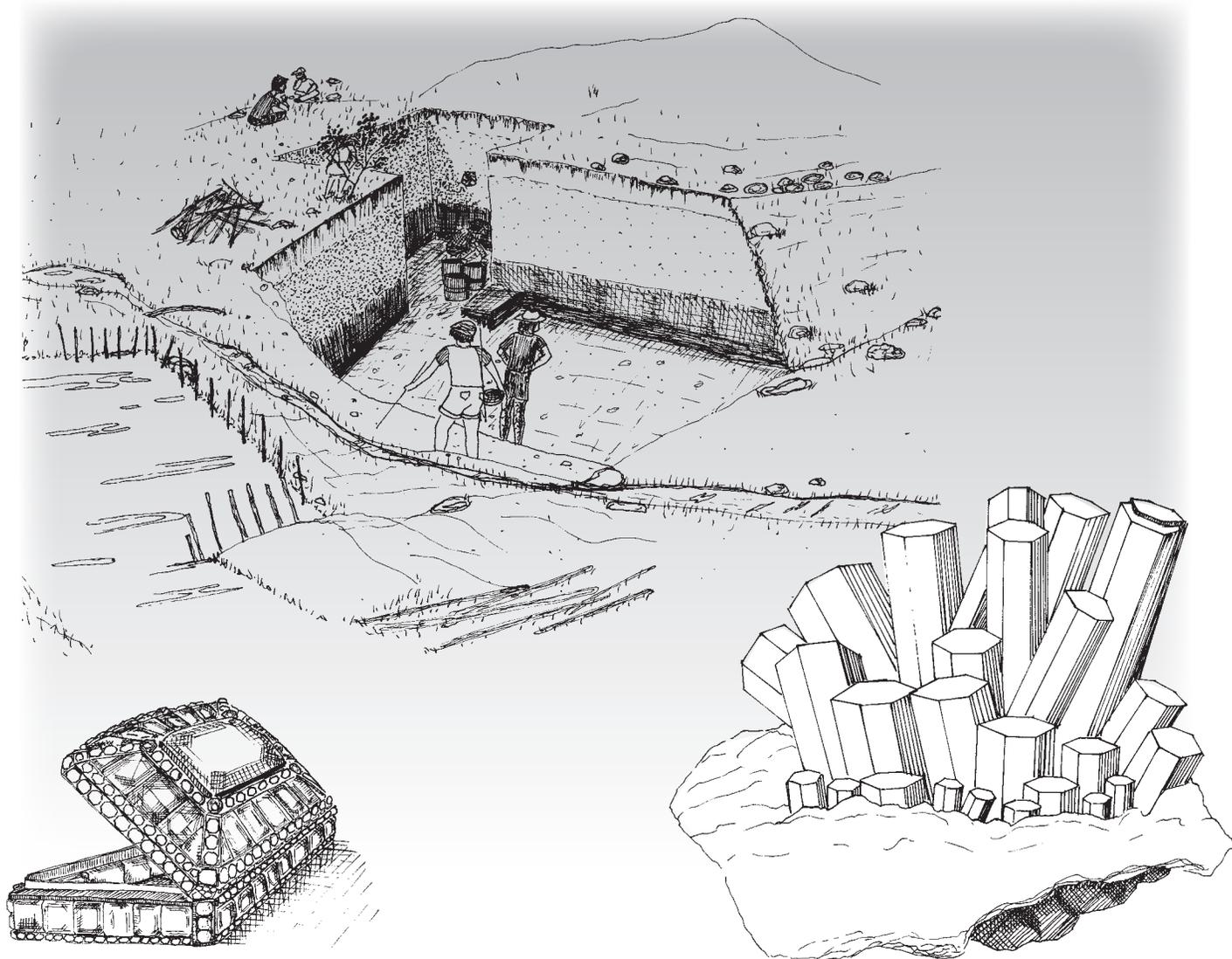


OPEN FILE 2004–10

EXPLORATION CRITERIA FOR Coloured Gemstone Deposits in the Yukon

by Lori Walton
Tigerstar Geoscience

May, 2004



Illustrations by
Christine Bannerman

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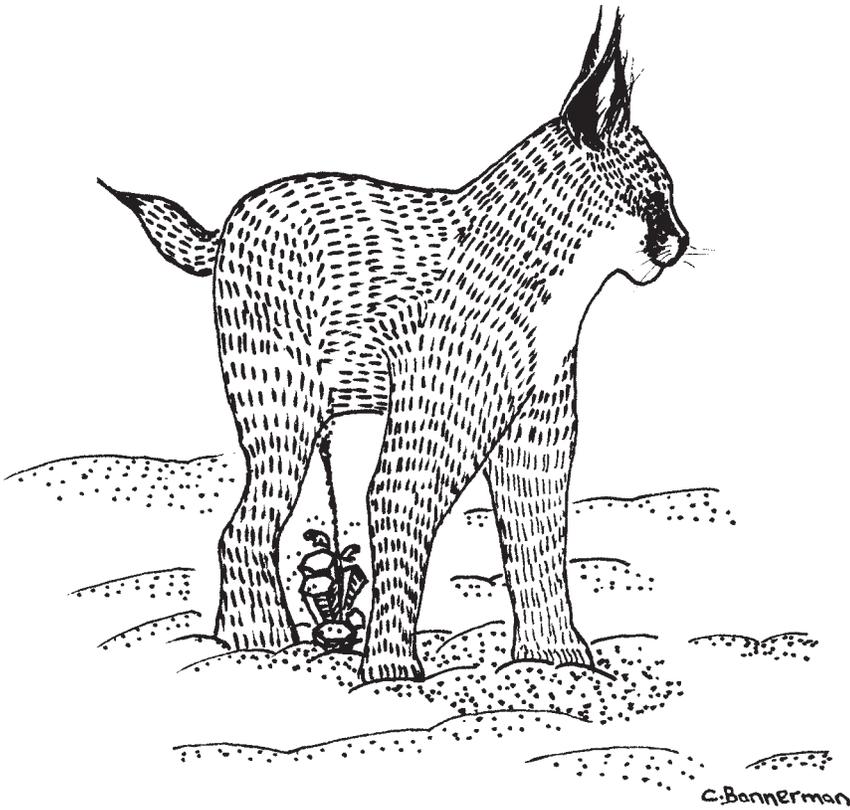
Illustrations by Christine Bannerman.

Note: All prices in this report are given in U.S. dollars.

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PREFACE



The ancient Greeks believed that four elements — fire, air, water and earth — comprised the universe and that metals in ore deposits were water elements. There is some scientific evidence today that the mysterious fifth element first postulated by the Greeks may in fact exist as ‘dark energy’ or ‘dark matter’ comprising 95% of our universe. Ancient Greek philosophers/naturalists/historians were, like all humans throughout history, fascinated by geology and gemstones, especially the beautiful coloured gems that came from the island of Serendipity, or Sri Lanka. The physico-chemical controls on gem formation were beautifully described in those days by the philosopher Theophrastus who declared gemstones to be ‘solidified lynx urine’ and in fact valuable gem crystals grew wherever this beautiful feline decided to pee. Before scoffing, we must think about how our present day ideas and models for gemstone formation may be viewed not just 100 years in the future, but 1,000 or even 10,000 years. Some of the best and most useful work on gemstone deposits is not the fluid inclusion and stable isotope laboratory work, but the careful, detailed and precise descriptions, sometimes hand drawn, of the geology, mineralogy and general nature of the deposit. So little is known about some of the best gem deposits on our planet, such as the ruby deposits of Burma or the sapphire deposits of Kashmir, India. We must rely on descriptive geology done many years ago until we can unleash our modern scientific arsenal to decode how and why these fabulous gems formed and if there is potential for finding world-class coloured gemstone deposits in Canada.

ACKNOWLEDGEMENTS

I would like to gratefully acknowledge the funding granted for this report by the Yukon Geological Survey, Department of Energy, Mines and Resources, Government of Yukon.

Many individuals contributed their expertise and took the time to discuss aspects of gemstone deposits and I thank all of them. I would also like to thank the people who contributed to the editing. Brad Wilson, Robert Simpson, Peter Long and Diane Emond. K-L Services did their usual outstanding job. I would also like to thank my family for their support.



1. INTRODUCTION

For over 20,000 years and probably longer, humans have looked for beautiful and durable natural materials from which to make personal ornaments and attractive decorative objects. Shell necklaces from graves near Rome have been dated at 22,000 years old and amazingly, would not look out of place around the neck of a woman from the 21st century. Magnificent jewellery sets of gold, lapis lazuli and carnelian agate, belonging to a Sumerian queen in the area we now call Iraq, continue to astonish us by their intricate beauty. Besides being beautiful, gems are an important part of our cultural heritage on this planet. For centuries, gemstones have been a globally recognized and easily transportable form of wealth. Their acquisition can cost lives, as in the conquest of the Indian tribes of South America by the Spaniards in the 16th century, or save lives, as in the efforts of Jewish people to leave Nazi Germany before and during the Second World War. A more recent example is that of emerald mining in Afghanistan, which helped finance the Northern Alliance rebellion against Taliban-ruled Afghanistan in the late 1990s up to 2001. Now, at the beginning of the 21st century, consumers are becoming more and more aware of the manner in which gems are mined and marketed. Canada's fledgling gem trade has no long tradition or history behind it, but we can market our stones as being mined in a socially and environmentally responsible manner.

For decades, Canadian geologists have been at the leading edge of developing exploration guidelines and techniques for exploring for gold, silver, copper, lead, nickel and zinc deposits, and, more recently diamond deposits. Before diamonds were discovered in the Northwest Territories, Canadian geologists and prospectors really had no idea what the kimberlitic host rock for diamond looked like and how to find it. Since then, there has been a flood of technical special volumes, short courses, seminars and papers outlining diamond exploration guidelines for geologists and prospectors. In fact, in less than 15 years, the geologists of Canada have become world-leaders in the geology of diamond deposits and how to explore for them.

When it comes to coloured gemstones like ruby, emerald and sapphire, geologists and prospectors know very little about how to explore for and evaluate occurrences of these very rare minerals. Recent discoveries of emerald mineralization in the Yukon, Northwest Territories and Ontario have generated a flurry of scientific papers and heightened awareness of the coloured gemstone market, but it is still an unfamiliar market, not only to exploration geologists, but also to governments, securities commissions and investors.

A main area of concern is that of identification of gem rough in the field. Many, if not most coloured gemstones we see today in jewellery stores are coated, fracture-filled, dyed and/or irradiated in linear accelerators in efforts to enhance their appearance. Heat treatment is the most common technique used. The gemstones

1. Introduction

that one sees in the jewellery store, the vivid violet-blue tanzanites, midnight blue sapphires, crimson red rubies and brilliant yellow sapphires, are typically, almost without exception, heat-treated or treated in some other manner to improve their appearance. In some cases this improvement is dramatic, as in the heat treatment of tanzanite, which transforms non-descript greyish crystals to vivid violet-blue stones. Buckets of plain white, cloudy corundum (sapphire) crystals can be heat treated to a clear, sparkly midnight blue. Emeralds are quite easy to identify in the field, although almost all of them have been oiled after mining to improve the clarity of the stone. Most gem crystals are difficult to identify in the field in their rough form and embedded within the host rock, or within a bucket of placer concentrate.

SCOPE OF THIS OPEN FILE

This report is an updated version of an Open File report (Walton, 1996) describing the geology and geochemistry of gemstone deposits and applicable exploration criteria. At the time of the 1996 report, emeralds had not yet been reported in the Yukon or NWT and yet it was obvious that Canada's geology is very prospective for significant coloured gemstone deposits. Exploration efforts in the north are hampered by the short exploration season and harsh climate. The 1996 report and this update are both aimed at exploration geologists and prospectors who are unfamiliar with the geology of gemstone deposits and how to explore for them. Its objective is to provide information on gemstone deposit geology and provide general guidelines for the identification of, and exploration for, gemstone occurrences. The report focuses on a selection of some of the most valuable

Educating the Canadian mining industry

Listed below are some significant papers, seminars and short courses on the subject of the geology of coloured gemstones. In addition, the Canadian Institute of Gemology and the Canadian Gemological Association sponsor gemstone talks and seminars throughout the year, and there are articles on gemstones on the Canadian Rockhound website.

Papers

Gemstones of Canada, by Warren F. Boyd and Willow Wight. *Journal of Gemmology*, 1983, vol. 18, no. 6, p. 544–562.

Gemstone Occurrences in British Columbia, by Bradley Wilson, *Canadian Gemmologist*, 1997, vol. 18, no. 3.

Explosion of New Interest in Canadian Gemstones, by Willow Wight, *Canadian Gemmologist*, 1999, XX(2), p. 45–129.

Canadian Gemstones: Old & New, by Willow Wight. (Excerpts from a presentation, Canadian Gemological Association Conference in Toronto, 1994.) *Canadian Gemmologist*, 1995, XVI (3) p. 82–87.

Sessions and short courses

Coloured Gemstones and Ornamental Stones II Session, Chaired by G. Simandl and D. Lefebure, Canadian Institute of Mining and Metallurgy, April 27–30, 1997, Vancouver, British Columbia.

Gemstones of the Pacific Rim Session, Meeting of the Cordilleran Section of the Geological Society of America, April 27–29, 2000, Vancouver, British Columbia.

Northern Gems Short Course, organized by L. Walton, H. Falck and S. Craig, presented at 2002 Geoscience Forums in Whitehorse and Yellowknife.

Gem Materials and Mineralogy, special session organized by L. Groat, University of British Columbia, Geological Association of Canada – Mineralogical Association of Canada Annual General Meeting, Vancouver, 2003.

Websites

Canadian Rockhound:
www.canadianrockhound.com

Canadian Gemological Institute:
www.cigem.ca

Canadian Gemological Association:
www.canadiangemological.com



gemstones in the global gem trade: ruby, sapphire, emerald, chrysoberyl, tsavorite garnet, tanzanite and the gem minerals (topaz, aquamarine, tourmaline) found in pegmatites or rhyolites. Exploration criteria for other gemstones such as opal, nephrite jade, jadeite jade, zircon, lapis lazuli and rhodonite are beyond the scope of this report.

For each gem mineral covered in this report, background information is introduced and the physical and chemical characteristics of the gem are presented. The geology and genesis of each gem deposit type is summarized and exploration guidelines are listed. Because pegmatites are so closely associated with several gemstones, such as aquamarine, tourmaline and topaz, there is a chapter devoted to pegmatites and their gem minerals. Topaz rhyolite is a distinctive deposit type which is discussed in Chapter 8. Application of the exploration criteria to Yukon geology is given in Chapter 9. Reference lists are provided to those readers who want to pursue further details.

For this version of the Open File, the existing English language literature on gemstone deposits was identified through databases such as GEOREF and the Geological Survey of Canada catalog. Research was carried out on-line, through interviews and by utilizing the Geological Survey of Canada library in Ottawa, the University of British Columbia library, the main public library in Vancouver, the University of Alberta library and various magazines and newspapers. An invaluable source, as always, was the Government of the Yukon, Department of Energy, Mines and Resources library in Whitehorse, Yukon and its very knowledgeable librarians.

One of the difficulties in developing exploration guidelines is that many of the world's gem deposits are unique. The global supply of tanzanite (the fifth largest selling coloured gemstone in the United States jewellery trade), for example, comes from one deposit in northern Tanzania. The largest and most prolific emerald deposits in the world are in Colombia; and these deposits have a unique paragenesis which is not duplicated anywhere else in the world. It is difficult to determine the range of variations and physico-chemical conditions under which a particular type of gemstone deposit may form, if there is only one deposit to study.

ABOUT COLOURED GEMSTONES

There are over 4,000 known mineral species, however, very few of these are gemstones. A gemstone can be defined as a mineral, or in the case of coral or pearl, an organic substance, which looks attractive when fashioned into an ornamental object such as a bead, carving, box, cabochon or faceted stone. A gemstone's value is based on its beauty, rarity, durability and history behind that particular stone. Well known gemstones such as diamond, emerald, ruby and sapphire have all four of these qualities, which makes them more valuable than, for example, quartz, which is beautiful, attractive and durable, but not rare.

The carat is the standard unit of measure in the global gem trade. One carat is equal to 1/5 of a gram or 200 milligrams. The size of a one carat faceted gemstone will differ according to the specific gravity of that gem. For an easy reference, the size of an eraser at the end of a pencil is usually about one carat.

The global gem trade is divided into two broad categories: diamonds and coloured stones. (A third smaller category includes organic materials such as pearl and

1. Introduction

coral.) Unlike diamonds, there is no standard grading or pricing system in place for ruby, sapphire, emerald or other coloured stones. The price of coloured gemstones fluctuates according to supply and demand and depends on the quality and size of the gemstone rough. The price set also depends on the country from which the gemstone was mined. For instance, a quality ruby from Burma because of its superior colour, fetches a higher price than a comparable ruby from any other source. In order to take advantage of this price premium, rubies in the wholesale trade may be described by sellers as 'Burmese,' 'Burma-like,' 'Burmese pigeon-blood red,' etc. The stone may have actually been mined in Africa, but the dealer knows that rubies from Burma are more valuable, and this is reflected in the 'name' given to the stone to make it sell at a higher price.

From its discovery in some far-off land to its final destination in a jewellery store window, a gemstone's value is marked up several times. The increase in value to size is not a one-to-one relationship, since larger coloured gemstones are more rare. Hughes (1997) describes the 'Indian Law' or 'Tavernier's Law' formula for determining the price of a gem:

$$Wt^2 \times C = \text{price per stone}$$

Where Wt = weight of gem in carats

C = Cost of a one-carat gemstone of equal quality

Price per stone = the weight of the gem squared multiplied by the price of a one-carat gemstone

As Pliny, the historian of the ancient Greek world put it so eloquently, "To tell the truth, there is no fraud or deceit in the world which yields greater gain and profit than that of counterfeiting gems."

Obviously, the price paid by the consumer in a jewellery store and the amount of money earned by the diligent gemstone prospector or miner in selling the gem rough are grossly different (Table 1.1). Also spectacular is the progression of heat treatment, irradiation, dying, and other kinds of treatment to improve upon a gem's natural colour or clarity. Naturally, as long as humans have sought after and lusted after gems, they have created a multitude of methods to create fake gems. As an example, Pliny, the natural historian who lived from 23 to 79 A.D., described how stones could be soaked in vinegar to improve their colour. Ancient Sanscrit translations describe how to cook gems over a fire to improve their colour; an early description of heat treatment (Hughes, 1997). Besides heat treating, people have used more 'natural' methods of treating gems; for example pearls. As Hughes (1997) reports, the whiteness and luster of pearl is improved by the grinding action and acidic conditions of the intestinal track of chickens.

Table 1.1. This chart illustrates a hypothetical 'mark-up' of a 5-carat rough ruby mined in southeast Asia and eventually cut and sold in an American retail jewellery store. Modified from Hughes (1997).

Distributor	Purchase price	Mark-up	Selling price
Miner	5-carat rough ruby	–	\$100/carat rough
Small-time gem rough buyer	\$100/carat rough	30%	\$130/carat rough
Cutter (a 5-carat rough stone cut to a 1-carat stone)	\$130/carat rough	30%	\$845/carat cut
Dealer	\$845/carat cut	20%	\$1014/carat cut
Bangkok dealer	\$1014/carat cut	28%	\$1300/carat cut
U.S. buyer	\$1300/carat cut	40%	\$1820/carat cut
U.S. jewellery manufacturer	\$1820/carat cut	50%	\$2730/carat cut and set
U.S. retail jeweler	\$2730/carat cut and set	100%	\$5460/cut and set
U.S. consumer	\$5460 cut and set		



One of the main problems in the coloured stone trade is the lack of deposits which produce a regular supply of facetable material. For example, tsavorite garnet is a beautiful gem that has never been able to fetch the higher price it deserves, simply because the supply of tsavorite is very limited. Only a handful of mines in the world provide regular supplies of good to excellent grade of coloured gemstone rough; and the jewellery industry needs to ensure that a regular supply is definitely available before the money is spent on marketing and promoting the stone.

A problem specific to Canada, and perhaps a few other countries, is the lack of awareness in the mining community about the coloured gemstone trade and its value. This lack of awareness creates problems in government departments and agencies, especially in the area of ore reserve estimation and valuation. It is hoped that this updated Open File will help promote awareness of the geological and geochemical environments in which coloured gemstones form, and that Canada will soon be known as a producer of the full spectrum of quality gemstones, from diamond to emerald, rubies, sapphires and other beautiful gems.

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2. FIELD IDENTIFICATION OF GEMSTONES

INTRODUCTION

Gemstone deposits can be discovered by using the same basic prospecting and exploration techniques used for precious metal and base metal exploration and diamond exploration. Most of the techniques used by geologists and prospectors such as surface prospecting, heavy mineral sampling, soil sampling and geochemical surveys can be adapted for gemstone deposit prospecting. The most important factor is that the exploration geologist or prospector must be aware of the appearance of gemstone rough in the field and the geological environments in which gemstones can form. The book *Prospecting for Gemstones and Minerals* by John Sinkankas is recommended as a practical guide to the techniques of gemstone prospecting and collecting.

Gemstones can be found in place (*in situ*) or in secondary eluvial, colluvial and alluvial deposits (Figure 2.1). Most gemstones are hard, resistant to weathering, and

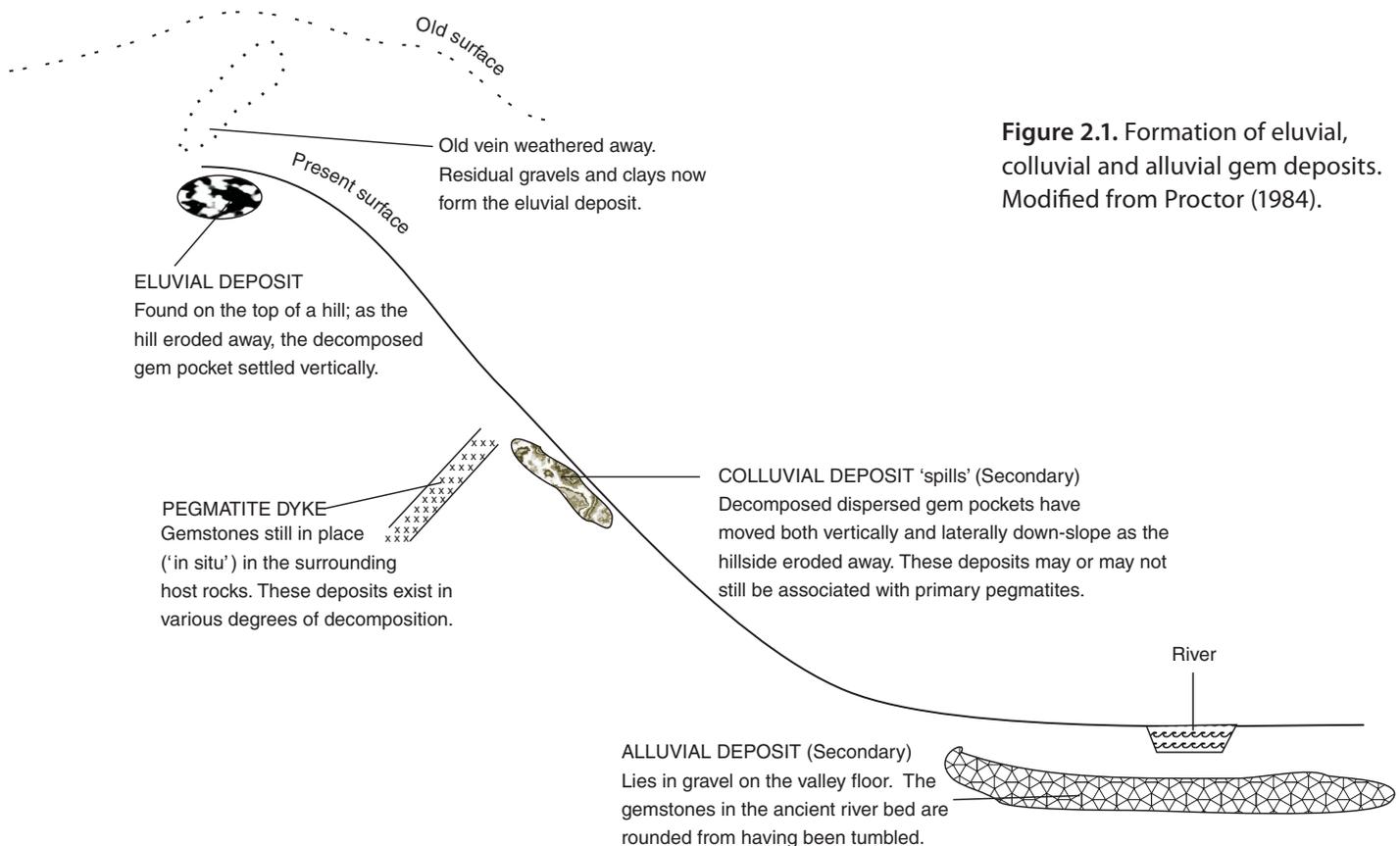


Figure 2.1. Formation of eluvial, colluvial and alluvial gem deposits. Modified from Proctor (1984).

2. Field identification of gemstones

have a specific gravity higher than that of the common rock-forming minerals. They concentrate in alluvial deposits the same way that gold placers develop.

This chapter provides some supplemental information on field techniques and equipment which might help find and identify gemstone rough.

The most basic exploration technique is to closely observe bedrock, eluvial and alluvial deposits for any bright coloured or unusual crystals. This is accomplished by visual prospecting, and sampling gravels and sediments in streams. In areas where outcrop is rare, rock and mineral fragments in soil samples can be used as indicators for bedrock or mineral deposits below the surface. Canadian geologists have long used this same technique by studying the waste dirt piles created by the ubiquitous digging beast known as the ground squirrel, gopher and many other not-so benign names. Unusual or glittering mineral grains spotted within the handy little heaps of dirt provide a glimpse of what lies under the surface. In gem-rich Tanzania, where everyone is aware of the value of what lies underneath the flat African grassland, prospectors and tribal bushmen alike make it a habit to examine anthrills for gemstone fragments. They also lift up tufts of grass to examine the dirt underneath, much like Canadian geologists and prospectors like to examine uprooted tree stumps for gold nuggets.

Most prospectors and exploration geologists are familiar with basic mineral identification tools such as a knife, streak plate, magnet and hand lens, and know how to use them. Gemstone prospecting requires some additional field equipment. Effective use can be made of instruments routinely used for gemstone identification in the gem and jewellery trade. Depending on one's enthusiasm for mineral and gemstone identification, a home 'lab' can be set up at very little expense using hand-made instruments or, for more expense, bought instruments (Dunn, 1993). Although some of these instruments require special training, a few of them can be adapted for use in gemstone exploration. Gemstone identification reference books by Liddicoat (1981) and Webster (1983) are recommended.

INSTRUMENTS FOR IDENTIFYING GEMSTONE ROUGH

Thermal testing probe

Thermal testing probes were first introduced to the jewellery market in the late 1970s as a quick and easy method of separating diamond from diamond simulants. I have successfully used one of these probes, the GEM DiamondMaster (specifically called the "Pocket Diamond Tester¹"), for identification of diamond rough and gem corundum (ruby and sapphire) rough. A description of the thermal properties of gems and the use of the Pocket Diamond Tester probe in gem identification is given by Hoover (1983). The probe measures the thermal inertia of a gemstone, which is how fast the surface temperature of a material can be changed by application of a given quantity of heat-per-second to the surface. This property is illustrated by the cold feeling of mineral crystals compared to the warm feeling of glass or plastic when held in one's hand.

¹Available from the Gemological Institute of America; follow the 'gem instruments link' at www.gia.org.



The copper rod tip is placed on a gemstone and the temperature difference between the hot internal junction and the surface temperature of the gem material is measured. Many probes on the market operate by emitting a single beep or showing a red light when diamond is identified; these kinds of probes are not very useful for identification of gemstone rough. The Pocket Diamond Tester provides a semiquantitative analysis by the use of a meter, which helps to identify other gemstones in addition to diamond. Thermal testing instruments should never be used as a conclusive test to identify a gem, but instead used to help confirm an identification or as a guide. In addition, the Pocket Diamond Tester is extremely rugged; over the years I have lent it out to various prospectors for entire field seasons, and it is still in good working condition.

Next to diamond, the most useful identification is that of corundum, which has the largest thermal inertia next to diamond. It may be possible to separate spinel and garnet as well. When the probe tip is placed on a corundum grain, the meter gives an average reading of 60% of the scale. Spinel gives a reading of 35% of the scale and garnet registers 0%. Topaz should register between garnet and corundum.

Dichroscope

Some minerals split light into two rays when light passes through the stone. This feature, called double refraction, is based on the internal crystal structure and chemical composition of the mineral. Minerals or gems which are doubly refractive will show two or even three different or slightly different colours when viewed through a dichroscope. A dichroscope is a small tube, about 2.5 cm long, which contains two polaroid plates, or pieces of optical calcite, at right angles to each other. It is used to determine pleochroic colours. One can observe pleochroic colours by looking at the gem through the tube while shining a light behind the gem. A dichroscope works best on larger, transparent crystals. For example, ruby crystals (doubly refractive) can easily be separated from two other (singly refractive) red gemstones, garnet and spinel. Gemstones which are singly refractive such as spinel and garnet do not show pleochroic colours. Care must be taken to look for pleochroic colours in more than one direction.

Heavy liquids

Canadian exploration geologists and prospectors became more aware of the use of heavy liquids in the early 1990s because of their use in separating out diamond indicator minerals. Minerals with a low specific gravity will float, while minerals with a higher specific gravity will sink. Most gemstones will sink in methylene iodide liquid (specific gravity of 3.32), which is an easy method of separating them from quartz, feldspar and other common minerals (Table 2.1).

A small vial of methylene iodide can be carried in the field to provide a quick specific gravity test. A couple of density 'standards' like a tourmaline crystal (will sink) can be left in the liquid to ensure it is calibrated. A copper penny left in the vial will help prevent the liquid turning brown or black on exposure to light (due to release of free iodine). Although methylene iodide is the least toxic of several heavy liquids, care must be taken to keep the vial from being broken and to keep it away from children. A less toxic heavy liquid called sodium polytungstate is being sold. It is

2. Field identification of gemstones

Table 2.1. Specific gravity of gemstones. Modified from Anderson (1990)

Specific gravity	Gemstone	Specific gravity	Gemstone
1.08	Amber	3.18	Spodumene
1.29	Tortoiseshell	3.33	Jadeite Jade
1.80	Ivory	3.34	Peridot
2.00	Bone	3.35	Zoisite (tanzanite)
2.00	Fire Opal	3.52	Diamond
2.10	Opal	3.53	Topaz (pink)
2.40	Obsidian	3.53	Topaz (yellow)
2.57	Moonstone	3.56	Topaz (white)
2.60	Chalcedony (agate, carnelian)	3.53	Sphene
2.65	Quartz	3.60	Spinel
2.68	Coral	3.65	Garnet (hessonite)
2.69	Beryl (aquamarine)	3.7 to 3.8	Garnet (pyrope)
2.69	Beryl (yellow)	3.72	Chrysoberyl
2.71	Beryl (emerald)	3.85	Garnet (demantoid)
2.80	Beryl (pink)	3.9 to 4.20	Garnet (almandine)
2.71	Pearl (natural)	3.99	Corundum
2.75	Pearl (cultured)	4.0 to 4.5	Zircon (green)
2.70	Turquoise (American)	4.69	Zircon (blue, white, golden)
2.80	Turquoise (Iranian and Egyptian)	4.90	Pyrite
2.8	Lapis Lazuli	5.10	Hematite
3.00	Nephrite Jade	10.50	Silver
3.05	Tourmaline	19.3	Gold
3.15	Andalusite	21.50	Platinum
3.18	Fluorite		

not volatile and, unlike methylene iodide, has no noxious odor. It has a base density of 2.8.

Pans and screens

Most gemstones are heavier than common minerals like quartz and feldspar. One of the most efficient ways of prospecting for gemstones in a particular area is to sample and examine the heavy mineral fraction of gravels, stream sediments or eluvial deposits. By doing this, the gemstone potential of the entire drainage area can be evaluated.

One method is to concentrate the heavy minerals by using a gold pan. This technique is often used by crews carrying out mineral exploration for precious and base metals, or diamond exploration crews looking for pathfinder minerals. The concentrate can be examined with an ultraviolet light (see next section) and then sent on for chemical assay. The problem with examining the heavy mineral fraction is that the material tends to be very fine grained and it may be difficult to pick out gemstone material that is not brightly coloured or does not glow under ultraviolet light.

One of the best ways to separate heavy gemstone minerals from soil, clay, sand or other minerals is to use screens. Sinkankas (1970) describes the use of two types of screens, an ordinary box screen and a cone screen.



ORDINARY BOX SCREEN

An ordinary box screen is good for separating gem minerals from soil, gravel, clay or common minerals. Sinkankas (1970) gives detailed instructions on how to construct a box using the desired screen size. The screen can be used with dry material or with water. He recommends a rectangular screen no more than 18 inches x 24 inches in size be used for a single person to operate. These screens or sieves can be purchased at most geological field supply stores.

CONE SCREEN

By using a cone screen, heavy minerals of a particular size can be examined. When the screen is filled about half full with unsorted material, it is moved up and down in water and the heavy minerals settle at the apex of the cone. The cone screen can then be taken and flipped over. Heavy minerals settled at the apex will show up at the top of the pile. Sinkankas (1970) tested the cone screen method by mixing garnets, which are high in specific gravity, with lighter feldspar. He used a cone-shaped kitchen sieve, about 8 inches in diameter to separate 15 lbs of garnet from 100 lbs of unsorted material in about 1 hour.

Ultraviolet light

An ultraviolet light is one of the most useful instruments for gemstone identification. It is the quickest method, for example, of distinguishing between ruby and garnet. There are several small, portable models of ultraviolet light which emit both longwave and shortwave radiation.

Other tools

A few other instruments which may be useful in gem rough identification include the Chelsea Filter, refractive index oils, spectroscope, and using the refractive index of heavy liquids to estimate the refractive index of the gem rough.

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3. RUBY AND SAPPHIRE

INTRODUCTION

Although it had been suspected for centuries, it was only in the year 1802 that ruby and sapphire were proven to be varieties of the same mineral species, corundum (Hughes, 1997). The word 'ruby' is derived from the Latin word *ruber*, meaning red, and refers to transparent or translucent red corundum crystals. The exact origin of the word 'sapphire' is unknown, but in ancient times 'sapphire' was used to refer to all blue gemstones, including lapis lazuli. Today, blue gem (translucent or transparent) corundum is called sapphire and all other colours including yellow, orange, violet, green, brown and black corundum are referred to by colour (e.g., yellow sapphire, green sapphire, pink-orange sapphire).

Ruby and sapphire in jewellery first appeared in Europe in Greco-Roman times. Ancient jewellery such as a necklace dating back to 400 A.D. found in Carthage, Tunisia featured blue sapphires, most likely from Sri Lanka. In Pliny's *Natural History*, written 2,000 years ago, he discusses the gem 'carbunculus' (some of which were probably rubies) and how ancient lapidaries used to treat the gems with vinegar to enhance their appearance (human nature has remained consistent throughout the centuries).

Ruby and sapphire are the most important coloured gemstones in today's world gem trade; together they account for over 50% of global gem production (Hughes, 1990). Ruby is the world's most expensive gemstone; the best Burmese rubies are more valued than an equivalent-sized flawless diamond. The world record price at auction paid for a ruby is \$227,300 per carat in 1988 for a 15.97-carat Burmese ruby (total \$3.63 million)¹. The world record price paid at auction for a blue sapphire is \$2.8 million for a spectacular 62-carat rectangular-cut royal blue Burmese sapphire; this works out to \$45,000 per carat.

For the previous edition of this Open File, the book *Corundum* by Hughes (1990) was an invaluable comprehensive gemological and geological overview of gem corundum. For this edition, the successor book *Ruby and Sapphire* by Hughes (1997) is even more splendid in its literary treatment and content. Hughes accomplishes the notable feat of relating rubies and sapphires to sex, in addition to discussing the origin of our universe, all in one page (no. 258). The book is a fascinating treatise on absolutely everything to do with ruby and sapphire. The in-depth *Geology of Gems*, recently translated from Russian (Kievlenko, 2003) and edited by Canadian Art Soregaroli, provides a wonderful chapter on ruby and sapphire deposits with a focus on the geology. *Gemstones of Afghanistan* by Bowersox and Chamberlain (1995) is full of geological information on the famous 'lost' ruby mines in this war-torn country. For a general overview, the book *Rubies and Sapphires* (Ward, 1995)

¹The only exception is a record \$926,315 per carat paid for a .95-carat red-purple diamond at auction in 1987.

3. Ruby and sapphire

is recommended. This is an easy-to-read book full of first-hand information and photographs. The book is an extension of articles about gemstones written for National Geographic Magazine. For readers interested in buying fine quality ruby and sapphire, the book *The Ruby and Sapphire Buying Guide* by Newman (1994) is recommended.

Global sources of ruby and sapphire

Most Canadian geologists and prospectors are familiar with statistics citing the rarity of diamond deposits. From recent short courses, papers, seminars and articles in Canadian mining newspapers and magazines, geologists are aware that of approximately 6,000 known kimberlites, only 10% have diamonds and of those only 1%² have been mined. Diamond deposits are indeed rare, however, there are several significant new Canadian diamond mines and prospects in Canada and active exploration for diamonds is locating diamondiferous kimberlite around the globe. The situation is much different with ruby and sapphire.

Commercial deposits of rubies are very, very rare. Hughes (1990) lists only 10 deposits world-wide which produce significant amounts of ruby and/or sapphire of facetable or even cabochon quality (Table 3.1). An updated map is shown in Figure 3.1. Cabochon quality means that the crystals are not transparent, however, they are translucent enough that they can be polished into an attractive dome-shape (e.g., star sapphires). Significant occurrences of ruby discovered since 1990 include those in Vietnam, Madagascar and the Mong Hsu area of Burma (Burma). Other deposits not listed are known to occasionally produce gem corundum; these include Idaho (U.S.), North Carolina (U.S.), Mozambique, China, Malawi, and Russia (Table 3.2).

Table 3.1. Major sources of ruby and sapphire. Modified from Hughes (1990).

Locality	Mode of occurrence
Mogok, Mong Hsu, Burma	Ruby is most common, also blue sapphire, yellow, violet and green sapphires, stars and colour change (marble host rock)
Chanthaburi, Kanchanaburi, Trat and Phrae provinces, Thailand and Pailin, Cambodia	Ruby, blue, yellow, green and black star sapphires (alkali basalt host rock)
Sri Lanka	All colours of gem corundum except green (granulite facies metamorphic rocks)
Luc Yen, Vietnam	Ruby, other (marble)
Madagascar	Ruby and sapphire
Kashmir, India	Blue sapphire, rare pink, also star sapphire (feldspar pegmatites)
Queensland and New South Wales, Australia	Blue, green, yellow and black star sapphires (alkali basalt)
Jagdalek, Afghanistan	Ruby (marble)
Umba Valley, Tanzania	All colours of gem corundum (ultramafic intruded by pegmatite)
Mangari District, Kenya	Ruby (ultramafic intruded by pegmatite)
Yogo Gulch, Montana, U.S.	Blue and lilac sapphires (lamprophyre dyke)
Kaduna, Nigeria	Mainly blue sapphires, also greens, yellows and bicolour (alkali basalt)

²From Northern Gems Short Course, Whitehorse, Yukon, 2002, talk by M. Dufresene, Apex Geoscience Ltd.





Figure 3.1. Ruby and sapphire deposits.

For over 800 years, the alluvial deposits at Mogok, Burma³ have been the source of the world's 'best' rubies. Official closure of the mines in 1962 led to the promotion of easily attainable Thailand and Cambodian rubies, long considered to be inferior, as the new global 'ideal.' Traditional sources in Chanthaburi, Thailand, and Pailin, Cambodia were major producers of ruby during the 1980s (Shigley *et al.*, 1990). Ruby deposits in Kenya, Vietnam, and Madagascar became significant as the traditional areas in Thailand became depleted. Hughes (1990) reports that sapphire and ruby mining proceeded at such a frantic rate in Thailand during the 1980s that he observed one operation where the miners dumped gem-bearing mud into a tunnel that ran directly beneath their houses into a jig on the other side. The enterprising Thai gem industry now absorbs sapphire production from Australia and Sri Lanka. The prolific Pailin gem district in Cambodia now suffers from the horrific aura of being the last Khmer Rouge stronghold in Cambodia, leaving a legacy of deadly land mines and

Table 3.2. Minor sources of ruby and sapphire. Modified from Hughes (1990).

Locality	Mode of occurrence
North Carolina, U.S.	Mainly ruby, also sapphires of various colour (ultrabasic rocks)
Hunza Valley, Pakistan	Mainly ruby, some purple to violet sapphires (marble)
Mingxi Fujian Province, China	Yellow-green, green, blue-green and blue sapphires (alkali basalt)
Penglai and Wenchang, Hainan Island, China	Translucent to opaque ruby (alkali basalt)
Sichuan Province, China	Translucent to opaque ruby
Mercaderes-Rio Mayo area, Cauca, Colombia	Blue and green sapphires, yellows, pinks, reds and colour-change stones (alkali basalt)
Rio Coxim, Mato Grosso, Brazil	Blue sapphires
Ural Mountain area, Russia	Ruby, pink corundum
Chimwadzulu Hill, Malawi	All colours
Barauta, Zimbabwe	Blue sapphire (pegmatite)

³In 1989, the military dictatorship government changed the country's name to the Union of Myanmar. For this Open File, the historic name of Burma is used.

3. Ruby and sapphire

The story of the rise of the Australian sapphire

Sapphires were first discovered in 1851 in Australia by an observant state geological surveyor, who noticed the gems in a gold sluicibox.

During the 1980s, Australia emerged as a major supplier of sapphires, due to increased mining efficiencies and the heat treatment processes of Thai sapphire buyers. The Anakie field, the largest of two Australian sapphire districts, was developed in the years before World War I by German gem merchants to supply the Russian Imperial Court with sapphires.

Australian sapphires have always been considered 'inferior' and 'substandard' in the gem trade due to strong blue/green pleochroism and the dark blue, almost black colour of the stones. Depending on how the stone is cut, many Australian sapphires end up showing a greenish tint which is considered unattractive.

Broughton (1979) states that the Russian nobility favoured the deep, inky blue colour of the Australian sapphire. Hughes (1990) suggests that perhaps the Russian court favoured the much lower price of Australian sapphire as opposed to Burma or Sri Lankan sapphire, and that colour was not as much of an issue.

In any case, mining was intermittent until the 1980s when, owing to declining production in Thailand and Cambodia, Australia emerged as the primary source of sapphire in the world. Almost all Australian production in the 1980s and 1990s was sold to Thai buyers who took the stones to Thailand, heat-treated them and put them on the global marketplace (sometimes as Thai stones). It is estimated by Coldham (1985) that 50% by weight of sapphire sold through

Thailand in the 1980s was actually mined in Australia.

An increased volume of sapphire mined from Thailand in the 1990s has decreased the Australian share to 25 to 30% (Levinson and Cook, 1994). As noted in Hughes (1997), there are continual complaints from Australians who are resentful that the bulk of their gem sapphire production is sent to Thailand for processing, cutting and distribution, however, without Thai efficiency and skill at heat treatment, the sapphire industry would never be able to sustain itself due to high Australian labour costs.

ex-Khmer Rouge soldiers digging for gems. During the last couple of years, the military dictatorship government of Burma was loosening trade restrictions and a brand new ruby deposit at Mong Hsu provided a much needed global source of excellent Burmese rubies. Most recently, in July, 2003, the U.S. government announced an embargo in response to an attack on government opposition leader and Nobel laureate Aung San Suu Kyi that bans the import into the U.S. of any Burmese precious gemstones, jewellery and mineral specimens. Since Burma supplies 95% of the higher-end rubies in the global coloured stone trade⁴, there will definitely be an impact. Another government policy which may have a significant impact on the global coloured gemstone market is the anticipated upcoming announcement by the Sri Lankan government to ban all export of gueda sapphires. These are colourless sapphires routinely sent out of the country to Thailand to be heat-treated and sold.

The ruby and sapphire gem market and pricing

One of the great connoisseur's of ruby and sapphire is the gem dealer Richard Hughes, who devotes a fascinating chapter in his book (Hughes, 1997) on how to judge the quality of fine ruby and sapphire. Although starting off with a rather weird discussion about eating pork and flat earth theory, he then summarizes what to look for when buying ruby and sapphire. The following information is taken largely from that chapter.

One of the more interesting sections in the chapter is a ranking of rubies and sapphires in order of importance by origin, meaning a list of most valuable, per carat, to least valuable. This is summarized at the top of the following page.

⁴From www.ruby-sapphire.com and interesting articles on the Burma situation by R. Hughes (1997).



QUALITY RANKING OF RUBIES BY COUNTRY

1. Burma
2. Vietnam
3. Sri Lanka
4. Kenya, Tanzania
5. Afghanistan
6. Thailand/Cambodia
7. India

QUALITY RANKING OF BLUE SAPPHIRES BY COUNTRY

1. India (Kashmir)
2. Burma
3. Sri Lanka
4. All other sources: Australia, Cambodia, China, Nigeria, Thailand, U.S.

When buying a quality ruby or sapphire, the colour, clarity, cut and overall look of the stone are important.

A customer in a Canadian jewellery store can expect to pay \$1,500 to \$4,000 per carat (CDN) for a fine quality one-carat blue sapphire. A fine quality one-carat red ruby may go for between \$5,000 to \$8,000 (CDN). Prices may fluctuate from store to store by as much as \pm \$2,000 per carat for the same gem. This is because the definition of 'fine' may vary from one store to another, the original wholesale price of the gem may vary, and each store's mark-up from wholesale to retail pricing is different⁵.

As mentioned earlier, the effect of heat on rubies and sapphires has been known and used for hundreds if not thousands of years. Hughes (1997) points out that Sanskrit texts dating back a thousand years mention heat treatment to improve the appearance of what are probably Sri Lankan sapphires. It was only during the 1970s that treatment on an industrial scale began and spread so pervasively that now, sadly, it is very, very rare to see a ruby or sapphire that has not been heat-treated. Heat treatment on such a large scale began when Thai gem dealers found that they could easily heat treat a cloudy, colourless to pale type of sapphire crystal from Sri Lanka, called geuda, to produce a beautiful clear blue gem by changing the valence state of the iron and melting the rutile inclusions. Now crystals from Thailand, Australia and other places are routinely heat-treated.

A trained gemologist can not only detect heat treatment, but also diffusion treatments, glass infilling of cracks, irradiation, coatings, dyes and oils. There are also the ubiquitous vermeil synthetic rubies, responsible for over 90% of all synthetic corundums produced worldwide (Hughes, 1997). Even at the 'source,' gem miners will acquire cheap vermeil rough and break it, burn it, heat it, cool it and tumble it so it looks like a genuine rough gem corundum crystal. In fact, initial parcels of Vietnamese rough sold to U.S. and European dealers shortly after the discovery of gem ruby in Vietnam in the early 1990s contained so much synthetic ruby that this source quickly lost favour with gem trade dealers for quite some time. Synthetic star sapphires produced by Linde are a popular stone. There are hydrothermal synthetic rubies and a myriad of flux-grown synthetics that are often sold as natural stones. Once again, when buying a piece of jewellery with a ruby or sapphire, buy from a reputable firm with graduate gemologists on staff and ask lots of questions. Jewellers are supposed to disclose to the public all treatments made to natural gems.

For everything about corundum, from a corundum enthusiast's point-of-view, check out the website at www.corunduminium.com. There are lots of photos of rough corundum crystals from many localities, as well as jokes and humour relating to corundum.

⁵For detailed price information on quality ruby and sapphire, check www.ruby-sapphire.com.

PHYSICAL AND CHEMICAL PROPERTIES

The physical and chemical properties of gem corundum are listed in Table 3.3.

Cause of colour in ruby and sapphire

Pure corundum, an aluminum oxide mineral (Al_2O_3) is colourless. The remarkable array of gem corundum colours, the vibrant reds, royal blues and pastel oranges, pinks, purples and greens are all due to impurities in the corundum crystal structure. Hughes (1997) provides an excellent summary of the colour, spectra and special luminescence of gem ruby and sapphire. Another excellent, technical discussion of colour in corundum is provided by Emmett *et al.* (2003).

When chromium in the form of Cr^{3+} enters the corundum structure and replaces aluminum, a rich crimson red colour results if the Cr^{3+} content reaches 0.1 to 3.0% (Hughes, 1997). Colour in ruby, as with other gemstones such as sapphire, tourmaline, tanzanite, emerald and alexandrite, results from selective absorption of certain wavelengths of visible light. The ability of ruby to absorb light is the result of interaction between incoming white light and electrons 'orbiting' around the Cr^{3+} ions at different levels, akin to our own sun and the solar system. When white light hits the electrons they 'jump' from one orbital to another. As a result, green-yellow and violet wavelengths are absorbed and we see ruby as having a red body colour. The energy used to make the electrons jump from one orbital to another must reappear at some point in order to balance the equation, so when the electrons fall back down to their home orbital, energy is released in the form of red fluorescence. It is a wonderful coincidence in nature that the various wavelengths, orbitals and electrons converge to infuse in ruby not only a rich red body colour but also vivid red fluorescence. Hughes (1997) reports that about 0.4 to 2.0% of chromium must be present in ruby for a rich red colour. The type of light hitting the stone and the physiology of the observer's eye will also affect the colour seen.

Red fluorescence is easily seen under ultraviolet light and will be discussed later. With certain rubies, especially those from Burma, and more recently, Vietnam, the red

Table 3.3. Physical and chemical characteristics of corundum.

Chemical formula	Al_2O_3 (aluminum oxide) It is a member of the Hematite group and is related to hematite and ilmenite.
Crystal system	Hexagonal crystal system The corundum structure is based on hexagonal closest packing of oxygen atoms. Al^{3+} cations are in octahedral coordination. Chromium as Cr^{3+} replaces Al^{3+} cations in the corundum structure.
Habit	Ruby: Tabular hexagonal prisms modified by rhombohedron faces. Tend to be barrel shaped. Sapphire: Spindle-shaped hexagonal pyramids and bipyramids.
Colour	Ruby: Red Sapphire: All other colours
Hardness	9.0
Fracture	No cleavage
Cleavage	Distinctive parting
Parting	
Specific gravity	3.98 to 4.06
Pleochroism	Strong for red, blue, green, orange, violet Weak to distinct for yellow See Table 3.4
Fluorescence	See Table 3.5



fluorescence is visible even in daylight. This red fluorescence combined with the rich red body colour causes these particular rubies to glow as if a fire was burning inside. Rubies from other localities such as Thailand and Cambodia do not show as strong a fluorescent red colour. Unlike rubies from Burma and Vietnam, rubies derived from alkali basalt tend to contain more iron, which quenches and reduces the fluorescent effect. This is why rubies from Burma are up to tens of thousands of dollars more expensive than rubies from anywhere else. They show a unique red fluorescence and are historically the standard against which all other rubies in the world are judged.

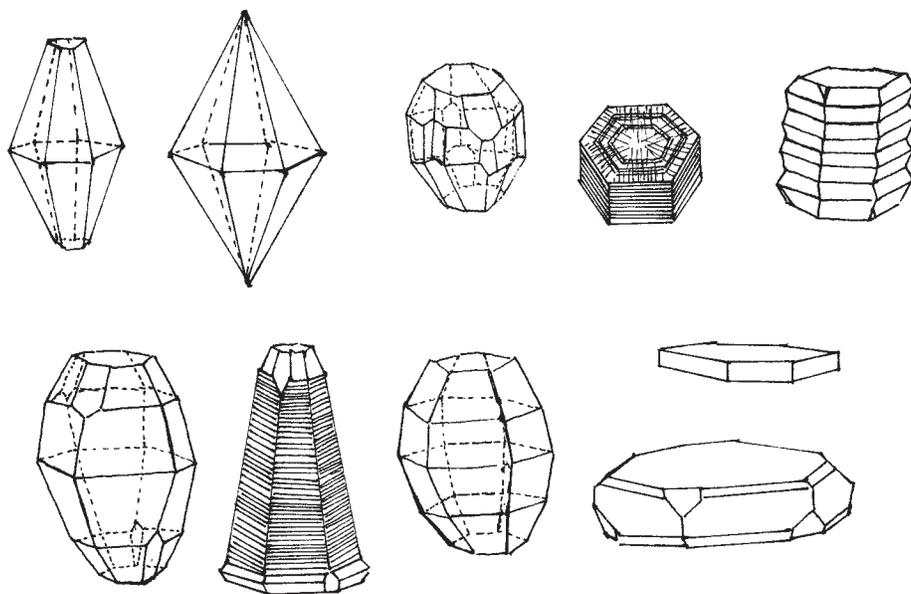
The gorgeous blue colour of sapphire results from a different mechanism, the substitution of iron and titanium for aluminum in the corundum structure, specifically ferrous iron (Fe^{2+}), which interacts with titanium to produce the desired blue colour. Very little (less than .01%) iron and titanium are needed to colour blue sapphire, however, iron must be in the ferrous state rather than the ferric (Fe^{3+}) state. Heat treatment under reducing conditions transforms Fe^{3+} to Fe^{2+} . In general, the impurities that replace aluminum in the corundum crystal structure can be the direct cause of colour, can chemically interact with one another to cause colour or can modify the saturation of a colour (Emmet *et al.*, 2003). Green, purple and orange corundum colours are caused by combinations of iron, titanium, chromium and magnesium impurities.

Crystal habits of ruby and sapphire

Although ruby and sapphire are varieties of the same mineral (corundum), they tend to have different crystal habits (Figure 3.2).

Ruby tends to form hexagonal tabular crystals which are wider in the middle and truncated at the ends. The overall effect is that of a six-sided barrel or 'keg of beer' shape. The crystals commonly show a series of horizontal lines or striations, similar to the ones sometimes seen on quartz crystals. When ruby crystals weather out of their host rock and are subjected to mechanical weathering in streams, they break up into thick, six-sided slabs, or 'plates.' The six-sided nature of the crystal becomes more and more vague as erosion and mechanical weathering soften the crystal edges.

Figure 3.2. Ruby and sapphire crystals. Modified from Hughes (1990).



3. Ruby and sapphire

Table 3.4. Pleochroic colours in ruby and sapphire crystals.
Modified from Hughes, 1997.

Variety	Pleochroic colour		Strength
Ruby	Slightly purplish red	Slightly orangy red	Moderate to strong
Blue sapphire	Slightly violetish blue	Slightly greenish blue	Moderate to very strong
Violet and purple sapphire	Bluish purple to violet	Yellowish purple to greenish blue	Strong to very strong
Yellow and orange sapphire	Slightly reddish yellow to orange	Slightly greenish yellow	Weak to very weak

Sapphire crystals tend to grow as hexagonal ‘spindle-shaped’ or ‘barrel-shaped’ crystals (Figure 3.2). This is nicely illustrated by the beautifully formed sapphire crystals found in Sri Lanka and Kashmir, India. Sapphires from Montana tend to be more flattened and can show raised, triangular-shaped figures on crystal faces. In the Australian placer deposits, sapphire crystals are usually somewhat shapeless but infrequently may form elongate prisms, pointed at one end and rounded to resemble ‘fangs’ or as they are called locally, ‘dog’s teeth’ (Broughton, 1979).

In certain corundum crystals, tiny needle-like crystals of rutile or hematite may align along three crystallographic axes which intersect at 060°/120°. When the corundum crystal is polished into a ‘cabochon’ or dome-shape, a six-rayed star may be visible when light is reflected off the stone.

Pleochroism can be seen in transparent corundum crystals when viewed through a dichroscope. The standard pleochroic colours are listed in Table 3.4.

Ruby and sapphire show varying reactions to ultraviolet light. Table 3.5 lists some of the more common responses.

Corundum has a high thermal inertia compared to spinel or garnet. Certain types of diamond-tester probes used by jewelers to identify natural diamonds can also be used to identify ruby and sapphire.

Corundum’s major industrial use is as an abrasive, due to its high hardness, however, it also has superior insulating qualities. This insulating quality, in addition to high stability under harsh conditions, makes colourless sapphire ideal for use in space probes.

FIELD IDENTIFICATION OF RUBY AND SAPPHIRE

Ruby and sapphire have a high specific gravity (3.9–4.1) and are physically and chemically resistant; they will show up in placer deposits and stream concentrates.

Any hard crystals showing a six-sided shape, barrel shape or spindle shape should be examined. Colourless or pale-coloured crystals should not be ignored; they can, in some cases, be heat-treated to improve their appearance.

The minerals most likely to be confused with ruby are red spinel and garnet. Red tourmaline usually forms elongated slender crystals which are striated. In some countries, red spinel is found with ruby in placer concentrate. Ultraviolet light is an easy way of separating ruby and red spinel (both valuable gemstones) from red garnet (less valuable). Ruby and spinel will both fluoresce red under longwave and shortwave light; garnet is inert. To distinguish ruby and red spinel, look at:



3. Ruby and sapphire

1. Crystal form: Ruby crystals often show a six-sided shape or barrel shape; spinels form octahedrons. However, 'pseudo octahedral' ruby crystals do exist, most notably from Tanzania, and look remarkably similar to spinel.
2. Thermal inertia: A thermal inertia probe can be used to separate ruby (moderate reaction) from spinel (low reaction).
3. Pleochroism: If the crystals are large enough and transparent, the presence of pleochroism will separate ruby (red/orange pleochroic colours) from spinel (non-pleochroic).

For other colours of gem corundum, note any ultraviolet light reaction and examine the crystal form. Compare fluorescence to Table 3.5 and look for six-sided forms, especially spindle shapes. Do not ignore opaque corundum crystals. If you see six-sided crystals that look opaque or have a 'silky' texture, wet them with a drop of water and shine a light on the surface. Look for a six-rayed star, indicative of a star sapphire. Star sapphires can exist in many different colours.

Table 3.5. Fluorescent colours of gem corundum. Modified from Hughes, 1990.

Variety	Long wave	Short wave
Ruby, Burma, Sri Lanka	Moderate to very strong red or red-orange	Moderate to strong red or red-orange, slightly weaker than long wave
Ruby, Thailand, Cambodia	Weak to moderate red or red-orange	Inert to moderate red or red-orange, slightly weaker than long wave
Ruby, Kenya	Strong to very strong red or red-orange	Moderate to very strong red or red-orange, slightly weaker than long wave
Ruby, other sources	Weak to very strong red or red-orange	Inert to very strong red or red-orange, slightly weaker than long wave
Blue sapphire, Sri Lanka	Inert to strong red or orange	Inert to strong red or orange, or, in heat-treated stones, weak to moderate chalky blue-green or green (the colourless areas fluoresce)
Blue sapphire, Burma	Inert to moderate red or orange	Inert to moderate red or orange
Blue sapphire, Cambodia, Australia, Thailand	Generally inert	Generally inert, rarely weak chalky blue to green
Blue sapphire, Kashmir	Inert to moderate red or orange	Inert to moderate red or orange
Blue sapphire, other sources	Inert to strong red or orange	Inert to moderate red or orange or weak to moderate chalky blue to green
Yellow and orange sapphire, Sri Lanka	Inert to strong orange to orange-red	Inert to strong orange to orange-red
Yellow and orange sapphire, Thailand, Australia	Inert to moderate red	Very weak to weak red
Yellow and orange sapphire, other sources	Inert to strong orange to red	Inert to strong orange to red
Purple and violet sapphire, Sri Lanka	Weak to strong red to orange-red	Inert to strong red to orange red
Purple and violet sapphire, other sources	Inert to strong red to orange-red	Inert to strong red to orange red
Green sapphire, all sources	Generally inert, rarely weak to moderate red to orange	Generally inert, rarely weak red to orange, or weak chalky blue to green
Colourless sapphire, Sri Lanka and other sources	Inert to strong orange to orange red	Inert to moderate orange to orange red, rarely weak to moderate chalky blue to green

GEOLOGY OF RUBY AND SAPPHIRE DEPOSITS

Ruby and sapphire associated with alkali basalt

Most rubies and sapphires in the gem trade are mined from alluvial placer deposits spatially associated with alkali basalt. Gem corundum occurs as rare megacrysts in the basalt. Much like diamonds that are formed deep within the earth and then brought up to surface by kimberlitic magma, rubies and sapphires also form at great depths and are brought up by alkali basalt magma. The association between gem corundum and alkali basalt has been noted at the following localities:

- Thailand (Chanthaburi-Trat, Denchai, Bo Ploi, Khorat Plateau)
- Cambodia (Pailin, Bokeo Plateau, Xuan Loc Plateau, Cardomones Massif, Solovens Plateau and Kassens Plateau)
- Vietnam (Haut Chalong Plateau, Pleiku Plateau, Darlac Plateau, Djiring Plateau)
- Southern China (Kouang Tcheoci Wan, Hainan Island)
- Gimi Valley (Nigeria)
- Australia (New England, Anakie)
- Kenya (Lake Turkana)
- Colombia (Mercaderes Rio Mayo)
- Rwanda
- Burundi

Basalt is a dark coloured, fine-grained extrusive volcanic rock composed predominantly of calcic-plagioclase and pyroxene. Levinson and Cook (1994) review the occurrence, classification and mineralogy of basalt. Most basalt found on the continents is 'tholeiitic,' meaning the magma formed at shallow levels (20–30 km depth) in the earth's crust, and has a certain chemical composition distinct from other types of basalt (Table 3.6). Alkali basalt, on the other hand, originates from the lower continental crust or upper mantle at depths of 50 to 60 km (Figure 3.3).

Table 3.6. Mineralogy and chemistry of tholeiite and alkali basalts. Modified from Barr and MacDonald (1978).

Minerals and chemical content	Tholeiite basalt	Alkali basalt
Major minerals		
Calcium-rich plagioclase	Yes	Yes
Calcium-rich pyroxene	Yes	Yes
Minor and characteristic minerals		
Quartz (normative)	Yes	No
Low-calcium pyroxene	Yes	No
Feldspathoid minerals	No	Yes
Olivine (e.g., nepheline)	Locally	Yes
Chemical content (average)		
SiO ₂	48.62 wt %	46.33 wt %
Na ₂ O	2.76 wt %	3.20 wt %
K ₂ O	0.84 wt %	1.28 wt %



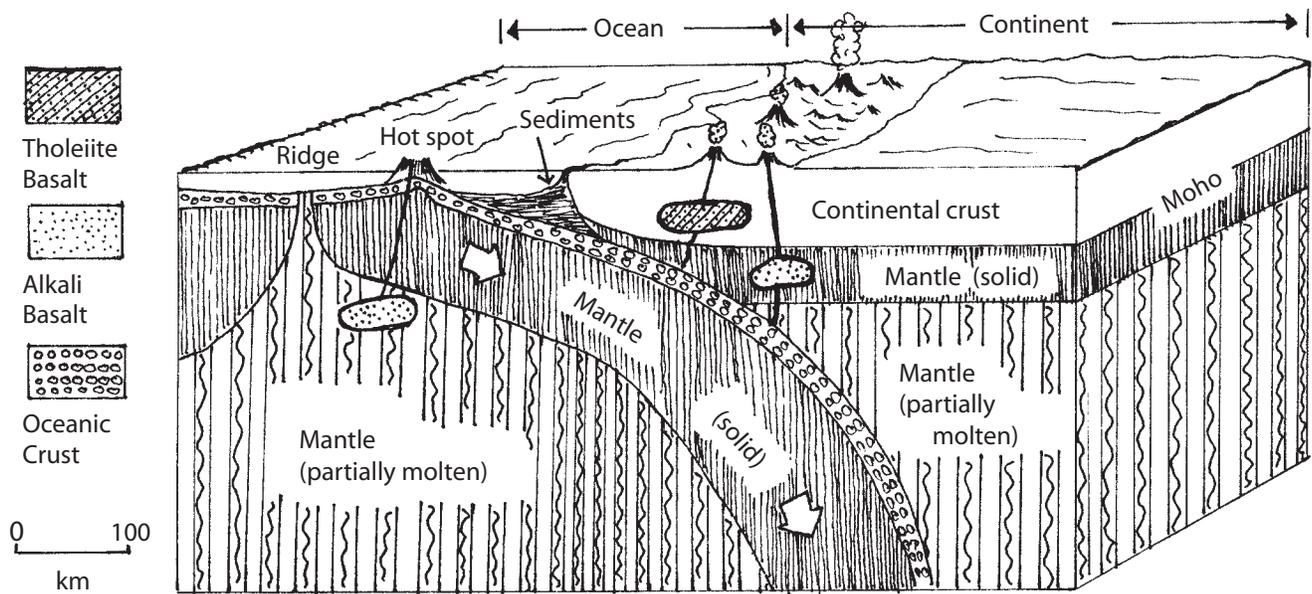


Figure 3.3. Subduction zone and origin of alkali and tholeiite basalt. Modified from Levinson and Cook (1994).

About 10% of continental basalt is alkali basalt. The alkali group of basalts typically contain undersaturated minerals like olivine or nepheline, instead of quartz. Undersaturated minerals would normally react with silica to form other minerals.

The classification of a basalt into either the 'tholeiitic' or 'alkali' class is not usually made in the field since the two types can be identical in appearance. Petrographic studies and chemical analysis of the rock must be conducted before positive identification.

A list of characteristics shared by ruby and sapphire deposits hosted by alkali basalt is given by Coenraads *et al.* (1990):

- alkaline basalt (except China, Nigeria), including nephelinite, nepheline hawaiite, basanite and basanitoid
- the alkali basalt forms small hills and volcanic plugs
- crater lakes, cones, cone remnants or plugs are common
- ultramafic mantle xenolith are common, especially spinel-lherzolite xenoliths
- older tholeiitic flows, younger alkaline flows
- sapphire megacrysts are corroded
- *in situ* megacrysts are corroded
- *in situ* corundum megacrysts are extremely rare
- zoning of gemstone types and corundum colours within a small area (less than 10 km)
- accessory heavy minerals in alluvial deposits include zircon, spinel (especially black spinel), ilmenite, olivine, clinopyroxene, garnet, magnetite or feldspar.

Southeast Asia

Buried placer deposits of rubies and sapphires in rich-brown volcanic soil are scattered throughout southeast Asia, and more recently have been recognized in China. It is reported by Furui (1988) that sparkling blue sapphire crystals were first recognized on Hainan Island in the early 1960s by a local farmer who received \$1.00 from the local geological brigade for his discovery.

3. Ruby and sapphire

Sapphires in Rwanda

Rwanda, given its location in gem-rich east central Africa, is now known to have the potential to host coloured gemstone deposits. Krzemnicki *et al.* (1996) spent two months investigating a basalt find in the mid-1990s, at the time of the horrific genocide. The authors trenched and sampled an area of approximately 200 km² to determine areas of interest. Due to the intense tropical climate in Rwanda, the sapphires have easily weathered out of Tertiary-Quaternary alkali olivine basalts, and have accumulated in stream deposits. Several areas of potential economic interest were identified.

GEOCHEMISTRY OF THE BASALTS

The occurrence of corundum megacrysts in basalt is rare. Furthermore, for a particular alkali basalt field to contain economic alluvial gem corundum deposits is extremely rare. Many alkali basalt provinces contain spinel-lherzolite nodules and associated megacrysts, yet they do not carry corundum or any other type of gem material. Depending on the exact mechanism of formation for corundum, there may be a connection between the chemistry of the alkali host rock and its gem-bearing potential.

RESULTS OF THAILAND STUDY

The geochemistry of Cenozoic (12 to 0.5 million years old) alkaline basalts of Thailand was studied by Barr and MacDonald (1978) to determine if there were chemical differences between gem-bearing basalt and non-gem-bearing basalt. A later study looked at linking new geochemical data for the basalts with the origin of the corundum (Barr and Dostal, 1986). Cenozoic basalts in Thailand were found to be mainly alkalic. Specifically, hawaiite, mugearite, nepheline hawaiite, nepheline mugearite, alkali olivine basalt, basanite and nephelinite and tholeiitic basalt were classified on the basis of petrography and chemical analysis. In general, it was found that gem corundum is restricted to the more undersaturated rocks, mainly nepheline hawaiite, basanite and nephelinite (Barr and MacDonald, 1978). These rocks are dark, dense, aphanitic, and contain ultramafic nodules and megacrysts. Megacrysts include quartz, nepheline, sanidine, anorthoclase, oligoclase, clinopyroxene, orthopyroxene, spinel and magnetite. Corundum megacrysts are extremely rare. The ultramafic nodules are spinel-lherzolite or, more rarely, dunite and pyroxenite. The petrochemistry of the megacrysts was described by Barr and Dostal (1986).

In a study of trace element geochemistry of Upper Cenozoic basaltic rocks of Thailand, Cambodia and Vietnam, Barr and James (1990) found that nephelinites are characterized by enrichment in most trace elements including barium, strontium, zirconium, yttrium, niobium, vanadium, lanthanum, cesium and neodymium.

RESULTS OF AUSTRALIAN STUDY

The study by Stephenson (1976) showed that there were no special chemical characteristics to distinguish between corundum-bearing and 'barren' Cenozoic alkali basalt in Australia. The exception was elevated strontium, zirconium and niobium as trace elements in the gem corundum-bearing basalts, similar to what Barr and James (1990) noted for corundum-bearing nephelinites in Thailand. Australian basalts associated with gem sapphire were classified chemically as nepheline basanite, basanitoid, hawaiite, trachybasalt, trachyandesite and alkali basalt. The rocks are strongly nepheline normative.

AGE OF BASALT AND GEM CORUNDUMS

Coenraads *et al.* (1990; 1995) dated zircons in sapphires using U-Pb isotope dating methods. In Australia, the age of the inclusions (33 to 35 million years) falls within the range of basalt K-Ar ages of 19 to 38 million years and 2 to 49 million years for the timing of volcanism, based on zircon fission track ages. In Thailand, U-Pb isotope dating of zircon gives an age of 1 to 2 million years which falls within the K/Ar ages of 0.44 to 3.0 million years for the alkali basalt volcanism in the Chanthaburi province.



Coenraads *et al.* (1995) suggest that once more information becomes available, accurate mapping of alkali basalt of the proper age may target drainage basins with high gem potential.

DISTRIBUTION OF GEMSTONES

The gemstone distribution across placer deposits overlying an alkali basalt province may be zoned. If only zircon is discovered in a stream draining a basalt field, there may be potential for more valuable ruby and sapphire in streams draining different parts of the basalt.

A regional zoning pattern of ruby, sapphire and zircon is evident in the great Cenozoic alkali basalt province which extends across Asia, from southern China to Vietnam, Cambodia, Laos, Burma and Malaysia. In southern China, only blue sapphires are found (Furui, 1988), although more varieties of corundum may be discovered through additional working of the deposit. In Vietnam and eastern and north-central Cambodia, zircon is the primary gemstone associated with alkali basalt fields. Further west at Pailin, just inside the Cambodian border with Thailand, blue sapphire and ruby are predominant. Other colours of corundum are rare. On the Thailand side of this same alkali basalt field, at Chanthaburi-Trat, ruby is the most common gemstone, with blue sapphire and zircon decreasing in abundance. West of Bangkok at Kanchanaburi, sapphire is predominant over ruby. Even particular gem fields are zoned with respect to the alluvial gems recovered. For instance, in the famous Chanthaburi-Trat gem region, the western deposits produce blue, blue-green and yellow sapphires in addition to black star sapphires (Hughes, 1990). About 50 km east, the Bo Rai/Bo Wain mining area produces mainly ruby.

In Australia, Coenraads (1990) notes that sapphires may vary in colour and shape as mining proceeds along a particular stream. For example, sapphires may be blue-yellow parti-coloured in one area, proceeding to blue and then to a blue-green.

HEAVY MINERALS ASSOCIATED WITH RUBY OR SAPPHIRE

A characteristic set of heavy minerals is associated with alluvial ruby and sapphire deposits derived from alkali basalt. The most common minerals are listed below:

- Black spinel: may be partly corroded
- Black clinopyroxene
- Zircon: brown to pale reddish and orange-brown
- Garnet: mainly pyrope, pale to dark reddish brown
- Ilmenite
- Magnetite
- Olivine

Less common: phlogopite, sanidine

Spinel is very common as a heavy mineral. Although red and pink gem spinel is used as a pathfinder mineral, black spinel, sometimes called 'pleonast' is used most commonly. Pleonastic spinels are iron-rich, where iron has replaced magnesium

3. Ruby and sapphire

in the spinel structure. Spinel can also contain appreciable amounts of titanium and zinc. Black spinel is typically octahedral, and strongly resembles chromite or magnetite, which show the same octahedral form.

In each particular gem field, the miners look for certain heavy minerals as a guide to the gem-bearing layer of gravel: for instance, an abundance of black spinel or the presence of phlogopite in the basaltic topsoil. Coldham (1985) notes that since pleonastic (black) spinel has a specific gravity similar to that of sapphire, it is often used as an indicator mineral when mining for sapphires.

In the New South Wales gem fields of Australia, Coenraads (1990) reports that when sapphire is found, zircon is always found with it. Abundant spinel or limonite indicates that fluvial concentration of heavy minerals has taken place, although sapphires and zircons are not necessarily present. *In situ* soils from basalts and associated volcanoclastic rocks in that area contain sapphire, zircon, pleonaste, chromium spinel, titanium magnetite-ulvospinel and ilmentite in varying amounts.

Coenraads (1990) tested for differences in mineral constitution and composition within and between drainage catchments and found no significant differences in mineral composition from the various drainage systems. However, there was some variation in the abundance of certain mineral species, the type of mineral species, and the corundum/zircon ratio.

Ruby and sapphire crystals mined from placer deposits associated with alkali basalts tend to be 'glassy' and exhibit corrosion or etching on the crystal faces. The corrosion is not a result of mechanical abrasion, but is a result of chemical corrosion during the transport of the corundum crystal in the host magma from depth.

ABUNDANCE OF RUBY AND SAPPHIRE IN THE ALKALI BASALT HOST ROCK

The alluvial ruby and sapphire deposits in Southeast Asia and Australia required a tremendous amount of fluvial concentration in order to concentrate the gems into economic deposits. The tropical weathering conditions and intense rainfall in Southeast Asia aided the process. Ruby and sapphire crystal are extremely rare *in situ*. Coenraads (1990) studied methods of outlining areas of sapphire (and alluvial diamond) exploration based on interpretation of structure, volcanic activity, and geomorphological processes which operated during the Tertiary. In short, the sapphire grade of the underlying alkali basalt source rock is extremely low. Economic concentrations of sapphire formed very close to host rock sources after favourable hydrogeologic conditions vigorously reworked the material through a largely vertical movement. The finer, lighter material was washed downstream.

GENESIS OF RUBY AND SAPPHIRES IN BASALT

There is uncertainty about the genesis of ruby and sapphires found associated with alkali basalt, although most researchers now believe that the gems formed at great depths, due to either magmatic or metamorphic processes, and then were simply transported upwards by alkalic basalt magma. Levinson and Cook (1994) list three critical observations regarding the occurrence of gem corundum with alkali basalt:

1. Corundum does not crystallize from alkali basalt melt in laboratory experiments.



2. The surface of corundum crystals found in alkali olivine basalt fields is commonly etched, suggesting that the corundum crystals were partially absorbed into the alkali olivine basalt magma.
3. Inclusions contained within sapphire and ruby are composed of elements such as vanadium, thorium, zirconium, niobium and tantalum. The sapphires must have grown in an environment rich in these elements, alkali elements (sodium and potassium), iron, aluminum and volatile gases. This host environment is incompatible with an alkali basalt melt.

The exact mechanism by which rubies and sapphires form at depth is unresolved — whether they form as a result of magmatic or metamorphic processes.

Limtrakun *et al.*, (2001) summarize the various models proposed for ruby and sapphire crystallization associated with alkali basalt:

1. Plutonic crystallization of corundum at high pressures requiring aluminous and trace element-rich magma.
2. Generation of gem corundum by magma mixing at mid-crustal levels.
3. Generation of gem corundum by metamorphic recrystallization.
4. Recrystallization of aluminum-rich and silicon-poor host rock by either ocean floor subduction or contact metamorphism.

Current research indicates support for several different models. Limtrakun *et al.* (2001) concluded that the gem sapphires at Denchai, Thailand were produced at the lower crust or upper mantle and then ascended to the surface during a subsequent alkali-magmatic event. Further work on the oxygen isotope composition (Yui *et al.*, 2003) suggests a hybrid origin model for Denchai sapphires, where a melt derived from the mantle interacted with a lower- to middle-crustal aluminum-rich rock.

Also in Thailand, Sutthirat *et al.* (2001) studied an inclusion of ruby within a clinopyroxene xenocryst in alkali basalt from the Chanthaburi-Trat area of eastern Thailand. Results indicated crystallization temperatures between 800 and 1150°C at depths of 35 to 88 km, within the upper mantle.

One theory for corundum formation suggests that corundum crystallized from a second magma distinct from the alkali basalt magma that brought the gems to the surface. Barr and Dostal (1986) suggest, based on their studies on Cenozoic basalts in Southeast Asia, that feldspar, nepheline, gem corundum, magnetite and zircon crystallized from a more evolved, highly fractionated alkalic and felsic magma and were later incorporated into the alkali basalt host. They speculate that the highly fractionated magma for the megacrysts could have been derived from trachytic or phonolitic liquids or be produced by mechanical disintegration of coarse-grained rocks like pegmatites or nepheline syenites during transport.

From studies in Australia, Coenraads *et al.* (1990) argue that because U-Pb dating of zircon in sapphires falls within the range of K-Ar ages for the gem-bearing alkali basalts in Australia, there is a complex genetic link between the gem-corundum megacrysts and the generation of alkali basalt magma. They present the results of a study of an unusual sapphire-zircon-magnetite xenolith from Chanthaburi, Thailand as evidence of pegmatite-like crystallization of the xenolith in an incompatible-element-enriched, silica-poor magma in the deep crust or upper

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mantle. The xenolith was transported by rising alkali basalt magma (Coenraads *et al.*, 1995). Guo *et al.* (1994) also suggests mixing of magmas, however, their model implies a more complicated process of mixing different types of magmas. Sutherland *et al.* (1998) compared suites of gem corundum from Australia and Cambodia and distinguished two distinct suites of gems. One suite appears to be produced by metamorphic recrystallization of aluminous material (metamorphic). A second suite appears to have crystallized at depth (magmatic).

Levinson and Cook (1994) note that alkali basalts associated with gem corundum are found in association with subduction zones involving ocean-continental plate collisions and therefore propose a metamorphic, as opposed to an igneous, origin for gem ruby and sapphire. They suggest that gem corundum could form when aluminum-rich rocks such as shales, laterites or bauxites are subducted to depths of about 25 to 50 km, where metamorphism takes place and corundum crystals form. Alkali basalt, which forms at similar depths, then carries the gems up through the crust, much like kimberlite transports diamonds.

Pecover (1987) suggests that alluvial sapphires in New South Wales, Australia were not derived from the alkali basalt at all, but from tuffs which carried the corundum up to the surface. Preferential weathering of the tuffs, compared to the overlying basalt, released the corundum but the tuffs were hidden under the volcanic pile. The tuffs, in addition to extensive deposits of laterites and bauxites, occur at or near the base of the volcanic pile. This would imply that gem corundum can be found in tuffaceous rocks in addition to alkali basalt.

Sapphires associated with lamprophyre dykes

MONTANA, U.S.A.

Excellent accounts of the discovery and subsequent mining history in Montana are given by Hughes (1997) and Voynick (1985). Sapphires were discovered there in 1894 by gold prospectors who collected small flat blue wafers they found in their sluiceboxes and goldpans. Once the stones were identified as fine blue sapphires the rush was on with the first of many mining efforts, all of which failed, largely because of difficulties in marketing an American gemstone to the gem trade and the public. The latest venture involves a series of heat-treating experiments aimed at improving the colour saturation of the sapphires.

The unique geology of this deposit is described in Meyer and Mitchell (1988) and Brownlow and Komorowski (1988). The sapphires are derived from a lamprophyric host rock known as the Yogo dyke which averages 2 m in thickness and has a length of about 8 km. Chemical analysis by Meyer and Mitchell (1988) showed that the lamprophyre dyke can be classified chemically and mineralogically as an 'ouachitite.' An ouachitite is a basic lamprophyric rock which contains abundant pyroxene, mica and magnetite with common apatite as well as an unknown glassy substance. The composition of the Yogo dyke is given in Table 3.7. Texturally, the Yogo dyke is finer grained than other documented ouachitite occurrences. Fresh rock is dark grey to greenish grey and contains numerous angular to rounded, light-coloured inclusions, mostly of calcite. Small biotite flakes are common and pyroxene megacrysts are visible in the fine- to medium-grained groundmass. Exposed bedrock on surface has altered the dyke rock to a yellowish clay. Sapphires occur rarely as unusually clear,



Table 3.7. Compositions and norms for the Yogo lamprophyre, average monchiquite, and average bassanite (wt %). Modified from Brownlow and Komorowski (1988).

	Yogo lamprophyre	Average monchiquite	Average bassanite
SiO ₂	38.54	41.06	44.30
TiO ₂	1.06	2.63	2.51
Al ₂ O ₃	11.73	13.20	14.70
Fe ₂ O ₃	3.33	4.39	3.94
FeO	3.58	7.16	7.50
MgO	11.30	8.88	8.54
CaO	15.60	11.15	10.19
Na ₂ O	1.00	3.25	3.55
K ₂ O	2.32	1.99	1.96
H ₂ O ⁺	2.33		1.20
H ₂ O ⁻	1.34		0.42
P ₂ O ₅	1.18	0.84	0.74

	Yogo lamprophyre	Average monchiquite	Average bassanite
CO ₂	5.56	2.13	0.18
BaO	0.41	0.21	
orthoclase	12.2	11.2	11.6
albite		4.7	12.2
anorthosite	23.8	17.3	18.4
leucoxene	3.0		
nepheline	6.0	13.0	9.7
diopside	28.9	27.0	21.0
olivine	15.2	12.8	12.9
magnetite	5.7	6.8	5.7
ilmenite	2.3	5.0	4.8
apatite	3.2	2.2	1.8

pale blue to steely blue megacrysts with flattened crystal form, with the average weight less than one carat. The outer surface of the sapphire crystals are commonly corroded and, like sapphires derived from alkali basalt fields, may be coated with a thin layer of spinel. Meyer and Mitchell (1988) suggest that the sapphires in the Yogo dyke are an 'accidental' product brought up by the lamprophyric magma.

A complex tectonic history for the Yogo deposit is proposed by Baker *et al.* (2003), where a sequence of continent-continent collisions and flat-slab plate tectonic events accounts for emplacement of the Yogo dyke.

The source of alluvial sapphire in western Montana, U.S., is a mystery, since there is no recognized bedrock source. Surprisingly, trace element chemistry and inclusion analysis suggests that the sapphires might be of metamorphic origin (Garland, 2003). Examination of temperature-pressure stability fields suggests that the Montana alluvial sapphires formed within 580 to 720°C at about 30 km depth. She suggests that the sapphires formed when a lobe of a large granitic batholith intruded and re-metamorphosed metamorphic rocks at mid-crustal levels. Cretaceous thrust-faulting exposed the rocks by early Tertiary. In contrast, Berg (2002) noted rhyolite and volcanic glass on two of the alluvial sapphires from western Montana and suggests that dacitic volcanic rocks, flows and breccias are a possible source rock.

SCOTLAND

Sapphires embedded in a lamprophyre dyke at Loch Roag, Isle of Lewis in Scotland were exposed during cutting of an access track to peat diggings (Jackson, 1984). The sapphires are small, thin blue platelets up to 25 mm in diameter in a monchiquite of lamprophyric affinities. The dyke contains mantle xenoliths and megacrysts of augite, apatite, sanidine, anorthoclase and rare sapphire. Only 10,000 years of weathering have taken place since the last glaciation in the Loch Roag area, so placer deposits of sapphire have not yet formed. The Loch Roag deposit is the result of late Paleozoic intrusive igneous activity confined to a small area. Jackson (1984) noted that alkalic volcanic rocks associated with ruby and sapphire deposits are generally significant outpourings of Tertiary basaltic lavas from volcanic vents and dykes, for example, in

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Thailand or Australia. The Loch Roag dyke is similar in composition to the Yogo dyke in Montana, but the Yogo dyke lacks mantle xenoliths and large megacrysts.

Corundum associated with porphyry copper deposits

Corundum has been reported as an accessory mineral at a number of porphyry deposits, including the Empress copper-gold-molybdenum mine in southwestern British Columbia and the El Salvador deposit in Chile. A possible mechanism for corundum growth is the movement of cool meteoric water over a thermal anomaly. The rapid heating of the meteoric fluids would prevent the influx of quartz.

A detailed paper by Simandle *et al.* (1997) describes the results of a study on the use of heavy minerals in exploration for sapphires using the Empress copper-gold-molybdenum deposit. At the Empress mine, in southwestern British Columbia, corundum up to 3 mm in diameter is reported in association with andalusite-pyrophyllite rock as noted in drill core and in float. Corundum occurs in quartz-free zones within a plagioclase-quartz-pyrophyllite-andalusite unit. The methodology was to collect sediment samples from sites draining the deposit area and concentrate and examine the heavy mineral fraction to determine the effectiveness of detecting corundum. The authors found that close-spaced stream sediment sampling was effective in recovering corundum fragments — some of them transparent, colourless and blue. Interestingly, they also noted scheelite in the heavy mineral samples, a mineral that had not been tested for in drill-core samples.

Ruby and sapphire associated with marble

Metamorphism, either regional or contact, is the mechanism for formation of the world's best ruby and sapphire deposits. Many of these wonderful gem deposits hosted in marbles or ultramafic rocks have the process of 'desilication' to thank for the bounty of gem ruby and sapphire. When a pegmatite, rich in silica, intrudes a host rock such as marble or ultramafic rock that does not contain silica, then the silica from the pegmatite reacts with the host rock minerals to form new minerals that contain silicon. Some of the silica used to form feldspar is thus used up, and remaining aluminum can combine only with left-over oxygen to form corundum crystals. Recent studies of the marble-hosted ruby deposits in central and east Asia indicate that regional metamorphism is also an important mechanism for gem ruby and sapphire formation and that, like the emerald deposits in Colombia, evaporitic sequences with organic matter played an important genetic role in ruby formation. The world's best ruby and sapphire deposits are in remote, inhospitable places where very few scientists have been allowed to study and sample the deposits.

The association between gem corundum and marble has been noted at the following ruby/sapphire deposits, including:

- Mogok Stone Tract, Burma
- Mong Hsu Stone Tract, Burma
- Luc Yen region, Vietnam
- Ekaterinburg, Ural Mountains
- Morogoro, Tanzania



- Hunza, Pakistan
- Jagdalek, Afghanistan
- Nepal

In addition to the above deposits, marble has been noted where gem corundum deposits are associated with ultramafic rocks.

MOGOK STONE TRACT, BURMA

For 800 years, the 175 km² of gem-bearing alluvial gravels of the Mogok Stone Tract in Burma have produced what some consider to be the only true rubies in the world. As discussed previously, Burmese rubies appear to literally glow red like a flashlight because of a high chromium content which gives them a rich red body colour overlain by vivid red fluorescence. Burmese rubies lack the iron which would quench the fluorescence. For centuries, Burmese rubies have been among the most expensive and sought after gemstones in the world. It should be noted that Burma produces gorgeous blue sapphires in association with the famous rubies. Some of these are found as gigantic crystals (Hughes and Win, 1995), including the famous Rockefeller sapphire, a beautiful blue 62-carat gem that fetched the world record price at auction for a blue sapphire.

Sparkling rubies and spinels were undoubtedly picked up by the earliest humans living in the area thousands of years ago who could not have missed the radiant rough crystals. In later years, European explorers and travelers were fascinated by the exotic Burmese people and their ruby mines. Throughout those years, Burmese monarchs controlled the Mogok area and acquired, by law, all of the larger stones. In 1885, the British annexed Burma, including the Mogok area, and Burma Ruby Mines Ltd. started operation.

Like so many other mining operations, past and present, little thought had been given to the remote location, rugged jungle and lack of infrastructure to launch a mining venture on the scale envisioned by Burma Ruby Mines, Ltd. and eventually it went bust and the area reverted back to old-fashioned native mining methods. In 1963, the military dictatorship government took over the ruby mines from private interests and severely restricted the legal gem trade. Although fine Burmese stones still showed up in Thailand through smuggling, significant quantities of Burmese ruby were almost non-existent until the early 1990s when a spectacular new ruby find was made at Mong Hsu. The usual rush ensued and over 2,000 miners were in the area by the time the rubies hit the market in Bangkok in 1992. The military dictatorship in Burma is starting to loosen restrictions on international travel and trade. Burmese rubies from both Mogok and Mong Hsu are now available on the global gem market, however, the easy-to-find alluvial deposits are becoming depleted and there is more mining of the bedrock in order to extract the rubies. To make matters more complicated, in 2003, the United States put an embargo on the import of gem material from Burma to the United States, in protest of the government's treatment of government opposition leader Aung San Suu Kyi.

For a deposit that has produced the world's best rubies and spectacular sapphires for over eight centuries, there is very little information on geology and geochemistry of the Mogok Stone Tract, although many gemological studies have been made of its

Burma Ruby Mines

Hughes (1997) reproduces newspaper accounts of what happened the day after the Times of London published the prospectus for the newly formed Burma Ruby Mines, Ltd. in 1889. The next day, the £1 shares went to £4 and chaos ensued.

“The crowd around New Court was so dense that Lord Rothschild and other members of the house were unable to get in by the door, so a ladder had to be got, and the spectacle was seen of a number of great financiers entering their own office in a burglarious fashion. The clerks had to be smuggled in by a back entrance behind the Mansion House. The surging crowd in front drove a telegraph boy right through the window of a baker's shop opposite, the poor fellow being rather severely hurt. The fortunate possessors of Ruby Mine application forms, which were being hawked at five shillings, had to pass between files of policemen to hand in their applications.”

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The SLORC Ruby

The story of the SLORC ruby in Burma has been known for a number of years, but Hughes (1997) provided an update on the fate of the owner.

This ruby, with the most appalling name, was discovered in 1990 at one of Mogok's famed ruby mines. It was huge at 496 carats. The fortunate/unfortunate miner who unearthed the large stone was supposed to disclose the discovery to the local State Law and Order Restoration Committee (SLORC), but instead chose to smuggle it into Thailand. It was recovered by SLORC military intelligence, triumphantly brought back to Burma and is duly known as the 'SLORC' ruby ever since. The owner was imprisoned.

gemstones. Keller (1983) provides a summary of geology and gemological findings up to that date. The first western researchers to visit the Mogok Stone Tract since the government take-over in 1963 were R. Kane in 1991 and R. Kammerling in 1992. Their article summarizes the geology and reports on the mining status and methods (Kane and Kammerling, 1992).

In the last few years, there have been visits by western researchers and gem dealers to the legendary deposits. Waltham (1999) reports on several hardrock mines in the area. He describes the hostrock as crystalline marbles and notes that productive calcite (richest in ruby) is clearer than the milky rhombs of the main marble. Another mine follows a 2- to 3-m-wide calcite vein rich in ruby that appears to be a hydrothermal feature within a narrow band of marble within gneiss. The vein has been followed to an incredible depth of 300 m; in fact it takes the miners over an hour to scramble down, without the benefit of ladders, to the working faces where the ruby-bearing calcite is broken out of the vein and lifted up by hand-powered winches.

Geological mapping and prospecting of terrain around the Mogok Stone Tract is extremely arduous. Harsh weather comprising intense seasonal rainfall and tropical heat, combined with dense jungle fauna inhabited by elephants, tigers, bears, cobras and leopards increase the challenge of geological mapping and exploration. Bedrock is buried under a thick mantle of soil and weathering products. Despite the difficulties, Iyer (1953) produced a geological map of the Mogok Stone Tract, which remains the sole source of geological information about the area.

It appears that the famous rubies and red/pink spinels are weathered from marbles interbedded with complex high-grade metamorphic schists and gneisses. The marble is coarsely crystalline, typically pure white, slightly pinkish or yellowish. Ruby, spinel, diopside, phlogopite, forsterite, chondrodite, scapolite, sphene, garnet and graphite are present. Feldspar and diopside mark areas of contact metamorphism where granitic rocks have intruded the marbles. The metamorphic complex consists of scapolite and garnet-rich biotite gneisses, calc-granulites, quartzites, garnet-sillimanite-rich gneisses and hornblende schists and gneisses. Intrusive rocks include granite, augite and hornblende granite, syenite and tourmaline granite. Pegmatites containing topaz, tourmaline and aquamarine occur within the area.

Iyer (1953) suggests that the granite, which has generated numerous quartz and topaz-bearing pegmatites, with cassiterite, is responsible for contact metamorphism and subsequent ruby and spinel formation. However, the Mogok Stone Tract shares many similarities with regions in which rubies form in marbles as a direct result of high-grade regional metamorphism: for example, the Ural Mountains deposit described later in this chapter. It is amazing that so little is known about the paragenesis of the best rubies on the planet.

MONG HSU STONE TRACT, BURMA

It is reported (Peretti *et al.*, 1995) that a miner from the Mogok area may have been the first person to notice rubies in a stream in Mong Hsu, Burma, approximately 250 km southeast of Mogok. The usual staking rush ensued and thousands of miners were in the area by the time the rubies entered the global gem market.



The newly discovered Mong Hsu deposits are situated at the contact of upper Paleozoic marbles and other Paleozoic rocks. The major host rocks are mica schist, phyllite and calc-silicate rocks. The rubies are hosted in dolomite marble and are also mined in secondary deposits associated with the marbles. Peretti *et al.* (1995, 1996) suggest that, based on observed mineral assemblages, Mong Hsu formed under regional metamorphic conditions, however, the marbles and metapelitic rocks formed under amphibolite facies conditions as opposed to upper amphibolite-granulite facies at Mogok.

An unusual feature of rubies from Mong Hsu is that many have a black sapphire core and others show multiple zoning from ruby to violet sapphire to black sapphire within a single crystal. The violet to black zones in the rubies are due to high concentrations of titanium and chromium. Geochemical analysis indicates that Mong Hsu rubies were formed at temperatures between 500 and 550°C, and at pressures of 2 to 2.5 kilobars. Fluorite inclusions were noted in the rubies, indicating that fluorine played an important role during ruby precipitation from water-bearing multi-volatile CO₂-rich fluids. These fluids were enriched in chromium as well as fluorine. Fluorine complexes with titanium in solution. The concentration of titanium at Mong Hsu was strongly influenced by variations in temperature and fluorine concentration. Peretti *et al.* (1996) further speculate that infiltration of fluorine-rich fluids from metapelites migrated into the host carbonates during metasomatism. Precipitation of fluorite would affect the titanium concentration in the corundum structure, accounting for the odd colour zonation.

LUC YEN REGION, VIETNAM

The first report of corundum in the mountains north of Hanoi was in 1983. In 1987, geologists informed the government that they had discovered rubies near the town of Luc Yen, 270 km northwest of Hanoi. Subsequent discoveries were made at Quy Chau, south of Hanoi. Millions of carats have been mined through legal and illegal means since the initial discovery.

Descriptions of the geology and mining of the new finds are given by Kane *et al.* (1991) and Kammerling *et al.* (1994 a,b). The alluvial deposits, which cover at least 50 km², are underlain by Upper Proterozoic-Lower Cambrian marbles and crystalline schists and quartzites intruded by pegmatites. Gemological studies carried out on the rubies suggest they formed in a comparable geological environment to the Mogok and Hunza ruby deposits.

HUNZA, PAKISTAN

The paragenesis and petrogenesis of a corundum and spinel-bearing marble at Hunza (Pakistan) is described by Okrusch *et al.* (1976). This is one of the few published papers which discusses the physico-chemical conditions of gemstone formation. A geology overview and gemological study is given by Gübelin (1982). An overview of the tectonic history of this part of the world is provided by Kazmi (1989). This area of Pakistan is noted for its spectacular emerald deposits.

The colour photographs accompanying the Gübelin (1982) paper show some of the most magnificent scenery in the world. The marble hosting the gem corundum and spinel crystals is located in the Hunza Valley surrounded by mountains of the

3. Ruby and sapphire

Karakorum Range in a remote corner of north Pakistan. Majestic mountains attaining over 7,500 m a.s.l. tower over the Hunza valley, which was virtually unknown until construction of the Karakorum Highway in the early 1970s penetrated the rugged terrain.

Intercalations of white to grey to yellowish marble 1- to 5-m thick are easily visible sandwiched between layers of garnet-bearing mica schists and biotite-plagioclase gneisses. Phlogopite, amphibole, chlorite, margarite and green muscovite are accessory minerals in the marbles. Discordant veins of aplite and pegmatite cut the metasedimentary rocks. Ruby, and more rarely, sapphire crystals accompany red, brownish red, plum red, lilac, violet and blue spinel crystals up to 5 cm or more in size in the marble. The contrast of crimson red ruby crystals on a white marble background is very dramatic.

Okrasch *et al.* (1976) studied the mineral assemblages and chemical compositions of individual minerals from the deposits and suggests that the marble is derived from what was a limestone complex in which aluminum was enriched relative to silica. The lateritic weathering of an impure limestone, perhaps in a karst environment, would enhance aluminum enrichment. This would also explain the higher concentrations of titanium seen in the deposit. Ruby, sapphire and spinel formed during a Tertiary regional metamorphic event, related to the collision of India with Asia, which generated temperatures of 600 to 620°C and pressures of 7 kbar.

This view is explored further by Garnier *et al.* (2003), Pecher *et al.* (2002), and Giuliani *et al.* (2003) who are studying the marble-hosted ruby deposits of Burma, Jagdalek (Afghanistan), Pakistan, Kashmir, Nepal and Vietnam with a regional view. The Ar-Ar and U-Pb ages of these deposits were compared against the ages from some of the host rocks, in order to determine the relationship between marble, pegmatite and other rocks (Garnier *et al.*, 2003). A study of fluid inclusions from marble-hosted ruby deposits in Luc Yen and Quy Chau, North Vietnam indicates that rubies probably grew during regional metamorphism of an evaporitic sequence with organic matter. At the Nanga Parbat Himalaya ruby occurrence in Kashmir, ruby is found within 0.1-to-2 cm-thick shear-veinlets and gash-veins cutting dolomitic marbles and carbonate-bearing bands. The marble is underlain by high-grade metamorphic gneisses. Isotopic analysis of the marbles suggest that metamorphic fluids derived from decarbonation of the marbles. Chromium and aluminum were leached from the marbles to form rubies in shear-zones. At Hunza, Garnier *et al.* (2003) determined that ruby crystallization was contemporaneous with emplacement of the Karakorum batholith, approximately 95 million years ago, and is probably genetically related.

SOUTHERN URAL MOUNTAINS, RUSSIA

Although pink and blue opaque corundum crystals up to 20 cm in diameter had been known since 1855 from the southern Ural Mountains near Ekaterinburg, it was assumed that the crystals were genetically linked to the intrusion of abundant pegmatites in the area. After noting similarities between the widespread marbles in the Ekaterinburg area and the host rocks in the Mogok Stone Tract, Kissin (1994) speculated as to whether the corundum might have originated within the marbles (the pegmatites are presumed to be coincidental). He travelled to a marble quarry to test his hypothesis and promptly discovered ruby, pink sapphire and other



corundums embedded within the marble. Since then, several other primary or alluvial gem corundum deposits associated with marbles have been found in a linear belt about 600 km long. Several new deposits have been found using exploration techniques based on studies of the original discovery in the quarry.

Kissin (1994) studied the geology of the quarry occurrence as a model for gem corundum exploration. The corundum deposits are hosted in a series of Middle to Upper Paleozoic marbles contained in linear belts of metamorphic complexes. Metamorphism took place 300 million to 260 million years ago. Alternating domes and graben-synclines characterize the complexes. Granitic dykes and pegmatites have intruded the complexes, and pink topaz and green tourmaline occur in silicified fractures. Metamorphic amphibolite facies rocks (typical of moderate to high-pressure and high-temperature metamorphism) have been identified in the domal structures. Metamorphic albite-epidote-amphibolite facies rocks (formed under lower pressures and temperatures) occur in the graben-syncline structures. The corundum occurrence at the quarry is located in the axial part of a graben-syncline structure in which marbles are particularly widespread.

Kissin (1994) identified three types of marbles:

1. Calcite marble (corundum is not found in this marble)
 - contains less than 0.05% MgO
 - formed during prograde metamorphism
2. Magnesian calcite marble (contains corundum)
 - contains 0.1 to 0.9% MgO
 - formed during prograde metamorphism
3. Dolomitic calcite marble (contains corundum)
 - contains greater than 1% MgO up to 22% MgO
 - formed by magnesium metasomatism in the magnesian calcite marble during retrograde (lower temperature/pressure) metamorphism.

Three types of corundum crystals are identified, each related to specific types of marble and specific metamorphic conditions of temperature and pressure.

Type A: Ruby formed in magnesian calcite marbles during prograde metamorphism as a result of fluid activity on limestone. During subsequent retrograde metamorphism of the magnesian calcite marble to form dolomitic calcite marble, most of the ruby was converted to spinel. As a result, most of the rubies that survived show good colour, but are heavily fractured.

Type B: Pink sapphire formed during an early stage of retrograde metamorphism of magnesian calcite and dolomitic calcite marbles. Where the marble had a high magnesium content, spinel formed in place of pink sapphire.

Type C: Other sapphire formed under conditions of decreasing temperature, changes in the fluid regime (increasing role of H₂O) and high CO₂ pressure. The metamorphic fluid formed in and filled fractures in both the magnesian calcite and dolomitic calcite marbles. When the CO₂ pressure decreased, orange-red spinel formed instead of

3. Ruby and sapphire

corundum. Spinel is found in both types of marble, where it replaced ruby and pink sapphire that had formed earlier.

The main geologic factors in the formation of ruby and sapphire are metamorphism and magnesium content of the marble.

The Al_2O_3 content of the marble does not seem to be a critical factor in the Ural deposits. Kissin (1994) notes that the Al_2O_3 content of the gem-bearing marbles is lower at 0.08 to 0.13% than for the marbles that do not contain corundum (0.15 to 0.18%).

Rubies and sapphires are rarely found in the contact zones between pegmatite and marble- or aluminum-bearing rocks.

MOROGORO REGION, TANZANIA

Rubies in their rough form characteristically show a six-sided prismatic shape or modified variations of this form. Red spinels are typically octahedral. In 1987, parcels of gem-quality spinel rough from Tanzania were examined by Hänni and Schmelzer (1991) and found to contain up to 10% gem quality ruby crystals. The ruby crystals are of an unusual flattened rhombohedral form which closely resembles the typical spinel octahedron. Comparisons of gemological characteristics between these rubies and rubies from the Mogok Stone Tract show that the two are very similar; both are found with red and purple spinels and therefore probably formed under similar geological conditions.

NEPAL

The first gemological studies of ruby, and pink and violet sapphire from a reported locality in Nepal is given by Harding and Scarratt (1986), and Kiefert and Schmetzer (1987). The mineral assemblage of corundum associated with carbonates, phlogopite, apatite, graphite and calcium-aluminum-silicate minerals such as margarite, zoisite, epidote and anorthite is similar to the Mogok Stone Tract and the Hunza deposit in Pakistan.

AFGHANISTAN

The geology and occurrence of ruby and sapphire in the Jagdalek area of Afghanistan is described by Hughes (1997) and by Bowersox *et al.* (2000), who thanked Commander Ahmed Shah Massoud in the Acknowledgments section of his paper. As the world sadly knows, this is the person assassinated by Al Qaeda assassins masquerading as journalists two days before the horrendous September 11, 2001 attacks. Much of Afghanistan's coloured gemstone mining was under the control of the Northern Alliance during the late 1990s and even during the Russian occupation of the country.

Fabulous gem deposits never seem to be located in easily accessible pleasant areas and the gem-rich areas of Afghanistan are no exception. The fabulous emerald mines, lapis lazuli deposits and occurrences of rubies, spinels, tourmalines and many other gemstones are concentrated in the extremely rugged eastern portion of the country that borders Pakistan and Tajikistan.

Historical accounts of ruby mining in Afghanistan

When workers in our Canadian mines or other industries are feeling hard done by, then they might be advised to keep in mind the fate of mine workers in 17th century Afghanistan. Sparse, intermittent production from the ruby mines was partly caused by flooding and inadequate ventilation at the lower levels. A local chief of the area became displeased with the small profit and marched all inhabitants of the district, about 500 families, to Kunduz and then disposed of them in the slave market (Hughes, 1997).



There seems to have been much confusion throughout history as to whether red rubies and spinels were mined at one time in Afghanistan, and if so, then where from? We know now that the Jagdalek ruby mines are located approximately 60 km east-southeast of Kabul. The deposits are hosted by metamorphosed limestones (marbles) that were originally deposited along the margins of the Asian and/or Indian plates. The collision between the Indian and Asian tectonic plates took place between 40 to 66 million years ago and resulted in the formation of the Himalaya, Karakoram, Hindu Kush and Pamir mountain ranges. The host rocks are interstratified Proterozoic gneisses and marbles, approximately 1.5 to 1.9 billion years old. The marble horizons range from 0.5 m up to 200 to 300 m thick and are essentially pure calcite with small amounts of magnesium impurities (0.68 to 4.78% MgO). The gneisses are composed of kyanite-amphibole-pyroxene, pyroxene-biotite, biotite-amphibole and other assemblages. Both the gneisses and marbles are intruded by numerous Oligocene granitic dykes and desilicated pegmatites. Bowersox *et al.* (2000) state that the Jagdalek deposit probably formed by regional metamorphism of the marble and gneiss, with local contact metasomatic effects from the intruded granitic rocks. The aluminum, magnesium and chromium necessary for ruby development were likely present within the host marbles as impurities that were concentrated before the marbles were metamorphosed.

THE SAPPHIRE OCCURRENCE AT KASHMIR, INDIA

Just as the rubies from Burma are considered superior because of the red fluorescence on top of red body colour, Kashmir sapphires are considered superior because of their unique, velvety appearance. The velvety appearance is due to the presence of layers of microscopic liquid inclusions. Kashmir sapphires (almost all of which were mined during a period of only seven years between 1881 to 1887) are so rare that Atkinson and Kothavala (1983) report that attempts by top gem dealers around the globe to secure a fine 25-carat Kashmir sapphire for Prince Charles to give to Princess Diana at the 1980 British royal wedding failed (the gorgeous sapphire in the ring is reportedly from Sri Lanka).

This deposit was discovered just over 100 years ago, yet already is considered to be legendary. The sapphire occurrence is situated in the Zanskar Range, part of the Great Himalayan mountain range. The area is politically unstable; the Kashmir area has been affected by China's occupation of Tibet in 1950, two Indo-Pakistan wars, and Russia's invasion of Afghanistan in 1979. Tribal unrest and guerilla warfare add to the chaos. The deposit itself is situated in a small glacial cirque approximately 1,000 m long and 400 m wide. It takes a minimum of 8 days by foot over a tortuous trail to get to the mountain valley situated at 4100 m above sea level. Aside from a 'police post,' which is really a stone corral situated in mist and fog under a rock overhang at the mine, the nearest 'village' is a couple of huts 3.2 km away and 1,000 m lower. Mining can only take place from between 30 to 90 days in the summer, when the valley is free of snow.

Beautiful blue spindle-shaped sapphires were exposed in an altered pegmatite high up on the cirque wall after a landslide in 1881. From 1883 to 1887, the small pit called 'the Old Mine' yielded what are acknowledged as the best and most beautiful sapphires in the world. The sapphires lay embedded in clay within altered pegmatite until miners dug them out like 'potatoes' or 'plums in a pudding.' The initial pit is

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Kashmir adventure

The account by Gaines (1951) is a story about how Gaines, a determined mineral collector and mining engineer who was stationed in India during the war and an army buddy set out on a 25-day journey over majestic mountain ranges which very few people had ever seen. Armed only with their military uniforms and some official looking papers from the Geological Survey of India, they managed to get permission to inspect

the Kashmir deposit. No fewer than six 'police inspectors' in this extremely remote corner of the world followed their every move, since they were not allowed to collect any sapphires. The irony of the story is that Mr. Gaines had to leave his 13 kg of host rock samples at the 'police station' to await official sanction to leave the area. Upon returning home to North America, Mr. Gaines applied for and received official sanction and

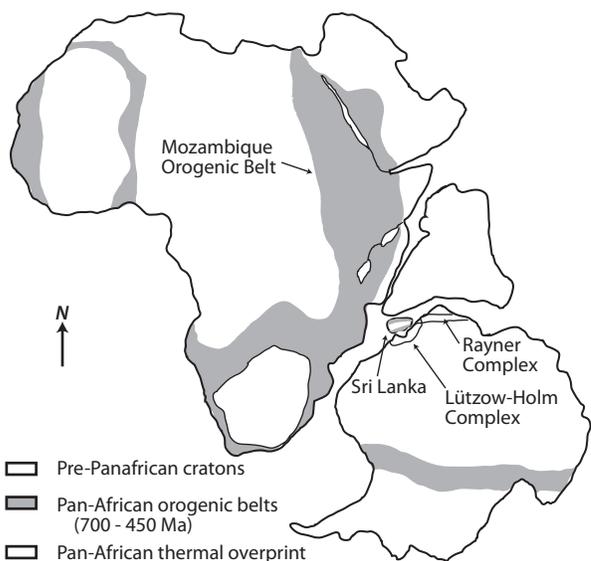
the samples were duly sent out by porter over the same tortuous mountainous terrain, shipped to Calcutta and then shipped across the ocean to the United States. After arriving at the dock, 18 months after the trip to the mine, the samples disappeared without a trace on the trip between the dock and Mr. Gaines' home in the United States.

worked out and despite intermittent attempts at exploration and mining, the deposit has remained idle, with only a small amount of material coming out each year.

Geologists working for the Geological Survey of India in the late 1800s and early 1900s produced descriptions of the deposit, although, as reported by Hughes (1990), the first geologists and mining engineers on the scene were criticized by Middlemiss (1931) for being so overwhelmed by the scenery and the spectacular sapphires in the 'Old Mine' that they failed to provide adequate descriptions of the deposit geology. The only westerners to have visited the site are R.B. Gaines in 1944 and D. Atkinson and R. Kothavala in 1981. Detailed state government surveys of the area done in the 1960s remain confidential.

The descriptive record and close attention paid to mineralogy and geology by Mr. Gaines provided the only published record of this deposit since the Geological Survey of India geology reports at the turn of the century. The only account since then has been that of Atkinson and Kothavala (1983) who, after several years of trying, obtained permission to visit the deposit in 1981. Hughes (1990) provides a good summary of the accounts to date and some of the fascinating Geological Survey of India reports are reproduced on the Pala Gems International website⁶.

Figure 3.4. Gondwanaland fit showing extent of Pan-African orogeny. Modified from Kriegsman (1995).



Geology: Although some detailed gemological work has been carried out on the sapphires themselves (Hänni, 1990), the only geological research to date has been visual observations, most recently by Atkinson and Kothavala (1983).

The geology of the Zaskar Range seems to be relatively unknown compared to the other mountain ranges in the area. At the Kashmir deposit, coarse marble up to 30 m thick is locally interbedded with biotite gneisses and schists. The gneisses contain graphite, hornblende and are sometimes garnetiferous. In places, the marble has been altered to form lens-shaped bodies of actinolite and tremolite. Within the lenses, the tremolite and actinolite form felted and radiating aggregate crystals that are olive-green to bright mint-green. The lenses range from one to hundreds of metres long and up to 30 m thick.

The medium-grade metamorphic strata are discordantly intruded by feldspar pegmatites. The greatest concentrations of sapphires are in

⁶www.palagems.com



quartz-free feldspar pegmatites where they intrude actinolite-tremolite lenses. The sapphires are embedded in lens-shaped pockets of plagioclase feldspar pegmatite which has been kaolinized. The pockets are approximately 1 m thick and 3 m to 4 m long.

Atkinson and Kothavala (1983) report that where sapphires are in contact with graphitic biotite schists, pink corundum crystals have been found. Other reported minerals include red and green tourmaline, hambergite, cookeite, prehnite, amblygonite, lazulite, amethyst, black and brown tourmaline, kyanite and fluorite.

Atkinson and Kothavala (1983) note that actinolite-tremolite lenses are a common feature of the regional geology. The gem potential of the area is excellent, however, exploration of the harsh terrain is restricted to only a short time in the summer, and the current political situation is not conducive to effective exploration.

Ruby and sapphire associated with ultramafic rocks

Unlike most other world-class gem deposits, the easily accessible ultramafic-hosted ruby (and tsavorite garnet) deposits of Kenya and Tanzania have been the subject of several detailed studies. The conditions of formation for ruby growth in southeast Kenya were defined by Key and Ochieng (1991a) and discussed further by Mercier *et al.* (1999). Exploration guidelines for ruby deposits in southeast Kenya are given by Key and Ochieng (1991b). The tectonic setting and physico-chemical controls on gemstone formation in the Mozambique belt are given by Malisa and Muhongo (1990). A first-hand view of mining and exploration for East African gemstone deposits is provided by Bridges (1982). A summary of East African geology and gemstone deposits is provided by Keller (1992).

To northern Canadian geologists and prospectors, the term terrane refers to exotic rock assemblages accreted to the ancient North American continent margin. The fault-bounded terranes are host to precious metal and base metal ore deposits. In eastern Africa, the Proterozoic Metamorphic Terrane within the Mozambique Orogenic belt refers to a ribbon of high-grade metamorphic rocks which originally lay across the ancient supercontinent called Gondwanaland. Sections of this unique belt survived the Gondwanaland disintegration (Figure 3.4) and presently underlie fields of alluvial and *in situ* gem deposits in Africa, Brazil, Sri Lanka, Australia, Madagascar, and, potentially, Antarctica. The Mozambique Orogenic Belt in Tanzania and Kenya is

Ownership dispute

For those in the Canadian mining industry who feel hampered by periodic uncertainty regarding land tenure, it is worth noting that things are or have been worse elsewhere in the world. Hughes (1997) summarizes a well publicized series of events where the original stakers, geologists John Saul and Elliott Miller, of the world-class Mangari ruby deposit in Kenya, obtained a fully legal permit to mine the deposit in 1974. Within a

year, so many high-ranking Kenyans including the President's wife, a friend who helped run the Kenya Trade and Development Corporation, and others 'requested' a cut that the total amount soon exceeded 150% of ownership. The two discoverers of the deposit (Saul was a long-term resident of Kenya) were booted out of Kenya and records of the original claims disappeared at the Ministry of Natural Resources. New

records appeared with the name of one of the President's closest friends. A lengthy diplomatic fracas ensued, and the mine at Mangari is still known as the 'John Saul' mine. After being dormant for a number of years, it was modernized and upgraded and, indeed, the original John Saul co-authored a recent paper on ruby formation at Mangari (Mercier *et al.*, 1999).

3. Ruby and sapphire

host to an incredible array of earth-history and natural resources in a relatively small area straddling the Kenya-Tanzanian border. The Serengeti Plain, Tsavo National Park, Olduvai Gorge, Mt. Kilimanjaro and fantastic gemstone deposits are contained within a small area (by Canadian standards).

The lithostratigraphic units within the Mozambique Orogenic Belt are Proterozoic in age, between 1,900 and 799 million years old. The rocks underwent a series of collision-related metamorphic and deformational events. The regional metamorphism reached amphibolite to granulite facies conditions, accompanied by igneous intrusion. Gemstones such as ruby and tsavorite garnet formed during this event (Key and Ochieng, 1991b). The tectonic events ended with the Pan-African orogeny 500 to 438 million years ago.

Ruby and sapphire deposits have been found in a variety of geological environments in Kenya and Tanzania. In addition, there are largely undeveloped and underexplored alkali basalt fields hosting alluvial gem sapphire deposits in Kenya and Tanzania. These deposits, covered earlier in this chapter, are potentially large producers of gem rough. Several of the remaining types of ruby and sapphire deposits are associated with ultramafic rocks. The two best known examples are the ruby and sapphire deposits in the Umba River area, Tanzania and the ruby deposit at Mangari, southeast Kenya.

The ruby discovery was important, since the Mangari deposit is one of the few ruby deposits in the world which produces a regular supply of facetable material. Rubies from the Mangari deposit are often passed off as Burmese stones since they show intense red fluorescence and contain very little iron. As mentioned earlier, when rubies contain iron, a brownish tint is produced and the red fluorescence is quenched.

The host rocks for both the Mangari and Umba River gem corundum deposits are metamorphic rocks of amphibolite to granulite facies ranging from banded gneisses to amphibolite facies marble and highly aluminous graphitic gneisses. The graphitic gneisses are also host to tsavorite garnet and tanzanite gem deposits (described in Chapter 7).

Ruby and sapphire deposits have been found in areas where feldspar pegmatites have intruded serpentinized ultramafic bodies. At Mangari, rubies are found in lenses on the inner side of the contacts between the ultramafic and metasedimentary rocks or in veins within the ultramafic bodies or forming their margin (Mercier *et al.*, 1999). The rubies are associated with plagioclase, mica, tourmaline and kyanite in the pegmatites, and with kyanite/sillimanite, tourmaline, and mica aggregates in the gneisses (Key and Ochieng, 1991b).

UMBA RIVER

Southeast of the Mangari ruby deposit, the Umba River meanders along the eastern edge of the Kenya-Tanzania border where it flushes into the Indian Ocean. Alluvial rubies, and then sapphires, were discovered in 1960. Subsequent exploration found a spectacular array of coloured sapphires associated with a serpentinized ultramafic body intruded by feldspar-rich pegmatites. The deposit is unique, in that the sapphires occur in virtually every colour: orange, yellow, violet, blue, colour-change and parti-coloured stones. According to Hänni (1987), the sapphire colours are related to varying iron, titanium, chromium and vanadium content.



At Uмба, the serpentinite body embedded within high-grade metamorphic rocks represents the core of a fold (Solesbury, 1967). Rubies and sapphires formed by 'desilication,' where any silica in the pegmatite is soaked up by the ultramafic body, leaving aluminum to precipitate as Al_2O_3 .

A second sapphire deposit was discovered 3 km south of the Uмба locality, in the Kalalani, Tanga Province area in Tanzania. This deposit produces gem-grade red pyrope-almandine garnet and rare reddish orange sapphire from a desilicated pegmatite that cross-cuts a small serpentinite massif. In 1994, tsavorite garnet (see Chapter 7) was discovered in the surrounding graphitic gneisses and there are indications of gem tanzanite (Seifert and Hyrsl, 1999).

GENESIS OF THE RUBY DEPOSIT AT MANGARI

Key and Ochieng (1991a,b) summarize the conditions of formation for the ultramafic-associated ruby deposits in Kenya and Tanzania. Mercier *et al.* (1999) advanced this work further to consider ruby formation within the entire Mozambique Metamorphic Belt. The three controls on ruby formation are:

1. Host rock lithology. The lithologic control are the chromiferous ultramafic bodies. The ultramafic bodies are of two different origins and ages, and rubies occur with both and are genetically related to them.

No stratigraphic control for ruby growth was found. There are other ultramafic bodies in southeast Kenya which do not host ruby deposits. Key and Ochieng (1991b) note that there must be chemical differences between the ruby/non-ruby ultramafic rocks which affected ruby formation. This has not been further studied.

2. Metamorphic control. Key and Ochieng (1991b) noted the presence of kyanite as the Al_2SiO_5 polymorph in the mineral assemblage, which indicates pressures greater than 7 Kbar. They suggest that ruby crystals formed during regional upper amphibolite to granulite facies conditions within the Mozambique Orogenic Belt. Growth of corundum crystals is dependent on the pressure, temperature, and activity of CO_2 and H_2O during regional metamorphism. Mercier *et al.* (1999) confined the metamorphic grade of the ruby-bearing rock as amphibolite facies, where temperatures were 700 to 750°C. In contrast, they found that the surrounding gneisses were subject to lower-grade amphibolite facies metamorphism at 650°C.

3. Chemical control. The red colour of rubies is due to the presence of trace amounts of chromium. The obvious source of chromium in the rubies is the ultramafic bodies which, in other localities in Kenya, host chromite pods. Key and Ochieng (1991b) note that chromium is also the colouring agent for green tourmaline and blue kyanite, which are found in the area.

Mercier *et al.* (1999) suggest that the rubies and the ultramafic ruby host rock at Mangari are exotic and are fragments of deeper crust brought up to present day erosion levels by thrust movement. The exotic nature of the ultramafic rocks is defined by the metamorphic grade which is granulite facies, compared with the amphibolite facies metamorphism of the host rocks. Mercier *et al.* (1999) further suggest that all rubies associated with ultramafic rocks in the Mozambique Metamorphic Belt, including Madagascar, only formed under granulite facies metamorphism and were tectonically inserted in country rocks.

Bead material

Low-grade gem material can still be made into carvings, cabochons and beads. Barot and Harding (1994) describe how most of the pink and reddish pink translucent gem corundum from Kitui, Kenya is collected and then sold and exported to India. There, the material is cut, polished in cabochons and beads. Some of the material is then dyed red and then sold as 'ruby' beads.

Gem corundum associated with granulite facies metamorphic rocks

In 334 B.C., beautiful translucent gems were described as having come from an island not far from Persia (Zwaan,1982). This island was Sri Lanka, host to the world's greatest concentration of gemstone wealth. Tens of thousands of carats of fine quality gemstones including ruby, sapphire, yellow sapphire, orange sapphire, violet sapphire, colourless sapphire, green sapphire, colour-change sapphire, star ruby and sapphire, spinel, garnet, peridot, beryl, tourmaline, quartz, zircon, chrysoberyl, alexandrite, moonstone, topaz, and lesser known gems such as taaffeite, ekanite and sinhalite have been mined from this island. It seems that almost everywhere gemstones can be found in the gravels. In the mid-1940s, a Sri Lankan engineer working on an irrigation project put his ring down along a river while he was bathing. While looking for his ring after he finished, he discovered blue and red pebbles (Gunawardene and Rupasinghe, 1986). The area eventually became the Elahera gem field, second largest gem field in Sri Lanka. The largest gem field is Ratnapura, in the southwest part of the island. The gem-bearing gravel, called illam, lies anywhere from 1 m to 10 m, sometimes up to 30 m, beneath the ground.

Despite incredibly rich alluvial deposits, gemstones are very rarely discovered *in situ* on Sri Lanka. For this reason, the genesis of the fabulous gemstone deposits of the island is uncertain. During the last 15 years, a number of geological and geochemical studies have been carried out on the placer gemstone deposits in an attempt to discover the 'motherlode,' much like Canadian mining companies continuously look for the 'motherlode' in the Dawson area, Yukon. A prospectors' guide map has been developed (Dissanayake and Rupasinghe, 1993) as part of an ongoing systematic study on the spatial distribution of gem deposits, their bedrock sources, and determining the geological and geochemical methods of readily identifying areas with high gem potential.

Alluvial gemstone deposits in Sri Lanka are derived from PreCambrian Highland/Southwestern Complex rocks. The rocks of the Highland/Southwestern Complex consist of closely interbanded pyroxene-granulite facies metamorphic rocks; charnockites (acid, intermediate, basic); undifferentiated metasedimentary rocks (garnetiferous granulites, garnetiferous biotite gneisses, garnet-sillimanite-biotite gneisses); khondalites (quartz-feldspar-garnet-sillimanite-graphite schist); quartzites, crystalline limestones, calc-gneisses and calc-granulites, amphibole granulites and amphibolites. Many of the gemstone deposits are confined to calciphyres, chamockites and cordierite-bearing gneisses in the southwestern part of the Highland Complex.

Dahanalyake (1980) studied sediments in gem pits in order to determine the modes of occurrence of the gem-bearing gravels and perhaps determine the nature of the source rocks. He suggests that gem corundum and spinels were derived from both garnetiferous gneisses and localized skarn deposits, while topaz, beryl, tourmaline and chrysoberyl may have come from pegmatites.

Rupasinghe *et al.* (1984) summarize a study of the geochemistry of beryllium and fluorine in the gem fields of Sri Lanka. They reviewed the findings of Munasinghe and Dissanayake (1981) who suggest that the gem corundums on Sri Lanka formed as a result of contact between basic charnockitic intrusions and highly aluminous metasedimentary rocks of the Highland Group. Beryllium-enriched fluids related



to the charnockitic intrusions reacted with the aluminum and silica in the Highland Group country rocks to form beryl and chrysoberyl. The contents of beryllium and fluorine and other elements in the gem sediments of Sri Lanka as compared to average rocks is elevated. In contrast, Silva and Siriwardena (1988) document the geology and origin of a rare *in situ* corundum-bearing skarn deposit. They suggest that the corundum crystals in the skarn formed by the reaction of late magmatic fluid from pegmatite intrusion with the marble which eventually enriched the fluids with aluminum, causing corundum (Al_2O_3) to precipitate. Although the corundum crystals formed were opaque light grey, Silva and Siriwardena (1988) suggest that this type of occurrence is the source rock in Sri Lanka for the gem varieties of corundum, sapphire and ruby.

Dissanayake and Rupasinghe (1992) recommend Sr/Rb ratios, thorium, uranium, fluorine, tantalum, niobium, yttrium and rare-earth elements (REE) as pathfinders for alluvial gem deposits in heavy mineral surveys. The REE content of the gem-bearing sediments of Sri Lanka compared to shales, chondrites and crustal averages is elevated.

In developing the prospectors' guide map for Sri Lanka, Dissanayake and Rupasinghe (1993) used the lithology, stream drainage density, the presence of alluvium and the heavy mineral content to define previously unknown areas of gemstone potential.

Mendis *et al.* (1993) studied the application of structural geology in the exploration for residual gem deposits. They found that corundum deposits, in particular, are generally associated with axial plane areas of tight, doubly plunging synclinoria and anticlinoria where occurrences of marble and pegmatites are observed. In general, ruby and sapphire deposits are associated with structurally deformed areas where both marble and pegmatite or marble and granite occur.

Using the theory that pegmatites, granites and other magmatic bodies are associated with gemstone formation under granulite facies conditions, Gamage *et al.* (1992) studied the Rb-Sr ratios in stream sediments to delineate areas with high gem potential. They found that areas with higher Rb-Sr ratios correspond to high gem potential. Metamorphic complexes in Sri Lanka which do not underlie gemstone deposits were found to have lower Rb-Sr ratios. They suggest that depletion of Sr is a function of the fractionation of the parental granite during granulite facies metamorphism. The depletion of Sr and the enrichment of Rb during gem mineral formation yields a characteristic geochemical signature. They suggest that Rb-Sr ratios could be an effective tool when used in conjunction with geological, structural, and mineralogical studies.

Researchers have focused on linking the Highland Complex in Sri Lanka to similar complexes in Antarctica. Papers by Shiraishi *et al.* (1994) and Kriegsman (1995) report the results of two of many studies looking at the ancient supercontinent of Gondwanaland and its subsequent break-up into smaller blocks. Sri Lanka was originally connected to what is now the northeast coast of Antarctica (Figure 3.4). It is interesting to note that some reconstructions of Gondwanaland show that equivalents of the Highland Group Complex of high-grade metamorphic rocks, host rocks of the most varied and rich alluvial gemstone deposits in the world, are exposed in Antarctica as the Lützow-Holm Complex.

3. Ruby and sapphire

MADAGASCAR

Madagascar, once joined with its sister island, Sri Lanka as part of Gondwanaland, is emerging as a new 'island of gems' with an astounding array of gemstones and crystalline mineral species. Until the 1990s, deposits of gem-quality rubies and sapphires were uncommon, but the larger-scale exploitation of sapphire deposits starting in 1994 from the Andranondambo area has catapulted Madagascar into a leading supplier of sapphires.

A flurry of scientific gemological papers speculating on the paragenesis of the sapphires were published following the discovery of the Andranondambo sapphires. One of the first papers, by Kiefert *et al.* (1996), described the host rocks for the sapphires as small pegmatitic veins intruding Precambrian pyroxenite. A comparison was made to the famous Kashmir sapphire deposit, where water-rich feldspathic pegmatites intrude marble and basic rocks. Another paper by Milisenda and Henn (1996) suggested that the sapphires formed by high-grade granulite facies metamorphism of altered marbles and calc-silicate-gneisses. A third paper (Gübelin and Peretti, 1997) puts forward evidence suggesting that the sapphires formed as a result of various metasomatic skarn formation. They base this on the mineral inclusions within sapphires, which are typical for rocks described as Th-U skarns. Metasomatic skarn formation and corundum formation was in two stages.

Madagascar is underlain by very old, highly metamorphosed granulite facies rocks very similar to the rocks on Sri Lanka; in fact the two islands were once part of the Gondwana supercontinent and affected by the same Pan-African tectonothermal event before separation. The sapphires occur primarily in small pegmatitic veins 0.05- to 0.2-m thick and 5- to 50-m long consisting mainly of calcite and plagioclase which intrude pyroxenites in the Precambrian basement rocks. Sapphires can be seen *in situ*, but have also been concentrated into gem-rich residual gravels. They are specific to one type of miarolitic pegmatite-like host rock, and there is a close association between intruding hydrous aluminum-rich pegmatite-like vein and basic host rocks (Kiefert *et al.*, 1996). The deposits are underlain by altered marbles and calc-silicate gneisses in a belt of rocks which closely resembles the Highland Complex in Sri Lanka (Milisenda and Henn, 1996).

Amazingly, sapphires are not just found associated with the granulite facies metamorphic rock; they are also associated with alkalai basalts in the northern part of the island at Ambondromifehy, which is overlain by a large field of Tertiary basaltic

Mining of ruby and sapphire, Ambondromifehy region, Madagascar

Schwarz *et al.* (2000) report that there are two companies that have set up commercial sapphire-mining operations to recover the buried sapphires. One company, MENAVI International Ramat Gan from Israel, provided interesting mining statistics. Between 1996 and 1998, over 350 kg of corundum was recovered, of which 12 to 16% was facetable. In this particular operation, an excavator and water cannon were used

to transport gem-bearing soil into jigs where the heavy minerals were separated, collected and sorted by hand.

- 3 to 5 kg of sapphires were recovered in a typical 10 hour shift;
- 17% of the rough produced was usable for heat treatment and cutting;
- after initial sorting, samples were sent outside Madagascar for heat treatment;

- samples were then re-sorted after heat treatment;
- up to 10 separate heat treatments may be necessary.

In summary, about 5 kg of rough sapphire from this mine would be expected to produce 900 carats of faceted stones.

Mining operations halted in mid-2000 due to economics.



rocks. No sapphires have been found to date *in situ* (Schwarz *et al.*, 2000) in the Ambondromifehy area. It seems that sapphire-bearing alluvial material derived from the eroded alkali basalts was deposited in voids and crevices of an older underlying limestone. Miners prefer digging around the roots of trees since the greater decomposition of the soil makes it easier to cut through the soil.

MALAWI

Gem yellow/green sapphire and rubies have been recovered from eluvial deposits in southern Malawi since the 1960s. Rankin (2002) studied the inclusions within the gem sapphires and rubies to determine the source of the corundum. Although the sapphires and ruby are found in eluvial soils associated with a weathered, serpentized, ultramafic body intruded within metasedimentary gneisses and schists, the primary source for the gems had not yet been determined. The analyses suggests that indeed, these gems formed as a result of primary/hydrothermal processes as opposed to being associated with alkali basalt magmatism.

EXPLORATION CRITERIA FOR RUBY AND SAPPHIRE DEPOSITS

Ruby and sapphire associated with alkali basalt

Look for:

- alkali basalt host rocks, especially those which are undersaturated; for example nephelinite and nepheline hawaiite
- spinel-lherzolite nodules
- heavy mineral suite of zircon, spinel, ilmenite, olivine, clinopyroxene, garnet, magnetite or feldspar
- lamprophyre dykes

Rubies and sapphires associated with marbles or aluminum-rich metasedimentary rocks

HOST ROCKS

The presence of marble, either as beds, lenses or intercalations within schist and gneiss packages is important for gem corundum formation.

In the Urals, gem corundum preferentially precipitated with magnesian calcite marble and dolomitic calcite marble as opposed to calcite marble.

METAMORPHIC GRADE

Okrusch *et al.* (1976) reported regional metamorphism under conditions reaching 600–700°C and 7 kilobars. The host rocks for the Ural Mountains (Russia) ruby deposit were regionally metamorphosed under conditions of 620–660°C and 25 kbars. In general, the regional metamorphic conditions are medium to high-grade.

3. Ruby and sapphire

ALUMINUM CONTENT

At Hunza (Pakistan), it was suggested that the marbles were derived from aluminum-rich limestones (e.g. karst environment), however, in the Urals, Kissin (1994) states that the Al_2O_3 content of the marbles is not a factor.

PEGMATITES

Although pegmatites are abundant in the Urals, Kissin (1994) reports that they did not influence corundum formation. Pegmatites are commonly found associated with other ruby deposits, for example, the Mogok Stone Tract, but the geochemical relationship between pegmatite intrusion and ruby formation is unknown.

Gem corundum associated with ultramafic rocks (Mangari, Kenya)

HOST ROCK LITHOLOGY

Chromite-bearing ultramafic bodies are the most suitable host rocks for ruby and sapphire formation.

METAMORPHIC CONTROL

Ruby crystals formed during regional upper amphibolite to granulite facies conditions.

The controls listed above define a high-grade granulite facies regional metamorphic event. Ruby crystals grew adjacent to ultramafic/pegmatite or ultramafic/paragneiss contacts during an upper amphibolite to granulite facies metamorphic event, or in some cases may have formed within the ultramafic rocks and then were emplaced during a tectonic event. Although the lithology of the host rocks next to the ultramafic bodies is not important, the absence of fluids after the peak of regional

Table 3.8. Geophysical and geochemical properties of various rocks commonly associated with gemstone deposits in southern Kenya. Modified from Simonet and Okundi (2003).

Rock type	Radioactive properties	Total count (counts per second)	Resistivity	Log (Rho)	Geochemical properties
Marble	Low	90–120	Very high	2.4	Mg-, C- rich
Ultramafic rock	Low	60–150	Very low to low	1.2–18	Mg-rich, Si-poor Cr= 1300 to 3400 ppm Ni = 800 to 1600 ppm
Quartzite	Low	100–200	High	>2	
Quartzofeldspathic gneiss	Low–high	200–500	High	>2	
Gneiss (biotite-bearing)	Low		Medium	1.8–2.4	K-, Rb-rich
Gneiss (altered)	Low–high		Low	1.5–2	K-, Rb-, Cr-rich
Gneiss (graphite-bearing)	Medium–very high	300–800	Low-medium	1.8–2.4	V-, Cr- (U)-rich
Pegmatites	Medium–high	200–600	High	>2	K-, Rb-rich
Corundum-bearing metasomatic rocks (John Saul Ruby mine)	High–very high	400–800	High	Not measured	Mg-, Cr-, REE-, P-, Th-rich



Table 3.9. Size of various types of gemstone deposits and associated structures. Data from field work of Rockland Kenya Ltd. on several gemstone deposits in Kenya and Tanzania. Modified from Simonet and Okundi (2003).

Deposit type	Width	Horizontal extension (length)	Vertical extension (depth)	Dip (°)
Ruby – metasomatic veins	0.2 to 5 m	Up to about 150 m	Up to about 70 m	Common 90
Ruby – metasomatic pockets	0.2 to 1 m	A few m	A few m	Variable
Ruby – metamorphic (amphibolites)	0.2 to 1 m	Up to several 100s m	Up to about 200 m	Variable
Ruby – metamorphic (gneisses)	0.1 to 3 m	A few m to a few 10s m		Variable
Sapphire – igneous (e.g., Dusi)	0.1 to 6 m	A few 100s m to a few km	Probably up to a few km	Common 90
Sapphire basaltic tuff (e.g., Turkana)	0.5 to a few 10s m	Several 10s km	Not applicable	0
Tsavorite – planar reef	0.1 to 1.5 m	A few 10s m to a few 100s m	A few 10s m to a few 100s m	Variable
Tsavorite – linear reef	0.1 to 2 m	Not applicable	A few 10s m to a few 100s m	Common 15 to 30
Rhodolite (with ultramafic boudins)	0.5 to 1 m	Rarely more than a few 10s m	Rarely more than a few 10s m	Variable
Rhodolite (in shear zones)	0.5 to 2 m	Up to about 100 m	Up to about 100 m ?	Common 90
Rhodolite (in graphite gneisses, Tanzanian type)	0.5 to 1 m	Up to several 100s m	Up to several 100s m	Variable
Tourmaline – metamorphic (in gneisses)	0.1 to 0.2 m	Up to a few m	Up to a few m	Variable
Tourmaline – metasomatic (in marbles)	0.1 to 3 m	Individual veins: up to a few 10s; Groups of veins: up to a few km	Individual veins: up to a few 10s m; Groups of veins: up to a few 100s m	Common close to 90
Aquamarine pegmatites	5 to 50 m	Up to a few km	Up to a few km	Common 90
Carbonated ultramafic bodies	30 to 1000 m	50 to 2500 m	Variable, linked to length	Not applicable
Ophiolitic complexes (in Kenya)	Up to a few km	Up to a few 10s km	Not applicable	Not applicable
Baragoian–Barsaloian shear zones	1 m to a few 10s km	A few 10s m to a few 100s km	A few 10s to a few 10s km	90

metamorphism prevented retrograde mineral reactions during cooling and allowed the preservation of gem corundum.

PROSPECTING METHODS

Simonet and Okundi (2003) describe various geological, geochemical and geophysical prospecting techniques used in Kenya to explore for coloured gemstone deposits. A starting point in deciding which exploration tools to use in Africa depends on the geophysical and geochemical properties of various rocks associated with gemstone deposits and they present a table with this data (Table 3.8). The ultramafic rocks associated with many ruby deposits have low apparent resistivity and low radioactivity compared with the host rocks. They provide another interesting table (Table 3.9) with the size of primary gem deposits in Africa. The size of the sampling grid is important since so many gemstone deposits are small, commonly less than a kilometre. Resistivity mapping was found to be an efficient method to locate and delineate carbonatized ultramafic bodies completely covered by soil in Kenya.

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4. EMERALD

INTRODUCTION

Emerald, the magnificent green gem variety of the mineral beryl, is the third most valuable gemstone in the world after diamond and ruby. Superior emeralds may command more than \$15,000 per carat for the best stones, although one can also buy a bag of 'emeralds' for \$5 on the Internet. The highest price ever paid for an emerald is \$1,149,000 for an exceptional 10.11-carat Colombian emerald in a ring sold at Christie's auction house in Hong Kong on May 2, 2000, which works out to an incredible \$115,000 per carat (Giuliani *et al.*, 2002). The pricing of emeralds is unique in the coloured gemstone market since a greater weight is put on the colour of the emerald rather than its clarity, brilliance (or 'sparkle') or other characteristics.

For most of recorded history, the only known emerald deposit was located in a bleak area of desert 700 km southeast of Cairo, Egypt. It is not known when the deposit was first mined; some estimates place the earliest workings at about 400 B.C. (Jennings *et al.*, 1993) or even earlier. Most of the Egyptian 'emeralds' mined in antiquity were quite pale and cloudy and nowhere near the stunning quality of their as-yet undiscovered Colombian counterparts. Despite this, the green colour of emerald had special significance for a people so linked to the life-giving green fertile valley lining the Nile River. In ancient Egypt, emeralds became a symbol for joy, desire and female fertility (Sinkankas, 1981). Jewellery featuring Egyptian emeralds was found in the ruins of Pompeii and Herculaneum. There is a historical ocular mystique about emeralds; in antiquity and through the Middle Ages in Europe there was a recurring belief of emeralds being beneficial for the eyes and eyesight.

Emerald deposits in Colombia were 're-discovered' by the Spaniards in the 16th century, although systematic mining and trading of emeralds took place by native Americans as early as 1000 A.D. throughout Colombia and neighbouring countries (Sinkankas, 1981). Word of the intense verdancy and gigantic size of the emeralds quickly spread through Europe and the Middle East where the vast majority of Colombian emeralds brought back by the Spaniards were traded to India and Persia in return for gold.

As one of the world's most sought after commodities, gemstones are often associated with violence, but the history of the Colombian emerald mines reveals an unusually bloody and riotous past. Despite their best efforts, it took the Spaniards five attempts in the sixteenth century to conquer the fierce Muzo tribe controlling the Muzo emerald mine. The secret weapon unleashed on the warriors to eventually win the battle for the Spaniards were packs of European-trained hunting dogs (Ringsrud, 1988). Slavery and poor working conditions were rampant. A cave-in at the Muzo emerald mine in 1646 buried 300 native people and Spaniard miners for over 200



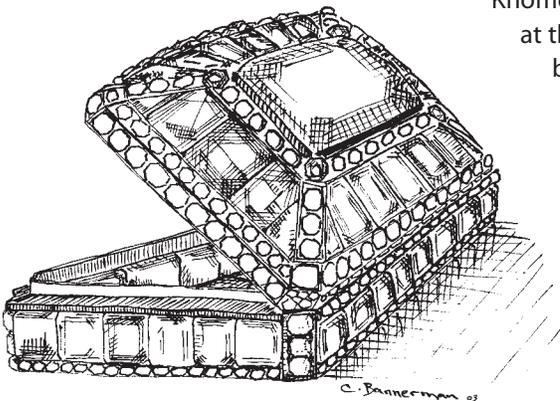
4. Emerald

years until their bones were discovered by miners in 1850 (Ringsrud, 1988). The mine manager's duties at the Chivor emerald mine in the 1920s and 1930s regularly involved shoot-outs with roving gangs of bandits (Feininger, 1970). In the 1970s, anarchy existed at the government-run mines with rampant illegal mining and selling of emeralds with little or no government control. Over 900 emerald-related murders were reported at the Muzo mine in 1973. Over the years the situation has stabilized and the major emerald workings are all underground, alleviating the tense situation where people could freely sift through the tailings from open pit workings.

The ripple effect of the Colombian emerald trade during the sixteenth and later centuries was astonishing. The most ardent gem collectors at the time were the maharajahs of India who loved all types of gems; they were ecstatic at the size and quality of emeralds coming out of Colombia. Over time, they enthusiastically accumulated thousands and thousands of emeralds from different sources; also over time the origin of these fabulous gems became murky, with many Indians insisting that the green gems were actually from an 'old mine' in either Egypt or India. Gem experts were doubtful, given the poor quality of Egyptian emeralds, although it was not out of the question that some of the emeralds in the Indian collections may have come from deposits in Pakistan, Afghanistan or Russia (Ward, 2001).

In an innovative study combining science with history, Giuliani *et al.* (2001) studied nine historic emeralds. They showed that by analysing the isotopic composition of the emerald, the country of origin and the emerald mine from which the stone originated could be determined. Jewellery from the Gallo-Roman occupation of France was historically thought to contain emeralds from Egypt or Austria, the only two known sources at the time; but in fact the emeralds were found to be from Swat, Pakistan. The treasury of the Nizam of Hyderabad, India is one of best gem collections on the planet. Many of the emeralds in this collection were thought to be from Egypt or from sources in Asia, however, three of the emeralds in this fabulous collection were found to be from Colombia and others were from Pakistan and Afghanistan. Although it does not appear that the emerald deposits of Pakistan and Afghanistan were formally mined in ancient times, people were apparently picking up the pretty stones on the surface and then trading them along the silk route. This study also shows that Indian royalty acquired Colombian emeralds earlier and with more vigour than was previously thought.

The world's best collection of emeralds today, and this is a truly subjective observation, is contained within the Crown Jewels of Iran. Remarkably, the collection remained intact through the deposition of the Shah of Iran in 1979 by Ayatollah Khomeini. Visitors to Tehran, the capital city of Iran, can now view the collection at the Crown Jewels Museum housed in an underground vault in Iran's central bank. The collection is not indigenous to Iran; it is essentially war booty from when Nadir Shah of Persia invaded India in 1739 and looted the Mogul palace. The world had its first view of the Crown Jewels in 1960 when the astonishing collection first went on display revealing trays and trays of gigantic uncut emeralds, tumbled emerald rough, Burmese rubies, thousands of pearls, spinels, be-jewelled thrones, tiaras, crowns, swords, a gold and gemstone globe and six cut diamonds larger than 100 carats. Also included within the collection is what many consider to be the most exquisite gemstone ornamental object in the world; a little box made of gigantic emeralds held together by gold studded with



diamonds. The Iran Crown Jewels collection is described fully in a wonderful book by Meen and Tushingham (1968).

Current emerald production

Due to the nature of coloured gemstone mining, it is almost impossible to quantify the production and value of emeralds, either globally or by country. Emeralds, like most coloured gemstones, are primarily produced at relatively small, low-cost operations in remote regions of developing countries.

After centuries of production, Colombia is still a prolific supplier of emeralds. In 2001, official production of emeralds was 5.5 million carats, of which 10% were kept in Columbia and 90% destined for export¹. In 2000, the official production was over 8 million carats². There is speculation that the emerald mines in Colombia are becoming depleted and there is pressure to find new reserves using geological and geochemical exploration techniques, however, Colombia still supplies an estimated 60% of emeralds in the world gem trade (Giuliani *et al.*, 2002) and probably accounts for over half the value of the estimated annual billion-dollar wholesale global emerald trade (Ward, 2001). Another South American country, Brazil, only started supplying emeralds in the mid-1960s but now produces about 10% of annual global emerald production. Brazil is a prolific producer of many gemstones including diamond, tourmaline, topaz and aquamarine, in addition to emerald. As reported in Giuliani *et al.*, 2002, the production of emeralds in Brazil in 1999 was worth \$50 million.

Fine emeralds have also been mined from Zambia, Zimbabwe, Madagascar, Nigeria, Namibia, Tanzania, South Africa, Afghanistan, Austria, Australia, Bulgaria, India and Pakistan (Figure 4.1). In Africa, Zambia used to be a prolific supplier of emeralds, but now Zimbabwe is the primary producer. Emeralds from Pakistan and Afghanistan are noted for their fine colour. China is now producing good quality matrix specimens of emerald.

Figure 4.1. World emerald occurrences. Modified from Giuliani *et al.*, 2002.



¹Torres, I.E., 2001. *The Mineral Industry of Colombia*. United States Geological Survey, International Minerals, Statistics and Information. website: www.minerals.usgs.gov/minerals/pubs/country.

²Bermúdez-Lugo, 2000

In North America, there are very few emerald localities. In 1875, emeralds were discovered near the town of Hiddenite, North Carolina, U.S.A. Emerald deposits in the Hiddenite area have been worked mainly by individual operators and production has been sporadic. Some large crystals have been discovered; one of the most recent is a massive 858-carat crystal unearthed in 1998.

One of the most promising new discoveries of emerald is the Regal Ridge emerald occurrence in Yukon Territory, Canada. This remote area is being explored by a public mining company called True North Gems³. The discovery of an emerald occurrence in Canada's remote north is welcome news for the emerald industry, with the expectation that Canadian coloured gemstone deposits will be mined in an environmentally and socially responsible manner. Some of the historical problems facing the emerald sector are due to the fact that emerald deposits are commonly located in countries with unstable political situations or socialist regimes where there is no confirmed security of mineral tenure. Typically, primitive mining techniques combined with little knowledge of exploration techniques combine to create inefficient mining practices. Smuggling tends to be rampant and as with all coloured gemstones, there is a lack of industry-wide standards for treatments and disclosure. A suspicious public drove the price of emerald downwards during the mid-1990s due to the failure of the industry to disclose 'oiling' and other commonly used techniques to improve an emerald's appearance. Despite the problems, emerald continues to be one of the most sought-after coloured gemstones in the world.

Classic references on emeralds

For a comprehensive overview of emeralds, including history, lore, properties and geology, the wonderful book *Emeralds and Other Beryls* by J. Sinkankas (1981) is recommended. The comprehensive *Emeralds of Pakistan* edited by Kazmi and Snee (1989) summarizes the results of an in-depth multi-disciplinary study of the emerald deposits of the Karakoram, Hindu Kush and Himalayas mountain ranges. The lush *Emeralds of the World* issue of extraLapis English No. 2: *The Legendary Green Beryl* (Guiliani *et al.*, 2002) is full of beautiful, stunning photographs of emeralds and emerald localities and presents the latest scientific information in an easy to read and understandable format. The book *Emeralds* by Fred Ward (2001) is an excellent introductory non-technical description of the world of emeralds. The comprehensive *Beryllium: Mineralogy, Petrology and Geochemistry*, edited by E.S. Grew (2002) and published by the Mineralogical Society of America, contains every known fact about the rare element, including the latest research on emerald deposits.

How to buy an emerald

As emphasized before, there are no set prices for coloured gemstones. A customer in a Canadian jewellery store may pay \$3,000 for a fine quality one-carat emerald or they may pay \$15,000 for a different one-carat emerald. As with most excellent quality coloured gemstones, there is almost a logarithmic scale involving price and carat weight. The poorest quality emeralds are so full of flaws that they have lost all transparency, and tend to be a milky, pale green colour. The best stones, from Colombia, are a transparent pure green to bluish green, medium-dark in tone and saturated with colour. The wholesale price of emerald is weighted more towards

³www.truenorthgems.com



colour than clarity. The reflectivity and sparkle of an emerald are not as important as with ruby or sapphire, for example. In fact, the well known step cut was specially designed to highlight the green colour of emerald and provide maximum exposure.

Customers, as always, should buy from reputable gem dealers or jewellery stores with graduate gemologists on staff. It is very difficult to separate natural emeralds from the vast array of synthetic, dyed and fake faceted emeralds seen in the gem trade and in many fine stores. As an example of one test, gemologists often use a Chelsea Filter to look at the light transmitted by an emerald. Real emeralds look red when viewed through the filter. Only a trained expert has the expertise to not only separate natural stones from synthetic emeralds, but to also advise the customer on the common practice of 'oiling' or 'fracture filling' treatments using Opticon and other fillers. Consumer confidence in the emerald trade took a downturn during the 1990s when it was determined that not all jewelers were disclosing to the customer that their emerald had been treated in some manner to improve the clarity. It is important to disclose this information to avoid the sad situation where a beautiful green emerald may turn colourless or cloudy after its owner or an uneducated jeweler routinely cleans it in an ultrasonic cleaner.

CRYSTAL CHEMISTRY

Emerald is a variety of the mineral beryl. Other gem varieties of the mineral beryl include aquamarine (blue-green), morganite (pink-peach) and heliodor (yellow). There is even a rich red beryl found in Utah, U.S.A. This rich red variety of beryl is discussed further in Chapter 8. The physical and chemical characteristics of emerald are given in Table 4.1.

The chemical formula of the mineral beryl is $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$. The beryl structure is defined by flat rings of SiO_4 tetrahedrons stacked on top of each other, like a perfectly stacked pile of donuts. The resulting hole is a hollow channel that can

Table 4.1. Physical and chemical characteristics of emerald.

Chemical formula	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$ (beryllium aluminum silicate)
Crystal system	Hexagonal crystal system: dihexagonal-dipyramidal crystal class. Beryl is a cyclosilicate mineral and has hollow channels through vertically stacked (Si_6O_{18}) rings. The structure consists of six-membered rings of Si tetrahedral lying in parallel planes. The rings are linked together both laterally and vertically by Be tetrahedra and Al octahedra, forming a three-dimensional framework that is a tectosilicate. Elements such as lithium, potassium, sodium, rubidium and cesium and even whole water molecules can fit into these spaces, generating open structural channels called corrosion tubes.
Habit	As single crystals with hexagonal six-sided prisms that can be short and stubby and long and slender with flat termination
Colour	Emerald: green
Hardness	7.5 to 8
Fracture Cleavage Parting	Indistinct basal cleavage
Specific gravity	2.67 to 2.84 g/cm ³
Pleochroism	Emerald: Strong
Fluorescence	Emerald: Longwave – inert to weak orange-red Shortwave – inert to weak orange-red

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be filled with sodium, cesium or even water molecules. As with corundum, pure beryl is colourless. The pretty colour of gem varieties of beryl — the emeralds, aquamarines andmorganites — is usually caused by the addition of trace elements, such as iron, chromium, vanadium or manganese, substituting for aluminum within the beryl mineral structure. For example, when the rather common element iron is incorporated within the beryl mineral structure, a green beryl may result, however, this colour of green is different from the rich, saturated more brilliant emerald green colour. Some people compare this common green colour to leeks. There is a very attractive green beryl of this sort mined in Finland for example, and set with gold nuggets of the region to make attractive jewellery. The valence state of iron makes a difference; for instance Fe^{2+} produces beautiful pale blue colour in beryl, the colour we call aquamarine, while Fe^{3+} produces a golden-yellow colour. When both Fe^{2+} and Fe^{3+} are present, a range of green colours between blue and yellow may result. When a small amount of chromium or less commonly, vanadium, substitute for aluminum in the emerald structure, emerald is the splendid result. This is because the elements chromium and vanadium are chromophoric; that is, due to the configuration of electrons around the atomic nucleus, chromium and vanadium selectively absorb purple, yellow and red light and transmit blue and green, whereas iron transmits yellow.

Emeralds are extremely rare. One reason is that their essential element, beryllium, has been rare since the time of the Big Bang, estimated at fifteen billion years

The difference between emerald and green beryl

Although the grass-green colour of emerald can result from the presence of chromium, vanadium or a mixture of both chromophores in the beryl structure, for years the accepted practice was to identify a gem as ‘emerald’ only if the colour was derived from chromium. ‘Emeralds’ coloured by vanadium were called the horrific name ‘green vanadian beryl,’ even though some of these crystals looked identical to emeralds mined from Colombia. In practice, this meant that prospectors would have had to carry a portable atomic absorption spectrophotometer lab to determine whether the beautiful green crystals they discovered could properly be called ‘emerald’! This restrictive definition of emerald fell by the wayside after beautiful dark green vanadium-rich emeralds were mined from Salininha, Brazil, and was finally discarded after the recognition that emeralds from Nigeria

contained a large iron component, in addition to chromium, resulting in somewhat pale crystals covering the range of colours between rich aquamarine and emerald.

Many gemological studies later, we know that the fabulous emerald colour depends on the physico-chemical conditions under which the gem precipitated and the balance of iron, vanadium and chromium in the beryl structure. Typically, iron itself cannot produce an emerald colour in a beryl, although it can contribute to the overall colour, commonly diminishing the richness of the emerald green colour by adding a greyish component. The human eye can reportedly distinguish between 10,000 shades of green (Guiliani *et al.*, 2002). At what point a green beryl can be called an emerald is subjective when looking at both colour tone and saturation. The author of this Open

File has been in that situation with the Lened green beryl/emerald occurrence in Canada’s NWT where most of the vanadium-bearing beryl crystals were undoubtedly most properly termed green beryl, and yet some crystals showed, though pale in hue, a distinct ‘emerald’ green tone and could legitimately be called ‘emerald.’ As reasoned by Dietmar Schwarz in an entire chapter (Guiliani *et al.*, 2002) devoted to the definition of an emerald, absorption spectroscopy remains the only modern, fast, non-destructive and objective method for determining the cause of colour in a green beryl or emerald. However, in a second entire chapter devoted to the definition of ‘emerald,’ a different author reminds us that there is no way to quantify the colour saturation which would separate green beryl from emerald, and in the end, this determination depends on whether one is the buyer or seller.



ago. It is unknown whether beryllium was forged at all in the primordial soup and subsequent infant galaxies and stars, since beryllium, along with its sister elements, lithium and boron, tend to be annihilated in stellar interiors as a result of fusion thermonuclear reactions (Grew, 2002). It is thought that beryllium can only form during nuclear processes that occur during rare supernova explosions. Indeed, the famous Tagish Lake meteorite, thought to contain small grains of material from the explosive death of a large star before our own solar system was formed, does contain trace amounts of beryllium (.052 ppm, Brown *et al.*, 2000), along with nanodiamonds and other exotic materials. In any case, beryllium on our planet is quite rare; it is usually a late-stage element associated with pegmatites, continental granites or certain hydrothermal fluids, sometimes related to metasomatic exchange between pegmatites and ultramafic rocks leading to the formation of biotite schists. It can also, as shown by the emerald deposits in Colombia, be leached out of black shales by hydrothermal fluids.

The element most commonly responsible for the glorious green colour of emerald is chromium, as Cr^{3+} . Chromium, as opposed to beryllium, usually precipitates early and is typically associated with ultramafic and other dark coloured igneous rocks. Chromium has a relatively large ionic radius and can readily substitute for aluminum in the beryl crystal structure, however, beryls do not usually form until late in the igneous process, and by this time all the chromium has typically already precipitated. Also, the size of the chromium and beryllium atoms are so different that a growing beryl crystal can only incorporate a limited amount of chromium without becoming too distorted or ceasing to grow. The element vanadium, as V^{3+} , can also produce a nice green colour in emerald.

Beryllium

The rare element beryllium is an essential component of several gemstones, including emerald, aquamarine,morganite, chrysoberyl and alexandrite. Aside from its contribution to the genesis of beautiful gemstones, beryllium has many important industrial applications. Although there are about 89 valid mineral species containing beryllium, only two beryllium minerals, beryl $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$ and bertrandite $\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$ are of commercial importance. Beryllium metal is very light, yet has a high melting point. When alloyed with copper and aluminum it is strong and resistant to corrosion. Beryllium metal and oxide are used extensively in the telecommunications and computer sectors, while beryllium

metal is used widely in aerospace and defense. Beryllium is used in nuclear reactors as a neutron moderator and in control rods. It was previously used as a triggering device in nuclear warheads. Beryllium remains an important strategic mineral for the United States. Before the giant bertrandite mine at Spor Mountain, Utah opened in the 1960s, the U.S. had to import most of the beryl needed to produce enough beryllium for U.S. consumption. The U.S. is now the largest producer of beryllium and beryllium products and is also the largest consumer. Other countries capable of supplying beryl ore are Madagascar, Mozambique, Rwanda, Zambia, South Africa, Asia, China, Kazakhstan, Portugal, Russia and Brazil.

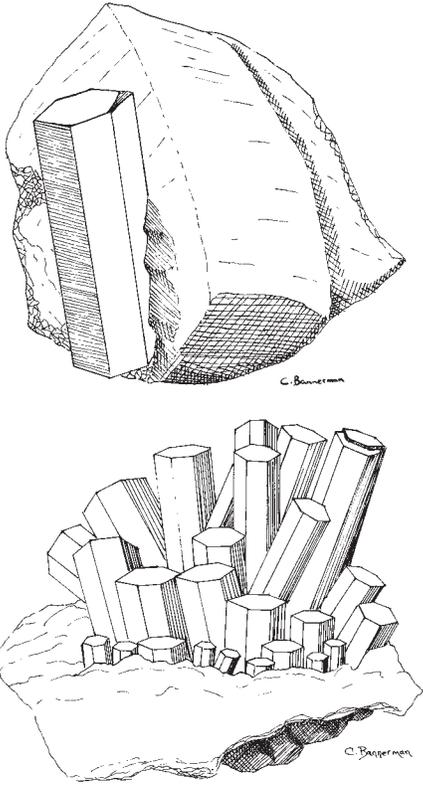
More information

Grew, E.S. (ed.), 2002. *Beryllium: Mineralogy, Petrology, and Geochemistry*. Reviews in Mineralogy and Geochemistry, Mineralogical Society of America, Washington, DC, U.S.A., vol. 50, 691 p., www.minsocam.org.

The United States Geological Survey (U.S.G.S.) produces detailed summaries of beryllium production and use on their website at <http://minerals.usgs.gov/minerals/pubs/commodity/beryllium>. The U.S.G.S. commodity specialist responsible for the beryllium sector is Larry Cunningham, available at (703) 648-4977 or lcunning@usgs.gov.

4. Emerald

Figure 4.2. Emerald crystal habit.



It is evident that, the very rare emerald variety of beryl can only form under very unusual or catastrophic geological conditions, and this is indeed the case as shown by some of the unique deposit models that have been developed to explain how and why this gem can precipitate.

PHYSICAL AND OPTICAL PROPERTIES

Emeralds typically form distinctive six-sided prisms (Figure 4.2). Only Colombia produces the interesting ‘traphiche’ emeralds. The dark six-rayed pattern is caused by carbonaceous impurities and small opaque mineral inclusions aligned along the crystallographic axes in the emerald.

Emerald shows two weak to distinct colours when viewed through a dichroscope. One colour is yellowish green and the other colour is bluish green. Pleochroic colours for the various beryl gems are listed in Table 4.2.

Fluorescence in emerald is not an important property. Some emeralds from Chivor, Colombia glow very weak red under longwave ultraviolet light. Other varieties of beryl weakly fluoresce.

FIELD IDENTIFICATION OF EMERALD

Emerald is a resistant mineral; it is hard and will not break down easily. However when it is heavily included it may not survive fluvial transport. It is not as heavy as most other gem minerals. The specific gravity of emerald is only 2.67 to 2.78, which is closer to that of quartz (2.66) than other gems such as ruby, sapphire, diamond, topaz, garnet and zircon. Emerald will tend to show up in stream sediment samples because of its resistant nature, but will not concentrate in the heavy mineral fraction.

Although its sister gems, aquamarine in particular, can form gigantic perfectly formed transparent crystals, it is very, very rare to find a larger emerald crystal. Aquamarine

Table 4.2. Pleochroic colours in beryl. From Sinkankas (1981).

Apparent colour	Dichroic colours		Intensity
Green (emerald)	Yellowish green	Bluish green	Weak to distinct
Green (other than emerald)	Colourless or slightly yellowish	Bluish green	Weak to distinct
Green	Colourless	Very pale green	Weak
Green (Maxixe type)	Green	Yellow	Distinct
Greenish blue	Colourless	Pale bluish green	Distinct
Greenish blue	Pale yellowish green	Pale bluish green	Distinct
Blue	Very pale yellow	Blue	Distinct
Blue	Colourless	Blue	Distinct to strong
Blue (Maxixe type)	Blue	Colourless	Strong
Blue (Maxixe type)	Blue	Pale pink	Strong
Yellow	Yellowish green	Pale bluish green	Very weak
Yellow	Greenish yellow	Yellow	Distinct
Yellow	Pale yellow	Lighter yellow	Weak
Pink (morganite)	Yellowish pink	Pink	Weak to distinct
Pink (morganite)	Pale pink	Pale bluish pink	Weak to distinct
Red (Utah)	Yellowish red	Purplish red	Distinct
Violet	Colourless	Violet	Distinct



and other pegmatite minerals such as tourmaline, spodumene and topaz can grow to large sizes in a relatively calm geological environment which allows for continuous crystal growth at the end stage of pegmatite crystallization. Emeralds tend to form in environments characterized by abrupt changes and mechanical stress, so crystals are smaller, more broken up and contain numerous healed or partially healed fissures.

When exploring for emeralds in the field, any bright green rough crystal should be examined. If the crystal is not emerald, it could be tourmaline, chrome diopside or tsavorite garnet, all of which are valuable gemstones. The six-sided prismatic crystal form of emerald is very diagnostic as is its flat top. A red reaction through the Chelsea Filter is an indication that the stone is emerald, however, other chromium-bearing green gems may show the same reaction.

GEOLOGY OF EMERALD DEPOSITS

For years the classic emerald model of beryllium-bearing pegmatites interacting with chromium-bearing ultramafic or mafic rocks seemed adequate, except for one glaring exception. The lack of pegmatites or granitic activity in the Colombian emerald district pointed to a completely different environment for emerald precipitation, one that did not have a magmatic component. In addition, researchers are recognizing that regional metamorphism and tectonometamorphic processes such as shear zone formation may play a significant role in certain emerald deposits. Emeralds, though exceedingly rare, can obviously form in a wider variety of geological environments than previously thought.

In the previous edition of this Open File (Walton, 1996), the classification of emerald deposits seemed self-evident; there was the Colombia model and then all others. This somewhat simplistic thinking was inspired by the wonderful detailed work presented in the classic *Emeralds of Pakistan* (Kazmi and Snee, 1989). Most of the world's emerald deposits, except for those in Colombia and Norway could be lumped into two categories: those hosted in recent suture zones, including the Pakistan and Afghanistan emerald deposits, and those hosted in old to very old suture zones which were somewhat obliterated over time and transformed into chlorite schists, greenstones and other host rocks.

Since then, a myriad of classification schemes have been presented; some of these are shown in the sidebar on the next page. For the purposes of this Open File, the "black shale" and "schist hosted" categories shall be used.

EMERALD DEPOSITS ASSOCIATED WITH BLACK SHALE

Spaniards received their first indication of an incredibly beautiful green gemstone in 1537 when Gonzalo Jiménez de Quesada, the conqueror of the interior of Colombia and the founder in 1538 of the city of Bogata, entered the valley of Guacheta and received nine emeralds as a gift from the local Indians. For a thousand years before this auspicious meeting and for centuries afterwards to the present day, the emerald deposits in Colombia have consistently produced the largest, most gloriously green emerald crystals on the planet.

Despite this prolificacy, the exact nature of the Colombian emerald deposits remained a mystery until advances in fluid inclusion and stable isotope analytical

4. Emerald

Classification schemes for emerald deposits

From *Emerald – the Most Valuable Beryl*, extraLapis English No. 2, Giuliani *et al.*, 2002

This classification scheme is based on what the authors refer to as a ‘collector’s’ approach; both practical and field oriented, based on the appearance and relationship between rock types. The criteria for classification include:

- what country rocks and host rocks are present
- what are the characteristics of their origin
- sources of beryllium, chromium and vanadium
- how and when do the emeralds crystallize?

1. Pegmatites without schist

The emerald crystals are hosted within granites and vugs within granites.

Example: Nigeria

Genesis: Be- and F-enriched magmatic fluids from granitic roof and F-enriched hydrothermal fluids interacted with the host rock to scavenge Cr and V

Interesting feature: No ultramafic or mafic schist involved, emerald is in vugs or in phlogopite alkali feldspar granites with quartz, blue topaz and aquamarine

2. Pegmatites and greisens with a phlogopite schist

Emerald crystals are in phlogopite schist at contact zone between ultramafic rocks and pegmatites

Example: Ural Mountains, also Egypt, W. Australia, Spain, Madagascar, Mozambique, Zimbabwe, Brazil

Genesis: At contact between rare element pegmatites and mafic or ultramafic rocks get metasomatism, resulting in formation of dark brown to black schist and emerald crystals, sometimes with chrysoberyl

Interesting feature: May be subject to tectonic deformation

3. Schists without pegmatites

a. Emerald in phlogopite schist

Example: Habachtal, Austria

Genesis: Same as (2.), but contact zone has been regionally metamorphosed and the emeralds are metamorphic porphyroblasts

Interesting feature: Rocks are intensely schistose, folded and split into nodules or lenses

b. Emerald in carbonate-talc-schists and quartz lenses

Emeralds are found in mélange of blue schist, green schist and ophiolites bordered by faults

Examples: Swat, Pakistan

Genesis: Recent suture zones where ophiolites interact with anatectic continental fluids

Interesting feature: Very good quality emeralds, well studied

c. Emerald in phlogopite schists and carbonate talc schists

Emerald mineralization is stratabound

Example: Santa Terezinha, Brazil

Genesis: Emeralds developed preferentially along schistose layering of phlogopite and carbonate-talc-schists from infiltration of hydrothermal fluids during tectonic events.

Interesting feature: Beryllium origin is unknown.

4. Black shales with veins and breccias

Emeralds are found in vugs with carbonates, pyrite and albite

Example: Colombia

Genesis: Brines react with organic matter in black shales, releasing Be, Cr and V into solution

Interesting feature: Need structural preparation of shales for permeation of brines

From Mineralogical Society of America Special Issue on Beryllium, Grew (ed.), 2002

Barton and Young (2002) discuss emerald deposits in terms of beryllium, geological setting, sources and depositional environment.

1. Occurrences of emerald with direct igneous component

Main example – beryllium-bearing pegmatite intruding mafic or ultramafic rocks

2. Occurrences of emerald with indirect or absent (non-magmatic) igneous component

Main example would be Colombian emerald deposits.

Another example would be those emerald deposits formed as a result of regional metamorphism (e.g., Austria).

From *Geology of Gems* by Kievlenko (2003)

1. Endogenetic

a. Pegmatite

b. Greisen

1. Ultramafic greisen

2. Carbonate-siltstones

c. Hydrothermal

1. Telethermal in ultramafic rocks

2. Telethermal in black shales and carbonate rocks

2. Exogenetic

From Groat *et al.* (2003) paper on the Regal Ridge emerald occurrence in Yukon

1. Magmatic associated

2. Tectonic hydrothermal

- found near crustal faults or shear zones

From Mineral Deposit Profiles – British Columbia Geological Survey

1. Schist Hosted Emerald Deposits (Simandl *et al.*, 1999)

2. Shale Hosted Emerald Deposits (Simandl *et al.*, 1999)

From Walton (1996)

1. Emeralds associated with bituminous black shales

2. Emeralds associated with pegmatitic or granitic rocks interacting with chromium-bearing rocks

a. Recent suture zones

b. Ancient suture zones

From Emeralds of Pakistan (Kazmi and Snee, 1989)

- Focus is on sources of beryllium and sources of chromium

- Look at the geological process that brings Be and Cr together

- Based on transport mechanism that carries Be to Cr-rich rocks

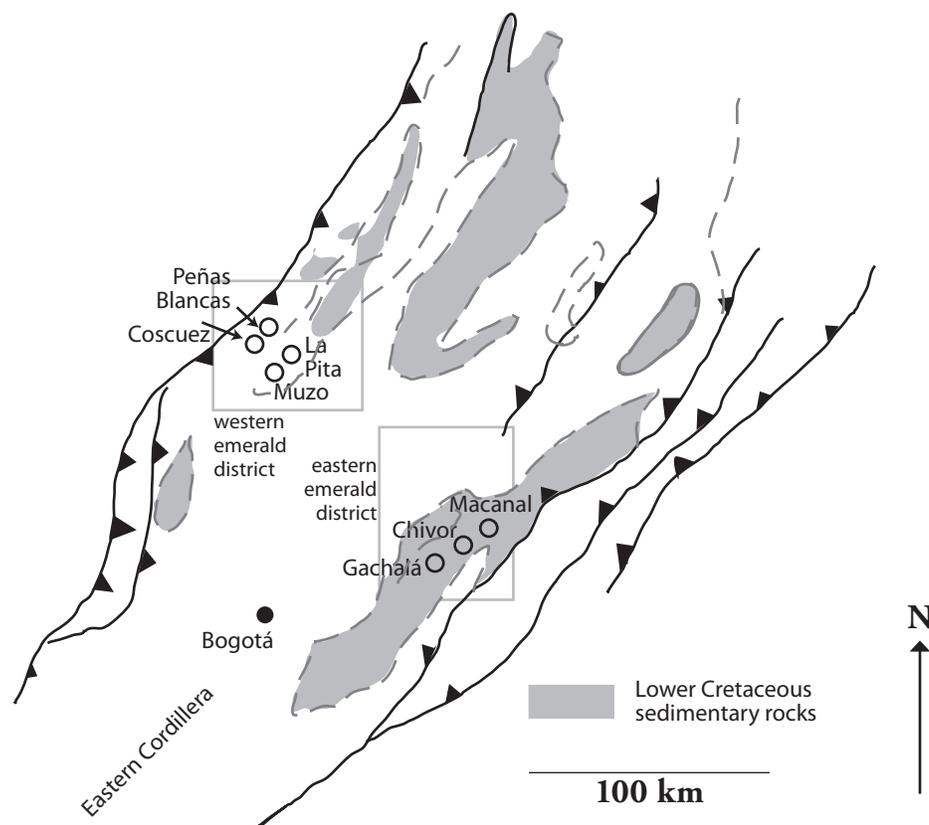


techniques enabled researchers to gain valuable scientific insights as to how and why the emeralds formed. Although there have been excellent descriptions of the local geology of the Colombian deposits (Oppenheim, 1948; Gilles, 1966), detailed mapping of the Colombian emerald districts has always been hindered by thick vegetation and steep terrain, not to mention the violent history of the area. Even though there was no evidence of igneous activity in the area, it had been presumed that the Colombian emerald deposits had formed as a result of igneous activity of some sort because of the almost ubiquitous global association noted between emeralds and pegmatites. Mention was often made of a presumed igneous presence somewhere at depth, after all, geologists reasoned, since all other emerald deposits known at the time were associated with granites and pegmatites, therefore the Colombian emerald deposits must be as well. Only within the last fifteen years have researchers developed a somewhat odd model relating emerald mineralization to a unique sedimentary environment where organic material played a key role in emerald precipitation.

LOCATION

The over 200 emerald deposits in Colombia are located in a mountain range called the Cordillera Oriental, which is the easternmost of three ranges split off from the northern end of the Andes (Figure 4.3). The Cordillera Occidental (west) and Cordillera Central are known for their gold production. About 50 to 80 km northeast of Bogota are the emerald deposits, contained within a northwest-trending belt 50 to 70 km wide and 200 km long. The Chivor, Gachalá and Macanal emerald districts are on the eastern flank of the Cordillera Oriental and formed 65 million years ago

Figure 4.3. Location and geology of the eastern and western emerald districts, Colombia. Modified from Cheilietz *et al.* (1994) and Guiliani *et al.* (2002).



(Chielletz *et al.*, 1994). Muzo, Coscuez and La Glorieta-Yacobi emerald districts are on the western flank of the Cordillera Oriental and are estimated to be 31–38 million years old (Cheilietz *et al.*, 1994).

TECTONIC SETTING

The emerald deposits are the result of a two-stage process during which shortening tectonics affected the two borders of the Eastern Cordillera and provoked decollement planes, thrusting and thrust-fault related folds in an Early Cretaceous black shale series laid down in two back-arc basins (Branquet *et al.*, 1999). The sedimentary environment at the time was that of organic material, mud, silt and limestone laid down in an anoxic lagoonal setting (Ottaway, 1991). High salinity and reducing conditions inhibited decomposition of organic matter which accumulated in places to 1 to 2%. Streams draining into the lagoon area contained beryllium-bearing sediments, derived from continental granitic and volcanic rocks. Organic material was in the form of algal mats, balls and fecal pellets. Evaporite deposits formed locally and salt diapirs intruded the sequence.

During late Miocene to Pliocene, thrusting and uplift of the Eastern Cordillera took place in response to collision between the Caribbean arc system and South America. The back arc basins were deformed during these tectonic episodes and subsequently inverted during the Cenozoic. This action uplifted the emerald deposits where they are presently exposed on the surface, a total of 6,000-m vertical displacement (Cheilietz *et al.*, 1994).

GEOLOGY OF THE EMERALD DEPOSITS

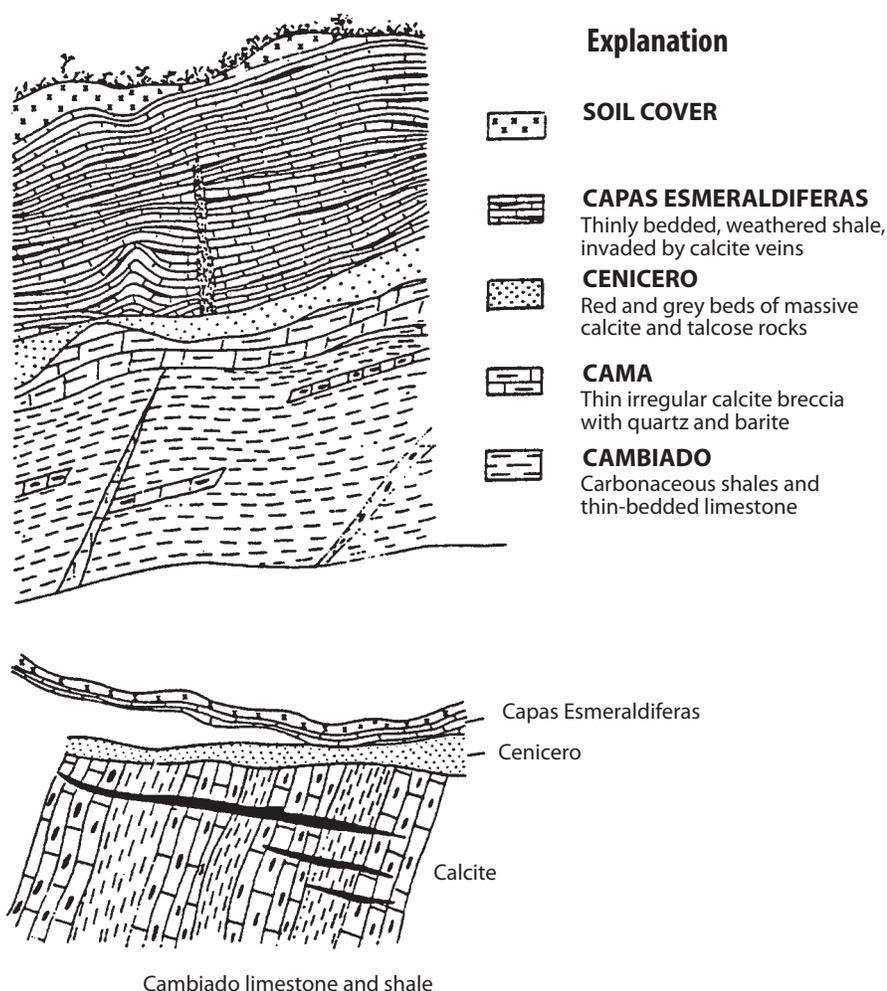
A good overview of the geology of the emerald deposit host rocks is given in Sinkankas (1981). The Colombian emerald deposits are hosted in mainly lower to middle Cretaceous sedimentary rocks including siltstones, sandstones, carbonates and black shales with some horizons of sedimentary pyrite nodules. The sedimentary sequence is cut by northeast-trending regional faults. Saline diapirs, evaporite deposits, salt and gypsum mines are spatially related to the emerald deposits. The evaporite deposits typically contain 'rute' and a high iron content as shown by extensive pyrite and hematite. Rute zones are believed to be the residue of leached evaporites and consist of brecciated gypsum, shale fragments, abundant pyrite, doubly-terminated quartz, calcite crystal fragments and fibrous calcite. A rotten egg smell is common because of coatings of native sulphur (Ottaway, 1991).

The character of the host rocks at the Muzo mine is described by Keller (1981), and Ottaway (1991). The host rocks consist of a thick sequence up to 100 m of intensely folded and fractured soft, sooty, black carbonaceous shale and minor limestone. Keller (1981) notes that the black shales are so carbon-rich that they leave smears on one's hands when handling the rocks. Ottaway (1991) noted that the black shales make a 'clinking' sound when banged together. Emeralds are found in numerous white calcite fracture-filling veins that cut the black shales.

Ottaway (1991) describes two distinct formations at Muzo; the Emerald Formation and the Cambiado. The Emerald Formation consists of moderately folded and faulted thinly bedded carbonaceous limestones and shales which weather to a yellow-grey or brownish orange colour. Emeralds are contained within discordant



Figure 4.4. Geologic cross-section of the Muzo emerald deposit, Columbia. Modified from Kazmi and Snee (1989).



calcite-albite-pyrite veins. The Cambiado Formation disconformably underlies the Emerald Formation (Figure 4.4). It consists of dark to medium-grey limestones and shales which weather bluish green to white. Emeralds do not occur in this formation, although calcite-dolomite veins do. Two more distinctive horizons occur at the Emerald Formation and Combiado contact: the Cama, which is an agglomerate of large calcite crystals cemented by hyaline quartz and the Cenicero, which is described in the next section.

At the Coscuez emerald mine, also in the Muzo district, emeralds are found in calcite veins that partly or completely fill fractures in a thick black shale sequence with minor limestone. The sedimentary sequence has been faulted and fractured. As at Muzo, there are two types of rock units: an underlying black carbonaceous shale with thinly bedded limestone overlain by black to yellowish grey shale.

At the Chivor emerald mine in the eastern emerald district, the rock units are mainly heavily folded and faulted Cretaceous shales and argillites with minor limestone and sandstone (Keller, 1981). There appears to be a 'cap' of sorts overlying the emerald-bearing rocks consisting of a poorly cemented yellowish shale. Three pyritic and

limonitic bands appear to control the vertical distribution of emeralds since most emeralds are below the bands.

There is no evidence of igneous intrusion or contact metamorphism relating to igneous bodies in the emerald-bearing areas (Beus, 1979), and studies by Ottaway (1991) and Cheilietz and Giuliani (1996) show no magmatic component to the emerald-mineralizing fluids.

MINERALOGY OF THE EMERALD DEPOSITS

Giuliani *et al.* (1995) report that in general, emeralds from the Colombian deposits occur within calcite-dolomite-pyrite veins. They list three stages of mineralization:

1. white fibrous calcite, pyrite, albite, quartz and green mica
2. white or grey rhombohedral calcite, dolomite, albite, pyrite, quartz and some kerogens
3. fluorite, parasite, REE-rich dolomite, pyrite, quartz and emerald

Abundant calcite and pyrite are common to both the first and second stages.

At the Muzo mine, calcite, dolomite, albite and pyrite are the predominant gangue minerals. Quartz and barite are uncommon. Emeralds are spatially associated with fluorite and parasite (a fluorine-bearing rare earth carbonate mineral found only at Muzo) (Ottaway, 1991). The emeralds range in size up to 10 cm. The narrow calcite veins (less than 15 cm) contain the best emeralds. Green opaque beryl called 'moralla' is also used by miners as a pathfinder mineral.

There is no visible difference in host rock between a barren area and a rich pocket of emerald crystals only a few centimetres away. Ottaway (1991) lists visual guidelines used by miners at Muzo to indicate the presence of emeralds:

1. Emeralds occur predominantly in the calcite/albite veins.
2. Indicator minerals for emerald mineralization include fluorite, parasite, apatite and opaque green beryl.
3. Intersections of two or more veins are more favourable than single veins.
4. Veins less than 15 cm are more productive.
5. A 'gritty, scraping' feeling felt when scuffing one's mining boots over the limestone means the ground is more favourable than smooth-feeling limestone.
6. The veins are rarely productive below the water table.
7. The best emeralds are found where there is abundant pyrite.

At the Muzo emerald mine, there are odd ash-grey 'Cenicero' zones within the organic black shales that are interpreted as either the product of an exothermic reaction with briny fluids (Ottaway, 1991) or stratiform tectonic polygenetic breccias composed of fragmented black shales and albitites cemented by pyrite, albite and crushed black shale (Cheilietz and Giuliani, 1996). These zones, up to 1 m wide, are composed of fine-grained crystals and calcite, dolomite, quartz, barite, pyrite and shale fragments



within a groundmass of carbonate. Native sulphur is sometimes present. Trapiche emeralds occur in the outer parts of these zones. Emeralds are confined in the distal parts of calcite-albite veins radiating from the Cenicero zones.

At the Chivor mine, emerald mineralization within a 10 by 5 km area is stratigraphically controlled by three 'iron bands' 50 m apart, which are composed of large veins and beds of partially limonitized pyrite crystals and localized hematite. As at Muzo, emerald crystals are found in calcite-albite veins. Accessory minerals include goethite, calcite, quartz, allophanite, halloysite, muscovite, fuchsite, apatite, hematite and opal. Fluorite and parasite have not been noted at Chivor.

At the Coscuez emerald mine, there are numerous calcite veins up to 35 cm thick and several metres in length. The veins are both concordant and discordant to the host black shales. The calcite mostly completely fills the fractures, but there are open cavities locally within the calcite which may contain free-standing emerald crystals. In these areas of emerald-mineralized rock, the shale and limestone are often discoloured to yellowish grey and emerald crystals are mostly found in the narrower veins. The minerals pyrite, quartz, dolomite, parasite and more rarely fluorite, apatite, albite and barite are associated with emerald at Coscuez (Ringsrud, 1986).

REGIONAL GEOCHEMICAL ALTERATION HALOS

In one of the very few published papers on exploration geochemistry for a gemstone deposit, Beus (1979) presents the results of a United Nations-sponsored geochemical survey of the streams draining emerald mines in the Muzo and Chivor areas. The goal of the study was to determine the geochemical features of an emerald-bearing region and apply the results in regional exploration programs for emerald deposits. The geochemical criteria are important, since the Cretaceous sedimentary package contains both mineralized and unmineralized zones.

The spatial distribution of areas containing emerald mineralization was linked, on a regional scale, to intersections of northeast and northwest fault zones. The tectonic blocks are 200 to 300 m in width. The black shales in the tectonic blocks which contain emerald mineralization are enriched in carbon dioxide, calcium, magnesium, manganese, sodium and depleted in potassium, silicon and aluminum (Table 4.3, Table 4.4). Beus (1979) reported that even if one could not visually see the alteration, it was simple to determine geochemically whether a tectonic block was altered.

In a separate study of the geology and geochemical expression of the Gachalá emerald district in Colombia, Escobar (1978) reports that sodium enrichment and depletion of lithium, potassium, beryllium and molybdenum in the host rocks were found to be very good indicators for locating mineralized areas.

The results of the United Nations study were tested in the Muzo area in a stream sediment sampling program, where it was found that stream sediments collected from emerald-bearing tectonic blocks had anomalously low K/Na ratios when compared with those from background areas (Table 4.5). Overall, when the results of the project were applied to regional emerald mineralization, it was found that the measure of Na alone in the stream sediments was the best indicator of the mineralized zones in the drainage basins. Several new emerald occurrences were found by U.N. teams using the results of this study. Although Na was a great pathfinder for locating mineralized blocks, the geochemical results were too

4. Emerald

Table 4.3. Chemical composition of the Villeta black shales in the Muzo area. Modified from Beus (1979).

	Outside the main tectonic zone			Within the main tectonic zone			Emerald-bearing zone inside the main tectonic zone
	1	2	3	4	5	6	
SiO ₂	69.16	76.69	69.23	38.57	44.49	27.42	30.09
Al ₂ O ₃	14.7	13.04	17.14	12.56	8.33	6.59	7.03
Fe ₂ O ₃	7.61	3.11	4.85	4.72	5.32	6.71	2.30
MnO	0.04	0.05	0.08	0.17	0.15	0.20	0.19
MgO	0.28	0.12	0.13	4.02	4.42	7.52	4.08
CaO	0.19	0.29	0.40	15.08	14.17	22.06	26.29
Na ₂ O	0.83	0.88	1.12	5.04	3.37	2.39	3.58
K ₂ O	1.07	1.12	1.24	0.67	0.24	0.19	0.31
TiO ₂	0.87	1.15	0.96	0.43	0.52	0.22	0.29
F	0.37	0.36	0.41	0.46	0.56	0.32	0.65
H ₂ O-	trace	trace	0.11	0.38	trace	0.15	0.14
H ₂ O ⁺	3.18	2.48	3.74	1.35	1.56	1.74	0.88
P ₂ O ₅	0.21	0.09	0.17	0.30	0.31	0.29	0.44
CO ₂	1.72	not detected	not detected	11.63	13.62	21.08	22.18
S	0.09	0.10	0.11	1.43	3.42	3.29	0.66
SO ₃	not detected	not detected	not detected	1.22	0.54	0.43	-
Loss on ignition	0.43	0.81	1.06	2.06	1.54	1.60	1.71
Subtotal	100.75	100.29	100.74	100.69	102.56	102.20	100.82
-O=F ₂	-0.20	-0.15	-0.18	-0.19	-0.29	-0.14	-0.28
-O=S	-0.05	-0.05	-0.05	-0.71	-1.71	-1.65	-0.33
Total	100.50	100.09	100.51	99.79	100.56	100.41	100.21
Na ₂ O/K ₂ O	0.78	0.79	0.90	7.52	14.0	12.6	11.5

Table 4.4. Average values of some indicator elements in stream sediments in the Muzo area. Modified from Beus (1979).

Location	Na	K	K/Na	Li	Mo	Pb	Be
Background (outside an influence of the mineralized tectonic zones)	0.25	1.35	4.6	95	50	26	4.1
Rio Itoco tributaries which drain the main mineralized zone	2.9	1.07	0.30	31.4	18	16	2.8
Threshold value (break in cumulative curve)*	0.5	-	2.6	35	-	2	-

*Established and applied by the U.N. Mineral Project



Table 4.5. Potassium and sodium distribution in the black shales (%). Modified from Beus (1979).

	(a)				(b)			
	Outside the mineralized tectonic zones (background)				Within the mineralized tectonic zones		Concentration ratio (CR) b/a	
	Na	K		Na	K	Na	K	
	S	X	S	X	X			
Muzo	0.8	0.27	3.2	0.74	4.1	0.95	5.26	0.30
Gachalá	0.6	0.25	3.9	0.89	2.9	1.18	4.76	0.30
X = arithmetical mean; S=standard deviation								
Muzo: 38 samples outside and 50 samples within the mineralized tectonic zones								
Gachalá: 16 and 65 samples, respectively								

nebulous to narrow it down further within those blocks to find the actual emeralds — a difficult task in dense jungle terrains. Ringsrud (1986) reports that Colombian geologists were analysing for sodium, lithium and lead in soil samples collected from altered tectonic blocks to delineate emerald mineralization.

Cheilletz *et al.* (1994) report that the background beryllium content in the black shales away from the leached mineralized areas ranges between 3.4 to 4 ppm. Values of beryllium in the leached areas range from 0.1 to 3.0 ppm (Beus, 1979).

PARAGENESIS OF THE EMERALD DEPOSITS

Researchers now believe that the Colombian emerald deposits formed as a result of thermochemical reduction of mesothermal brines by organic-rich black shales. The recognition that brine fluids could leach the required elements from the black shale in the absence of an igneous intrusion or pegmatite was proposed as far back as 1981 (Escobar and Mariano, 1981). This model has evolved over the years and refined most recently by Giuliani *et al.* (2000) who published detailed chemical and stable isotope analyses in support of the model. There is no evidence of a magmatic component and in fact, the current model bears most resemblance to that of sediment-hosted stratabound and strataform base metal deposits. Giuliani *et al.* (1995) note that the brine fluids responsible for emerald formation are remarkably similar to oil-field brines and brines involved in the formation of Mississippi Valley-type lead-zinc deposits.

The black shale sequences that host the emerald deposits in Colombia were derived from shallow basins, indicated by evaporite sequences and salt beds interbedded with the black shales. In the back arc basins, the black shale sequence was buried to depths of at least 7 km (Giuliani *et al.*, 2000) and reached temperatures of at least 250°C.

A compressional tectonic event during the Oligocene and an extensional event during the Late Cretaceous opened decollement planes between a thick sequence of Early Cretaceous black shales and underlying more competent units formed on both sides of the Eastern Cordillera. Hydrothermal fluids formed at depth from meteoric and formational water interacting with salt beds. Banks *et al.* (2000) studied the contents of fluid inclusions and suggested that there were two types of parent brines associated with emerald deposition: a sodium-rich basinal brine and another fluid with less sodium that was generated by reaction of formation water with halite (Giuliani *et al.*, 2000).

Colombian emerald colour

Colombian crystals are valued for their rich, saturated green colour which is considered superior to the colour of other emeralds, most of which come from pegmatite-schist deposits. Much like in the Burmese rubies described in Chapter Three, the presence of chromium in the beryl structure causes a red fluorescence that enhances the luminosity of the green colour. If iron is present in the emerald crystal, this fortunate effect is suppressed. In the Colombian deposits, iron is taken out of the system by the coeval precipitation of abundant pyrite. Miners at Muzo report that better quality emeralds are found in areas of abundant pyrite (Ottaway, 1991).

The briny fluids were highly alkaline, up to 40 wt % NaCl and migrated upwards through the sedimentary sequence along the decollement thrust planes and then interacted with black shales. During sodium and calcium metasomatism, the major elements silicon, aluminum, potassium, titanium, magnesium and phosphorus in addition to trace (barium, beryllium, chromium, vanadium, carbon, boron and uranium) and rare-earth elements were leached from the enclosing black shale; this stage was accompanied by development of a vein system filled by fibrous calcite, bitumen and pyrite. The next stage is characterized by extensional vein sets and hydraulic breccia development filled by muscovite, albite, rhombohedral calcite and dolomite, pyrite, bitumen, and by the precipitation in drusy cavities of fluorite, apatite, parasite, dolomite, emerald and quartz.

Temperatures of precipitation are generally between 250 and 400°C; Ottaway (1991) gives a temperature of 325°C for emerald precipitation at Muzo and Cheilletz *et al.* (1994) calculate temperatures between 290 to 360°C for Coscuez and Quipama-Muzo.

OTHER EMERALD DEPOSITS ASSOCIATED WITH BRINY FLUIDS

There are other emerald deposits in the world that show evidence of brine fluid involvement, whether the brines are of evaporitic or metamorphic origin:

1. Uinta Mountains in northeastern Utah (Keith *et al.*, 1997, 2002): A single emerald crystal is reported from carbonate-rich veins that cut black shales.
2. Brumado, Bahia, Brazil: Emerald and aquamarine are found in magnesite deposits. Associated minerals are uvite, dolomite and topaz in quartz veins. Magnesite is commonly of basinal brine origin. There are no associated igneous rocks in the area.
3. Mingora and other emerald deposits of Swat, Pakistan (and perhaps some of the Afghanistan emerald deposits): Beryl-carbonate-quartz veins cut ultramafic-bearing metamorphic rocks. As reported in Kazmi *et al.* (1989), fluid inclusion analysis indicates salinities of up to 20% NaCl, suggesting a possible evaporitic component and/or mixing with other fluids.

Franz and Morteani (2002) report that the Afghanistan emerald deposits of Panjshir are very similar to those in Colombia, in terms of low iron content and saturation of chromium and vanadium. They suggest that leaching of a metaevaporite sequence generated a briny fluid which caused strong sodium-potassium-boron metasomatism. The resulting rock is white. The metamorphic grade of the host rocks is higher than at the Colombian emerald deposits. In addition, emerald precipitation in Afghanistan was probably caused by the tectonism that preceded uplift of the Himalayan orogen.

4. Gravelotte, South Africa: Researchers Nwe and Morteani (1993) suggest that brines of metamorphic origin were associated with the late-stage emerald precipitation.



OTHER EMERALD DEPOSITS ASSOCIATED WITH BLACK SHALES

An emerald deposit is associated with organic black shales at Edsvoll, Norway. The emeralds are within a pegmatitic quartz-feldspar-fluorite-topaz vein intruded into Cambrian-age aluminum-bearing bituminous shales (Kazmi and Snee, 1989).

At the Lened occurrence in Northwest Territories, Canada, emeralds are in quartz-calcite veins cutting skarn within a metalliferous black shale (Marshall *et al.*, 2003). This deposit is described in more detail in a later section.

It is interesting for Canadian geologists familiar with the Pine Point lead-zinc deposit in the Northwest Territories to note that the chemistry of the emerald fluids in Colombia is very similar to that observed in oil-field brines and in Mississippi Valley-type deposits (Giuliani *et al.*, 1995). Indeed, Ottaway (1991) proposes the Mississippi Valley-type Pine Point deposit in the NWT as a lower temperature analog to the higher temperature Colombian emerald deposits.

SCHIST-HOSTED EMERALD DEPOSITS

The 'classic' host rock for emerald deposits is a biotite or phlogopite schist developed in the metasomatic contact zone between beryllium-bearing pegmatites and chromium- or vanadium-rich rocks. The contact boundary can be tectonic or intrusive.

An excellent summary of characteristics of schist-hosted emerald deposits is given by Simandl *et al.* (1999a). The list of synonyms for 'schist-hosted' is especially informative and many are derived from Russian scientific literature; suture-zone-related, pegmatite-related schist-hosted, exometamorphic, exometasomatic, biotite-schist-type, desilicated pegmatite-related and glimmerite-hosted have all been used. Most emerald deposits in association or separate from chrysoberyl and phenakite can be put into this category. Many are situated in or near to suture zones. Some deposits, such as those in Pakistan, are situated in a relatively 'recent' suture zone (Fig. 4.5). Others may be related to 'ancient' suture zones in granite/greenstone terrains, where there is a link between emerald mineralization, biotite schist and pegmatites. Emerald deposits of this type are hosted in much older tectonic terrains which, in some cases, exhibit the result of over one billion years of rifting, collision, deformation and metamorphism. These could be very, very old suture zones, but the exact geological relationships are uncertain.

There are, as always, exceptions to this lumping together of emerald deposits with schistose rocks. Some emerald deposits, such as those in Nigeria, are hosted within pegmatites and, closer to home, the Red Mountain emerald locality near Stewart, British Columbia, is in quartz-calcite veins cutting volcanic andesite.

Typically the host rocks for schist-hosted emerald deposits are metamorphosed serpentinitized peridotites, amphibolites, greenstones or other mafic to ultramafic units. The metamorphic grade is upper greenschist to amphibolite facies, rarely granulite facies. The beryllium-bearing rock is typically granitic pegmatites or aplites or beryllium-rich metasedimentary and metavolcanic rocks. The contact between the beryllium-bearing rock and chromium-bearing rock can be tectonic or intrusive.

A schematic model for pegmatite/schist-hosted emerald deposits is given in Figure 4.6.

The metasomatic contact zone between the two rock types is often represented by biotite schist or phlogopite schist. These areas are called 'blackwall zones' and can be several metres thick. Phenakite (Be_2SiO_4) is commonly formed before emerald. Emeralds typically grow within veins and in biotite-rich selvages around the veins. Common accessory minerals are K-feldspar, tourmaline, fluorite, apatite, molybdenite and scheelite. Pegmatite dykes are variably metasomatically modified ('desilicated'), typically expressed by lack of K-feldspar, abundance of plagioclase and diminished amounts of quartz. Where there has been intense chemical exchange between the host rock and incoming fluids, it may be impossible to tell whether the fluids are magmatic or hydrothermal, and how much of a role regional tectonometamorphic events had on emerald deposition. Aquamarine and common beryl may be present in protected interiors of pegmatites and veins, whereas emerald is most common in enveloping zones of metasomatic biotite-plagioclase-quartz.

In peridotite- or serpentinite-associated emerald deposits, the outer metasomatic contact zones may consist of chlorite, talc, actinolite plus other amphiboles. Chrysoberyl and alexandrite, both beryllium-bearing gemstones, may be embedded with emeralds in the phlogopite schist.

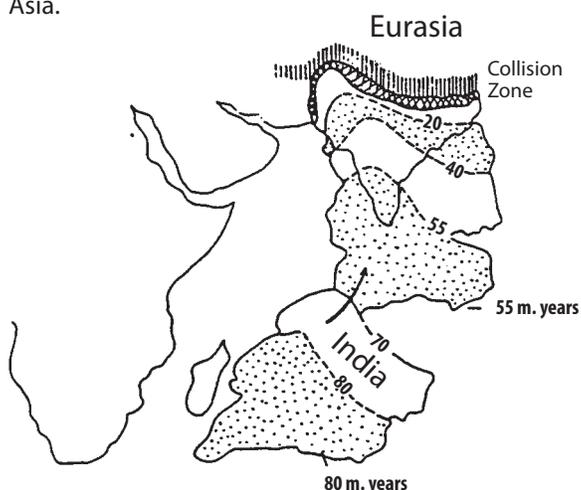
Mafic rocks commonly only develop a biotite-rich envelope between the central veins or dykes and the host rock.

Excellent descriptions of schist-hosted emerald deposits and occurrences are given in Sinkankas (1981), Kazmi and Snee (1989), Giuliani *et al.* (2002), Černý (2002), Franz and Morteani (2002), and Barton and Young (2002). The following sections rely on the wonderful detail provided by the above-mentioned and other authors.

The emerald deposits of Pakistan and Afghanistan

The remote border regions of Pakistan and Afghanistan are marked by the imposing Karakoram, Hindu Kush, Pamirs and Himalayan mountain ranges. This is one of the most tectonically active areas in the world, where entire continents have collided and pushed up the tallest mountains on the planet. The catastrophic and extreme geological conditions made it possible for the elements beryllium and chromium to interact and produce what are some of world's best emeralds.

Figure 4.7. India colliding with Asia.



PAKISTAN

Most of the following information on the emerald deposits of Pakistan is taken from the landmark book, *Emeralds of Pakistan*, edited by Kazmi and Snee (1989).

Tectonic setting

An overview of the geological history and geology of Pakistan is provided by Kazmi (1989). When the Indian continent separated from Gondwanaland and started its journey towards the Eurasian continent, the two continental masses were separated by the Tethys Ocean (Figure 4.7). Smaller fragmented blocks of Gondwanaland had made the journey earlier and had collided with Eurasia in Early to Middle Jurassic time to form parts of present day Afghanistan, Iran, and other Eurasian areas. India collided with Eurasia about 40 million

years ago. The spectacular Himalayan mountain range was thrust upwards and the Himalayan orogenic belt was formed. The Tethys Ocean floor was obducted onto the Indian block and subsequently overridden by Kohistan island arc rocks. Metasomatic alteration at depths up to 12 km transformed the ocean-floor rocks to a talc-dolomite mélange. The deep burial of the frontal part of the Indian plate also generated anatexitic granites and late pneumatolytic and hydrothermal fluids.

Geology

The geological setting of emerald deposits in Pakistan is described in detail by Lawrence *et al.* (1989). Pakistan is host to several other types of gemstone deposits, most notably ruby, spectacular pink topaz and aquamarine, particularly in its northern area, which has proven to be particularly favourable for providing the proper physico-chemical conditions for gemstone formation. The area is one of the most rugged and dangerous places in the world, both geographically and politically.

All the emerald deposits in Pakistan, except for one, are contained within the Mingora ophiolitic mélange of the Indus suture zone. The exception is the Khaltaro deposit, which is outside the suture zone area, but is closely associated with ultramafic rocks.

The Indus suture zone is a complex zone of diverse rock assemblages including tectonic blocks of ophiolites, blueschists, greenschists, and metavolcanic and metasedimentary rocks in a matrix of sheared and variously metamorphosed fine-grained sedimentary rocks and/or serpentinite.

Emerald mineralization

Descriptions of emerald mineralization are given by Kazmi *et al.* (1989). The best and largest emerald deposit in Pakistan is the only urban gem deposit in the world. The Mingora emerald deposit spreads out over 180 acres on the northern edge of the city of Mingora, located in the lower hills southwest of the Hindu Kush Mountains. At Mingora, emeralds are located within a talc-dolomitic mélange containing tectonized clasts of serpentinite, dolomite, greenschist and graphitic schist up to hundreds of metres in size set in a fine- to coarse-grained ductilely deformed matrix.

Kazmi *et al.* (1989) summarize four modes of emerald occurrence at Mingora:

1. Associated with fuchsite and tourmaline in faults and fractures;
2. Fracture fillings;
3. Associated with fuchsite and tourmaline in quartz stockwork;
4. In talcose rock surrounding tension gashes in talc-chlorite-dolomite schist.

The second largest emerald deposit in Pakistan, the Gujarkili emerald deposit was discovered in 1981 as a result of extensive geological exploration by the Gemstone Corporation of Pakistan. Colour photographs of the deposit in Kazmi *et al.* (1989) show it to be in a picturesque valley. The deposit is in a small triangular outcrop of ophiolitic mélange which is barely 1.5 hectares across. Emeralds occur in a brown to yellowish green, medium-grained talc-chlorite schist with associated muscovite, fuchsite, siderite, magnesite and calcite.



The Indus suture zone in the Kot-Pranghar area consists of randomly oriented blocks of greenstone, greenschist, metavolcanic rocks, serpentinite, pyroxenite, periodotite and talc-chlorite-dolomite schist. This area is host to several emerald deposits.

As mentioned earlier, the Khaltaro emerald deposit differs from the other deposits because the emeralds occur within pegmatite dykes located near a major suture zone. The dykes intrude medium- to coarse-grained amphibolite-grade biotite schist and gneiss with marble, calc-silicate gneiss and subordinate amphibolite. The deposit was discovered in 1985 by the Gemstone Corporation of Pakistan while exploring for gem pegmatites in the Haramosh region. Kazmi *et al.* (1989) stress that the tectonic setting of this deposit is one of the most extraordinary in the world. It is situated within extremely rugged and complex terrain. The uplifted area is at the junction of three major suture zones: the Indus, Tsangpo and Karakoram suture zones. In this tortuous terrain are not only emerald deposits, but also deposits of tourmaline, topaz, aquamarine and garnet.

Genesis of the emerald deposits in Pakistan

According to Lawrence *et al.* (1989), the beryllium for emerald formation was provided by early Miocene anatectic granites. The chromium to give emerald its colour was provided by ophiolitic suture zone rocks.

During the collision of the Indian plate against Eurasia, the ocean floor ophiolitic rocks were buried to an estimated depth of 12 km and metasomatic alteration transformed the once ocean-floor volcanic rocks to a talc-dolomite mélangé. The deep burial of the frontal part of the Indian plate also generated anatectic granites and late pneumatolytic and hydrothermal fluids. These fluids, the end result of such a catastrophic joining of plates, moved through overlying rocks and along shear zones. Where this fluid, containing beryllium, aluminum and silicon from the continental anatectic granites, penetrated the soft, permeable chromium talc-dolomite mélangés which were once the ocean floor rocks of the Tethys ocean, emerald precipitation took place.

An important criterion for the percolation of the beryllium-bearing fluids was the metasomatism of hard ultramafic ocean floor rock to soft, porous and permeable talc-dolomite mélangé matrix. It should also be noted that although the mélangé rock was a suitable host, emerald precipitation could not take place until beryllium was chemically transported to the chromium-bearing rocks (Lawrence *et al.*, 1989).

AFGHANISTAN

The Jurassic collision between Asia and the microcontinent, known as Cimmeria, spawned not just a geologically complex, but also, an ultimately politically turbulent area now called Afghanistan. Afghanistan is rich in gemstones; a remote deposit of the gorgeous blue ornamental stone lapis lazuli has been continually mined for over 5,000 years. Afghanistan is also known to produce tourmaline, aquamarine, ruby, topaz, kunzite and spinel. In the 1970s, the gem world became aware that velvety green emerald crystals rivaling those mined from Colombia were being mined from the Panjshir Valley in Afghanistan, although it is likely that these green crystals had been traded on the 'Silk Road' many years ago (Giuliani *et al.*, 2001). The

comprehensive book *Gemstones of Afghanistan* by Bowersox and Chamberlain (1995) provides excellent descriptions of the gem mines and occurrences in Afghanistan.

Most of the gem deposits in Pakistan and Afghanistan, including the emerald deposits of the Panjshir Valley, are situated in the treacherous and extremely rugged mountain terrain close to the Pakistan border. The landmark paper *Emeralds of the Panjshir Valley, Afghanistan* by Bowersox *et al.* (1991) described for the first time in detail the emerald mines of this remote area. It is with a sense of disorienting horror in rereading this paper that one realizes the western world is familiar with the ominous geographical place names (Hindu Kush Mountains, Kabul) and even some of the people. Bowersox, the lead author of the article and a gemstone dealer, began traveling to Afghanistan in search of gemstones in 1972 at the time of the ill-fated Soviet occupation of Afghanistan. He struck a personal friendship with Commander Ahmad Shah Massoud who led the emerald mining efforts in the Panjshir area. Proceeds from the emerald mining helped finance Massoud's Northern Alliance army efforts against the Soviet occupying forces and then later against the Taliban, until his assassination on September 10, 2001. Bowersox reports⁴ that the emerald mines are now under the political control of one of the members of the Northern Alliance. Individual mines or pits are owned and operated by teams of five to seven men.

A good description of the deposit and mining methods of the Panjshir emerald deposits are given in Bowersox (1989). The words 'Occupational Health and Safety' do not exist in this part of the world, as shown by some spectacular examples of unsafe mining methods described in this paper. The various groups of miners do not monitor the amount of or timing of explosives, which seem to go off at random. No one wears hardhats, and carbon monoxide poisoning inside the narrow tunnels is common. There is no formal record keeping of property, so disputes over mining rights between various groups are complicated and in fact, Mr. Massoud had acted as a Mining Recorder of sorts for the area in sorting out emerald property disputes and shaft ownerships. Agreements were made on sharing the proceeds and paying taxes. To complicate matters, the area around the emerald deposits has to be demarcated before expansion of the mining activities and more sophisticated exploration can take place. Bowersox estimated that the country's emerald production could increase from a current production of \$2 million to \$150 million by 2006, using modern exploration techniques. In total, the country's entire gemstone production could be worth between \$300 and \$400 million. Another setback is that government records detailing the coordinates and particulars of Afghanistan's gemstone deposits were destroyed in a rocket attack on the Ministry of Mines in 1995. Traditionally, Peshawar in the North West Frontier Province of Pakistan remains the traditional destination for Afghani gem material. After Afghanistan stabilizes, the expectation is that Kabul or one of the other Afghan cities can evolve into a gem buying and cutting centre.

The Panjshir emerald deposits are in a sequence of upper greenschist facies metasedimentary rocks including schists, quartzite and marble of probably Paleozoic to Mesozoic age. The package has been intruded by sills and dykes of gabbro, diorite and quartz porphyry. Emerald crystals are contained within small quartz-ankerite and dolomite veinlets and silicified shear zones that contain phlogopite, albite, tourmaline and pyrite. Some of the emeralds are in veinlets that cut metasomatically altered

⁴www.gems-afghan.com



gabbro and meta-dolomite, marble, quartz-biotite schist and quartz-porphyry. The emerald crystals are commonly intergrown with quartz, ankerite or calcite. Kazmi and Snee (1989) suggested that the emeralds from the Panjshir Valley are suture related. Fluid inclusion studies (Vapnik and Moroz, 2001) indicate that the overall salinity of the emerald-forming fluids is surprisingly high; perhaps 80 to 90%, with temperatures of about 400°C. Franz and Morteani (2002) suggest a metaevaporite component to the emerald formation.

Brazil

As with most gemstone occurrences, the emerald deposits of Brazil were found accidentally, one by one, starting in 1963 when the Salininha deposit was discovered. Significant emerald deposits were discovered in the Itabira-Nova era region after a railroad built in 1978 opened up the area. The highly productive Santa Terezinha deposit was found in the late 1970s when a farm road was opened by a bulldozer and local children collected 'green stones' to throw at birds. A gem dealer identified the stones as emeralds in 1981. In time-honoured Brazilian fashion, a tremendous staking rush resulted in the usual chaos, largely due to the small 4 m by 4 m legal size of the mining claims. Brazil has a history of riotous and violent staking rushes; the most recent involved the fantastic find of alexandrite described in Chapter 6. Amazingly, in Brazil, there are still emerald deposits being discovered, even in areas which have been heavily prospected.

During the 1980s, Brazil became a significant emerald producer and by the end of the century was exporting \$50 million annually in emeralds. Researchers have just begun to deconstruct the complex geology of the deposits. Detailed studies have been carried out on individual deposits and a landmark paper on the origin of emerald deposits of Brazil was published by Giuliani *et al.* (1990). Since then, more detailed work on the complex structure, tectonic history and chemistry of individual deposits has led to an increased understanding of the complexity of the Brazilian emerald deposits and the nature of the emerald mineralizing fluids.

Giuliani *et al.* (1990) examined the geology of Brazilian emerald deposits and were able to divide the deposits into three type:

Type I: Mafic-ultramafic host rocks, granitic proximal intrusive rocks and related pegmatites.

Type II: Emeralds hosted in biotite schists characterized by absence of pegmatitic veins and developed in ductile shear zones.

Type III: Emerald deposits related to the presence of aquamarine, beryl and/or niobium-tantalum-cassiterite-bearing pegmatites of uncertain origin.

The geology, mineralogy and chronology of the different types of deposits are given in Table 4.6.

The host rocks are typically Archean basement rocks (tonalitic gneisses, migmatites, diatexites or granite gneiss), Proterozoic volcano-sedimentary sequences (intercalated iron formation, felsic and mafic-ultramafic horizons, cherts and quartzites) and granites or their magmatic equivalents. The Proterozoic sequences sometimes form greenstone belts, imbricated structures or are intensely folded and deformed.

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Table 4.6. Geology, mineralogy and chronology of the three main types of emerald deposits of Brazil.
BA – Bahia State, GO – Goiás State, MG – Minas Gerais State, CE – Ceara State. Modified from Giuliani *et al.* (1990).

	Deposits/ occurrences	Type I		Type II	Type III			
		¹ Carnaíba BA	Pirenópolis GO	Santa Terezinha de Goiás GO	Itabira MG	¹ Tauá CE		
		² Socotó BA				² Coqui		
Volcano-sedimentary series (V.S.S.)	Nature	Serpentinites	Talc-chlorite schist	+Carbonate-talc schist +Chlorite schist +Quartz-sericite schist	-Biotite schist -Talc-chlorite schist	-Amphibolite -Biotite schist -Tremolite schist -Augen gneiss		
	Metamorphism	Greenschist facies	Greenschist facies	Greenschist facies	Greenschist facies	Amphibolite facies		
	Age	Lower Proterozoic	Middle Proterozoic	Lower Proterozoic (?)	Lower Proterozoic	Upper Proterozoic		
	Name	V.S.S. of Serra da Jacobina	Araxá Series	V.S.S. of Santa Terezinha	Metasedimentary rocks of Minas Supergroup	¹ Independência complex ² Caico and Nordeste complexes		
Intrusive rocks	Nature	Pegmatitic veins	Pegmatitic veins	–	Pegmatitic veins	Pegmatitic veins		
	Typical mineral association	Beryl (molybdenite)	Garnet	–	Beryl Aquamarine	Colombite Tantalite Beryl ² Aquamarine ² Cassiterite		
	Related	¹ Carnaíba ² Camp formoso	Quebra Rabicho	–				
	Age	Transamazonic 1.9 Ga	Pre-Uruçuano (?)	–	Probably Brazilian 0.5 to 0.7 Ga	¹ Brazilian? ² Brazilian 0.5 to 0.7 Ga		
Emerald and metasomatic rocks	Nature	Phlogopite	Phlogopite	+Phlogopite +Phlogopite-talc-carbonate schist +Phlogopite-carbonate schist	Phlogopite	Phlogopite		
	Typical mineral association	Molybdenite ¹ Alexandrite Scheelite Apatite Tourmaline ² Phenakite	Tourmaline Apatite (cassiterite)	Pyrite Chromite (Mg, Al) Carbonate (Mg)	Alexandrite Chrysoberyl	Apatite ¹ Bismutite		
	Emerald composition	1	2			1	2	
	Cr ₂ O ₃	0.28	0.29	0.08	0.57	0.31	0.19	0.04
	FeO	0.62	0.75	0.61	1.15	0.73	1.05	0.04
	MgO	1.51	2.05	2.73	2.84	1.48	2.48	0.66
	Na ₂ O	1.29	1.09	1.77	1.77	0.92	1.84	0.59



A number of conclusions were presented (Giuliani *et al.*, 1990) regarding the geology and genesis of the Brazilian deposits:

- Biotite schist is the host rock for all the deposits.
- For type I emerald deposits, molybdenum and, to a lesser degree, tungsten are good pathfinders.
- In Type II emerald deposits, intense pyritization accompanied emerald formation. This is also a good geological setting for gold.
- Type III emerald deposits are associated with aquamarine, tin and niobium-tantalum.

GENESIS OF THE BRAZILIAN DEPOSITS

In general, Giuliani *et al.* (1990) report that emerald mineralization in the biotite schists of Brazil results from K-metasomatism of serpentinites, talc schists, or tremolitic schists from a volcano-sedimentary sequence usually metamorphosed in the greenschist facies. Emeralds form when acid beryllium-bearing fluids, also enriched in fluorine, chlorine, potassium and aluminum, penetrate mafic or ultramafic rocks rich in chromium. Emerald precipitation took place at temperatures greater than 500 degrees, as indicated by the presence of associated pathfinder minerals scheelite and molybdenite (Schwarz and Eidt, 1989).

Age dating of mineral and rock samples from the emerald deposits at Capoeirana and Belmont was published by Preinfalk *et al.* (2002). The age dating has enabled researchers to place emerald mineralization in the context of tectonometamorphic events. The following sequence of events is suggested:

1. High-grade metamorphism at 1.9 billion years.
2. Synmetamorphic injection of pegmatite veins at 1.9 billion years.
3. Synmetamorphic intrusion of beryllium-rich anatectic pegmatites into ultrabasic rocks.
4. Synmetamorphic crystallization of emerald by reaction of beryllium-rich anatectic pegmatites with ultrabasic rocks.
5. Metasomatic alteration of original pegmatitic feldspar into plagioclase of albitic to oligoclastic composition.
6. Formation of pegmatitic schlieren in granitic gneiss.

The suggestion is that regional metamorphism and tectonic activity may play a greater role in emerald mineralization than previously thought, and in fact may be more important than contact metasomatism between pegmatites and chromium-bearing host rocks.

Australia

Kazmi and Snee (1989) provide an excellent overview of Australia's emerald occurrences. Brown (1984) relates the discovery of Australia's first emerald mine near the town of Emmaville. In 1890, a mineralogist noted emerald crystals in an abandoned tin deposit and a mining operation was duly started. Out of 25,000 carats

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originally mined, only 0.01 to 0.02% were of gem quality. Since then the mine has been re-opened and closed several times. Emeralds are contained within pegmatite veins containing fluorite, beryl, quartz and topaz with associated arsenopyrite and cassiterite. The crystals are embedded in granitic cavities that have weathered to kaolin clay. The emeralds from Emmaville were found to be low in chromium and vanadium and higher in iron.

Only 40 km away from Emmaville is the Torrington emerald occurrence. Emeralds occur in quartz and pegmatite veins and are associated with quartz, feldspar, biotite and wolframite.

Kazmi and Snee (1989) describe eight localities of emerald in western Australia and two localities in eastern Australia (Emmaville and Torrington). Most of the occurrences of emerald are associated with pegmatites intruding Archean greenstone terrains and some are overprinted onto gold districts. At Poona, the pegmatite dykes contain biotite, muscovite, lepidolite, zinnwaldite, topaz, tourmaline, fluorite, cassiterite, manganocolumbite monazite and emerald. The emeralds at Poona are the result of metasomatism and pegmatitic hydrothermal processes associated with granitic intrusion into an Archean amphibolite. At Menzies, the emeralds are found in feldspar-quartz pegmatites which have concordantly intruded metamorphosed ultramafic rocks of basaltic komatiite to peridotitic komatiite composition in which a bladed spinifex texture is preserved. The chlorite schist is altered by contact metamorphism and pegmatitic hydrothermal processes to crenulated tremolite/actinolite-phlogopite/biotite schist with bladed spinifex texture.

Austria

The emerald deposit at Habachtal, Austria is a historic emerald occurrence that may have been mined by the Celts and the Romans. It also has the distinction of being one of the few bedrock gemstone deposits to be mined profitably not just once, but several times. This was the case in the mid-1800s when Viennese jeweler Samuel Goldschmidt obtained the rights to the deposit and subsequently had the foresight to send a mining official (who one presumes was a geologist) to investigate before starting mining operations. Since then a number of tunnels have been excavated to follow emerald-bearing schist horizons. The mine has recently been dormant, although mineral collectors scour the dumps.

The emeralds at Habachtal, Austria are found in biotite schist, chlorite schist and tremolite-actinolite-talc schist which formed at the margins of metasomatically altered serpentinite. This deposit is somewhat unusual in that there are no pegmatites associated with the deposit. Grundmann and Morteani (1989), suggested that the Habachtal emeralds formed as porphyroblasts during regional metamorphism. The regional metamorphism caused reactions between ultramafic rocks containing chromium and mica-rich quartzofeldspathic rocks containing beryllium. The beryllium in silicate minerals such as feldspar and muscovite was liberated during metamorphism and these minerals were replaced by biotite, chlorite or talc.

Egypt

The famous 'Cleopatra's Emerald Mine,' Egypt, is hosted in a district of Late Proterozoic metasedimentary rocks, ophiolitic mélangé and associated intrusions. Younger tin- and beryllium-bearing granites intrude the package. Biotite



schists associated with either quartz, actinolite or tourmaline contain emeralds or are cross-cut by quartz veins with emerald. Kazmi and Snee (1989) report that aeromagnetic surveys of the emerald-bearing region show three deep-seated faults extending deep into the crust in this region, which may have provided pathways for pneumatolytic and hydrothermal mineralizing fluids associated with tin-bearing granite. The fluids caused intense alteration of the older rocks, including the ophiolitic *mélange* unit, and precipitated tin, niobium, beryllium, tungsten, molybdenum, bismuth, baron and fluorine minerals. A regional geochemical survey showed a beryllium-rich zone parallel to one of the deep-seated faults. The ultramafic *mélange* serpentinites are strung out bead fashion along this beryllium-enriched zone, which contains emeralds and tin-bearing granites.

Mozambique

Emeralds are found in the portion of the Proterozoic Mozambique orogenic belt which passes through Mozambique, southeastern Africa. Emeralds occur at the contact between beryl-rich granitic pegmatites, and amphibolite and talc-actinolite schist. Molybdenite, pyrite, scheelite, stilbite, apatite, calcite and fluorite are associated minerals. The emeralds are found mainly within the metasomatic contact zone between basic-ultrabasic rock and pegmatite. The emerald-bearing biotite-phlogopite-talc schist zone varies between 50 and 80 cm and shows boudinaged structure. Emeralds are associated with quartz and plagioclase within the zone (Giuliani *et al.*, 2002).

A study of the fluid inclusions in emerald from the Maria deposit in Mozambique was published by Vapnik and Moroz (2002). They found that the fluid during emerald growth was strongly alkaline and that an alkali-carbonic acid solution was responsible for emerald formation.

Tanzania

The emerald and alexandrite deposit at Lake Manyara in Tanzania, southeastern Africa, is described by Gübelin (1974) and Keller (1992). The deposit was discovered in 1970 by a prospector who had been shown some emerald crystals. The emeralds occur as aggregates with alexandrite in the contact zone between biotite-actinolite schists and pegmatites. Over a million carats of emerald were mined in the first two years of production; then alexandrite (a very valuable variety of the mineral chrysoberyl) crystals were discovered in 1972 when labourers were digging a hole for a swimming pool at the mine. Interestingly enough, rubies were also found in the same amphibolite schist unit along with the emeralds, chrysoberyl and alexandrites (Giuliani *et al.*, 2002).

South Africa

Emeralds at Gravelotte, South Africa, an area rich in antimony and gold deposits, occur in the contact zone between a highly metasomatized albitite pegmatite body and lenticular masses of amphibole-muscovite schist and talc-biotite schist enclosed in older granites. The schists are believed to be the alteration products of ultramafic rocks. The emeralds formed 2.7 billion years ago during a period of regional metamorphism and are associated with scheelite, native bismuth, molybdenite, black tourmaline, fluorine-rich apatite and phenakite.

The physico-chemical controls on emerald mineralization were defined by Grundmann and Morteani (1989), and Nwe and Morteani (1993). These authors, as summarized in Franz and Morteani (2002), suggest that regional metamorphism, and in particular tectonometamorphic events, are more significant than previously thought for certain 'classic' emerald deposits hosted in schists.

Zambia

Emerald mineralization in Zambia, southern Africa, has been known since the 1920s, and at one point in the 1980s, Zambia was producing \$100 million annually in emeralds. Many of the productive open-pit mines could not make the orderly transition to an underground operation, and shortly afterwards Zambian emerald production began to fall in comparison to Zimbabwe.

In the Miku area, emerald and tourmaline crystals are found in phlogopite schists and are associated with talc-chlorite-magnetite-amphibolite schists and pegmatites.

In the Kafubu area, emeralds are found predominantly in serpentinites with tremolite and phlogopite, or in quartz-tourmaline veins adjacent to the pegmatites. At the Kamakanga mine, the emeralds occur mainly in metasomatic zones that developed between tourmaline veins and mafic talc-schist. Tourmaline-bearing pegmatites provided beryllium, and ultramafic units provided chromium (Sliwa and Nguluwe, 1984). During pegmatite intrusion, the wall rocks were altered to phlogopite-biotite schist, and emeralds formed in response to pneumatolytic alteration. Emplacement of the Kafubu pegmatites seemed to have occurred in two phases. The first phase involved injection of quartz-feldspar-tourmaline pegmatites, while a second phase of tourmaline and quartz-tourmaline crystallization followed. The sequence is described by Sliwa and Nguluwe (1984):

"Most beryl/emerald mineralization seems to be related to the pneumatolytic-hydrothermal quartz-tourmaline phases of pegmatite activity. These late, highly volatile, mainly gaseous phases, enriched in silica and boron and devoid of feldspar produced virtually bi-mineralic rocks, composed of quartz and schorl (iron-rich tourmaline). They were commonly emplaced along glide surfaces formed by intraformational detachment of schist, especially where these planes formed suitable structural traps. It seems that undulating but generally flat planes of schistosity created the most suitable structural traps to facilitate crystallization of emeralds. The pegmatites cooled slowly, with temperatures believed to have ranged from 300 to 500°C and pressure of 1–2 kbar. Crystallization of beryl is believed to have taken place chiefly during the metasomatic reaction between pegmatites and surrounding rocks. Thus, the majority of emeralds lie within the zone of metasomatic biotite-phlogopite schists developed along the contacts of the veins with the country rocks."

They also note that after emeralds crystallized, the region was subject to intense shearing and folding during orogenic events. This post-crystallization activity may be the reason why so many of the crystals are fractured and opaque.



Zimbabwe

Emeralds in Zimbabwe, southern Africa, first noted in 1956 when the country was called Rhodesia, crystallized some 2.6 billion years ago in some of the oldest rocks on the planet. At that time, numerous potassium-rich beryllium and lithium pegmatites intruded into greenstones containing chromium-rich serpentinites and schists. Subsequent tectono-metamorphic events allowed for mobilization of essential elements for emerald formation and emeralds precipitated in albitites and phlogopite schists. Tourmaline grew across the foliation of the mica schists (Anderson, 1978a,b).

Emerald deposits found during the 1950s were romantically named Zeus, Orpheus, Aeres 3, Vulcan and others. The Zeus mine, now known as the Sandawana mine, made a successful transformation from open pit to a modern underground operation. Emeralds from the Sandawana mine are known for their exceptional colour and quality (Giuliani *et al.*, 2002).

Significant emerald deposits at Machingwe in Zimbabwe were discovered in 1987 and described by Kanis *et al.* (1991). At Machingwe, the emeralds are found in phlogopite produced as a result of metasomatic reactions within the serpentinites.

Madagascar

Like Sri Lanka and Tanzania, the island country of Madagascar, southeastern Africa, overflows with gemstones, mineral specimens and fossils of all kinds, so much so that the publishers of Lapis magazine dedicated an entire issue to this wonderful island (Pezzotta, 2001). The fourth largest island in the world, Madagascar is home to 14 million people and is exceptionally rich not only in gemstones but also rare species of animals and plants. Political unrest and difficulties in effective natural resource management in light of a poor economy has led to a fluctuating coloured gemstone supply from this beautiful island⁵.

Madagascar was, as recently as 150 million years ago, still connected as part of the Gondwanaland supercontinent to its sister gem-rich areas in Africa and India and Antarctica. The oldest rocks in Madagascar are more than 3 billion years old and have been extensively intruded by rare-element pegmatites that are loaded with beryllium.

Emerald mineralization was known for a long time on Madagascar, but had not been studied in detail until recently. Cheilletz *et al.* (2001) completed geological, petrographic and geochemical analysis of the emerald-bearing areas and proposed two distinct models for emerald formation.

1. Emerald deposits associated with pegmatites (Mananjary region)

Emerald mineralization in the area of Mananjary occurs at the contact zone between pegmatitic and basic/ultrabasic rocks, mainly serpentinite and amphibolite and Archean (1.89 billion years old) schists, gneisses, green-schists and migmatites. The emeralds are in a phlogopite schist zone created after metamorphic and metasomatic processes during an

⁵In the fall, 2003 issue of *Gems and Gemology*, *Gem News International*, a visitor to the gem-mining areas of Madagascar describes robberies and gunfights, and that was just the first night of the visit.

orogenic event remobilized elements. Later magmatic events introduced molybdenite, wolframite and pyrite.

2. Emerald deposits with pegmatites absent (lanapera region)

Emeralds are situated within an isoclinal fold related to shear zones within Precambrian volcano-sedimentary rocks. The emerald mineralization occurs in reaction zones developed within lenses of serpentinite and amphibolite in the absence of pegmatites. Emeralds have formed in quartz-phlogopite tourmaline-bearing veins that are scattered within tremolite-chlorite schists. Giuliani *et al.* (2002) mention that given the absence of pegmatites, the lanapera emeralds may have formed from the circulation of metamorphic deep-seated fluid released during the Pan-African orogeny 530 to 500 million years ago. This is similar to the Santa Terezinha deposit in Brazil.

India

The rulers of India loved emeralds and accumulated them with great enthusiasm, but emeralds were not discovered within India until 1943, near Rajasthan. Emeralds are found in talc, biotite and actinolite schist intruded by tourmaline granite and associated pegmatite veins. Minerals associated with emerald include beryl, tourmaline, apatite, quartz, feldspar, muscovite and biotite. The host rocks contain kaolin, sericite, chlorite, albite, tourmaline, vermiculite, calcite, talc, serpentinite, tremolite and anthophyllite.

Ural Mountains, Russia

Emerald deposits in the Ural Mountains are described by Sinkankas (1981), Snee and Kazmi (1989), Schmetzer *et al.* (1991), and Laskovenkov and Zhernakov (1995). It is interesting to note that the emerald deposits are located about 100 km northeast of the infamous city of Ekaterinburg (which was a famous lapidary and mining centre in the mid-1880s), whereas the ruby deposits described in the previous chapter are southwest of Ekaterinburg. During the Late Paleozoic, Europe and Asia collided, resulting in the formation of the Ural Mountains chain which divides the two continents. Emeralds occur in a band of biotite and actinolite schists associated with granite pegmatites. The metamorphic rocks consist of serpentine, talc, chlorite, talc-phlogopite and tremolite, amphibolite, amphibole gneisses and quartzites. Laskovenkov and Zhernakov (1995) call the phlogopite-rich pods where emeralds are found "glimmerite ore bodies." The 'glimmerites' average 1 m in thickness, are typically 25 to 50 m long, and consist of 95 to 99% phlogopite. Emeralds are tightly enclosed by phlogopite. Minerals associated with emerald are phlogopite, plagioclase, fluorite, topaz, apatite, chrysoberyl, phenakite, alexandrite and fluorite.

Laskovenkov and Zhernakov (1995) report that special portable neutron-activation analysis machines called 'beryllometers' are used to locate emerald occurrences by mapping the beryllium content of the host rocks. Pathfinder minerals associated with emerald mineralization are also helpful for finding ore zones.

This deposit has produced some very large emerald crystals. Laskovenkov and Zhernakov (1995) report that an 11,000-carat crystal of grass green colour was found



in 1831 and, more recently, a 4,400-carat stone was faceted from a rough Uralian emerald in 1990.

EMERALDS IN NORTH AMERICA

The few documented emerald occurrences in North America are in a wide array of tectonic settings and host rocks:

1. Quartz veins that cut migmatitic host rocks (Hiddenite, North Carolina, U.S.A.).
2. Emerald crystals reported in oil-rich black shales (Uinta Mountains, Utah, U.S.A.).
3. Quartz-tourmaline veins that cut lower greenschist chlorite schists (Regal Ridge, Yukon, Canada)
4. Quartz-calcite veins developed in tungsten skarn within metalliferous black shales (Lened, Northwest Territories, Canada)
5. Rare-element pegmatites (Ghost Lake, Ontario, Canada).
6. Quartz veins in andesite (Red Mountain, British Columbia, Canada).

North Carolina

North Carolina is a gem-rich state. It is host to alluvial ruby and sapphire, and bedrock occurrences of emeralds. In fact, until emeralds were identified in northern Canada, the only well documented and producing emerald localities in North America, were in North Carolina. The emeralds are found with a lesser-known green gemstone called hiddenite, which is gem-quality green spodumene. Steeply dipping quartz-calcite-emerald veins cut migmatitic host rocks including biotite schist interbedded with lenses of calc-silicate rock. Very large emerald crystals have been recovered from workings in the Hiddenite area, however, the emeralds tend to have a greyish tinge. Research reported by Wise and Anderson (2003) suggests that vein emplacement was after intensive anatexis and regional deformation.

Utah

Keith *et al.* (1997, 2002) report that three emeralds have been recovered from within a fault zone between Mississippian carbonate units and Proterozoic shale in the Uinta mountain range, Utah. The emeralds are within the fault zone and shale, and are associated with pyrite, barite, vein quartz, fibrous calcite, bleached shale and green mica. The shale is a 1-km-thick sequence of organic black shale with arkosic arenite units. A model very similar to that thought responsible for emerald deposit formation in Colombia is proposed.

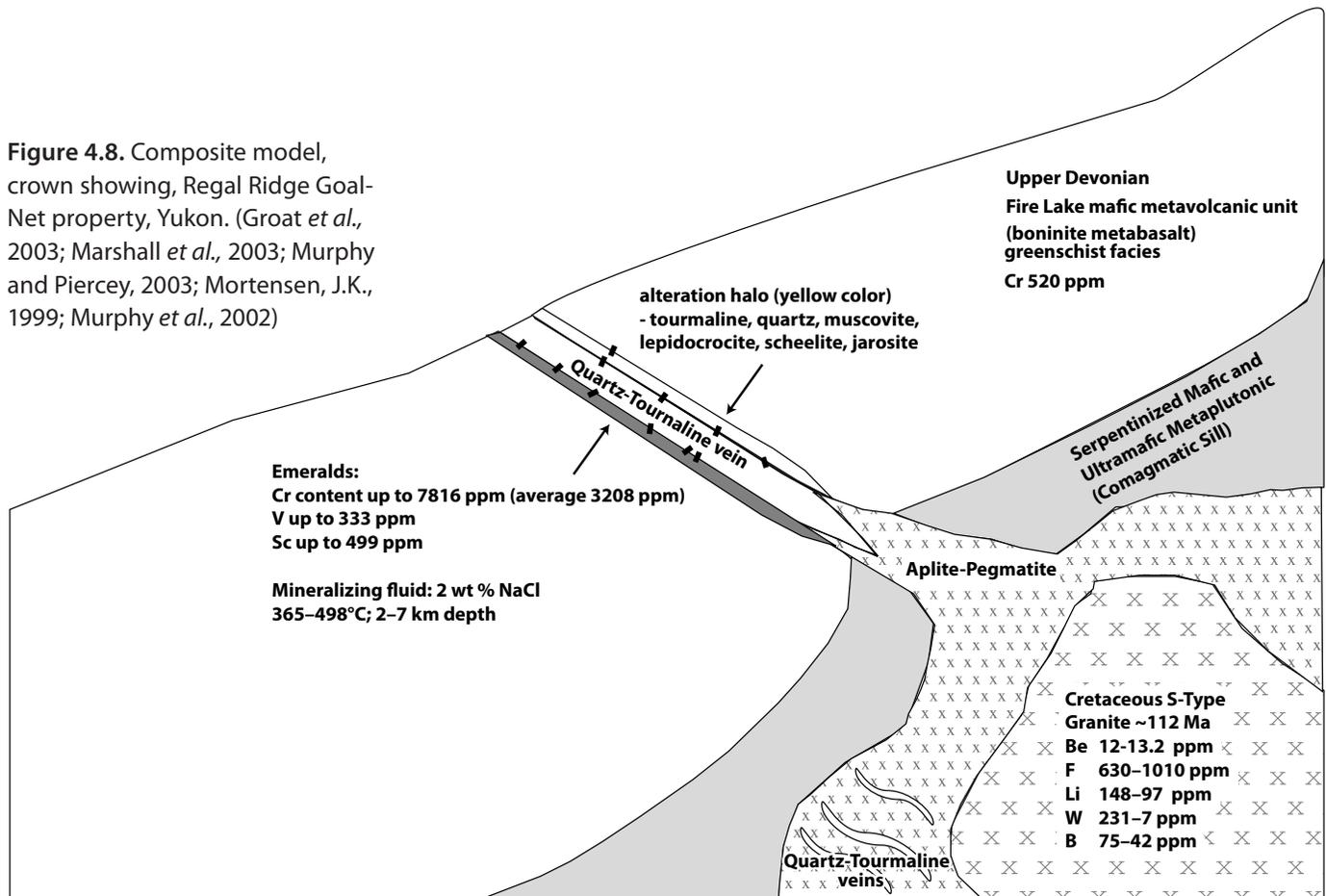
Emeralds in Canada

REGAL RIDGE, YUKON

Emeralds were discovered in August, 1998 in the Finlayson Lake area, southeastern Yukon by geologist William (Bill) Wengzynowski, who was working for Expatriate Resources at the time. While exploring for signs of base metals, Mr. Wengzynowski recognized emerald mineralization in a 900 by 400 m area on both sides of an east-trending ridge on the Goal-Net claim group. True North Gems Inc. has since purchased the property and has been working to evaluate the extent and quality of the emerald mineralization. The first comprehensive scientific papers on the Regal Ridge emerald occurrence were recently published (Groat *et al.*, 2003; Marshall *et al.*, 2003). The following information is taken largely from their work and from Rohtert and Montgomery (2001). A compilation of the research data to date is shown in Figure 4.8.

The host rocks for the Regal Ridge emerald occurrence are Upper Devonian Fire Lake mafic volcanic rocks (chlorite schist) intruded by a 112-million-year-old peraluminous granitic intrusion exposed about 600 m from the emerald occurrence. There is a smaller exposure of the granitic intrusion between the main exposure and the emerald occurrence. The granitic intrusion contains up to 13.2 ppm beryllium. The mafic volcanic rocks consisting of chlorite schist with local muscovite schist are classified as boninitic in composition. One of the geochemical characteristics of

Figure 4.8. Composite model, crown showing, Regal Ridge Goal-Net property, Yukon. (Groat *et al.*, 2003; Marshall *et al.*, 2003; Murphy and Piercey, 2003; Mortensen, J.K., 1999; Murphy *et al.*, 2002)



boninites are their elevated nickel, chromium and cobalt content (Piercey *et al.*, 2001). The boninitic host rocks in the Regal Ridge area are chlorite schists and contain elevated chromium (up to 520 ppm) and vanadium (up to 190 ppm). The Fire Lake unit overlies a slab of variably serpentinized mafic and ultramafic rock, which has been interpreted as a comagmatic sill to the Fire Lake unit (Murphy and Piercey, 2000). The rocks are greenschist facies metamorphic grade.

Emeralds are found along the margins of discordant quartz-tourmaline veins genetically related to the nearby mid-Cretaceous biotite (\pm muscovite) quartz monzonite. The quartz monzonites grades to quartz-tourmaline pegmatites and aplite, locally containing beryl before evolving to quartz-tourmaline (calcite) veins with emerald. Emeralds are concentrated with an alteration envelope of massive, fine tourmaline crystals which contain local minor scheelite. Emeralds are more prevalent where the chlorite schist contains abundant muscovite and has weathered a distinctive 'golden' colour. Black tourmaline is ubiquitous on the property as attractive 'birdsfoot' arrangements on foliation planes within the schist and as massive, felted fine needles in the alteration zones to the quartz-tourmaline veins. It is also in the nearby granite, aplites and quartz veins.

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Researchers are trying to determine whether the emerald mineralization is related to magmatic events after the classic pegmatite schist model for emerald mineralization, or whether tectonic-hydrothermal events were predominant. Initial fluid inclusion and stable isotope results reported by Groat *et al.* (2003) and Marshall *et al.* (2003) are inconclusive, but do indicate a 2 wt % NaCl fluid with vein formation at 365 to 498°C. It is likely that fluorine played a significant role in emerald precipitation since the granitic intrusion at Regal Ridge contains highly elevated fluorine (up to 1010 ppm) and fluorite is reported associated with emerald precipitation. Groat *et al.* (2003) also noted a strong association of tungsten and local molybdenite.

LENED, NORTHWEST TERRITORIES

Green beryl crystals had been noted at the Lened tungsten skarn by field crews exploring for tungsten, lead and zinc during the 1970s and 1980s. In fact, a green beryl crystal was donated to the Royal Ontario Museum where it rested within the 'Beryl' specimen drawer in the museum's research collection. It wasn't until Yukon prospector Ron Berdahl staked the property for its tungsten value and then, in 1997, noted the attractive green crystals while prospecting with his son, that the Lened was 'rediscovered' and recognized as an emerald occurrence.

Researchers have focused on identifying the paragenesis of the Lened emerald occurrence, since the geological setting is rather mundane, with no unusual features that would normally be required to form an emerald occurrence. The mineralogy and geochemistry of the Lened emerald occurrence is reported by Marshall *et al.* (2003) and summarized on the website for the C.S. Lord Northern Geoscience Centre⁶ in Yellowknife, NWT. The emeralds at Lened occur in a garnet-diopside skarn outcrop about 40 m by 15 m. The occurrence is situated about 500 m southeast of a mid-Cretaceous granitic pluton (Lened pluton). The beryllium content of the Lened pluton is 6 ppm. The skarn has formed at a fault contact between Devonian to Mississippian Earn Group metalliferous black shales and Upper Cambrian and Lower Ordovician Rabbitkettle Formation limestone. The vanadium content of the black shale averages 1934 ppm. The skarn is cut by about 35 quartz-carbonate veins 2 to 30 cm wide. Slender pale green beryl crystals up to 2.5 cm in length, some of which could be called emerald, are concentrated at the contact between the vein and wallrock and within the vein. The beryl crystals found were pale and small, but there is a high proportion of transparent crystals.

The emerald crystals at Lened are coloured by vanadium; the vanadium content averages 0.25 wt % V₂O₃. Fluid inclusion studies and preliminary isotope data by Marshall *et al.*, 2003 indicate that the skarn and subsequent quartz-carbonate-emerald veins are the result of contact metamorphism related to the adjacent Lened intrusion.

Falck and Marshall (2003) tested the effectiveness of a gamma-ray spectrometer⁷ in delineating emerald-bearing quartz veins at the Lened emerald locality. They found that the quartz veins were too narrow to have definitive signatures, but the method might be useful for delineating fault contacts.

⁶www.nwtgeoscience.ca

⁷Exploranium GR-256 model



GHOST LAKE, ONTARIO

Emeralds from the Taylor #1 pegmatite, Mavis Lake rare-element pegmatite group near Dryden, Brownridge Township, Kenora district, were first recognized as such in the early 1990s by Fred Breaks, a student at the time doing fieldwork for a Ph.D. thesis on the Taylor pegmatite. The emeralds were recognized in a known pegmatite, one that was noted in the 1940s for containing opaque, milky beryl crystals. Mr. Breaks, now a geologist for the Ontario Geological Survey, donated a sample of the emerald to the Canadian Museum of Nature where the emerald identification was confirmed and duly noted⁸. The green colours were determined, through electron microprobe analysis, to be chromium. The museum arranged to facet a gem out of the donated specimen and a 0.13-carat light green, irregularly shaped faceted emerald was produced. The green colour was determined, through electron microprobe analysis, to be chromium and the emerald identification was duly noted.

A local prospector staked the showing, which by then was attracting interest for tungsten, and carried out trenching but came to the conclusion that all the emeralds were gone. The next owner was a company exploring for tantalum, and when the claims became open, B. Wilson⁹ staked the property. He promptly discovered and identified the emerald mineralization. True North Gems Inc. optioned the property in 2003 and carried out field work during the summer.

RED MOUNTAIN

A excellent paper, *Gemstone Occurrences in British Columbia*, published in Canadian Gemmologist (Wilson, 1997) describes small, fractured, opaque emeralds discovered in 1989 in narrow quartz-calcite-pyrite veins that cut volcanoclastic rocks adjacent to a quartz monzonite intrusive body on Red Mountain near Stewart, B.C. Mr. Wilson had been working for a mining company in 1989 looking for gold associated with galena and tetrahedrite in the Red Mountain area. A primary exploration target was malachite staining, which could indicate tetrahedrite ore. Mr. Wilson had noticed some green staining on a quartz-calcite-pyrite vein and, upon close inspection, immediately recognized emerald crystals. The description in *Gemstone Occurrences in British Columbia*, is as follows:

“Emerald green beryl was discovered in 1989 in narrow quartz-calcite-pyrite veins that cut volcanoclastic rocks adjacent to a quartz monzonite intrusive on Red Mountain (near Stewart). Since then, several other specimens have been found in this area by geologists who were searching for gold. Microprobe analysis shows that this beryl is coloured green by trace amounts of vanadium (G. Robinson, pers. comm.). Although all of the crystals found so far have been small, fractured and opaque, their presence suggests that better quality emerald may occur elsewhere in the province.”

Mr. Wilson (pers. comm., 2003) confirmed that the emeralds were contained within small quartz-calcite-pyrite stringer veins cutting andesitic volcanoclastic rocks. There are no evident pegmatitic phases present.

⁸Breaks, F.W. and Moore, J.M., Jr., 1992. *The Ghost Lake batholith, Superior Province of Northwestern Ontario*. Canadian Mineralogist, vol. 30, p. 835–875.

⁹www.alpinegems.net

EXPLORATION CRITERIA FOR EMERALD DEPOSITS

Besides the suggestions given below, Simandl *et al.* (1999a,b) provide excellent summaries and exploration guides for both the shale-hosted and schist-hosted types of emerald deposits (see Appendix A).

Emeralds associated with black shales (Columbian type)

HOST ROCKS

- Thick, intensely folded and faulted sequences of bituminous shales, sandstones and limestones.
- Evaporites, salt domes, salt plugs, salt beds, briny hot springs associated with above sequence (e.g. bituminous sedimentary sequence containing evaporite beds or intruded by salt diapirs).

REGIONAL HOST ROCK GEOCHEMISTRY

Bituminous host rocks of mineralized areas on a regional scale (100s metres) are:

- Enriched in sodium, magnesium and manganese.
- Depleted in potassium, aluminum, silicon, lithium, molybdenum, barium, zinc, chromium and vanadium.
- A host Na/K ratio of less than 1.1 was used in Colombia to separate altered blocks from unaltered blocks.

REGIONAL STREAM SEDIMENT GEOCHEMISTRY

- Sodium is the best single geochemical pathfinder for determining mineralized from unmineralized areas.
- Lithium, molybdenum and lead may also be useful to determine if an area has undergone leaching.

STRUCTURE

Structural analysis of regional faults in conjunction with either host rock geochemistry or stream sediment geochemistry may show regional faults separating areas of Na metasomatism from unaltered areas.

Branquet *et al.* (1999) suggest that Columbian emerald deposits are almost exhausted and the finding of new deposits will necessitate prospecting that is structurally oriented, focusing on the localization of (1) structural traps along regional tear faults in the western zone and (2) the stratiform brecciated level in the eastern zone.

GROUND PROSPECTING

In general, one should look for areas with calcite-albite-dolomite vein networks, fibrous calcite, bands of hematite, folded and brecciated sedimentary rocks, calcite veins with abundant pyrite or albite and areas where veins intersect. Altered light grey Cenicero zones generally contain brecciated calcite, albite, muscovite, pyrite and quartz in a carbonate matrix. The zone may smell like H₂S and native sulphur may be



present. If one of these zones is found, prospect for trapiche emeralds in the outer parts of the alteration zone and gem emeralds in veins emanating away from the alteration zone.

Fluorite, apatite and pale green opaque beryl in calcite veins are good indicators of nearby emerald mineralization. The mineral parasite, which forms fudge-coloured stubby hexagonal crystals is another good indicator.

As inspiration, it should be noted that a single pocket of emeralds discovered in a calcite vein at Chivor had an estimated value of \$6,000,000 (Ottaway, 1991).

Emeralds associated with bituminous sedimentary rocks (Norway type)

- Pegmatites intruding bituminous aluminum-rich sedimentary rocks.

Emeralds associated with pegmatite/granites interacting with chromium-bearing rock

HOST ROCKS

It seems that the exact lithology of the host rock is not as important as the requirement that it contain chromium — the more chromium the better:

- Talc-dolomite schist, serpentinite, peridotite, dunite, biotite schist, biotite-actinolite schist, phlogopite schist, tourmaline-biotite schist, talc schist or other metamorphosed ultramafic rocks.
- Associated pegmatite, especially beryl-bearing pegmatite, tourmaline-bearing pegmatite or anatectic granitic intrusion.
- Metasomatic contact zones between the pegmatites and meta-ultramafic rock. This is usually a zone of biotite-phlogopite schist.
- Biotite schist, phlogopite schist, biotite-talc-carbonate schist and carbonate-biotite schist without cross-cutting pegmatite dykes. Hydrothermal fluids may carry beryllium from pegmatitic source rocks through fault conduits and channelways.

STRUCTURE

- Areas of intensive tectonism, fracturing and folding are preferential hosts for emerald mineralization. It is easier for beryllium-bearing fluids to permeate and interact with chromium-bearing host rocks.

GEOCHEMISTRY

- The higher the chromium content of the ultramafic or metamorphosed ultramafic rocks, the better chance there is of emerald formation. Look for chromite pods or crystals in the meta-ultramafic host rocks. This indicates abundant chromium content.
- Zones of beryllium enrichment coincident with biotite schist or other metamorphosed ultramafic rocks.

- Zones of beryllium enrichment coincident with chromium, fluorine, tin, molybdenum and/or tungsten anomalies, especially in areas containing meta-ultramafic rocks.
- Rare-element pegmatite dykes intruding biotite schist or ultramafic rocks.

PATHFINDER MINERALS

- Thin to thick selvages of biotite-phlogopite.
- Molybdenite, alexandrite, scheelite, apatite, chrysoberyl, tourmaline, phenakite and/or pyrite in the metasomatic contact zone.

GEOPHYSICS

- Zones of beryllium enrichment coincident with magnetic highs on aeromagnetic maps.

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5. TSAVORITE GARNET AND TANZANITE

INTRODUCTION

These two beautiful gemstones, one green and one violet-blue, are very closely related in terms of their chemistry and mode of occurrence. They are the two ‘newest’ gemstones to be introduced to the gem trade on a large scale within the last 25 years, and are both mined from the bountiful Mozambique Orogenic Belt extending down the length of Africa, from Tanzania, through Kenya and eventually to South Africa.

“Tavorite what??” Canadian geologists and prospectors say, and yet this splendid green garnet has been on the gem market for 20 years. It looks especially attractive when set with Yukon nugget gold, yet most people have never heard of it. Tanzanite gets much the same reaction, yet this violet-blue gemstone is now one of the top five coloured gemstones in the United States in terms of retail sales (Table 5.1). Tanzanite is also becoming well known in Canada; tanzanite jewellery sells in the larger department stores and is now cultivating awareness among the general public (tanzanite jewellery is for sale in the 2003 Sears catalog).

The proper mineralogical name for tavorite garnet (the “t” is silent) is vanadium grossular garnet, however, ever since its discovery in the 1970s it has been marketed under the more glamorous and exotic name of tavorite in honor of Tsavo National Park in Kenya, where tavorite was first found. To date, the world’s supply of tavorite garnet has come from a handful of small mines in Kenya and Tanzania, many of them clustered near the Kenya-Tanzania border. The Mgama-Mindi Ridge complex in southeast Kenya, near the Tanzanian border, and the Lelatema, Merelani Hills and Komolo areas in Tanzania, are host to several tavorite mines and significant deposits. Currently, in the Taita Taveta district in Kenya, Bridges Exploration Ltd. and First Green Garnet Mining Co. Ltd. produce tavorite. The value of tavorite garnet

Table 5.1. Top ten selling coloured gemstones in the United States (*Coloured Stone*, January/February 2003)

2000	2001	2003
Blue sapphire	Blue sapphire	Blue sapphire
Ruby	Pearl	Ruby
Emerald	Tanzanite	Emerald
Amethyst	Ruby	Tanzanite
Tanzanite	Emerald	Amethyst
Tourmaline	Amethyst	Rhodolite garnet
Garnet	Green tourmaline	Pearl
Fancy sapphire	Rhodolite garnet	Opal
Pearl	Fancy sapphire and pink tourmaline (tie)	Peridot
Blue topaz	Blue topaz	Blue topaz

5. Tsavorite garnet and tanzanite

production in Kenya in 2001 was \$744,000¹. More recently, tsavorite garnet has been discovered on the gem-rich island of Madagascar, and another showing has been noted in Pakistan.

The correct mineralogical name for tanzanite is 'blue zoisite.' A gemstone with an unappealing name like this would sink on the world gem market, and therefore in 1969, Tiffany and Company introduced this new gemstone as 'tanzanite' in honor of the only country in the world from which it is mined. The bulk of the world's supply of tanzanite comes from a single deposit near the town of Merelani in the Lelatema Mountains in Tanzania, 24 km southwest of the Kilimanjaro International Airport. Tsavorite is also produced at this mine. Much of the tanzanite rough is auctioned in the town of Arusha whose name may sound familiar for a sad reason: it is where the International Criminal Tribunal for Rwanda is based to deal with prosecuting those responsible for the Rwandan genocide in 1994.

The discovery of tsavorite garnet

It has been known for many years that garnets occur in all colours except blue. Besides the familiar red shades, there are also purple, pink, orange, orange-brown, yellow, yellow-green, and colourless garnets. Placer miners in the Yukon are familiar with garnets, since, as a heavy mineral they tend to show up in placer gold concentrate. Exploration geologists look for certain types of pyrope garnets when exploring for diamond-bearing rocks. A beautiful yellow-green andradite garnet from Russia called demantoid enjoyed popularity in the early part of the century. More recently, demantoid garnet has enjoyed a resurgence of popularity due to the re-discovery of 'lost' demantoid garnet deposits in the Ural Mountains. Rare chromium-bearing uvarovite garnet that shows a beautiful, vivid emerald green colour has been found only in small quantities and very small crystals.

According to various accounts (Gübelin and Weibel, 1975; Keller, 1992; Bridges, 1982), green garnets were first discovered by geologist Campbell Bridges in 1967 about 31 miles (50 km) from Arusha, Tanzania, although he had noted sparkling green garnets much earlier in other parts of Africa. In 1970, he discovered significant tsavorite in the Mindi Hills in southeastern Kenya in 1970. By early 1973, two groups, one under the direction of South African mining engineer P. Morgan and the other under Campbell Bridges discovered additional deposits in the Mgama Ridge-Mindi Hills area. The gem-rich Precambrian rocks in this area are buried under a thin veneer of red soil, 'kunkar' limestone or reddish cellular siliceous ironstone weathering products. The dry, flat grasslands are home to many animals, including roaming lions and poisonous snakes. Although 40 to 50 different tsavorite localities in Kenya and Tanzania have been mined over the years, only a handful are now producing the green gem. Mr. Bridges now operates the Scorpion tsavorite mine in Kenya, in which two tunnels are at 320 feet depth, providing a steady source of tsavorite material to the world market. The Scorpion tsavorite mine and the recently developed Elephant Skull mine are described on Campbell's website², along with nice photos and interesting comparisons between tsavorite garnet and emerald. Another tsavorite locality is being mined in Kenya and a minor amount has been noted as an accessory

¹United States Geological Survey, 2001, Mineral Resources by Country, Kenya and Uganda by Thomas Yager.

²www.tsavorite.com



mineral in gem deposits in Pakistan. In 1991, tavorite garnet was discovered on the gem-rich island of Madagascar, however the deposits in Kenya and Tanzania are the most important sources of this beautiful, rare gem.

Tavorite market

The supply from the East African deposits is small, yet the price of good quality one-carat stones has steadily climbed ever since its introduction by Tiffany and Company to the world market in 1974. One can expect to pay \$1,500 to \$3,000 for a one-carat stone, a bargain when one considers an equivalent Colombian emerald would be almost three or four times as much. Faceted tavorite is rarely seen in sizes above 5 carats, and top quality tavorite may fetch \$8,000 per carat retail³. An attractive feature of tavorite garnet is that it is one of the few coloured gemstones which has not been heat-treated, dyed, irradiated, oiled or treated in some other manner to improve its appearance; most tavorite bought in jewellery stores is 'natural.'

The discovery of tanzanite

Tanzanite is the popular name given to the gem-quality blue transparent variety of the mineral zoisite ($\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}\text{OH}$). Tanzanite is not the only variety of zoisite used as a gemstone. Rare transparent green and transparent yellow zoisite have been found at the tanzanite mines. Green (grass green) massive opaque zoisite and bright red opaque rubies are associated with hornblende at Longido in Tanzania. This rock, locally called 'anyolite,' makes spectacular carving material. Another gem variety of zoisite is one found just outside the city of Whitehorse, Yukon, Canada in the Whitehorse Copper Belt. It is 'thulite,' a massive pink opaque variety of zoisite, coloured by manganese.

Tanzanite was discovered in 1967 near Merelani in northern Tanzania. According to Keller (1992), a tailor from Arusha was prospecting for rubies about 40 km southeast of Arusha when he was shown a surface deposit of unknown blue stones by a local Masai tribesman. Despite his disappointment that the blue stones were too soft to be sapphires, he staked and registered the ground, thereby starting the standard staking rush and long convoluted history of disputed mining rights and government interference. The original mining area was relatively small, approximately 5 km long by 1 km wide (Barot and Boehm, 1992). Open pits are up to 100 m deep (Keller, 1992), however, most of the mining is now taking place underground (Barot and Boehm, 1992). Most freshly mined tanzanite must be heat-treated to drive off undesirable brownish hues in the stone, leaving it violet-blue. Those first crystals discovered by the tribesman may have been naturally 'heat-treated' by the hot African sun to turn them a more noticeable blue colour.

Political instability over the last 20 years led to uneven supplies of this gemstone, especially when the Tanzanian government took over the mines in the 1980s. They lost control of the tanzanite mining area in the late 1980s when tens of thousands of illegal, independent miners appeared, which led to total anarchy, murder and a glut of tanzanite on the world market. By the early 1990s, tanzanite was gaining popularity as a coloured gemstone in the United States and the Tanzanian government took control of the mines again, by dividing the mining area into four blocks and leasing

³from www.palagems.com

5. Tsavorite garnet and tanzanite

the mining rights to private companies. Barot and Boehm (1992) report that in 1991, 7,000 local people worked at the mines, down from 35,000 during the anarchy years in the late 1980s. It wasn't until the late 1990s that some semblance of organized mining and marketing efforts took place, with the entry of the African Gem Resources Company (AFGEM) into the business of tanzanite mining and marketing. The company has persevered during tumultuous times including continued unrest from neighbouring miners, a story linking tanzanite mining to terrorism, and development of the Tucson Tanzanite Protocol.

Tanzanite market

Tanzanite has gained considerable recognition and popularity in the United States, and is starting to make a significant impression in the more conservative Canadian jewellery market. The highest prices are paid for intense blue tanzanite gemstones. Tanzanite crystals of enormous size and excellent clarity can be mined, therefore most good quality tanzanite is eye-clean. Almost all tanzanite is heat-treated at approximately 500°C, which converts the brown pleochroic colour to blue. Tanzanite prices tend to fluctuate wildly, largely due to irregular production

Tanzanite mining and AFGEM

The African Gem Resources company (or AFGEM) was formed in the late 1990s in order to mine and promote the gemstone tanzanite. The company raised funds for the acquisition of mining blocks and then listed on the Johannesburg Stock Exchange. AFGEM promotes itself as one of the first vertically integrated coloured gemstone companies; in other words AFGEM conducts the exploration, mining, beneficiation and marketing of tanzanite. A key component of AFGEM's marketing strategy, through its 'Tanzanite Foundation,' was development of a branding strategy for tanzanite in order to develop new markets and promote the product by ensuring a regular supply of material, supporting downstream demand and building brand awareness among customers.

AFGEM claims the market for tanzanite is \$100 million per year; other estimates place the market at \$200 million. During the six months from Jan to Sept., 2003, AFGEM produced 812,526 carats of tanzanite. The sale of rough tanzanite

accounted for 61% of total revenue. Sale of polished tanzanite makes up 39% of AFGEM's total revenue with more than 80% of the polished gems sold in South Africa to tourists.

In December, 2003, AFGEM announced that it will sell its Tanzanite business for 158 million rand (about \$25 million) to a group called Tanzanite One. Tanzanite One will list on the Alternative Investment Market of the London Stock Exchange as well as the Dar es Salaam Stock Exchange, which should provide better access to capital.

When AFGEM was awarded the right to mine its tanzanite block in the late 1990s, local small scale miners of tanzanite from the neighbouring block objected. They were particularly incensed at the 'branding' of tanzanite and did not want AFGEM to advertise that they were the only producer of tanzanite. The Tanzanian government also took this view; that they wanted to advertise tanzanite as a Tanzanian resource and not the product of an individual company. The miners did not like the fact that AFGEM claimed, based on

detailed pre-feasibility studies, a 15 year mine life. It was the miners' view that government should cancel the company's license in order to preserve the tanzanite resource for future generations. AFGEM took the view that although tanzanite has been mined for 33 years from Tanzania, Tanzania has seen no benefits, no formal employment, no investment of capital or re-investment of profits, no foreign exchange earnings and no value-added industry.

There have been several bloody confrontations, where the local miners literally tried to invade the AFGEM mining blocks, either on surface or by tunneling underground onto the AFGEM block. There have been several horrific incidents involving cave-ins and flooding at the tanzanite mine; these accidents have all taken place on the unregulated blocks mined by the local people. Things came to a head when the local miners and dealers sued AFGEM, however, the Court in Tanzania handed down an unanimous decision to dismiss the lawsuit with costs.



Tsavorite garnet vs emerald

Both gems are formed under conditions of great stress, and are seldom found in sizes large enough to cut clean stones above two or three carats. Tsavorite is extremely rare, much rarer than emerald. Tsavorite sells for about 1/4 the price of emerald, is more brilliant due to a higher refractive index (1.74 vs. 1.596) and is harder than an emerald. Finally, almost all emeralds are oiled. Tsavorite is not usually treated in any manner to enhance its appearance.

from the mines. For extremely fine stones of less than 50 carats, prices can reach up to \$1,000 per carat. Tanzanite is not particularly well suited for everyday wear in a ring; it is sensitive to thermal shock and susceptible to cleavage breakage. Tanzanite jewellery should not be exposed to extreme temperature changes or to many bumps. It can also be affected by hydrochloric and hydrofluoric acid. Tanzanite jewellery should be cleaned using warm, soapy water. Ultrasonic cleaners and steam cleaners should never be used.

PHYSICAL AND CHEMICAL PROPERTIES

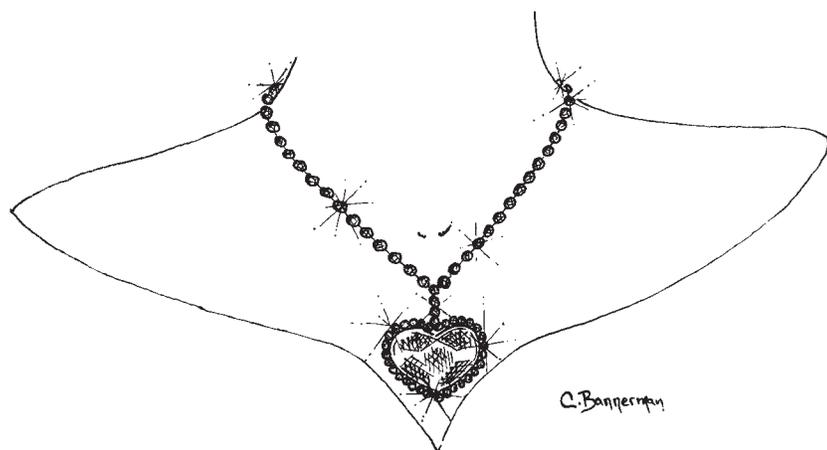
Tsavorite garnet

Tsavorite is the name given to the gem variety of the mineral species 'grossular garnet.' The garnet group is composed of structurally and chemically related mineral species that crystallize in the isometric crystal system. The most important garnet species and their ideal chemical compositions are given below:

Pyrope	$Mg_3Al_2(SiO_4)_3$
Almandine	$Fe_3Al_2(SiO_4)_3$
Spessartine	$Mn_3Al_2(SiO_4)_3$
Grossular	$Ca_3Al_2(SiO_4)_3$
Andradite	$Ca_3Fe_2Si_3O_{12}$
Uvarovite	$Ca_3Cr_2Si_3O_{12}$

There is usually some mixing between the garnet species; for instance, the beautiful rose-red 'rhodolite' garnet found in Tanzania is a mixture of pyrope and almandine.

Grossular garnets, the calcium aluminum garnet species, can be colourless, yellow, orange, brown or green. The common name for yellow, orange or brown transparent grossular garnet is 'hessonite' or 'cinnamon stone' as it is often called. This beautiful gemstone is found in Canada at the Jeffrey Mine in Quebec and in Sri Lanka.



The 'Heart of the Ocean' necklace from the Titanic

The popularity of tanzanite soared in 1997 when the movie *Titanic* was released. Actress Kate Winslet wore the famous 'Heart of the Ocean' necklace, featuring a large, heart-shaped tanzanite surrounded by diamonds. This gorgeous necklace was dramatically hurled into the Atlantic Ocean at the end of the movie. The necklace centerpiece was originally supposed to be a blue sapphire, however, movie producers preferred the look of tanzanite.

5. Tavorite garnet and tanzanite

Pure grossular garnet is colourless. When both vanadium and chromium are present, with the $V_2O_3:Cr_2O_3$ ratio greater than 1:1, then a pure, vivid green colour results (Manson and Stockton, 1982). Light green tavorite crystals contain 0.1% vanadium, and dark green tavorite crystals contain up to 1.5% vanadium (Keller, 1992). It is reported that some vivid green grossular garnets, for instance those found at the Jeffrey Mine in Quebec, are coloured mainly by Cr_2O_3 (Wright and Grice, 1982).

Well crystallized tavorite crystals are very rare; most gem rough is as shards, fragments and pieces broken off from the potato-like nodules from which they formed. Faceted tavorite crystals of three carats or more are very rare. Spectacular well formed tavorite crystals were found, interestingly enough, at the Tanzanite deposit in the Merelani Hills area. The crystals are described in detail by Kane *et al.* (1990).

Physical and chemical characteristics of tavorite garnet are given in Table 5.2.

Well formed tavorite crystals fluoresce moderate to dull chalky orange under longwave ultraviolet light.

Tanzanite

Tanzanite is the popular name given to transparent blue zoisite. Zoisite, an orthorhombic polymorph of clinozoisite, is a species of the epidote group. Tanzanite tends to form bladed, edge-shaped crystals (Figure 5.1). Vanadium is responsible for the violet-blue colour of tanzanite. It substitutes for aluminum in the zoisite crystal structure. There are minor amounts of chromium present. The physical and chemical characteristics of tanzanite are given in Table 5.3.

Tanzanite crystals can grow very large. A 2,500-carat rough crystal was found in the late 1960s (Keller, 1992). Barot and Boehm (1992) note that faceted violet-blue tanzanite crystals tend to be flawless, because most inclusions that could fracture the stones during heat treatment are removed during the cutting process.

In its natural form, most 'mine-run' tanzanite crystals are greyish brown, greyish purple, brownish purple, bluish and greenish brown. After heat treatment for two

Table 5.2. Physical and chemical characteristics of tavorite garnet.

Chemical formula	$Ca_3Al_2(SiO_4)_3$ Member of garnet family – calcium-aluminum silicate
Crystal system	Cubic
Habit	Well formed crystals are exceedingly rare. Kane <i>et al.</i> (1990) measured eight different crystallographic forms, including one unique to the garnet group
Colour	Light to deep green
Hardness	7 to 7.5
Fracture	Subconchoidal to uneven fracture, no cleavage
Cleavage	
Parting	
Specific gravity	3.57 to 3.67
Pleochroism	None
Fluorescence	Well formed crystals fluoresce moderate to dull chalky orange under longwave ultraviolet light



Table 5.3. Physical and chemical characteristics of tanzanite.

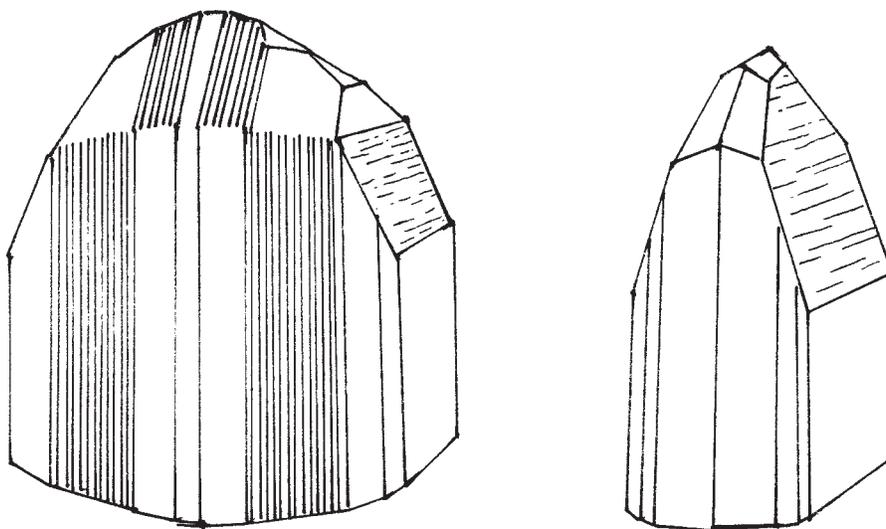
Chemical formula	$\text{Ca}_2\text{Al}_2(\text{SiO}_4)_3(\text{OH})$ Zoisite belongs to the epidote group of minerals
Crystal system	Orthorhombic
Habit	Crystals are generally well formed. Bladed, wedge-shaped
Colour	Greyish brown, greyish purple, brownish purple/blue
Hardness	6 to 7
Fracture	One good cleavage
Cleavage Parting	
Specific gravity	3.35 to 3.55
Pleochroism	Very strongly trichroic: blue, purple-red and green-yellow to brown
Fluorescence	Inert

hours at 320°C or higher, the undesirable yellow-green-brown colour is driven off, leaving a pretty violet-blue colour.

Transparent green zoisite has been discovered recently in the tanzanite mines at Merelani, Tanzania. Its colour is caused by chromium and minor vanadium. Barot and Boehm (1992) report that local miners call the stone 'Combat,' because it resembles the green of some military uniforms.

Tanzanite is strongly trichroic. This means that it will show a different colour depending on which direction it is viewed from. The three colours are sapphire blue, purple-red to red, and green-yellow to brown.

Figure 5.1. Tanzanite crystals.
Modified from Hurlburt (1969).



FIELD IDENTIFICATION OF TSAVORITE GARNET AND TANZANITE

Tsavorite garnet

Tsavorite rarely occurs as well formed crystals but instead forms rounded 'potato' nodules which are typically fractured, thereby reducing the amount of facetable material. In placer concentrate, tsavorite would probably show up as small, rounded green stones. The colour of green can be very pale to vivid emerald green, grading to a yellowish green. The green is vivid; it is very distinctive. Many Canadian geologists are familiar now or have at least seen some samples of chrome diopside; tsavorite is this shade of green, but is usually lighter in tone and slightly more yellowish. Kane *et al.* (1990) report that well formed tsavorite crystals from Tanzania fluoresce moderate to low dull chalky orange under longwave.

Tanzanite

In its rough form, tanzanite can resemble clear, slightly smoky or greyish quartz or topaz and shows about the same hardness. The bladed crystal form of tanzanite might be apparent, as opposed to the hexagonal crystal form of quartz. A piece of transparent tanzanite rough held up to sunlight and rotated will show a distinct colour change, depending on which direction the stone is viewed from. This is because tanzanite is so strongly pleochroic. Transparent quartz held up to the sun and rotated will not show a colour change.

GEOLOGY OF TSAVORITE GARNET AND TANZANITE DEPOSITS

Tsavorite garnet and tanzanite are found within the Mozambique Orogenic Belt. The tectonic setting of gemstone mineralization in the Mozambique Orogenic Belt is described by Malisa and Muhongo (1990). The physical and chemical controls on tsavorite formation are described by Key and Hill (1989), Suwa *et al.* (1979) and Key and Ochieng (1991). Keller (1992) provides a summary of the geology and mining of East African gem deposits. A firsthand account of the discovery and mining of tsavorite is given by Bridges (1982). The following descriptions of regional and deposit geology are taken from these sources.

Tsavorite and tanzanite deposits in East Africa are hosted in the great Proterozoic Mozambique Orogenic Belt, which trends north-south through Kenya and Tanzania (Figure 3.4). The Mozambique Orogenic Belt also hosts many other types of gem deposits, most notably the ruby deposits at Mangari described in Chapter 3. The portion of the Mozambique Orogenic Belt which hosts the tsavorite and tanzanite deposits is a unique succession of thick marbles and major graphitic units, which represent altered marine continental shelf deposits laid down over 800 million years ago. Subsequent collision-related deformation resulted in folding and thrusting accompanied by high-grade metamorphism. An additional metamorphic event proceeded subsequent to upright folding and finally, the last thermal event, the Pan-African Orogeny took place about 500 million years ago.



Geology and genesis of tsavorite garnet deposits

The most significant tsavorite deposits to date are hosted in the upper portions of the Durase Group, in the Lualenyi Member of the Mgama-Mindi Formation. The Durase Group is overlain by a thick monotonous sequence of quartz-feldspar gneiss interbedded with epidote amphibolites. The Mgama-Mindi Formation consists of orthogneiss, paragneiss, mica schist, kyanite schist, graphite schist and lesser quartzite, calc-silicate rock and marble.

Tsavorite garnet deposits are confined to where graphitic schists or gneisses are interbedded with or immediately adjacent to marble. The marble is dolomitic, coarse-medium grained, white to grey and commonly forms resistant high ridges on the flat grasslands. Accessory quartz, plagioclase, muscovite, diopside and grossularite are present in addition to disseminated graphite. The graphitic schists and gneisses are less abundant than the marble, and consist of quartz, alkali feldspar, biotite and graphite with accessory sillimanite, epidote, allanite, sphene, zircon, apatite, hematite and magnetite. The interbedded graphitic units and the marble have been folded and overturned. The graphitic gneisses are interlayered with schists and 10-cm to 2-m-thick marble bands. The rocks have undergone two metamorphic events, the first to the kyanite-almandine-muscovite subfacies of the amphibolite facies, and the second to the sillimanite-muscovite subfacies of the amphibolite facies. A third retrograde metamorphic event was of upper greenschist facies.

Bridges (1982) describes the mode of occurrence of tsavorite. Tsavorite is associated with gypsum in a thrust-fault plane within a graphite-gneiss horizon and overlain, at a distance of about 15 m, by marble. In other deposits, the marble will be in the immediate hanging wall of the 'ore shoot.' Tsavorite occurs as randomly distributed nodules, or 'potatoes,' averaging 5 cm in diameter. The nodules are commonly rimmed by a narrow green shell of microcrystalline scapolite, epidote, quartz, clinopyroxene and spinel. The crests and troughs of folds are the most favourable sites for tsavorite deposition. Bridges (1982) reports that fragments of green garnet are sometimes found in the surface dirt or in antheaps. Arid conditions preclude any placer alluvial deposits; most elluvial crystals are found by hand-jigging and sorting. The ore shoots are opened by removing the hanging wall or footwall with picks, shovels, jackhammers, and, rarely, blasting. The green garnet nodules are extracted using a six inch nail and small chisel and hammer. As they are chipped out, the valuable green fragments are caught in a spoon.

The graphitic schists and gneisses are enriched in vanadium. Key and Hill (1989) report that the graphite is derived from bituminous black shales, in which vanadium preferentially concentrates. They suggest that the great extent of graphitic gneisses within the Mozambique Orogenic Belt indicates a major phase of organic seabed activity during the Late Proterozoic. The vanadium content of graphitic gneisses is shown in Table 5.4.

Vanadium is relatively immobile during high-grade metamorphism (Key and Hill, 1989), so it would have remained in the original host rock to enter new metamorphic assemblages. Marble provided calcium, gneiss provided aluminum, and silicon came from feldspar and quartz. As mentioned above, vanadium was supplied by graphite derived from carbon-rich shales. Keller (1992) reports that upper amphibolite facies conditions for tsavorite garnet formation were suggested by Pohl and Niedermayr (1978). More recently, work by Key and Hill (1989) on the role of CO₂ in garnet

5. Tsavorite garnet and tanzanite

Table 5.4. Vanadium, chromium and titanium dioxide contents of graphitic gneisses from the Mozambique Orogenic Belt of East Africa, from Key and Ochieng (1989).

Locality	V (ppm)	Cr (ppm)	TiO ₂ (wt %)
KENYA			
Lualenyi	1259	732	0.78
OI Doinyo Ng'iro: low grade	748	284	1.41
OI Doinyo Ng'iro: high grade	1697	331	2.02
Taita Hills	1052	985	0.82
TANZANIA			
Morogoro	249	91	2.19
Merelani	446	72	1.31
Madini Pit	934	79	1.31
Daluni	680	219	1.10
MALAWI			
Katengeza	630	718	2.12
Lumbadzi River	588	1015	1.09
Lobi Pit	1902	701	3.37
ZIMBABWE			
Lynx Mine	239	152	0.29

crystallization suggests that granulite facies conditions were necessary for tsavorite garnet formation, where temperatures exceeded 750 degrees and pressures exceeded 5 kilobars. They note that geologically suitable areas which show only upper amphibolite facies metamorphism lack tsavorite deposits.

Geology and genesis of tanzanite deposits

The world's most significant tanzanite deposit, near Merelani in Tanzania, is situated in the crest of an anticlinal fold. The host rocks are the same sequence of 2.0 to 1.8-billion-year-old interbedded kyanite-sillimanite-biotite-graphitic gneisses and marbles that host the tsavorite deposits. Tanzanite crystals are found in the cavities or at the margins of boudinaged quartz veins which have developed in the fold hinge. Hydrothermally altered wallrock associated with tanzanite precipitation varies from 0.5 to 6 m wide and extends at least 9 km in length. The alteration assemblage consists of bytownite-grossular-diopside-zoisite.

Tanzanite, like tsavorite garnet, occurs in fault zones within interbedded graphitic gneisses and marbles. Tanzanite crystals have been dated at 585 million years (Naeser and Saul, 1974), about the time of massive pegmatite intrusion and the Pan-African event. Although some authors (Naeser and Saul, 1974) suggested that tanzanite mineralization was related to pegmatite intrusion, Malisa and Muhongo (1990) suggest that the tanzanite deposit formed after intrusion of the pegmatites during the final phase of the Pan-African orogenic event. Heated groundwater circulated through the metamorphosed and folded pile and accumulated vanadium, chromium and other chromophores. Tanzanite preferentially precipitated from hot hydrothermal fluids in the fold crests and along fold hinges. The distinctive-looking alteration zone represents the dissolution of the gneisses and marbles by hot hydrothermal fluids. The name 'merelanite' has been given to the bytownite-grossular-diopside-



zoisite assemblage. Tanzanite formed at temperatures less than 500°C and pressures of less than 2 kilobars.

Other gem minerals including tsavorite, chrome diopside and chrome tourmaline are associated with tanzanite at Merelani. Tanzanite also occurs as alteration shells on tsavorite 'nodules' in some southern Kenya tsavorite mines (Keller, 1992).

Barot and Boehm (1992) report that at least one portion of the Merelani deposit appears to be zoned. Miners report finding rare, green transparent zoisite crystals in the deep parts of the mine. Barot and Boehm (1992) suggest that the chromium-bearing green zoisite crystals formed under the same geological conditions as the vanadium-bearing violet-blue variety, but under deeper, hotter conditions. Yellowish or blue-green transparent zoisite forms in the transition zone.

It is interesting to note that the most well formed tsavorite garnet crystals ever found were discovered in the eastern block (Karo Pit) of the Merelani tanzanite deposit (Kane *et al.*, 1990).

EXPLORATION CRITERIA FOR TSAVORITE AND TANZANITE DEPOSITS

Like the emerald deposits in Colombia, the tsavorite garnet and tanzanite deposits in East Africa are unique, to date, in the world. It is difficult to predict how variable the conditions of formation may be for gemstone deposition when there is only one deposit to study. Even though high-grade metamorphic conditions are required for tsavorite garnets to form in East Africa, perhaps in other parts of the world variation in rock chemistry or some other feature will change the metamorphic grade required.

Controls on tsavorite garnet formation were first listed by Pohl and Neidermayr (1978) and expanded upon by Key and Hill (1989) and Key and Ochieng (1991). Most of the controls can also apply to tanzanite formation. The only difference is that tanzanite precipitated from hydrothermal fluids rather than through regional metamorphism. The exploration criteria for tsavorite garnet and tanzanite are as follows:

Host rocks

The target host rock is marble interbedded with graphitic schist or gneiss where the graphite is derived from bituminous black shales.

Graphitic gneisses are targets for ground and airborne electromagnetic surveys. In Kenya, enhancement of high-resolution satellite images is used to locate concealed graphitic gneiss/marble since the marbles have distinct spectral signatures (Key and Ochieng, 1991).

Metamorphic grade

Tsavorite garnets grew under granulite facies metamorphism conditions at temperatures of about 750°C and 5 kilobars. Key and Ochieng (1991) suggest that tsavorite will not grow when the metamorphic conditions are only upper amphibolite grade.

5. Tsavorite garnet and tanzanite

Tanzanite crystals precipitate from hot, vanadium-rich hydrothermal fluids, therefore one would suspect that the actual metamorphic grade of the host rocks is not as critical.

Geochemistry

Graphitic gneisses in East Africa are enriched in vanadium (up to 1697 ppm). Key and Ochieng (1991) list comparison values of 56 ppm for U.S.A. surficial deposits and 59 ppm vanadium for Canadian shield rocks. Vanadium is the colouring agent for both tsavorite garnet and tanzanite.

The anomalously high vanadium and chromium content of the graphitic gneisses are a target for soil/stream sediment geochemical exploration programs.

Structure

Mineralized rock is concentrated in intensely folded and faulted sequences of interbedded marbles and graphitic gneisses. Tsavorite garnet, tanzanite, and other vanadium- and chromium-rich gemstones will preferentially form 'nodules' and crystals in the nose and hinges of the fold.

A discussion of specific prospecting methods for tanzanite and tsavorite deposits is given in the paper by Simonet and Okundi (2003). This is one of the few 'nuts and bolts' papers on how to use various sophisticated geophysical and geochemical prospecting techniques to explore for coloured gemstone deposits. Besides the criteria listed above, Simonet and Okundi (2003) point out that graphite gneisses, when enriched in uranium, may be associated with high radioactivity, and in any case if they have cohesive graphite content, they may have a relatively low resistivity and generate self-potential anomalies. Tsavorite deposits tend to be small, with a width of 0.1 to 2 m extending 10 m to a few 100s m in depth (Table 3.9), so any grid sampling would have to be done on a very small (metre) scale. Surficial geology is important, since a thick soil cover can mask a geophysical response. The self-potential geophysical method has been tested in Kenya to delineate graphite-bearing units, however, this method was ineffective because the individual graphite flakes within the gneisses were not always interconnected and there was sensitivity to lateral variations in the degree of alteration of sulphide minerals.

In summary, a suitable target area for deposits of tsavorite and tanzanite is a highly deformed sequence of high-grade marbles and graphitic gneisses which is anomalous in vanadium, and, possibly, chromium.



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6. CHRYSOBERYL

INTRODUCTION

Chrysoberyl is a greenish yellow transparent gemstone of great hardness and durability that is named after the Greek word 'krisos' for golden and 'beryllos' for beryl. Chrysoberyl is a beryllium-aluminum oxide mineral that is genetically related to emerald in many deposits, so the two gems are often found together. Two well known rare and very expensive varieties of chrysoberyl — alexandrite and cat's-eye — display unusual optical effects. 'Plain' chrysoberyl, alexandrite and cat's-eye are all beautiful gemstones, but the rarity of alexandrite and cat's-eyes, in particular, make them among the world's most sought after gemstones.

The story of alexandrite, the most valuable and rare variety of chrysoberyl, goes back to the beginning of the 19th century to Imperial Russia. At that time, as described in Bancroft (1984), the Siberian city of Ekaterinburg, founded in 1723 by Tzar Peter the Great and named after his amorous wife, Catherine, was the historical and economic centre of the Ural Mountains. The lapidary factories at Ekaterinburg were already renowned for their work in the lapidary arts and stonecutting. Two events in the early 1800s further promoted the remote city: the discovery of large amounts of placer gold in the Urals, and the discovery of emeralds in the roots of an upturned tree, which led to the opening of the first emerald mine in 1831. Shortly after the emerald mines opened, a wonderful new gemstone that changed colour from green in daylight to red under artificial light was identified and duly named 'alexandrite' after the heir apparent to the Russian Throne at the time, soon to become Tzar Alexander I. Red and green, the two colours of the new gemstone were also the colour of the Russian Imperial Guard. The exciting new gem became a sensation in the Imperial Russian Court. It was decreed by the Tzar that the imperial lapidary in Ekaterinburg receive nothing but the best gem material to work with, including quality pieces from the treasure trove of emerald, chrysoberyl, alexandrite, aquamarine and blue topaz available in the Ekaterinburg area. Sadly, the substance of the Romanov regime could not keep pace with the splendor, and the end of Imperial Russian rule came on June 16, 1918 at Ipatiev House in Ekaterinburg, when Tzar Nicolas Romanov II and his family were murdered by the Bolsheviks.

Alexandrite is the variety of chrysoberyl which shows a mysterious change of colour effect. The finest examples of this exotic gem approach emerald green in daylight and raspberry red in incandescent light. Cat's-eye, or cymophane (from Greek meaning 'wavelike') as it is also called, is the other well known variety of chrysoberyl. This unusual gemstone is considered to be the most beautiful of all gemstones which show a chatoyant 'cat's-eye' effect. Chrysoberyl is an extremely hard and durable gemstone, so in its cat's-eye form, it takes an excellent polish. The

silvery colour of the eye, paired with the honey colour of the stone, is a striking combination. Cat's-eye chrysoberyl is popular with Japanese men who like to display this gem in rings, cuff-links and tie-tacks.

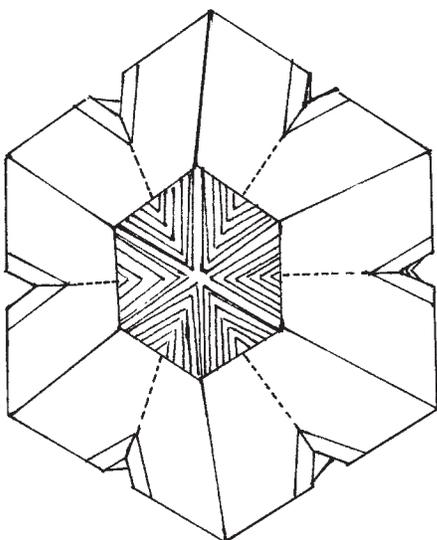
The remote mines in the Urals produced some of the best alexandrite crystals in the world. Competition arrived in 1986, at least for a short while, with a spectacular strike of alexandrite in Brazil which produced alexandrite crystals of a quality to rival that of the best Russian material. Other sources of alexandrite in the world today include Sri Lanka, Zimbabwe, Burma, Tanzania, Madagascar, India and Brazil. There are four recorded occurrences of alexandrite in Australia; the one near Dowerin has been reported on by Downes and Bevan, 2002. In most recent years, much of the world's alexandrite has come from Tanzania and Madagascar. Unusual 'blue' alexandrites, where the colour range is more blue-green than green in daylight, has been described from Brazil, Tunduru, Tanzania and Madagascar.

Alexandrites and cymophane are two of the most expensive gemstones in the world. A top-quality, one-carat alexandrite from Brazil or Russia can cost from \$3,000 to \$10,000. The Pala Gem International¹ website offers a fine, 1.89-carat Russian alexandrite, cushion cut, for \$18,144. Fine cat's-eyes will cost between \$2,500 and \$5,000 per carat. A splendid transparent greenish yellow chrysoberyl will cost between \$400 and \$800 per carat.

Richard Hughes of Pala Gem International provides a good summary of what to look for when buying alexandrite. The distinct colour change is the most important characteristic of alexandrite; the purer the red and green colour, without any brown or grey tones, the more valuable it is. Faceted alexandrites without any flaws are exceedingly rare in sizes over one carat. Chrysoberyl and its varieties are not usually subject to treatment like oiling, heat-treating, dying or other enhancement before entering the global gem market.

The author has noticed, partly due to the stone being featured on home-shopping TV networks, a profusion of synthetic alexandrite, or synthetic colour-change corundum in jewellery, which is sometimes misrepresented or misinterpreted to be natural alexandrite. Synthetic colour-change sapphires have been around since the early 1900s and are fairly common in antique jewellery or family heirloom jewellery.

Figure 6.1. Chrysoberyl crystal. Modified after Hurlburt and Klein (1977).



PHYSICAL AND CHEMICAL PROPERTIES

Chrysoberyl, an orthorhombic beryllium oxide mineral is normally yellow, greenish yellow or brownish yellow. The yellow, green and brown varieties owe their colour to Fe^{3+} . Alexandrite is the chromium-bearing variety of chrysoberyl. It is transparent green in daylight and red under incandescent light. Cat's-eye is the chatoyant variety of chrysoberyl which shows a sharp line on a honey golden-brown background.

The physical and chemical characteristics of chrysoberyl are given in Table 6.1.

Chrysoberyl is only rarely found as single untwinned prismatic crystals. It is usually found as contact twins, penetration twins or pseudo-hexagonal twins. When found as a contact twin, it generally forms a V-shape. The most sought after chrysoberyl crystals are complete pseudo-hexagonal twins, termed 'trillings' (Figure 6.1).

¹www.palagems.com



Table 6.1. Physical and chemical characteristics of chrysoberyl.

Chemical formula	BeAl ₂ O ₄ Beryllium aluminum silicate
Crystal system	Orthorhombic
Habit	Forms tabular crystals or short prismatic crystals. Commonly twinned – flattened, thin V-shaped twins or pseudohexagonal multiple-contact and penetration twins.
Colour	Chrysoberyl: yellow to yellow-green to brownish yellow Variety Alexandrite: In daylight is green to blue-green and in incandescent light is purple to purplish red.
Hardness	8.5
Fracture	Uneven to conchoidal fracture.
Cleavage Parting	May show three cleavages: distinct, imperfect and poor.
Specific gravity	3.71 to 3.75
Pleochroism	Alexandrite: strongly trichroic, greenish, reddish and yellowish Chrysoberyl: colourless, pale yellow, greenish yellow
Fluorescence	Usually inert, alexandrite may glow faint red

The remarkable colour-change effect that defines alexandrite is caused by trace amounts of Cr³⁺ replacing Al³⁺ in the chrysoberyl structure. Chromium affects the absorption and transmission of light through the stone. Daylight is richer in the blue-green part of the spectrum, whereas artificial light is richer in red. The strong pleochroism of alexandrite enhances the colour change.

The precise ‘eye’ in the cat’s-eye variety is caused by the reflection of light from very fine, densely packed fibrous inclusions in a crisp line along the dome top of a stone when cut into a cabochon.

Chrysoberyl is trichroic, meaning that it shows three pleochroic colours. Yellow chrysoberyl shows colourless, pale yellow and greenish yellow pleochroic colour. Alexandrite shows green, yellowish and red.

Common yellow-green chrysoberyl shows little or no reaction under ultraviolet light. Alexandrite shows a weak red glow under longwave and shortwave light.

FIELD IDENTIFICATION OF CHRYSOBERYL

Chrysoberyl is not the easiest gem to recognize in the field, and it may go unrecognized, especially in pegmatites. The ‘V-shape’ characteristic of chrysoberyl twins is diagnostic, as is the ‘trilling’ twin form. In addition, the strong trichroic pleochroism is very diagnostic, especially for alexandrite. Chrysoberyl which will show a cat’s-eye has a silky lustre.

Most gem chrysoberyl is generally found as waterworn crystals. It is an extremely hard and resistant mineral. Cassedanne and Roditi (1993) provide excellent descriptions of the appearance of chrysoberyl in both primary and alluvial deposits. They note that in alluvium, chrysoberyl occurs as rounded or subrounded grains, chips and variably sized fragments, commonly long or wide with right-angled or sub-square section, or else platy, with longitudinal grooves upon the larger

faces. As mentioned earlier, twins are common, mostly V-shaped formed by two prisms or flat crystals.

Cook (1999) and Jacobson (1982) provide good summaries of localities in the United States, Canada and world-wide that have produced nice specimens of chrysoberyl, not necessarily gem-grade, but with good crystal form. It should be noted that unlike corundum or beryl, chrysoberyl has no industrial importance, except as a gem material and as specimens for mineral collectors.

GEOLOGY OF CHRYSOBERYL DEPOSITS

Chrysoberyl is a rare mineral found in granitic rocks, pegmatites, and mica schists. Research on physico-chemical controls of chrysoberyl, alexandrite and cat's-eye mineralization is scarce. Soman and Nair (1985) and Soman *et al.* (1986) describe the genesis of chrysoberyl in the pegmatites of southern India. Franz and Morteani (1984) presented experimental data supporting their hypothesis that chrysoberyl formation in certain pegmatites was due to post-intrusion metamorphism. The role of beryllium and fluorine in gemstone mineralization in Sri Lanka was studied by Rupasinghe *et al.* (1984). Descriptions of chrysoberyl, alexandrite and cat's-eye deposits in Brazil are provided by Proctor (1988) and Cassedanne and Roditi (1993). A mention of chrysoberyl-alexandrite from Zimbabwe is given in Brown and Kelly (1984). Martin-Izard *et al.* (1995) studied an occurrence of alexandrite, emerald and phenakite associated with metasomatism at a granitic pegmatite-dunite contact zone at Franqueira, Spain. Marcos-Pascual and Moreiras (1997) compared the Franqueira occurrence to an occurrence of alexandrite, emerald and phenakite in the Ural Mountains, Russia. Chrysoberyl is discussed in several papers in the Mineralogical Society of American volume on Beryllium (Grew, 2002; Barton *et al.*, 2002; Černý, 2002).

The genesis of gem chrysoberyl deposits is poorly understood because many of the world's great deposits of these gems are in Brazil and Sri Lanka where the primary chrysoberyl deposits have completely decomposed. In fact, Cassedanne and Roditi (1993) provide an excellent description of the occurrences and report that all chrysoberyl production from Brazil is from detrital deposits. The heavy minerals associated with chrysoberyl, alexandrite and cat's-eye from detrital deposits in Brazil are amethyst, aquamarine, garnet, smoky quartz, topaz and tourmaline and lesser amounts of andalusite, rose quartz, moonstone, rutile, sapphire and zircon.

Chrysoberyl is relatively widespread in pegmatites, but much less so than beryl. Chrysoberyl tends to form within pegmatites, at a higher temperature than beryl, but then reacts with K-feldspar to form beryl + muscovite at decreasing temperature and increasing water, which accounts for its scarcity. After chrysoberyl forms, either within a pegmatite or by intrusion of beryllium-bearing pegmatites into ultramafic host rocks, metamorphic or tectonometamorphic events can have an effect on consolidated pegmatite bodies by promoting the breakdown of beryl into chrysoberyl-bearing assemblages. Grew (2002) describes the role that metamorphic processes can play with beryllium-bearing minerals, including chrysoberyl. He points out that during metamorphism, beryllium can be accommodated in common rock-forming minerals, so formation of beryl and chrysoberyl is relatively rare. Franz and Morteani (2002) describe how a metamorphic overprint is important for formation of chrysoberyl. There is a transition between emerald and chrysoberyl mineralization



related to metamorphism as opposed to metasomatism. Most emerald and alexandrite deposits show the typical appearance of metamorphic porphyroblasts with a crystal size of less than 2 cm in length, which indicates metamorphic origin. In addition, pegmatites can be strongly tectonized with original K-feldspar transformed into albite, which indicates the strong influence of deformation and metasomatism during emerald formation (Franz and Morteani, 2002).

Deposits of chrysoberyl, alexandrite and cat's-eye can be divided into three broad types, however, all three types may be subject to regional metamorphic or tectonometamorphic events.

1. Chrysoberyl associated with pegmatites intruded into ultramafic rocks.
2. Chrysoberyl associated with pegmatites intruded into aluminum-rich rocks.
3. Chrysoberyl as a primary mineral of rare-element pegmatites.

CHRYSOBERYL ASSOCIATED WITH PEGMATITES INTRUDED INTO ULTRAMAFIC ROCKS

Chrysoberyl is associated with other beryllium minerals such as emerald and phenakite in metasomatic contact zones developed between beryllium-bearing granitic pegmatites and ultramafic rocks or their metamorphosed equivalents. The biotite schists associated with this deposit type are important host rocks for emerald, and details of many of these deposits are described in Chapter 4. The schematic model for emerald mineralization shown in Figure 4.6 also applies to chrysoberyl. Černý (2002) discusses the uncertainty in applying the desilicated pegmatite model to some of the emerald-alexandrite-chrysoberyl deposits in the Ural Mountains, Russia.

Franqueira emerald-alexandrite-phenakite deposit, Spain

A paper by Martin-Izard *et al.* (1995) describes geological and geochemical information on the Franqueira occurrence of chrysoberyl (alexandrite variety), emerald and phenakite, which is the first documented example of such a deposit in western Europe. The Franqueira deposit was exposed during road construction in 1971 when a local school teacher noticed emerald crystals (Calvo and Garcia, 1997). Alexandrite crystals were first noted in 1990. The deposit host rock is dunite associated with hornblende gabbro which has been intruded and metasomatically altered by granitic pegmatite. The beryllium content in the pegmatite is 18 ppm (Martin-Izard *et al.*, 1995; Table 6.2). The dunite is composed mostly of olivine, some of which is partially serpentized. Chromite is disseminated through the dunite. Nickeline, maucherite, pyrrhotite and small quantities of pentlandite, westerveldite, millerite and chalcopyrite fill cavities in the dunite. At the contact between pegmatite and dunite, the dunite has almost completely altered to phlogopite. Away from the pegmatite contact, the dunite has altered to tremolite. Immediately surrounding the dunite is a band of orthoamphibole. Simple zoned pegmatites with aplite borders contain quartz, albite and muscovite with rare K-feldspar. Apatite, tourmaline and zircon are accessory minerals. Alexandrite, emerald and phenakite occur in the phlogopite schist marking the metasomatic

6 . Chrysoberyl

Table 6.2. Representative whole-rock compositions, Franqueira Suite, from Martin-Izard *et al.* (1995).

Rocks	Pegmatite	Phlogopite	Tremolite	Altered Dunite	Marum* Dunite	Gabbro
Wt %						
SiO ₂	74.8	44.18	56.97	48.22	39.8	47.26
Al ₂ O ₃	14.48	14.99	4.76	3.07	0.04	21.75
Fe ₂ O ₃	0.54	9.31	4.86	8.68	7.24	12.57
MgO	0.11	18.28	18.38	30.88	49.93	1.14
CaO	0.33	0.04	10.61	3.61	0.05	12.15
Na ₂ O	5.58	0.28	0.25	1.11	0.00	0.57
K ₂ O	1.84	10.27	2.03	1.33	0.00	0.52
TiO ₂	0.01	0.44	0.32	0.12	0.00	0.52
MnO	0.44	0.09	0.10	0.12	0.11	0.24
P ₂ O ₅	0.12	0.07	0.04	0.06	0.00	0.21
Cr ₂ O ₃	0.00	0.21	0.41	0.36	0.42	0.01
Loss on ignition	1.80	1.40	1.10	2.20	2.52	1.90
ppm						
As	5	151	6	1220	No data	10
Ni	10	500	353	1547	2520	12
Cu	2	29	3	4	4	24
Co	5	49	12	69	No data	5
Be	18	9	6	4	No data	20
Li	247	568	173	22	No data	49
Ba	135	1288	161	34	No data	159
Sr	32	41	86	29	0.00	434
La	16	6	19	2	No data	81
Zr	10	21	29	5	No data	396
Y	5	5	5	5	No data	120
Total iron as Fe ₂ O ₃						
*Chemical composition of dunite from the Marum Ophiolite (in Middlemost, 1985) for comparison with Franqueira altered dunite.						

contact zone between the pegmatite and dunite. Accessory minerals are tourmaline, garnet, apatite and zircon.

The genesis of this deposit, as presented by Martins-Izard *et al.* (1995), resembles that of similar emerald-alexandrite deposits in the Urals, Brazil and Zimbabwe. Fluid inclusion and geochemical data presented by Martin-Izard *et al.* (1995) suggest that gemstone formation took place when dunite and hornblende gabbro derived from obducted ophiolite complexes were intruded by peraluminous heterogeneous two-mica granites and associated pegmatite bodies. Pegmatite fluids, rich in beryllium-boron-phosphorus intruded the dunite and flooded the dunite with water, silicon, aluminum and potassium. In the metasomatic zone closest to the dunite, orthoamphibole (anthophyllite) and phlogopite crystallized. Tremolite developed further away from the dunite, incorporating silicon and water introduced from the pegmatite. The dunite provided the magnesium and chromium necessary to form anthophyllite, phlogopite and tremolite. Tourmaline, apatite, then the alexandrite variety of chrysoberyl, and phenakite formed in the metasomatic zone. Emerald,



the last beryllium mineral to form, partially replaces chrysoberyl and lastly phenakite. Precipitation of beryllium minerals took place at about 400°C.

Marcos-Pascual and Moreiras (1997) noted the similarity between the Franqueira alexandrite, emerald and phenakite deposit to similar deposits, such as Tokovaja, in the Ural Mountains, Russia. Both deposits show the same mineral assemblage of beryl, chrysoberyl and phenakite and they have similar geology and alteration. The Tokovaja deposit is much larger and shows more variety of accessory minerals, whereas the Franqueira deposit is only visible for 15 to 20 m, but may be part of a larger deposit. Beryllium minerals at both deposits formed in the metasomatic contact zone between acidic rocks (granites and pegmatites) and ultramafic rocks such as dunites and gabbros. In both deposits, beryllium, boron and phosphorus migrated into the more mafic rocks and transformed these rocks into phlogopite. Gem minerals, including emerald, alexandrite and chrysoberyl, generally form within the metasomatic contact zone. At the Tokovaja deposit, the metasomatic contact zone is complex and consists of serpentinite, talc-serpentinite, talc, talc-chlorite, talc-phlogopite, tremolitic rocks, amphibolites, amphibole-gneisses, quartzite and others. The mineral assemblage associated with alexandrite at the Tokovaja deposit consist of phlogopite, phenakite, apatite, tourmaline, beryllium-margarite, fluorite and some beryl.

Černý (2002) pointed out that there is some ambiguity as to whether the Ural Mountain emerald-alexandrite deposits are actually derived from regional metamorphism as opposed to contact metasomatic events.

In Brazil, Cassedanne and Roditi (1993) explain that chrysoberyl and alexandrite from granitic pegmatites associated with ultramafic rocks are collected as by-product of emerald mining. In the Serra de Jacobina area which is host to the large Carnaiba emerald mine, quartz, apatite, biotite, molybdenite, emerald and minor scheelite and alexandrite are found near the contact of pegmatites intruding a sequence of quartzite and chromium-rich ultramafic rocks.

CHRYSOBERYL ASSOCIATED WITH PEGMATITES INTRUDING ALUMINUM-RICH ROCKS

As mentioned earlier, there is uncertainty over to what extent regional metamorphism, as opposed to metasomatic reactions between silica-poor country rocks and pegmatites, are involved in the formation of chrysoberyl. Franz and Morteani (1984) suggest that the mineral assemblages in pegmatite samples from Kolsva, Sweden and Marsikov, Czechoslovakia indicate that chrysoberyl formation is due to a post-pegmatitic event at high pressure and temperature conditions.

Although gemstones *in situ* are very rarely found in Sri Lanka, detailed geochemical surveys have helped determine the character of the source rocks for the many gemstones found there. Two of the most valuable gemstones, of many, found in Sri Lanka are corundum and chrysoberyl, including the phenomenal varieties, alexandrite and cat's-eye. As mentioned in the corundum chapter, it is believed that corundum crystals formed during regional granulite-facies metamorphism of aluminous sedimentary rocks or in the contact zone of aluminum-rich sedimentary rocks intruded by pegmatites. In Sri Lanka, Rupasinghe *et al.* (1984) studied the geochemistry of beryllium and fluorine in the gem fields and determined that

beryllium-enriched pegmatitic fluids associated with chamockitic magmatism intruded and reacted with aluminum and silicon in the highly aluminous metasedimentary country rocks.

The South Kerala area of India is host to a field of chrysoberyl pegmatites derived from tectonomagmatic activity during early Palaeozoic (Soman and Nair, 1985). The pegmatites are associated with a niobium anomaly and high thorium and uranium values. The gem fields of southern India, Madagascar and Sri Lanka may share a similar provenance, as discussed in the chapter on ruby and sapphire.

At Dowerin, western Australia, emerald, chrysoberyl and rare alexandrite are in granulite facies gneiss adjacent to the margin of a batholith. The beryllium minerals are in plagioclase-quartz-biotite-garnet gneiss and cross-cutting tourmaline-plagioclase veins situated adjacent to lenses of actinolite-cumingtonite-phlogopite schist. Chrysoberyl formed during granulite-facies metamorphism, where the beryllium and boron required to form chrysoberyl, beryl and tourmaline may have been released by metamorphic reactions in host-rock metapelites during prograde granulite-facies metamorphism (Downes and Bevan, 2003).

CHRYSOBERYL IN RARE-ELEMENT PEGMATITES

Černý (2002) describes the occurrence of beryllium minerals, including chrysoberyl, in granitic pegmatites. Massive chrysoberyl is present in what he terms 'run of the mill,' moderately differentiated, relatively high temperature pegmatites, such as those in the Black Hills of South Dakota.

Cassedanne and Roditi (1993) provide an excellent review of chrysoberyl in Brazil contained within pegmatites not obviously associated with any nearby ultramafic rock. The pegmatites intrude granite, gneiss and mica schists. In some cases, the chrysoberyls recovered were the rare and highly sought-after trilling twins. Cassedanne and Roditi (1993) commented on the scarcity of known chrysoberyl deposits *in situ*, especially in light of the fact that chrysoberyl is so widely distributed as a detrital gemstone in Brazil. They confirmed that chrysoberyl does not coexist with aquamarine in Brazilian pegmatite deposits, but instead is found close to the base of the aquamarine-bearing pegmatite zones. Chrysoberyl occurs in quartz veins with feldspar and mica and in thin pegmatite veins. The pegmatite veins, being characteristically thin, look uninteresting and uneconomic at first glance.

OTHER

The Masters thesis of G.A. Rock² describes physico-chemical controls on alexandrite formation where granitic rocks have intruded a metasedimentary sequence. Analyses of samples collected from the Golden Mountain Granitic Massif indicate that alexandrite formed at amphibolite facies conditions at temperatures of 450 to 550°C and pressures of 4.1 to 5.4 kilobars. Staurolite, kyanite, garnet and alexandrite formed in the metasomatic contact zone between granitic magma of the massif and metasedimentary interbanded felsic and mafic schists. Alexandrite preferentially

²From summary of M.Sc. thesis by Gustavo Adolph Rock, 'Petrology and Genesis of Alexandrite Mineralization in the Southern Border of the Saws Golden Granitic Massif (GO),' University of Brasilia, Institute of Geosciences, thesis supervisor: Prof. Márcia Abrahão Moura. Translated from University of Brasilia website, www.unb.br.



formed associated with mafic bands of garnet-staurolite-kyanite-biotite-quartz schist which contained elevated chromium levels. It is suggested that beryl initially crystallized in the granitic magma but decomposed to chrysoberyl in the later stages of contact metamorphism. The entire area was subject to a later greenschist facies orogenic events which caused cracking of the garnet, kyanite, staurolite and alexandrite crystals.

The chrysoberyl placer deposits of Brazil

For almost 200 years, tens of thousands of carats of chrysoberyl, alexandrite and cat's-eye have been mined from the famous pegmatite districts in Brazil. The deposits are described by Proctor (1988), and Cassedanne and Roditi (1993). The chrysoberyl is mined from placer deposits in the Santana and Americana valleys. In the Americana valley, local cattle ranchers had been throwing the gems away until they were identified in the early 1900s. The bedrock is granite and granitic gneiss with innumerable pegmatite intrusions. The chrysoberyl is found in colluvial-alluvial gem gravels beneath layers of red soil and grey or black clay and/or sands of various colours. Accessory heavy minerals include black tourmaline, beryl, topaz, rhodolite garnet, andalusite, quartz and olivine. The pegmatites in the area are very decomposed, and it is very rare to find chrysoberyl *in situ*.

EXPLORATION CRITERIA FOR CHRYSOBERYL

Chrysoberyl is so closely associated with emerald in the biotite-schist type of emerald deposit that the same exploration criteria defined in Chapter 4 for emerald deposits hosted in ultramafic rock apply to chrysoberyl.

Chrysoberyl can also be found in rare-element-rich pegmatites. The exploration criteria outlined in Chapter 7 would apply. It should be noted that chrysoberyl generally forms in deeper, hotter pegmatites than those which host aquamarine and topaz deposits.

Cassedanne *et al.* (1992) noted that chrysoberyl does not coexist with aquamarine in Brazilian primary pegmatite deposits. Chrysoberyl tends to occur in quartz (with feldspar and mica) veins and in thin pegmatites devoid of aquamarine, easily missed or dismissed because of their narrow size. Typically, the chrysoberyl-bearing pegmatites occur close to the base of the aquamarine producing zones.

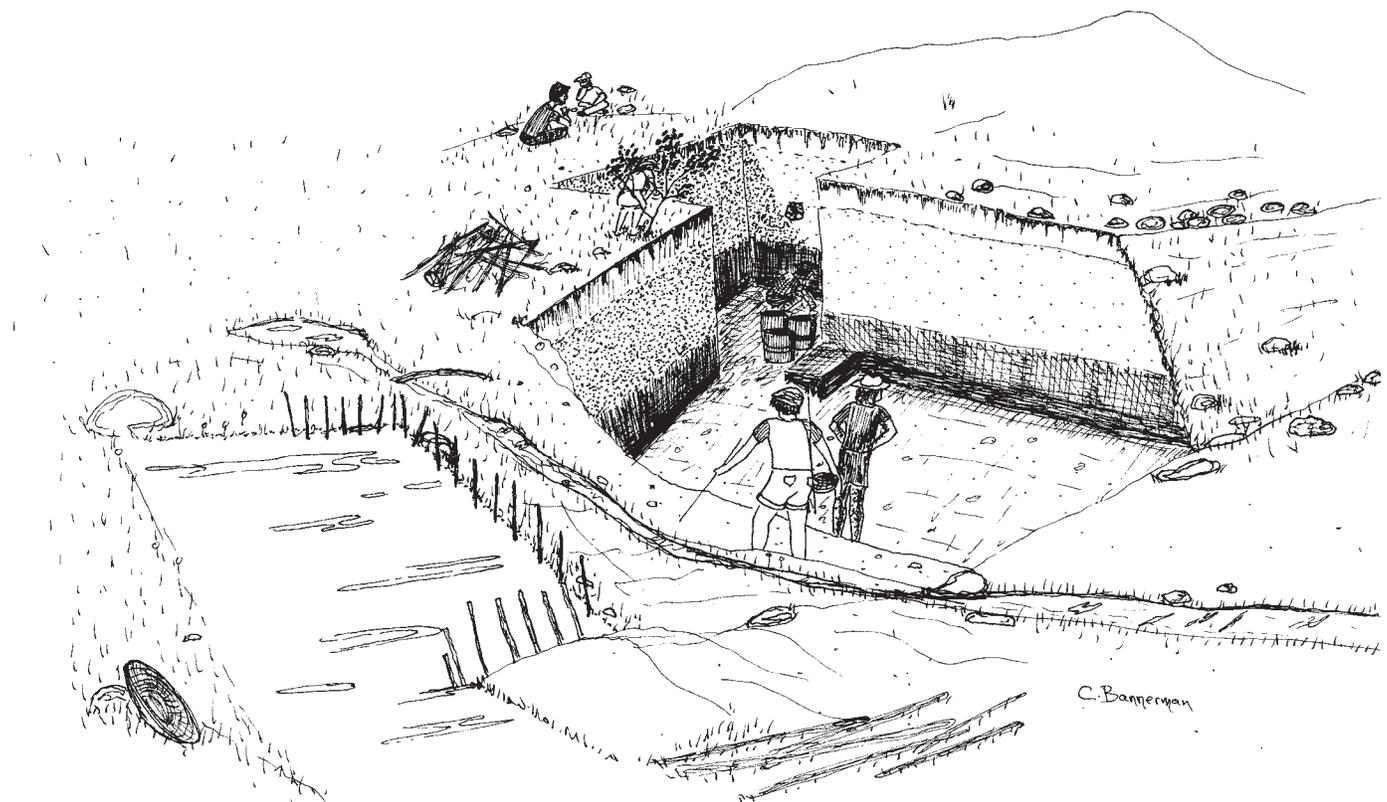
The discovery of alexandrite crystals at Hematita

There is a certain difficulty in documenting the geology of new gemstone finds in Brazil because of the army of 'garimpeiros' which invade an area after news of a discovery. According to Brazilian law, a licensed garimpeiro may work unprohibited on any state-owned lands where gems and minerals have been found, and on private land with 'consent' of the owner. Over the years, several spectacular staking rushes for Brazilian gemstones have taken place, none as savage as the Hematita staking rush for alexandrite.

As reported by Proctor (1988), in 1986, two 10-year-old boys collected rough gems from two brooks which cut through a homestead on a plantation owned by a Brazilian steel company. They sold their latest finds to a man in the nearest city who mistook

the stones for andalusite. Eventually a gem dealer recognized the pebbles as the best alexandrites, without exception, in the world. By this time, one of the boy's fathers and some others were attempting to dig out more of the stones from the brooks. Two of the parties involved formed companies and after the usual bickering and squabbling between the two groups, they joined up and began mining, trying to suppress the news of their spectacular discovery. The first five faceted stones, totalling only 11 carats, sold for \$40,000 to Japanese buyers in January, 1987. One month later, several gem dealers and garimpeiros discovered the location of the find and by the end of March, over 3,000 garimpeiros had invaded and completely dug up the 200 m x by 150 m small valley and brook, hoping to get a share of the

riches. Cassedanne and Roditi (1993) describe the area as an almost unsorted kaolinitic gravel in which the alexandrite grade is exceptionally high. A few small pieces of alexandrite rough represented a fortune, and there was not enough land, literally, to go around. At times the miners slept standing or sitting up, like packs of Emperor penguins, shoulder to shoulder since they dared not leave their pits unguarded. Fights, gun battles and robberies — carried out by the obligatory professional thieves — and the general chaos prompted the military police to move in and close the area on June 18, 1987 by putting a barbed wire fence around the entire property. The prospectors, without money or food and with no way now of making a living, rebelled and hundreds of miners each night would go through



the fence and mine or battle with the 60 to 100 military police, who, in many cases, were sneaking off and mining in the pits themselves. An American gem dealer arrived on August 18 and re-opened the mine, allowing 300 of the 800 garimpeiros back inside. Within two days, another 2,000 garimpeiros arrived and one of the most violent nights in Minas Gerais mining history ensued. In August, the military police rerouted one of the creeks and flooded the mining area. Cassedanne and Roditi (1993) report that the detrital reserves of this deposit, the richest concentration of alexandrite in the world, are nearly exhausted.

A lively debate broke out in the gemological community regarding the quality of these alexandrites, and whether they were more outstanding than the historical material from the Ural Mountains. The colour change of alexandrites from both localities, Hematita and the Urals is truly outstanding. Under incandescent light the stones are raspberry red, and under fluorescent light, the colour changes to beautiful blue and blue-green.

Given the situation in the area (members of the International Gemological Conference in 1987 were allowed only 45 minutes at the mine), there have been no geological or

geochemical studies carried out on the gravels or possible host rocks for these fabulous crystals. Some of the crystal faces are very sharp, indicating less than 100 m of movement downstream. Proctor (1988) reports that geologists who were able to study the gem gravels felt that the alexandrites may have originated from decomposed pegmatites, and that the alexandrites in this deposit, unlike the usual emerald-alexandrite deposits in the Urals and elsewhere in Brazil, may have formed within a pegmatite rather than from interaction between pegmatites and chromium-rich rocks.

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7. GEM-BEARING PEGMATITES

INTRODUCTION

If a person had to choose one rock type in which to prospect for gemstones, pegmatites would be the obvious choice. More beautiful and valuable gemstones are associated with pegmatites than with any other rock type. Pegmatites are genetically linked to almost all of the gemstones discussed in this report. Gem tourmaline of all colours, aquamarine, chrysoberyl, kunzite, garnet, topaz and many other gems and rare minerals are found in the fabulous pegmatite districts of many countries, including Brazil, Madagascar, Mozambique, Namibia, Afghanistan, Pakistan, Russia, and the United States (California, Colorado and Maine). In Canada, there has been production of mineral specimens and some gem crystal from pegmatites in British Columbia, Northwest Territories, Manitoba, Ontario and Quebec, however, none have matched the splendor of the gigantic, flawless crystals of tourmaline, topaz, aquamarine and many others recovered from pegmatites in other parts of the world.

Many of the gemstones found in the rich alluvial deposits of Sri Lanka are believed to be derived from decomposed pegmatites. Most of the world's emerald deposits are genetically linked to pegmatite intrusion into ultramafic rock or metamorphosed ultramafic rock. Ruby and sapphire are sometimes found when silica-poor pegmatites intrude ultramafic rock.

Gemstones found in pegmatites may form spectacular crystals of gigantic proportions under the proper pressure-temperature conditions. Proctor (1984) gives an account of the discovery and extraction of a 110.5 kg (244 lb) doubly terminated, hexagonal aquamarine crystal which was absolutely flawless; one could read through it from end to end. The crystal, which measured 48.5 x 38 cm, was discovered in the gem-rich Brazilian state of Minas Gerais in 1910. A miner digging a colluvial-alluvial pit in search of gemstones had given up in disgust, and two brothers took over the abandoned working. Less than one metre below the pit bottom they discovered the crystal. At that time there was a strong relationship between the beginning Minas Gerais gem trade and German gem dealers who would ship their purchases to the gem cutting and lapidary centre at Idar-Oberstein, Germany. The two brothers sold the crystal to two German gem dealers who happened to be in the area, for the equivalent of \$25,000. It was estimated that the crystal would produce 200,000 carat of finished gems. It took 20 days to haul the aquamarine crystal to the coast where it was duly shipped to Germany and offered for sale at \$139,000. When no buyer stepped forward, the crystal was cut up and the only uncut remnant, at 6 kg, ended up in the American Museum of Natural History in New York. It is estimated that the current value of this 6 kg remnant of the original crystal is close to \$25 million dollars.

This chapter provides a summary of pegmatite geology and genesis in addition to brief descriptions of the three most valuable, of many, gemstones that are commonly found in gem pegmatites: topaz, tourmaline and aquamarine. In addition to pegmatites, topaz can also occur in rhyolites and greisens (see Chapter 8). Gem topaz found associated with rhyolite is discussed in Chapter 8. Pegmatites are also known for their production of lesser known gemstones such as morganite (pink-peach beryl), kunzite (lilac-pink spodumene), smoky quartz and charming arrangements of sharply crystallized rock-forming minerals such as mica and feldspars.

PEGMATITE-RELATED GEMSTONE DEPOSITS

There are two broad types of gemstone deposits associated with pegmatites:

1. Gemstones that crystallize within a pegmatite (tourmaline, aquamarine, topaz).
2. Gemstones that crystallize in the metasomatic contact zone between a pegmatite and host rock (ruby, sapphire, emerald, chrysoberyl, alexandrite).

Metasomatism means 'change in body or substance.' For example, when a granitic body intrudes limestone or marble, calc-silicate minerals form a 'skarn' along the contact zone. When carbonatites or silica-undersaturated magmas intrude limestones, a 'fenite' composed largely of sodic clinopyroxene and amphibole forms along the contact zone. When the intruding body is a pegmatite magma, rich in volatiles and rare-elements, rare minerals including gemstones may form in the contact zone, depending on the host rock composition. If the intruding pegmatite magma is a rare silica-poor type, and the host rocks are chromium-bearing ultramafic rocks, then corundum crystals including gem ruby and sapphire may form. If the pegmatitic magma is the more common granitic type and contains the rare element beryllium, then beryllium-bearing minerals like emerald and alexandrite may form in the contact zone with a chromium-bearing ultramafic rock. This type of pegmatite-related gemstone deposit has been described in previous chapters.

This chapter will focus on the first category gemstones that crystallize within a pegmatite.

THE RARE-ELEMENT CONNECTION

Although pegmatites are relatively common, only a very small percentage contain rare elements and, of those, even fewer contain the rare elements required for gemstone crystallization. Rare elements such as beryllium, boron, lithium, manganese, phosphorus and fluorine can combine with available silicon, aluminum and oxygen to form aquamarine, tourmaline, topaz, chrysoberyl, morganite, kunzite and other gem minerals. For the prospector and exploration geologist, pegmatite prospecting for gemstones has an added advantage in that certain rare elements found in the pegmatites are mined for use in industry. Černý (1991a) lists lithium, rubidium, cesium, beryllium, gallium, scandium, yttrium, rare-earth elements, tin, niobium, tantalum, uranium, thorium, zirconium and hafnium as examples of rare elements mined from pegmatites. A brief listing of the uses of rare elements mined from pegmatites is as follows (from Černý, 1991a):



Lithium: used in storage batteries, ceramic ware and smelting of aluminum ores.

Beryllium: Beryllium alloys are used in aircraft, satellite and space-vehicle frames; beryllium metal is used in heat shields, rocket motors, aircraft and space-shuttle brake discs, inertial navigation systems and X-ray windows.

Gallium: Used in light-emitting diodes, photodiodes, laser diodes and solar cells, fibre optics and computers.

Tantalum: Used in computers, capacitors of solid-state circuits, chemicals and prosthetic devices.

Gemstone-bearing pegmatites are a subclass of the rare-element group of pegmatites, and most of the published information on rare-element pegmatites can be adapted for gemstone prospecting. An excellent review of the petrogenesis and classification of rare-element granitic pegmatites is given by Černý (1991a,b). A global review of gem-bearing pegmatites is given by Shigley and Kampf (1984). A review of exploration criteria for rare-element pegmatites is compiled by Trueman and Černý (1982). A detailed summary of the mineralogy of the element beryllium in granitic pegmatites is given by Černý (2002).

DEFINITION OF PEGMATITE

The term pegmatite, first used in the early 1800s, is mainly a textural term used to describe an extremely coarse-grained igneous rock. The vast majority of pegmatites are chemically and mineralogically very similar to ordinary granites, and are therefore referred to as 'granitic pegmatites.' A few unusual corundum-bearing pegmatites (see chapter on ruby and sapphire), which contain mainly alkali feldspar with little or no quartz, are a rare exception.

Pegmatites commonly form during the final stages of magmatic intrusion and can crystallize at the same time as the host magma; these are called syngenetic pegmatites. Syngenetic pegmatites commonly form distinct segregations, lenses or veins within the granitic host. Epigenetic pegmatites are more common and form when late-stage volatile-rich pegmatitic fluids are injected into a host rock during the late stages of granitic magma emplacement. Pegmatites typically occur as swarms of dykes, veins or flat lenses within or at the margins of batholiths, stocks or other granitic intrusions.

An essential process in pegmatite formation is 'fractionation,' which is the precipitation of successive crystal fractions from a residual magma. A highly fractionated or 'evolved' pegmatite contains concentrations of boron, lithium, beryllium, phosphorus, fluorine and water. During the final stages of pegmatite crystallization, volatile-rich fluids may exsolve and produce primary pockets or vugs that may be lined with beautiful gem-quality crystals.

The host granite from which rare-element and gemstone-bearing pegmatites are derived is called 'fertile' as opposed to 'barren.' Much research has concentrated on determining characteristics of fertile granites as a starting point for rare-element pegmatite prospecting.

MINERALOGY

The mineralogy of most granitic pegmatites reflects that of granite: quartz, feldspar (microcline and plagioclase) and mica (muscovite and biotite) along with common accessory minerals (Table 7.1).

Pegmatites which contain the classic quartz-feldspar-mica mineral assemblage are often called simple pegmatites and are of little interest for the purpose of this report. Zoned pegmatites which contain accessory rare-element minerals are far more interesting in terms of gemstone prospecting (Figure 7.1, Table 7.1). Complex pegmatites are those which are zoned with metasomatic alteration or replacement zones surrounding them.

Table 7.1. Chemical and mineralogical comparison of granite and granitic pegmatites. From Shigley and Kampf (1984).

Component/phase	Granite ^a	Common pegmatite ^b	Gem bearing pegmatite ^c
Chemistry	percent	percent	percent
SiO ₂	72.34	74.2	70.22
Al ₂ O ₃	14.34	15.0	17.2
FeO + Fe ₂ O ₃	1.81	0.6	1.76
TiO ₂	0.26	–	–
MnO	0.02	–	0.28
H ₂ O	0.36	0.6	0.39
MgO	0.37	–	trace
CaO	1.52	0.3	1.36
Na ₂ O	3.37	4.6	4.45
K ₂ O	5.47	4.2	2.85
Li ₂ O	–	–	1.49
P ₂ O ₅	–	0.3	0.7
F	–	0.1	0.11
B ₂ O ₃	–	–	0.18
BeO	–	trace	trace
Rb ₂ O + Cs ₂ O	–	–	trace
Total	99.86	99.9	100.36
Mineralogy			
Major phases	Microcline	Microcline	Microcline
	Quartz	Quartz	Quartz
	Plagioclase	Albite	Albite
	Muscovite	Muscovite	Muscovite
	Biotite		
Minor phases		Beryl	Beryl
		Tourmaline	Tourmaline
		Apatite	Apatite
		Garnet	Garnet
			Spodumene
			Rhodizite
			Lepidolite
			Hambergite
			Danburite

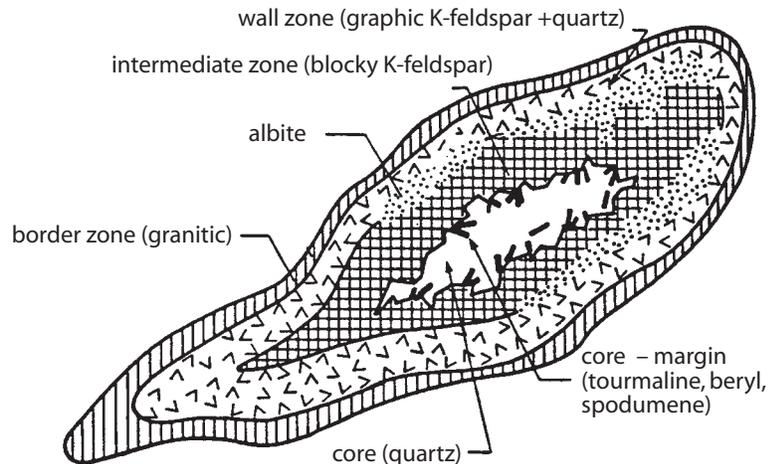
a Westerly granite, Westerly, Rhode Island (Tuttle and Bowen, 1958)

b Diamond Mica pegmatite, Keystone, South Dakota (Norton, 1970)

c Gem-bearing pegmatite, Manjaka, Madagascar (Schneiderhohn, 1961)



Figure 7.1. Cross section of a complex pegmatite.



Pegmatites can also be classified according to the geological environment in which they formed. Gem-bearing pegmatites and those with the most potential for rare-earth elements are those (often called rare element and miarolitic) which formed at relatively shallow depths beneath the earth's surface. These pegmatites contain rare elements which do not fit into the quartz, feldspar or mica mineral structures. Pegmatites which form at depths of less than 7 km are the best hosts of gemstone mineralization. These types of pegmatites are clearly igneous in origin, whereas deeper, simple abyssal or muscovite pegmatites are thought to form through the partial melting of, or metamorphic recrystallization of, rocks essentially in place. These deeper pegmatites contain fewer rare-earth elements and more uranium, thorium and molybdenum.

Shigley and Kampf (1984) describe the relationship between geological environment and depth of emplacement:

1. Pegmatites formed at great depths are commonly found in metamorphosed rocks that form the ancient cores of continents. (Examples: U-REE pegmatites near Bancroft, Ontario)
2. Pegmatites formed at deep to intermediate depths are commonly found in folded and metamorphosed rocks in mountain belts. (Examples: mica pegmatites in Soviet Union, beryl-spodumene pegmatites of Black Hills, South Dakota)
3. Pegmatites formed at shallow depths are generally associated with large, buried masses of intrusive igneous rocks such as plutons or batholiths that most commonly underlie mountainous areas. This class of pegmatite, often called rare-element or miarolitic, is associated with gemstone crystallization. An important subclass of this group, called LCT (for lithium, cesium and tantalum) tends to be peraluminous and commonly contains beryllium, rubidium, tin, gallium and boron. The NYF subtype of pegmatite stands for niobium, yttrium and fluorine enrichment, and is characterized by the absence of beryllium phosphates and lower amounts of boron (Černý, 2002). (Examples: Southern California, Madagascar and Minas Gerais district in Brazil)

PEGMATITE POCKETS AND CAVITIES

Gemstones in pegmatites are commonly found in 'pockets' which are irregular openings, usually towards the centre of the pegmatite (Figure 7.2). In syngenetic pegmatites, the pockets occur mainly in the roof zones or apexes of granitic intrusions. It is estimated (Shigley and Kampf, 1984) that less than 1% of all pegmatites contain pockets and even fewer have the rare elements necessary to form gem minerals. They report that even though some pockets several metres across have been reported, most pockets are less than a few centimetres wide. Pocket distribution is very irregular and unpredictable. Within a single pegmatite region, some pegmatites will contain rich gemstone pockets and others nearby will have no pockets, let alone gem-bearing ones. Even the mineral content from pocket to pocket may vary. Shigley and Kampf (1984) report that there is no relationship between the dimensions of a pegmatite and the size, shape and distribution of its pockets. Pegmatite pockets are commonly filled, or partially filled, with clay minerals that formed after gemstone precipitation.

Largest gem pegmatite pocket

The largest pegmatite gem pocket ever found, in the Jonas mine in Minas Gerais, Brazil, was discovered in 1978. The remarkable story of this truly awe-inspiring crystal cavern is related by Proctor (1985b). A garimpeiro, Ailton Barbosa, wished to mine the same pegmatite his father, also a garimpeiro, did in the early 1940s. Mr. Barbosa teamed up with a gem dealer who put up the money and arranged to lease the mine from the land-owner. After six weeks of fruitless labour involving expensive blasting, Mr. Barbosa, who had noticed signs of pegmatite pockets (presence of lepidolite, etc.) eventually surrendered title on his Volkswagen to raise funds to keep going for one more week. During the critical last days, as he was labouriously cleaning out a pocket of worthless opaque black tourmaline, albite, quartz and mica mixed with mud and water, he noticed water trickling down from the roof. He stuck his hand up into an opening he had carefully made into the area from which the water was draining and pulled out a large, almost flawless gem rubellite (red) tourmaline crystal. He shone his light into the opening and saw the largest and most valuable pegmatite gem

pocket ever discovered. It was a cave large enough to walk into (3 m x 3 m x 2.5 m) lined with beautiful raspberry-red tourmaline crystals, snow-white albite crystals, transparent quartz and pink lithium-bearing lepidolite. The largest tourmaline crystal was more than 3 feet long and weighed more than 135 kg (300 lbs). There was no sign of any secondary replacement or clay mineral formation, and the crystals were so clean they did not even need to be washed.

After only eight days the pocket was cleaned out and the invaluable cargo taken under guard to the city. In light of the ubiquitous violence and robberies after any major Brazilian gemstone discovery, a small army of old-time gunfighters was hired to secure the treasures in the warehouse. The specimens were supposedly wired to dynamite stacked underneath the crystals to emphasize the fact that the miners would rather blow the whole thing up than succumb to robbers or, even worse, letting Brazilian Internal Revenue agents view the booty. The precautions worked, and the first crystals were offered for sale, starting at \$9 million for the four largest. One of the crystals sold for \$1.3 million.

As usual, after the main discovery there was internal disagreement between the mining partners and the mine tunnel was dynamited about 30 m inside. A wheelbarrow full of unstable, decomposing dynamite was left outside. The mine was leased to a new set of miners who, through a different access route, came across what they thought could be another spectacular pocket. They were so excited that they forgot to wait after lighting the dynamite charge that opened the pocket and rushed in to see what they had found. The head miner looked in the pocket and promptly passed out from inhaling fumes left over from the explosion. After recovering in the hospital he rushed back and discovered another pocket with a single, spectacular rubellite crystal hanging upside down embedded in moist sand. This single specimen has been featured in many mineral and gem collecting books and was eventually sold to the author of the article (Mr. Proctor).

Proctor (1985b) reports that the pegmatite which contained these magnificent gem pockets is 12 m wide and 200 m long.



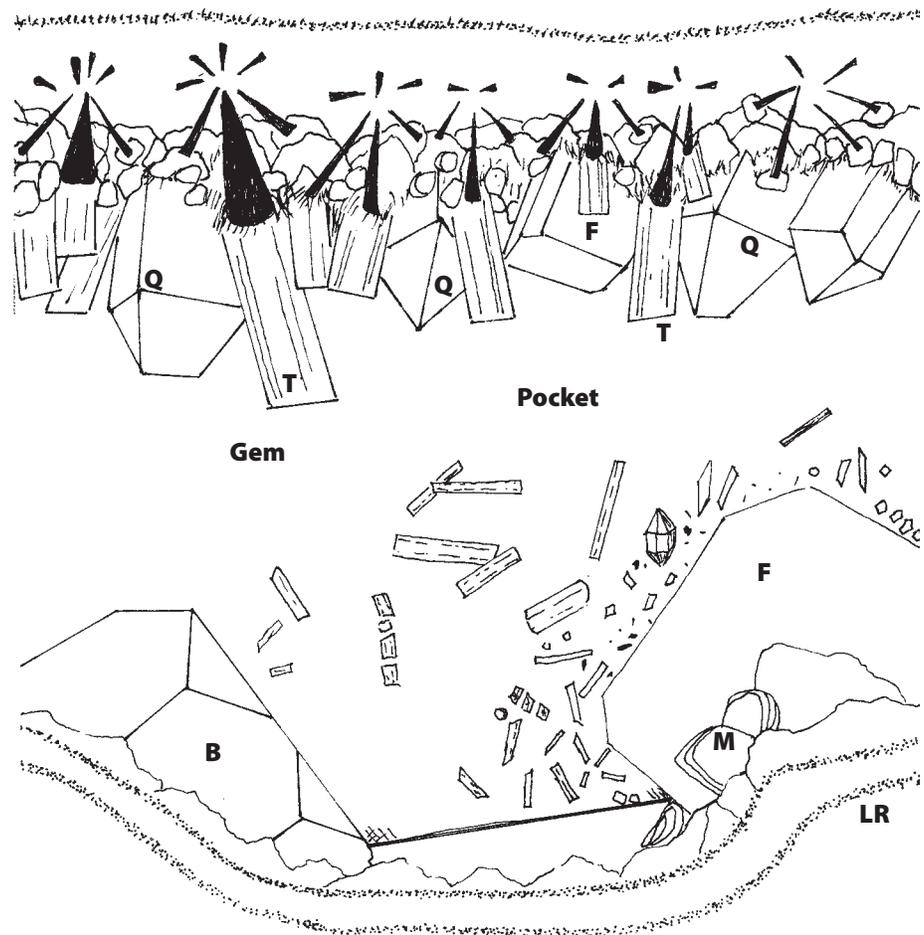
Miarolitic pockets may form in pegmatites crystallizing within the parent granite host rock. The residual pegmatitic magma exsolves an aqueous fluid in which all the components needed to form rare-element minerals are concentrated. London (1986) states that the presence or absence of miarolitic pockets is controlled by the timing and extent of volatile exsolution from silicate melt. The miarolitic cavities are soon rimmed with the first crystals to precipitate from this highly concentrated fluid.

The gem crystals in pegmatite pockets are commonly etched or corroded, and locally show some replacement by secondary minerals. Crystals that have broken from the roof or floor of the pocket may lie scattered or embedded within clay. Some minerals, for example gem tourmaline, may exhibit a spectacular change in colour, which reflects compositional zonation within the crystal. Shigley and Kampf (1984) note that some tourmaline crystals may start as black opaque crystals embedded in solid pegmatite, and then change to transparent pink, green and blue where they approach and project into a pocket.

Figure 7.2. Schematic representation of regional zoning in a cogenetic granite and pegmatite group.

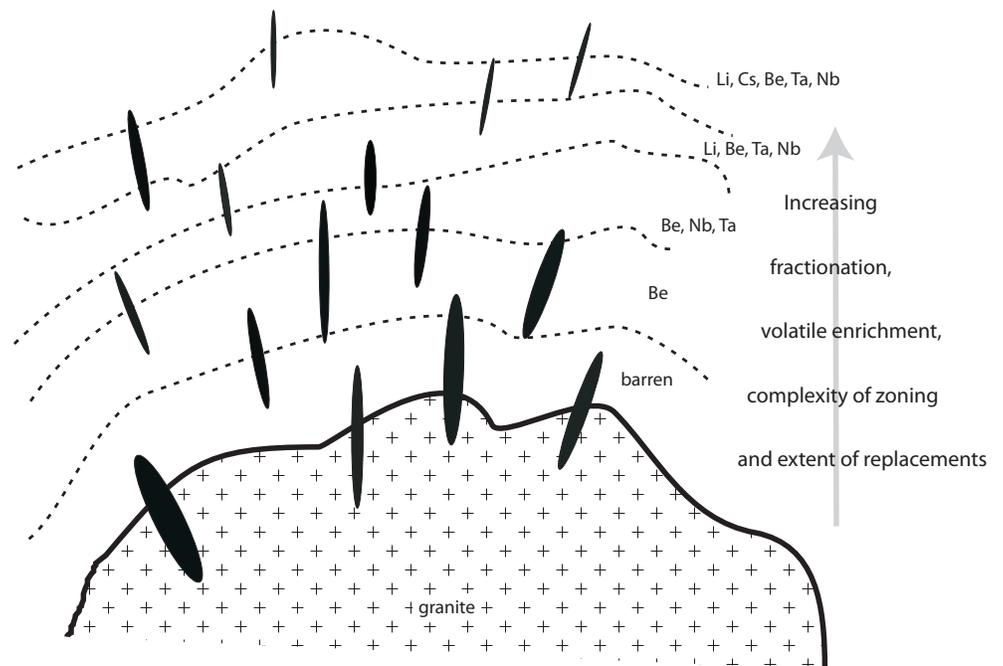
KEY

- A albite (cleavelandite)
- B beryl
- F feldspar
- L lepidolite mica
- LR line rock
- M muscovite mica
- Q quartz
- T tourmaline



7. Gem-bearing pegmatites

Figure 7.3. Schematic representation of regional zoning in a cogenetic granite and pegmatite group. Modified from Černý (1991b).



REGIONAL ZONING PATTERNS

There is a typical zoning pattern around a parent granite which reflects the increasing fractionation of the pegmatite fluids away from the granitic host. Trueman and Černý (1982) stress that this zoning can be irregular and depends on local structure. A typical zoning pattern is shown in Figure 7.3.

Epigenetic gemstone-bearing pegmatites are typically the furthest away from the parental granite, reflecting the high degree of fractionation required to concentrate the rare elements found in gem minerals.

GENESIS OF GEM-BEARING PEGMATITES

Shigley and Kampf (1984) and Keller (1990) summarize the genetic model first proposed by Fersman (1931) and expanded upon by Jahns and Burnham (1969) relating to internally zoned, granitic pegmatites which contain gemstones. The following description of the genesis of gem-bearing pegmatites is a compilation from Shigley and Kampf (1984), Keller (1990), Černý (1991b), London (1986), Falster *et al.* (2002) and Černý (2002).

A silicate magma, rich in volatile constituents such as water, fluorine, boron, lithium, carbon dioxide and/or potassium, and rare elements such as beryllium, cesium, niobium, tantalum and tin, is derived from the final stages of granitic-magma crystallization. This pegmatitic magma crystallizes as segregations within the host granite (syngenetic pegmatite) or is injected into pre-existing country rocks (epigenetic pegmatite). Quartz, feldspar and mica crystallize first, when the temperature drops below 1000°C, forming a fine-grained rim bordering the pegmatite cavity. The fine-grained border zone insulates against heat loss, and as a result, the remaining magma cools very slowly and forms larger crystals. Crystals of quartz, potassium feldspar and mica along with beryl and spodumene crystallize next, along the wall and in the intermediate zone. The remaining magma, by this time, is



concentrated with all those elements which do not fit into the quartz, feldspar or mica structures. The water content is also very concentrated with volatile elements. At a certain point, around 650 to 750°C, an aqueous fluid, rich in volatile elements and rare elements separates from the remaining pegmatitic magma. This aqueous fluid has a number of desirable properties, as listed by Shigley and Kampf (1984):

- lower viscosity permits more rapid transport of chemical nutrients to growing crystals
- greater concentration of volatiles contributes to the partitioning of elements between magma and fluid
- aqueous liquid rises within pegmatite magma chamber leading to vertical segregation of minerals
- minerals crystallize from the liquid at lower temperatures than from the magma
- the aqueous liquid can redissolve earlier-formed minerals with which it comes in contact

The last bit of magma crystallizes at between 500 and 600°C. The innermost portions of the pegmatite are filled with large crystals of quartz, feldspar and possibly opaque spodumene or beryl. The remaining aqueous fluid, very rich in volatile constituents and rare elements, is trapped in a few isolated pockets between the larger crystals in the centre of the pegmatite. It is at this point that gemstone crystals start to crystallize.

When the concentration of volatile constituents and rare elements is high enough, unusual and rare minerals precipitate and grow towards the centre of the pocket. The crystals may become more 'gemmy' (transparent) or change colours towards the end, a result of the changing chemical composition of the remaining liquid as more and more gemstones solidify. At temperatures of 250°C or so, crystallization is complete. Webber *et al.* (1999) suggest that at the end stages of crystallization, gem crystals may form in a matter of days to years, as opposed to thousands of years.

In order to preserve the gem crystals in the pockets, the remaining volatiles must be released very gradually into the host rock. Instead, what usually happens is that the pocket ruptures. The sudden and dramatic drop in pressure and temperature catastrophically cracks the newly formed gem minerals. What were once well formed crystals are left in shards on the pocket floor or are heavily fractured. The late-stage volatile fluid responsible for this destruction seeps out into the surrounding pegmatites and eventually forms replacement minerals.

What causes this all-too-common annihilation of the gem crystals? Shigley and Kampf (1984) suggest that the fluid pressure in the last bit of aqueous fluid is too high and exceeds the strength of the pegmatite host. Cooling and contraction of the pegmatite body, or earth movements near the pegmatite body may also cause rupturing.

This explains why gemstones in pegmatites, or even pockets in pegmatites are more common at shallower levels where the pressure of the surrounding rocks is less and the treasure-laden aqueous liquid is able to exsolve from the parent granitic magma.

TOURMALINE-BEARING PEGMATITES

One of the most sought-after pegmatite gemstones is tourmaline. This beautiful gemstone forms distinctive slender crystals showing vivid colour, sometimes two or three colours in one stone. Beautiful tourmaline gems are available in nearly all colours. Tourmaline was once thought of as a scholar's stone associated with wisdom and the power of knowledge. Its strange magnetic and electrical properties have been known for centuries. The tourmaline group of minerals is described in detail in Dietrich (1985) and Falster *et al.* (2002).

Tourmaline is found in many different rock types and geological environments. In addition to pegmatites, which are the most important host-rock for gem tourmaline, tourmaline is also found in sedimentary rocks, metamorphic rocks, greisen zones and alteration zones (tourmalinization), however, the largest and most spectacular tourmaline crystals are found in pegmatites.

The physical and chemical characteristics of tourmaline are listed in Table 7.2. Tourmaline is a complex borosilicate mineral group consisting of 14 separate and distinct species: elbaite, schorl, dravite, olenite, buergerite, chromdravite, povondraite, liddicoatite, uvite, feruvite, rossmanite, foitite, magnesiofoitite and vanadiumdravite.

Tourmaline commonly forms slender, elongated crystals showing striations along the length of the crystal. Terminations on the ends of the crystals can be complex but mostly consist of a rounded triangular habit. Crystals may be grouped in fibrous masses that appear to fan outward from a single crystal. Exceptions to the common slender, striated form exist. For example, Dietrich (1985) reports that dravite (brown tourmaline) crystals from Australia were mistakenly identified as garnets.

Tourmalines come in virtually any colour and some gem crystals can show two or even three vivid colours. The cause of colour is due to several events: interaction between major elements, trace elements, structural defects and possibly natural

Table 7.2. Physical and chemical characteristics of tourmaline.

Note: Tourmaline is a complex borosilicate mineral group consisting of fourteen separate species. Falster *et al.* (2002) provide an excellent summary of the different tourmaline species. The chemical formula provided in the adjacent table is from Hurlbut and Klein (1977).

Chemical formula	$(\text{Na, Ca})(\text{Li, Mg, Al})(\text{Al, Fe, Mn})_6(\text{BO}_3)_3(\text{Si}_6\text{O}_{18})(\text{OH})_4$
Crystal system	Cyclosilicate
Habit	Typically elongated crystals that are striated with trigonal pyramids at the ends. Usually acicular, may be single or in radiating groups. Can also get more equant crystals.
Colour	Can be almost any colour
Hardness	7 to 7.5
Fracture	Subconchoidal to uneven fracture, poor cleavage
Cleavage	
Parting	
Specific gravity	2.98 to 3.20 g/cm ³
Pleochroism	Strongly pleochroic
Fluorescence	Mostly non-fluorescent under longwave ultraviolet light, but some species may show a reaction under shortwave light.



radiation. Some of the more common colours, and the name given to that particular colour of gem tourmaline are given below:

Red/pink: This colour of gem tourmaline is sometimes called 'rubellite.'

Green: The green tourmalines cover a wide range of hues. The most valuable is called 'chrome tourmaline,' which closely resembles tsavorite garnet or emerald.

Brown/yellow: This variety is called 'dravite.'

Black: Black, opaque tourmaline is often called 'schorl.'

Blue: Pure blue tourmaline, called 'indicolite' is very rare, since most blue tourmaline has some green in it.

Bi- and tri-coloured tourmaline: The change in colour is a result of a change in supply of the elements which cause the colour. Green-pink combinations, either along the length of the crystal or from inside to outside, are common. In some specimens, the core of the tourmaline is one colour and the outside rim is a different colour, for instance 'watermelon tourmaline.' Spectacular complex colour-zoned tourmalines called liddicoatite are mined in Madagascar.

Some tourmalines, especially bluish green ones may show a cat's-eye effect due to light reflecting from hollow, tube-like inclusions inside the stone. Tourmaline is strongly pleochroic.

Some tourmaline crystals develop a magnetic charge ('pyroelectricity') after the crystal is heated, or develop an electric charge after the crystal is subjected to stress ('piezoelectricity'). In fact, Dietrich (1985) reports that most jewellers do not display tourmaline jewellery in show-windows that get heated by the sun, because the resulting electric charge attracts dust. Falster *et al.* (2002) describe the various

Paraíba tourmaline

In August, 1988, the most sought after and valuable species of 'electric blue-green' tourmaline was first discovered at Batalha, in the state of Paraíba, northeastern Brazil. Termed 'paraíba tourmaline,' the crystals are a stunning vivid, intense blue, violet, emerald-green and beautiful turquoise-blue due to the unusual presence of copper. The copper was probably derived from copper-bearing sediments. Good crystals are also exceedingly rare, since almost all the good crystals shattered in the pegmatite pockets or are heavily etched. The best quality paraíba tourmaline as a cut gem can command up to \$20,000 per carat.

This area of Brazil, a long 1,500 km away from the gem-rich pegmatite province of Minas Geras, was only known for its industrial columbite-tantalum pegmatite minerals. A local mineral and gem dealer discovered some tiny, sand-sized grains of coloured tourmaline in the tailing of a nearby tantalum mine, and he and his team dug for five and a half years, acquiring the name 'Heitor the Fool' by the bemused locals. After finally striking the first electric blue crystals, the team continued digging by candlelight using small hand tools, and found wonderful crystals in stunning shades of copper

green, blue and turquoise. As a result of the obligatory legal and political battle over control of the mine, the flow of tourmaline trickled, but by 2001, the mine was being upgraded and developed further.

Paraíba tourmaline remains a unique locality, although copper-coloured tourmaline, not quite as vivid, has also been found in Nigeria (see Wilson, 2002 and Falster *et al.*, 2002).

practical uses of tourmaline, including its ubiquitous use in jet engines as part of a gauge used to monitor vibration.

Most tourmaline does not fluoresce. Some yellow stones may fluoresce yellow and some red or pink stones may show faint violet.

Geology and genesis of tourmaline pegmatites

The general geology of gemstone-bearing pegmatites is reviewed above. Almost all gem tourmaline is derived from pegmatites. An exception is dravite (gem brown) tourmalines which can be found in metasomatic zones in carbonate rock (Dietrich, 1985).

The gem tourmaline-bearing pegmatites of Brazil are described by Proctor (1984, 1985a,b). Another pegmatite district famous for its gem tourmaline is the Pala district in San Diego County, California. The Pala pegmatite district, including the Himalaya mine, the Pala Chief mine and the Tourmaline Queen mine has been producing wonderful green and red tourmalines since the early 1900s. It is reported (Bancroft, 1984) that over 100 tons of gem and ornamental tourmaline came from just one of the mines between 1902 and 1910. One of the most prolific consumers of gem tourmaline at that time was Empress Tzu Hsi of China, who loved carved tourmaline so much that Sino/San Diego trade pacts flourished until the Chinese government collapsed in 1911.

London (1986) reviewed the conditions of formation of tourmaline-rich pockets in miarolitic pegmatites, based on studies of pegmatites in Afghanistan and San Diego County, California. He determined that the temperature at the time of pocket formation was 425 to 475°C at pressures of 2400 to 2800 bars. This is similar to pressure-temperature conditions for massive pegmatites (pegmatites which do not contain miarolitic cavities), like the Tanco mine in Manitoba. Crystallization of tourmaline does not occur until the late stages of pegmatite crystallization. Tourmaline crystallization uses up alkali borate in the melt, which results in the deposition of other alkali aluminosilicate and oxide minerals, and the consequent exsolution of large amounts of water. The separated aqueous phase, rich in volatile elements, may enter pockets within the last stages of pegmatite crystallization or may seep out along fractures to react with previously crystallized pegmatite or host rocks.

London (1986) notes that field observations support a genetic link between gem tourmaline pocket formation, late-stage boron-rich albitic liquids and adjacent tourmalinization of wall rocks. Stem *et al.* (1986) suggests that high fluorine plus boron contents enhance tourmaline crystallization by depressing the temperature of crystallization and by affecting the distribution of the alkali constituents.



Gem tourmaline in Canada

Gem tourmaline has been found on the 'Stargazer' claim on the O'Grady granitic batholith in the Northwest Territories, close to the Yukon border. Brad Wilson has been exploring for and collecting brownish pink gem tourmaline up to about 10 cm from miarolitic cavities within lithium-mineralized pegmatite intruding the granite (Wilson, 1997). The pegmatite was recently recognized as the first confirmed Canadian occurrence of the elbaite subtype of rare-element granitic pegmatite (Ercit *et al.*, 2003). For more information, go to www.alpinegems.com.

TOPAZ-BEARING PEGMATITES

Historically, topaz has been one of the more 'confusing' gemstones because its name has been misused so much. This prevails in today's jewellery industry where fine golden citrine quartz is often labelled 'topaz quartz' or brown, smoky quartz is sold as 'smoky topaz.' 'Imperial' topaz, which originally identified rare pink topaz in Russia coveted by the Imperial family during the 19th century, is used for almost any yellow-orange shade of topaz. The popularity of blue topaz during the late 1980s and early 1990s confused consumers even more.

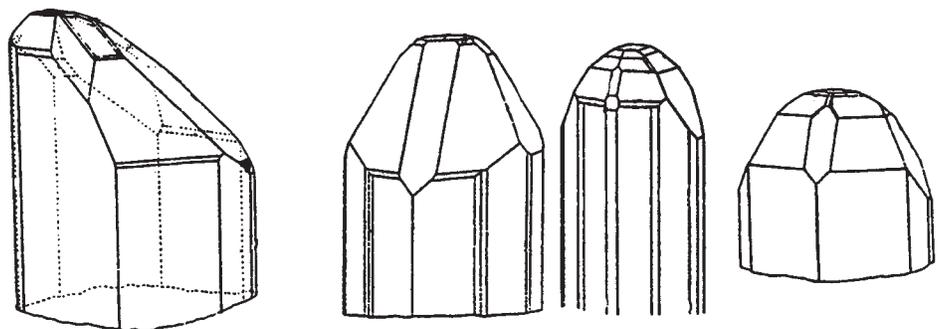
The mineralogy, geology and occurrence of topaz is described in a wonderful series of articles by Menzies (1995) and others in an issue of the Mineralogical Record Magazine devoted totally to topaz. Abstracts of current research into topaz geology are included and full-colour photographs of spectacular topaz crystals complement the articles. Much of the information in the following section is derived from this 'must-have' issue.

Topaz has a wide colour range which includes yellow, orange, brown, pink, red, violet, blue and white. In general, intensely coloured reddish orange, red or deep pink topaz is the most valuable. Deep golden peach and orange colours are next. At the bottom of the scale are the yellow and sherry brown colours and blue colours (irradiated; see below).

Although natural blue topaz crystals have been known for a long time, it was only when large amounts of 'sky-blue' topaz began swarming the gem trade in the mid-1980s that the public really became aware of the gem. Suppliers began placing large amounts of natural colourless topaz from Brazil, Sri Lanka or Africa in nuclear reactors or linear accelerators where they were bombarded with neutrons or electrons to produce a blue colour. The irradiated stones were heat-treated to stabilize the colour and then released to the global gem trade, where they have become very popular low-cost alternatives to aquamarine or the more expensive colours of topaz. For a time, there was a radioactivity scare associated with some batches of these stones, but that was only temporary. Besides irradiation, orange topaz containing chromium as an impurity is often heat-treated in an attempt to produce the more desired pink colour. Most of the sherry-coloured topaz from rhyolites and pegmatites fades gradually in sunlight.

The physical and chemical characteristics of topaz are given in Table 7.3. Topaz is an orthorhombic fluorine hydroxyl silicate mineral. Hydroxyl can substitute up to 30% for fluorine (F). The more hydroxyl that has substituted for fluorine, the lower the temperature of formation. Topaz crystals have a characteristic crystal form, some of which are shown in Figure 7.4.

Figure 7.4. Topaz crystals.



7. Gem-bearing pegmatites

Table 7.3. Physical and chemical characteristics of topaz.

Chemical formula	$Al_2SiO_4(FOH)_2$
Crystal system	Orthorhombic
Habit	Typically prismatic with lozenge-shaped cross section and striations parallel to cleavage. The termination is characteristically wedge-shaped.
Colour	Colourless, sherry-brown, yellow, blue, pink
Hardness	8.0
Fracture	Perfect basal cleavage
Cleavage	
Parting	
Specific Gravity	3.4 to 3.7 g/cm ³
Pleochroism	Weak to distinct
Fluorescence	Colourless: non to pale yellow (longwave) Red: weak (LW) Yellow: weak orange-yellow

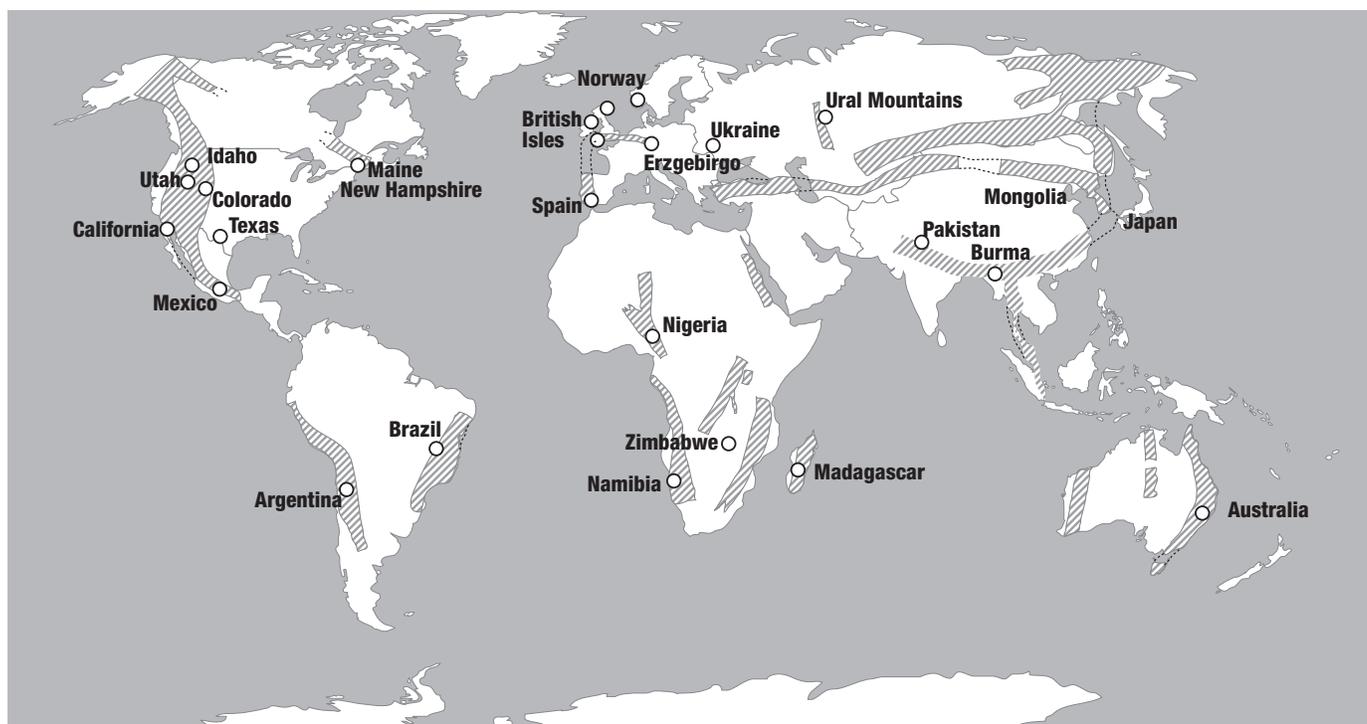
Topaz crystals can reach enormous size. Menzies (1995) reports on a Brazilian topaz crystal measuring 3 x 5 x 10 m and weighing 350 tonnes.

Geology and genesis of topaz deposits

In a study of 80 gem topaz deposits, Menzies (1995) determined that about 80% of the deposits are pegmatite-related, 10% are rhyolite-hosted and the rest are in greisens and rarely veins and skarns. More than 85% of all gem topaz deposits fall within 'rare metals belts' as shown in Figure 7.5. The belts cover rift zones in continental crust and/or collisions involving continental plates.

Figure 7.5. Rare metals belts and major topaz deposits.

Topaz is derived from highly evolved granites and rhyolites that are rich in both fluorine and silica. Most topaz is primary, although it can replace feldspars. Topaz



deposits occur more frequently in 'closed systems' such as pegmatites or rhyolites where the fluorine-rich fluid is enclosed rather than 'open systems' like a greisen or skarn where the hot fluid or magma seeps unhindered into the host rock (Table 7.4, Figure 7.6).

Figure 7.6. Deposit types formed from fluorine-rich magmas (modified after Burt *et al.*, 1982). Deposit types are ordered by increasing depth and magma water content.

KEY

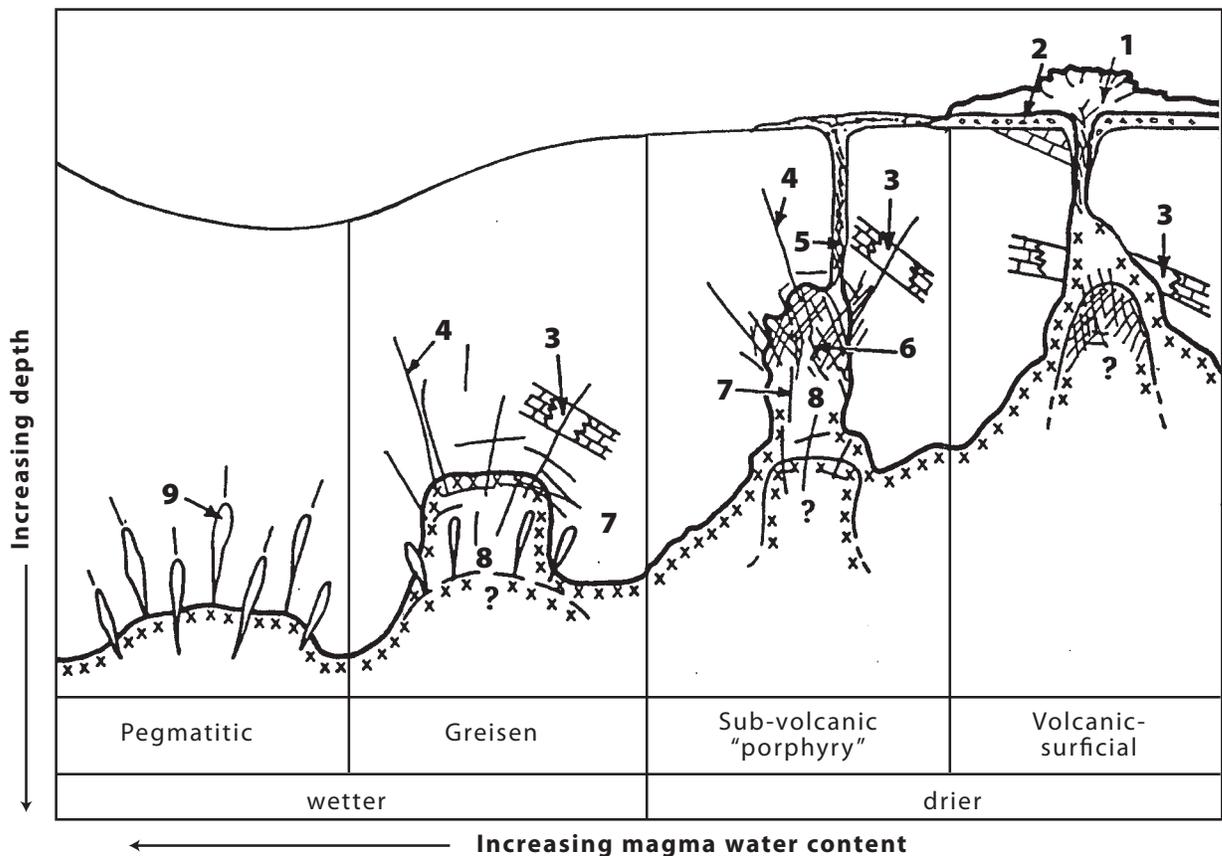
1. Topaz rhyolites and volcanic tin deposits
2. Pyroclastic (explosive volcanic) beryllium deposits
3. Skarns
4. High-temperature veins
5. Breccia pipes
6. Porphyry greisen
7. Greisen
8. Mirolitic cavities in granite
9. Pegmatites

Fluorine-rich magmas are generated in long-lived, tectonically active zones. Menzies (1995) lists two tectonic regimes that are particularly favourable for topaz mineralization:

1. **Orogenic.** This regime is typical of tectonic collision and crustal compression such as the Andes, Himalayas or Coast Ranges.
2. **Anorogenic.** This regime involves rifting and faulting during crustal expansion and deformation above hot spots. Examples would be the western U.S. and Mongolia.

The source rock is typically a highly evolved, fluorine-rich leucocratic biotite ± hornblende or muscovite granite intruded to shallow depths at the latest stage in any magmatic episode.

Gem topaz crystallizes from water-rich residual melts remaining in the final stages of magma crystallization. Topaz-bearing pegmatites are typically the shallow, rare element class, as described by Černý (1991a) and can be further divided into syngenetic pegmatites (NYF: niobium-yttrium-fluorine) as described by Černý (1991a) and epigenetic pegmatites (LCT: lithium-cesium-tantalum) pegmatites.



7. Gem-bearing pegmatites

Table 7.4. Topaz deposit types (modified from Menzies (1995)).

Geologic environment	Deposit type	Formation temperature (°C)	Fluid activity/ replacement	Percentage fluorine in rock	Typical associated species	Example localities	Comments
Volcanic	Gas cavities in rhyolite	850–600	Deposition from gas phase	<1	Red beryl, garnet, quartz, hematite, Mn-beryl	Thomas Range, Utah Central Mexico	Fine crystals and groups
Magmatic	Ongonite	1000–600	Quenched magmas	<3.5	Albite, quartz	Young, Arizona Transbaikalia, Siberia	Rare rock type. Equivalent of rhyolite
	Topazite	Ca. 600	Phase separation?	<6.5	Quartz	Eastern Australia	Rare rock type. May also be hydrothermal
LATE to POST MAGMATIC							
Pegmatites NYF type	Syngenetic: Pegmatites in granite (simple cavities, zoning uncommon)	750–450	Localized, slight	<1 Higher	Quartz, albite, microcline (including amazonite), zinnwaldite, fluorite, iron species. Uncommonly beryl, phenakite. Rarely spessartine, tourmaline	Sawtooth Range, Idaho Pikes Peak, Colorado Mourne Mts., N. Ireland Volhynia, Ukraine Klein Spitzkopje, Namibia	Commonly excellent crystals, many of gem quality
LCT type	Epigenetic Pegmatites, intruded into country rocks (complex zoned)	Extensive in lower zones	Lower	High to very high	Quartz, microcline, albite, lepidolite/muscovite, tourmaline, fluorite, columbite-tantalite. Other lithium and rare-element species, rarely beryl	San Diego Co., California Minas Gerais, Brazil Pakistan/Afghanistan	Topaz uncommon. Fine crystals, commonly large, many of gem quality, in cavities
Hydrothermal: (Higher temperature)	Greisen (in or associated with granite)	550–300	Intensive to extensive	High to very high	Quartz, micas, fluorite, cassiterite. Tungsten species in some deposits. Less commonly beryl, tourmaline	Erzgebirge District, Germany/Czech Republic Transbaikalia, Siberia	Smaller crystals in cavities. Topaz typically intergrown. Significant portion of host granite may be converted to topaz.
	Skarns (in carbonate rocks)	>500 to 400	Extensive	Low	Calcium silicates, micas, tourmaline, fluorite, magnetite, cassiterite, sulphide minerals	Lost River, Alaska Trumbull, Connecticut Tasmania, Australia Laacher See, Germany	Rare occurrence for topaz
	Quartz (–feldspar veins)	>400–<300	Intensive	Low	Quartz, feldspars, muscovite, beryl, cassiterite	Eastern Australia	Good crystals in cavities, especially in nearer-surface deposits
Hydrothermal: (Lower temperature)	Quartz-feldspar veins	400–<200	Intensive	Low	Quartz, cassiterite, also euclase, hematite, rutile (Brazil)	Eastern Australia Ouro Preto, Minas Gerais, Brazil	Fine crystals, some of gem quality
	Sulphide mineral veins		Extensive	Low	Quartz, sulphide minerals, fluorite	Cornwall, England	Rare occurrence for topaz
	Carbonate veins and alpine clefts	Ca. 200	Extensive along fractures	Low	Calcite, quartz	Brumado, Brazil Mardan, Pakistan Untersalzhachtal, Salzburg, Austria Val Lugnex, Grisons, Switzerland	Very rare occurrence for topaz
High-grade metamorphic sedimentary		High	Extensive	High	Quartz, sillimanite, kyanite	Tanzania Colorado South Caroline	Massive material
	Eluvial		Decomposition of deposit		Durable minerals of original deposit	Minas Gerais, Brazil	Fine crystals
	Alluvial		Transported by water		Durable minerals of original deposit	Minas Gerais, Brazil Eastern Australia Sri Lanka	Typically water-worn crystals



Gem topaz in syngenetic pegmatites

Syngenetic pegmatites crystallize as compact, pegmatitic coarse-grained segregations within the parent granitic host rock. The host rock is usually an anorogenic (intruded during episodes of crustal extension) granite emplaced at shallow depths to 5 km (Menzies, 1995). Menzies (1995) reports that the parent magmas are leucocratic and calcium-poor. They are typically associated with volcanic rocks and breccia pipes. Topaz crystals form after bubbles of fluorine-rich aqueous fluid separate from the magma and form miarolitic cavities. A good example of an area hosting syngenetic topaz-bearing pegmatites is the 45-million-year-old Sawtooth granitic batholith in Idaho which was emplaced as a result of crustal extension. Topaz typically occurs in 10-cm to 50-cm-wide cavities along with smoky quartz, microcline, mica and rarer fluorite and hematite. This area is also known for its aquamarine crystals.

Topaz crystals are typically found on quartz or feldspar crystals in syngenetic pegmatites. Larger cavity size and changes in iron content can result in different minerals forming with topaz in the miarolitic cavities. Smoky quartz, feldspars, zinnwaldite mica (lithium-bearing), fluorite may be present along with less common beryl and phenakite, and rarely spessartine and tourmaline.

Gem topaz in epigenetic pegmatites

Gem topaz is also found in epigenetic pegmatites which form after residual fluids left over from granitic intrusion are injected into host rocks. Menzies (1995) reports that the pegmatites may intrude as far as several kilometres into the surrounding host rock. Typically, gem topaz crystallizes with lepidolite and albite pegmatites, which are commonly the last to form furthest away from the parent granite. The pegmatites correspond to Černý's LCT type, which have received great attention as major hosts for commercial rare-metal deposits.

The gem minerals in epigenetic pegmatites are typically more iron-rich, as opposed to lithium-rich in syngenetic pegmatites. Topaz is associated with quartz, feldspar, lepidolite and muscovite micas, elbaite (green) or schorl (black) tourmaline, fluorite, columbite-tantalite and less commonly beryl.

AQUAMARINE-BEARING PEGMATITES

Aquamarine, the beautiful transparent green-blue variety of the mineral beryl, is named after the Latin term for 'colour of the sea.' This gemstone was particularly favoured not only by the ancient Greeks, but also in present history by Queen Elizabeth II.

The colouring agent of aquamarine is iron. The deeper blue varieties of aquamarine are the most valuable; in fact, most aquamarine is heat-treated to drive off the green component. Aquamarine crystals are typically slender, six-sided prisms with a flat termination. The physical and chemical characteristics of aquamarine are given in Table 7.5. Detailed information on the mineralogy and geology of aquamarine is given in Sinkankas (1981).

Aquamarine is typically found in pegmatites which contain iron-rich minerals such as black tourmaline and pyrite. The aquamarine crystals generally occur in the feldspar-

7. Gem-bearing pegmatites

Table 7.5. Physical and chemical characteristics of aquamarine. Note: Aquamarine, like emerald, is a variety of the mineral beryl.

Chemical formula	Be ₃ Al ₂ (SiO ₃) ₆ (beryllium aluminum silicate)
Crystal system	Hexagonal crystal system: dihexagonal-dipyramidal crystal class. Beryl is a cyclosilicate mineral and has hollow channels through vertically stacked (Si ₆ O ₁₈) rings. The structure consists of six-membered rings of Si tetrahedral lying in parallel planes. The rings are linked together both laterally and vertically by Be tetrahedral and Al octahedral forming a three-dimensional framework that is a tectosilicate. Elements such as lithium, potassium, sodium, rubidium and cesium and even whole water molecules can fit into these spaces, generating open structural channels called corrosion tubes.
Habit	As single crystals with hexagonal six-sided prisms that can be short and stubby and long and slender with flat termination.
Colour	Pale blue, light blue-green, pale green, rare deep blue
Hardness	7.5 to 8
Fracture	Indistinct basal cleavage
Cleavage	
Parting	
Specific gravity	2.67 to 2.84 g/cm ³
Pleochroism	Aquamarine: strong

quartz wall zone and project into the white quartz core. Proctor (1984) gives an excellent description of the aquamarine-bearing pegmatites of Minas Gerais.

Aquamarine is also found in miarolitic cavities found in A-type granites (anorogenic granites) described earlier in the section on topaz. Jacobson (1993) provides a good overview of aquamarine localities in the United States. Aquamarine also occurs in hydrothermal veins and in related scheelite-tin-molybdenite greisens.

Association between topaz and aquamarine

Menzies (1995) discusses the association between gem topaz and aquamarine. Curiously, topaz and aquamarine rarely occur together in pegmatite pockets, especially those in syngenetic pegmatites or those formed in greisens. Proctor (1984) also notes that topaz and aquamarine in Brazil commonly occur in the same pegmatite deposit, but never the same pocket. Epigenetic pegmatites in, most notably, the Gilgit area in Pakistan and pegmatite deposits in the Urals are notable exceptions; at Gilgit, spectacular groupings of topaz and aquamarine are mined from pegmatite cavities. In areas of syngenetic pegmatites, such as the Sawtooth Range in Idaho mentioned above, Menzies (1995) notes that cavities containing topaz occur within metres of those containing aquamarine, but the two never occur together. The same situation exists at another famous aquamarine locality, Mt. Antero, Colorado. Menzies (1995) suggests that the association of beryl with topaz requires a very restricted range of fluorine content, influenced heavily by fluid loss.



EXPLORATION CRITERIA FOR GEM-BEARING PEGMATITES

Perhaps the most basic exploration guideline for the Yukon prospector is to observe when simple quartz-feldspar-mica pegmatites become more 'complex.' Increasing complexity is marked by changes in the mineralogy — perhaps black tourmaline crystals are visible in addition to the basic mineral assemblage, or the internal texture of the pegmatite changes; perhaps the pegmatite is starting to show an internal zoning pattern, and the minerals start forming layers surrounding a central quartz core.

Use of simple zoning patterns may help identify gemstone-bearing pegmatites. A prospector might notice some opaque green beryl in pegmatites near a granitic intrusion. Closer to the intrusion are simple quartz-feldspar-mica pegmatites. Figure 7.3 shows that a good place to look for gemstones (and rare elements) is obviously farther away from the parent granite — the pegmatites furthest from the parent granite (may be several kilometres away) have the best potential.

It is easier to delineate large granitic bodies on geology maps and on the ground than it is to spot smaller pegmatite segregations or veins. To evaluate the potential a particular granite host rock might have for yielding gemstone and rare-element-bearing pegmatites, Trueman and Černý (1982) provide a detailed listing of guidelines for the exploration geologist to help determine the potential of a pegmatite field. The guidelines are based on studies of rare-element pegmatites in shield areas. Some of the relevant guidelines are summarized below.

Geochemistry

Stream sediment sampling is recommended as an initial approach. Trueman and Černý (1982) note that cassiterite and niobium-tantalum minerals will be retained as heavy mineral fractions. When concentrating the stream-sediment sample to the heavy mineral fraction, by panning for example, the lighter but resistive minerals like tourmaline, beryl or spodumene may be present. The rejected fraction should be examined for these pegmatite minerals.

Geology and structural control of parental granites

The most favourable parental granites for rare-element pegmatites have the following features:

- generally small to moderate in size (5 to 150 km² in outcrop)
- late or post tectonic
- associated with deep, regional faults or lithologic boundaries
- in shield areas, parental granites and their pegmatites may intrude the contact between pre-existing batholiths and their host rocks.

Composition and texture of parental granites

- leucocratic
- carry biotite, or 'two-micas,' rarely hornblende and biotite together
- may have cordierite, andalusite and/or Mn-enriched garnet in peraluminous types late, anhedral K-feldspar
- inhomogeneous

Geochemistry of parental granites

- widely variable K/Ba ratios

Zoning of pegmatite swarms

Trueman and Černý (1982) suggest noting the accessory minerals present in a pegmatite, the complexity of internal minerals and the metasomatic mineral assemblage at the pegmatite/host rock contact zone. They also note that other types of veins, genetically related to granitic intrusion may extend outside the area of the pegmatite swarm. These might include quartz veins with beryl, wolframite, cassiterite, scheelite, gold, molybdenite and/or other sulphide minerals.

Quest for the dark blue aquamarines

The highest quality, most valuable aquamarines are those rare crystals that are a natural dark blue colour. The beautiful gem of the sea, aquamarine, is typically a pale bluish green when mined, and then a light blue after heat-treating. The element iron is responsible for the sublime colour, although there is some discrepancy, as described by Černý (2002) as to the exact mechanism. Some researchers have attributed the yellow tones to Fe^{3+} and blue tones to Fe^{2+} ions hosted in the channels; while others attribute the blue, green and yellow tones to varying Fe^{2+} and Fe^{3+} .

In 1917, beautiful dark blue beryls, the likes of which had never been seen before, were discovered at the Maxixe mine, in the Minas Gerais region of Brazil. Unfortunately the colour faded in these gems when exposed to sunlight. The Maxixe beryls have another unusual feature. Most aquamarines are strongly dichroic, that is they show their best colour when one is looking perpendicular to the length of the rough crystal. Maxixe beryls show their best colour looking parallel to the length of the crystal. The deep blue colour of Maxixe beryls is thought to be due to natural radiation (Nassau *et al.*, 1976).

Proctor (1984) describes a 1964 find of eluvial dark blue aquamarine

fragments in the Marambaia Valley area of Brazil; the colour was said to have the colour of fine blue tourmaline. When the fragments were put together, it measured 68.5 x 10.9 cm and weighed 22 kg. In addition, it was entirely 'clean.' Four of the crystal fragments were sold to the first dealer on site for \$45,000; an enormous amount for the garimpeiro who discovered the aquamarine.

Another beautiful aquamarine with rich blue natural colour was deemed the 'Marta Rocha' crystal. This crystal weighed a staggering 34.7 kg with superb colour which ultimately yielded 57,200 carats of beautiful cut aquamarines (Proctor, 1984).

Of course, Madagascar, so rich in gems and fine mineral crystals, has also produced deep blue gem beryl crystals from the Ambositra pegmatite (Pezzotta, 2001). The host rock is a beryl-columbite pegmatite.

In October, 2003, True North Gems Inc., a Canadian junior mining company, announced the discovery of a unique dark blue beryl in the Yukon and proclaimed the discovery as a new gemstone for Canada¹. Their fact sheet on the gemstone explained that the crystals are the aquamarine variety of the mineral beryl, however, they go further in stating that it should be described

as a specific type of aquamarine. True North Gems calls this variety 'True Blue aquamarine.' Analysis has shown that the True Blue beryl is high in iron and sodium; in fact, the iron content is one of the highest reported for any type of gem beryl. The deep blue colour is attributed to channel Fe^{2+} . The crystals show the same type of reverse pleochroism seen in Maxixe-type aquamarines described above, however, the chemical composition is distinctly different from Maxixe aquamarines.

The crystals were first noted as a curiosity in 1976, and then investigated further by True North Gems in 2003. The crystals are embedded within quartz-carbonate-tourmaline veinlets that cut a 320-million-year-old fluorite-bearing syenite stock associated with rare-earth elements. The site is east of the Regal Ridge emerald occurrence in the Finlayson Lake area, Yukon. To date, blue beryl has been mapped in a zone measuring 600 x 100 m over 100 m in elevation, and there is much additional prospecting to do to delineate this interesting discovery.

¹www.truenorthgems.com



Mineral zoning

PLAGIOCLASE

- becomes more sodic and albitization increases away from the parental granite

ROSE QUARTZ

- rose quartz patches are found in quartz cores of barren, tourmaline-bearing and beryllium-, niobium-tantalum-mineralized pegmatites including those with lithium, iron and manganese-phosphates
- not found in spodumene-rich, rare-element or lithium, fluorine-bearing pegmatites
- Brazilian pegmatites with beautiful miarolitic rose quartz is the exception

MUSCOVITE

- Barren pegmatites typically contain brownish and dirty green muscovite
- Coarse-flaked yellow-green and silvery muscovite is typical of beryllium-, (niobium, tantalum)-bearing and spodumene pegmatites

BLACK TOURMALINE

- boron is not closely related to the rare metals
- found in barren and simple beryllium (niobium, tantalum)-bearing pegmatites
- becomes blue and green tourmaline with tin, niobium and tantalum mineralization in albitized pegmatites
- green, pink and colourless tourmaline indicate increased lithium, rubidium and cesium

BERYL

- appears as a primary coarse, columnar mineral of greenish, yellow or brownish colour in simple pegmatite
- blocky pegmatites with negligible albitization
- away from parental granites, the fluid is enriched in alkalis so the beryl becomes pale coloured to white, associated with albitization and lepidolite replacement assemblage
- white to pink, stubby or tabular beryl is typical of rare-element pegmatites and of the lithium-enriched type with tantalum, lithium, rubidium, cesium mineralized rock

COLUMBITE-TANTALITE

- is the main niobium-tantalum mineral in moderately fractionated pegmatites

SPODUMENE

- green spodumene indicates spodumene pegmatites with low niobium-tantalum and beryllium potential, but high lithium content
- white spodumene adjacent to quartz core is characteristic of rare-element pegmatites with diverse mineralization

Minerals in metasomatic contact zones

BIOTITE-PHLOGOPITE

Trueman and Černý (1982) note that biotite-phlogopite is a common reaction product, usually in thin seams, along pegmatite contacts with amphibolites and similar basic wall rocks. Large quantities of biotite-phlogopite occur when there has been internal albitization.

TOURMALINE

Tourmaline along contact zones does not indicate any particular pegmatite type. Dravite (brown tourmaline) occurs typically in marbles and serpentinites.

Trace element chemistry

Trueman and Černý (1982) note that where zoning is difficult to determine, the K/Rb ratios in K-feldspars or alternatively K/Rb, K/Cs or Mg/Li in pegmatites can be used to show progressive fractionation.

When it comes to determining the potential of a pegmatite body, Trueman and Černý (1982) list several types of geochemical indicators, commonly trace element amounts or ratios in the individual pegmatite body, that can be used to help indicate the rare-element potential of a pegmatite. These indicators are used to help assess rare element pegmatites before expensive drill programs are carried out, but are not immediately useful to prospectors working in the field. This type of analysis may help if a gemstone pegmatite field is discovered.

Geophysical methods

Trueman and Černý (1982) recommended that gravity anomalies can be used to delineate the relative densities of different pegmatite zones; for example, a simple quartz-feldspar-mica pegmatite can generate a gravity low, while a spodumene dyke may generate a high. Magnetic and EM methods are best used to delineate host rock structures and stratigraphy.

Cook (2002) provides an excellent summary of results to date in using geophysics to explore not just for diamonds but for coloured gemstones in pegmatite pockets, in particular, advances in the application of 'micro-scale' techniques such as high frequency ground-penetrating radar and ultra high frequency seismology. Until recently, the resolution of geophysical techniques has not been sufficient to delineate potential gem-bearing cavities of less than 1 m in pegmatites. Application of ground-penetrating radar in the search for pegmatite cavities has been tried in the past, however more recent tests have been successful. In particular, ground-penetrating radar was successful at locating a gem-bearing pocket in California that had



previously been missed; several gorgeous gem tourmaline crystals were found inside and more than 25 additional cavities were found and excavated over a seven week period. This survey was successful in identifying cavities smaller than 10 cm.

Indicators of pegmatite pockets

Shigley and Kampf (1984) list features in the solid pegmatite that are used as signs by miners that a pocket may be close by:

- black, opaque tourmaline embedded within the wall changes colour or increases in amount, presence of lepidolite (purple lithium-bearing mica), increased transparency of quartz
- manganese-oxide staining
- extensive rock alteration
- presence of clays

Proctor (1984) lists some indicators of gemstone pockets in Minas Gerais, Brazil, where the pegmatites are decomposed. Prospectors generally try to find softened areas where pocket-filling clay minerals are exposed or look for the mineral residue of a gem pocket.

White kaolin forms after chemical alteration of pegmatite feldspars into clay minerals. The more resistant gemstone minerals such as tourmaline, quartz, beryl and topaz remain intact in the decomposed pocket.

Prospectors will take a stick and try to poke it in the rock. If it sinks down, the prospector may have found the soft white kaolin clay. They also look for fine muscovite flakes in the soil and clear or smoky quartz crystals with sharp faces.

Dietrich (1985) compiled a number of characteristics regarding gem tourmaline-bearing pegmatites:

- green tourmaline (elbaite) and liddicoatite (colour-zoned tourmaline) is found in pockets in the central zones of complex, Li-bearing pegmatites.
- tourmaline, especially short (black, opaque tourmaline), is typically found in aplites that are spatially and genetically related to pegmatites; green and pink tourmaline-bearing pegmatites tend to be farther from their parent granites than black tourmaline-bearing pegmatites; the uranium-content of tourmalines is greater in albitized than non-albitized pegmatites and rubidium and cesium, as well as lithium, are apparently sequentially enriched in later generations.
- Lithium-bearing tourmalines appear to be most common in core borders, whereas black tourmaline is more common in wall and intermediate zones.

At the Little Three pegmatite gemstone mine in the Ramona pegmatite district of San Diego County, California, roots and organic material are particularly concentrated near pegmatite pockets, due to increased fracturing allowing in surficial waters and organic material. Underground, numerous live, intertwining roots were removed from the clay contents of one of the pockets.

Pegmatites in the Canadian Cordillera

Groat et al. (1995) list characteristics of fertile pegmatites in the Canadian Cordillera as follows:

- late post-tectonic
- emplaced at moderate to shallow crustal levels
- texturally inhomogeneous, megacrystic pods highly silicic, leucocratic and meta to para-aluminous (cordierite, andalusite or garnet-bearing)
- typically mica-bearing, especially two-mica granites, more rarely biotite granites and biotite-hornblende granites
- S-type granite geochemical signature
- initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios are high
- K/Rb, K/Cs and K/Li ratios are low

There have been detailed studies on two areas of rare-element pegmatites in the Cordillera: the O'Grady batholith (Ericit *et al.*, 2003) in Northwest Territories near the Yukon border and the Little Nahanni rare-element pegmatite field, also in the western part of the Northwest Territories (Groat *et al.*, 2003).

Muscovite is typically green in the nonpocket pegmatite portion of the dyke and is commonly colourless or very light pink in the pocket zone. Muscovite is more abundant near the pockets. Black tourmaline crystals get larger near the pockets, and orange-brown to reddish brown idiomorphic spessartine crystals increase in abundance as well.

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8. GEM TOPAZ AND RED BERYL ASSOCIATED WITH RHYOLITES AND GREISENS

INTRODUCTION

There has been more research published on topaz rhyolites than on any other type of gemstone deposit discussed in this report. The reason for all the interest is not the subtle beauty of the sherry-brown topaz crystals which are found in the rhyolites, but instead, the close spatial and genetic association of topaz rhyolite with volcanogenic beryllium, tin, uranium and fluorine mineral deposits. Topaz rhyolites may also serve as subsurface indicators of silver, fluorite, molybdenum (subvolcanic Climax-type porphyry deposits), tin and tungsten (greisen-type or skarn-type deposits) or deeper rare-element pegmatites (Burt, 1995).

Entire books and special volumes have been published on the genesis and exploration for topaz rhyolites. Comprehensive overviews include:

The Geology and Geochemistry of Cenozoic Topaz Rhyolites from the Western United States, Geological Society of America Special Paper 205, Christiansen *et al.* (1986).

Topaz Rhyolites: Distribution, Origin and Significance for Exploration, Burt *et al.* (1982).

Topaz, Special issue of the Mineralogical Record focusing solely on gem topaz (Menzies, 1995).

The chapter by Barton and Young (2002) in *Beryllium Volume* produced by the Mineralogical Society of American has information on topaz rhyolites in relation to associated beryllium deposits.

DEFINITION OF TOPAZ RHYOLITE

Topaz rhyolites are fluorine-rich alkaline silicic lavas and shallow intrusions that are characterized by the presence of topaz.

DISTRIBUTION AND AGE OF TOPAZ RHYOLITE

The greatest concentration of topaz rhyolites occur in a 'rare-metals' belt which extends from Alaska, through the Yukon, B.C, western United States and Mexico (Figure 7.5). Topaz in rhyolite was first identified within this belt in 1884 in Colorado (Burt *et al.*, 1982). Similar rocks have been identified in Mongolia and the Soviet Union, where they are called 'ongonites.'

Topaz rhyolites in the western United States have been dated at between 0.5 and 50 million years.

FIELD RECOGNITION

The defining feature of this deposit type is, of course, the presence of topaz. Burt *et al.* (1982) report that the host rhyolite resembles other silicic magmas. It ranges from typically grey or chalky, phenocryst-rich, massive and miarolitic to pinkish grey to tan, phenocryst-poor, flow-banded, lithophysal types. A distinctive honeycomb-like weathering pattern may be visible. Most topaz rhyolites are strongly flow-banded. Topaz may not be present in all the gas cavities or in all portions of the topaz rhyolite lava flow or dome, but when it is present, Burt *et al.* (1982) suggest that 15 to 30 minutes of searching with a hand lens will reveal it. Transparent topaz crystals in freshly exposed cavities are generally yellowish to pinkish brown; these colours gradually fade on exposure to sunlight. Topaz may be confused with quartz when both crystals are present in a cavity. The quartz generally forms small stubby crystals coating the walls whereas topaz forms large single crystals growing into the cavity centre. Other minerals which may occur in the cavities include red to black manganese-iron garnet, black cubes of bixbyite, black acicular pseudobrookite and black platy specular hematite, colourless crusts of sanidine, tabular to prismatic, pink to red hexagons of beryl, colourless to purple fluorite and ruby red, stubby to platy cassiterite and opal.

GEOCHEMISTRY

All topaz rhyolites contain high SiO₂ with elevated fluorine, sodium, potassium, iron/magnesium and low titanium, magnesium, calcium and phosphorus. They are also enriched in incompatible lithophile elements (rubidium, uranium, thorium, tantalum, niobium, yttrium, beryllium, lithium and cesium). Elements compatible with feldspars (strontium, europium, barium), ferromagnesian minerals (titanium, cobalt, nickel, chromium) and zircon (zirconium, hafnium) are depleted (Christiansen *et al.*, 1986).

GENESIS OF TOPAZ RHYOLITES

Topaz crystallizes at temperatures between 600 to 850°C within cavities formed by the release of fluorine-rich gas directly from volcanic magmas extruded as lava domes and other features on the earth's surface.

OCCURRENCE OF RED BERYL

A very rare variety of red beryl is found in typical 22 to 23 million-year-old topaz-bearing rhyolites in the Thomas Range, Utah (Shigley and Foord, 1985) and the Wah Wah Mountains, Utah (Keith *et al.*, 1994; Christiansen *et al.*, 1997). The red beryls are coloured by trace amounts of manganese. Their genesis is the same as that of the topaz, except that the vapor phase released from the rhyolitic magma was enriched in beryllium as opposed to fluorine.

GREISENS

Gem topaz crystals may form in greisen deposits. Typically, topaz greisens form when very hot, acidic silica-rich and fluorine-rich fluids react with aluminum leached out of feldspars when the hot fluid invades a granitic rock. When the original minerals are removed during the early stages of greisenization, there is room for topaz and other



8. Gem topaz and red beryl associated with rhyolites and greisens

minerals to grow, particularly when there have been explosions (explosion breccia) leaving lots of open cavities in which topaz and other minerals can crystallize. Tin-tungsten- and topaz-bearing granites formed in Europe during the continental collision involving North Africa, western Europe and Britain in Devonian to late Permian time.

SKARNS

Skarns form where a hot fluid intrudes a carbonate host. Gem topaz is rare in these deposits because most of the fluorine present combines with calcium and forms fluorite. Associated minerals are magnetite and fluorite.

VEINS

Hydrothermal vein deposits very rarely produce gem topaz crystals, however, one of the most outstanding topaz deposits in the world, the Ouro Preto deposit in Minas Gerais, Brazil consists of highly weathered kaolinite-quartz-K-feldspar veins. The veins are contained within a narrow fracture zone in granite-intruded phyllites. Menzies (1995) reports that the exact genesis of this deposit is uncertain.

EXPLORATION CRITERIA

The parent granites of topaz-bearing rhyolites belong to the same group of granites related to economic deposits of rare metals including pegmatite-hosted lithium, beryllium, tin, tantalum, niobium, molybdenum and tungsten high-temperature veins. Tin, tungsten and, more rarely, beryllium can occur in greisens associated with intrusion of granitic magma and hot fluids.

There is a strong link between tin and rhyolite-derived topaz. Menzies (1995) reports that cassiterite and topaz crystals are frequently found together in tin placer deposits.

Any district showing signs of greisen mineralization is a good target, especially tin and tungsten deposits which correspond to known topaz mineralization. Accessory minerals to tin and tungsten may include lesser molybdenum, bismuth and sulphide minerals.

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9. APPLICATION TO YUKON GEOLOGY

INTRODUCTION

The single best resource for generating coloured gemstone targets in the Yukon is the website for the Yukon Geological Survey (www.geology.gov.yk.ca). The site contains information on Yukon geology, but also includes links for mineral claim maps, assessment reports, library holdings, and databases such as Yukon MINFILE (Deklerk, 2003). The site has many downloadable digital files, including those for the posters mentioned in the emerald section below.

The following references are also recommended.

British Columbia Mineral Deposit Profiles (see Appendix A)

1. Alkali basalt and lamprophyre-hosted sapphire and ruby (Simandl and Paradis, 1999a)
2. Ultramafic-related corundum (Simandl and Paradis, 1999b)
3. Corundum in alumina-rich metasedimentary rocks (Simandl and Paradis, 1999c)
4. Colombia-type emeralds (Simandl *et al.*, 1999d)
5. Schist-hosted emeralds (Simandl *et al.*, 1999e)

Industrial Minerals, Gems and Minor Metals in the Yukon

by G. White (2003), ISBN 1-55362-126-3, www.emr.gov.yk.ca/Mining/YRMDP

Public mining company websites and securities commission filings

(look at technical reports and annual information forms), www.sedar.com

RUBY AND SAPPHIRES ASSOCIATED WITH ALKALI BASALT AND OTHER VOLCANIC ROCKS

Most of the world's rubies and sapphires are derived from deposits associated with alkali olivine basalt. The information and suggestions provided in the 1996 Open File (Walton) are still valid and summarized below, along with some new information.

Alkali olivine basalt is the primary rock type, especially those containing ultramafic mantle xenoliths such as spinel-lherzolite nodules. The geographical expression of the alkali basalt may be small hills, volcanic plugs, crater lakes and cinder cones. Two papers by Francis and Ludden (1995), and Carignan *et al.* (1994) discuss mid-Tertiary to recent alkaline volcanic complexes in the northern Cordillera. More recent

9. Application to Yukon geology

research by D. Francis¹ and others is focusing on more detailed examination of the chemistry and origin of the xenoliths and the recent alkaline magmas in the Canadian Cordillera. There is information on alkali olivine basalt volcanic complexes on the Geological Survey of Canada website² and a detailed mineral deposit profile is in Simandl and Paradis (1999a).

Alkaline basalt occurrences in the Yukon include, but are not limited to the following:

1. Alligator Lake (Eiche *et al.*, 1987; Francis, 1987)
2. Watson Lake area
3. Fort Selkirk region (Francis and Ludden; 1990)
4. Southwest Dawson map sheet near the head of Moose Creek (Mortensen, 1988)

Spinel-lherzolite nodules have been documented at several localities including Alligator Lake and Fort Selkirk. Megacrysts of clinopyroxene, orthopyroxene, olivine and spinel occur at Alligator lake (Eiche *et al.*, 1987). The Alligator Lake locality contains the highest concentration of ultramafic nodules (D. Francis, pers. comm., 1996). Results of chemical analysis on the alkali basalt indicate that the chemical composition of the lavas is of the nepheline hawaiite, basanite and nephelinite groups, cited by Barr and MacDonald (1978) as possibly having a relationship to gem corundum. The volcanic complex at Fort Selkirk contains a large concentration of spinel-lherzolite nodules and is chemically similar to gem-bearing corundum in Thailand and Australia. The lavas at Fort Selkirk are very young, in fact the latest eruption was within the last 100 years. In addition there are some alkali olivine basalt occurrences near the Yukon, on the Alaska side of the border. Flynn (2003) mapped the boundary area in Alaska near the border with the Yukon, and reports basanite float rock about 0.5 km north of the customs area on the Top of the World highway. There are other alkali basalt occurrences in Alaska and northern British Columbia, including Prindle Mountain, a young alkali olivine basalt cinder cone south of the Boundary area (Foster *et al.*, 1966; Roughley *et al.*, 2000).

Although one can directly prospect the alkali basalt occurrences in the Yukon, the chances of finding a ruby or sapphire gem megacryst in bedrock are extremely remote. A better method is to pan the streams draining the alkali basalts, in the hopes that there has been some concentration of heavy minerals, especially in unglaciated areas like the Klondike and Yukon/Alaska border region.

An exploration strategy for exploring for ruby and sapphire associated with alkali basalt in the Yukon may be:

1. Examine published data on basalt occurrences and concentrate on those basalts which are truly alkalic as opposed to tholeiitic, especially those which are very undersaturated (nephelinites, etc.) Those which contain spinel-lherzolite nodules should be given highest priority.

¹<http://www.eps.mcgill.ca/~donf/index.html>

²http://www.nrcan.gc.ca/gsc/pacific/vancouver/volcanoes/volcanoes_e.html



2. If a suitable target is discovered, then heavy mineral stream sediment sampling from streams draining the basalt field should be done using a cone sieve and looking for corundum or pathfinder minerals. Indicator heavy minerals include black spinel, magnetite, clinopyroxene, ilmenite, garnet and olivine. Special attention should be given to a search for zircon crystals, which are often closely associated with gem corundum in alluvial deposits overlying alkali basalt fields. For example, if one stream contains gem zircon, a different stream 10 km away may contain gem yellow and green sapphire. Use standard techniques for finding placer gold to find concentrations of gem corundum in the gravel.

Lamprophyre dykes

The occurrence of sapphires in dykes of lamproitic affinity from Montana and Scotland obviously illustrates that gem corundum can be brought up by igneous rocks other than alkali basalts. Although there are no areas of abundant ultrapotassic intrusions in the Yukon, locally, single lamprophyric dykes are present. These dykes should be examined for sapphire content directly or by examining concentrate from creeks draining them.

Porphyry deposits

Corundum is known to be associated with porphyry copper deposits. The streams draining porphyry deposits should be examined for signs of gem corundum (Simandl *et al.*, 1977a,b; Simandl and Hancock, 1997).

RUBY AND SAPPHIRE DEPOSITS ASSOCIATED WITH ULTRAMAFIC ROCKS/FELDSPAR PEGMATITES

Ultramafic rocks associated with ruby deposits in Kenya are anomalous in chromium, nickel and cobalt. Key and Ochieng (1991a,b) note that a successful exploration program for rubies in Kenya utilized sieved and panned stream sediments. Wet-sieving the 0.2 to 2.0 mm fraction is recommended since the red ruby colour is more obvious. One of the authors notes that the ultramafic rocks have distinctive spectral signatures and are easily recognized on high resolution satellite images. Simonet and Okundi (2003) offer several prospecting suggestions for exploring for coloured gemstone prospects, however, most are more suitable for a tropical climate.

Any feldspar-rich pegmatites intruding ultramafic or basic rock would be a good target. Other gemstone exploration targets are aluminum-rich metasedimentary rocks, perhaps originally derived from a bauxite deposit (Simandl, 1999), that have been intruded by feldspar pegmatites. Ruby or sapphire crystals may be found in the unit as a product of regional high-grade metamorphism, or at the contact zone between pegmatites or granitic rocks and the metaluminous unit. Grey, opaque star sapphire associated with alkali pegmatites cutting syenite-monzonite gneiss has been noted in Alaska (Richter, 1970).

MARBLES AND HIGH-GRADE METAMORPHIC TERRAINS

The 'best-quality' rubies and sapphires are commonly found with marbles in high-grade metamorphic rocks. Marble and high-grade metamorphic terrains are host to several important gem deposits including ruby, sapphire, tsavorite garnet and tanzanite. Obviously, there are very few similarities between Yukon geology and the geology of the high-grade Highland Group rocks in Sri Lanka or rocks in the Mozambique Orogenic Belt in East Africa; for example, the Sri Lankan rocks have been subject to over a billion years of metamorphic and deformational effects. In general, the metamorphic grade in the Yukon does not reach the levels that are needed for ruby, sapphire and tsavorite garnet formation during regional metamorphism. With this in mind, the Yukon-Tanana Terrane specifically does show some potential for containing metamorphic rocks of sufficient temperature and pressure to form gem corundum and other minerals. Marble beds, lenses or intercalations are good targets for ruby and sapphire crystals, especially if they are within high-grade metamorphic sequences or associated with ultramafic rocks. Abundant marble beds and lenses containing tremolite-actinolite lenses occur in the Ashihik Lake area. The metamorphic grade in this area reached upper amphibolite (S. Johnston, pers. comm., 1996). Aplite dykes and pegmatites, also a good target, are located at the margins of the Ashihik Batholith.

Rb/Sr isotopic ratios have been used in Sri Lanka as an exploration tool, however, since the Rb/Sr ratio is a function of granulite facies metamorphism in Sri Lanka, it would be of little value in the northern Canadian Cordillera.

Other places in Canada have better potential for high-quality ruby and sapphire deposits. Two areas in particular are particularly promising for gem-quality ruby and sapphire production: the Slocan Valley in British Columbia and Baffin Island in Nunavut.

The Slocan Valley area in British Columbia

The gemstone occurrences in the Slocan Valley are described in detail in a technical report filed by Anglo-Swiss Resource³. The Blu Starr property is located within high-grade metamorphic rocks making up a portion of the Valhalla Metamorphic Core Complex, a belt of high-grade metamorphic rocks of the garnet-amphibolite sub-facies. Sapphires were first discovered in 1991 by prospector Rod Luchansky in a rock cut exposed along an old Canadian Pacific railway grade. The sapphires are mainly black and bronze, but good quality blue, grey, yellow, green and mixed colours are present. At a different showing the gems are in a foliated leucocratic biotite syenite gneiss intruded by feldspar-amphibole pegmatite sills and dykes, with a notable absence of quartz. The syenite gneiss is tightly folded into a series of recumbent isoclinal folds with an amplitude of 5 to 10 m. Small low-angle thrust faults were developed during the folding episode and host a series of narrow pegmatitic sills. The best blue gem sapphires occur on the hinge of a recumbent fold, directly above a pegmatite sill and within the sill's metasomatic halo. The sapphires occur sporadically in the syenite gneiss for at least 50 m in length and are from 1 to 10 carats in size.

The company took a 150 tonne bulk sample of hand-sorted high-grade material and recovered an estimated 20,000 carats of rough sapphire.

³See www.sedar.com.



It is interesting to note that flake crystalline graphite in grey amphibole gneiss associated with numerous felsic sills and white marble was noted on the property. Depending on the metamorphic grade and other factors, it may have potential for tanzanite and tsavorite garnet.

On a more regional scale, the British Columbia Geological Survey discovered a sapphire occurrence in similar high-grade metamorphic rocks in the Revelstoke area, and Anglo-Swiss Resources investigated the gem potential of land a few kilometres away from the discovery.

Baffin Island, Nunavut

Nunavut is highly prospective for high-quality ruby and sapphire associated with marble and high-grade metamorphic rock. The Paleoproterozoic Lake Harbour Marble unit in southern Baffin Island in Nunavut shows particular promise as a gem-producing locality. Lapis lazuli (Cade *et al.*, 2003), spinel, gem hornblende (Wight, 1986) and other minerals associated with calc-silicate lenses in marble have been reported from within this unit, and True North Gems Inc. optioned property on Baffin Island with confirmed sapphire mineralization. Two cut sapphires of 0.20 carats and 0.68 carats show gorgeous deep blue colour.

HIGH-GRADE GRAPHITIC METAMORPHIC ROCKS AND MARBLE

One of the criteria for tsavorite garnet formation is graphitic high-grade metamorphic rocks interbedded with marble. Although graphitic schists and gneisses are found in the Yukon (Nasina Schist in the Klondike area), the metamorphic grades in the Yukon, in general, do not reach anywhere near the required granulite facies for tsavorite garnet formation. Although the area around the Aishihik Batholith shows evidence of upper amphibolite to granulite facies metamorphism, and there are marble units, there is little or no graphite (S. Johnston, per. comm., 1996).

Target areas using regional stream geochemical data might include vanadium anomalies which correspond with graphitic schists or marbles in a highly metamorphosed sequence of rocks. In general, the highest vanadium values in the Yukon are concentrated along the Yukon/NWT border. Tanzanite and tsavorite exploration could be carried out in conjunction with ruby and sapphire exploration in high-grade marble terrains, particularly in areas that are known to have a high graphite content. There may be potential for tsavorite garnet at certain asbestos localities; for example, B. Wilson of Alpine Gems sells small, zoned, faceted tsavorite garnet from the Jeffrey Mine (asbestos mine) in Quebec. Any asbestos locality has potential for not only tsavorite garnet, but also a rare chromium garnet called uvarovite.

ORGANIC BLACK SHALE SEQUENCES

Chapter 4 in this report describes the relationship between emeralds and organic black shale sequences. Although there are thick sedimentary shale sequences in the Yukon, none of the packages have associated interbedded evaporite sequences. Also, most of the Yukon shale basins formed in deeper water than a lagoonal or restricted basin setting. More suitable environments for emerald deposition may be located in sedimentary sequences in western NWT, northern British Columbia

or northern Alberta. Nelson *et al.* (2002) examined the timing of mineralization, isotopic characterization and tectonic setting of Mississippi Valley-type deposits in the northern Canadian Rocky Mountains. The general model for Mississippi Valley-type deposits, and in particular the Pine Point deposit in NWT is mentioned several times (Giuliani *et al.*, 1995; Ottaway, 1991) as comparable to the Colombian emerald model. Comparison of the characteristics for northern Canadian Mississippi Valley-type deposits to features noted in Colombian emerald deposits may lead to identification of prospective areas for emerald mineralization. Evaporite sequences interbedded with black shales would be of particular interest. Within the Western Canada Sedimentary Basin, the Lower to Middle Devonian Elk Point Group is a thick evaporitic sequence. It would not appear, on a regional scale, that this group has undergone the same deformation and tectonic compression as in Colombia, but there may be other similarities. It should be noted that black shale sequences in Canada are more exposed than in the heavily forested jungle terrain of Colombia. Areas where the black shales appear 'bleached' to a light grey colour should be investigated. These areas may be spotted by air, noted on air photos or on satellite photos. Weathering of the large amounts of pyrite associated with Colombian-type emerald deposits may produce a traditional reddish orange gossan.

A different approach might be to examine the total metal content of black shale sequences. The Lened emerald occurrence is genetically associated with vanadium-rich black shales. Although the black shale basins of the Yukon may not be prospective for Colombian-type emerald mineralization, they may have potential for localized emerald occurrences based on late stage intrusive fluids interacting with metalliferous black shales. The exploration target would be, on a regional scale or a local scale, rare-element parental granites and pegmatites intruding metalliferous black shales enriched in chromium or vanadium. The Yukon Geological Survey has compiled geochemical stream sediment data onto maps showing areas in the Yukon of regional enrichment in vanadium and chromium (Murphy *et al.*, 2002). The "Roll out the Beryl" poster (Lewis *et al.*, 2003, see Appendix B) shows anomalous uranium, tin, tungsten and molybdenum stream geochemistry (Héon, 2003).

PEGMATITES

Pegmatites are intrinsic to the formation of many types of gemstone deposits. In particular, granites that may have potential to spawn rare-element pegmatites should be targeted for examination, using some of the same information sources given in the above section.

White (2003) published *Industrial Minerals, Gems and Minor Metals in the Yukon*. The publication is full of useful information for gemstone exploration and is available on-line⁴ at the Department of Energy, Mines and Resources, Yukon Government website or at the Department of Energy, Mines and Resources library. The detailed sections and location maps of rare elements and minerals that are typically contained in gemstone pegmatites are of particular interest to the gemstone permatite prospector. This includes cassiterite, fluorite, topaz (in the section on gemstones), mica, minor metals (beryllium, cesium, niobium, gallium, germanium, lithium, tantalum, thorium, tungsten and yttrium), nepheline syenites and rare-earth elements. It should be noted that the new blue beryl occurrence discovered by True

⁴<http://www.emr.gov.yk.ca/Mining/YRMDP/>



North Gems in 2003 is near two documented rare-earth element occurrences (Guano, Yukon MINFILE 105F 081 and Nokluit, Yukon MINFILE 105F 080, Deklerk, 2003). In addition, White offers sections pertaining to chromite and vanadium, two elements of interest in emerald formation.

Rare-element pegmatites in the Yukon and closeby in neighbouring Northwest Territories have been documented and studied by Groat *et al.* (1995), Ercit *et al.* (2003) and Groat *et al.* (2003). In their paper describing results of research on granitic pegmatites in the Yukon, Groat *et al.* (1995) note that considerable research has been done on granitic pegmatite suites in the Canadian shield, for instance in NWT and Manitoba, however, very little has been done on the economic potential (rare-element or gemstone) of pegmatites in the Canadian Cordillera. By using the following criteria, Groat *et al.* (1995) identified pegmatites or granites in the Yukon and NWT of potential interest for rare-element content or rare-mineral species.

Groat *et al.* (1995) list the following characteristics used to identify granites which may have formed gem-bearing or rare-element pegmatites in the Canadian Cordillera:

- Parent granite stocks are commonly isolated and typically small (less than 30 km²)
- These are S-type granites (derived from supracrustal source material)
- Commonly of mid-Cretaceous age
- Peraluminous (ASI index 1–2), commonly megacrystic and leucocratic
- Show initial ⁸⁷Sr/⁸⁶Sr ratios greater than 0.7100 (mostly 0.7200 to 0.7400)
- They commonly have a peraluminous accessory mineralogy (two-mica granite, garnet or andalusite-bearing) or rare-element bearing accessory mineralization (lepidolite = lithium)

The areas in the Yukon which were targeted by Groat *et al.* (1995) using the above criteria are listed below:

- McQuesten River Region, central Yukon
- Clea Pluton, Selwyn Plutonic Suite, Yukon
- Ice Lakes area, Cassiar Batholith, southern Yukon
- Little Nahanni Pegmatite Group (on the NWT border) and O'Grady Batholith (near the NWT border)
- Seagull Batholith, southern Yukon
- Thirtymile Pluton and Ark Stock, southern Yukon
- Mount Mye Batholith, Anvil Plutonic Suite, central Yukon
- Sekwi Mountain area, northern Yukon
- Macmillan Pass, eastern Yukon
- Whitehorse area, mid-Cretaceous suite, southern Yukon
- Emerald Lake, east-central Yukon

9. Application to Yukon geology

The most interesting areas, the Little Nahanni area (Groat *et al.*, 2003) and O'Grady Batholith (Ericit *et al.*, 2003) are not in the Yukon, but are situated just across the border in the NWT. Gem-quality tourmaline of cutting grade was noted at the O'Grady Batholith locality in pegmatites at topographically high levels of the batholith. The gem tourmaline⁵ is associated with lithium in the form of lepidolite mica. The presence of lithium-enriched pegmatites was unexpected and further geochemical studies of the batholith are being carried out.

Most of the other promising areas correspond to granitic intrusions related to molybdenum, tungsten and tin deposits. The nature and distribution of granite-related molybdenum, tungsten and tin deposits in the northern Canadian Cordillera and related references are given in the posters produced by the Yukon Geological Survey that are described in the next section. The association between tin, tungsten and molybdenum deposits, pegmatites and gemstone deposits is a very strong one. This association holds not just for gemstones crystallizing with pegmatites but for those gemstones, especially emerald and chrysoberyl, which form in the metasomatic contact zone between rare-element pegmatites and ultramafic host rock. The "Roll out the Beryl" poster (Lewis *et al.*, 2003) shows anomalous uranium, tin, tungsten and molybdenum from the compilation of regional geochemical datasets (Héon, 2003).

The granites in the tin-tungsten district in the Mayo region should be evaluated and examined for pegmatites, especially in the margins of the intrusions. Groat *et al.* (1995) did just this by examining the granitic plutons in the McQuesten River region of central Yukon and found tourmaline-bearing segregations in the margins of the Two-Sisters batholith, but no sign of actual pegmatites or rare-element enrichment. The extent of this district is quite large (D. Murphy, pers. comm., 1996) and there are numerous other granitic intrusions (Emond, 1992; Emond and Lynch, 1992)

EMERALD EXPLORATION IN GENERAL

Three specific posters produced by the Yukon Geological Survey (see Appendix B or the Yukon Geological Survey's website) provide essential information on emerald exploration in the Yukon.

"WHAT ABOUT THOSE EMERALDS, EH?" (Murphy *et al.*, 2003⁶)

This poster presents information on the emerald occurrence at Regal Ridge, the geology of the host rocks and prospective areas to explore for emeralds in the Finlayson Lake area. Nearly all the areas outlined as prospective targets were staked and then explored for emeralds in the summer of 2003. Also on the poster is a series of maps showing geochemical data for the Yukon that is pertinent for emerald exploration, including Yukon maps showing:

- Chromium reservoirs (occurrences of ultramafic rocks, volcanic rocks and Earn group (metalliferous black shales) rocks in the Yukon

⁵www.alpinegems.net

⁶Murphy, D.C., Lipovsky, P.S., Stuart, A., Groat, L., Fonseca, A. and Piercey, S.J., 2002. "What about those Emeralds, Eh?" Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, poster.



- Beryllium reservoirs: Occurrences of mid-Cretaceous intrusions and plutonic rocks
- Where both types of reservoirs occur together.

Regional stream sediment value plots for cobalt, chromium, nickel and vanadium are also given (Héon, 2003).

“ROLL OUT THE BERYL” (Lewis et al., 2003⁷)

This poster presents an excellent ‘state of the art’ compilation of beryl mineralization, occurrences and exploration criteria for gem beryl in the Yukon.

“YUKON’S TUNGSTEN ADVANTAGE” (Hart and Lewis, 2002⁸)

Tungsten is an element associated with many emerald deposits, including Regal Ridge, Yukon, where scheelite precipitated during the waning stages of vein precipitation and wallrock alteration. This poster presents an excellent review of tungsten mineralization in the Yukon, including hardrock and placer tungsten.

From studies of the Regal Ridge emerald occurrence, the following exploration criteria (from a field perspective) can be used while prospecting to explore for potential ‘Regal Ridge’-style emerald occurrences.

- Devonian Fire Lake Unit chlorite schist (contains up to 5 ppm chromium)
- Cretaceous two-mica granite
- Black tourmaline along foliations in the chlorite schist
- Black tourmaline-quartz veins
- ‘Golden’-coloured schist
- Late-stage scheelite
- Fluorite

On a regional or detailed scale, soil geochemistry for beryllium, tungsten, chromium ± tin, copper and fluorine are effective up to a depth of 2 m.

ELEMENTAL THRESHOLD VALUES (IN PPM)

Rohtert and Montgomery (2001) report the following elemental threshold values for soil geochemistry at the Regal Ridge area.

Element	Weak	Moderate	Strong	Peak value (ppm)
Copper	50	100	200	1605
Beryllium	1	2	4	28.5
Tungsten	15	30	60	790

Note: The beryllium and tungsten values in this chart are based on partial digestion process. Talus fines and soil samples were sieved at -80 mesh, digested with standard aqua regia leach and analysed for 32 elements by Induced Coupled Plasma technique (ICP) at Chemex Labs Ltd. in Vancouver, B.C.

⁷Lewis, L., Hart, C. and Murphy, D, 2003. *Roll Out the Beryl*. Yukon Geological Survey, Energy, Mines and Resources, Yukon Government, poster.

⁸Hart, C.J.R. and Lewis, L., 2002. *Yukon’s Tungsten Advantage*. Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, poster.

Unattractive, opaque pale green beryl has been noted in many places in the Cassiar Batholith. Groat *et al.* (1995) report on its presence in a zoned pegmatite field south of Ice Lakes on the Wolf Lake map sheet, southern Yukon; it is also present at the Logtung deposit and discussed in Hart and Lewis (2002). Groat *et al.* (1995) suggest that although the beryl pegmatites in the interior of the intrusion are uneconomic, exploration should be carried out on known marginal to exterior pegmatites at the eastern contact of the batholith, where more distal phases of the pegmatites might be exposed. Most of the localities are associated with the Seagull Batholith or Cassiar Batholith. Several excellent exploration targets for beryl are presented on the Hart and Lewis (2002) poster.

Gem-quality topaz in miarolitic cavities has been found in the Cassiar Mountains area east of Seagull Creek. This locality is described by Grice and Gault (1985). Sherry-coloured topaz associated with alluvial cassiterite is reported from the Klondike area from Germaine Creek and in the Selwyn Basin in skarn at the TEE claim (White, 2003).

EARTHQUAKES AND LANDSLIDES

A number of significant gemstone deposits have been discovered after landslides and earthquakes exposed previously covered gem-bearing terrain. For example, it was reported that the Kashmir sapphire deposit was exposed after a landslide in a mountain cirque in 1881. Walthan (1999) notes that landslides exposed sapphires in the Mogok area. A historical record on the ruby mines of Afghanistan reports that the ruby and spinel deposits were not exposed until "after a sudden shock of an earthquake, in Badaskhan, had rent asunder a mountain in that country, which exhibited to the astonished spectators a number of sparking pink gems the size of eggs." The funny part is that women of that time valued lapis lazuli, which they crushed and used to colour ultramarine pigment. When they found they could not crush the pink-red gems (ruby) into powder, they threw them away (Hughes, 1997).

THE BE AND CR (OR V) OR WHATEVER.....CONNECTION

In the 1996 edition of this open file, geological and geochemical exploration for coincident sources or anomalies of beryllium and chromium were emphasized. A primary gemstone exploration target would be those areas where rare-element pegmatites intrude or are close to any type of chromium-bearing rock or vanadium-bearing rock. The chromium-bearing rock can be relatively fresh, for example, peridotite, or be tectonically deformed and altered (talc-dolomite melange) or metamorphic (biotite schist, serpentinite). The higher the amount of chromium, the better the chance of emerald and/or chrysoberyl mineralization. In Africa, stream sediment surveys are used in conjunction with airborne magnetic surveys to delineate zones of anomalous beryllium and chromium. In areas covered with overburden, the airborne surveys help define ultramafic rock formations under the surface. This would include beryllium anomalies in areas showing geochemical chromium anomalies, areas of ultramafic rock or aeromagnetic anomalies which could represent buried ultramafic host rocks.

All of the above is still valid, but it has become undeniable that the criteria for emerald deposits, at least, is less strict than it was ten years ago. One should not only be aware of the beryllium and chromium/vanadium connection, but also the



chemical composition of the host rocks, intrusions, structures and nearby mineral occurrences.

Gemstone deposits of any type are extremely rare compared with the more familiar and common precious metal, base metal and even diamond deposits. There is no doubt that Canada will become a producer of quality coloured gemstones one day. It is hoped that this report will generate interest in the exploration and identification of these valuable gemstone deposits.

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APPENDICES

- A. Summaries of shale-hosted and schist-hosted types of emerald deposits and exploration guides**
- B. Coloured posters available for downloading at www.geology.gov.yk.ca/metallogeny/index.html**



ALKALI BASALT AND LAMPROPHYRE- HOSTED SAPPHIRE and RUBY

Q10

by G.J. Simandl¹ and S. Paradis²



IDENTIFICATION

SYNONYMS: Alkali basalt-hosted, lamprophyre-hosted or volcanoclastic-hosted gem corundum deposits.

COMMODITIES (BYPRODUCT): Sapphire and ruby (zircon).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Mark diatreme (082N089); *Yogo Gulch (Montana, USA) Braemar, Stratmore and Kings Plains Creek (New South Wales, Australia), Changle (China)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sapphires and rubies are found as xenocrysts in some hypabyssal or eruptive alkalic rocks. The residual soil or regolith overlying these rocks can be enriched in sapphires and rubies due to intense weathering which liberates the megacrysts from the matrix.

TECTONIC SETTINGS: Host rocks occur in continental and pericontinental settings related to rifts, deep faults and/or hot-spots. In some cases they are interpreted to be subduction zone-related.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Corundum gems are brought to the surface by alkali basalt eruptions. The highest grades are associated with diatreme and base surge lithologies that erode quickly unless capped by weathering-resistant rocks, such as lava flows. Significant corundum can also be present in lava flows and hypobysal equivalents of these corundum-rich volcanic pulses.

AGE OF MINERALIZATION: Post-dates tectonic and metamorphic events. Typically hosted by Cenozoic or younger rocks. Oligocene and Miocene in New South Wales, Australia.

HOST/ASSOCIATED ROCK TYPES: Lava flows, hypabyssal intrusions and volcanoclastic rocks of alkali basalt, lamprophyre, nephelinite, basanite or phonolite composition. Highly altered and/or weathered volcanoclastic rocks, including reworked lahar flows and base surge and ash-fall deposits commonly have the highest gem corundum content. Mantle and crustal rock xenoliths, including lherzolites, peridotites and in some cases corundum-bearing gneiss, occur in the above lithologies. There are little or no restrictions as to the lithology of the wallrock.

DEPOSIT FORM: With the exception of diatremes and volcanic necks, host igneous rocks are generally tabular bodies (dykes, lava flows, pyroclastic flows). The flows and their erosional remnants vary from less than a metre to several metres in thickness and extend from hundreds of metres to more than several kilometres. Extensive, thin, heavy minerals-enriched layers can carry higher grades. They form volcanoclastic aprons around diatremes and are possibly produced by base surges. High grade zones may also form thin blankets associated with unconformities or recent erosional surfaces. The lamprophyre dykes, such as Yogo, may consist of several en echelon segments from less than a metre to several metres thick and hundreds of metres in length.

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COLOMBIA-TYPE EMERALDS

Q06

G.J. Simandl¹, S. Paradis² and T. Birkett³



IDENTIFICATION

SYNONYMS: Emerald veins, Muzo and Chivor-type emerald deposits.

COMMODITIES (BYPRODUCTS): Emeralds (pale-green and colorless beryl gemstones).

EXAMPLES (British Columbia - Canada/International): No Colombia-type emerald deposits are known in British Columbia. *Chivor, La Mina Glorieta, Las Cruces, El Diamante, El Toro, La Vega de San Juan, Coscuez and Muzo (Colombia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Colombia-type emerald deposits consist mainly of carbonate-pyrite-albite quartz veins forming “en échillon” or conjugate arrays and cementing breccias. So called “stratiform tectonic breccias” may also contain emeralds. Emeralds are disseminated in the veins as clusters, single crystals or crystal fragments; however, the best gemstones are found in cavities. Country rocks are black carbonaceous and calcareous shales.

TECTONIC SETTING: Probably back arc basins (shales deposited in epicontinental marine anoxic environments spatially related to evaporites) subjected to a compressional tectonic environment.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The deposits are controlled by deep, regional decollements, reverse or thrust faults; hydraulic fracture zones, intersections of faults and by permeable arenite beds interbedded with impermeable black shales.

AGE OF MINERALIZATION: Colombian deposits are hosted by Cretaceous shales. Ar/Ar laser microprobe studies of Cr-V-K-rich mica, believed to be penecontemporaneous with the emerald mineralization, indicate 32 to 38 Ma for Muzo area and 65 Ma for Chivor district. It is not recommended to use these age criteria to constrain the exploration programs outside of Columbia.

HOST/ASSOCIATED ROCK TYPES: Emerald-bearing veins and breccias are hosted mainly by black pyritiferous shale, black carbonaceous shale and slate. Claystone, siltstone, sandstone, limestone, dolomite, conglomerate and evaporites are also associated. Two special lithologies described in close association with the deposits are albitite (metasomatized black shale horizons) and tectonic breccias (“cenicero”). The latter consist of black shale and albitite fragments in a matrix of albite, pyrite and crushed black shale.

DEPOSIT FORM: The metasomatically altered tectonic blocks may be up to 300 metres in width and 50 km in length (Beus, 1979), while individual productive zones are from 1 to 30 metres in thickness. Emeralds are found in en échelon and conjugate veins that are commonly less than 10 centimetres thick, in hydraulic breccia zones and in some cases in cenicero.

TEXTURE/STRUCTURE: Emeralds are found disseminated in veins as clusters, single crystals or crystal fragments, however, the best gemstones are found in cavities. Quartz is cryptocrystalline or forms well developed hexagonal prisms, while calcite is fibrous or rhombohedral. In some cases, emerald may be found in black shale adjacent to the veinlets or cenicero.

ORE MINERALOGY [Principal and subordinate]: Emerald; *beryl specimens and common beryl.*

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CORUNDUM IN ALUMINA-RICH METASEDIMENTS P06

by G.J. Simandl¹ and S. Paradis²



IDENTIFICATION

SYNONYMS: Corundum-bearing schists and paragneisses; corundum in metapelites and metabauxites are covered by this model.

COMMODITIES (BYPRODUCTS): Industrial-grade corundum (gem corundum) and emery.

EXAMPLES (British Columbia - Canada/International): Blu Starr (082FNW259); *Elk Creek, Bozeman and Bear Trap deposits (Montana, USA), Gangoda and Tannahena occurrences (Sri Lanka)*,

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Corundum occurs as porphyroblasts or idiomorphic, xenomorphic or skeletal crystals within high grade, regionally metamorphosed belts. It is confined to specific metamorphic layers and concordant lenses of alumina-rich gneisses and schists. It is rarely of gem quality. Emery is a fine-grained, black, granular rock composed of intergrowths of corundum, magnetite, hercinitite or hematite that commonly forms in medium to high grade metamorphic environments.

TECTONIC SETTINGS: Corundum in gneisses occurs mostly in fold belts or deep cratonic (catazonal) environments exhumed in thrust belts or by erosion. Emery and related meta-bauxites may be found in wide variety of tectonic environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Most of these deposits form in high-grade, mainly granulite facies, dynamothermal metamorphic (catazonal) environments. Metasedimentary belts containing aluminous strata or lenses, in some cases intruded by igneous rocks, are particularly favourable. Emery deposits are also known to occur in similar and lower grade metamorphic environments.

AGE OF MINERALIZATION: Corundum is considered syn-metamorphic. The protolith may be Precambrian or younger. Rocks that were exposed at the surface during periods of extreme chemical weathering are particularly favourable

HOST/ASSOCIATED ROCK TYPES: Corundum-bearing gneisses and schists are associated with sillimanite-garnet-biotite gneisses, kyanite-mica schists, quartzites, clinopyroxenites, pegmatites, syenites or alkaline intrusions, anorthosites, charnockites, migmatites, granitic and intermediate intrusive rocks, quartz-mica schists, granulites, aplites, marbles, cordierite-bearing gneisses, amphibolites and wollastonite-scapolite rocks. The lithologies hosting metasedimentary emery lenses are commonly lower metamorphic grade equivalents of above listed rocks.

DEPOSIT FORM: Corundum-bearing, stratabound and discontinuous layers and lenses in gneisses are from 20 centimetres to a few metres in thickness and may be traced for tens to hundreds of metres along strike. These layers are commonly strongly deformed, with coarse-grained "sweat outs" which may cut across the gneissic texture. Emery may form lenses from 5 to more than 50 metres thick and more than 100 metres in length.

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SCHIST-HOSTED EMERALDS

Q07

G.J. Simandl¹, S. Paradis² and T. Birkett³



IDENTIFICATION

SYNONYMS: Emerald deposits commonly described as “suture zone-related”, “pegmatite-related schist-hosted” or “exometamorphic”, “exometasomatic”, “biotite schist-type”, “desilicated pegmatite related” and “glimerite-hosted” are covered by this model.

COMMODITIES (BYPRODUCTS): Emerald (industrial grade beryl, other gemstones, such as aquamarine, chrysoberyl, phenakite, tourmaline).

EXAMPLES (British Columbia - Canada/International): *Socoto and Carnaiba deposits (Brazil), Habachtal (Austria), Perwomaisky, Mariinsky, Aulsky, Krupsky, Chitny and Tsheremshansky deposits (Russia), Franqueira (Spain), Gravelotte mine (South Africa), Mingora Mines (Pakistan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Emerald deposits principally related to mafic and ultramafic schists or unmetamorphosed ultramafic rocks in contact with felsic rocks, either pegmatoid dykes, granitic rocks, paragneisses or orthogneisses. Such contacts may be either intrusive or tectonic.

TECTONIC SETTINGS: Found in cratonic areas as well as in mobile belts. In many cases related to major Phanerozoic or Proterozoic suture zones that may involve island arc-continent or continent-continent collision zones. The lithological assemblages related to suture zones commonly form a “tectonic mélange” and in some areas are described as “ophiolitic mélange”.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Mainly in greenstone belts, but also in other areas where Cr-bearing rocks may be adjacent to pegmatites, aplites, granites and other felsic rocks rich in beryllium. Metamorphic grade is variable; however, it typically reaches green schist to amphibolite facies.

AGE OF MINERALIZATION: The deposits are hosted by Archean age rocks or younger. The age of mineralization is typically linked to either a period of tectonic activity or a time of pegmatoid emplacement.

HOST/ASSOCIATED ROCK TYPES: Biotite schists (“biotites”, “phlogopitites” and “glimerites”) are a particularly favourable host. Other favourable hosts are metamorphosed mafic volcanic rocks, such as epidote-chlorite-actinolite-bearing rock, chlorite and chlorite-talc schists, talc and talc-carbonate schists, white mica schists, mafic schists and gneisses and amphibolites. Less commonly emeralds occur in unmetamorphosed mafic or ultramafic rocks and possibly listwaenites. Pegmatites or quartz veins in the contact zone between granitic rocks and mafic rocks may in some cases host emeralds. A wide variety of rocks can be associated with schist-hosted emerald deposits, including granite, syenite, tonalite, granodiorite, a variety of orthogneisses, marbles, black phyllites, white mica schists, mylonites, cataclasites and other metasedimentary rocks.

DEPOSIT FORM: Most of the mineralization is hosted by tabular or lenticular mafic schists or “blackwall zones”. Favourable zones are a few metres to tens of metres wide and follow the contacts between felsic and mafic/ultramafic lithologies for distances of tens to hundreds of metres, but economically minable portions are typically much smaller. For example, minable bodies in the Urals average 1 metre in thickness and 25 to 50 metres in length. Pegmatoids, where present, may form horizontal to steeply dipping pods, lens-shaped or tabular bodies or anastomosing dykes which may be zoned.

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ULTRAMAFIC-RELATED CORUNDUM

Q09

(CONTACT METAMORPHIC/METASOMATIC)

by G.J. Simandl¹ and S. Paradis²



IDENTIFICATION

SYNONYMS: Plumasite and marundite deposits, contact-metamorphic corundum and emery, “desilication” or metasomatic sapphire.

COMMODITIES (BYPRODUCTS): Rubies, sapphires, industrial grade corundum and emery.

EXAMPLES (British Columbia - Canada/International): *Corundum Hill (North Carolina, USA), Emery Hill (New York, USA), Natal and Birdcage camp (South Africa), Umba (Tanzania), Kinyiki Hill and Penny Lane ruby mine (Kenya).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sapphire, ruby and industrial grade corundum occur within, or adjacent to, aplite, pegmatite, albitite, plumasite or marundite dykes, sills and rarely plugs cutting mafic and ultramafic rocks and their metamorphosed equivalents. Industrial grade corundum is also found commonly along contacts of mafic/ultramafic intrusions with metapelites or other felsic country rocks. It may occur both within country rock and the intrusion.

TECTONIC SETTINGS: These deposits occur in orogenic belts where felsic rocks are thrust against silica-undersaturated rocks and within the stable cratons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Corundum is commonly found in quartz-free reaction zones located along contacts of silica-deficient rocks, such as ultramafic and mafic rocks, with pegmatite, paragneiss, syenite gneiss or other felsic rocks. Country rocks are typically affected by medium to high grade regional metamorphism.

AGE OF MINERALIZATION: Archean or younger. Abrasive-grade corundum deposits are commonly contemporaneous with contact metamorphism, while gem-quality corundum may post-date metamorphism and the peak of the tectonic activity.

HOST/ASSOCIATED ROCK TYPES: Common host rocks are vermiculite ± chlorite ± asbestos-bearing rocks, plumasite (coarsegrained rock consisting of anhedral corundum crystals in an oligoclase matrix), syenite, pegmatite, aplite or hornfels. Associated rocks are ultramafics, a variety of mafic lithologies including gabbro, amphibolite, anorthosite, serpentinite, anthophyllite-chlorite-talc schist, peridotite and dunite and peraluminous orthogneisses or paragneisses.

DEPOSIT FORM: Most of the dyke-associated or fracture-controlled deposits that crosscut ultramafic and mafic rocks are planar or lens-shaped; rarely forming vertical plugs. They are less than a metre to 10 metres in thickness and may extend from few metres to several tens of metres along strike. These deposits exhibit several types of mineralogical zoning from the center of the deposit outwards:

- a) Corundum-chlorite > spinel - chlorite > enstatite > talcose rock > friable dunite > dunite;
- b) plumasite > biotite > pegmatite > serpentinite;
- c) aplite > plumasite > spinel-magnetite rock > vermiculite and/or chlorite > actinolite > talc > serpentinite;
- d) barren pegmatite > marundite > talc-chlorite zone > amphibolite (pegmatite may not be present).

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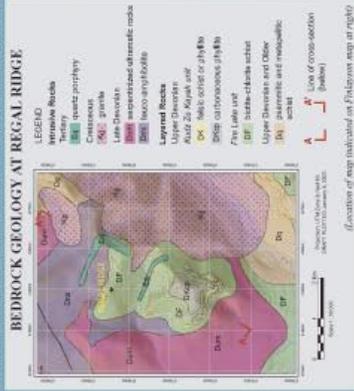
'WHAT ABOUT THOSE EMERALDS, EH?'

Geological Setting of Emeralds At Regal Ridge (SE Yukon) Provides Clues to Their Origin - And To Other Places To Explore

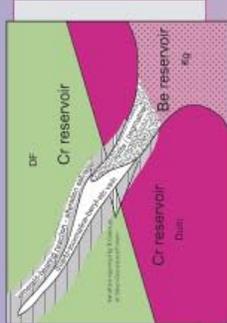
Donald C. Murphy
 Anna Fonseca
 Panya S. Lipovsky and Amy Stuart Akhbar Geological Consulting
 Whitehorse, Yukon
 Yukon Geology Program
 Stephen J. Piercey
 Laurentian University
 University of British Columbia



In 1998, a new occurrence of emeralds was discovered in Finlayson Lake area, south-western Yukon. Emeralds occur in the alteration selvages of quartz-tourmaline (sclerite-muscovite-beryl) veins cutting biotite-chlorite metavolcanic schist in the metamorphic aureole around one of the area's largest bodies of mid-Cretaceous granite. In the area of the showing, the mafic schist, part of the widespread Upper Devonian Fire Lake unit, is meta-basalt of boninitic composition (see spidergram below) which overlies a thick, laterally tapering slab of variably serpentinized mafic and ultramafic meta-ophanitic rocks. Using various geometric and geological criteria, this slab is inferred to be a sill, conterminous with the Fire Lake unit, which intruded laterally from feeder dykes localized along a nearby syntectonic fault.



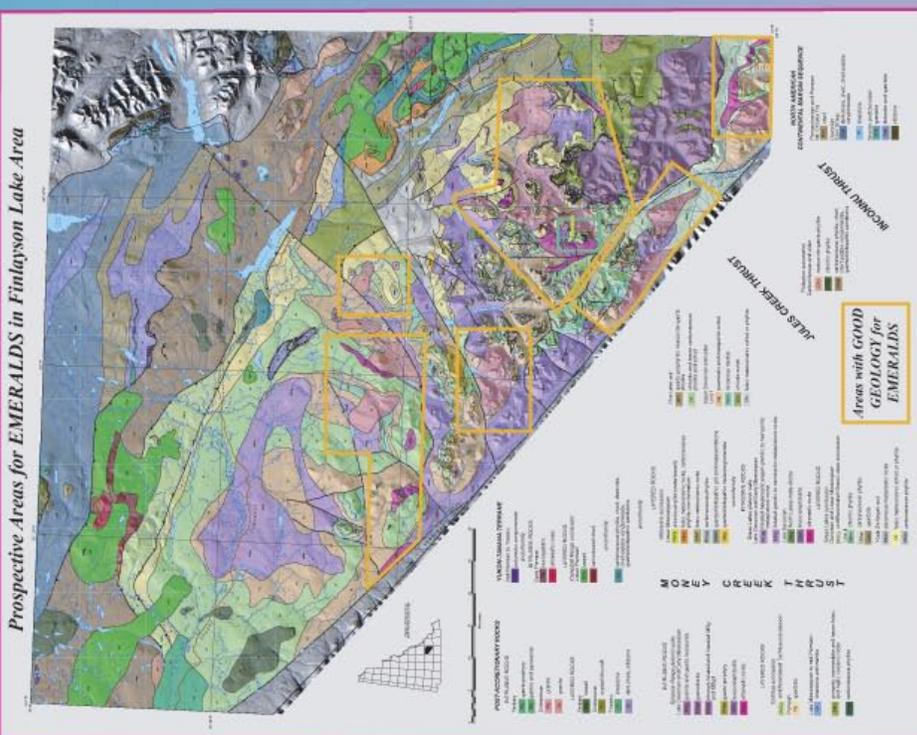
The map trace of the western contact of the granite lies about 2 km east of the Crown showing. The granite is biotite-muscovite-bearing, discordant with respect to planar fabrics of the host metamorphic rocks, yet locally weakly foliated, indicating late- to post-kinematic emplacement. As with most Cretaceous granites in the area, tourmaline is a common accessory phase, occurring disseminated throughout the body or in quartz vein arrays both in and around the granite. The western contact of the granite is observed to be gently west-dipping, underlying the Crown showing at a relatively shallow depth.



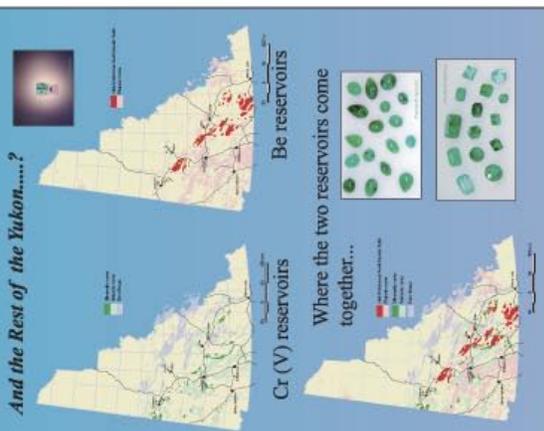
The orientations of the western granite contact and the contact between the Fire Lake unit and the co-magmatic mafic and ultramafic sill are such that the granite likely intrudes through the ultramafic sill at depth. Furthermore, the gentle orientation and local map traces of the granite contact suggests that the exposed granite is near its roof, ideal for the concentration of volatile-rich fluids.

EMPIRICAL MODEL FOR THE FORMATION OF EMERALDS AT REGAL RIDGE

The intrusion of relatively evolved granite into rocks of Cr-rich rocks (mafic and ultramafic composition) seems an ideal setting for the formation of emeralds. The alteration of host mafic and ultramafic rocks by hot, volatile-rich fluids emanating via vein arrays off the roof of the granite would put Be in the same place as Cr, an obvious, but geologically difficult to attain, precondition for emerald formation.



It's pretty clear that new staking in the area was done with geology in mind...



Mid-Cretaceous granite and mafic and ultramafic rocks occur together elsewhere locally in the Finlayson Lake area but also regionally throughout Yukon. This combination is an attractive exploration target for emeralds.

