Mineralogical and geochemical study of the True Blue aquamarine showing, Shark property, southern Yukon

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ABSTRACT

The True Blue aquamarine occurrence in the Quiet Lake area of southern Yukon is underlain by Paleozoic Cassiar Platform miogeoclinal clastic and carbonate rocks, a Mississippian syenite stock, Mississippian felsic metavolcanic rocks (Pelly Mountain Volcanic Belt), and a small carbonatite body associated with the syenitic intrusion. Beryl occurs in quartz veins and tension gashes, and is restricted to those that cut the syenite. Accessory minerals in the quartz veins include varying amounts of fluorite, siderite, calcite, allanite and ilmenite. Mineralization has been dated at 172 ± 5 Ma, using the Sm-Nd system on fluorite from several veins. Aquamarine discovered on the property is distinctive because of its deep blue colour and high Fe^{2+} concentration, up to 5.79 wt.% FeO. During the 2004 field season, diamond chainsaws were used to extract beryl-bearing vein material from the syenite.

RÉSUMÉ

Le gisement d'aigue-marine True Blue, situé dans la région du lac Quiet, dans le sud du Yukon, recouvre des roches clastiques et carbonatées miogéoclinales de la plate-forme de Cassiar datant du Paléozoïque, un stock de syénite du Mississippien, des roches métavolcaniques felsiques du Mississippien (ceinture volcanique de Pelly Mountain), ainsi qu'un massif de carbonatite associé à l'intrusion syénitique. Du béryl est présent dans des veines de quartz et des fissures d'extension, et se limite à celles qui ont recoupé la syénite. Les minéraux accessoires dans les veines de quartz comprennent des quantités variables de fluorine, de sidérite, de calcite, d'allanite et d'ilménite. L'âge de la minéralisation a été établi à 172 ± 5 Ma par la méthode Sm-Nd appliquée à la fluorine provenant de plusieurs veines. L'aigue-marine découverte dans la propriété se distingue par sa couleur bleu foncé et par sa concentration élevée de Fe^{+2}, la proportion de FeO pouvant atteindre 5,79 % en poids. Au cours des travaux sur le terrain de 2004, on a utilisé des scies à chaîne à tranchants au diamant pour extraire les matériaux de la veine bérylifère de la syénite..

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INTRODUCTION

The True Blue aquamarine occurrence on the Shark claims is situated in the Ketza-Seagull District in southern Yukon, and is wholly owned by True North Gems Inc. (True North). The contiguous 94-claim block lies within NTS map sheets 105F/8, 9 and 10 with central coordinates of 61°30' latitude north and 132°30' longitude west (Fig. 1).

Dark blue gem beryl mineralization was identified in quartz veins cutting a Mississippian syenite during the 2003 field season and exploration continued into 2004. Recent work on the property consisted of geological mapping, geochemical soil and silt sampling, specimen extraction, and laboratory investigations following the field seasons. These further investigations make up an MSc thesis by the first author at the University of British Columbia. Mineralogical, geochemical and geochronological studies of the veins and host rock are currently being pursued in order to better understand the geology and mineralogy of the True Blue aquamarine occurrence. These studies will provide essential information for developing a deposit model that will more specifically define exploration parameters for this style of beryl mineralization. In this article we discuss the results of our fieldwork and the most recent findings on the geological setting of this occurrence.

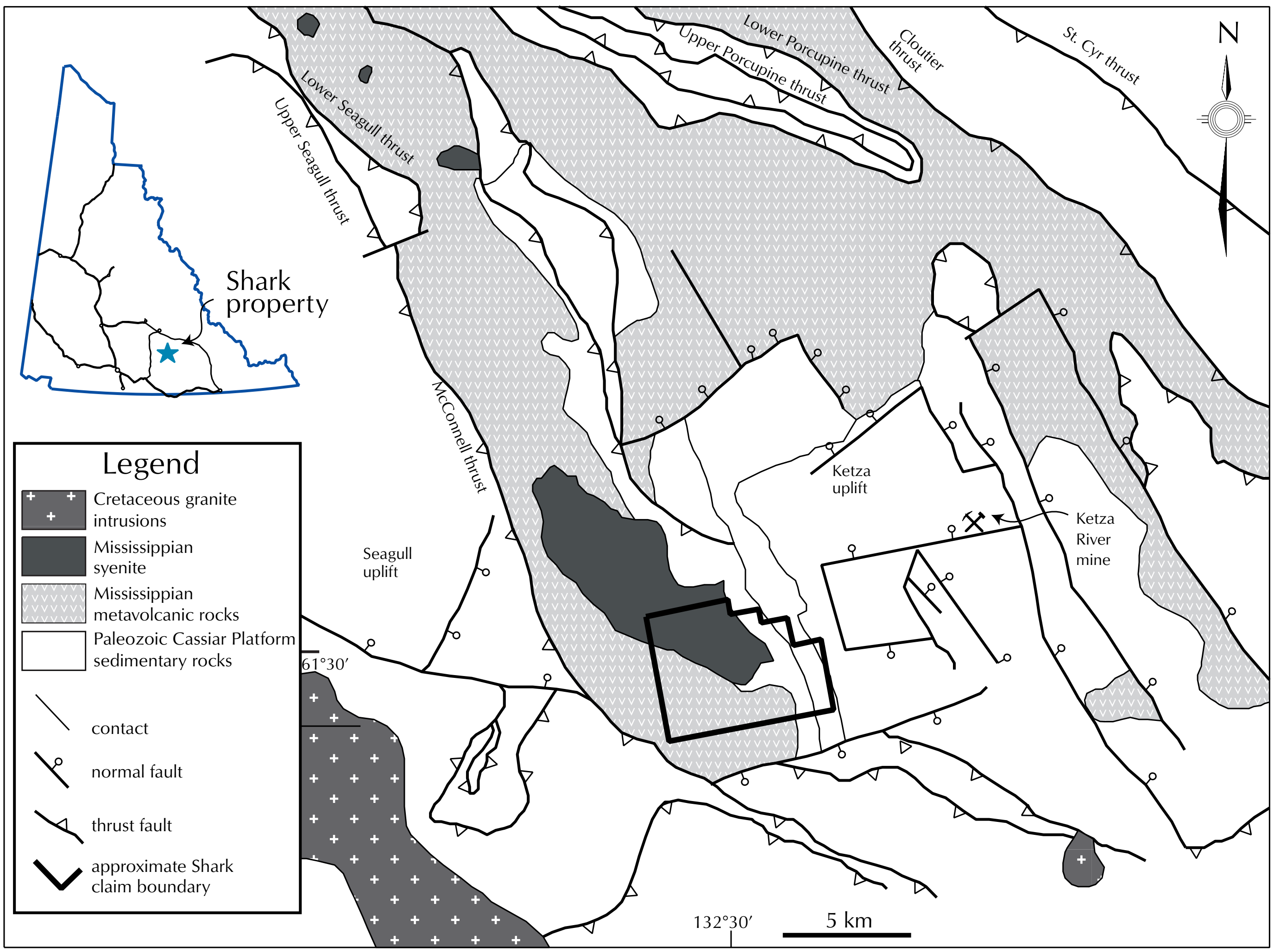

Figure 1. *True Blue property location and regional geology of the Ketza-Seagull District, southern Yukon. Modified after Tempelman-Kluit (1977) and Gordey and Makepeace (2003).*

PROPERTY EXPLORATION HISTORY

Since the late 1960s, considerable work has been done in the Ketza-Seagull District. Exploration has focused on lead-zinc veins, gold-rich vein and manto deposits, uranium-rare earth element prospects, and volcanogenic massive sulphide (VMS) mineralization (Deklerk, 2003).

In 1976, the Guano claims were staked by Ukon Joint Venture (Chevron Minerals Limited and Kerr Addison Mines Limited) to cover the eastern portion of the present Shark property. Those claims were explored for uranium and rare earth elements (REE) associated with skarns and veins developed peripheral to a Mississippian syenite stock (Archer, 1977). In 1979, an Msc thesis that focused on uranium-REE enrichment at the Guano property was completed at the University of British Columbia (Chronic, 1979).

In the late 1980s, the White and PS claims were staked by Mountain Province Mining Inc. to cover a large gold target. Most of those claims were north of the Shark claims but some covered the eastern portion of the current Shark property (Deklerk, 2003).

In 1988, B. Hall staked the Matthew claims, which included what now is the southwestern corner of the Shark property, in order to cover a Kuroko-type VMS target. After a number of option agreements, the Matthew claims expired during the 1990s and were restaked as the Mamu-Bravo-Kulan claims (Deklerk, 2003).

While conducting exploration peripheral to the Guano claims during the 1976 Ukon Joint Venture program, D. Eaton of Archer Cathro discovered an unidentified blue mineral within a quartz vein that cut a syenite boulder. The occurrence was documented in a traverse report but its importance was not appreciated until L. Groat identified the mineral as beryl in fall 2002. In response to the confirmation of beryl, Archer Cathro staked the Shark claims on behalf of True North as part of a regional gem-beryl exploration program.

2004 FIELD SEASON WORK

Exploration during the 2004 field season was conducted by Archer Cathro for True North, and focused on Shark Bowl and Guano Ridge (Fig. 2). Shark Bowl is the main area of dark blue gem-beryl mineralization and Guano Ridge has geological characteristics similar to Colombian-type emerald occurrences.

A diamond-disc hand saw had been used to extract material during the 2003 field season; however, this only allowed incisions up to ~12 cm deep. As a result, quartz vein extraction within Shark Bowl during the 2003 field season focused on beryl mineralization on exposed vein surfaces. Although gem-grade material was obtained in 2003, some of the crystals had suffered damage from natural surficial processes such as rock fall. Accordingly, the potential for gem-quality stones was thought to be better in unexposed quartz veins and as such, work during 2004 focused on extracting undamaged quartz veins.

During and following the 2003 field season, hypotheses were developed about the conditions of beryl crystallization and a paragenetic sequence. However, no key minerals were identified within the veins that positively indicated the presence of beryl. Consequently, only those veins that showed beryl mineralization on the surface were examined and sampled in 2004, with particular attention being paid to those crystals with dark blue colouration.

During the 2004 field season, several improvements were made to the extraction process. Two 18-inch (~ 40 cm) diamond chain saws were used to facilitate deeper cuts for removal of larger amounts of intact veins. To cool the saws, three pumps, drill hose and a number of holding drums were flown via helicopter to the head of the Shark Bowl, to prepared sites at approximately 70-m vertical intervals. At each pump and active cutting site, 170-litre drums were used to hold water and supply hydraulic head to the saws via garden hoses. In total, 785 kg of concentrated vein material was extracted from syenite talus and bedrock exposures in Shark Bowl during a two-week period. Following completion of the extraction work in August, the concentrate was moved from the Shark property to Regal Ridge (located 100 km to the east-southeast). Processing of the concentrate is scheduled for early in the 2005 field season.

The geological setting of Guano Ridge is similar to the setting of Colombian-type emerald deposits (Walton, 2004). Furthermore, previous geochemical data showed enrichment of both beryllium and chromium, which are essential components for emerald mineralization. Soil sampling and prospecting was conducted on this portion of the property, but no beryl has been identified thus far.

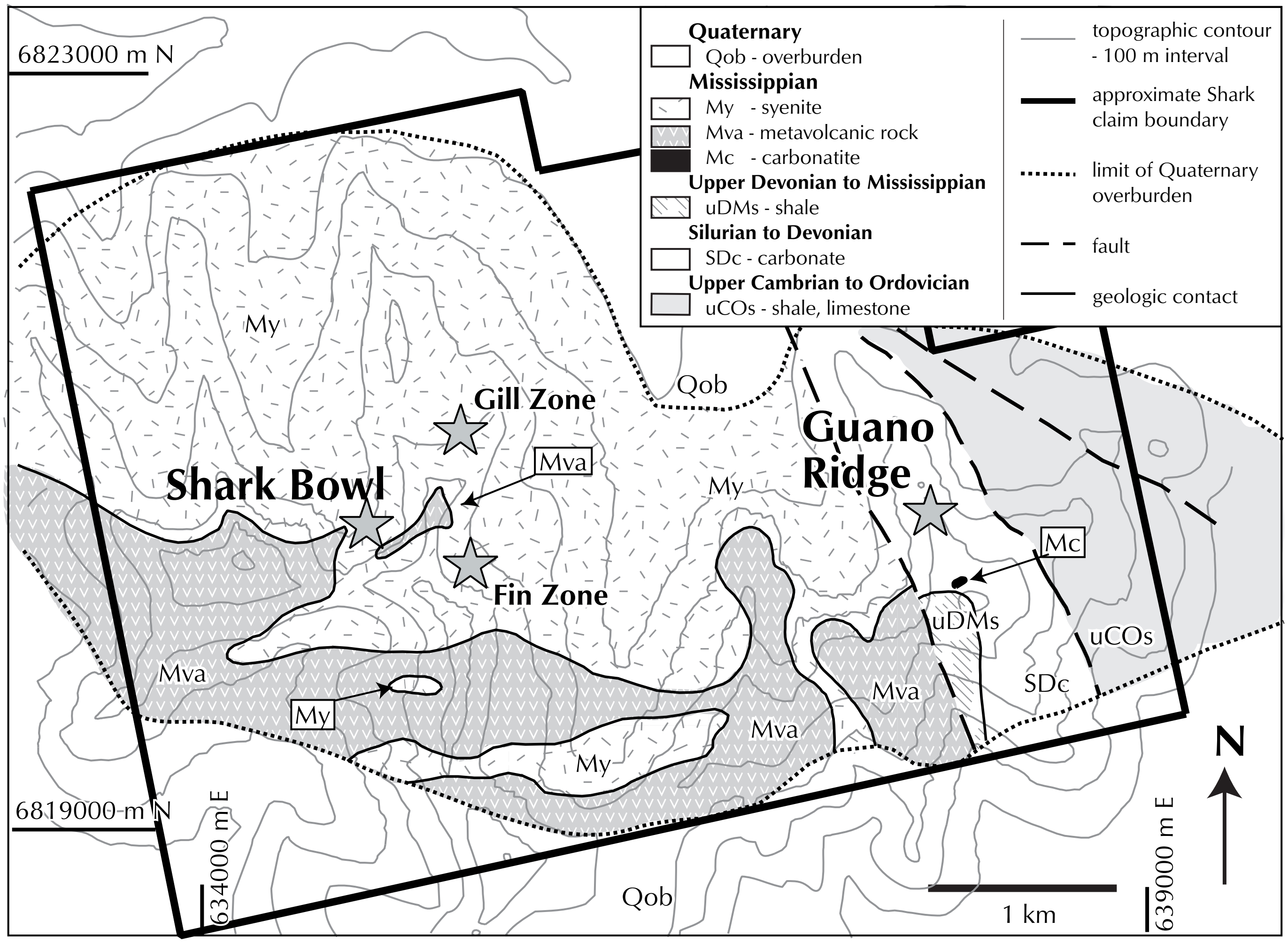

Figure 2. *Geology map of the True Blue property. Grid coordinates are UTM zone 8. Labelled stars indicate beryl targets.*

REGIONAL GEOLOGY AND STRUCTURAL SETTING

The Shark property is located within the Cassiar Platform, which is a displaced tectonic element composed of Lower Paleozoic miogeoclinal clastic and carbonate rocks (Fig. 1) that are overlain and interfingered with felsic to mafic metavolcanic rocks of Mississippian age. These volcanic rocks form the arcuate northwest-trending Pelly Mountain Volcanic Belt (Hunt, 1997) and are believed to have been deposited in a continental rift environment (Mortensen, 1982). Roughly coincident with the southwestern edge of the volcanic belt is a 32-km-long string of syenite intrusions, which are thought to be the subvolcanic equivalent of extrusive components of the Pelly Mountains Volcanic Belt. The largest of the syenite intrusions is partially covered by the Shark claim block (Figs. 1 and 2). This entire package of rocks was subject to several phases of deformation and faulting during arc-continent collision. Early phases of deformation, likely post-Late Triassic in age, are thrust-related events that produced several "southwest-dipping thrust panels and northeasterly verging folds within the region" (Gibson et al., 1999, p. 238). Locally, this deformation event produced foliations that are both parallel and subparallel to bedding in the layered rocks. Late-phase deformation is characterized by normal faults that cross-cut prior structures and are likely related to Cretaceous intrusions of the Cassiar Suite.

In a detailed study of the Ketza River mine area, Fonseca (1997) described two phases of regional ductile deformation, followed by regional thrusting, and finally local extension. The latter extension was accompanied by influx of hydrothermal fluids, which are thought to have been related to a buried Cretaceous intrusion.

PROPERTY GEOLOGY

The largest pluton within the suite of Mississippian syenitic intrusions and its extrusive equivalents underlie the bulk of the Shark property (Fig. 2). Older metasedimentary units (uCOs, SDc and uDMs) are intruded and overlain by these Mississippian igneous rocks. The following paragraphs describe each of the units, from oldest to youngest.

Unit uCOs is Late Cambrian to Ordovician in age and comprises grey to black, lustrous phyllite and minor black shale. The rocks are typically thinly bedded and moderately deformed. Quartz-calcite veining in the unit is predominantly deformed and bedding parallel.

Unit SDc includes thinly to thickly bedded, grey limestone and orange-weathering dolomite with minor quartzite. This Silurian to Devonian unit forms the bulk of Guano Ridge and hosts a subeconomic REE skarn (Chronic, 1979). Minor brecciation and quartz-calcite cementation is present within this unit.

Unit uDMs consists of thinly laminated, dark grey to black shale that weathers to blocky cobble- and smaller-sized clasts. Quartz veins in this unit are rare, barren and up to 4 cm in width.

Unit Mva is a package of felsic metavolcanic rocks with minor sedimentary interbeds. It includes phyllite, argillite, chert, lapilli tuffs, volcanic breccias, trachyitic flows, and sericite and chlorite-talc-altered schist. Metamorphic grades range from lower greenschist to lower amphibolite facies. This unit typically ranges from pale green to grey to maroon in colour, and weathers to form platy to blocky talus. Quartz veins hosted in this unit typically contain siderite and rarely fluorite and sulphide minerals. Vein abundance generally increases with proximity to the syenite.

Unit My forms a 12-km-long, 3-km-wide syenite stock, the southeastern half of which is located on the Shark property. It is medium- to fine-grained, equigranular and perthitic. Accessory minerals identified in thin section include magnetite, zircon, apatite, fluorite and pyrite. The colour is variable, ranging from light grey to pink to dark green. The rock is massive and weathers resistantly to form prominent cliffs along ridges. Pockets of Mva, possibly roof pendants too small to be mapped at a regional scale, are present within this unit. Zircons from unit My have been dated at 362.7 ± 3.6 Ma using U-Pb methods (J.K. Mortensen, pers. comm., 2004). Tension gashes are locally abundant in this unit, comprising up to 30% of the rock and ranging in size from mm- to m-scale.

Unit Mc, a light to dark green carbonatite, crops out just outside the margin of Unit My within Unit SDc. Macroscopic minerals include a possible feldspathoid that stands out from the more recessive matrix on weathered surfaces, and a black tourmaline-like mineral with similar habits.

Unit KqC comprises quartz monzonite and granite of Cretaceous age that has been assigned to the Cassiar Plutonic Suite, with ages between 100 and 110 Ma (Mortensen et al., 2000). This unit has not been recognized thus far on the Shark property, and the closest outcrop of the unit lies ~10 km to the southwest. However, Cretaceous granite may underlie the map area and thus warrants a description. Locally in the Ketza-Seagull District, the Cassiar Suite intrusive rocks typically consist of grey-weathering, equigranular, medium- to coarse-grained quartz monzonites.

PROPERTY-SCALE STRUCTURES

Unit uCOs is separated from units SDc and uDMs by a near-vertical, north-northwest (330°) trending fault. A second fault (located ~800 m to the southwest and trending approximately 335°) separates the carbonate and clastic rocks in the eastern part of the property from the main body of syenite and metavolcanic rocks to the west. Bedding in stratified units across the property strikes roughly northeast and dips moderately to the southeast.

VEIN MINERALOGY

Beryl mineralization on the True Blue property occurs in quartz veins and tension gashes and is restricted to veins that cut the syenite. Vein mineralogy is currently being investigated using a variety of techniques, including thin section petrography, scanning electron microscopy (SEM) and electron probe micro-analysis (EPMA). Major components of the quartz veins include beryl, siderite, fluorite and allanite, and minor phases include ilmenite, pyrite and calcite. Tourmaline was identified in the field; however, these grains were subsequently identified as allanite by powder X-ray diffraction. Additional samples are currently being investigated in order to determine if tourmaline is indeed present at the True Blue property.

BERYL

The beryl ranges in colour from dark blue to light blue, and from yellow-green to green to turquoise. Colour zonation has been noted in several crystals, and is characterized by blue cores surrounded by green rims. Variable amounts of iron in beryl are known to result in blue, green and yellow colours (Sinkankas, 1981). Some of the colour-zoned crystals occur adjacent to allanite, suggesting that iron is partitioning favourably into that phase. Beryl is most commonly observed as externally euhedral crystals in both finely crystallized masses, as well as in larger single crystals or clusters of crystals. Single crystal sizes discovered thus far range from submillimetre to ~2.5 cm in width, and up to several centimetres in length, whereas clusters of crystals have been found to measure up to 9 cm x 8 cm. The clarity of the beryl ranges from opaque to transparent. Poor clarity is commonly due to fractures perpendicular to the *c*-axis and, less commonly, mineral inclusions.

Euhedral to anhedral cores (single and multiple) and complex internal zoning are present in many crystals when observed in back-scatter electron (BSE) mode in the SEM (Fig. 3). Mineral inclusions observed in the beryl include siderite, calcite, quartz, and a calcium-REE phase. A total of 142 analyses of major and minor elements from numerous beryl specimens have been acquired via EMPA. Weight % FeO values average around 2.5 and range up to 5.79, which are the highest FeO contents ever described in scientific literature for beryl. Significant amounts of Na, Ca and Mg have also been detected. Figure 4 shows octahedral Al-site substitution by cations Fe^{2+} and Fe^{3+}, Mg^{2+}, Mn^{2+}, Cr^{3+}, V^{3+} and Sc^{3+}. Specimens with lower total FeO content show typical patterns of octahedral substitution, while those with higher FeO content exhibit higher over-substitution at the Al site. This deviation from normal behaviour may be due to iron residing in the channel sites within the beryl crystal, and is likely the cause of the dark blue colour of the high-FeO-content beryl. This phenomenon is being investigated further with single crystal neutron diffraction and Mössbauer spectroscopic techniques.

Dark blue beryl is very rare, having been recognized only in United States (Lone Pine), Madagascar (Ambositra), Pakistan (Gilgit), and a small number of localities in Brazil (e.g., Marambaia and Paraiba). Unfortunately, none of these sites have received detailed investigations and none of these sites have consistently produced gem-quality material. Since there is no steady supply of dark blue beryl in today's market, valuation of the True Blue beryl is difficult.

CARBONATES

Siderite is the dominant carbonate mineral present in the veins, and forms euhedral crystals up to several centimetres in width with a purplish metallic lustre, as well more typical euhedral crystals with brownish submetallic lustre. Much of the siderite has been heavily weathered

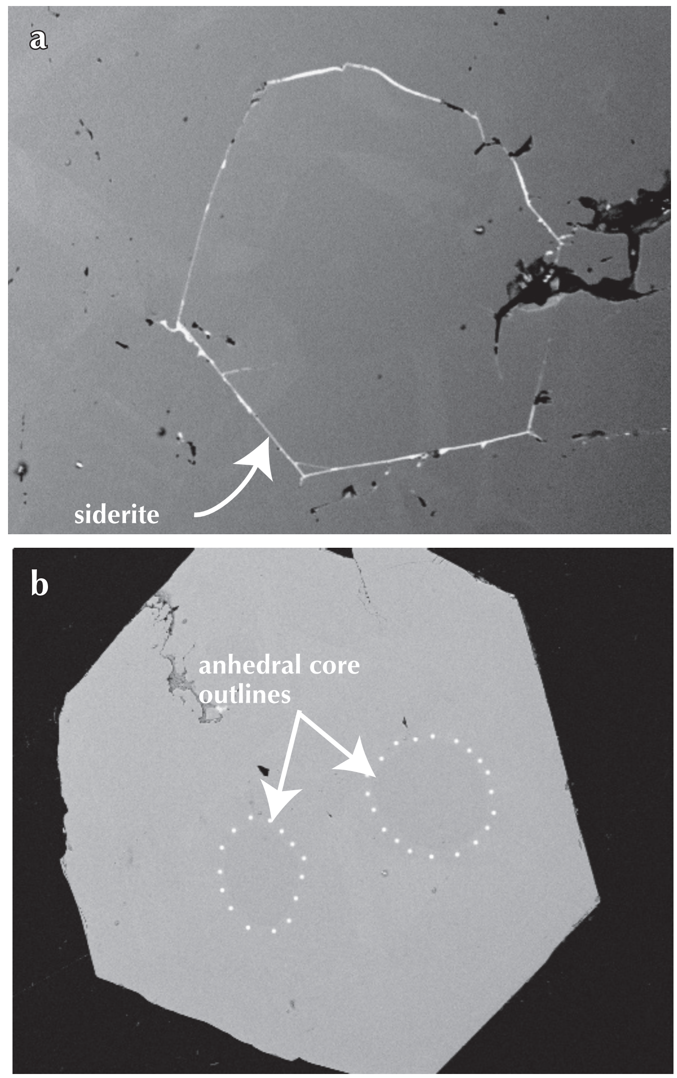

Figure 3. *SEM photomicrographs (BSE mode) of beryl from True Blue.* ***(a)*** *A euhedral core surrounded by siderite inclusions (light tone);* ***(b)*** *an example of beryl with multiple anhedral cores and complex compositional zonation. Field of view is ~800 μm for each image.*

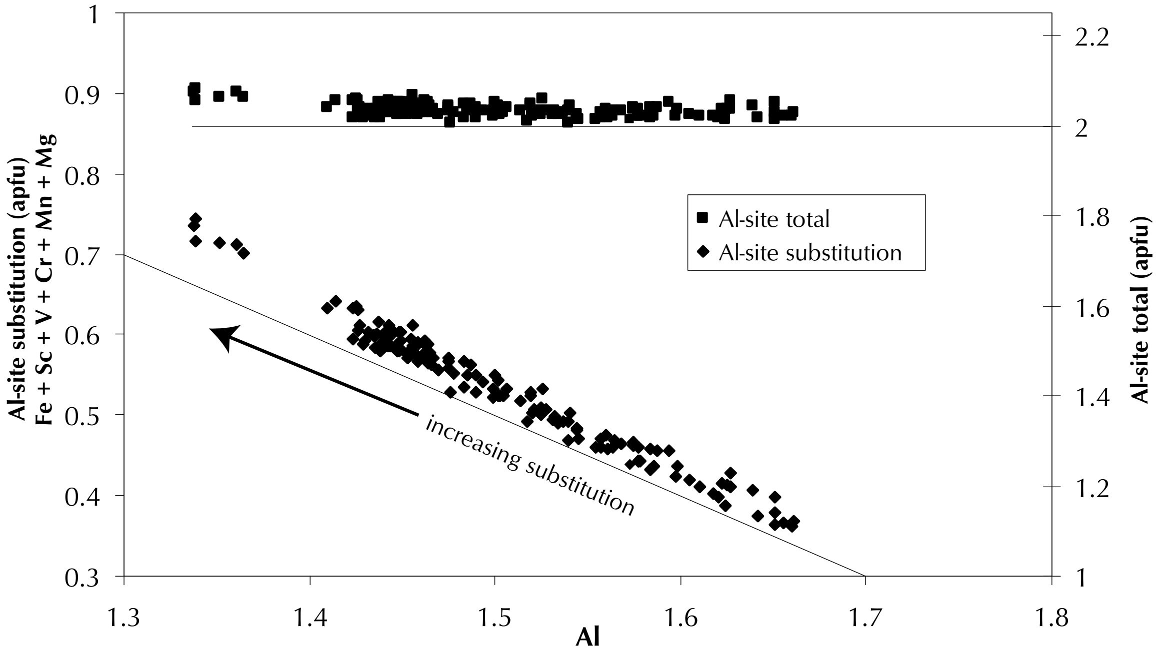

Figure 4. *Transition metal substitution for Al and total occupation of the octahedral Al-site within beryl (ideal formula = $Be_3Al_2Si_6O_{18}$) from the True Blue occurrence. The outlying set of data with low Al contains the highest FeO contents and shows the deepest blue colouration. APFU=atoms per formula unit.*

and carbonate-pitting in exposed veins is common. Minor magnesium-calcium-carbonate has also been observed in the veins, and trace amounts of what is most likely a REE-carbonate have been observed with the SEM. Carbonates are the next abundant phase after quartz in the tension gashes.

FLUORITE

Clear and light to dark purple fluorite are common components of quartz veins. Fluorite commonly makes up the entire width of individual veins, forming clots up to 10 cm across as opposed to euhedral crystals. Figure 5 shows REE compositions of fluorite collected during geochronological studies. REE concentrations are moderately elevated and show a prominent negative Eu anomaly when compared to chondritic values (McDonough and Sun, 1995). The variability of light rare earth elements (LREE) is likely due to the presence or absence of proximal allanite, which preferentially incorporates LREE over HREE (Giere and Sorensen, 2004).

ALLANITE

Allanite was positively identified using X-ray powder diffraction techniques after unusual textures and X-ray patterns were observed from what was initially thought to be tourmaline. Crystals form individually up to several centimetres in length and as radiating masses up to several centimetres in length and width. A total of 39 EPMA analyses have been carried out on allanite crystals, which display up to 29 wt.% REE_2O_3, classifying the allanite as the cerium-dominant variety (Ercit, 2002). Figure 6 (Petrik et al., 1995) confirms this classification in the epidote mineral group and also estimates a Fe^{3+}/Fe_{total} value of ~0.25. Unusual zoning and REE-carbonate inclusions are apparent with the SEM in BSE mode.

ILMENITE AND PYRITE

Trace amounts of pyrite and ilmenite have been found within the quartz veins. It is unlikely that either of these minerals is critically involved in beryl precipitation; however, their systematics will be used to constrain fluid conditions. Ilmenite forms platy euhedral crystals up to 1 cm in diameter and 3 mm thickness, whereas the pyrite occurs as fine-grained masses.

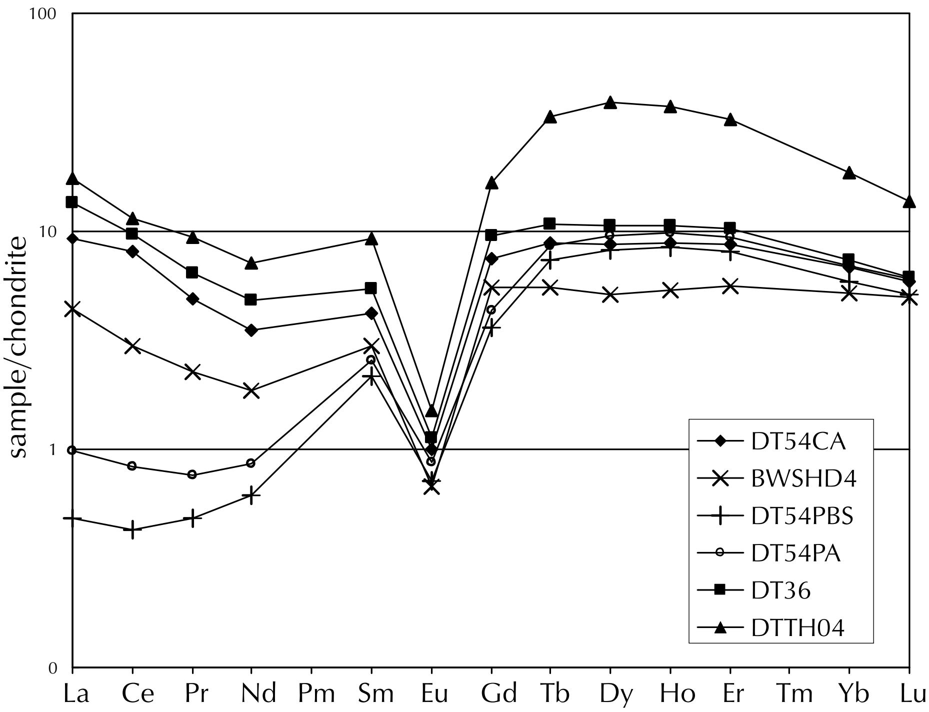

Figure 5. *Chondrite-normalized REE profiles of fluorite from tension gashes cutting syenite within Shark Bowl. Note the variable LREE concentrations and pronounced negative europium anomalies.*

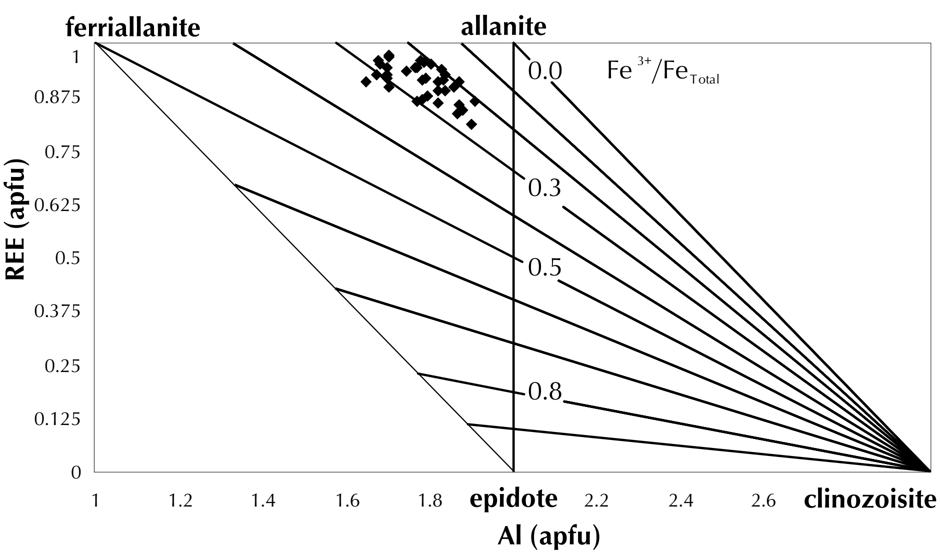

Figure 6. *Discrimination diagram between four members of the epidote group. Lines of constant Fe^{3+}/Fe_{total} value originate from clinozoisite and allow an estimation of this value (after Petrik et al., 1995).*

PARAGENETIC SEQUENCE OF VEIN MINERALS

A full paragenetic sequence for vein components is currently being developed, although the relative timing of some individual mineral phases remains unclear. However, a few general statements about system conditions and mineral relationships may be inferred:

- Siderite is present in virtually all tension gashes, both within the syenite host and outside within the metavolcanic wall rocks.
- Siderite crystallized both before and after beryl, and between beryl growth periods as inclusions around beryl cores.
- Ubiquitous fluorite suggests that beryllium and REEs were being complexed by fluoride anions, which is supported by examples of beryl and allanite that crystallized adjacent to one another.
- Large variations in LREE concentrations within fluorite suggest co-precipitation of the fluorite and LREE-enriched allanite.
- Ilmenite crystallized both before and after beryl and allanite.
- Resorbed cores in beryl indicate periods of fluid conditions out of equilibrium with previously crystallized minerals.

Initial investigations suggest that multiple disequilibration and re-equilibration events occurred as fluid conditions changed through vein mineral crystallization and wall-rock alteration. Pressure-temperature changes and fluid mixing are also potential mechanisms for mineral crystallization, and are being investigated.

GEOCHRONOLOGY

A sample from the northern end of the syenite stock was dated at 362.7 ± 3.6 Ma by Mortensen (J.K. Mortensen, pers. comm., 2004) using U-Pb techniques, and skarn related to the syenite to the south yielded a three-point Rb-Sr isochron of 333 ± 10 Ma (Chronic, 1979). Granitic magmatism of the Cassiar Suite has been dated as Cretaceous (~110 Ma; Mortensen et al., 2000), and gold mineralization at the nearby Ketza River mine has also been dated as Cretaceous (~108 Ma; Fonseca, 1998).

The exact timing of vein emplacement on the Shark property is unclear; however, constraining this event is necessary to understand the origin of the beryl. Fluorite in the veins has been dated as mid-Jurassic (172 ± 5 Ma) using Sm-Nd techniques (D. Weis and B. Keiffer, pers. comm., 2004). This date does not correspond to known igneous events in the area; consequently additional dating techniques (e.g., U-Pb on allanite) will be used to attempt to verify this age.

DEPOSIT MODELS

Beryllium enrichment in the form of beryl is typically associated with late-stage fluids derived from a highly differentiated intrusion, commonly of granitic or less commonly syenitic composition (Barton and Young, 2002). Consequently, in order to understand occurrences and develop exploration parameters for this style of mineralization, a source of beryllium (Be) must first be defined. At the True Blue aquamarine occurrence there are four possible Be sources:

1. late-stage fluids related to the Early Mississippian syenite;
2. late-stage fluids related to unrecognized or buried Cretaceous granite;
3. beryllium leached from syenite; or
4. beryllium leached from unidentified source rocks.

If the mid-Jurassic age from the fluorite is disregarded, the two simplest explanations for beryl formation involve late-stage igneous fluids. If mineralization occurred during the waning stages of syenite intrusion, late deformation could produce tension gashes and a place for Be-rich fluids to escape. Since whole-rock geochemical values for the syenite show enrichment in REE and Be, this would allow for a simple system.

If mineralization were attributed to Cretaceous magmatic fluids, a buried granitic intrusion would have to be invoked and a mechanism for restricting beryl crystallization to the syenite host would also be needed. In addition, the high REE and low tungsten, tin, molybdenum and boron concentrations in the veins would have to be explained. Since both of these hypotheses do not correspond with a mid-Jurassic age (~172 Ma), they would require that the age from the fluorite be dismissed and an indisputable age of ~100 Ma or ~360 Ma be determined from another phase in the vein.

If mid-Jurassic (~172 Ma) is the true age of mineralization, then a regional metamorphic fluid was likely the medium from which the veins crystallized. In this scenario, the most probable source for Be was through leaching of the syenite, although other unidentified Be sources cannot be discounted at this time. Thrust-faulting in the region occurred during the Jurassic, and thrust-related deformation could explain the presence of tension gashes as well as a regional metamorphic fluid. If this fluid were out of equilibrium with the host rocks (syenite), alteration along the vein selvages would likely occur. If the altered phases contained minor amounts of Be or REE, that could explain the presence of beryl and allanite, as well as their restriction to the limits of the intrusion. Furthermore, a reduced oxidation state within the silica-saturated quartz veins is expressed through a number of minerals with ferrous (Fe^{2+}) iron such as siderite, allanite, ilmenite and beryl. This contrasts with the magnetite-bearing (Fe^{3+}) silica-undersaturated syenite, thus supporting the hypothesis of a later regional fluid in disequilibrium with the host syenite.

CONCLUSION AND FUTURE WORK

The True Blue aquamarine occurrence contains gem-beryl with exceptionally dark blue colour, which is likely due to high ferrous (Fe^{2+}) iron content. A handful of other dark blue beryl occurrences exist elsewhere in the world; however, all of these are poorly characterized, and beryl examined from these sites exhibits a lighter colour. Currently, the True Blue occurrence of gem beryl appears to be markedly different from other beryl occurrences in Yukon.

Future work at the University of British Columbia will constrain the conditions of mineralization and the source of beryllium and rare earth elements. This will be accomplished using geochemical, mineralogical and petrographic investigations of all phases within the veins, host syenite, and possible alteration zones associated with the veins. Further in-depth mineralogical studies of the beryl will be carried out with a focus on understanding element substitutions and their effect on colour. A deposit model will then be created to help develop guidelines and parameters for further exploration, with an emphasis on Yukon targets.

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