnetometric survey,

conventional prospecting, trenching, channel sampling, humus geochemistry, and drilling (Girard, 2013). Between 2010 and 2012, systematic prospecting by Sirios Resources, Golden Valley Mines and IOS Services Géoscientifiques Inc. were completed and led to the sampling of numerous gold-bearing grabs (Girard, 2013). In 2013, a drilling campaign included 41 m at 0.74 g/t Au (Turcotte, 2014). Between 2014 and 2017, more drill hole intersections confirms the presence of an auriferous system, including 1.53 g/tAu over 19.5 m (Sirios, 2014), 12.8 g/t over 20.3 m (Sirios, 2016), 11.9 g/t Au over 13.5 m (Sirios, 2017).

Gold mineralization on the Cheechoo property is spatially associated with the Cheechoo intrusion dated at 2612±1 Ma (Fontaine et al., 2015), an age close to the Vieux Comptoir granitic suite from the La Grande and Opinaca subprovinces (Goutier et al., 1999; Goutier et al., 2000), and to the 2620-2600 Ma pegmatite dykes (Ravenelle et al., 2010). The intrusion has a tonalitic to locally granodioritic composition (Figure 8A). The intrusion is part of the reduced ilmenite series (Figures 8 B and C) The mineral assemblage in the host granodiorite/tonalite is composed of local feldspar phenocrysts in a matrix of quartz, feldspars (plagioclase and microcline), biotite, amphibole and local traces of diopside and actinote (Figure 8F). Various textures ranging from aplitic, granoblastic, gneissic to nematoblastic are developed. The intrusion is deformed and recrystallized and the main foliation (S<sub>2</sub>) is defined by elongated biotite, chlorite and amphibole (Figures 8 D, E and F). Locally, the tonalite shows progressive transition to quartz-feldspar pegmatite dykes. Highly foliated amphibole- and biotite-rich mafic dykes or wacke are locally present as clasts incorporated within the pegmatite dykes. Some of these clasts contain traces of diopside and fine disseminated arsenopyrite and pyrrhotite and can be gold-bearing.

The gold-bearing zones are hosted in bleached granodiorite/tonalite (Figures 8D, E and F) or in amphibole-biotite schist (Figure 8G), and at the contact with surroundings metasedimentary rocks. Silicified and albitized zones containing traces of disseminated fine arsenopyrite and pyrrhotite and local quartz veinlets host gold mineralization. Visible gold locally occurs in grey colored quartz replacement zones or within sheeted quartz or quartz-feldspar veinlets. These veinlets are commonly deformed by the main S<sub>2</sub> foliation (Figure 8E). Undeformed coarse quartz-feldspar pegmatites are also locally auriferous and are commonly abundant in the vicinity of the contact between the granodiorite/tonalite and metasedimentary rocks. Metasedimentary rocks at the contact are highly deformed and metamorphosed into paragneiss. Aluminosilicate-bearing wacke and amphibole-biotite schist (e.g. mudstone or lamprophyres) are located within a strongly mylonitized contact with the Cheechoo intrusion. Tonalite offshoots are injected within the deformed contact and within the metasedimentary rocks. The ca. 2612 Ma age of the host granodiorite/tonalite provides a new constraint for the maximum age of gold mineralization at Cheechoo. A network of quartz, pyrite and arsenopyrite veins with local traces of scheelite is locally present (Figure 8F).



**Figure 8:** Geochemical classification diagram for the Cheechoo intrusion and associated alteration and mineralization features. A: SiO<sub>2</sub> vs Zr/TiO<sub>2</sub> diagram (Winchester and Floyd, 1977); B: FeO+MnO, MgO, Fe<sub>2</sub>O<sub>3</sub>+TiO<sub>2</sub> ternary diagram (Ishihara, 2004) revised from Ishihara (1971) defining the magnetite (oxidized) and ilmenite (reduced) series; C: Fe<sub>2</sub>O<sub>3</sub>/FeO vs SiO<sub>2</sub> diagram from Ishihara (1981), modified by Sinclair (2007); D and E: Array of quartz veins with minor amount of feldspar, arsenopyrite rare visible gold. Some are folded while others are axial planar to these folds. Pegmatite dykes cuts these arrays; F: Quartz-pyrite-arsenopyrite-scheelite vein in the albitized Cheechoo granodiorite/tonalite; G: Biotite-amphibole schist injected by quartz-feldspar veins and with arsenopyrite disseminations.

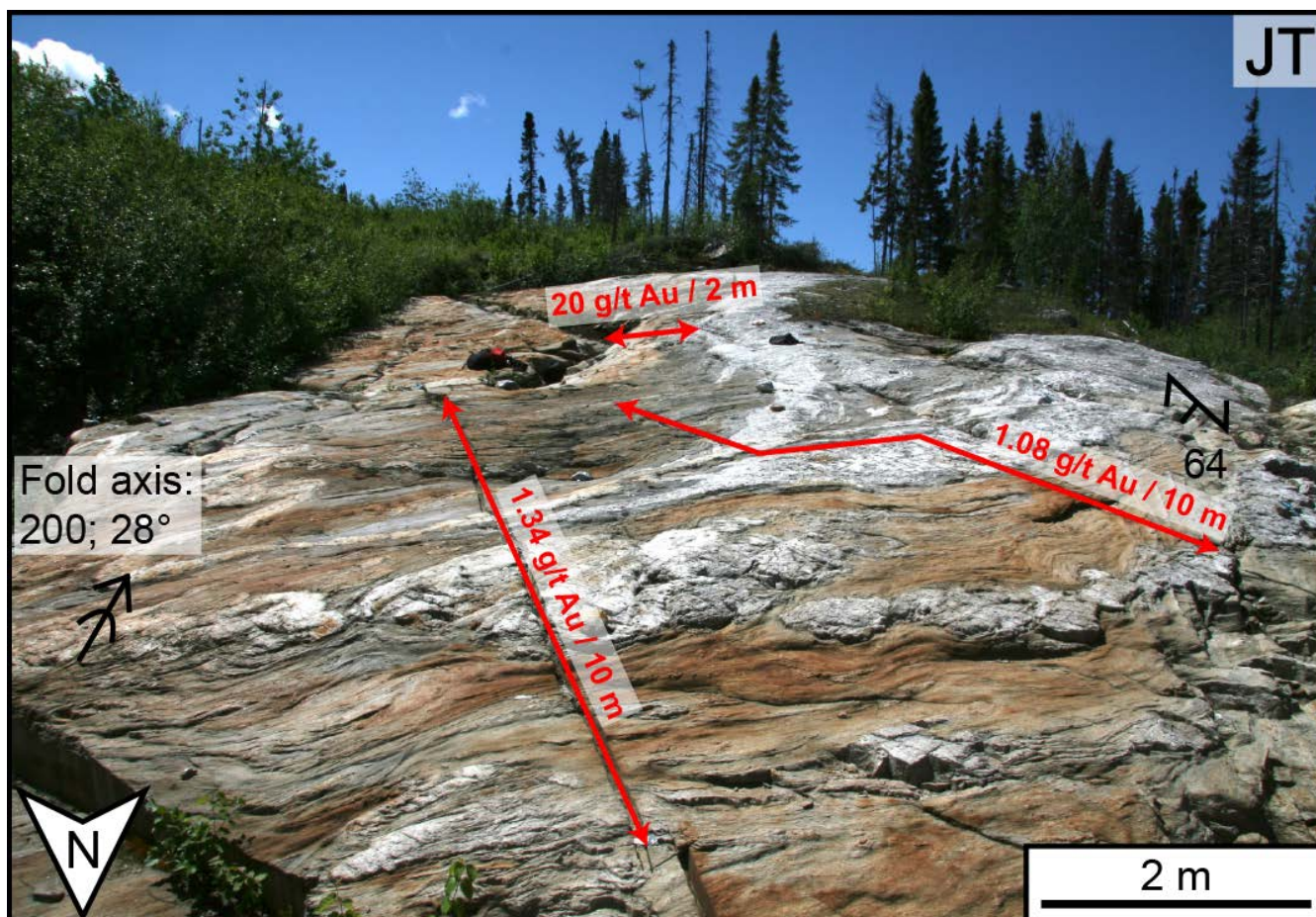


### Éléonore South (Azimut Exploration / Goldcorp / Eastmain Resources Joint Venture)

The Éléonore South property is located ~15 km southeast of the Éléonore mine and partly covers the Cheechoo tonalite. In 2005, Eastmain Resources conducted a B-horizon soil survey (more than 7,000 samples) on the Éléonore South property leading to the recognition of a 15 km-long gold-arsenic soil anomaly (Azimut, 2005). Altered, sulphide-bearing siliceous and/or potassic fine grained tonalite and, aluminosilicate-rich metasediments grabs were collected in an area up-ice of the soil anomaly (Azimut, 2006).

Several mineralized zones have been found including the JT, Moni and FD showings located within the Cheechoo tonalite intrusion, along its contact with metasedimentary rocks, or in the metasediments but close to the intrusion. The local geology is characterised by highly deformed and metamorphosed wacke, conglomerates, breccia, iron-formation, paragneiss, the Cheechoo granodiorite/tonalite, pegmatite and leucogranitic dykes (Figure 9).

The JT showing (including 1.49 g/t over 16 m) is located at the western boundary of the Cheechoo intrusion (Figure 2). Gold mineralization is mainly hosted by highly deformed paragneiss (Figure 9), tonalite and pegmatite dykes. The Moni prospect, hosted in tonalite and pegmatite, located 1 km southwest of the Cheechoo discovery, has provided channel samples including 49.18 g/t Au over 4 m (Azimut, press release November 3, 2016) and, in the same area, drill hole intersection at 4.9 g/t Au over 45 m including 13 g/t Au over 10.5m (Azimut, press release May 2, 2017). The tonalite is silicified and albitized with quartz stockwork and variable amount of biotite, actinolite and chlorite in association with  $\leq 1-2\%$  arsenopyrite, pyrite, pyrrhotite and traces of scheelite. Quartz-feldspar pegmatite dykes may contain visible gold and 1% sulphides, particularly where these cut or grade into mineralized tonalite (Azimut, press release November 21, 2016). Recent release by Sirios Resources suggests the extension of the Moni showing into the Cheechoo property to the north. The FD prospect is located 4.5 km north of the JT prospect along the contact between the Cheechoo tonalite and the deformed wacke (Azimut, press release August 29, 2016).



**Figure 9:** Éléonore South property (JT showing). Multiple locally auriferous, pegmatite dykes, in paragneiss and leucogranite dykes. Fold axis (10-30°) are shallow plunging typical of the Opinaca Subprovince structural pattern formed by the interplay of D<sub>2</sub> and D<sub>3</sub> deformation events coeval with injection of leucogranitic melt.

## IMPLICATIONS FOR EXPLORATION

### Host Rocks Influence

The strong anisotropy within the finely bedded wacke has influenced the development of the Roberto gold zone. The <2675 Ma thinly bedded wacke assemblage represent the youngest sedimentary rocks in the area. They are characterized by a high degree of preservation in the upper part of the deposit (e.g. cross-bedding stratification, normal grading and load structures on the Roberto outcrop). Their local preservation is probably due to strain partitioning.

### Structural Features

The interpreted north-northwest-trending D<sub>1</sub> fault may represent a subsidiary structure of the Opinaca-La Grande contact. In the mine area, overprinting deformation and metamorphism obliterates many primary features and has influenced the final geometry of the ore zones. Thinly bedded sedimentary rocks deformed by near-vertical F<sub>2</sub> and F<sub>3</sub> folds with steeply plunging fold axes, and locally injected by pegmatitic dykes in the vicinity of the Opinaca-La Grande contact are key exploration targets.

### Metamorphic Events

The deposit is deformed and metamorphosed. Ravenelle (2013) suggested that this is related to a diachronism of peak metamorphism and coeval D<sub>2</sub> deformation. In the Opinaca Subprovince, regional granulite facies metamorphism and anatexis occurred over >30 m.y. (Morfin et al., 2013). Syn-D<sub>2</sub> metamorphism, deformation and contemporaneous leucogranite veins/dykes injection occurred earlier in the granulite facies migmatites of the Opinaca from the metamorphic peak at ca. 2671 Ma to the granite solidus at 2637 Ma (Morfin et al., 2013). Whereas within the lower-grade La Grande supracrustal rocks, it lasted to ca. 2620–2603 Ma (Dubé et al., 2011), suggesting diachronism in the timing of tectono-metamorphic events from the high-grade Opinaca to the lower grade La Grande in a “deep-earlier” process (Stüwe, 1998). In this context, the numerous intrusive rocks (e.g. Cheechoo granodiorite/tonalite, pegmatites) have generated a temperature increase of an entire region by advection of heat into the crust related to the crystallization of leucogranitic melt with a slow cooling rate as suggested by Morfin et al. (2013).

### Magmatic Events

Various magmatic suites that include gabbro, diorite, granodiorite, monzodiorite, monzonite, syenite, tonalite, trondhjemite, granite, lamprophyre/albitite dykes and lithium, cesium, and tantalum (LCT) pegmatite dykes are associated with Archean intrusion-related and stockwork-disseminated gold systems in the Superior Province (Dubé et al., 2015). This is well illustrated in the Éléonore 10 km<sup>2</sup> mine area (Figure 7) by the feldspar-phyric diorite (<2674–2668 Ma), the Cheechoo granodiorite/tonalite (ca. 2612 Ma) and leucogranite veins and pegmatites (ca. 2620–2603 Ma) as all of them host gold mineralization. As proposed by Ravenelle et al. (2010), pegmatite dykes (2620–2603 Ma) are coeval, with at least part

of high-grade quartz vein-type gold mineralization. However, most of the pegmatite dykes cut the 5050 and the 6000 zones and some contain foliated fragments of the ore. Such chronology suggests a protracted period of time where leucogranite and pegmatite dykes are injected syn- to late-D<sub>2</sub>, to early D<sub>3</sub> deformation.

The presence of reduced magmatism (ilmenite-series) at ca. 2612 Ma (Cheechoo granodiorite; Figure 8E) appears to be important for exploration in the area. The apex part of such intrusion and wallrocks could host reduced-intrusion related gold mineralization (Thompson et al., 1999).

### Alteration Mineralogy and Geochemical Features

Elevated K<sub>2</sub>O/Na<sub>2</sub>O (Figure 5C), SiO<sub>2</sub>/Na<sub>2</sub>O, and CaO, MnO, MgO, B and Sb enrichment anomalies appear the most indicative pathfinder ratios or elements to locate proximal pervasive alteration and potential ore zones. Enrichment in K<sub>2</sub>O, CaO and MnO combined with Na<sub>2</sub>O depletion, particularly in the hanging-wall aluminosilicate-bearing metapelite, are documented in close association with the presence of replacement metasomatic alteration, associated with the auriferous system.

Recognizing metamorphosed and transposed alteration assemblages and gold mineralization is a critical feature in hydrothermal system strongly overprinted by metamorphism and deformation (McFarlane et al., 2007). Calcium-bearing metasomatism, containing up to 200 ppb Au, is present as replacement bands strongly affected by subsequent deformation. These metasomatic zones are characterized by a metamorphic assemblage containing various proportions of actinolite, diopside, quartz, clinozoisite and minor amount of quartz, anorthite and garnet. In the study area, presence of microcline, phlogopite, muscovite, dravite or schorl finely disseminated arsenopyrite, lollingite and pyrrhotite, coupled with calcium-bearing veinlets are strong indicators of the ore zones or proximity to potential high-grade gold mineralization (> 15 g/t Au). Silicification, tourmalinization associated with hydrothermal breccia and stockwork of dravite and/or sulphide veinlets parallel or at high angle to the bedding are ubiquitous features in the 6000 and the 5050 zones, hosting the bulk of the gold at Éléonore (Ravenelle et al., 2010; Fontaine et al., 2015).

## CONCLUDING REMARKS

The discovery of the Roberto deposit was the result of field work, vision, perseverance and standard field-based exploration methodology including a combination of systematic prospection, geological reconnaissance and grab sampling, systematic description of erratic boulders, all in the vicinity of the historical showings area. The exploration program was designed to locate the source of mineralized boulders and led to the discovery of the Roberto showing, 5 km northeast of the Eil Lake showing. Mechanical stripping, geological and structural mapping, channel sampling and drilling confirmed the presence and continuity of the Roberto gold deposit and were crucial for the development of the Éléonore mine. Extensive geophysical (IP, ground magnetic) and geochemical surveys (soil and bottom lake sediments) with glacial trend and sense of direction help to further extending of the mineralized Eil Lake system to the

northeast. These have permitted geologists to delineate new geophysical, geochemical or geological targets located in the northeast shore of the Opinaca reservoir.

The formation, evolution and preservation of gold mineralization in the Éléonore area is related to the Opinaca-La Grande first-order structure and associated strong metamorphic gradient and magmatism, Ca-K-Si-B hydrothermal activity associated with Au-As±Sb-Bi-W-Sn-Se-Te signature, polyphase deformation with intrusion of a 2612 Ma granodiorite/tonalite and 2620–2603 Ma pegmatites and leucogranite veins. D<sub>1</sub> and early-D<sub>2</sub> deformation have provided key structural features, and/or ground preparation for the infiltration and/or trapping of the metamorphic, magmatic, or more probably a combination of both, hydrothermal system. The deposit recorded a complex multistage history, illustrated by the original characteristics of the hydrothermal system locally preserved in the subsurface which evolved with depth into a deformed and metamorphosed ore locally hosted within paragneiss. On a regional point of view, the deposit shares analogies with syn- to post-peak metamorphism hypozonal gold deposits as described by Kolb et al. (2015). However at deposit scale, the ore has been deformed and metamorphosed during the main deformation event (D<sub>2</sub>). The injection of leucogranitic veins and pegmatites in the supracrustal La Grande rocks occurs syn- to late D<sub>2</sub> and during early-D<sub>3</sub>. This is supported by a barren pegmatite cutting the main ore zone and containing foliated ore fragments. The auriferous calc-silicate-bearing veins and replacement could represent metamorphosed equivalent to quartz-carbonate veins and carbonate alteration (Ravenelle et al., 2010). Alternatively, the early stage of the bulk of the mineralization relative to the main deformation and metamorphism in the deposit area, the metallic signature, ore and alteration assemblages, proximity of a reduced granodiorite-tonalite intrusion (Cheechoo; Figure 2) and pegmatites share analogies with structurally-controlled sediment-hosted reduced intrusion-related gold deposits, a controversial group of deposits that shares attributes with pluton-related thermal aureole deposits and with some orogenic deposits (Thompson and Newberry, 2000; Wall et al., 2004; Goldfarb et al., 2005; Robert et al., 2007).

### ACKNOWLEDGMENTS

The authors would like to thank Goldcorp Inc, Éléonore mine and its staff for scientific input and logistical support on the PhD project of the first author. As the mine is under production, getting access to ore zones would not be possible without the full support of mine technicians (Catherine Vellet, Miguel Paradis, David Bélisle and Nicolas Dumais). Thanks to all the geologists for their contributions based on many constructive discussions on the geology of the mine. Particularly, we would like to thank Luc Théberge, Julie Doyon, Tony Brisson, Sally Goodman, Rob Penczak, Jacques Simoneau, Peter Lauder, Martin Perron, Sylvain Girardeau, Francis Larivière, and Olivier Vadnais-Le Blanc. Michel Gauthier is thanked for many passionate conversations on the Eeyou Istchee James Bay, the Cheechoo project and historical gold exploration and concepts applied to those areas. Robert Oswald, Mathieu Savard and Jean-François Ouellette are thanked for invaluable discussions related to Roberto discovery and geology. Jordi Turcotte, Dominique Doucet and Jacquelin Gauthier (Sirios Inc.) are

thanked for many discussions on the geology of the Cheechoo property. Jean-Marc Lulin of Azimuth Exploration is thanked for sharing his knowledge of the Éléonore South property. Valérie Bécu is thanked for many discussions on the geology of the Ell Lake showing and for giving access to unpublished data and samples. This research is funded by the Geological Survey of Canada through the Targeted Geoscience Initiative and Goldcorp-Éléonore. FRQNT (Fond de Recherche du Québec – Nature et Technologies) and NSERC (Natural Sciences and Engineering Research Council of Canada) are also thanked for providing a scholarship to the first author through the BMP (Bourse en milieu pratique) Innovation program. A. Fontaine would like to thank AQUEST and DIVEX for their financial support through scholarships.

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