Preliminary geological work on samples from Davdar in China indicate that emerald occurs in quartz veins hosted within upper greenschist grade Permian metasedimentary rocks including quartzite, marble, phyllite and schist. Fluid inclusion studies indicate highly saline fluids ranging from approximately 34 to 41 wt.% NaCl equivalent, with minimal amounts of CO₂ estimated at a mole fraction of 0.003. Fluid inclusion, stable isotope and petrographic studies indicate the Davdar emeralds crystallized from highly saline brines in greenschist facies conditions at a temperature of ~350ºC and a pressure of up to 160 MPa. The highly saline fluid inclusions in the emeralds, the trace-element chemistry and stable isotope signatures indicate that the Davdar emeralds have some similarities to the Khaltaro and Swat Valley emerald deposits in Pakistan, but they show the greatest similarity to neighbouring deposits at Panjshir in Afghanistan.

KEYWORDS: beryl, China, Davdar, emerald, fluid inclusion studies, greenschist facies, stable isotope geochemistry

Introduction

EMERALDS were discovered at Davdar in the western part of Xinjiang Province (Fig. 1), close to the borders of Pakistan, Afghanistan and Tajikistan, in 2000. Since the discovery, mining activity of a mostly artisanal nature has developed in an area of a few square kilometres. The deposit and the emeralds it produces were described by Blauwet et al. (2005); gems of good clarity and excellent colour have been found. The Davdar deposit is the second emerald discovery in China, the first being the Dyakou deposit in southern China, which was discovered late in the twentieth century (Xue et al., 2010).

Geological setting

The geology of the Davdar deposit is not well understood as geological maps of the area are incomplete. Field observations show that emeralds are found in quartz-carbonate veins associated with a major northwest–southeast trending fault zone. The faults have intermediate dips ranging from 30 to 60º to the northeast. The veins are hosted by lower Permian rocks including sandstone, dolomitic limestone, siltstone and shale, which have been metamorphosed at upper greenschist conditions (An, 2009) to produce metasedimentary host rocks which include quartzite, marble, schist and phyllite, prior to the emplacement of the emerald-bearing veins. Basaltic dykes of unknown age, which are up to 10 m wide and crop out along strike lengths of up to 200 m, are the only intrusive igneous rocks known in the area. The dykes are emplaced along the northwest–southeast fault zone. No contacts between the dykes and the emerald-bearing veins
are exposed, but the relative proximity of the two indicate that the dykes may have acted as a source of heat and possibly chromium for emerald formation.

**Vein petrology**

The emerald-bearing veins, which are up to about 20 cm wide, are predominantly quartz and contain up to a few percent green beryl locally. Other vein minerals include epidote, K-feldspar, tourmaline-group minerals, carbonates and iron oxides. Quartz and emerald crystals up to a few centimetres long are found in the veins; the other vein minerals typically occur as crystals up to a few millimetres long. The width of the alteration halo surrounding the veins ranges up to a few centimetres and is highly dependent upon the host rock lithology. In the sandstone and dolomitic limestone the alteration halo is barely visible, but it is conspicuous as a bleached white halo in the phyllite. The alteration halo is generally enriched in silica and recrystallized, containing variable amounts of quartz, biotite, muscovite, feldspar, carbonate and tourmaline. The minerals in the alteration halo are most commonly fine grained, but crystals ranging up to a few millimetres long are found locally. The mineralogy of the alteration haloes is representative of a retrograde metamorphic assemblage in that the host rocks contain typical greenschist facies minerals (epidote, plagioclase, potassic feldspar, quartz, biotite and chlorite) and these have been altered to produce an assemblage that includes these minerals plus beryl, tourmaline and minor muscovite. Some of the idiomorphic beryl shows evidence of zonation (Fig. 2) and multiple precipitation (Fig. 3). Emerald typically occurs in the quartz veins and not in the host rocks or the alteration haloes. The zoned emeralds provide excellent material for fluid inclusion studies and quartz-beryl oxygen isotope thermometry.

**Emerald compositions**

Back-scattered electron and cathodoluminescence imaging reveals concentric growth zones in Davdar emerald (Fig. 3). The Cr, V, Fe, Mg and Na contents (as wt.% oxide) in an electron microprobe traverse across a zoned emerald are shown graphically in Fig. 3 and listed in Table 1. Electron microprobe analyses were performed at

**Fig. 1.** Sketch map showing the location of the study area.

**Fig. 2.** Zoned idiomorphic emerald from the Davdar deposit showing good clarity and colour.
Carleton University using an automated four spectrometer Camebax MBX electron probe operating in wavelength-dispersive mode (WDX) at 15 kV accelerating potential with a beam current of 20 nA. Counting times were up to 50 s or 40,000 accumulated counts. The X-ray lines were chosen to minimize or eliminate elemental interferences. Raw X-ray data were converted to elemental wt.% via the Cameca PAP matrix correction program. The standards, X-ray lines and analysing crystals used were as follows: synthetic spinel, Al\(K\alpha\), TAP; Camargo olivine, Mg\(K\alpha\), TAP; albite, Si\(K\alpha\), TAP; wollastonite, Ca\(K\alpha\), PET; MnTi, Ti\(K\alpha\), PET; YVO\(_4\), V\(K\alpha\), PET; synthetic chromite, Cr\(K\alpha\), LIF; MnTiO\(_3\), Mn\(K\alpha\), LIF; synthetic fayalite, Fe\(K\alpha\), LIF; baryte, Ba\(K\alpha\), PET; microcline, K\(K\alpha\), PET; synthetic cesium doped glass, Cs\(L\alpha\), PET; scandium metal, Sc\(K\alpha\), PET; tugtupite, Cl\(K\alpha\), PET; jadeite, Na\(K\alpha\), TAP. The H\(_2\)O was measured via a manometer during stable isotope analyses and an average value used to complement the probe analyses. Oxygen was calculated by stoichiometry and Be was determined by inductively coupled plasma mass spectrometry (ICPMS) on representative samples and this value was used as a complement to all of the electron microprobe data.

There is good correlation between Cr, V, Mg and Na, and a relatively poor correlation between these elements and Fe. The chromophores that generally colour emerald are Cr and V. The emerald from the Davdar occurrence contains more Cr than V (Fig. 4), and has a range of Cr/V from approximately 1 to 2, with Cr\(_2\)O\(_3\), V\(_2\)O\(_3\), Fe\(_2\)O\(_3\), MgO, and Na\(_2\)O contents ranging up to 3.0, 2.0, 0.5, 1.8 and 3.4 wt.% respectively. The presence of Fe tends to quench the green colour in emerald as well as cathodoluminescence (CL) and dark CL bands at the edges and in the centre of the emerald crystal are shown in Fig. 3. However, rather than a distinct abundance of Fe accounting for the lack of CL, it would appear the drop in CL is probably due to lower concentrations of the major chromophores such as Cr and V coupled with elevated Fe concentrations (Fig. 3). The concentrations of Fe, Cr and V have been plotted relative to emerald analyses worldwide (Fig. 4). There is some spread in the data, but clearly some overlap between the Davdar emerald and other emerald worldwide, most notably, the neighbouring emerald deposits in Afghanistan and Kazakhstan. There is also some overlap with more distant deposits including some of those in Colombia. This may be due to similarities in the geneses of the deposits or may simply reflect the large amount of variation in emerald from Colombia. Figures 5 and 6 plot selected cation concentrations relative to Al and Mg + Mn + Fe.
### Table 1. Compositions of Davdar emerald determined by electron microprobe analysis.

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<tr>
<td>MgO</td>
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<td>MnO</td>
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<td>FeO</td>
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<tr>
<td>Na$_2$O</td>
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<td>K$_2$O</td>
<td>0.01 0.00 0.01 0.02 0.02 0.02 0.04 0.05 0.05 0.04 0.03 0.04</td>
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</table>
Note that H₂O at 2.38 wt.% is calculated as an average of 4 channel water analyses from the stable isotope analyses (see Table 3). The amount of BeO, LiO, and Ce₂O₃ were determined on a representative sample by ICPMS, fusion with Na₂O₂, and neutron activation at 11.52, 0.03, and 0.02 wt.%, respectively. All analyses are calculated based on 18 oxygens. Analysis numbers listed in bold correspond to points illustrated in Fig. 3.

![Fig. 4. A ternary FeO–Cr₂O₃–V₂O₃ (wt.%) plot of Davdar emerald compositions (grey hexagons) superimposed on the worldwide emerald compositions from literature data compiled in Groat et al. (2008). All Fe data is reported at FeO.](image-url)
Fig. 5. The Al content vs. the sum of other Y-site cations, in atoms per formula unit (a.p.f.u.). The Davdar compositions (grey hexagons) are superimposed on worldwide emerald data from Groat et al. (2008).

Fig. 6. The Mg + Mn + Fe content vs. monovalent channel-site cations, in atoms per formula unit (a.p.f.u.). The Davdar compositions (grey hexagons) are superimposed on worldwide emerald data from Groat et al. (2008).
concentrations, respectively. In both these plots there are distinct overlaps between the Davdar emerald and emerald from the neighbouring emerald deposits at Khaltaro in Pakistan and at Panjsher in Afghanistan. There is also overlap with the Colombian emerald as well and to a certain extent some Australian emerald.

**Fluid inclusions**

Fluid inclusion studies at Davdar identified a dominant fluid inclusion type (FIT) of three-phase (brine + vapour + halite) fluid inclusions. Necking down (Roedder, 1984) is common in the Davdar fluid inclusions and the only fluid inclusions clearly identifiable as distinct fluid inclusion assemblages (FIAs) are the three-phase fluid inclusions. In rare cases there were two halite cubes present within the fluid inclusions. The fluid inclusions occur within most of the transparent vein minerals and were measured in quartz and emerald. In this study quartz was the optimal host mineral, as all fluid inclusions measured within the emerald stretched or decrepitated prior to complete homogenization. This is common in salt-dominated fluid systems and noted for Colombian emerald by Cheilletz et al. (1994). Even the fluid inclusions within quartz showed some evidence of post-entrapment volume changes during microthermometric measurements. The Davdar fluid inclusions are prone to metastable behaviour. The stable room temperature assemblage may persist to temperatures below –180°C for extended periods of time and in some inclusions ice will not nucleate; this is common in saline fluid inclusions with high concentrations of calcium (Roedder, 1984; Marshall et al., 1993). Electron microscopy of opened fluid inclusion residua confirmed the presence of Ca within the Davdar inclusions. Measurements were made on fluid inclusions that displayed consistent microthermometric behaviour. Many others were observed and measured but not used to determine compositions or isochoric data. The fluid inclusions are abundant within quartz and emerald, and range in size from submicroscopic to 20 μm, with most of the measured fluid inclusions being ~5 μm. The fluid inclusions generally display secondary textures occurring along trails (Fig. 7) of healed fractures, but in some rare cases primary inclusions can be attributed to growth features. The fluid inclusions were grouped into distinct FIAs based on observable timing relationships between individual fluid inclusions and mineral growth features (Bodnar, 2003a; Goldstein and Reynolds, 1994). All FIAs exhibited relatively consistent phase ratios and microthermometry (below). The FIAs are interpreted as a single population trapped over a relatively short time interval, and regardless of their secondary or primary nature are related to vein formation. At room temperature, the inclusions contain a three-phase assemblage consisting of approximately 70 vol.% brine, 15 vol.% vapour and 15 vol.% halite cube(s). The emerald and quartz display faint growth zones in transmitted light. These zones are generally defined by areas of more-abundant vs. less-abundant fluid inclusions, fine-scale optical banding, growth-zone-perpendicular and c-axis-parallel elongate micrometre-sized fluid inclusions. The growth zoning is more

**Fig. 7.** Photomicrograph of a trail of secondary three-phase fluid inclusions along a healed fracture in idiomorphic quartz (qtz). In addition to the daughter halite (H) cube, carbonic vapour (V) bubble and a halite saturated liquid (L) that define the three-phase assemblage for this fluid inclusion population, some inclusions also contain rare accidental birefringent (biref) mineral inclusions. The same three-phase population of fluid inclusions is hosted within emerald (emd) as shown in the inset photomicrograph. The length of the largest emerald-hosted fluid inclusion is 6 μm. Photographs are taken in plane polarized light.
easily observed as layered concentric cathodoluminescent active zones within idiomorphic emerald (Fig. 3). Thus, the interpreted single fluid inclusion population is considered to be contemporaneous with the emerald and other vein minerals, based on the petrographic relationships between growth zones and fluid inclusions, the overall abundance of these fluid inclusions, the petrographic equilibrium observed between all the emerald-bearing vein minerals, and the lack of any other fluid population within the vein minerals. Samples were chosen from two quartz-emerald veins. There are no observable differences in the fluid inclusions from the individual veins (or host minerals) on the basis of petrography. Rarely, fluid inclusions contain additional birefringent material (Fig. 7). These birefringent phases were determined to be accidental inclusions as they did not dissolve during heating of the inclusion, and are not consistently present in all of the three-phase fluid inclusions.

Microthermometry

Upon rapid cooling from room temperature, the three-phase fluid inclusions nucleate clathrate at approximately −71°C and ice at approximately −82°C. In some cases, solid CO₂ is formed at approximately −100°C. Cooling to −190°C, produced no other phase changes. Heating the fluid inclusions from −190°C results in the first melting of ice at approximately −66°C and, in a few inclusions, the sublimation of the solid CO₂ in the temperature range −60.0 to −56.6°C (Table 2). Final ice melting temperatures range from −24 to −26°C, and final clathrate melting temperatures from −15 to −18°C. No salt-hydrates were observed and we interpret the melting of the phase between −15 and −18°C to be clathrate based on the observation of the characteristic double freezing and because the clathrate was observed to melt in direct contact with the vapour bubble. The depression of the NaCl–H₂O eutectic indicates there may be other divalent cations such as Ca or Mg or other cations present at relatively low concentrations. Further heating decreases the volume of the vapour bubble and halite cube until final homogenization of the fluid inclusion to the liquid phase occurs over a temperature range 242–340°C for inclusions where total homogenization is via halite melting (liquid + halite → liquid) and over the range 251 to 389°C for inclusions that undergo total homogenization via vapour bubble homogenization (liquid + vapour → liquid). Halite melting temperatures correspond to a range of salinities from 34.0 to 41.5 wt.% NaCl equivalent. Both the halite melting temperatures and the vapour homogenization temperatures define a normal distribution (Fig. 8) with the majority of the fluid inclusions undergoing total homogeniza-

![Graph](image-url)
Table 2. Microthermometric measurements on the fluid inclusions from emerald and quartz.

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<th>$T_n$ (ice)</th>
<th>$T_n$ (CO₂)</th>
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All temperatures are reported in °C; $T_n$ (cla) = clathrate nucleation temperature; $T_n$ (ice) = ice nucleation temperature; $T_n$ (CO₂) = solid CO₂ nucleation temperature; $T_m$ (CO₂) = solid CO₂ melting temperature; $T_{eutectic}$ = ice melting eutectic temperature; $T_m$ (ice) = ice melting temperature; $T_m$ (cla) = clathrate melting temperature; $T_m$ (hal) = halite melting/dissolution temperature; $T_h$ (vap) = vapour homogenization temperature into the liquid; the abbreviation nv = not visible. DAVDAR-inclusions are hosted in emerald, all others are hosted in quartz.
tion to the liquid via halite dissolution. This inconsistent behaviour can be explained by the observation that some inclusions decrepitated or stretched upon heating, by post-trapping volume changes (necking down), or trapping of a binary mixture in a neighbouring two-phase field. As stretching of inclusions was confirmed by observing the bubble volume at room temperature prior to the heating portion of microthermometric study vs. the bubble volume after heating, the interpretation of trapping a binary mixture is unlikely. The result of stretching inclusions is that vapour homogenization temperatures are shifted to falsely high values, whereas the halite melting temperatures remain virtually unaffected. Observations on inclusions using pre- and post-heating bubble volume comparisons indicate that the (unstretched) inclusions would ideally undergo total homogenization via halite melting. Where both measurements were obtained the relationships between halite melting and vapour homogenization temperatures are shown for individual inclusions in Fig. 9. Some of the fluid inclusions above the \( T_h = T_m \) line have stretched (Table 2) during microthermometric heating. The stretched inclusions were not used in the generation of isochores.

The rare birefringent phases (Fig. 7) present in addition to the liquid, vapour and halite do not homogenize on heating and are thus classified as accidental inclusions. The small size of these accidental inclusions and poor optical resolution prevents identification, but the relatively clear colour and birefringence suggest they are probably muscovite or a carbonate.

**Stable isotopes**

Beryl crystallizes in the hexagonal system and is composed of interconnected six-membered rings of silica tetrahedra producing channels parallel to the \( c \) axis. The channels are large enough to accommodate a range of aqueous fluids and dissolved cations that maintain charge balance. Fluids trapped within the channel contribute minimally to the overall \( \delta^{18}O \) of the beryl host, but more importantly, they contain the only hydrogen as molecular \( H_2O \) within the beryl structure and represent the original formational fluid in equilibrium with the beryl during crystallization (Taylor et al., 1992). Extraction and trapping of the channel fluids above 800ºC and subsequent \( \delta^D \) analyses have been used in conjunction with \( \delta^{18}O \) analyses of the beryl to distinguish between different

![Fig. 9. Vapour homogenization vs. halite melting temperatures for individual three-phase fluid inclusions hosted in quartz and emerald. Symbols represent individual fluid inclusion assemblages (FIAs) with primary and secondary fluid inclusion data plotted in darker and lighter grey, respectively. The double-headed arrow indicates the effect of stretching (Table 2) within individual fluid inclusions.](image-url)
emerald deposits, determine fluid source and deposit type (Giuliani et al., 1997). Hydrogen and oxygen stable isotope ratios from emerald channel fluids at Davdar (Table 3) are consistent with the $\delta^{18}O-\delta D$ signature of metamorphic rocks, but as they are very close to the field for highly evolved peraluminous granitic fluids, it is possible that there may also be some magmatic influence (Fig. 10). The measured $\delta^{18}O_{SMOW}$ values for quartz and beryl (Table 3) yield quartz–beryl fractionation values for the Davdar emerald occurrence that are consistent with temperatures ranging from approximately 325 to 375°C (Table 3) using the empirically derived equation of Xue et al. (2010). These temperatures are consistent with observed levels of wall rock alteration and the mineralogy of the metasomatic haloes surrounding the veins.

**Pressure, temperature, fluid estimates**

Although major advances have been made for some gas-bearing salt-undersaturated fluid inclusions (Diamond, 2001; 2003), it remains problematic to establish the exact composition of salt-saturated gas-bearing fluid inclusions. The fluid inclusion compositions and densities for this study have been derived using the microthermometric data and fluid inclusion liquid to vapour ratio estimates combined with the Flincor program (Brown, 1989). The halite melting temperatures (Table 2; Fig. 8) correspond to salinities ranging from approximately 34–41 wt.% NaCl equivalent. The CO$_2$ concentrations are minimal, but detectable via the fluid inclusion microthermometry and these measurements yield mole fraction ($X$-CO$_2$) estimates on the order of 0.003. All individual fluid inclusions were plotted as separate isochores, and the two bounding isochores for the entire isochore set were then further refined via the ISOC program of Bakker (2003) combined with the H$_2$O–NaCl data of Knight and Bodnar (1989) and an $X$-CO$_2$ of 0.003. These two derived isochores are plotted in Fig. 11 and were intersected with the independently obtained temperatures from the $^{18}O$ equilibrium between vein emerald and quartz to place estimates on the pressures and temperatures of formation for these emerald veins. The $P$–$T$ conditions ranging from 325 to 375°C and up to 160 MPa, and although dominantly contained in the one-phase (liquid) field conditions lie very close to two other fields for a 37.5 wt.% NaCl–H$_2$O fluid (Fig. 11). Thus inclusions may have been trapped in any one of the three fields of liquid, liquid + halite, and/or liquid + vapour. Entrapment of fluid inclusions within all three of these fields is consistent with the minor amounts of scatter and variable total homogenization phenomena, which is always to the liquid by either halite melting or vapour homogenization, during the fluid inclusion microthermometry. However, the lack of observed vapour-dominant or halite-dominant fluid inclusions suggests the majority of fluid inclusions were probably trapped.

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<th>Sample number and mineral</th>
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<th>Channel H$_2$O (wt.%O)</th>
<th>$\delta D$ (%o, SMOW)</th>
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* Equilibrium temperatures derived from Xue et al. (2010) quartz-beryl $^{18}O$ equation.
† Different quartz-beryl mineral pair in the same sample.
‡ Different crystals in the same sample.
Fig. 10. Channel $\delta^{18}$O for the Davdar emerald (hatched box) superimposed on data from a number of world localities from Groat et al. (2008). The isotopic composition fields are from Sheppard (1986) including the extended (Cornubian) magmatic water box (grey). The abbreviations are: MWL = meteoric water line; SMOW = standard mean ocean water. The Davdar $\delta^{18}$O channel water data have been calculated using the measured $\delta^{18}$O beryl values and the equation of Taylor et al. (1992) at specific equilibrium temperatures as listed in Table 3.

Fig. 11. Pressure—temperature diagram showing the constraints (dark grey) for the Davdar emerald veins derived from the intersecting areas of the fluid inclusion isochore constraints (light grey) and stable isotope thermometry. Isochores 1 and 2 are derived from the fluid inclusion microthermometric data with isochore 1 representing the isochore derived from the fluid inclusion data corresponding to lower vapour homogenization temperatures and isochore 2 representing fluid inclusions with higher homogenization temperatures. The stability field boundaries for fluid/halite phase assemblages for a 37.5 wt.% NaCl–H$_2$O fluid derived from the data of Bodnar (2003b) are shown as grey lines with grey text.
Discussion and conclusions

Most emerald worldwide is formed in a geological environment where Be-rich fluids interact with a source of Cr (+V). The three most common formational models are igneous, metamorphic and hydrothermal-sedimentary (or Colombian) type (Schwarz and Giuliani, 2001; Groat et al., 2008). The igneous model generally has Be-bearing evolved granitic rocks intruding into a Cr (+V) rich host rock. The metamorphic model involves Be-rich fluids travelling along major crustal conduits and interacting with Cr (+V) rich host rocks. The hydrothermal-sedimentary model has highly saline basinal fluids, derived from evaporates, interacting with Cr (+V) shales higher in the stratigraphic sequence to precipitate emerald.

As no Be-rich granitic rocks have been related to the emerald in the area, it would initially seem that the typical igneous model is not applicable to the Davdar deposits. However, there may be an unidentified granitic intrusion at depth. Saline inclusions have been linked to igneous related emerald occurrences such as the Jos occurrence in Nigeria (Vapnik and Moroz, 2002) and the nearby Miocene emerald deposits at Panjshir in Afghanistan (Vapnik and Moroz, 2001). The Swat valley (Arif et al., 1996), Khaltaro (Laurs et al., 1996) and Panjshir (Giuliani et al., 1997) occurrences show evidence of magmatic origins with varying contributions from metamorphic sources. Compared to the neighbouring emerald deposits, Davdar shows the greatest similarity to Panjshir on the basis of fluid inclusion and stable isotope evidence.

The Davdar deposit shares some similarities with the metamorphic model, as the deposit is hosted within a major fault system. However, the temperatures of formation at Davdar are somewhat lower than is normally the case in metamorphic emerald deposits (Grundmann and Morteani, 1989).

Another but less likely model that shows some similarities to the preliminary observations at Davdar is the hydrothermal-sedimentary model. The main lines of evidence are that the Davdar deposit has highly saline fluids and occurs in metasedimentary rocks. In this scenario, it is plausible that the highly saline brines are Be-bearing and have complexed Be and salts from the host metasedimentary rocks. These brines would have moved upwards within the stratigraphic sequence, and along the fault system, where the brines interacted with Cr (+V) bearing shales, phyllites and other rocks.

Despite the detailed emerald chemistry, isotopic, fluid inclusion and pressure–temperature data presented in this paper, a determination of the exact genesis of the Davdar emerald veins will require additional detailed geological studies, drilling and lithogeochemistry. Information currently available for the Davdar deposits suggests that all of the three general models for emerald formation have features in common with the emerald-bearing veins at Davdar.

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References


Association of Canada, Quebec, Canada.


