Ruby and Pink Sapphire from Aappaluttoq, Greenland

Christopher P. Smith, Andrew J. Fagan and Bryan Clark

Since 1966, rubies and pink sapphires have been recovered from the southwest coastal region of Greenland. Until recently, only minor amounts of gem material were produced by local people using small-scale artisanal mining techniques. In 2014, True North Gems Inc. (Vancouver, British Columbia, Canada) completed mine permitting, and an exploitation licence for the extraction of gem corundum was issued for the area around the Aappaluttoq deposit. The property changed ownership in November 2016, and the first sale of its rubies and pink sapphires is expected to take place in 2017. The mineralization is hosted by the Fiskenæsset Anorthosite Complex, primarily within a phlogopite-bearing metasomatic rock. Standard gemmological properties are consistent with metamorphic-metasomatic-type rubies and pink sapphires from other world deposits. Typical inclusion features consist of coarse particles and fine needles of rutile, as well as inclusions of mica, talc, pargasite, cordierite, sillimanite, plagioclase and boehmite. The chemical composition of the Greenland rubies and pink sapphires is characterized by relatively high Fe contents and comparatively low concentrations of Ti, V and Ga.

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Introduction

Little attention has been paid to the gem corundum localities of Greenland since their discovery in the 1960s. However, during the past several years, True North Gems Inc. applied detailed geological mapping, geophysics, drilling (more than 6,000 m of core), geochemical and heavy mineral concentrate sampling, and mini-bulk and bulk sampling techniques to characterize and define a minable reserve at their Aappaluttoq deposit (Weston, 2009; Reggin and Horan, 2015). In 2014, True North received an exploitation licence after undergoing strict environmental and social permitting that accompanied extensive baseline surveys of the local ecology and villages. However, in September 2016, True North Gems Greenland, the operating subsidiary of True North Gems Inc., was unable to raise sufficient working capital to put the mine into production, and the project was taken over by LNS Group of Norway, which continues to work towards production and sales in 2017.

With the development of the Aappaluttoq deposit, Greenland is poised to become a significant producer of ruby and pink sapphire (e.g. Figure 1). The deposit has the potential to make an important contribution to the global supply of ruby and pink sapphire for many years. This article provides an update on the geology of the Aappaluttoq deposit and gives a comprehensive gemmological description of its rubies and pink sapphires.

Figure 1: A range of colour and clarity is shown by these rubies and pink sapphires (0.61–2.37 ct) from Greenland's Aappaluttoq deposit. Photo by Bilal Mahmood.

Location and Access

The gem corundum deposits of south-west Greenland are located approximately 200 km south of Greenland's capital city, Nuuk (Figure 2). From there, the mine is accessible by either a 45 minute helicopter flight or a five hour speedboat trip; there are no roads nearby. The area receives significant snowfall during the winter, when the average temperatures range from −10°C to +10°C (Statistics Greenland, 2016). Compared to the climate of the diamond mines in northern Canada, it is easier to conduct a mining operation in the more temperate environment of south-west Greenland.

The coast of western Greenland is mountainous with deeply incised fjords that run from the Davis Straight (between Canada and Greenland) inland toward the permanent ice sheet. At Aappaluttoq, only the local fjords (and not the open sea) freeze during the winter, so the mine is considered to have year-round sea access—a major logistical advantage. The vast majority of the labour required for the mine can be sourced from local towns and villages; this ensures that staff is well accustomed to working through the winter and also throughout the long days of summer.

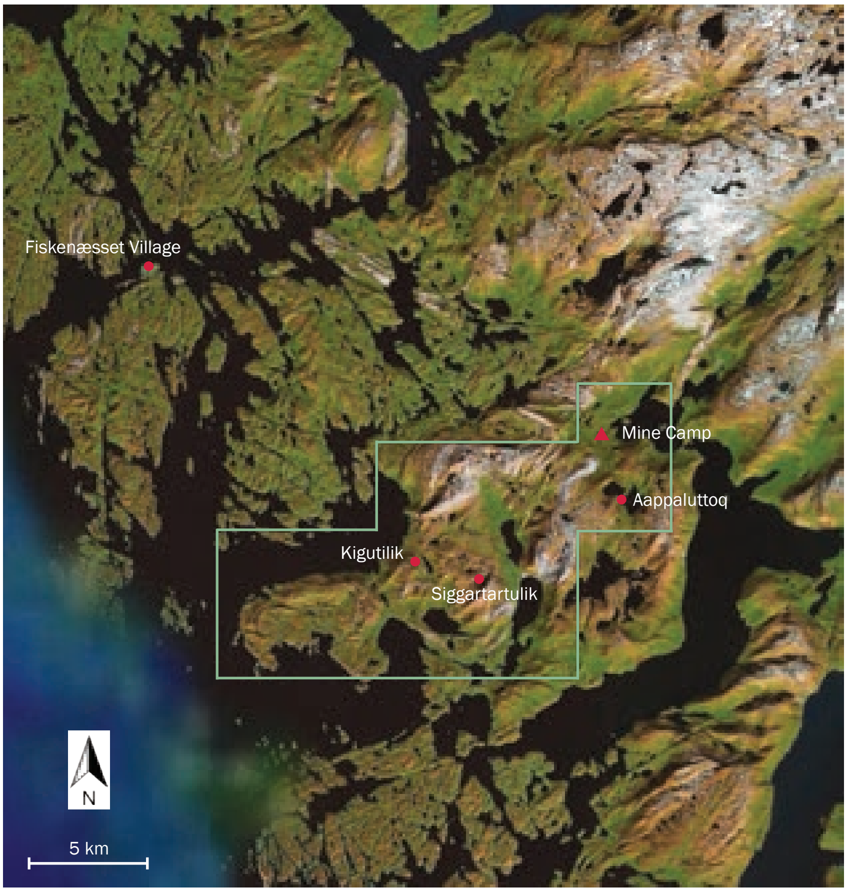


Figure 2: The Aappaluttoq deposit is located south of Greenland's capital city, Nuuk. This satellite image of the Fiskenæsset gem district shows the approximate outline of the area where True North has concentrated its exploration efforts since 2006. The prospective ruby and pink sapphire deposits include Aappaluttoq, Siggartartulik and Kigutilik. Base photo courtesy of True North Gems Inc.

Geology and Gem Formation

The geology of the Aappaluttoq deposit has been summarized in several papers and conference abstracts (Appel, 1995; Weston, 2009; Reggin and Chow, 2011; Fagan and Groat, 2014a,b; Giuliani et al., 2014; Fagan, 2015; Reggin and Horan, 2015), and is still being actively researched by a team of company and academic geologists.

The rocks at Aappaluttoq have been subjected to high-pressure, high-temperature metamorphism and are very old (Mesoarchean); recent research suggests an age of approximately 2.9 billion years (Polat et al., 2010). Research is ongoing to define the actual age of the gem mineralization; the gems probably are significantly younger than their host rocks, related to later regional metamorphism and metasomatism. Nevertheless, Aappaluttoq still may be one of the oldest coloured stone deposits in the world (Krebs et al., 2016).

Greenland's gem corundum deposits are hosted by the Fiskenæsset Anorthosite Complex (FAC; see, e.g., Herd et al., 1969; Myers, 1975, 1985). The mineralization at Aappaluttoq is hosted by a reaction zone that formed from metasomatic interactions between ultramafic rock (peridotite) and mafic rock (leucogabbro). The peridotite forms a small lens or layer within the FAC and is composed of olivine, clinopyroxene, orthopyroxene, green spinel, amphibole and ilmenite, with minor apatite, magnesite, pyrrhotite and chalcopyrite. This ultramafic rock has low SiO_2 (<45 wt.%) and contains various chromophore elements (particularly Cr, and also V, Fe and Ti) that are important for the formation of an economically significant gem corundum deposit. The leucogabbro is a large and well-defined layer within the FAC. It has an Al-rich composition and comprises varying amounts of plagioclase, amphiboles (mostly hornblende and pargasite) and micas (biotite and phlogopite) with minor quartz. Although both the peridotite and leucogabbro have been regionally metamorphosed, most of their original igneous layering and textures are preserved.

In the metasomatized reaction zone, the ultramafic rock is rich in phlogopite (and is therefore called a *phlogopitite*; Figure 3) and consists of a steeply dipping layer approximately 2–5 m thick that extends to a depth of more than 90 m. It is composed of phlogopite-biotite (~80%), corundum (~10%), plagioclase (~5%) and oxide minerals (~5%) with minor amounts of amphiboles (pargasite, hornblende and gedrite). Adjacent to the phlogopitite reaction zone, the peridotite has been altered to a sapphirine-gedrite-hornblende assemblage. The metasomatized leucogabbro hosts some corundum mineralization, but since it does not contain as much Cr as the peridotite, it contains pink sapphire rather than ruby.

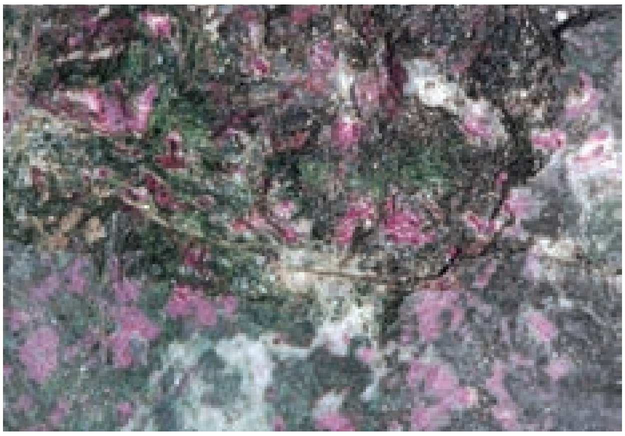


Figure 3: This unusually coarse-grained and high-grade corundum ore from Aappaluttoq consists of a phlogopitite rock that contains brown phlogopite-biotite, white plagioclase, dark green pargasite and pink-to-red corundum crystals up to 4 cm long. The lower part of the sample has been sawn, while the top part is a broken surface. Photo courtesy of True North Gems Inc.

Geochemical interactions between the differing rocks are thought to be responsible for forming the gem corundum. Although the general mechanism was suggested decades ago (Herd et al., 1969), new ideas regarding the geochemistry and timing have only recently been presented (Fagan and Groat, 2014a,b; Fagan et al., 2014; Krebs et al., 2016). According to these models, during regional metamorphism, fluid interactions between the two differing rock types created a metasomatic reaction zone encompassing part of the peridotite, the leucogabbro and the contact zone between the two units. Within this zone, silica was leached from the leucogabbro and the chromophoric elements were removed from the peridotite (Fagan and Groat, 2014). Upon regional cooling, the reaction zone formed significant volumes of stable phlogopite with corundum. Alumina (Al_2O_3), the main component of corundum, is believed to have remained stable in the residue of the altered leucogabbro. The concentration of Al in the reaction zone was high, and the availability of Cr from the adjacent peridotite

Figure 4: This aerial photo shows the construction of the processing plant and main workshop at the Aappaluttoq deposit, well underway. The processing plant will employ dense media and magnetic separation, as well as advanced optical sorting technology to extract the corundum. Since this image was taken in October 2015, the plant building has been completed. Photo courtesy of True North Gems Inc.

allowed the substitution of Cr^{3+} for Al^{3+} in the corundum, producing its pink-to-red coloration.

An examination of rough gem corundum derived from the 200 tonnes of rock extracted by True North from Aappaluttoq since 2006 reveals several crystal morphologies. The primary form for both ruby and pink sapphire is the hexagonal tablet, with crystals commonly ranging from 1.7 to 20 mm in dimension. These tablets formed between the layers of mica (phlogopite and biotite) in the main phlogopitite host rock. The morphology is not linked to coloration, with the tablets exhibiting all colours from deep red to 'lilac' pink. Within the altered leucogabbro, the dominant morphology consists of hexagonal prisms with pinacoidal terminations, in slightly larger sizes than those observed within the phlogopitite ore. In addition, hexagonal dipyramidal crystals up to 4 cm long rarely have been recovered from exploration samples.

Figure 5: Processing of ore from Aappaluttoq resulted in this rough concentrate of <4.6 mm-sized material. The pink-to-red corundum in this material will then be further separated with an optical sorter. Photo courtesy of True North Gems Inc.

Mining and Recovery

The Aappaluttoq deposit is being developed into one of the most advanced coloured stone mines in the world (Figure 4). Modern mining techniques are planned to maximize production, minimize cost and limit the opportunity for theft.

The extraction process is planned to begin with blocks of ore being quarried with large commercial wire saws—a technique borrowed from the dimension stone industry. These blocks will weigh approximately 20 tonnes each, and 5–8 of them will be produced each day. Each block will be transported to a processing facility, where it will be crushed into small pieces (initially 20 mm and processed down to 1.7 mm). Iterative crushing and recovery will ensure that the largest corundum stones are liberated rather than crushed. The material will be transported on closed conveyor belts to the Aappaluttoq Gem Recovery plant for further processing using dense media and magnetic separation followed by optical sorting technology to produce a corundum concentrate (e.g. Figure 5). This material will be sent to a separate facility in Greenland where the remaining host rock (approximately 25–30%) will be removed using a 24-hour hydrofluoric acid wash. The corundum will then be graded according to a customized sort matrix. After the opaque material is removed, the gem corundum (Figure 6) will be prepared for valuation and export. More

Figure 6: Initial sorting experiments of the rough gem corundum yielded these categories (from left to right) of 'medium pink', 'red' and 'lilac pink'. Photo courtesy of True North Gems Inc.

details on the ore processing and corundum recovery procedures are provided by Reggin and Horan (2015).

Production, Quality and Size

The use of modern exploration techniques at Aappaluttoq allows for a high degree of predictability in the grade and volume of gem corundum recovered from each mined block over the entire life-of-mine. This is unusual for a coloured gemstone deposit and should enable a dependable supply of rough material to the market.

Figure 7: These sapphires from Greenland range from light to intense pink; some also exhibit a subtle purplish colour modifier. The stones are eye-clean to moderately included and weigh 0.42–1.43 ct. Photo by Bilal Mahmood.

From the outset, True North Gems modelled the mine economics using only melee-sized (<4 mm) rough gem material. Although geological sampling has shown that larger stones are present within the deposit, their recovery is highly difficult to predict. The focus on melee-sized material will enable a steady supply of rough to partners in the marketplace, rather than relying on auctions that take place a few times per year. This improves mine cash flow and avoids 'peaks and surges' of gem corundum production. Although this strategy has led some to believe that Aappaluttoq will only produce small stones, this actually is not the case. Numerous faceted gemstones of >1 ct are held by the company in inventory recovered from exploration bulk samples; some of those gems were made available for this study (e.g. see the cover of this issue and Figure 7). The largest piece of corundum recovered to date is the carved opaque 440 ct Kitaa Ruby (see www.diamonds.net/News/NewsItem.aspx?ArticleID=15699).

The exploration bulk samples obtained during the early phases of the project have been processed for 'test-polishing' exercises, in which several kilograms of rough material were faceted to assess the quality of the material. The resulting sample inventory includes approximately 15,000 carats of polished material, ranging from cabochon-quality to extra-fine faceted material, in various colours, sizes and shapes. Pink sapphire makes up approximately 60–80% of this production, with ruby making up the balance. This colour proportion is in line with other deposits of this type, such as the Montepuez ruby mine in Mozambique (Roberts and Beare, 2015). For the highest quality polished stones from Aappaluttoq, valuations reached US$3,200/ct for intense pink sapphires and US$6,000/ct for deep red rubies.

Production from Aappaluttoq is expected to last for a minimum of nine years, and the deposit currently has defined minable reserves of 59.2 million grams of corundum, with an additional 21.8 million grams as inferred resources (i.e. exploration targets that could prolong the life-of-mine once they have been investigated further; see Reggin and Horan, 2015). Approximately 70% of the corundum is allocated to the non-gem 'opaque' category, 20–25% is 'near-gem' and 5–10% is 'gem'. These percentages are consistent with other large gem corundum deposits (e.g. Roberts and Beare, 2015).

Materials and Methods

Nineteen faceted samples were provided by True North Gems to American Gemological Laboratories for this study. These consisted of 10 rubies (0.29–2.53 ct; see cover of this issue) and nine pink sapphires (0.42–1.43 ct; Figure 7).

Standard gemmological instrumentation was used to record pleochroism, RI, birefringence, optic character, hydrostatic SG, UV fluorescence (with a 4 W combination 365 nm long-wave and 254 nm short-wave lamp) and optical absorption spectra (with a prism-type desk-model spectroscope) for all samples. A binocular microscope, incorporating fibre-optic and other lighting techniques, was used to document internal features in the stones.

Identification of mineral inclusions was performed using a Renishaw 2000 Raman microscope. Additionally, we utilized a Thermo Scientific Nicolet 6700 Fourier-transform infrared (FTIR) spectrometer to record the absorption of all samples in the near- to mid-IR region of the spectrum (7000–400 cm^{-1}). Polarized ultraviolet-visible-near infrared (UV-Vis-NIR) spectra in the range of 250–850 nm were recorded on four of the stones with a PerkinElmer Lambda 950 spectrometer. A Thermo Scientific ARL Quant'X energy-dispersive X-ray fluorescence spectrometer (EDXRF) was used to determine the semi-quantitative chemical composition of all samples.

Results and Discussion

Gemmological Characteristics

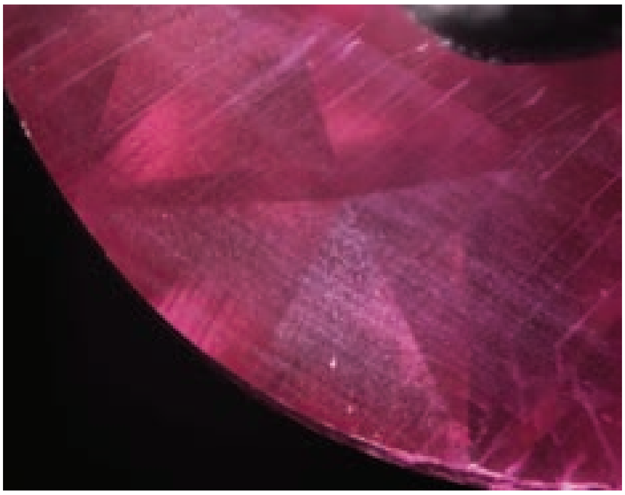
Colour and Visual Appearance: Ten of the samples possessed a richly saturated, pure red coloration that classified them as ruby (see, e.g., the cover of this issue). The remaining nine pink sapphires ranged from a light pastel pink to an intense pink face-up appearance (Figure 7). Several of the pink sapphires displayed a subtle purplish colour modifier. No eye-visible colour zoning was observed. The majority of the samples were transparent, while several trended towards semi-transparent due to the nature and number of their inclusions.

All samples exhibited moderate-to-strong dichroism when viewed perpendicular to the c-axis with a dichroscope. Yellowish orange to orangey red or pink coloration was seen parallel to the c-axis, and reddish purple to purple-red (for rubies) or purplish pink to purple-pink (for pink sapphires) was observed perpendicular to the c-axis.

Gemmological Properties: The standard gemmological properties were consistent with corundum in general, and also with past research on rubies and pink sapphires from Greenland (Thirangoon, 2009): RI—n_ω = 1.769–1.700 and n_ε = 1.760–1.762, birefringence—0.008–0.009, optic character—uniaxial negative and SG—3.98–4.01. In general, the ruby samples displayed moderate-to-strong red fluorescence when exposed to long-wave UV radiation, whereas the pink sapphires displayed a weak-to-moderate red reaction. All samples showed weaker red fluorescence to short-wave radiation, ranging from weak to none. Four of the samples contained unidentifiable inclusions that fluoresced bright orange when exposed to both long-wave and short-wave UV radiation.

Internal Features: A rich diversity of features were noted in the rubies and pink sapphires from Greenland. In addition to twinning (see below), the most commonly observed internal features were clouds of minute rutile particles (i.e. 'silk', see Figure 8), as well as some fine rutile needles and arrowhead-shaped platelets (Figure 9). Generally speaking, few additional mineral inclusions were observed. Of these, we identified whitish inclusions of talc (Figure 10), whitish to

Figure 8: Clouds of fine rutile particles are one of the most common inclusion features observed in the rubies and pink sapphires from Greenland. Photomicrograph by C. P. Smith; magnified 55×.



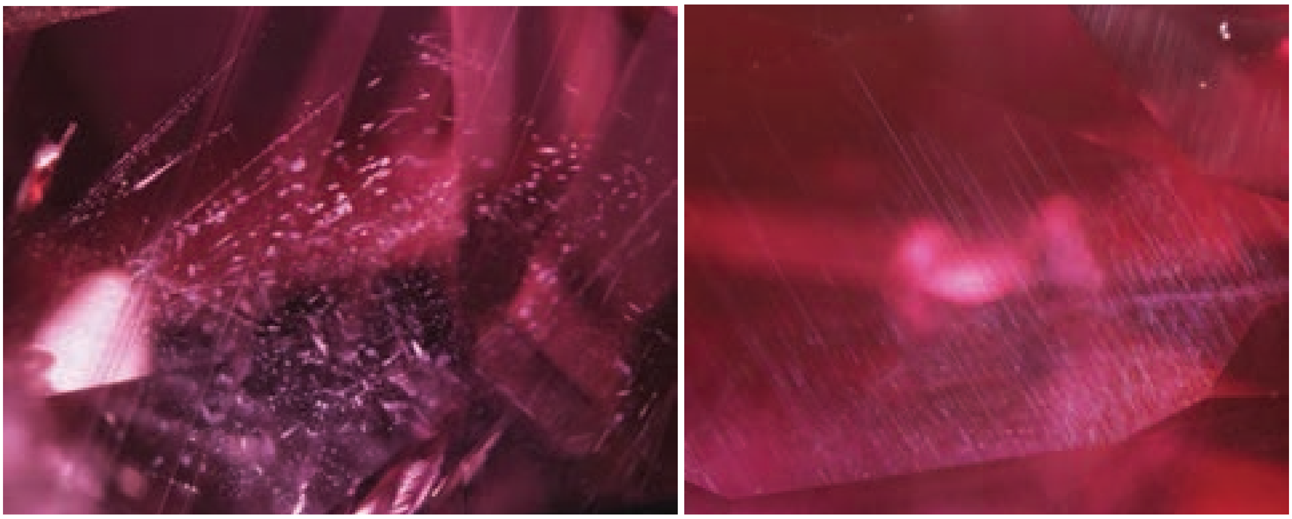


Figure 9: Fine exsolutions of rutile needles and platelets (sometimes arrowhead shaped) also are commonly encountered in Greenland gem corundum. Photomicrographs by C. P. Smith; magnified 58× (left) and 75× (right).

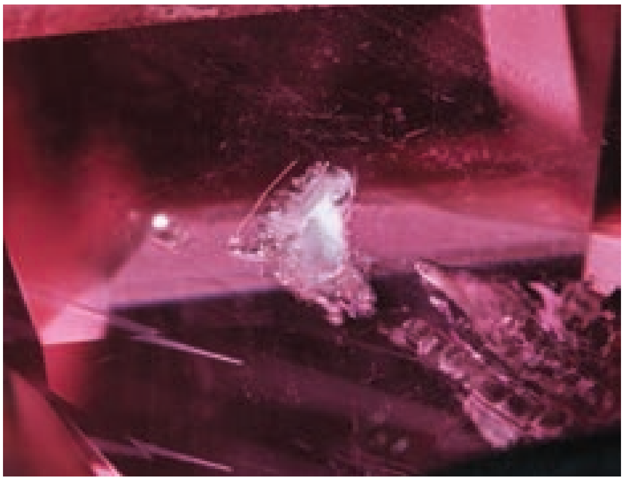


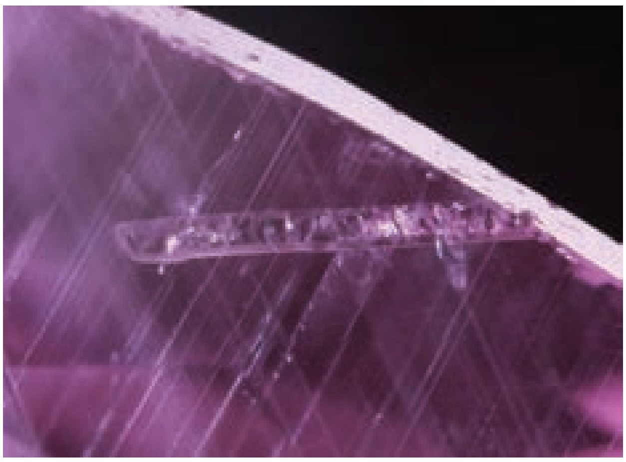
Figure 10: Of the various mineral inclusions identified, translucent, whitish inclusions of talc were the most commonly observed in the rubies and pink sapphires from Greenland. Photomicrograph by C. P. Smith; magnified 58×.

brownish crystals of mica (Figure 11), as well as cordierite, sillimanite, plagioclase and columnar crystals of pargasite (Figure 12). Additionally, we observed several rounded-to-oblong, colourless crystals that could not be identified with Raman spectroscopy (because Cr luminescence from the host gemstone swamped the Raman detector and resulted in a poor analysis); their appearance resembled apatite and zircon (Figure 13). Also present at the polished surface of some samples were inclusion assemblages composed of a variety of minerals, including talc, plagioclase, sillimanite and others.

We noted various patterns of partially healed fissures that were composed primarily of isolated (not interconnected) negative crystals (Figure 14).

Figure 11: Mica is another of the more common mineral inclusions identified in Greenland rubies and pink sapphires. Photomicrograph by C. P. Smith; magnified 60×.

Figure 12: Pargasite is not commonly found in rubies and sapphires, although a few samples in this study possessed columnar euhedral crystals of this amphibole-group mineral. Photomicrograph by C. P. Smith; magnified 62×.



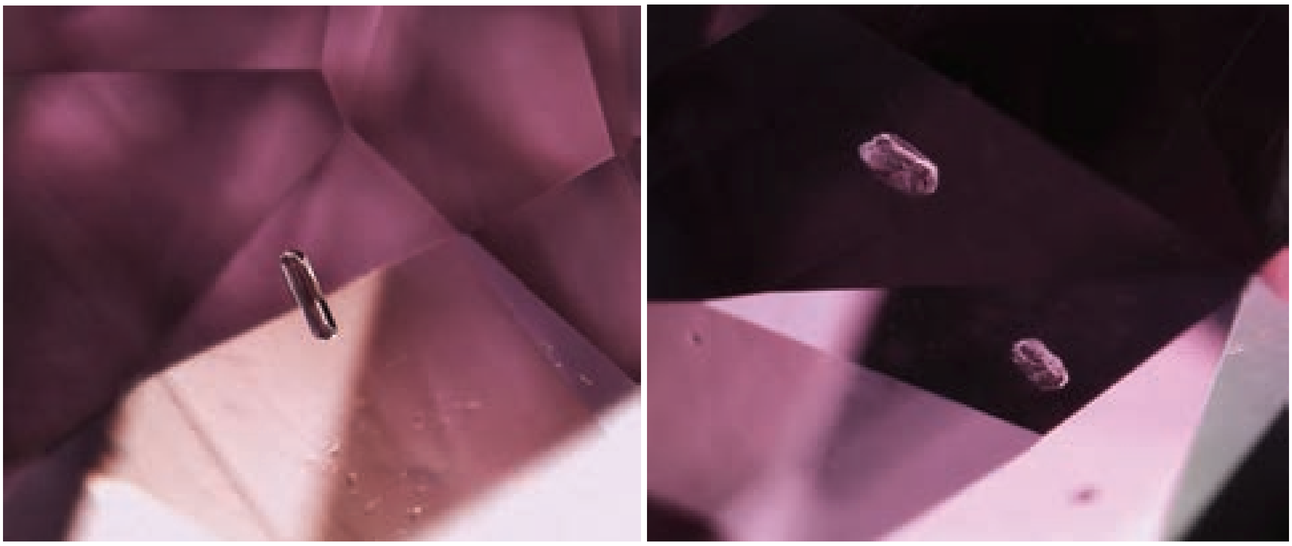


Figure 13: These inclusions could not be identified in this study, although they resemble zircon and/or apatite. Photomicrographs by C. P. Smith; magnified 60×.

In addition, one sample possessed basal-oriented thin films associated with negative crystals (Figure 15). The partially healed fissures and negative crystals seen in these samples interestingly did not trap any fluid phase. Also, the necking-down process of fissure healing typical of rubies and pink sapphires from most other deposits was not observed in these samples, and only tiny negative crystals were seen. It is possible that fluid may be present in these minute negative crystals but was too small to be recognized. It is also possible that there was not much fluid present under the high temperature and pressure conditions that the gems formed (i.e. near granulite metamorphic conditions).

Boehmite (identified by mid-IR spectroscopy) commonly formed an alteration product along a series of coarse, whitish intersection tubules occurring at the intersection of two or three twinning/parting planes (Figure 16). Open fissures also were commonly observed, and often they were lined by epigenetic minerals such as boehmite, kaolinite, goethite and other weathering minerals.

Additional mineral inclusions of catapleiite, chlorite, cosalite, dolomite, magnesite, margarite, pyroxene and sapphirine have been identified in

Figure 14: Partially healed fissures composed of groups of isolated negative crystals are a common feature in Greenland rubies and pink sapphires. Photomicrograph by C. P. Smith; magnified 55×.

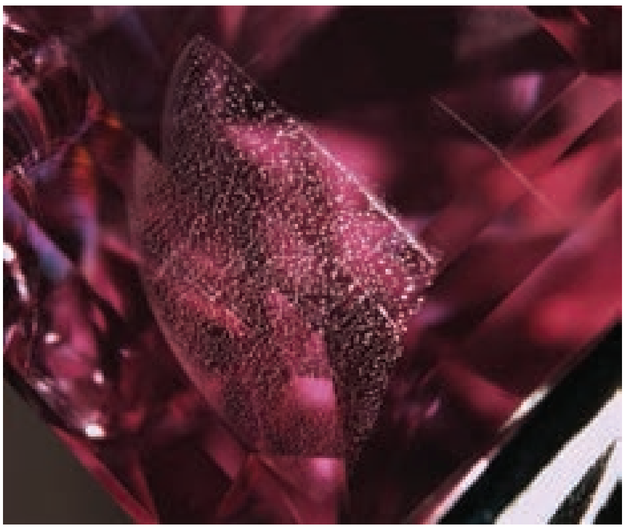


Figure 15: A series of fine, platy negative crystals and thin films are oriented along the basal growth planes in this pink sapphire. Photomicrograph by C. P. Smith; magnified 50×.

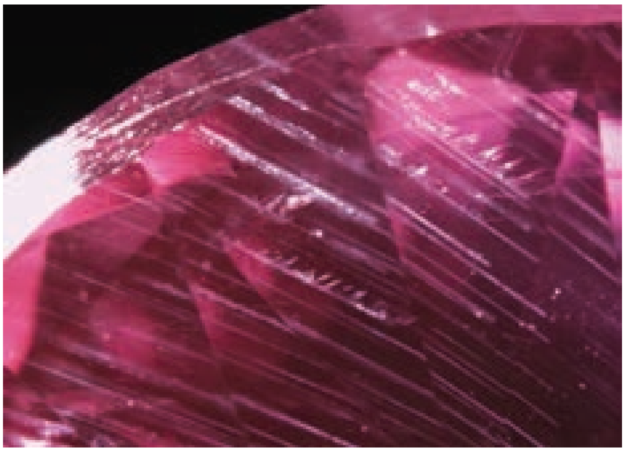


Figure 16: Boehmite is found along intersection tubules that commonly occurred at the crossing of twinning (and sometimes parting) planes in the rubies and pink sapphires. Also visible are a series of stress fractures along the length of some of the tubules. Photomicrograph by C. P. Smith; magnified 60×.

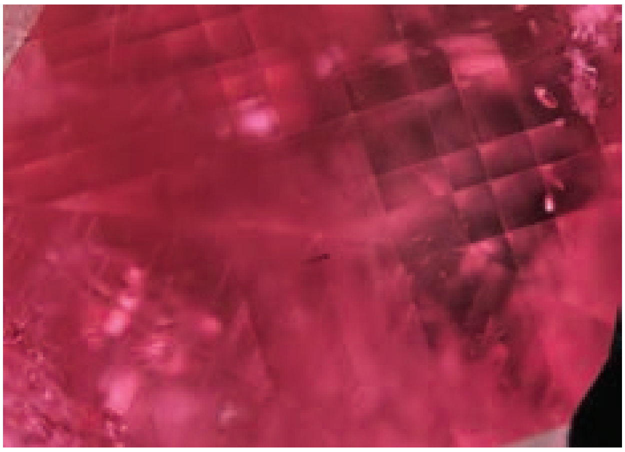


Figure 17: Intersecting twinning along different directions of the positive rhombohedron r {10$\bar{1}$1} create a checkerboard pattern in this ruby. Photomicrograph by C. P. Smith; magnified 42×.

Greenland rubies and pink sapphires by other researchers (e.g. Thirangoon, 2009).

Internal Growth Structures, Colour Zoning and Twinning: Generally, the samples contained rare-to-no internal growth structures, and their colour was homogeneous. A few showed subtle planar growth structures, and weak-to-distinct pink-to-red colour zones were rarely noted.

Several of the stones displayed twinning parallel to the positive rhombohedron *r* {10$\bar{1}$1}. Typically we noted only one direction of laminated twinning, parallel to a single series of *r* planes. Occasionally, however, there were as many as three directions of twinning parallel to additional *r* planes. Parting parallel to *r* also was prominent in a few samples. The intersections of twinning and/or parting planes created a checkerboard pattern (Figure 17).

Visible and UV-Vis-NIR Spectroscopy

All spectra were dominated by chromium absorption features. The strength of the absorption bands varied with the intensity of the pink-to-red colour of the gems.

Desk-model Spectroscope: In the visible range, a general absorption to approximately 450 nm was apparent, along with weak-to-distinct lines at 468 nm and at 475/476 nm (doublet). A broad absorption band was observed from approximately 525 to 585 nm; its width depended on the saturation of pink-to-red colour. We also noted faint lines at 659 and 668 nm, plus two strong lines at 692 and 694 nm (which appeared as a bright emission line at 693 nm).

UV-Vis-NIR Polarized Spectroscopy: Two broad bands, centred at approximately 405 and 550 nm, as well as weak-to-distinct sharp peaks recorded at 468, 475, 476, 659, 668, 692 and 694 nm, are

*Table I: Semi-quantitative EDXRF chemical analyses of rubies and pink sapphires from Greenland.**

Variety	Ruby (sample no.)									
Element	**1681**	**1889**	**1945**	**1952**	**2165**	**2236**	**2309**	**2311**	**3403**	**3426**
Al	99.27	99.43	99.33	99.24	99.09	99.30	99.46	99.39	98.88	99.44
Ti	228	1227	141	95	112	124	81	139	128	156
V	72	46	64	67	62	72	83	36	38	44
Cr	4552	2701	4353	5242	6860	5084	3358	3086	8387	2754
Fe	2261	2686	1999	2058	1837	1624	1728	2706	2435	2507
Ga	49	49	55	54	53	54	56	41	52	42

* Data are in wt.% for Al and in parts per million by weight (ppmw) for all other elements. Approximate detection limits are Ti = 22, V = 20, Cr = 18, Fe = 11 and Ga = 7 ppmw.

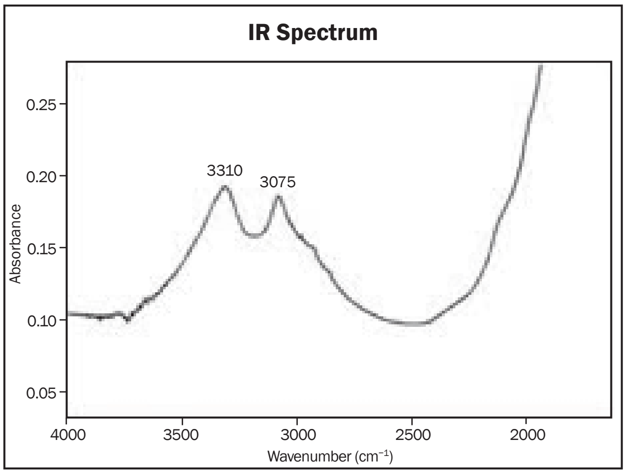


Figure 18: In the mid-infrared region of the spectrum, some rubies and pink sapphires from Greenland showed distinct bands at approximately 3310 and 3075 cm^{-1} (and weak bands at approximately 2100 and 1980 cm^{-1}). These features indicate the presence of boehmite, which was mostly concentrated along intersection tubules related to twinning and/or parting planes. Such absorption characteristics are helpful not only for identifying the presence of foreign mineral phases, but also for proving that a gem has not been heated.

all ascribed to Cr^{3+}. A weak band was also occasionally observed at 450 nm, attributed to Fe^{3+} pair transition.

FTIR Spectroscopy

In addition to the dominant IR absorption characteristics of corundum between 1000 and 400 cm^{-1} (i.e. approximately 760, 642, 602 and 450 cm^{-1}: Wefers and Bell, 1972), the rubies and pink sapphires in this study commonly had weak-to-very strong absorptions related to structurally bonded OH groups and foreign minerals. A nominal, sharp band was recorded at 3310 cm^{-1} in several samples. Additionally, a weak series of absorptions with the dominant feature at 3161 cm^{-1} was found in one stone. These are all associated with structurally bonded OH groups (Smith and van der Bogert, 2006). Also common were two dominant bands positioned at approximately 3310 and 3075 cm^{-1} (Figure 18), with an additional pair of weak bands at approximately 2100 and 1980 cm^{-1}. These features are related to OH-stretching frequencies associated with boehmite, an aluminium hydroxide mineral (Farmer, 1974; Wefers and Misra, 1987; Smith et al., 1997). Several samples had additional absorptions in this region that further signalled the presence of kaolinite, goethite and other weathering minerals (cf. Smith and van der Bogert, 2006). The specific mineral phase could not be identified in all instances.

The presence of boehmite was generally traced to locations along parting planes, interpenetrating intersection tubules and open fissures, whereas the presence of kaolinite, goethite, etc. was generally attributed to epigenetic staining present in surface-reaching fissures.

Chemical Analyses

The most significant minor- to trace-element variations were recorded in Cr concentrations, which again correlated to the intensity of the red-to-pink colour. Ti and Fe were the next most significant trace elements, followed by very small amounts of V and Ga (Table I). Although higher Ti contents were recorded previously by Thirangoon (2009), other elements (Cr, V, Fe and Ga) were consistent with that study. Mg was below the detection limit of EDXRF spectroscopy in all samples. Although Keulen and Kalvig (2013) also analysed corundum from Greenland, a direct comparison to their dataset is impossible due to their use of normalized data and the absence of any verifiably comparable gem-quality

Pink Sapphire (sample no.)								
1512	**1519**	**1849**	**1888**	**1891**	**1894**	**1895**	**1896**	**1897**
99.73	99.80	99.71	99.56	99.64	99.63	99.69	99.74	99.74
141	149	128	81	56	130	143	108	139
94	42	32	69	82	38	40	37	67
561	869	750	2269	1524	1070	1058	775	298
1784	886	1919	1895	1788	2407	1705	1580	1997
40	31	57	50	63	58	63	42	60

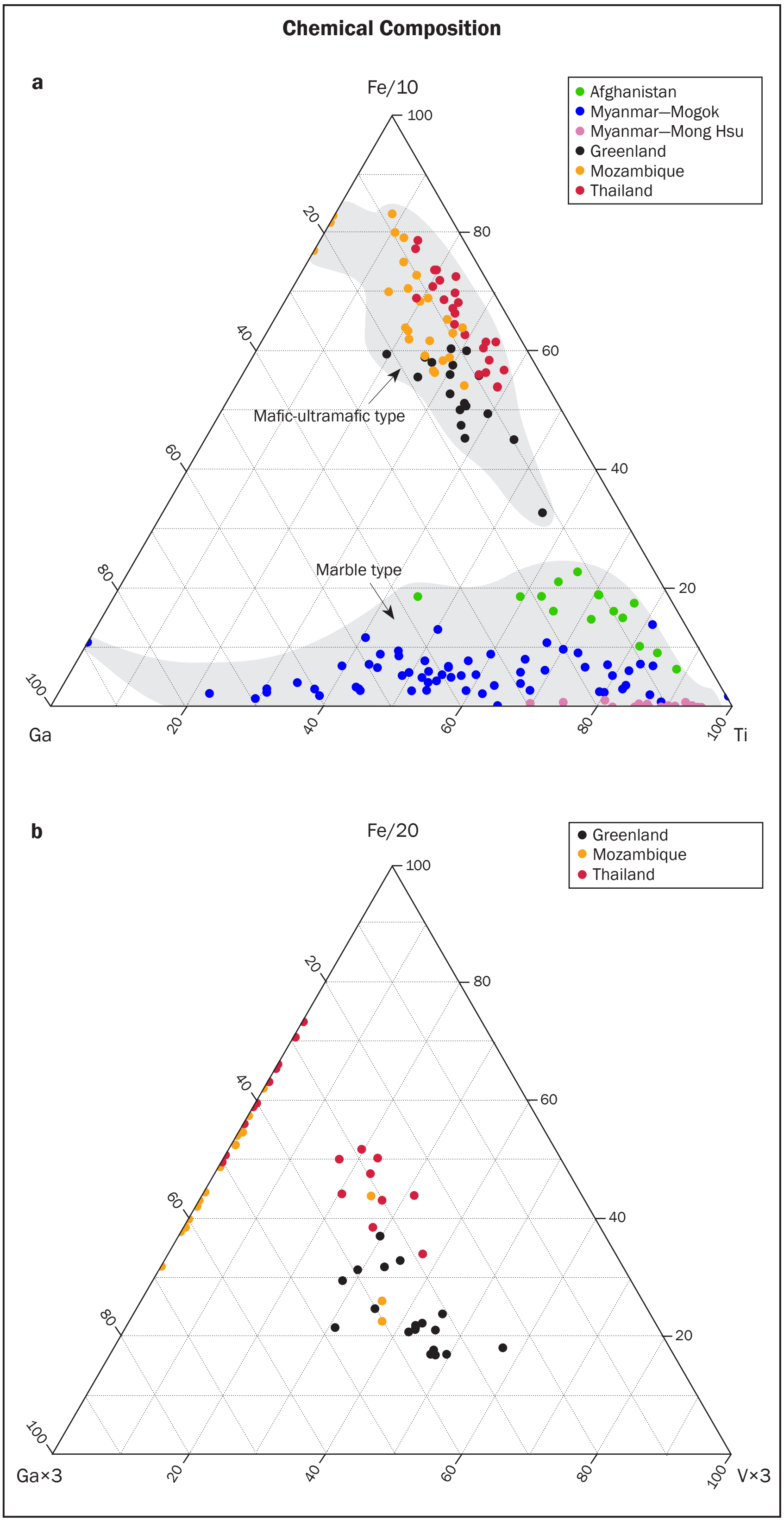


Figure 19: (a) The concentrations of Fe, Ti and Ga are plotted for the rubies and pink sapphires from Greenland as compared to some other major world sources, including marble-type deposits from Afghanistan (Jegdalek) and Myanmar (Mogok and Mong Hsu), mafic metamorphic-metasomatic rocks from Mozambique (Montepuez) and alkali basalts from Thailand (Chanthaburi and Trat). The relatively higher Fe contents of the mafic-ultramafic-derived gems from Greenland, Mozambique and Thailand readily separate these sources from marble-type deposits. (b) Further correlations of these and other elements such as V help to separate the relatively higher-Fe sources from those of Greenland, although there is some overlap—particularly with stones from Mozambique.

samples from the same deposit. In the present authors' opinion, the analyses of opaque material in a geographic origin study do not normally compare well to those of the high-quality stones that are routinely submitted to gemmological laboratories.

Figure 19 illustrates how the composition of the rubies from Greenland compares to that of rubies from some other major deposits. Further geochemical and isotopic work is ongoing in association with the University of Alberta (Krebs et al., 2016) and the University of British Columbia.

Geographic Origin Determination

There are a number of features that may help gemmologists recognize a ruby or pink sapphire from Greenland. Their relatively high Fe content separates them from the majority of stones from marble-type deposits, such as those in Afghanistan, Myanmar, Nepal, Pakistan and Vietnam, as well as plumasites (i.e. Mangare, Kenya) and metasomatized mafic dykes in marble (i.e. Mahenge and Matombo in Tanzania). For pink sapphires, this also includes the placer deposits of Sri Lanka and Madagascar (Ilakaka).

Rubies and pink sapphires from basalt-related deposits also contain relatively high Fe, although correlations between other trace elements can help to separate them from those of Greenland (again, see Figure 19). In addition, the typical inclusion features of thin films oriented along basal growth zoning and associated with doubly truncated negative crystals, such as those found in the basalt-related deposits of Thailand, Cambodia and Kenya (Lake Baringo), were not encountered in our Greenland samples. The Fe content of our Greenland stones was similar to that of some rubies and pink sapphires from East Africa (Madagascar, Mozambique, Tanzania and Malawi). Further work on the trace-element and isotopic composition of the Greenlandic material is ongoing and should prove helpful for origin fingerprinting (Fagan and Groat, 2014a,b; Krebs et. al., 2016).

Some typical microscopic properties of Greenland gem corundum include the relative fineness of the rutile silk as compared to the typically coarser rutile particles observed in a number of the East African deposits. In addition, certain mineral inclusions such as cordierite, cosalite and catapleiite that have been identified in previous studies (Thirangoon, 2009) may also point to a Greenland origin.

It should be noted that none of the rubies and pink sapphires included in this study were heat treated, and this is one of the current marketing points of the Greenland gem corundum. However, and the majority of the rubies and pink sapphires sold in the market have been heat treated, it should be expected that heated Greenland gems will also become available (directly or indirectly) at some point. Once a stone has been heated, geographic origin determination becomes more difficult, as key identification features such as rutile patterns and other mineral inclusions become altered.

Conclusions

In the near future, it is expected that rubies and pink sapphires from Greenland will become a significant new addition to the gem and jewellery market. Although gem corundum was first discovered there in the 1960s, a full mineral exploration study was not completed until 2011. Since then, the Aappaluttoq deposit has gone through the mine permitting process, and an exploitation licence was issued in 2014. Once fully financed and constructed, large-scale mining activities will commence.

Mineral inclusions in these rubies and pink sapphires are consistent with the metamorphosed and metasomatized mafic-ultramafic host rocks. Inclusions of mica (mostly brown phlogopite-biotite), feldspar (plagioclase) and pargasite are typical minerals of the phlogopitite and leucogabbro host rocks. Inclusions of talc are consistent with the alteration of ultramafic rocks, and boehmite also may be attributed to a retrograde metamorphic alteration of the host corundum. The presence of sillimanite and cordierite inclusions is consistent with the pressure-temperature conditions expected for the Aappaluttoq stones. Other researchers have also identified catapleiite, chlorite, cosalite, dolomite, magnesite, margarite, pyroxene and sapphirine inclusions in rough ruby and pink sapphire samples from Greenland (Thirangoon, 2009). The minor-to-trace-element composition of the Greenland gem corundum revealed relatively high Fe with comparatively low Ti, V and Ga.

By taking into account the complete array of gemmological characteristics and chemical data, we found that it is possible to separate the gem-quality Greenland rubies and pink sapphires from those of the more commercially important deposits in Myanmar, Thailand, Madagascar, Mozambique, Kenya, Vietnam and elsewhere.

Despite the poor mining finance climate that currently exists, it is likely that Aappaluttoq will go into production in 2017. Thus the gem and jewellery trade should expect an influx of Greenland rubies and pink sapphires in the near future.

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The Authors

Christopher P. Smith FGA and Bryan Clark
American Gemmological Laboratories (AGL)
580 5th Avenue, Suite 706, New York,
New York, USA
Email: chsmith@aglgemlab.com

Andrew J. Fagan
True North Gems Inc., 700–1055 West Georgia Street, Vancouver, British Columbia, Canada

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