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Résumé de l'article

Le présent article traite de la géologie, de la minéralogie et de l'origine de variétés gemmifères de béryl (vert), dont l'émeraude et l'aigue-marine (bleue). Il traite principalement de l'Ouest canadien, particulièrement du Territoire du Yukon, région où la plupart des découvertes ont eu lieu. Toutefois, des découvertes faites en Ontario sont aussi considérées, incluant la première au Canada, en 1940. Le Béryl ($Be_3Al_2Si_6O_{18}$) est relativement commun et associé aux granites et aux pegmatites granitiques, mais l'émeraude est rare parce qu'elle nécessite le remplacement de l'Al dans la structure cristalline du béryl par du Cr et/ou du V, et ces éléments ne se retrouvent généralement pas dans en concentrations suffisantes dans les roches granitiques. Les facteurs géologiques nécessaires pour que le Be et le Cr et/ou le V soient mis en contact font l'objet de discussion, tout comme les facteurs à considérer et les techniques à employer dans l'exploration de gisements de béryls gemmifères.

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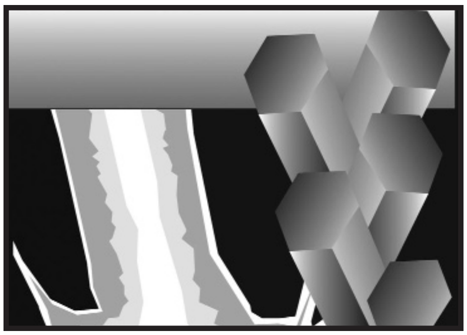

Emerald and Aquamarine Mineralization in Canada

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SUMMARY
This paper reviews the geology, mineralogy, and origin of the gem varieties of beryl, including emerald (green) and aquamarine (blue); it focuses on western Canada, especially the Yukon Territory, because this is where most of the recent discoveries have been made. However, emerald occurrences in Ontario are also considered, including Canada's first reported discovery in 1940. Beryl ($Be_3Al_2Si_6O_{18}$) is relatively common and spatially associated with granites and granitic pegmatites, but emerald is rare because trace amounts of Cr and/or V are required (to replace Al in the crystal structure) and these elements generally do not occur in sufficient concentrations in granitic rocks. The geological conditions needed to bring Be into contact with Cr and/or V are briefly discussed, as are the factors to consider and techniques to use in exploring for gem-quality beryl.

SUMMAIRE
Le présent article traite de la géologie, de la minéralogie et de l'origine de variétés gemmifères de béryl (vert), dont l'émeraude et l'aigue-marine (bleue). Il traite principalement de l'Ouest canadien, particulièrement du Territoire du Yukon, région où la plupart des découvertes ont eu lieu. Toutefois, des découvertes faites en Ontario sont aussi considérées, incluant la première au Canada, en 1940. Le Béryl ($Be_3Al_2Si_6O_{18}$) est relativement commun et associé aux granites et aux pegmatites granitiques, mais l'émeraude est rare parce qu'elle nécessite le remplacement de l'Al dans la structure cristalline du béryl par du Cr et/ou du V, et ces éléments ne se retrouvent généralement pas dans en concentrations suffisantes dans les roches granitiques. Les facteurs géologiques nécessaires pour que le Be et le Cr et/ou le V soient mis en contact font l'objet de discussion, tout comme les facteurs à considérer et les techniques à employer dans l'exploration de gisements de béryls gemmifères.

INTRODUCTION
Beryl, $Be_3Al_2Si_6O_{18}$, is a common, rock-forming cyclosilicate mineral, generally occuring within granites and granitic pegmatites. Gem varieties of beryl include emerald (green), aquamarine (blue), red beryl, goshenite (colourless), heliodor (yellow), and morganite (pink or peach). Of these, emerald is the most prized, and can be worth more than US$100,000 per carat. The colour of emerald reflects the trace amounts of Cr and/or V replacing Al in the crystal structure; it may be diminished by the presence of Fe which can add a greyish tint (Walton, 2004). Emerald is rare because Be and Cr are generally insoluble, and the geological conditions needed to bring Be into contact with Cr and/or V are, typically, incongruous.

There is debate over the difference between emerald and green beryl (see Conklin, 2002, and Schwarz and Schmetzer, 2002). However, a definition that appears to be attaining broad acceptance is that of Schwarz and Schmetzer (2002): "emeralds are yellowish green, green or bluish green, natural or synthetic beryls, which reveal distinct Cr and/or V absorption bands in the red and blue-violet ranges of their absorption spectra."

There are many classification schemes for emerald deposits. Most recently, Schwarz et al. (2002) and Grundmann (2002) divided emerald deposits into the following categories: pegmatites without schist, pegmatite and greisen with schist, schists without pegmatites, and black shales with veins and breccias. Most emerald deposits, and all of those described in this paper (with the possible exception of the Lened property) belong to the first three classes. The "black shale" category is typified by the Colombian deposits where emerald occurs in calcite + dolomite + pyrite ± albite veins in black shales and related rocks. In this type of deposit, the emerald is considered to have formed because of the thermochemical reduction of mesothermal brines by organic-rich black shales, which is effective at releasing Be, V, and Cr into solution. This model has most recently been espoused by Giuliani et al. (2000).

Recent discoveries of emerald in northwestern Canada have led to increased exploration expenditures; for example, in 2003, approximately 30% of exploration expenditures (>$3.5M) in

Figure 1. Map of Canada showing the occurrences described in the text and the Western Canadian Beryl Belt. The blue and green hexagons represent aquamarine and emerald showings, respectively.

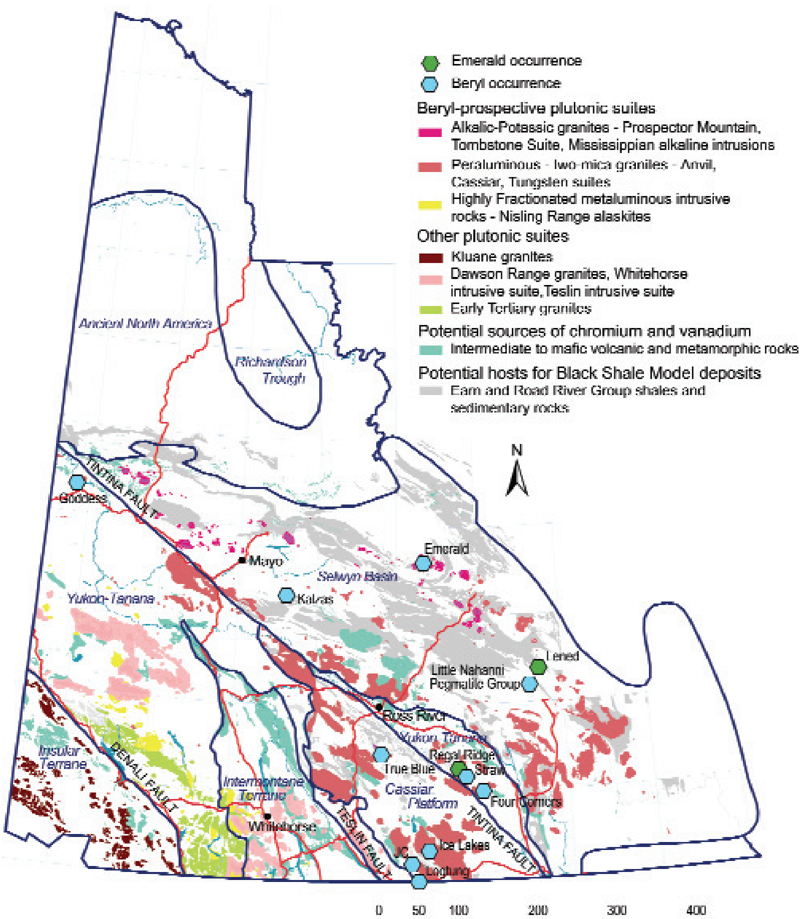

Figure 2. Map of the Yukon Territory showing occurrences described in the text.

the Yukon Territory were directed toward emerald exploration (mostly at True North Gem Inc.'s Tsa da Glisza property). Although it is uncertain if any of the existing properties will become producers, given the size of the Canadian land mass, the low population density, the diverse geology, and the (until recently) low level of exploration for coloured gems, there will almost certainly be more discoveries. This paper reviews the geology, mineralogy, and origins of the existing properties and suggests strategies for future exploration. It focuses on western Canada, especially the Yukon Territory because this is the location of most recent discoveries and exploration efforts.

REGIONAL FRAMEWORK

Beryl occurrences in Canada are mostly associated with either Archean pegmatites in the Canadian Shield or Mesozoic/Cenozoic granitoids in the Cordilleran. The late Archean Superior and Slave provinces host several examples of rare-element (i.e., beryllium) bearing pegmatites (Breaks et al., 2003; Tomascak et al., 1994). The pegmatites in the Superior Province are associated with S-type peraluminous granites and leucogranites which include the post-collisional Ghost Lake batholith (see below) and Separation Rapids pluton (~2650 Ma; U-Pb/monazite; Larbi et al., 1999).

In the Cordillera, Legun (2004) compiled information on all known beryl occurrences in British Columbia and produced a map showing a "beryl belt" running the length of the eastern side of the province, with a "principal area of emerald potential" in the north-central part of the province, extending to the B.C.–Yukon border (Fig. 1). Legun's "beryl belt" corresponds to the terranes that underlie the Omineca belt and the bordering eastern margin of the Intermontane belt, where Mesozoic and Cenozoic granite intrusions and associated pegmatites cut tectonic slices of ultramafic and oceanic rocks (Legun, 2004). In this paper, the belt is extended northward to encompass beryl occurrences in the Yukon Territory and it is referred to as the "Western Canadian Beryl Belt" or WCBB. The WCBB's eastern and northern boundaries mostly follow the margins of the Selwyn Basin, which is also the limit of Cretaceous granitoids; its western boundary is just west of the Tintina Fault and is dominated by the Yukon-Tanana Terrane but jogs as far west as the Teslin Fault in southern Yukon to encompass beryl occurrences associated with plutons in the Cassiar Terrane. The Tintina Fault is a large, through-going, dextral strike-slip fault with significant (430 km) displacement that is mostly early Cenozoic (D.C. Murphy, pers. comm. 2004).

TSA DA GLISZA, YT

In 1998, W. Wengzynowski discovered emerald at Tsa Da Glisza ("green stones" in the Kaska language; formerly Regal Ridge) in the southeastern Yukon Territory (61° 16.6´ N, 130° 35.5´ W, NTS 105G/7; Figs. 1 and 2). The geology, mineralogy, and origin of the occurrence are described in Groat et al. (2002), Marshall et al. (2003), Neufeld (2004), and Neufeld et al. (2003, 2004). The mineralization is associated with quartz-tourmaline veins and aplite dykes that intrude mafic metavolcanic rocks of the Yukon-Tanana Terrane. Pale green to green-blue to "emerald green" beryl crystals up to 4 cm in length occur in 12 mineralized zones within a 900 x 900 m area (Fig. 3 top). Chromium (average 3208 ppm) is the predominant chromophore (Fig. 4). Some of the smaller crystals, and sections of larger crystals, are gem-quality, and a number of small gems (up to 2.4 ct) have been fashioned from the Tsa da Glisza samples (Fig. 3 bottom). The property currently belongs to True North Gems Inc.

The Yukon-Tanana Terrane in the Tsa da Glisza area is mainly composed of pre-Late Devonian quartz-rich metaclastic and carbonate rocks, and Devonian and Mississippian metavolcanic and metaplutonic rocks, which are inferred to have formed in a continental magmatic arc (Mortensen and Jilson, 1985; Mortensen, 1992; Murphy and Piercey, 2000) and back-arc settings (Piercey et al., 2000). The oldest rocks are in the pre-Late Devonian to earliest Mississippian Grass Lakes succession. The Fire Lake Formation, composed mainly of chloritic phyllite of mafic metavolcanic composition (Murphy et al., 2002), is the second oldest Formation within the succession, and hosts the emerald mineralization at Tsa da Glisza. The rocks were thrust onto the North American miogeocline between Late Triassic and the earliest Cretaceous (Murphy, 2004). The Yukon-Tanana Terrane rocks are intruded by several granite intrusions (ca. 112 to 100 Ma) of the Cassiar-Anvil plutonic suite, one of which underlies the Tsa da Glisza property. The Tintina Fault lies 14 km southwest of the property; faults, possibly related to the Tintina fault, run through the Finlayson Lake district. Both the mafic schists of the Fire Lake Formation, and the Cretaceous granitic rocks, will be discussed here in detail.

The main host rock for the emerald mineralization is the chlorite-plagioclase schist that forms part of the Fire Lake Formation (DF unit of Murphy et al., 2002). Geochemical analyses show that the schist is a high-Ca boninite (high-Mg andesite to basalt). The Cr in the emerald is most likely from the schist which has an average Cr content of 960 ppm. Medium-grained, foliated metavolcanic rocks also of boninitic composition are closely interfingered with the mafic schist, and are known to host mineralization. Variably serpentinized Devonian mafic

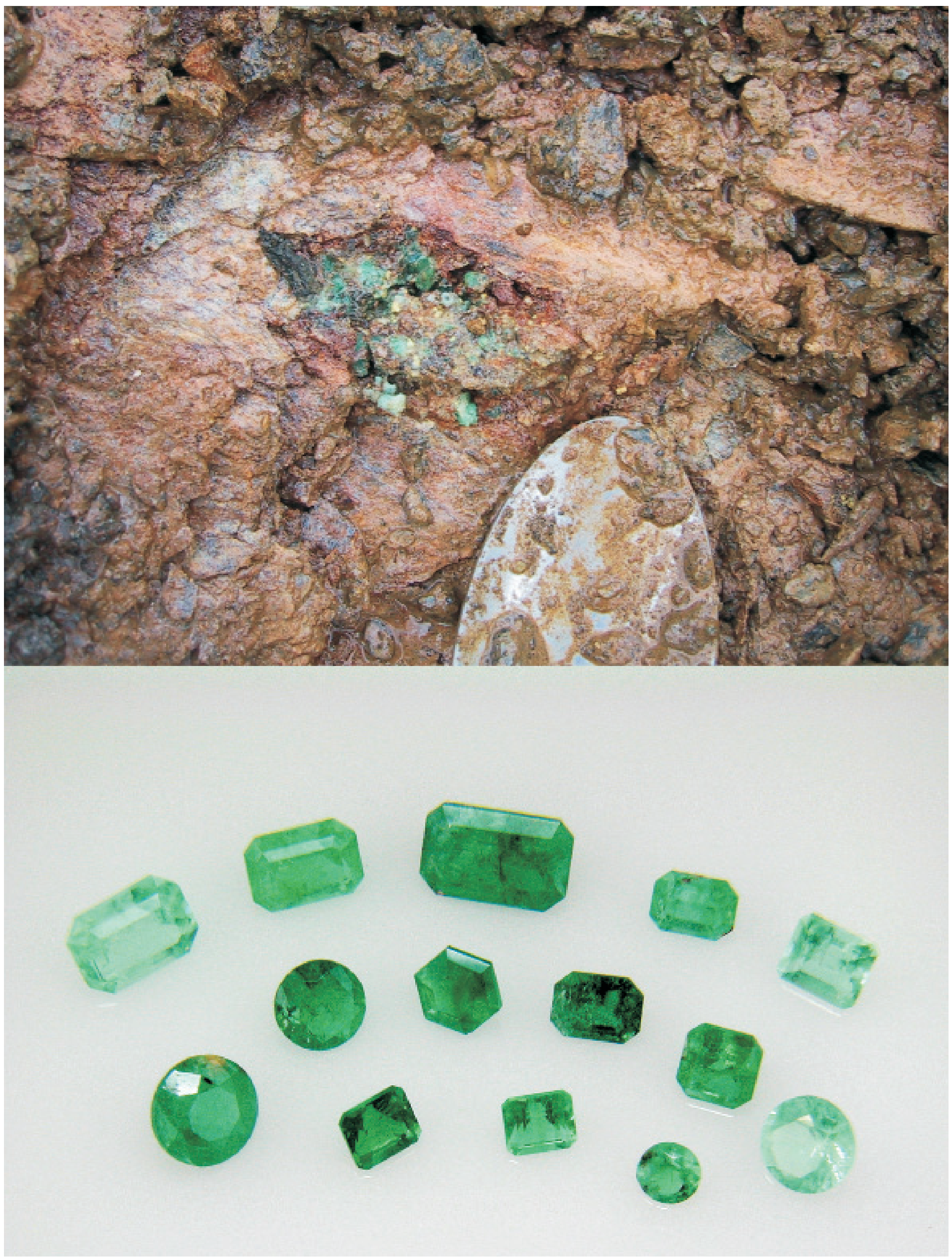

Figure 3. (top) An emerald-bearing "pocket" at Tsa da Glisza (soup spoon for scale). (bottom) Faceted stones from Tsa da Glisza; the largest weighs approximately 0.5 ct. Both photographs are courtesy of True North Gems Inc.

and ultramafic intrusive rocks (Dum and Dmi units of Murphy et al., 2002) occur in the western and northern parts of the map area. The ultramafic and mafic intrusive rocks are cut by very few quartz veins and have not been found to host beryl or emerald.

The emerald occurrence is underlain (at a depth of at least 300 m) by a 112 Ma two-mica (biotite >> muscovite) granite pluton, which crops out within 500 m to the east and south of the mineralized area. The pluton belongs to the Anvil plutonic suite of 112-100 Ma felsic intrusions (Mortensen et al., 2000). It is weakly foliated to unfoliated and has shallowly dipping contacts. Geochemical results (Neufeld et al., 2003) confirm that the pluton is an evolved peraluminous S-type granite (low in Eu and Lu, rich in Li, F, and W). Although the Be content of the granite (9.8-13.2 ppm) is not anomalously high, the close proximity and the consistent correlation of Be with Sn, W, and Bi in the geochemical data (whole-rock and soils) indicate that it is the source of the Be. Numerous aplitic leucogranite dykes ranging from 40 cm to 5 m in width, occur on the property, mostly within the schist. At least two Eocene feldspar porphyry dykes or sills intrude Tsa da Glisza, and appear to have followed the same planes of weakness as the aplite dykes.

Quartz veins are abundant throughout the property and most appear to be related to Cretaceous deformation of the country rocks. Early veins are typically thin, foliation-parallel, sulfide-rich, and contain no tourmaline. All other quartz veins are associated with at least some tourmaline, either within the veins or in the vein selvages. When in association with beryl and/or emerald, the tourmaline is dravite to uvite, otherwise it is schorl. The degree of alteration surrounding the veins varies from none to metre-wide horizons of rusty-weathering schist. This rustiness likely reflects weathering of finely disseminated sulfides (especially pyrrhotite) that are commonly present in the alteration zones adjacent to the veins.

Emerald is found associated with veins in several different orientations. Mineralization appears to be particularly well developed in the areas of intersection between veins. Emerald occurs most commonly along the margins of quartz veins, but is also found within the quartz veins themselves, and in highly altered zones within the schist that extend past the veins and are interpreted to be fluid pathways. There is no significant variation in the mineral chemistry of emeralds associated with quartz veins, which may indicate that the mineralizing fluid was relatively homogeneous. However, there is a general trend of decreasing substitution of Al in beryl (primarily by Mg and Fe) from east to west and with decreasing altitude. Lithium, F, and Sn concentrations increase in the schist in the alteration envelopes of mineralized quartz veins but are low within the veins, and Be, W, and Bi concentrations peak within the veins or less commonly in the immediate vein selvages. Beryllium concentrations can vary by as much as 300 ppm over a distance of 1 m along an individual vein.

The Tsa da Glisza emerald occurrence best fits the magmatic-hydrothermal genetic model (e.g., Barton and Young, 2002). The ^{39}Ar-^{40}Ar and U-Pb geochronology confirms that mineralization occurred synchronous with regional deformation and metamorphism related to intrusion of the granite pluton from approximately 112 to 108 Ma (Neufeld et al., 2004). In particular, mineralization was syn- to late-tectonic, coinciding with the waning stages of granite emplacement. The temperature, based on the quartz-tourmaline geothermometer of Kotzer et al. (1993), was 365-498 ºC (Marshall et al., 2003). Some

Table 1: Beryl occurrences and associated granitoids in the Yukon and western Northwest Territories.

Occurrence	Pluton	Pluton Age (Ma)	Mineralization Age (Ma)	Suite	Type of Granitoid	MINFILE/ NORMIN*	Other References
Pluto	Pluto	73 and 60	67	Prospector Mtn	alkalic	116B/134	
Emerald Lake	Emerald	95		Tombstone	alkalic	115O/9	
Kalzas	not exposed	91		Tombstone?	?	105M/66	
True Blue	Guano	350	???	Pelly Mtn	alkalic	105F/81	
Regal Ridge		112	109	Cassiar	peraluminous	105G/147	Groat et al. (2002)
Ice Lakes	Cassiar	101		Cassiar	peraluminous		Groat et al. (1995)
JC	Seagull	101		Seagull	peraluminous	105B/40	
Logtung	Logtung	58			metaluminous?	105B/39	
Lened	Lened	93		Tungsten	peraluminous	105ISE3	Marshall et al. (2004)
LNPG	not exposed?	81		Tungsten?	peraluminous	105ISE15, 25, 50-56	Groat et al. (2003)

Notes: *www.geology.gov.yk.ca/minfile/ and www.nwtgeoscience.ca/normin of the emerald-bearing veins have been affected by late deformation as evidenced by the presence of fractures and secondary fluid inclusions in emerald and micro-boudinage of tourmaline grains within vein quartz. At least two of the aplite dykes contain beryl or emerald, which supports the hypothesis that there is a genetic link between the granite intrusion, aplite and pegmatite bodies, and beryl-bearing quartz veins (Neufeld, 2004; Neufeld et al., 2003, 2004; Fig. 5). The aplite and quartz vein geochemistry suggest that Be was carried within the mineralizing fluids as fluoride and hydroxide complexes. Chromium entered the fluid system through interaction of the Be-bearing fluids with either hydrothermal fluids that had percolated through the host and extracted Cr, or via element exchange during metasomatic alteration of the vein selvages by the mineralizing fluids. Oxygen and H isotopic data show evidence of isotopic mixing between the schist and intruding fluids for the beryl-bearing veins, whereas non-mineralized veins show no evidence for mixing and are likely increasingly hydrothermal in origin. Beryl crystallization may have been triggered by several factors: (1) mixing with cooler hydrothermal fluids; (2) crystallization of tourmaline, which would have removed B and possibly some Li and F from the fluids and/or lowered the aluminum activity of the fluids, all of which would have resulted in a reduced solubility of Be in the fluid (cf. London and Evensen, 2002); (3) an increase in the Ca content of the fluids by interaction with the host schist; (4) an increase in host-rock permeability or porosity reflecting either rock type differences or fracture propagation related to deformation accommodating cooling of the granite pluton below; (5) precipitation of lepidolite within the vein selvage, removing F (ligand) and Li (buffer) from the fluids; or (6) simply because of decreases in pressure and/or temperature. Likely all of these factors played some role in initiating beryl precipitation, particularly where mineralization is contained within highly altered vein selvages.

LENED, NT

Transparent pale-green emerald crystals were discovered at the Lened property in the late 1970s. The occurrence is located north of the Yukon–NWT border, 55 km northwest of the town of Tungsten in the Logan Mountains (128° 40´ W, 62º 22´ N, NTS 105I/7; Figs. 1 and 2). The regional and property geology was described most recently by Gordey and Anderson (1993) and Glover and Burson (1987). The occurrence is located on the eastern margin of the Selwyn Basin, which consists of deformed and weakly metamorphosed Neoproterozoic to Devonian-Mississippian sedimentary rocks interpreted as a continental terrace wedge along the western margin of the North American Craton. The basin is separated from the craton by a major tectonic flexure known as the Redstone arch. Plutonism is widespread in this segment of the basin, and it varies from stocks to batholiths; compositions range from diorite to high-silica granite. In the vicinity of the study area, the intrusions are late Early Cretaceous. Prior to Cretaceous magmatism, the region underwent three major episodes of deformation. The sedimentary package in the area of the Lened property consists of three major unconformable successions. The oldest comprises siliciclastic rocks of the Vampire Formation (Neoproterozoic to Early Cambrian), which locally consists of a rusty-weathering phyllitic shale that is grey on fresh surface and, in places, calcareous. Above this is the Rabbitkettle Formation (Cambro-Ordovician), which in the area of the emerald-bearing veins is a dolomitic limestone. Overlying, and in thrust fault contact with, the Rabbitkettle Formation are black shales and black cherty siltstones of the Earn Group (Portrait Lake Formation). These rocks are fine grained and weather a rusty brown. Locally, they are cut by many minor faults and thrusts and bedding generally trends northeast-southwest. Folding on the scale of a few hundred metres can be observed in the valley walls.

All of these units were intruded by the Lened quartz monzonite stock

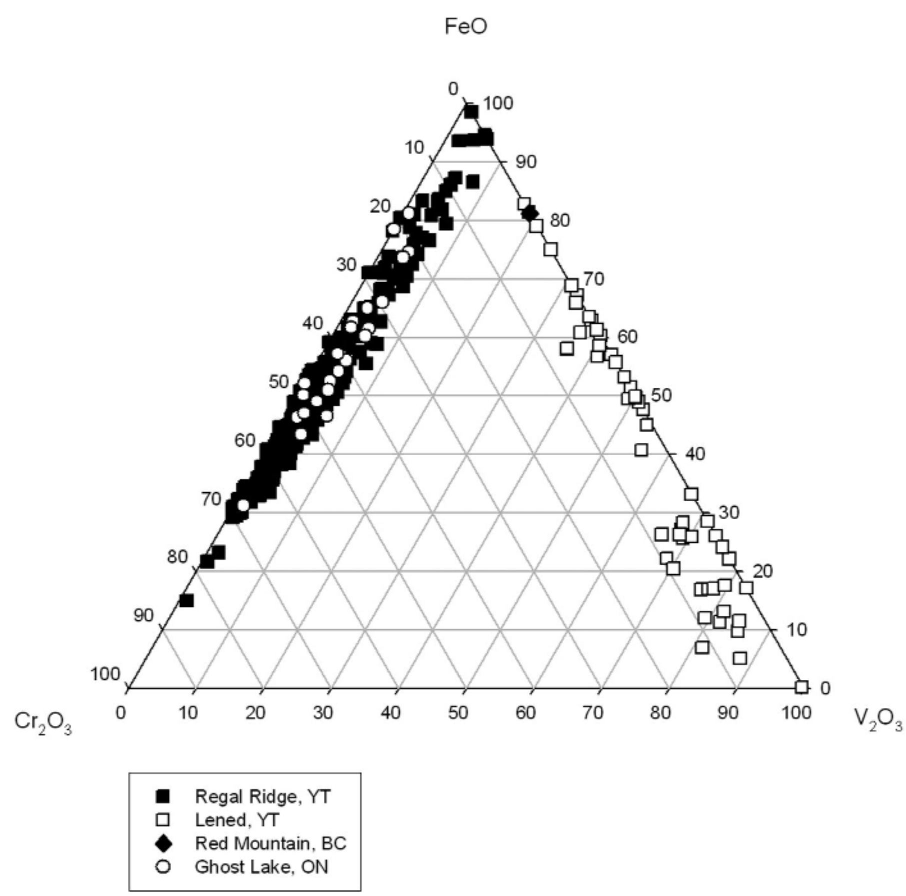

Figure 4. Triangular diagram of Cr_2O_3-FeO-V_2O_3 weight percentages from analyses of emerald.

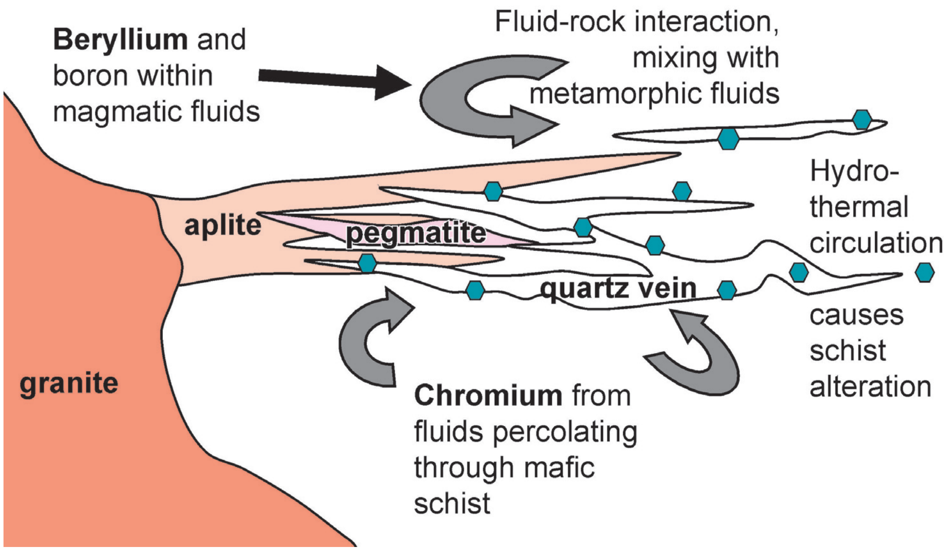

Figure 5. Proposed genetic model for the emerald mineralization at Tsa da Glisza (after Neufeld, 2004). Hexagons represent emeralds.

that has been dated at 93 ± 1 Ma, using K-Ar on biotite (Gordey and Anderson, 1993). The stock is quasi-concentrically zoned from a central fine-grained core, through a dominant megacrystic phase, to a peripheral equigranular margin. Metamorphic aureoles around the granitic rocks are estimated to extend on the order of 1 km from the granitic rocks (Gordey and Anderson, 1993).

Emerald at the Lened emerald showing is hosted by quartz-carbonate veins developed within a skarn assemblage. The veins (2-30 cm wide) extend perpendicularly from the thrust fault across the skarn and pinch out in overlying rhythmically bedded limestone. The black shale footwall unit is devoid of emerald mineralization. The emerald is intergrown with quartz and calcite adjacent to the wallrock and concentrations are highest near vein-fault intersections. The veins are surrounded by a 5- to 10-cm-wide alteration zone that consists of calcite, dolomite, diopside, hedenbergite, vesuvianite, and base-metal sulfides. Emerald crystals from Lened are typically euhedral, up to 3 cm in length and 3 mm in diameter, although the longest crystals tend to be quite narrow. Most of the crystals are pale green to yellow, but some are dark grassy-green (Fig. 6). Chemical analyses indicate that the emerald is richer in vanadium (up to 0.5 wt.% V_2O_3) than in chromium (0.04 wt.% Cr_2O_3, Fig. 4), and that $\delta^{18}O$ varies greatly from 12.4 to 13.45‰. A fluid inclusion study (Marshall et al., 2004) suggested that the emerald crystals formed at temperatures of 250-550 ºC and pressures <3,700 bars.

Figure 6. Emerald crystal from the Lened occurrence, Northwest Territories. The crystal is about 2 cm in length.

The host skarn ranges from a pyroxene-garnet-amphibole facies at the fault contact with the shale, to a distal pyroxene-garnet facies. Pyroxene and garnet chemistries vary abruptly from $Di_{0.1}Hd_{0.9}$ and $Go_{0.8}Gr_{0.2}$ (goldmanite with 24 wt.% V_2O_3) in proximal skarn to $Di_{0.9}Hd_{0.1}$ and $Gr_{0.9}Ad_{0.1}$ in distal skarn.

The probable source of Be is the Lened stock. The core contains slightly more Be (~8 ppm) than the outer zones (~5 ppm). The probable source of the V is the black shale, which has over 3,000 ppm V. This might suggest that Lened belongs to the "black-shale hosted" category of emerald deposits but unlike the Colombian deposits there is no evidence that the source of the Be is non-magmatic.

Marshall et al. (2004) suggested that hot fluids from the cooling Lened pluton, travelling along the thrust, produced the contact metamorphic rocks. The calc-silicate contact metamorphic rocks were more brittle than the surrounding unmetamorphosed country rocks. Prolonged pluton emplacement and cooling resulted in further deformation of the country rocks with the calc-silicate rocks behaving in brittle fashion, and the unmetamorphosed rocks behaving in a ductile fashion. This resulted in a set of sub-parallel fractures in the contact metamorphic rocks. These fractures became conduits for hydrothermal fluids expelled from the cooling granitic rocks, and quartz and beryl were precipitated in these fractures resulting in the series of sub-parallel veins.

TRUE BLUE, YT

The True Blue property is located in the Ketza-Seagull District of the southern Yukon Territory, within the Cassiar Platform and southwest of the Tintina Fault (61° 30´ N, 132° 30´ W, NTS 105F/8, 9, 10; Figs. 1and 2). Beryl was discovered on the property in 1976, and aquamarine in 2003 (Rohtert et al., 2003). The crystals occur in a swarm of closely spaced quartz ± siderite ± fluorite ± allanite veins that fill tension gashes in a Mississippian-age (~360 Ma) syenite stock. The veins range in thickness from 0.5 to 20 cm, and locally comprise up to 30% of the rock. The vein zone measures 700 × 400 m in outcrop at the surface, and is exposed over an elevation range of 100 m. Within this area, more than 100 individual occurrences have been discovered. The vein zone is developed near the upper contact of the syenite with the lower Paleozoic pelitic and carbonate country rocks. The syenite is sodic in composition (~8 wt.% Na_2O) and contains moderately high concentrations of Be (to ~10 ppm), F (to ~4000 ppm), and rare-earth elements.

The beryl crystals range in size from a few mm to 5 × 2.5 cm, and in colour from pale to medium green and from pale to dark blue (Fig. 7). Some of the crystals, especially those occurring with tourmaline, show a blue core and green rim. Because of its rarity, exploration efforts were focussed upon the dark blue material; a total of 57.9 g of material was collected from a 65 kg bulk sample. Individual crystals from this sample ranged up to 38 mm long and 11 mm in diameter. Five stones weighing up to 0.82 ct have been cut to date. According to Rohtert et al. (2003), the colour is maintained at exceptionally small sizes for aquamarine. The main constraints on the size of the stones faceted to date are the abundant fractures present in the material gathered from the surface. Microscopic examination revealed that all five stones were also fairly heavily included, which significantly affects their transparency (Rohtert et al., 2003). Internal features include fractures, "fingerprints," growth tubes, two-phase fluid-and-gas inclusions, and transparent near-colourless quartz crystals. One of the small stones had a surface-reaching inclusion of siderite surrounded by a thin layer of pyrrhotite (Rohtert et al., 2003).

Electron microprobe analyses of the dark blue material show high concentrations of Fe (to 5.79 wt.% FeO), Mg (to 3.27 wt.% MgO), and Na (to 2.51 wt.% Na_2O). The Fe concentration is the highest we know of for true beryl. The only member of the beryl family with more Fe is stoppaniite, which occurs in miarolitic cavities in volcanic ejecta at Latium, Italy, and contains up to 19.30 wt.% Fe_2O_3 (Della Ventura et al., 2000). However, stoppaniite is light blue, probably because all of the Fe is in the ferric state.

Although rare, dark blue aquamarine crystals have also been recovered from the Ambositra beryl-columbite pegmatite in Brazil (Pezzotta, 2001). Proctor (1984) describes the discovery (in 1964) of eluvial dark blue aquamarine fragments totalling 22 kg in the Marambaia Valley in Brazil. Proctor (1984) also describes a 34.7 kg crystal (dubbed the "Marta Rocha" crystal) which ultimately yielded 57,200 carats of dark blue aquamarine. Other localities include Lone Pine, California, the Tatu mine in Brazil, and Lajes Pintada, Rio Grande do Norte, Brazil. There is some evidence that the True Blue material is darker than the beryl from California or Brazil. "Maxixe" is a dark blue gem beryl from Brazil in which the colour is caused by radiation-induced colour centres that fade with prolonged exposure to light (Nassua et al., 1976).

The mechanism responsible for colour in beryl is not completely understood. In the case of the True Blue material, it almost certainly involves intervalence charge-transfer (IVCT) between Fe^{2+} and Fe^{3+} cations. An absorption spectrum of the dark blue aquamarine shows that the greatest absorption is when the electric vector (E) is parallel to the *c* axis. This suggests that the Fe atoms involved in IVCT are arranged along (or sub-parallel to) the *c* axis. However, none of the conventional sites in the beryl structure are aligned in this way. One suggestion is that the blue colour reflects IVCT between Fe^{2+} cations at the Al sites and small amounts of Fe^{3+} at the interstitial octahedral (6i) position, a location with sixfold (trigonal prismatic) coordination that lies between the Al sites and is normally empty (Platonov et al., 1979). However, there is no evidence of this from X-ray single-crystal data. We are presently using Mössbauer spectroscopy and neutron single-crystal diffraction to study the cause(s) of colour in aquamarine from the True Blue property.

Figure 7. Dark blue aquamarine with quartz and fluorite from the True Blue property in the Yukon Territory. The crystal is approximately 38 mm in length.

BRITISH COLUMBIA

Crystals of deep-green beryl were discovered in 1989 at Red Mountain (NTS 103P/13; Fig. 1), near Stewart on the central coast of British Columbia (Wilson, 1997). The beryl occurs as small opaque crystals having numerous fractures in narrow quartz-calcite-pyrite veins cutting volcaniclastic rocks adjacent to a quartz-monzonite intrusion. Electron microprobe analyses show 1612 ppm V and 1.04 wt.% FeO (average of six analyses), and no detectable Cr.

Wilson (1997) reported on aquamarine from Mt. Foster (near Bennett; NTS 104M/14?), the Horseranch Range (near McDame; NTS 104P/24), and the B-Q claims (near Passmore; NTS 82F/6E). He also reported that the following locations have produced aquamarine crystals which either have been cut or could be cut into gems under 0.3 ct: Ash Mountain (near McDame; NTS 104O/13E), Dunn peak (near Barriere; NTS 82M/5), Skookumchuck Creek (near Kimberley; NTS 82F/16E), and in the Atlin and Prince George areas.

The aquamarine at Mt. Foster occurs in miarolitic cavities containing gem-quality fluorite, microcline, phenacite (Be_2SiO_4), smoky quartz, and topaz. The aquamarine is colourless to light blue and the two largest stones cut so far weighed 8.63 and 2.99 ct. The larger stones have many inclusions, but the smaller ones, weighing under 2 ct, are described as virtually flawless (Wilson, 1997). Wight (1986), describes a light blue, slightly greenish aquamarine from Mt. Foster (0.86 ct, rectangular step cut) in the National Gem Collection (maintained by the Mineral Sciences Division of the Canadian Museum of Nature, Ottawa).

Beryl in the Horseranch Range occurs as euhedral crystals embedded in granite pegmatite dykes that cross-cut high-grade metamorphic gneiss. Although most of the beryl is fractured and opaque, a few transparent crystals have been found. Cut stones are colourless to very pale blue; the largest at the time of writing weighed about 1 ct (Wilson, 1997).

At the B-Q claims, beryl occurs with dark red garnet, smoky quartz, and black tourmaline in miarolitic cavities in a granite pegmatite dyke that cuts across the foliation of a high-grade metamorphic gneiss (Wilson, 1997). Wilson (1997) reports that the largest aquamarine crystal discovered weighed 47.2 g, and has dimensions of 3.3 x 3.2 x 2.3 cm, but Brown (2004) suggests that gem-quality crystals, up to 10 cm in length, have been recovered from the pegmatite. Cut gems are pale blue-green and tend to have numerous parallel planes of inclusions oriented parallel to the *c* axis. According to Wilson (1997) the largest faceted stone weighed 5.26 ct.

Brown (2004) reported two aquamarine crystals more than 8 mm in diameter and dozens of transparent to translucent crystals less than 3 mm across from the Blue Hammer showing (west of the Kootenay River; NTS 82K/01). The beryl occurs in granite pegmatite dykes that cut aplite dykes and quartz monzonite of the White Creek batholith. Brown (2004) also describes several ice-blue aquamarine crystals, up to 6 mm in diameter, from the OMG claims (west of Kootenay Lake). The crystals occur in quartz veins extending outward from the quartz cores of pegmatite dykes into surrounding aplite and/or sedimentary rocks.

ONTARIO

Canada's first emerald occurrence, known in the literature as the Taylor 2 pegmatite, after J.G. Taylor, was discovered near Dryden (49° 49.0´ N, 92° 43.7´ W, NTS 52F/15; Fig. 1) in northwestern Ontario ca. 1940 (Breaks, 1989). The Taylor 2 pegmatite belongs to the Mavis Lake Pegmatite Group, which is southeast of the S-type peraluminous Ghost Lake batholith (2685 Ma; Breaks and Janes, 1991; Garland, 2004). Porcellaneous white to pale green beryl crystals, up to several cm long and 5 cm wide, are found within a 3.5 by 1.5 km area (Garland, 2004). The beryl is concentrated in two pegmatite dykes situated 340 m south of the Ghost Lake batholith, but only the Taylor 2 pegmatite contains emerald (Breaks, 1989). The occurrence is found at the eastern end of a large conformable sill of altered ultramafic rock (peridotite; Satterley, 1941), exposed as an E-W trending ridge approximately 80 m long and 10 m wide. The pegmatite, which consists of three separate limbs, intrudes a wide zone of chlorite schist that sits between rusty metavolcanic biotite-feldspar schist and the end of the ultramafic sill (Garland, 2004). Most of the beryl and emerald occurs within a "zone of mixing" between the southern and central limbs of the pegmatite (Garland, 2004). The "zone of mixing" consists of relict K-feldspar crystals from the pegmatite in a matrix of albite, biotite, and tourmaline. The beryl occurs as euhedral crystals up to 2.3 × 1.8 cm in dark matrix material proximal to the relict feldspar crystals (Garland, 2004). Most are opaque white to pale green, but about 10% of the crystals are emerald green (Fig. 8). Electron microprobe analyses show up to 0.47 wt.% Cr_2O_3, 0.05 wt.% V_2O_3, and 0.50 wt.% FeO (Fig. 4). Some of the crystals contain inclusions of very fine-grained tourmaline or euhedral, green-blue apatite, and some are veined by fine-grained, equigranular apatite that is indicative of albitic replacement (Breaks, 1989). According to Breaks and Janes (1991) the geologic setting at Ghost Lake is similar to that of the Somerset Hill mine in the Gravelotte district in South Africa, where emerald occurs in a biotite-rich schist at the contact between an albitic pegmatite and a talc-chlorite schist (Robb and Robb, 1986). This occurrence has also been suggested to be of metamorphic origin.

Parsons (1934) found large crystals of beryl with "amazonstone" and rose quartz near Quadeville in Lyndoch Township, Renfrew County (NTS 31F/6; Fig. 1). Most of the beryl is flawed, but some parts of the crystals are transparent and free of cracks. In such cases a few greenish-blue aquamarines were cut. Three of these can currently be found in the National Gem Collection (3.09, 1.80, and 1.35 ct) (Wight, 1986). Waite (1945) describes an aquamarine from near Kearney, Butt Township, Nipissing District (NTS 31E/11?) weighing 2.1 ct and "flawed but with fine colour"; this is also in the National Gem Collection (Wight, 1986). He further describes a 3.1 ct stone from the Quadeville occurrence (probably the 3.09 ct stone described by Wight, 1986) and states that "the colour and clarity of these stones matches the best from Brazil."

PLUTONIC ASSOCIATIONS

Compiled information on the magmatic associations of 12 documented beryl occurrences in the Yukon and western

Northwest Territories (Lewis et al., 2003) identified some interesting commonality and diversity in their characteristics (Table 1). In addition to Lened, Tsa da Glisza, and True Blue, beryl has been reported from (west to east) Pluto, Kalzas, Ice Lakes, JC, Logtung, Emerald Lake, Straw, Four Corners and the Little Nahanni Pegmatite Group (LNPG; Fig. 2). The occurrences are related to at least six different plutonic suites where the plutonic ages range from 58 to 350 Ma, but most are Cretaceous (92-112 Ma). Most importantly, however, the beryl occurrences are associated with peraluminous, alkalic, and probable metaluminous granitoids. This is surprising because most occurrences reported in the literature are associated with peraluminous rocks.

Peraluminous granitoids, and therefore their parent magmas, have a greater proportion of Al to combined Ca+Na+K, such that the magma cannot accommodate the excess Al in feldspars, but must precipitate more-enriched aluminous phases. Although biotite is capable of this, other minerals such as muscovite, garnet and cordierite are more efficient and preferentially occur in strongly peraluminous rocks. This excess in Al is an important feature because more-aluminous magmas require lower levels of Be before reaching Be saturation and therefore, are more likely to precipitate beryl (London and Evensen, 2002).

Most beryl occurrences, particularly economic beryl deposits, are in pegmatites derived from peraluminous magmas. However, the diversity observed in the Yukon agrees with the assertion, developed by London and Evensen (2002) in response to their experiments and modelling of silicate melts, that "no one granite source rock is uniquely or specially predetermined to produce beryl-bearing pegmatites." This emphasizes the importance of processes over the natural source materials in developing beryl mineralization.

BERYL GENESIS

All of the previously described beryl occurrences, and most others in Canada, are apparently derived from a magmatic source as suggested by an adjacent granitic pluton, or associated dykes. However, the typical background Be values for most granites are in the range of 2 to 10 ppm (Beus, 1966), far below the typical levels of saturation of a few thousand ppm Be (at 900 °C) to a few hundred ppm Be (at 600 °C) as indicated by London and Evensen (2002). Beryllium is best enriched in magmas through the process of fractional crystallization whereby Be behaves incompatibly, is not taken up in a crystallizing mineral phase, and is thereby enriched in the residual melt fraction. Many high-field strength elements, as well as halogens (Cl and F) and small ions (such as B) are also typically enriched in residual melts, and play a role in depressing the solidus (London et al., 1996) such that Be enrichments continue to take place, even at low temperatures with low percentages of remaining melt. Beryllium saturation levels in melts are mostly affected by temperature, but also decrease with increasing alumina and silica activity (London and Evensen, 2002), which explains the empirical association of beryl with silica-rich peraluminous magmas.

However, experimental work by London and Evensen (2002) has indicated mechanisms whereby Be can be scavenged and therefore depleted from the melt by specific mineral phases, including: (1) plagioclase; Be contents peak in plagioclase composition An_{30} (oligoclase-andesine) such that a magma crystallizing this composition of plagioclase will not increase in Be content until more albitic plagioclase crystallizes; (2) white mica; Be can enter the mica structure, therefore intrusions containing white mica potentially have higher Be contents, and are less capable of producing subsequent high-Be melts; and (3) cordierite; it can incorporate a large amount of Be and garnet cannot; therefore, late magmas associated with garnet-bearing intrusions are potentially more Be-rich. Future work on the beryl occurrences that are not associated with peraluminous granites might help shed light on beryl genesis.

There is also the question of why Be contents of the (presumed) parental granitoids at Lened, Tsa da Glisza, and True Blue are not exceptional. Again, London and Evensen (2002) state, "It may seem logical that, as likely sources of the beryl-rich pegmatitic melts, these granites are themselves depleted in Be and other incompatible components." This might suggest, counter-intuitively, that exploration efforts should focus on low-Be granitoids.

Although the magmatic processes of Be enrichment are important, gem beryl occurrences are often associated with quartz veins formed from hydrothermal fluids that are assumed to have been derived from a magma that reached water-saturation. The efficacy of partitioning of elements into an exsolving fluid from a melt is dependent on numerous factors, including the content of that element in the melt and the availability and content of potential ligands in the fluid phase. A good example are the metals Zn and Pb which easily partition to the fluid phase if there is significant Cl in the fluid. Among other features, the common association of fluorite and/or F-rich mica with gem beryl occurrences suggests that F may be an important component of the fluid phase in order to effectively partition Be into the fluid.

Another factor of importance is the mobilization of Cr. This relatively inert metal requires extreme geological conditions in which to make it soluble. Most hydrothermal alteration leaves the rock depleted in all other elements except Cr. Such is the case with very hot, CO_2-rich fluids that form orogenic gold deposits in ultramafic rocks where the altered rock (listwaenite) consists of silica, carbonate, and residual Cr which forms green, Cr-rich micas. It may be that low-pH fluids enriched in HF are more effective agents at increasing the solubility of Cr in hydrothermal fluids.

EXPLORATION

Readers interested in exploring for gem beryl should begin with a thorough literature search, keeping in mind the geology and diversity of the mineralization at Tsa da Glisza, Lened, and True Blue. Good places to start are Mulligan (1968) and Walton (2004); the latter reference, in particular, contains a detailed compendium of material from the literature concerning gem beryl. Information on specific occurrences can be found in the MINFILE and NORMIN databases, for Yukon and NWT, respectively, although beryl is likely more common than reported in these databases and the clever explorationist may consider searching for allied characteristics such as tourmaline, pegmatite, fluorite, scheelite, etc. We note that the True Blue property was rediscovered by searching through a private database (although the beryl was originally misidentified as kyanite, a sample was retained and was later identified using X-ray diffraction).

Inspection of a terrane map of the Yukon Territory shows that the Tsa da Glisza occurrence is in a segment of the Yukon-Tanana Terrane (the "banana") which is offset from the rest of the Yukon-Tanana Terrane by the Eocene displacement along the Tintina Fault. Reconstruction of the Yukon-Tanana Terrane would place Tsa da Glisza in the area north of Dawson City; therefore, the area south of the fault in the Dawson area could be prospective for beryl but fewer mid-Cretaceous granitoids are found there. The Pluto occurrence is in this locality but is Late Cretaceous, and not related to the same granite suite as occurrences in the Tsa da Glisza area. It is interesting to note that the Tsa da Glisza and True Blue properties are approximately 14 km northeast and 30 km southwest of the Tintina Fault, respectively, which might indicate a genetic connection. In the south-central Yukon and north-central British Columbia, there is a cluster of beryl occurrences (Fig. 1) that could be considered as a Be-rich area within the WCBB.

Murphy et al. (2002) plotted potential Be reservoirs (plutonic rocks, especially the mid-Cretaceous Anvil-Cassiar suite) and Cr and V reservoirs (ultramafic rocks, volcanic rocks, and the Earn Group) in the Yukon Territory and suggested that the best place to look is where the two come together. Murphy et al. (2002) also plotted Regional Geochemical Survey (RGS) data for the Yukon Territory; they show high Cr near Dawson City and high V close to the Yukon-NWT border (across from the Lened property), corresponding to Cambrian to Silurian Marmot Formation mafic volcanics and Earn Group rocks, respectively. Goodfellow and Aronoff (1988) used Landsat imagery and surficial geochemical data to search for buried, and hence overlooked, plutons in the western Northwest Territories, and this might be a good approach for other regions as well.

Lewis et al. (2003) noted that all beryl occurrences in the Yukon Territory are intrusion-related, but for an intrusion to become enriched enough to reach Be-saturation, it must be "ultra-fractionated". Numerous lithological and geochemical features (e.g., tourmaline, Rb/Sr ratio in whole rock, K/Rb ratio in potassic feldspar, Eu depletions) can help pinpoint fractionated pegmatites with elevated gemstone potential.

Figure 8. Emerald crystal from the Ghost Lake occurrence, Ontario (photo courtesy of True North Gems Inc.).

Companies exploring for emerald in northwestern Canada have been relying heavily on Be and Cr analyses of stream-sediment and soil samples. Commercial analyses utilizing rapid single-stage digestion techniques may not adequately dissolve the refractory mineral phases that typically incorporate Be and Cr. In addition, the use of mass spectrometry to analyse Be, which is an extremely light element, in an analytical package that includes numerous heavy elements, may decrease the sensitivity of the Be analyses. This is an untested exploration approach for emerald exploration and it will be interesting to see if this results in any new discoveries. It is important to note that exploration for gem beryl could result in the discovery of new occurrences of non-gem beryl or other Be minerals that could become new sources of Be and Be oxide. Most Be is used as an alloy, metal, or oxide in electronic and electrical components and aerospace and defence applications. About 60% of world production is from bertrandite [$Be_4Si_2O_7(OH)_2$] ore mined from an epithermal deposit at Spor Mountain in Utah (Cunningham, 2004). Granite-focussed exploration could also result in the discovery of other commodities such as Au, Ag and W.

What about berylometers? These instruments use Sb^{124} as a gamma-radiation source. At least two models are commercially available. The most portable unit weighs 2 kg, but requires counting times of 2-5 minutes, and has a lower detection limit of only 0.01% BeO. The second model requires counting times of 1-2 minutes and has a lower detection limit of 0.003% BeO, but weighs 17 kg! The weights, counting times, and detection limits likely limit their application to property studies at best.

At the end of the day, geology and geochemistry will dictate where to look, but new occurrences will most likely be discovered by careful prospecting.

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