canada/yukon economic
development agreement

INDIAN AND NORTHERN AFFAIRS CANADA
NORTHERN AFFAIRS: YUKON REGION

Open File 1996-2(G)

EXPLORATION CRITERIA FOR GEMSTONE DEPOSITS AND THEIR APPLICATION TO YUKON GEOLOGY

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ACKNOWLEDGEMENTS

I would like to gratefully acknowledge the funding granted by the Canada/Yukon Mineral Development Agreement which enabled me to take the time to work on this report. Several individuals took time to discuss certain aspects of the project - G. Abbott, D. Brent, A. Doherty , C. Hart, S. Johnston, J. Mortensen, D. Murphy, D. Ouellette and many others. The library staff at the Department of Indian and Northern Affairs, Yukon helped tremendously in finding some fairly obscure references. P. Erdmer provided many useful comments. H. Keyser provided editing support.

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CHAPTER ONE

INTRODUCTION

Scope

The discovery of diamond-bearing kimberlite in the Northwest Territories has generated a wealth of papers, special volumes and short courses outlining diamond exploration guidelines for exploration geologists and prospectors. Most geologists and prospectors carrying out exploration programs in the Yukon are now educated on the geology of diamond deposits and what to look for in the field. Geological, geochemical, and geophysical exploration for diamonds in the Yukon was covered by Erdmer and Downing (1993).

Other types of valuable gemstone deposits could very well exist in the Yukon or the rest of Canada; however, published exploration guidelines for these deposits are practically non-existent. Although detailed descriptive accounts and gemological studies have been published, there has been little comprehensive research done on the genesis of gem deposits and the physio-chemical conditions under which they form. Only by understanding how mineral deposits form can the exploration criteria be determined.

Most prospecting and "gem hunting" guidebooks deal with the "how-to's" of collecting rather than presenting geological and geochemical guidelines on where to look. Multi-disciplinary studies on gemstone deposits are rare; the most notable example being the benchmark work "Emeralds of Pakistan - Geology, Gemology and Genesis" (Kazmi and Snee, 1989) and even in these works the exploration criteria are not usually discussed. There is the occasional gemstone deposit paper in *Economic Geology* or other widely distributed journals, but most published research on the geology and genesis of gemstone deposits is in three gemology journals (*Gems and Gemology, Journal of Gemmology, Australian Gemmologist*) which are relatively unknown outside the gemological world and difficult for most exploration geologists and prospectors to obtain.

Exploration geologists or prospectors may not be familiar with the appearance of gemstones in the field, since many gemstones in the jewellery trade today have been treated in some manner to improve their appearance. The gemstone rough discovered in the field may bear little or no resemblance to the gemstones one is familiar with in jewellery stores.

This report is a preliminary compilation of on-going work regarding the geology and geochemistry of gemstone deposits and applicable exploration criteria. The report is 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 gemstones. The report focuses on a selection of some of the most valuable 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 are presented. The geology and genesis of each gem deposit type is summarized and exploration guidelines listed. Because pegmatites are so closely associated with several gemstones including 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 Eight. Application of the exploration criteria to Yukon geology is given in Chapter Nine. A reference list is provided for those readers who want to pursue further details.

The exploration criteria presented are meant as guidelines only. One of the difficulties in compiling exploration guidelines is that many of the world's gemstone deposits are unique. The entire world's supply of tanzanite (the fifth largest selling 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; it will be shown that among emerald deposits, the Colombian ones have a unique paragenesis which is not known to have been duplicated anywhere else in the world. It is difficult to determine the range of variations and physio-chemical conditions under which a particular type of gemstone deposit may form, if there is only one deposit to study.

Diamonds are not covered in this report since the exploration criteria for diamond deposits in the Yukon was covered by Erdmer and Downing (1993) and information on diamond deposit formation and exploration techniques is widely available.

The existing English-language literature on gemstone deposits was researched through databases such as GEOREF and the GSC database. Research was carried out using the author's database and by utilizing resources at the Department of Indian and Northern Affairs library in Whitehorse, Yukon and the University of British Columbia. There are very few papers on exploration criteria for a particular gem deposit, in most cases, the geology of each gem deposit was studied and the applicable exploration criteria was extracted. When possible, geologists familiar with the geology of certain gem deposits or the geology of the Yukon were contacted to discuss points of interest.

Colored Gemstones

There are over 2,500 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 the 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 global gem trade is divided into two broad categories; diamonds and colored stones (a third smaller category includes pearls). Unlike diamonds there is no standard grading or pricing system in place for ruby, sapphire, emerald or other colored stones. The price of colored 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 deposit from which the gemstone was mined. For instance, a quality ruby from Myanmar (formerly called Burma), for reasons described in Chapter Three, 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 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 Myanmar (Burma) are more valuable.

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 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 from Hughes (1990) illustrates typical mark-ups on a piece of rough ruby, from the initial discovery to its final place in a piece of jewellery.

Two countries in particular, Pakistan and Tanzania have realized the importance of gemstone mining to the economy and have supported state geological surveys and studies of the gemstone deposits. As a result, Tanzania was a major producer of no less than eight different gemstones during the 1980's (Shigley et al., 1990).

One of the main problems in the colored stone trade is the lack of deposits which produce a large quantity of facetable material. It is hoped that this report will help promote awareness of the geological and geochemical environments in which gemstones form.

Distributor	*Purchase price*	*Mark-up* (%)	*Selling price*
Miner	5 carat rough ruby	–	$100 per carat
Smalltime rough buyer	$100 per carat rough	30	$130 per carat rough
Cutter – rough to cut = 20% yield 5 carat rough = 1 carat cut	$130 per carat	30	$845 per carat cut
Chanthaburi dealer	$845 per carat cut	20	$1014 per carat cut
Bangkok dealer	$1014 per carat cut	28	$1300 per carat cut
US buyer	$1300 per carat cut	40	$1820 per carat cut
US manufacturer	$1820 per carat cut	50	$2730 per carat cut and set
US jeweller	$2730 per carat cut and set	100	$5460 per carat cut and set
US consumer	$5460 per carat cut plus price of setting	–	–

Table 1.1 Mark-up on ruby rough From Hughes (1990)

CHAPTER TWO

FIELD IDENTIFICATION OF GEMSTONES

Gemstone deposits can be discovered by using the same 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 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 colored 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 to indicate 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 antheaps 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 rough reference sets are available to help the user identify potentially valuable gem minerals (Appendix A). Effective use can also 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.

1. Thermal Testing Probe

Thermal testing probes were first introduced to the jewellery market in the late 1970's as a quick and easy method of separating diamond from diamond simulants. The author has successfully used one of these probes, the GEM DiamondMaster, 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 GEM DiamondMaster probe in gem identification is given by

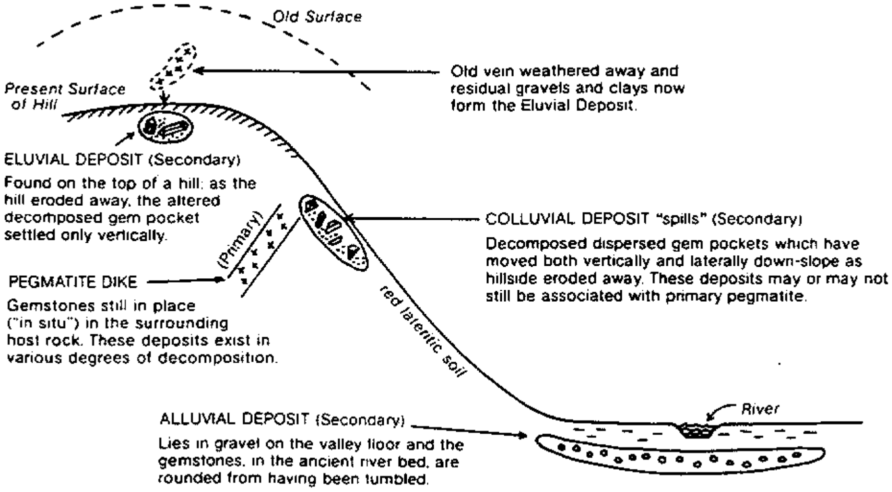


Figure 2.1 Formation of eluvial, colluvial and alluvial gem deposits From Proctor (1984)

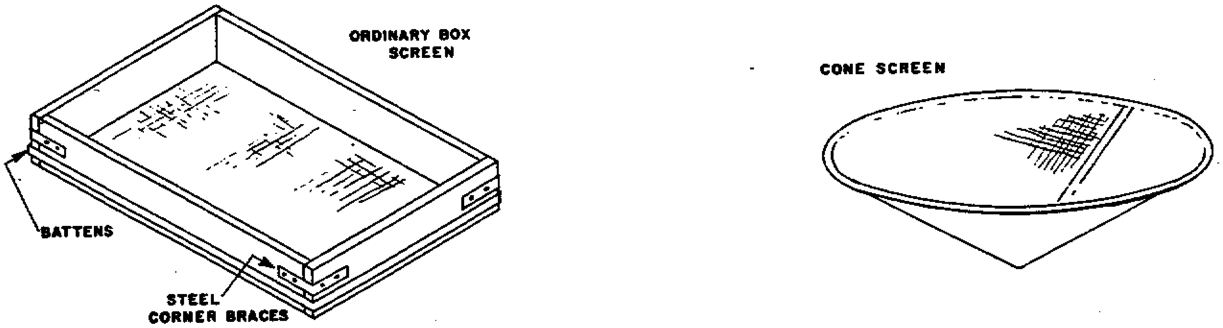


Figure 2.2 Ordinary box screen and cone screen From Sinkankas (1970)

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.

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. Other probes, for example the GEM DiamondMaster, provide 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.

Probably the most useful separation involves 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%.

2. Dichroscope

Some minerals split light into two rays when it 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 colors when viewed through a "dichroscope". A dichroscope is 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 colors. One can observe pleochroic colors by looking at the gem through the tube. A dichroscope works best on larger, transparent crystals. For example, ruby crystals (doubly refractive) can easily be separated from two other red gemstones, garnet and spinel (singly refractive). Gemstones which are singly refractive such as spinel and garnet do not show pleochroic colors. Care must be taken to look for pleochroic colors in more than one direction.

3. Heavy Liquids

Canadian exploration geologists and prospectors became more aware of the use of heavy liquids in the early 1990's because of their use in separating out diamond indicator minerals. Lighter mineral grains float in a liquid with a lighter density and heavier mineral grains 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 not volatile and, unlike methylene iodide, has no noxious odor. It has a base density of 2.8.

A hydrometer marketed through Mineralab (Appendix A) measures the specific gravity of individual mineral grains. The author has not yet seen or tested this device.

4. Screens

One of the best ways to separate 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 (Fig. 2.2).

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

Amber	1.08
Bakelite	1.26
Tortoiseshell	1.29
Erinoid	1.33
Celluloid	1.38
Vegetable ivory	1.40
Ivory	1.80
Bone	2.00
Fire opal	2.00
Opal	2.10
Obsidian	2.40
Moonstone	2.57
Chalcedony (agate, cornelian)	2.60
Quartz	2.65
Coral	2.68
Beryl (aquamarine)	2.69
Beryl (yellow)	2.69
Beryl (emerald)	2.71
Beryl (pink)	2.80
Pearl (natural)	2.71
Pearl (cultured)	2.75
Turquoise (American)	2.7
Turquoise (Iranian and Egyptian)	2.8
Lapis lazuli	2.8
Pink (conch) pearl	2.85
Nephrite	3.00
Tourmaline	3.05
Andalusite	3.15
Fluorspar	3.18
Spodumene	3.18
Jadeite	3.33
Peridot	3.34
Zoisite	3.35
Sinhalite	3.48
Diamond	3.52
Topaz (pink)	3.53
Topaz (yellow)	3.53
Topaz (white)	3.56
Sphene	3.53
Spinel	3.60
Spinel (synthetic)	3.63
Hessonite	3.65
Pyrope	3.7–3.8
Chrysoberyl	3.72
Demantoid	3.85
Almandine	3.9–4.20
Corundum	3.99
Zircon (green)	4.0–4.5
Zircon (blue, white, golden)	4.69
Pyrites	4.90
Hematite	5.10
Silver	10.50
Gold, 9 carat	11.40
Gold, 14 carat	13.93
Gold, 18 carat	15.40
Gold, 22 carat	17.70
Gold, Pure	19.30
Platinum	21.50

Table 2.1 Specific gravity of gemstones From Anderson (1990)

recommends a rectangular screen no more than 18" x 24" in size be used for a single person to operate.

Cone Screen

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 and then sent in 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 colored or does not glow under ultraviolet light.

By using a cone screen (Fig. 2.2), 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" in diameter to separate 15 lbs of garnet from 100 lbs of unsorted material in about 1 hour.

5. Ultraviolet Light

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

6. 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.

Cathodoluminescence is recommended by Mariano (1987) and Ponahlo (1988) as a gemstone exploration tool. Cathodoluminescence produces luminescence in a mineral by bombardment with high-energy free electrons. Mariano (1987) reports that in regional exploration programs for gemstones, cathodoluminescence can be used for direct identification of emerald, ruby, sapphire, chrysoberyl, topaz, spinel and tsavorite garnet.

CHAPTER THREE

RUBY AND SAPPHIRE

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, 1990). 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 colors including yellow, orange, violet, green, brown and black corundum are referred to by color (e.g. yellow sapphire, green sapphire, pink-orange sapphire).

Ruby and sapphire are important gemstones in the world gem trade; together they account for over 50% of global gem production (Hughes, 1990). Ruby is the world's most expensive gemstone. The only exception is a record $926,315 per carat paid for a .95 carat red-purple diamond at auction in 1987. The world record price at auction paid for a ruby is $227,300 per carat in 1988. In general, although fine quality rubies in the larger sizes are many times rarer than diamonds, they are only marginally more expensive. A customer in a Canadian jewellery store can expect to pay $1,500 to $4,000 per carat (CDN) for a fine quality 1 ct blue sapphire. A fine quality 1 ct red ruby may go for between $5,000 to $8,000 (CDN). Prices may fluctuate from store to store by as much as +/- $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 different.

A comprehensive gemological and geological overview of gem corundum is provided in the book "Corundum" by Hughes (1990). For a general overview, the book "Rubies and Sapphires" (Ward, 1992) 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 (1991) 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 5,000 known kimberlites in the world, fewer than 50 have been or are economic and only about 12 produce more than 3 million carats per year (Erdmer and Downing, 1993). Diamond deposits are indeed rare; however, there are several new world-scale prospects in Canada and active exploration is being carried out around the globe. The situation is much different with ruby and sapphire.

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). 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). An additional nine deposits classified as "minor world occurrences of gem corundum" do not produce significant amounts of ruby or sapphire (Table 3.2). New occurrences of ruby in Vietnam and the Mong Hsu area of Myanmar (Burma) are not included. Other deposits not listed are known to occasionally produce gem corundum; these include Idaho (USA), North Carolina (USA), Madagascar, Mozambique, South Africa and the Soviet Union.

Current Sources of Ruby

For over 800 years, the alluvial deposits at Mogok, Myanmar 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

Locality	*Mode of occurrence*	*Varieties*
Mogok, Burma	Ruby: found in alluvial gravels derived from metamorphosed crystalline limestones Sapphire: found in alluvial gravels derived from granitic pegmatites, or rarely from corundum syenites (Iyer, 1953)	Ruby (most common), blue sapphire; also yellow, violet, green sapphire, stars, colour-change sapphires, etc.
Chanthaburi, Kanchanaburi, Trat and Phrae Provinces, Thailand, and Battambang Province (Pailin), Cambodia	Ruby and sapphire: found in eluvial and alluvial gravels derived from nepheline normative and highly alkaline basalts, especially basanitoid basalts (Vichit, 1978)	Ruby, blue, yellow, green and black star sapphires
Sri Lanka	Ruby and sapphire: found in alluvial stream gravels derived from granulites, pegmatites, garnetiferous gneisses, skarns, cordierite gneisses and associated rocks (Heilmann and Henn, 1986)	All colours, except green (rare); also stars
Kashmir, India	Blue sapphire: found in feldspar pegmatites surrounded by modified actinolite–tremolite bodies and in alluvial gravels derived from these rocks (Atkinson and Kothavala, 1983)	Blue sapphire, rarely pink sapphire; also star sapphires
Queensland and New South Wales, Australia	Sapphires: found in eluvial and alluvial gravels derived from alkali basalts (Coldham, 1985). Recent work suggests that 'basaltic' tuffs may in fact be the source of the sapphire in New South Wales (Pecover, 1987)	Blue, green, yellow and black star sapphires
Jagdalek, Afghanistan	Ruby: occurs *in situ* within a metamorphosed dolomitic limestone cut by granitic intrusions of Oligocene age (Bowersox, 1985)	Ruby
Umba Valley, Tanzania	Ruby and sapphires: found in elluvial and alluvial gravels derived from limestones or pegmatite veins within or bordering a serpentinite pipe (Bridges, 1982)	All varieties
Mangari District, Kenya	Ruby: found *in situ* or in eluvial gravels derived from desilicified veins cutting through altered and serpentinized ultramafic rocks, or in or near the contact zone of a serpentinized pipe associated with desilicified pegmatoidal segregations (Bridges, 1982)	Ruby
Yogo Gulch, Montana, USA	Blue sapphire: commonly found in eluvial or alluvial gravels derived from a lamprophyric igneous dike intruded into a fault within the limestone country rock. The dike rock is also mined itself (Brown, 1982)	Blue and lilac-coloured sapphire
Kaduna, Nigeria	Secondary deposits associated with alkali basalts (Kiefert and Schmetzer, 1987)	Mainly blue sapphires, also greens, yellows and bicolours (green/yellow or blue/yellow)

Table 3.1 Major world occurrences of corundum From Hughes (1990)

Locality	*Mode of occurrence*	*Varieties*
North Carolina, USA	*In situ* and alluvial deposits mostly associated with basic magnesian rocks such as peridotite, pyroxenite and amphibolite (Pratt, 1933)	Mainly ruby, but also sapphires of various colours
Hunza Valley, Pakistan	*In situ* deposit of a ruby-bearing dolomitic marble (Gübelin, 1982)	Mainly ruby, some purple to violet sapphires
Mingxi, Fujian Province, China	Alluvial deposits associated with alkali basalts (Keller and Keller, 1986)	Yellow-green, green, blue-green and blue sapphires
Penglai and Wenchang, Hainan Island, China	Alluvial deposits associated with alkali basalts (Keller and Fuquan, 1986)	Blue and green sapphires
Sichuan Province, China	Undescribed (Keller and Fuquan, 1986)	Translucent to opaque ruby
Mercaderes – Rio Mayo area, Cauca, Colombia	Alluvial deposits associated with alkali basalts (Keller *et al.*, 1985)	Mainly blue and green sapphires, also yellows, pinks, reds and colour-change stones
Rio Coxim, Mato Grosso, Brazil	Unknown (Eppler, 1964)	Blue sapphires
Chimwadzulu Hill, Malawi	*In situ* and alluvial deposits derived from an epidotized amphibolite (Rutland, 1969)	Virtually all colours, from pinks and reds to blues, greens, yellows and oranges
Barauta, Zimbabwe	*In situ* and alluvial deposits derived from a pegmatite (Sweeney, 1971)	Blue sapphire

Table 3.2 Minor world occurrences of gem corundum From Hughes (1990)

Cambodian rubies, long considered to be "inferior", as the new global "ideal". In the 1980's, the traditional sources of Mogok, Myanmar; Chanthaburi, Thailand; and Pailin, Cambodia were the major producers (Shigley et al., 1990). New deposits from Tanzania, Kenya, Vietnam, Afghanistan, and Pakistan show promise. Initial parcels of Vietnamese rough sold to U.S. and European dealers shortly after the discovery of gem ruby in Vietnam in the early 1990's contained so much synthetic ruby that this source quickly lost favor with the gem trade. The Pailin gem district in Cambodia remains in the control of the Khmer Rouge, although Cambodian government forces tried to regain control in early 1996. The military government in Myanmar is loosening trade restrictions and a brand-new ruby deposit at Mong Shu in Myanmar is producing excellent material. The African deposits, while promising, are still not producing large quantities of rubies suitable for mass-produced jewellery.

Current Sources of Sapphire

Most sapphire in the 1980's was produced from Thailand, Australia, Sri Lanka and Myanmar (Shigley et al., 1990). Hughes (1990) reports that sapphire and ruby mining is proceeding at such a frantic rate in Thailand 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 African countries of Kenya, Tanzania, Nigeria, Malawi, Burundi and Rwanda produced sapphires in the 1980's. Most sapphires on the world gem market are heat-treated to improve either the color or clarity of the stone, or both.

Australia-A new major sapphire supplier

During the 1980's, Australia emerged as a major supplier of sapphires. The Anakie field, the largest of two Australian sapphire districts (Figure 3.1), was developed in the years before World War I by German gem merchants to supply the Russian Imperial Court

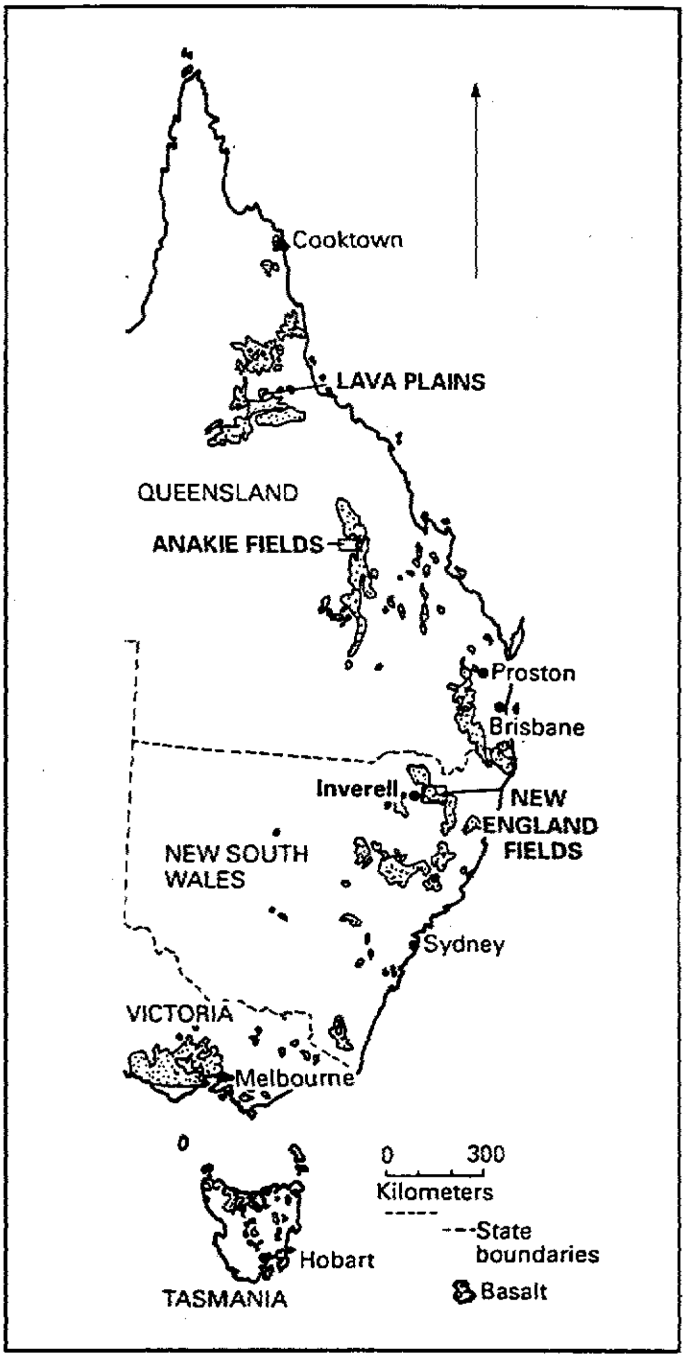


Figure 3.1 Sapphire mining districts of Australia From Hughes (1990)

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 color 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 favored the deep, inky blue color of the Australian sapphire. Hughes (1990) suggests that perhaps the Russian court favoured the much lower price of Australian sapphire as opposed to Myanmar or Sri Lankan sapphire, and that color was not as much of an issue. In any case, mining was intermittent until the 1980's when Australia emerged as the primary source of sapphire in the world owing to declining production in Thailand and Cambodia. Almost all the production in the 1980's and 1990's was sold to Thai buyers who took the stones to Thailand, heat-treated them and put them on the global marketplace. It is estimated by Coldham (1985) that 50% by weight of sapphire sold through Thailand in the 1980's was actually mined in Australia. An increased volume of sapphire mined from Thailand in the 1990's has decreased the Australian share to 25-30% (Levinson and Cook, 1994).

Physical and Chemical Properties

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

Pure corundum, an aluminum oxide mineral (Al_2O_3) is colorless. It is only when chemical impurities such as the elements Cr, Ti and Fe are present that colors result.

The Cause of Color in Ruby and Sapphire

The following description of one of several mechanisms of procuring color in gemstones is summarized from Hughes (1990). When chromium in the form of Cr^{3+} enters the corundum structure and replaces aluminum, a rich crimson red color results if the Cr content reaches 1% (Hughes, 1990). Color in ruby, as with other gemstones such as sapphire, tourmaline, tanzanite, emerald and alexandrite, results from selective absorption of certain wavelengths of visible light. When white light, such as sunlight, hits a ruby, green-yellow and violet wavelengths are absorbed and we see

	CORUNDUM	BERYL	CHRYSOBERYL	TANZANITE	TSAVORITE GARNET	TOURMALINE	TOPAZ
Chemical Formula	Al_2O_3	$Be_3Al_2(SiO_3)_6$	$BeAl_2O_4$	$Ca_2Al_3(SiO_4)_3(OH)$	$Ca_3Al_2(SiO_4)_3$	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$	$Al_2SiO_4(F,OH)_2$
Crystal System	Hexagonal	Hexagonal	Orthorhombic often twinned	Orthorhombic	Cubic	Hexagonal	Orthorhombic
Color	Red: Ruby Sapphire: Blue, Violet, Green, Pink, Orange, Yellow, Brown, Black:	Emerald: Green Aquamarine: Pale Blue-Green Morganite: Pink-Peach: Heliodor: Green-Yellow Red beryl is rare	Green, brown, yellow Alexandrite: green - daylight red-incandescent light	Greyish-brown, Greyish-purple, brownish-purple/blue	Light green, vivid emerald green, dark green	Black, brown, green, yellow, red-pink, blue, colorless	Colorless, sherry-brown, yellow, blue, pink
Hardness	9.0	7.5 to 8.0	8.5	6.5	7.0-7.5	7.0-7.5	8.0
Fracture Cleavage Parting	No cleavage, distinctive parting	Indistinct basal cleavage	Indistinct	One good cleavage	Indistinct cleavage	No cleavage	Perfect basal cleavage
Specific Gravity	3.95-4.03	2.67 to 2.84	3.65-3.8	3.35-3.55	3.59-3.63	3.01-3.2	3.4-3.7
Pleo-chroism	Strong:red, blue, green, orange, violet, Weak to Distinct: yellow	Strong:emerald Distinct: morganite Weak to Distinct: aquamarine Weak:heliodor	Distinct: green-yellow Very Strong: alexandrite	Very strong: blue, purple-red and green-yellow to brown	None	Strong	Weak to disinct
Fluoresc-ence	See Table 3.5	Emerald:inert to weak (LW) orange-red Morganite: weak red (SW,LW)	Alexandrite: weak red (LW,SW) Green-yellow: green yellow (SW)	Inert	Inert	Yellow:very weak Pink:weak violet (LW,SW)	Colorless: none to pale yellow (LW) Red: weak(LW) Yellow: weak orange-yellow (LW)

Table 3.3 Physical and Chemical Characteristics of Gemstones

only the purple-red wavelengths. The type of light hitting the stone and the observer's eye physiology will also affect the color seen. The ability of ruby to absorb light is the result of interaction between incoming white light and electrons "orbiting" around the Cr 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 color. The energy used to make the electrons jump from one orbital to another must reappear at some point in order to balance the equation. When the electrons fall back down to their home orbital, energy is released in the form of red fluorescence. It is coincidental that the various wavelengths, orbitals and electrons converge to infuse in ruby not only a rich red body color but also vivid red fluorescence.

Red fluorescence is easily seen under ultraviolet light and will be discussed later. With certain rubies, especially those from Myanmar, and more recently, Vietnam, the red fluorescence is visible even in daylight. This red fluorescence combined with the rich red body color causes these particular rubies to glow as if a fire was burning inside.

Rubies from other sources such as Thailand, Cambodia, Tanzania and Kenya do not show as strong a fluorescent red color. Unlike rubies from Myanmar and Vietnam, these contain iron, which quenches and reduces the fluorescent effect. This is why rubies from Myanmar 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 are rated.

Although up to 1% chromium is needed to produce a beautiful red color in ruby, very little (less than .01%) iron and titanium are needed to color blue sapphire. Other colors of sapphire (yellow, orange, green, violet) are caused by varying amounts of Fe and Ti.

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 six-sided 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. Often the crystals 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.

Sapphire crystals tend to grow as six-sided 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 in certain corundum crystals 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 colors 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.

Field Identification of Ruby and Sapphire

Ruby and sapphire have a high specific gravity 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. Colorless

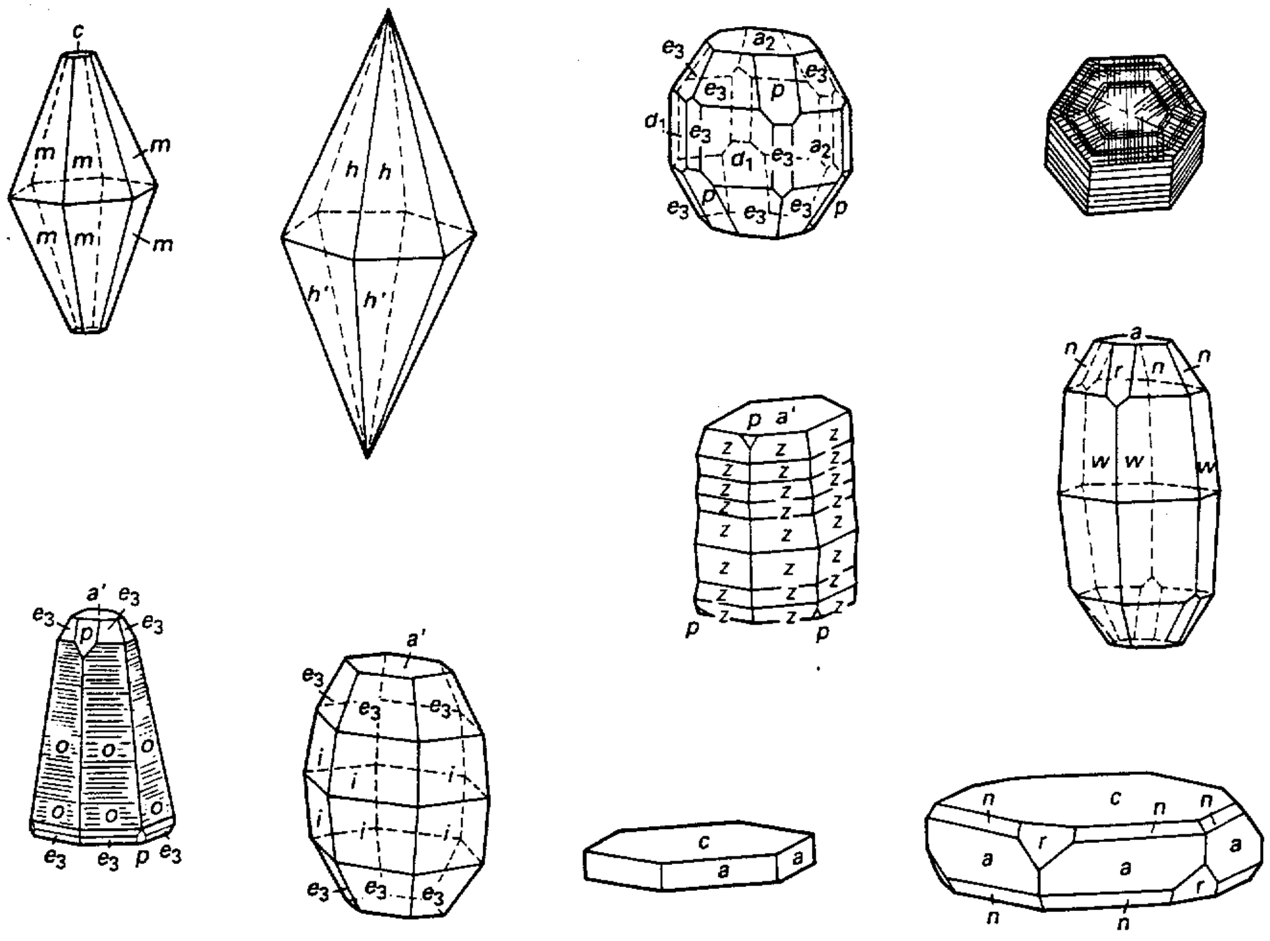
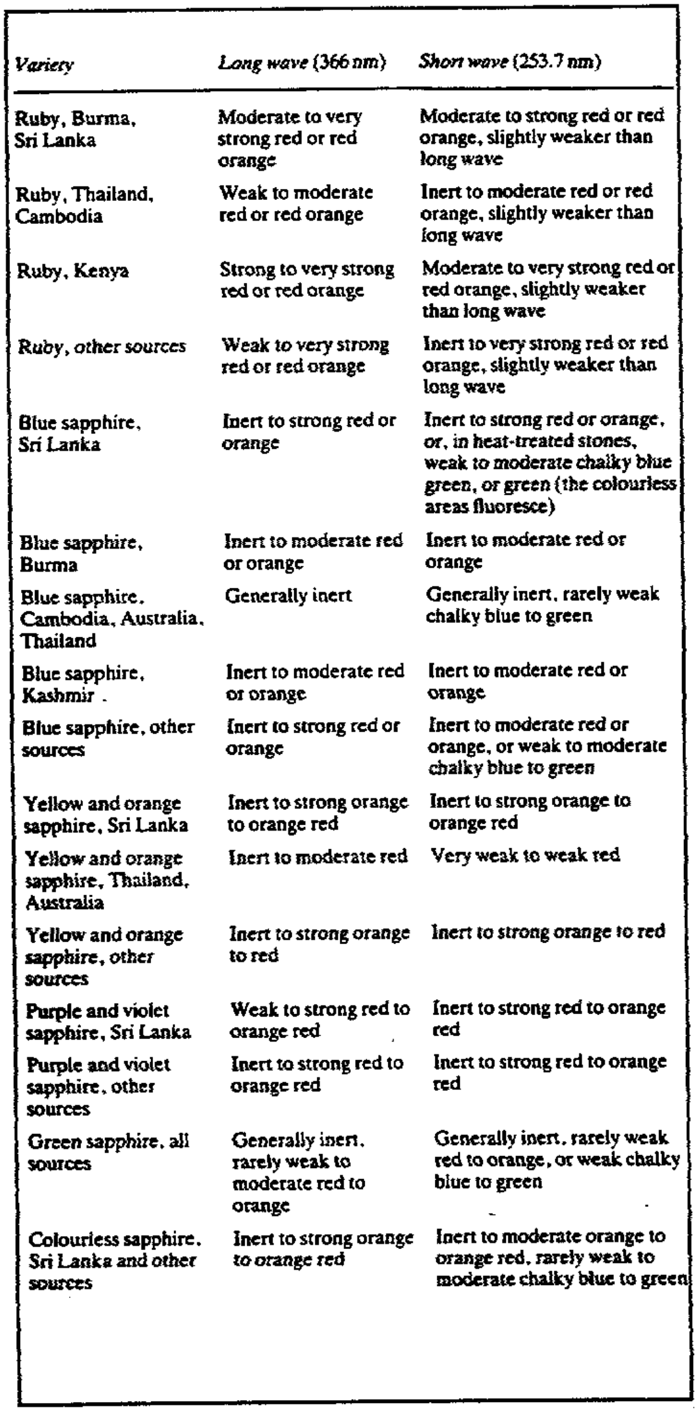


Figure 3.2 Ruby and sapphire crystals From Hughes (1990)

Variety	*Colour of ordinary ray* (ω)	*Colour of extraordinary ray* (ε)	*Strength*
Ruby	Slightly purplish red	Slightly orangy red	Moderate to strong
Blue sapphire	Violetish blue	Greenish blue to bluish green	Strong to very strong
Green sapphire	Bluish green to greenish blue	Yellowish green to greenish yellow	Strong to very strong
Violet and purple sapphire	Bluish purple or bluish violet	Yellowish purple or greenish blue	Strong to very strong
Yellow sapphire	Slightly orangy yellow or deep yellow	Slightly greenish yellow or pale yellow	Weak to very weak
Orange sapphire	Slightly reddish orange or deep orange	Slightly yellowish orange or light orange	Very weak to moderate
Colourless sapphire	Colourless	Colourless	None

Table 3.4
Pleochroic colors in gem corundum
From Hughes (1990)



Variety	*Long wave* (366 nm)	*Short wave* (253.7 nm)
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

Figure 3.5 Fluorescent colors of gem corundum
Hughes (1990)

or pale colored 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. Using an 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 will not inert. To distinguish ruby and red spinel, look at:

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, which looks 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) from spinel (non-pleochroic).

For other colors 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 colors.

Geology of Ruby and Sapphire Deposits

There is very little formal exploration for ruby and sapphire deposits; many deposits are found by accident, although government agencies in countries like Tanzania and Pakistan have had success in gemstone exploration for ruby, sapphire, emerald and pegmatite minerals. Most of the articles published in Canadian mining newspapers about gemstone deposits are about the mining and marketing of sapphires from the Montana 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. 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 colored, 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 Earths 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 (Fig. 3.3).

About 10% of continental basalt is alkali basalt. The alkali group of basalts typically contain undersaturated minerals like olivine or nepheline. These are minerals that 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 made.

Minerals and chemical content	Present in	
	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)	Sometimes	Yes
Chemical content (average)[a]		
SiO_2	48.62 wt.%	46.33 wt.%
Na_2O	2.76 wt.%	3.20 wt.%
K_2O	0.84 wt.%	1.28 wt.%

[a] Average of characteristic oxides; from Mysen (1987).

Table 3.6 Mineralogy and chemistry of tholeiite and alkali basalts
From Barr and MacDonald (1978)

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

- alkaline basalt (except China, Nigeria) including nephelinite, nepheline hawaiite, basanite and basanitoid form small hills and volcanic plugs
- crater lakes, cones, cone remnants or plugs are common
- ultramafic mantle xenoliths are common, especially spinel-lherzolite xenoliths
- older tholeiitic flows, younger alkaline flows
- sapphire megacrysts are corroded
- in-situ corundum megacrysts are extremely rare
- zoning of gemstone types and corundum colors within a small area (less than 10 km)
- Accessory heavy minerals in alluvial deposits include zircon, spinel

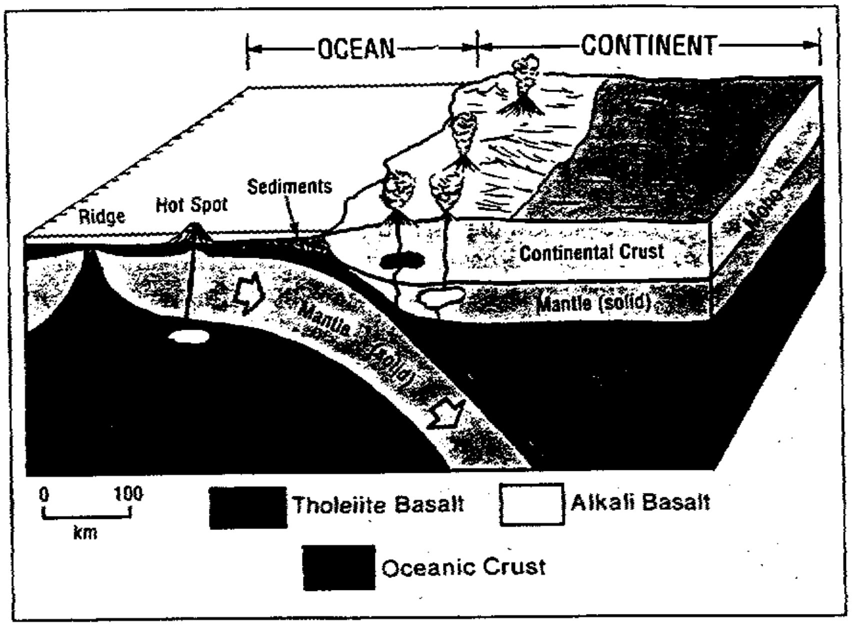


Figure 3.3 Subduction zone and origin of alkali and tholeiite basalt
From Levinson and Cook (1994)

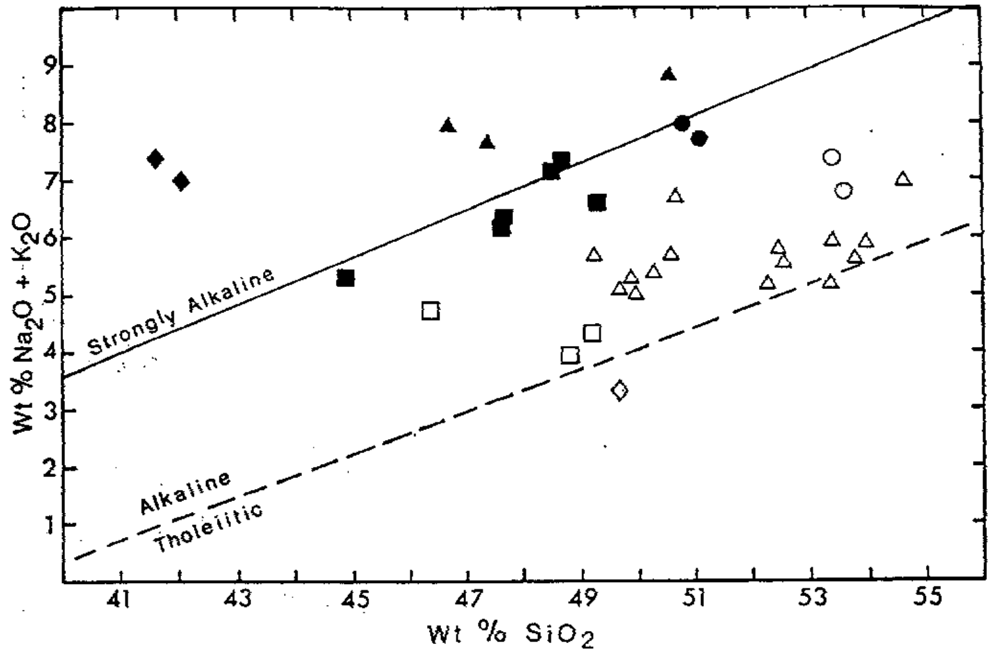


Fig. 3. Alkalies – silica diagram for Thai basalts. Analyses recalculated to 100% before plotting as described in text. Dashed dividing line after Macdonald (1968). Solid dividing line after Saggerson and Williams (1964). Closed symbols = Basanitoid Basalts; diamonds, nephelinites; squares, basanites; triangles, nepheline hawaiites; circles, nepheline mugearites. Open symbols = Hawaiitic Basalts; squares, alkali olivine basalt; triangles, hawaiites; circles, mugearites. Open diamonds = Tholeiitic Basalt.

Figure 3.5 From Barr and MacDonald (1978)

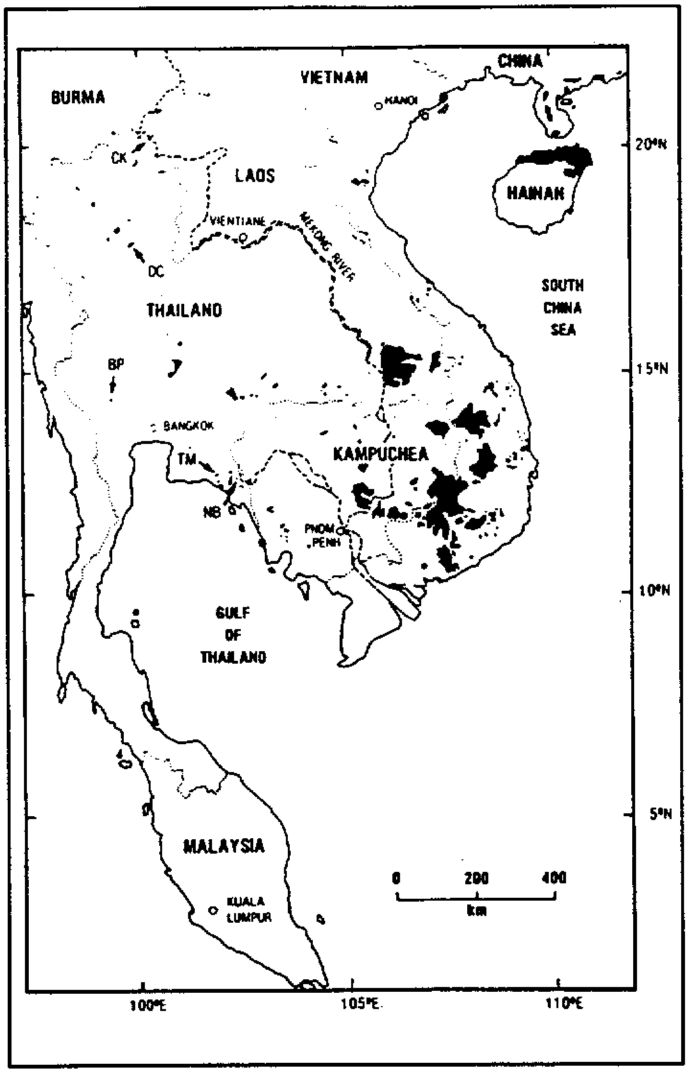


Figure 3.4 Occurrences of Upper Cenozoic volcanic rocks in Southeast Asia
From Barr and MacDonald (1978)

(especially black spinel), ilmenite, olivine, clinopyroxene, garnet, magnetite or feldspar.

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 exact 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. The distribution of Cenozoic basalt in southeast Asia is shown in Figure 3.4. 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 tholeittic 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; Figure 3.5). 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 Ba, Sr, Zr, Y, Nb, V, La, Ce and Nd.

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 Sr, Zr and Nb 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 (33-35 million years) falls within the range of basalt K-Ar ages of 19 to 38 million years and 2-49 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 1-2 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, Myanmar 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 colors 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 (Figure 3.6).

In Australia, Coenraads (1990) notes that sapphires may vary in color and shape as mining proceeds along a particular stream. For example, sapphires may be blue-yellow parti-colored 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:

1. Black spinel - may be partly corroded
2. Black clinopyroxene
3. Zircon - brown to pale reddish and orange-brown
4. Garnet - mainly pyrope, pale to dark reddish brown
5. Ilmenite
6. Magnetite
7. 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 "pleonaste" is used most commonly. Pleonaste spinels are iron rich, where Fe has replaced Mg 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 pleonaste (black spinel) has a specific gravity similar to that of sapphire, it is often used as an indicator mineral when mining for sapphires.

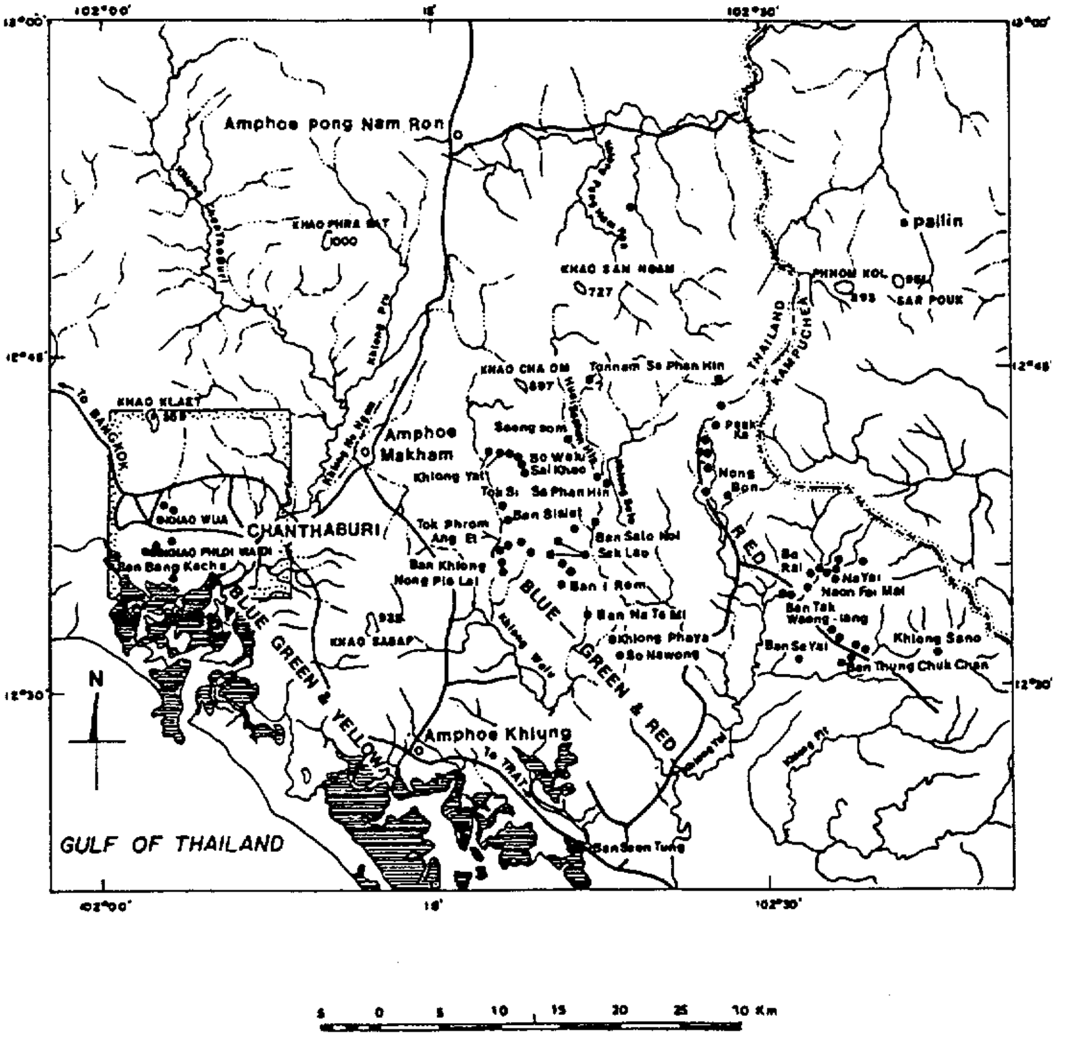


Figure 3.6 Gemstone zoning at Chanthaburi-Trat, Thailand From Hughes (1990)

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 ilmenite indicate that fluvial concentration of heavy minerals has taken place, although sapphires and zircons are not necessarily present. In-situ soils from basalts and associated volcaniclastic rocks contained 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 crystals 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 favorable 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

It is still unclear whether there is a genetic link between sapphire formation and the basalt magma. Levinson and Cook (1994) provide a summary of current theories involving the genesis of gem corundum. They 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 often 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 U, Th, Zr, Nb and Ta. The sapphires must have grown in an environment rich in these elements, alkali elements (Na and K), Fe, Al and volatile gases. This host environment is incompatible with an alkali basalt melt.

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 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.

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

Both Hughes (1990) and Voynick (1985) give accounts of the discovery and subsequent mining history of this area. Sapphires were discovered in 1894 by gold prospectors in Montana 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 color 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 two m in thickness and has a length of about eight 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.

	Yogo lamprophyre[1] (Clabaugh, 1952)	Average monchiquite (Rock, 1977)	Average bassanite (LeMaitre, 1976)
SiO_2	38.54	41.06	44.30
TiO_2	1.06	2.63	2.51
Al_2O_3	11.73	13.20	14.70
Fe_2O_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_2O	1.00	3.25	3.55
K_2O	2.32	1.99	1.96
H_2O^+	2.33		1.20
H_2O^-	1.34		0.42
P_2O_5	1.18	0.84	0.74
CO_2	5.56	2.13	0.18
BaO	0.41	0.21	
Or	12.2	11.2	11.6
Ab		4.7	12.2
An	23.8	17.3	18.4
Lc	3.0		
Ne	6.0	13.0	9.7
Di	28.9	27.0	21.0
Ol	15.2	12.8	12.9
Mt	5.7	6.8	5.7
Il	2.3	5.0	4.8
Ap	3.2	2.2	1.8

[1] Norm for Yogo lamprophyre calculated after subtracting CO_2, H_2O, and 3.5% CaO

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

Texturally, the Yogo dyke is finer grained than other documented ouachitite occurrences. Fresh rock is dark gray to greenish-gray and contains numerous angular to rounded, light-colored 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, pale blue to steely blue megacrysts with flattened crystal form with the average weight less than 1 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.

Scotland

Sapphires embedded in a lamprophyre dyke at Loch Roag, Isle of Lewis in Scotland were discovered when the previously covered host rock was exposed during cutting of an access track to peat diggings (Jackson, 1984). The sapphires are found as small thin blue platelets up to a maximum size of 25 mm 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 dyke has many similarities with the ruby and sapphire alkali host rocks described in a previous section. Jackson (1984) notes that the main difference is that the alkali basalt fields are generally outpourings of Tertiary basaltic lavas from volcanic vents and dykes, whereas the Loch Roag deposit is the result late Palaeozoic intrusive igneous activity confined to a small area. The Loch Roag dyke is similar in composition to the Yogo dyke, but the Yogo dyke lacks mantle xenoliths and large megacrysts.

Ruby and Sapphire Associated with Marble

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

- Mogok Stone Tract (Myanmar)
- Mong Hsu Stone Tract (Myanmar)
- Luc Yen (Vietnam)
- Ekaterinburg (Ural Mountains)
- Morogoro (Tanzania)
- Hunza (Pakistan)
- Nepal - not confirmed

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

Myanmar - Mogok Stone Tract

For 800 years, the 175 km^2 of gem-bearing alluvial gravels of the Mogok Stone Tract in Myanmar 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 color overlain by vivid red fluorescence. Burmese rubies lack the iron needed to quench the fluorescence. For centuries, Burmese rubies have been among the most expensive and sought after gemstones in the world.

In 1963 the Myanmar government took over the ruby mines from private interests and severely restricted the legal gem trade. Although fine Myanmar stones still showed up in Thailand through smuggling, significant quantities of Burmese ruby were almost non-existent until the early 1990's. 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 Myanmar 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.

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

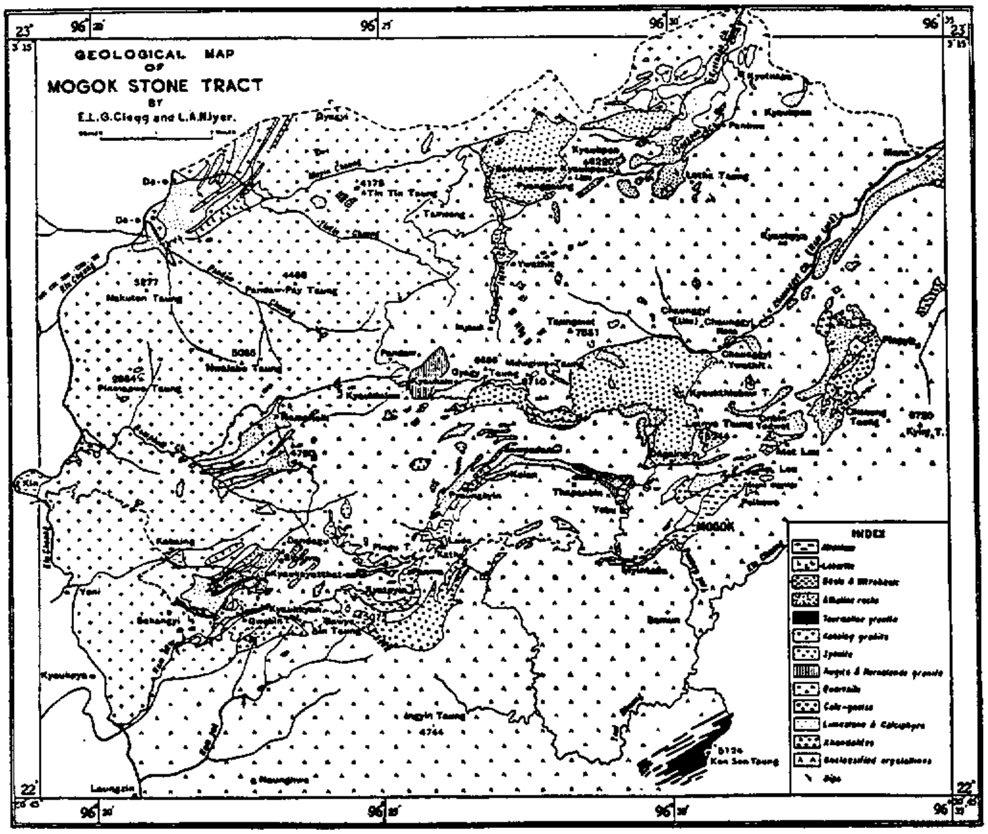


Figure 3.7 Geology of the Mogok Stone Tract From Iyer (1953)

the Mogok Stone Tract, which remains the sole source of geological information about the area (Figure 3.7).

For a deposit that has produced the world's best rubies for over eight centuries, there is very little information on geology and geochemistry of the Mogok Stone Tract, although many gemmological studies have been made of its gemstones. Some of the finest blue sapphires, in addition to other gemstones, most notably spinel, are also mined from the gravels. Keller (1983) provides a summary of geology and gemmological findings. 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 current mining status and methods (Kane and Kammerling, 1992).

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 or 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 the rubies form in marbles as a direct result of high-grade regional metamorphism: for example, the Ural Mountains deposit described later in this section.

Mong Hsu Stone Tract, Myanmar

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 on Mong Hsu, Myanmar, approximately 250 km southeast of Mogok. The usual staking rush ensued and over 2,000 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 marble. Peretti et al., (1995) 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.

Hunza, Kashmir

The paragenesis and petrogenesis of a corundum and spinel-bearing marble at Hunza (Kashmir) is described by Okrusch et al., (1976). This is one of the few published papers which discusses the physio-chemical conditions of gemstone formation. A geology overview and gemmological 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 color photographs accompanying the Gübelin (1982) paper show some of the most spectacular scenery in the world. The marble outcrops hosting the gem corundum and spinel crystals are located in the Hunza Valley surrounded by mountains of the 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 1970's penetrated the rugged terrain.

Intercalations of white to grey to yellowish marble 1-5 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.

Southern Ural Mountains, Russia

Although pink and blue opaque corundum crystals up to 20 mm in size 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 in situ in 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 <u>not</u> 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 color, 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 H_2O) and high CO_2 pressure. The metamorphic fluid formed in, and filled fractures in both the magnesian calcite and dolomitic calcite marbles. When the CO_2 pressure decreased, orange-red spinel formed instead of 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 0.08-0.13% than for the marbles that do not contain corundum (0.15-0.18%).

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

Vietnam - Luc Yen Region

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, which is 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., (1994a,b). The alluvial deposits, which cover at least 50 km^2, are underlain by Upper Proterozoic-Lower Cambrian marbles and crystalline schists and quartzites which are intruded by pegmatites. Gemmological studies carried out on the rubies suggest they formed in a comparable geological environment to the Mogok and Hunza ruby deposits.

Morogoro Region, Tanzania

Rubies in their rough form characteristically show a six-sided barrel shape or variations of this. Red spinels are typically octahedral. In 1987, parcels of gem-quality spinel rough from Tanzania were examined by Hänni and Schmetzer (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 gemmological studies of ruby, and pink and violet sapphire, from a reported locality in Nepal is given by Harding and Scarratt (1986) and Kiefert et al., (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. Not enough is known about the geology of this deposit to speculate on the conditions of formation of ruby and sapphire.

The Sapphire Occurrence at Kashmir, India

Just as the rubies from Myanmar are considered superior because of the red fluorescence on top of red body color, 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 7 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 ct Kashmir sapphire for Prince Charles to give to Princess Diana at the 1980 British royal wedding failed.

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

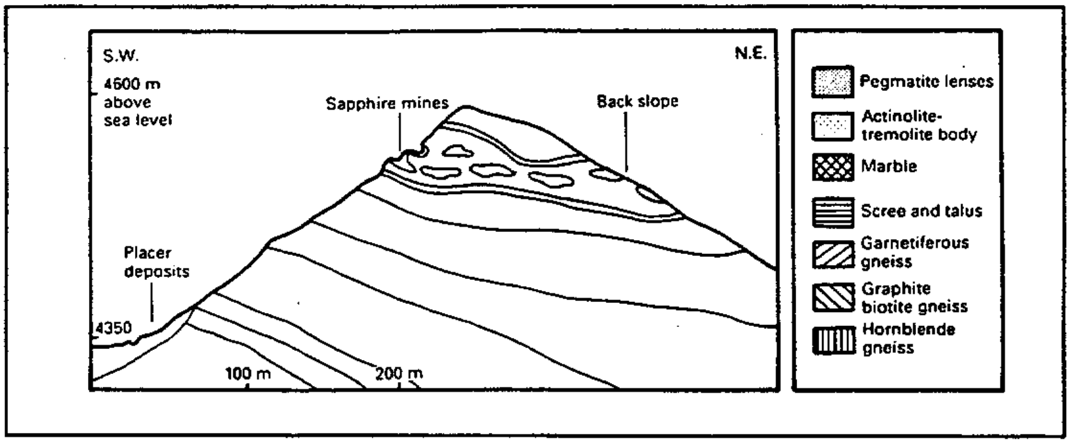
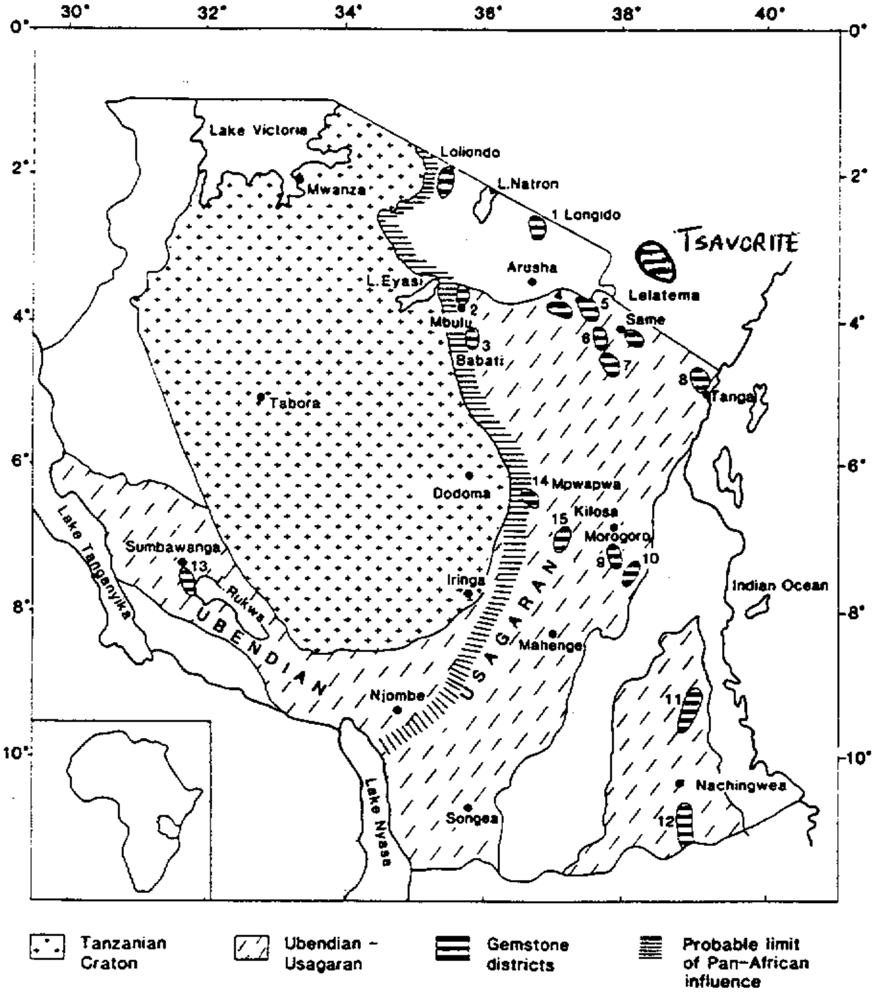


Figure 3.8 Geology of the Kashmir sapphire deposit
From Atkinson and Kothavala (1983)



Sketch map showing gemstone mineralization in the Mozambique Belt of Tanzania (from Geological Survey of Tanzania, 1982): (1) Longido, (2) Manyara, (3) Babati, (4) Merelani, (5) Lelatema, (6) Tiriri, (7) Landanai, (8) Umba, (9) Mvuha, (10) Magogoni, (11) Namaputa, (12) Nabunju, (13) Sumbawanga, (14) Mpwapwa, (15) Kilosa, (16) Loliondo.

Figure 3.10 Geology of Tanzania and location of gemstone deposits From Malisa and Muhongo (1990) 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 a.s.l. 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 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 1800's and early 1900's 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 1960's remain confidential. The account by Gaines (1951) is a story about how the determined mineral collector and mining engineer, 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 eighteen 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.

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.

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 Zanskar 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 (Figure 3.8). 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 meters long and up to 30 m thick.

The medium-grade metamorphic strata are disconcordantly intruded by feldspar pegmatites. The greatest concentrations of sapphires are in quartz-free feldspar pegmatites where they intrude actinolite-tremolite lenses. They are embedded in lens-shaped pockets of plagioclase feldspar pegmatite which has

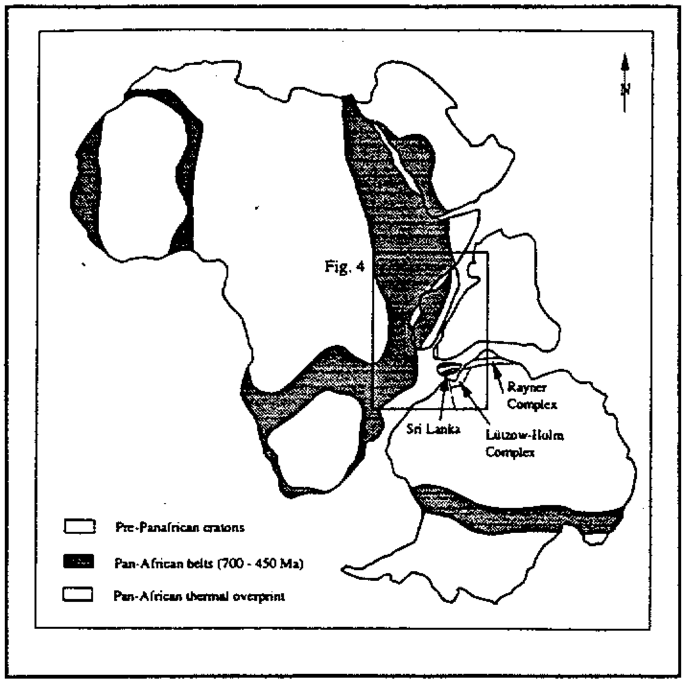


Figure 3.9 Godwanaland fit showing extent of Pan-African orogeny
From Kriegsman (1995)

been kaolinized. The pockets are approximately one m thick and three m to four 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 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 south-east Kenya were defined by Key and Ochieng (1991a). Exploration guidelines for ruby deposits in southeast Kenya are given by Key and Ochieng (1991b). The tectonic setting and physio-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 Africa 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 and presently underlie fields of alluvial and in-situ gem deposits in Africa, Brazil, Sri Lanka, Australia, Madagascar, and, potentially, Antarctica (Figure 3.9).

The Mozambique Orogenic Belt in Tanzania (Figure 3.10) and Kenya (Figure 3.11) is host to what could be the world's most remarkable array of gemstone deposits, in addition to gold and iron deposits. There is an incredible array of earth-history natural resources in a relatively small area straddling the Kenya-Tanzanian border. The Serengeti Plain, Tsavo National Park, Olduvai Gorge, Mt. Kilamanjaro and an incredible array of gemstone deposits are contained within a small area by Canadian standards.

The lithostratigraphic units within the Mozambique Orogenic Belt are Proterozoic in age, between 1900 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 anatexic 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 - 438 million years ago.

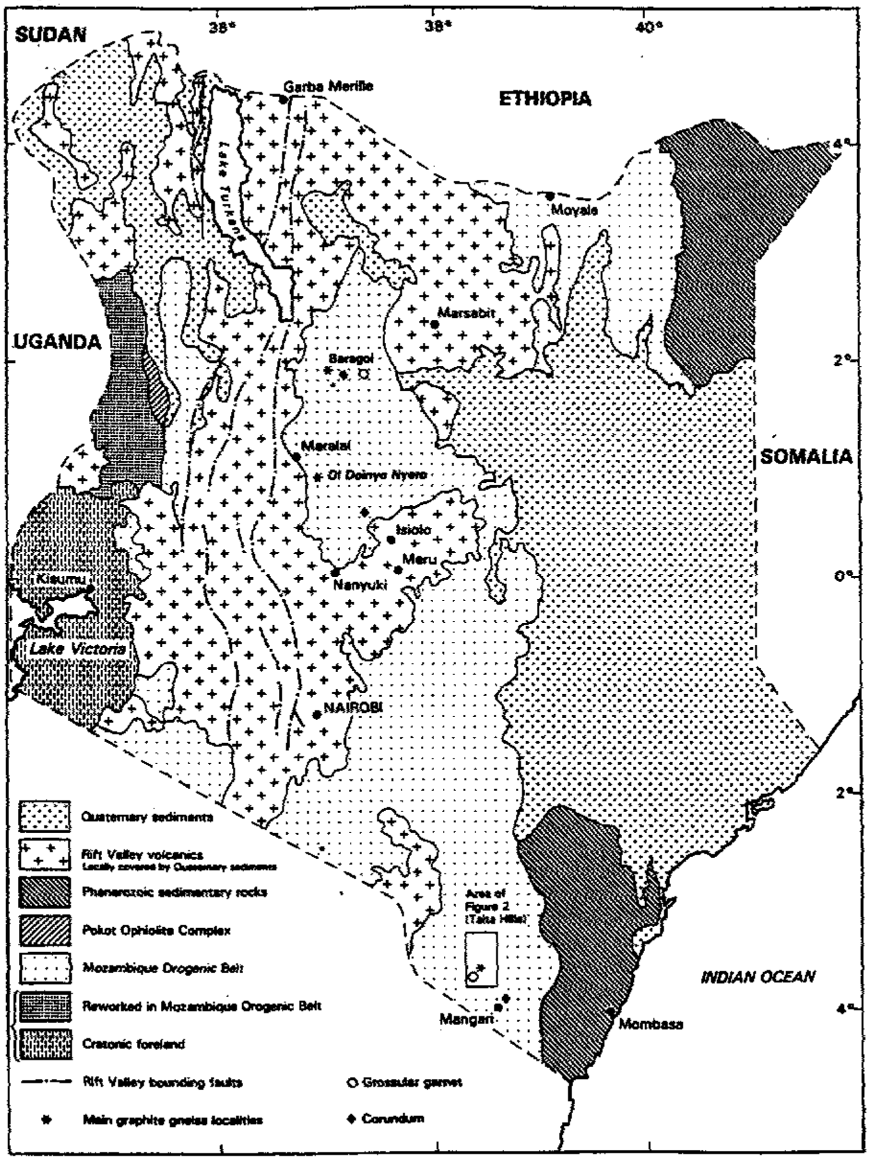


Figure 3.11 Geology of Kenya Key and Ochieng (1991a)

Ruby and sapphire deposits have been found in a variety of geological environments in Kenya and Tanzania. Largely undeveloped and underexplored alkali basalt fields hosting alluvial gem sapphire deposits are located in Kenya and Tanzania. These deposits, covered earlier in this chapter, are potentially large producers of gem rough. Of the remaining types of ruby and sapphire deposits, several 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, Kenya.

For those in the Canadian mining industry who feel hampered by periodic uncertainty regarding land tenure in Canada, it is worth noting that things are or have been worse elsewhere in the world. Hughes (1990) summarizes a well-publicized series of events where the original stakers 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 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. Despite protests from the American government, the ruby mine was never returned to the true owners.

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 Mangara and Umba River gem corundum deposits are generally metamorphic rocks of amphibolite to granulite facies ranging from high-grade metamorphic banded gneisses to amphibolite facies marble and highly aluminous graphitic gneisses. The graphitic gneisses are host to tsavorite garnet deposits, which will be described later.

Ruby and sapphire deposits have been found or identified in areas where feldspar pegmatites have intruded serpentinized ultramafic bodies. At Mangari, 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 showed a spectacular array of colored sapphires associated with a serpentinized ultramafic body intruded by feldspar-rich pegmatites. The deposit is unique, in that the sapphires occur in virtually every color: orange, yellow, violet, blue, color-change and parti-colored stones. According to Hänni (1987) the sapphire colors are related to varying Fe, Ti, Cr and V content.

Figure 3.12 shows the geology of the gem corundum deposit at Umba River. 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.

Genesis of the Ruby Deposit at Mangara

Key and Ochieng (1991a,b) summarize the conditions of formation for the ultramafic associated ruby deposits in Kenya and Tanzania. The four controls on ruby formation are:

1. Host Rock Lithology

The lithologic control is the chromiferous ultramafic bodies. The ultramafic bodies are of two different origins and ages, and rubies occur with both. Rubies are noted in a variety of host rocks adjacent to or intruding the ultramafic bodies:

- desilicated pegamatites
- metasediments
- desilicated diorite
- various lithologies of a volcano-sedimentary unit

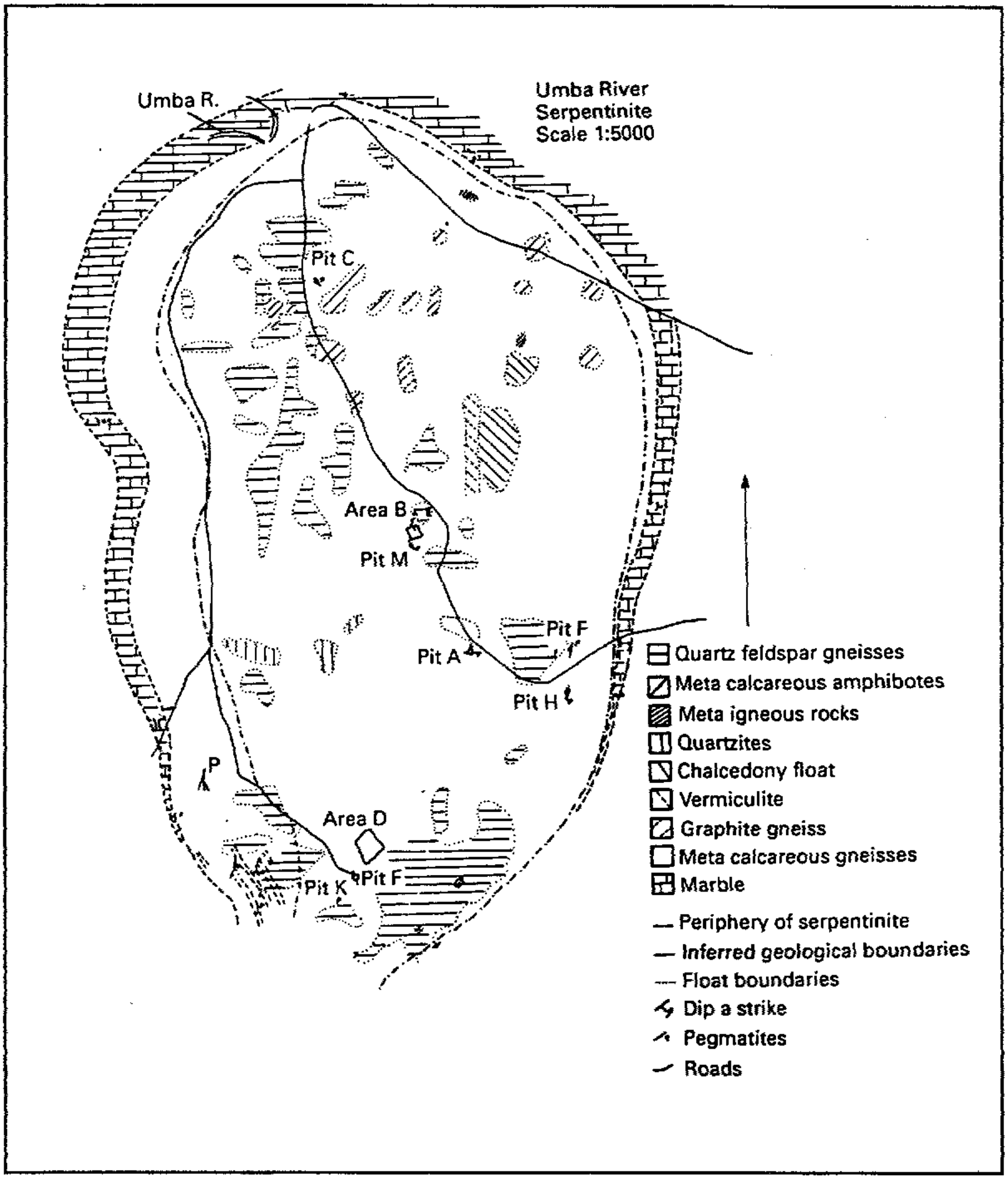


Figure 3.12 Geology of the Umba River sapphire deposit From Keller (1992)

No stratigraphic control for ruby growth was found. There are other ultramafic bodies in south-east 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

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. Key and Ochieng (1991b) note that the presence of kyanite as the Al_2SiO_5 polymorph in the mineral assemblages indicates pressures greater than 7 Kbar. They used two-feldspar geothermometry to determine that metamorphism temperatures were greater than 630°C.

Retrograde metamorphism and the development of new minerals after ruby formation was possibly prevented by the absence of a fluid phase.

3. Chemical Control

The red color 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 coloring agent for green tourmaline and blue kyanite, which are found in the area.

Ruby crystals grew adjacent to ultramafic bodies which supplied the chromium needed to color the crystals. Although the lithology of the host rocks next to the ultramafic bodies is not important, the absence of fluids after the peak of regional metamorphism prevented destruction of the rubies during retrograde mineral reactions during cooling.

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, colorless sapphire, green sapphire, color-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-1940's 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 one m to 10 m, sometimes up to 30 m, beneath the ground.

Despite incredibly rich alluvial deposits, gemstones are very rarely discovered in situ. 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. 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 (Figure 3.13). The rocks of the Highland/Southwestern Complex consist of closely interbanded pyroxene-granulite facies metamorphic rocks; charnockites (acid, intermediate, basic); undifferentiated metasediments (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, charnockites and cordierite

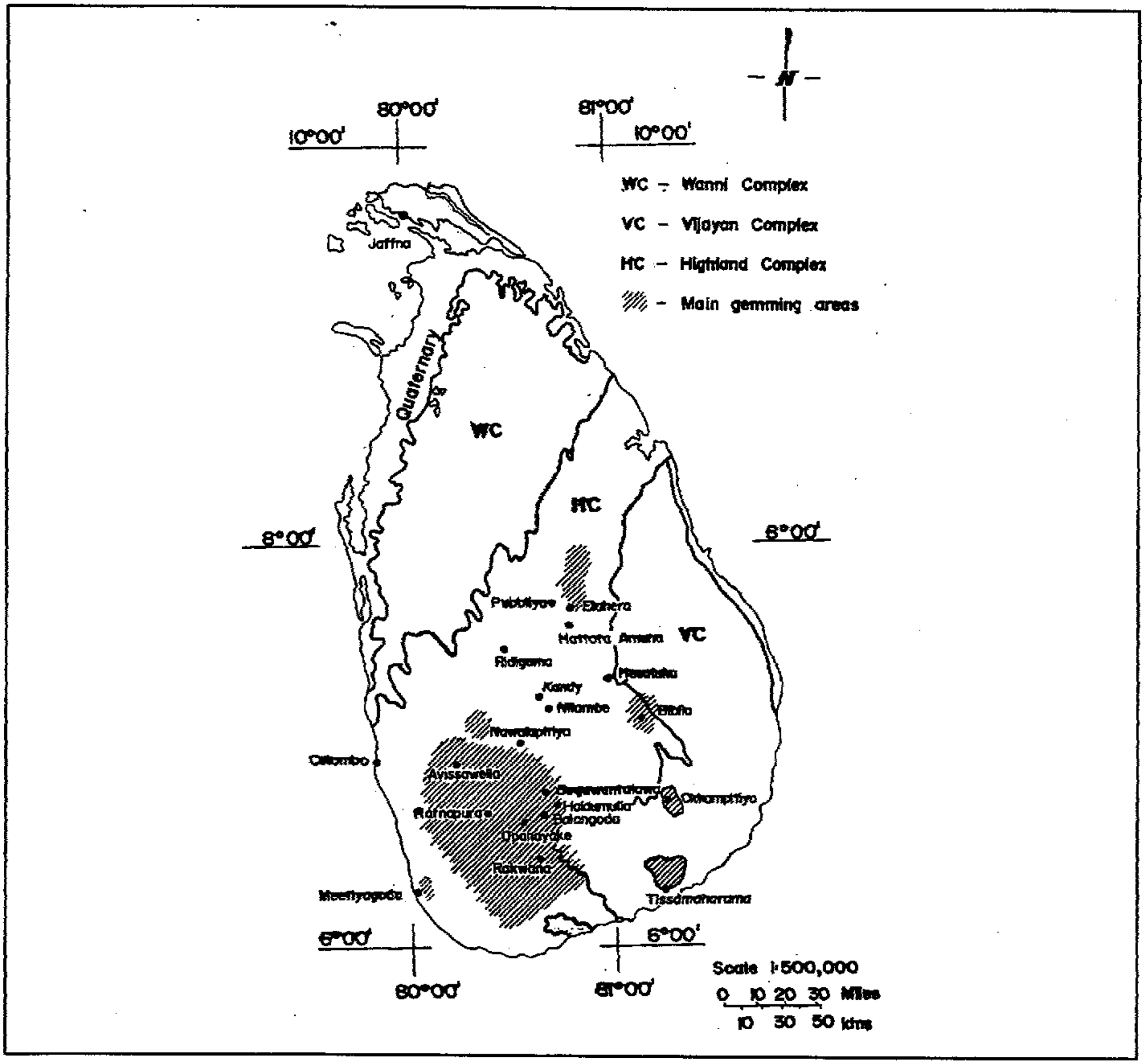


Figure 3.13 Geology of Sri Lanka From Dissanayake and Rupasinghe (1992)

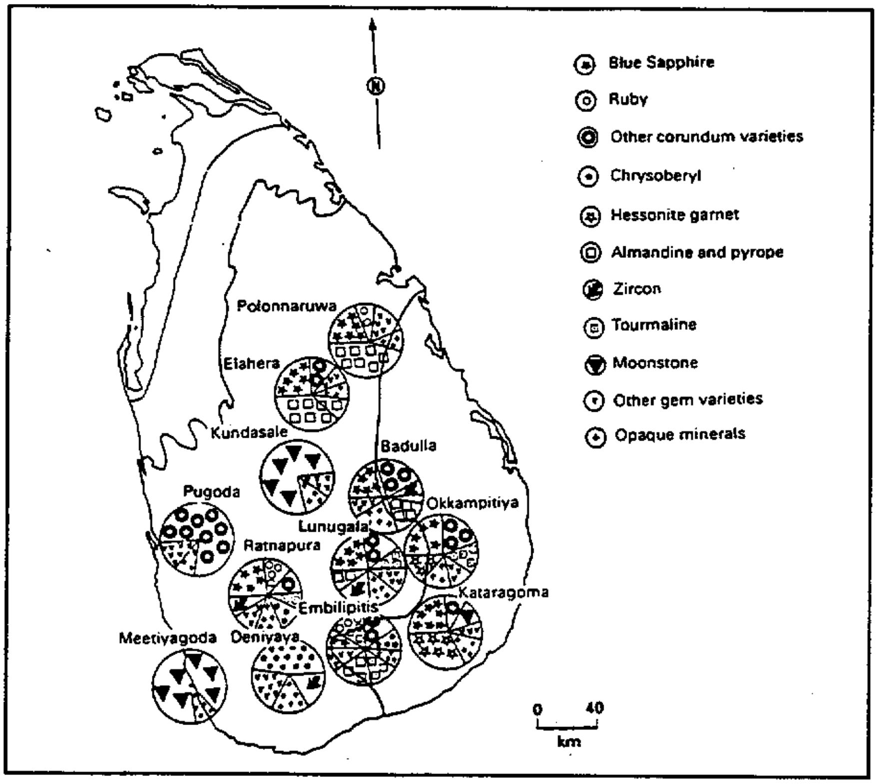


Figure 3.14
Gemstone distribution in Sri Lanka
From Hughes (1990)

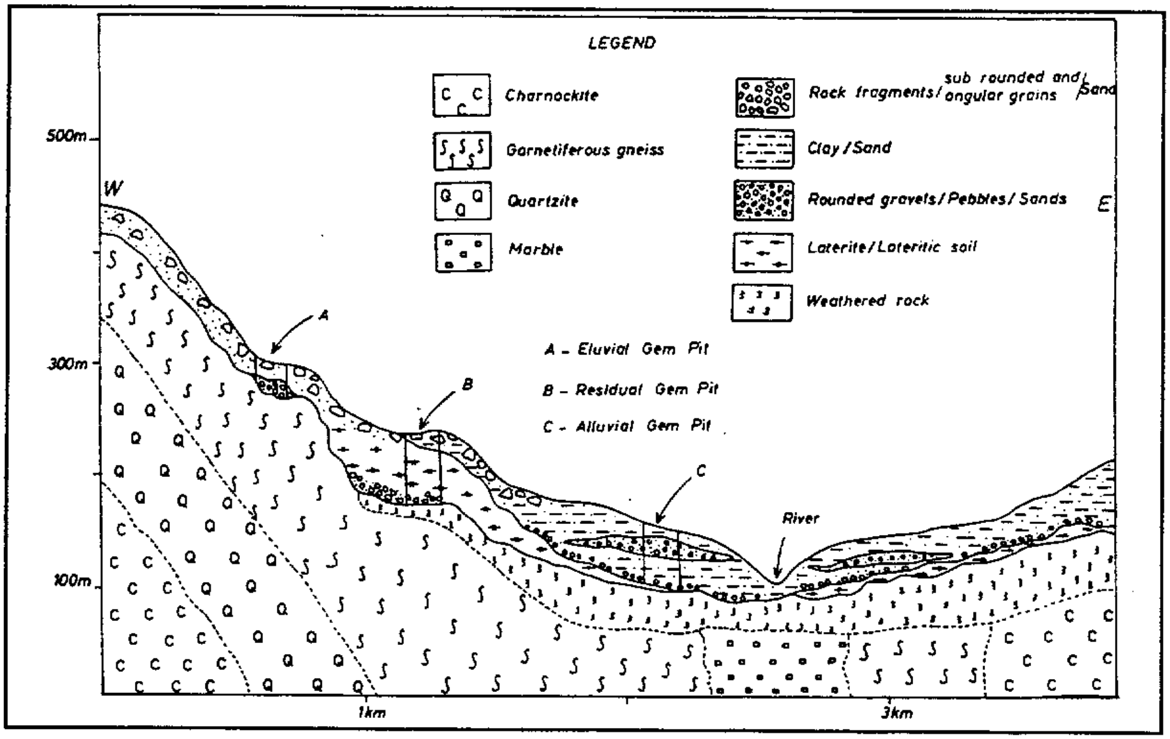


Figure 3.15 Different modes of occurrence of gemstones From Dahanayake (1980)

bearing gneisses in the southwestern part of the Highland Complex. The distribution of gemstones in Sri Lanka is shown in Figure 3.14.

Dahanalyake (1980) studied sediments in gem pits in order to determine the modes of occurrence of the gem-bearing gravels (Figure 3.15) and perhaps determine the source rocks. They suggest 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 on highly aluminous metasediments 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 Be, F and other elements in the gem sediments of Sri Lanka as compared to average rocks is shown in Table 3.8. 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 Al, 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 for the gem varieties of corundum, sapphire and ruby, in Sri Lanka.

Dissanayake and Rupasinghe (1992) recommend Sr/Rb ratios, Th, U, F, Ta, Nb, Y and rare-earth elements 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 shown in Table 3.9.

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 anatectic 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 (Figure 3.16). 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 3.9). 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.

Ratnapura Sample	Li ppm	Na_2O %	K_2O %	Rb* ppm	MgO %	CaO %	Sr ppm	Ba ppm	Al_2O_3 %	Zr ppm	TiO_2 %	V ppm	Cr ppm	Mn ppm	Fe_2O_3 %	Co ppm	Ni ppm	Cu ppm	Zn ppm	SiO_2 %	F ppm	Be ppm
1	51	0.55	2.31	n.a	2.81	2.32	100	370	21.92	971	2.07	263	319	364	9.88	43	337	114	242	43.65	n.a	7
2	36	0.38	1.94	n.a	0.93	1.01	85	694	18.97	620	2.47	94	187	298	8.44	35	136	54	215	n.a	n.a	6
3	29	0.54	3.54	n.a	0.63	0.46	141	1228	20.92	707	2.25	185	381	1007	17.00	82	182	40	254	n.a	n.a	7
4	46	0.34	2.64	n.a	0.32	0.25	84	811	24.90	500	1.30	179	305	309	6.25	67	119	45	158	54.84	590	11
5	64	0.32	2.12	n.a	0.65	0.36	76	643	26.06	536	1.32	264	251	301	6.52	43	238	87	263	44.48	770	6
6	52	0.41	4.70	n.a	0.44	0.23	93	937	23.05	298	0.39	134	136	264	12.60	45	130	54	205	43.10	484	7
7	20	0.65	1.89	86	0.48	0.46	141	540	22.22	560	0.82	248	363	279	19.81	48	172	121	240	43.53	720	4
8	23	0.11	1.73	n.a	0.50	0.19	80	558	21.65	503	1.18	203	257	604	13.13	62	105	79	185	47.44	860	5
9	23	0.13	1.14	n.a	0.84	0.07	80	425	35.75	226	1.25	230	200	291	7.35	12	112	49	120	43.49	n.a	13
10	30	0.46	2.55	n.a	0.55	0.21	82	522	22.26	491	1.28	220	168	293	12.64	20	140	53	140	42.94	1050	4
11	26	1.02	0.86	n.a	1.00	0.77	79	487	18.12	201	0.43	210	116	273	14.09	52	182	41	342	50.81	1130	5
12	29	0.11	0.87	n.a	0.21	0.40	61	168	27.74	446	2.05	424	342	308	14.83	17	280	57	177	42.73	n.a	8
13	21	0.10	0.65	n.a	0.05	0.06	84	192	20.41	507	1.11	270	158	347	15.36	30	107	92	164	50.42	430	4
14	33	0.09	0.29	n.a	0.27	0.58	100	170	32.61	465	1.78	363	240	703	18.38	28	202	117	205	35.86	n.a	8
15	49	0.70	1.02	58	3.52	2.42	57	616	17.31	385	0.51	113	81	3415	18.59	40	191	82	237	42.91	2060	7
16	64	0.45	1.29	93	3.39	2.63	150	999	17.95	242	0.71	130	155	3833	16.59	54	156	100	301	47.07	n.a	11
17	30	0.19	0.95	n.a	0.24	1.26	101	667	23.58	414	1.04	271	333	527	10.34	104	179	117	399	48.28	690	4
18	49	0.24	2.24	n.a	0.15	0.18	84	669	25.36	691	2.29	216	251	375	8.09	100	203	56	389	47.07	n.a	9
19	59	0.66	1.99	102	0.81	0.46	127	1100	28.70	842	0.73	140	105	941	13.91	120	166	88	458	41.90	n.a	5
20	31	0.11	0.81	n.a	0.29	0.20	109	184	28.76	285	1.06	174	167	351	16.92	24	117	63	145	29.19	750	2
21	15	0.05	0.32	20	0.08	0.06	50	201	30.69	614	1.46	218	154	60	6.96	4	155	47	25	45.16	490	6
22	34	0.67	1.72	n.a	0.66	0.63	89	712	26.15	314	1.47	237	212	2454	13.11	146	152	53	157	36.76	n.a	3
23	16	0.32	4.42	n.a	0.07	0.07	131	1025	26.08	469	0.53	92	82	297	12.31	13	161	51	119	46.98	n.a	2
24	28	0.11	1.24	n.a	0.38	0.06	80	659	27.78	290	1.03	184	161	308	17.49	18	84	67	138	31.34	890	9
25	22	0.09	1.10	n.a	0.16	0.09	30	330	31.38	436	1.00	185	129	290	3.58	6	103	38	93	47.22	n.a	12
26	18	0.12	0.59	n.a	0.11	0.11	103	301	25.26	344	1.00	281	400	1251	20.41	107	199	192	199	36.30	908	3
27	20	0.08	0.35	n.a	0.17	0.08	51	217	35.16	295	1.97	253	182	302	7.87	9	96	127	87	40.29	586	5
28	11	0.07	0.52	n.a	0.05	0.05	118	207	23.43	292	0.92	284	256	727	20.11	55	150	135	135	36.62	790	3
29	17	0.89	2.65	111	0.78	0.55	143	662	21.39	368	0.72	185	335	372	12.05	30	192	94	174	48.98	650	4
30	29	0.45	5.34	275	0.87	0.69	136	1458	21.16	202	0.62	65	110	421	6.19	23	79	13	109	47.79	444	4
Elahera																						
31	29	0.16	1.58	112	0.91	0.39	32	306	32.56	440	0.86	120	111	1506	10.02	29	107	34	82	40.53	438	6
32	68	0.12	1.05	n.a	0.26	0.12	10	457	25.87	473	0.80	156	124	1865	12.66	58	84	36	89	43.06	360	5
33	38	0.39	3.38	n.a	0.70	0.43	35	412	25.09	320	0.78	117	110	651	8.91	27	95	39	105	47.07	n.a	5
34	46	0.24	2.49	n.a	1.14	0.31	47	336	25.41	142	0.68	148	133	567	13.37	36	99	38	160	42.78	n.a	5
35	29	0.68	2.37	103	2.43	1.87	37	784	19.41	397	0.67	91	130	2749	7.78	45	105	22	90	49.20	n.a	5
36	25	0.81	4.73	n.a	0.59	0.39	28	425	18.57	375	0.65	107	196	1332	11.20	34	120	32	180	49.11	1262	5
Av. sed / Av. shale	0.29	0.27	0.46	0.60	0.37	1.96	0.61	0.82	1.21	2.57	1.31	2.02	2.72	1.71	1.83	3.68	4.02	1.54	2.13	0.72	1.02	1.52
Av. sed / Av. source rock	1.53	0.12	0.63	–	0.55	0.17	0.58	0.83	2.04	4.33	1.91	2.51	10.45	1.13	2.22	4.48	7.07	2.96	1.57	0.67	–	2.92

n.a = not analysed
* Rb determined by NAA

Table 3.8 The contents of Be, F and other elements in the gem sediments of Sri Lanka
From Rupasinghe et al., (1984)

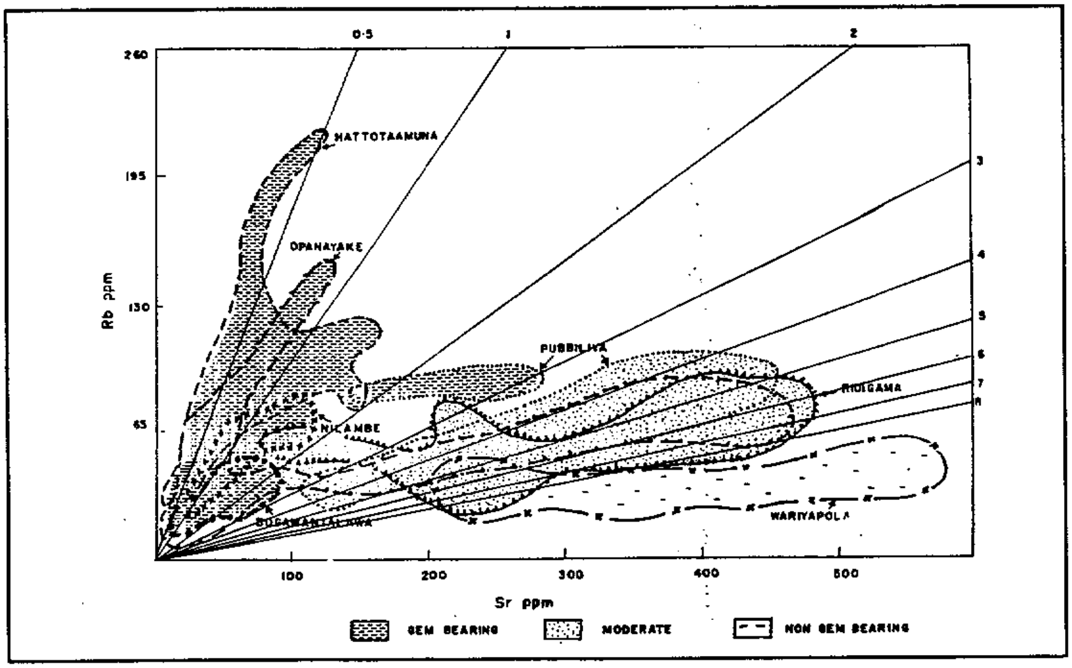


Figure 3.17 Delineation of gem-bearing areas on the basis of the Sr/Rb ratios of stream sediments From Gamage et al., (1992)

	PAAS	ES	NASC	AAS	Chondrites	Post-Archean upper crust	Archean exposed crust	Gem sediments of Sri Lanka	
								Ratnapura	Elahera
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
La	38.0	41.1	32.0	12.6	0.367	30.0	12.6	99.90	55.87
Ce	80.0	81.3	73.0	26.8	0.957	64.0	26.8	234.28	132.15
Pr	8.9	10.4	7.9	3.1	0.137	7.1	3.1	20.16	9.85
Nd	32.0	40.1	33.0	13.0	0.711	26.0	13.0	79.73	48.33
Sm	5.6	7.3	5.7	2.8	0.231	4.5	2.8	13.99	8.39
Eu	1.1	1.5	1.2	0.9	0.087	0.9	0.9	2.19	1.45
Gd	4.7	6.0	5.2	2.9	0.306	3.8	2.8	11.24	4.10
Tb	0.8	1.0	0.9	0.5	0.058	0.6	0.5	1.74	1.16
Dy	4.4	–	5.8	2.9	0.381	3.5	2.9	9.06	6.17
Ho	1.0	1.2	1.0	0.6	0.085	0.8	0.6	1.89	1.29
Er	2.9	3.6	3.4	1.8	0.249	2.3	1.8	3.11	2.88
Tm	0.4	0.6	0.5	0.3	0.036	0.3	0.3	–	–
Yb	2.8	3.3	3.1	1.8	0.248	2.2	1.8	5.39	3.59
Lu	0.4	0.6	0.5	0.3	0.038	0.3	0.3	0.86	0.53
ΣREE	183.0	198.0	173.2	70.3	3.89	143.3	70.3	483.54	275.76
LaN/YbN	9.2	8.4	7.0	4.8	–	9.2	4.8	18.53	15.56

(1) = Post-Archean average Australian Shale (Nance and Taylor, 1976); (2) = European Paleozoic Shale composition (Haskin and Haskin, 1966); (3) = North American Shale Composite (post-Archean) (Haskin and Paster, 1979); (4) = Archean average Sedimentary rocks (Australia) (Taylor and McLennan, 1981a); (5) = chondrite-normalizing factors derived from abundances in Type 1 carbonaceous chondrite (Evensen et al., 1978; Mason, 1979); multiplied by 1.5 to allow for removal of volatiles; (6) = taken to be 20% lower than PAAS to account for low REE-bearing rocks such as carbonates and evaporites (after Taylor and McLennan, 1981b, 1982); (7) = Same as AAS; (8) = Ratnapura gem sediments; (9) = Elahera gem sediments.

Table 3.9 The REE contents of the gem-bearing sediments of Sri Lanka and of shales, chondrites and crustal averages (ppm) From Dissanayake and Rupasinghe (1992)

Exploration Criteria for Ruby and Sapphire Deposits

The following are 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 hawaiitte
- 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 ruby deposit were regionally metamorphosed under conditions of 620-660°C and 2.5 kbars. In general, the regional metamorphic conditions are medium to high-grade.

Aluminum Content

At Hunza, 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 rock 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. Although the lithology of the host rocks next to the ultramafic bodies is not important, the absence of fluids after the peak of regional metamorphism prevented retrograde mineral reactions during cooling and allowed the preservation of gem corundum.

CHAPTER FOUR

EMERALD

Emerald, the green gem variety of the mineral beryl, is the third most valuable gemstone in the world, after diamond and ruby. According to the 1995 Guinness Book of World Records, the world record price paid per carat for an emerald is $107,569 in 1987.

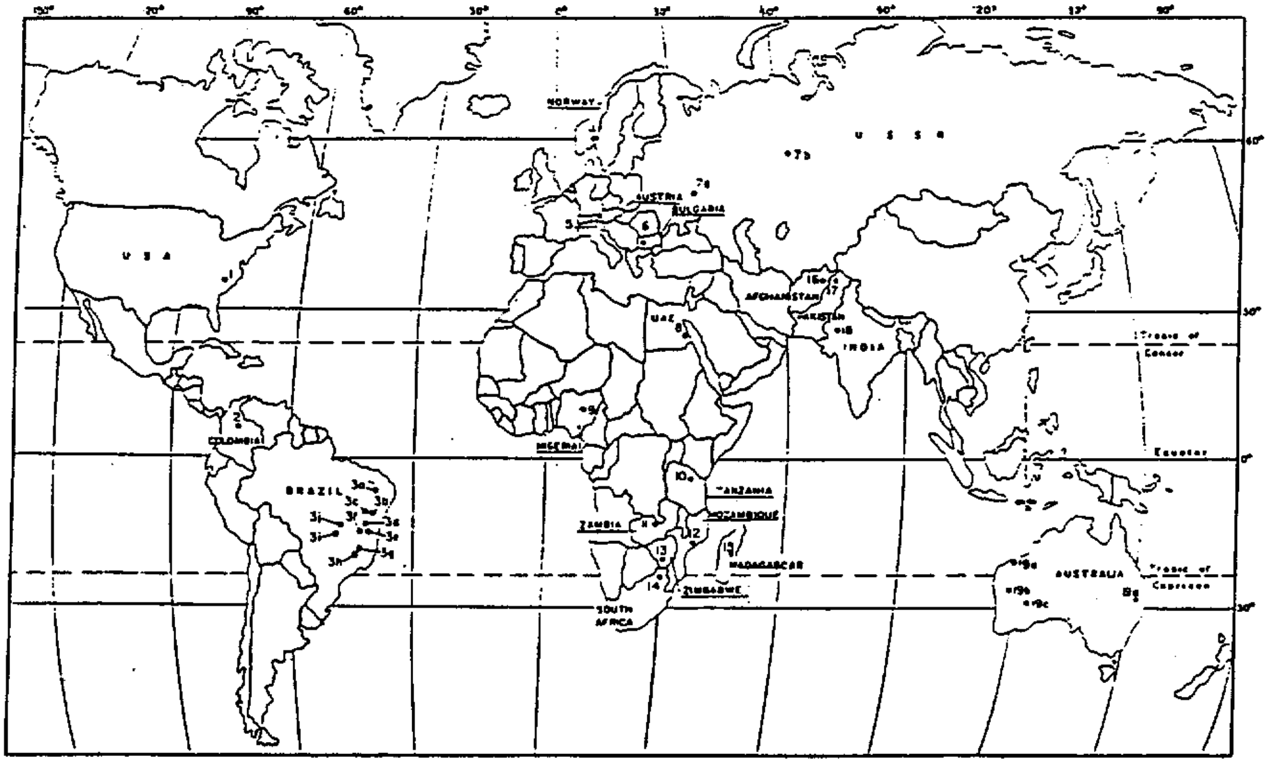
For most of recorded history, the only known emerald deposit was located in a bleak area of desert 700 km SSE of Cairo, Egypt. It is not known when the deposit was first mined; estimates place the earliest workings at about 400 B.C. (Jennings et al., 1993). Although not anywhere near the quality of their as-yet undiscovered Colombian counterparts, their green color had special significance for a people so linked to the life-giving green fertile valley lining the Nile River. In ancient Egypt, green emeralds became a symbol for joy, desire, and female fertility (Sinkankas, 1981).

Emerald deposits in Colombia were "re-discovered" by the Spaniards in the 16th century, although systematic mining and trading of emeralds took place as early as 1000 A.D. throughout Colombia and neighboring countries (Sinkankas, 1981). 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 over four attempts in the 16th century to conquer the fierce Muzo tribe controlling the Muzo emerald mine. The secret weapon unleashed on the warriors to eventually win the battle were packs of European-trained hunting dogs (Ringsrud, 1988). Slavery and poor working conditions were rampant. A cave-in at the Muzo mine in 1646 buried 300 native and Spaniard miners for over 200 years until their bones and mining implements were discovered by miners in 1850 (Ringsrud, 1988). The mine manager's duties at Chivor in the 1920's and 1930's regularly involved shoot-outs with roving gangs of bandits (Feininger, 1970). In the 1970's, 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 Muzo in 1973 alone (Keller, 1981), although the government has taken stronger control of the deposits in the 1980's and 1990's.

Although Colombia still provides over 30 percent of the world's emerald production (Shigley et al., 1990), fine emeralds are also produced from Brazil, Zambia, Zimbabwe, Madagascar, Afghanistan, Pakistan and Russia. Emeralds have been found in the following countries; Afghanistan, Australia, Brazil, Bulgaria, Colombia, India, Madagascar, Mozambique, Nigeria, Norway, Pakistan, South Africa, Tanzania, United Arab Republic, Russia, U.S.A, Zambia and Zimbabwe (Kazmi et al., 1989, Figure 4.1). Colombian emeralds are still considered the best in the world because of their superior color; however, some spectacular emeralds are being mined from the Swat Valley in Pakistan.

For a comprehensive overview of emeralds, including history, lore, physical and chemical properties and geology, the book "Emeralds and Other Beryls" by J. Sinkankas is recommended. More recently, "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. Geologists from the Gemstone Corporation of Pakistan teamed up with geologists from the United States Geological Survey to provide a detailed study of what is becoming one of the world's major gemstone producing areas.

As emphasized before, there are no set prices for gemstones. A customer in a Canadian jewellery store may pay between $3,000 to $7,000 for a fine quality one carat emerald. The wholesale price of emeralds is weighted more towards color than clarity. Customers, as always, should buy from reputable gem dealers or jewellery stores who have the expertise to separate natural emeralds from the array of synthetic, dyed and fake faceted emeralds seen in the gem trade today.



1. USA, N. Carolina emerald; 2. Colombia, Muzo and Chivor emeralds; 3. Brazil, (a) NE. Bahia-Salininha and Carnaiba green beryls, (b) SE. Bahia-Brumado emeralds, (c) Minas Gerais, Emerald dos Ferros and Itabira emeralds; 4. Norway, Eidsvoll emerald; 5. Austria, Habachtal emerald;.6. Bulgaria, Rila emerald; 7. USSR, (a) Ukrain and (b) Notlshoi Reft River emerald; 8. Egypt, Gebel Sikait and Gebel Zabara emeralds; 9. Nigeria, Jos emerald; 10. Tanzania, Lake Manyara emerald; 11. Zambia, Miku emerald; 12. Mozambique, Morrua emerald; 13. Zimbabwe, Ft. Victoria, Sandawana and Filabusi Emeralds; 14. South Africa, Gravelotte emerald; 15. Madagascar, Ankadilalana emerald; 16. Afghanistan, panjsher and Badel emeralds; 17. Pakistan, Gandao, Nawe Kili, Pranghar, Bucha, Khanori, Aman Kot, Maimola, Mingora, Charbagh, makhad, Gujurkili and Khaltaro emeralds; 18. India, Ajmer-Udaipur meralds; 19. Australia, (a) Wodgina emerald, (b) Warda Wara, Melville and Poona emeralds, (c) Menzies emerald, (d) Emmaville and Torrington emeralds.

Figure 4.1 World emerald occurrences
From Kazmi and Snee (1989)

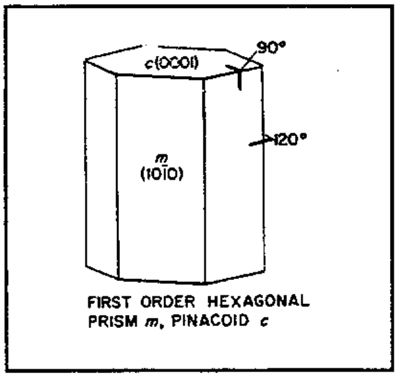


Figure 4.2
Emerald Crystal
From Sinkankas (1981)

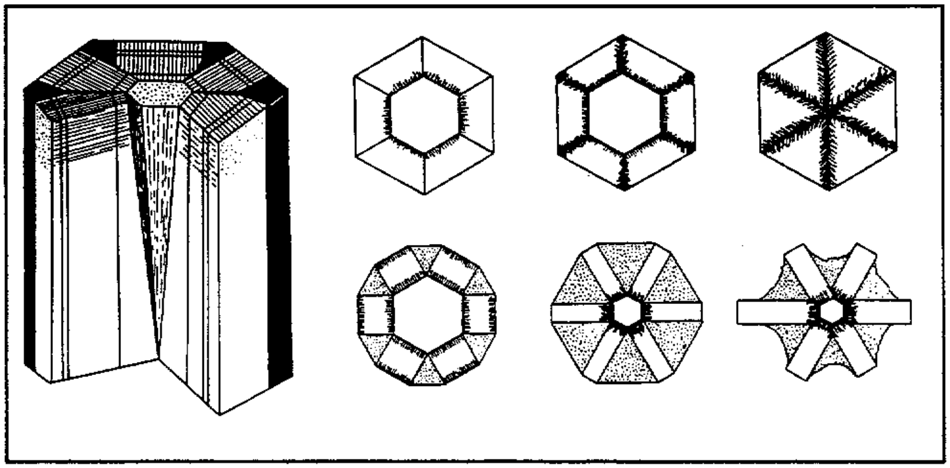


Figure 4.3 Trapiche emerald crystals from Colombia
From Sinkankas (1981)

Their jeweller should be able to inform them of the latest types of "oiling" or "fracture filling" treatments using Opticon and other fillers. This will avoid the all too common phenomenon of a beautiful green emerald turning colorless after its owner or an uneducated jeweller routinely cleans it an ultrasonic cleaner.

Physical and Chemical Properties

Emerald is a variety of beryl. Other gem varieties of beryl include aquamarine (blue-green), morganite (pink-peach) and heliodor (green-yellow). Physical and chemical characteristics of beryl are given in Table 3.3.

The chemical formula of beryl is $Be_3Al_2(SiO_3)_6$. As with corundum, pure beryl is colorless. When Cr or in some cases V or both substitute for Al in the beryl structure, green color results.

When is an emerald not an emerald? Although the grass-green color can result from chromium, vanadium or a mixture of both chromophores, the London Chamber of Commerce and Industry's Precious Stone Trade Section has proclaimed that only chromium coloration counts. "Emeralds" which are colored by vanadium should be called the rather unromantic name "green vanadian beryl" even though they look identical to beryl colored by chromium. Prospectors would have to carry a portable atomic absorption spectrophotometer lab to determine whether the beautiful green crystals they just discovered can actually be called "emerald"!

When a green beryl crystal does not contain Cr or V, the color is an attractive green much like the green of peridot. The different color of green produced by Cr or V is quite distinctive, more like a grass green. At what point a green beryl can be called emerald is somewhat subjective.

Emeralds are extremely rare. Two of the elements essential for its creation are incompatible geochemically. Beryllium, a rare element to begin with, is usually found in pegmatites or continental granites. Chromium, the element responsible for the green color of emerald, is usually found in basic to ultramafic dark colored igneous rocks. Even in those rare geological settings when both elements are present at the same time, the size difference between the small Be atom and the larger Cr and Al atoms makes atomic substitutions in the beryl crystal structure very difficult.

Emeralds typically form distinctive six-sided prisms (Figure 4.2). Only Colombia produces the interesting "trapiche" emeralds. The dark six-spoked pattern is caused by carbonaceous impurities (Fig. 4.3) aligned along the crystallographic axes in the emerald.

Emerald shows two weak to distinct colors when viewed through a dichroscope. One color is yellowish-green and the other color is bluish green. Pleochroic colors for the various beryl gems are listed in Table 4.1.

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 fluoresce weakly.

Field Identification of Emerald

Emerald is a resistant mineral; it is hard and will not break down easily. 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.

In general, any bright green rough crystal should be examined. If the stone is not emerald, then perhaps it is tourmaline, chrome diopside or tsavorite garnet, all of which are valuable gemstones. The six-sided prismatic crystal form of emerald is very diagnostic. 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.

Apparent Color	*Dichroic Colors*		*Intensity*
Green (emerald)	Yellowish green	Bluish green	Weak to distinct
Green (other than emerald)	Colorless or slightly yellowish	Bluish green	Weak to distinct
Green	Colorless	Very pale green	Weak
Green (Maxixe type)[a]	Green	Yellow	Distinct
Greenish blue	Colorless	Pale bluish green	Distinct
Greenish blue	Pale yellowish green	Pale bluish green	Distinct
Blue	Very pale yellow	Blue	Distinct
Blue	Colorless	Blue	Distinct to strong
Blue[b]	Blue	Colorless	Strong
Blue (Maxixe type)[a]	Blue	Colorless	Strong
Blue (Maxixe type)[a]	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[c]	Colorless	Violet	Distinct

[a] K. Nassau. Examination of Maxixe-type blue and green beryl. *Gems & Gemology* 14:131.
[b] B. W. Anderson. *Gem Testing*. 8th ed. (London: Butterworths. 1971). p. 235. Madagascar material.
[c] R. Webster. *Gems*. 3rd ed. (London: Butterworths. 1975). pp. 815-16.
Other information from personal observation and from other authorities.

Table 4.1 Pleochroic colors in beryl From Sinkankas (1981)

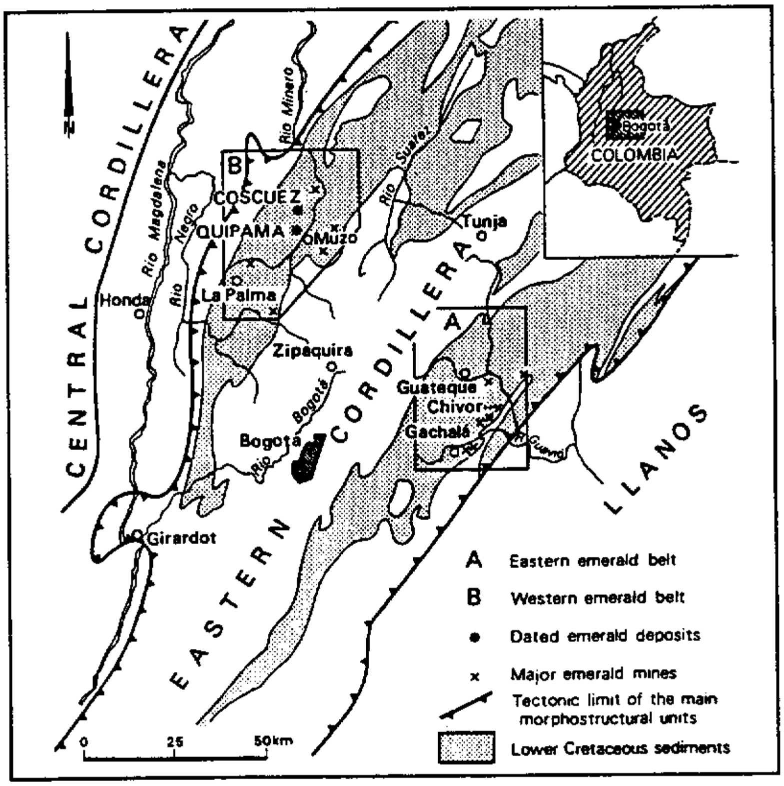


Figure 4.4 Geology of the two Colombian emerald belts From Cheilletz et al., (1994)

Geology of Emerald Deposits

In a broad sense, all emerald deposits can be divided into two types which form in remarkably different geological environments:

1. Emerald associated with bituminous black shales and sedimentary rocks

2. Emerald associated with pegmatitic/granitic rocks interacting with ultramafic rocks
    a. Recent suture zones
    b. Ancient suture zones

The geology of over 40 emerald deposits were studied for this report. All emerald deposits in the world are related to granites and/or pegmatites, except for one. As expected, the one emerald district which shows a truly unique genesis hosts the Colombian emerald deposits, the richest and most important emerald deposits in the world. A minor occurrence in Norway which shows features of both groups (pegmatite intruding bituminous shales) is the only other exception. For a review of the geology of the world's emerald deposits, the reader is referred to Kazmi and Snee (1989) and Sinkankas (1981). Most of the information below is from these two sources and from individual deposit studies as referenced.

Emeralds Associated with Bituminous Black Shales and Sedimentary Rocks

It is only within the last ten years that researchers have started to define the physio-chemical controls on the genesis of these unique deposits. Although there have been excellent descriptions of the local geology (Oppenheim, 1948; Gilles, 1966) detailed mapping of the Colombian emerald districts has always been hindered by the thick vegetation and steep terrain, not to mention the violent history of the region. Because of the almost ubiquitous global association noted between emerald mineralization and pegmatites, it had been presumed that the Colombian deposits formed as a result of igneous activity of some sort even though there was no evidence of igneous activity in the area. Mention was often made of a presumed igneous presence, although the geological and geochemical criteria for emerald precipitation remained unknown. Only within the last five years have researchers (Ottaway et al., 1994; Giuliani et al., 1995) converged on a model relating emerald mineralization to a unique sedimentary environment. The remarkable similarity in mineralogy and chemistry between all Colombian emerald deposits suggests that a single process produced emerald mineralization.

All the deposits 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 4.4). The Cordillera Occidental (west) and Cordillera Central are known for their gold production. About 50 km northeast of Bogota are the emerald deposits, contained within a northwest trending belt 50-70 km wide and 200 km long. The Chivor emerald district is on the eastern flank of the Cordillera Oriental and the Muzo emerald district is on the western flank. Of 100 known emerald occurrences, the three most important deposits are Muzo, Chivor and Coscuez.

Host Rocks

Lower to middle Cretaceous age sediments of the Villeta Group and Caqueza Group are the host rocks for most of the Colombian emerald occurrences (Figure 4.5). The sedimentary host rocks are heavily faulted and fractured in the areas of emerald deposition. Brine springs, evaporite deposits, salt and gypsum mines are scattered throughout the emerald district (Ottaway, 1991). 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.

At the Muzo mine, the Villeta formation consists of a thick sequence up to 100 m of intensely folded and fractured soft, sooty, black carbonaceous shale and minor limestone (Figure 4.6). Keller (1981) notes that the shales are so carbon rich that they leave smears on one's hands when handling the rocks. Ottaway (1991)

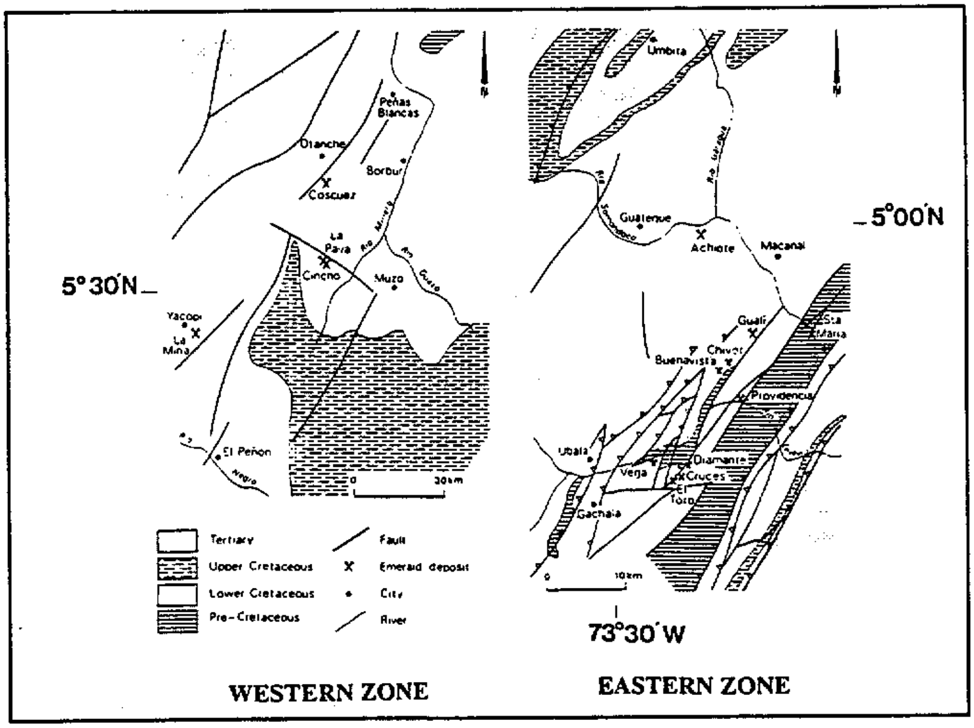


Figure 4.5
Geological and structural environment of the eastern and western Colombian emerald zones
From Giuliani et al., (1995)

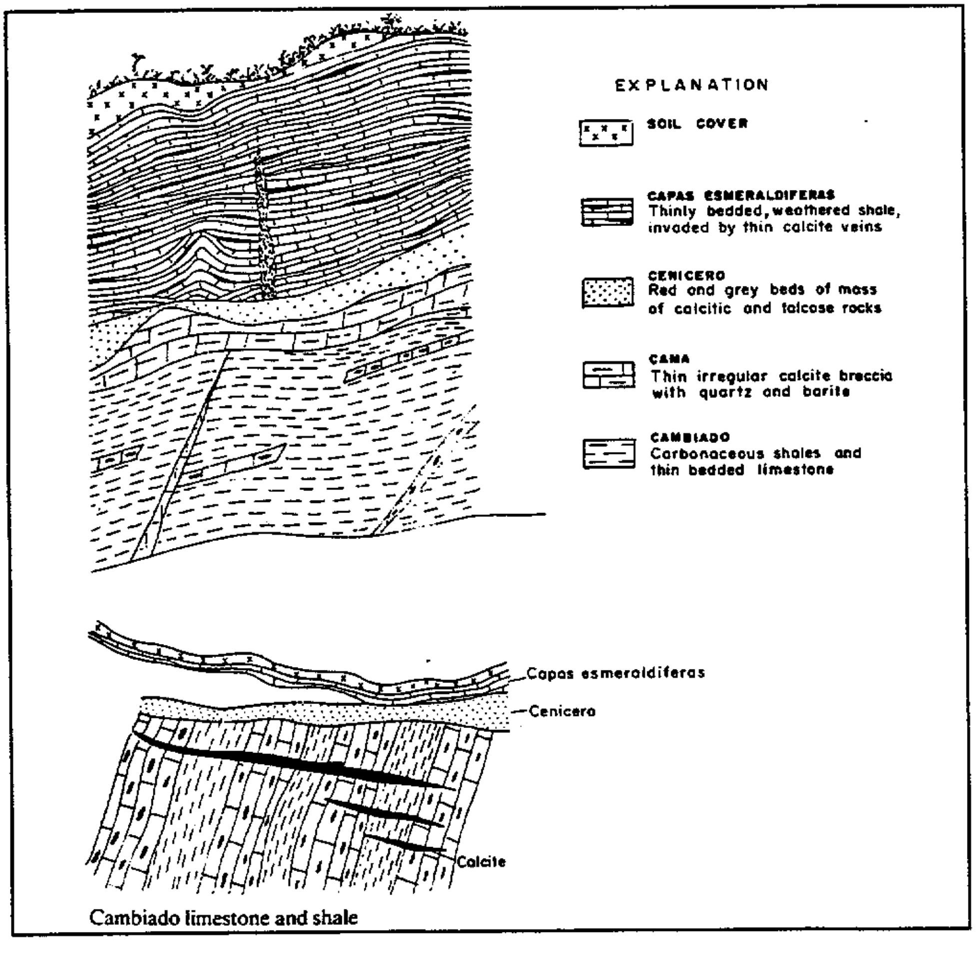


Figure 4.6 Geological cross-section of the Muzo emerald deposit
From Kazmi and Snee (1989)

noted that the shales make a "clinking" sound when banged together.

The Villeta formation is divided into two members 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 (Ottaway, 1991). Emeralds are contained within discordant calcite-albite-pyrite veins. The *Cambiado* formation disconformably underlies the Emerald Formation (Figure 4.6). It consists of dark to medium grey limestones and shales which weather blueish-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 *Cambiado* 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.

A thickness of at least 1,000 m of conformable bituminous light-grey to black shales, argillites with minor limestone, and sandstone host emeralds within pyrite and albite veins at the Chivor Mine. The emeralds are irregularly distributed within thin albite-pyrite veins (Ottaway, 1991).

There is no evidence of igneous intrusion or contact metamorphism relating to igneous bodies in the emerald bearing areas (Beus, 1979).

Mineralogy

Giuliana 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 micas
2. white or grey rhombohedral calcite, dolomite, albite, pyrite, quartz and some kerogens
3. fluorite, parisite, REE rich-dolomite, pyrite, quartz and emerald

At the Muzo mine, calcite, dolomite, albite and pyrite are the predominant gangue minerals (Figure 4.7). Quartz and barite are infrequent. Emeralds are spatially associated with fluorite and parisite (a rare F mineral found only at Muzo) and are good indicator minerals of emerald mineralization (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 centimeters away. Ottaway (1991) lists six visual guidelines used by miners at Muzo to indicate the presence of emeralds:

1. Emeralds occur predominately in the calcite/albite veins.
2. Indicator minerals for emerald mineralization include fluorite, parisite, apatite and opaque green beryl.
3. Intersections of two or more veins are more favorable than single veins.
4. Veins less than 15 cm wide are more productive.
5. A "gritty, scraping" feeling felt when scuffing one's mining boots over the limestone means the ground is more favorable than smooth-feeling limestone.
6. The veins are rarely productive below the watertable.

Ottaway (1991) notes that at the Muzo mine, emerald mineralization is spatially related to odd ash-grey zones in the organic black shales called *Cenicero* which in Spanish means "ash" (Figure 4.6). These zones, up to one m wide, are composed of fine-grained crystals and fragments of calcite, dolomite, quartz, barite, pyrite and shale fragments within a groundmass of carbonate. Native sulphur is sometimes present. The organic content is depleted and there is a color contrast between the black shales and the light grey cenicero zones. The *Cenicero* grades locally into granular grey, albitized rock. Trapiche emeralds occur in the outer parts of the ash-zones. Emeralds are confined to the distal

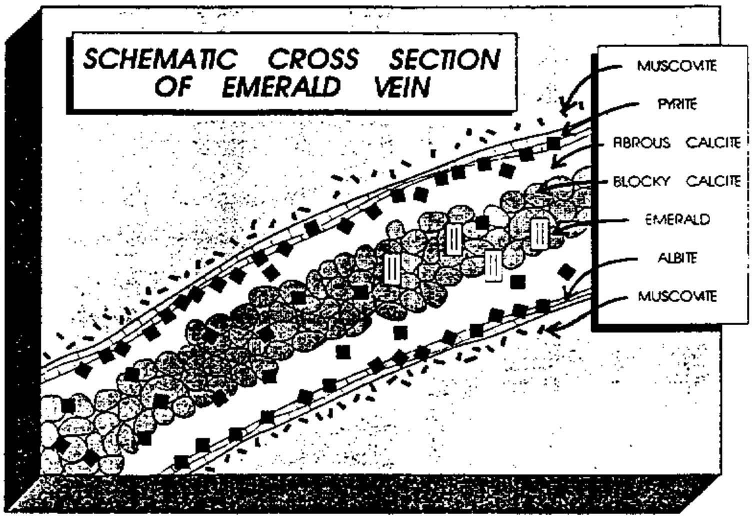


Figure 4.7
Schematic cross-section of emerald vein
From Ottaway et al., (1994)

Components	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_2O_3	14.70	13.04	17.14	12.56	8.33	6.59	7.03
Fe_2O_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_2O	0.83	0.88	1.12	5.04	3.37	2.39	3.58
K_2O	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_2O^-	tr	tr	0.11	0.38	tr	0.15	0.14
H_2O^+	3.18	2.48	3.74	1.35	1.56	1.74	0.88
P_2O_5	0.21	0.09	0.17	0.30	0.31	0.29	0.44
CO_2	1.72	n.d.	n.d.	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	n.d.	n.d.	n.d.	1.22	0.54	0.43	—
Lost on ignition	0.43	0.81	1.06	2.06	1.54	1.60	1.71
Sub-total	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_2O/K_2O	0.78	0.79	0.90	7.52	14.0	12.6	11.5

Table 4.2
Chemical Composition of the Villeta black shales in the Muzo area
From Beus (1979)

parts of calcite-albite veins radiating from the *Cenicero* alteration zones.

At the Chivor mine, emerald mineralization in the 10 x 5 km zone is stratigraphically controlled by three "iron bands" 50 m apart, which are composed of large veins and beds of partially limonitized pyrite crystals and occasional 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 parisite have not been noted at Chivor.

Although no *Cenicero* zones have been formally mapped at Chivor, Ottaway (1991) notes that in 1989 a large pocket of emeralds estimated at $6,000,000 U.S. was found at Chivor associated with an "ash-like" zone similar to those at Muzo.

Age of Mineralization

Cheilletz et al., (1994) dated emerald mineralization at the Coscuez and Quipama-Muzo deposit at 31 to 38 million years.

Alteration

The black shale hosting the emerald deposits have undergone metasomatic alteration. Albitization, pyritization and carbonate alteration halos around the emerald-bearing veins are pervasive, but not always visually apparent.

Relationship Between Regional Structure and Emerald Mineralization

Emerald mineralization in Colombia is structurally related to tectonic blocks formed by the intersection of regional fault zones striking north-northeast and northwest (Ottaway et al., 1994). The tectonic blocks containing the emerald mineralization are metasomatically altered by Na and Ca (Beus, 1979).

Regional Geochemical Alteration Halos

It would seem that since emerald is composed of Be and colored by Cr or V, that a regional stream sediment geochemical survey should target those three elements. This might be true, unless the exploration target is an organic black-shale hosted emerald deposit like the ones in Colombia.

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.

It was discovered that the spatial distribution of areas containing emerald mineralization was linked to intersections of northeast and northwest fault zones. The tectonic blocks are 200 to 300 m in width. The tectonic blocks which contain emerald mineralization are enriched in CO_2, Ca, Na, Mg, Mn, S and depleted in K, Si and Al (Table 4.2, Table 4.3). 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.

The altered shales are enriched in Na and K and depleted in Li, Mo, Ba, Zn, V and Cr. In Colombia, a number representing the ratio of Na to K, Li and Mo was used as the criteria to distinguish mineralized blocks from barren blocks. In a separate study of the geology and geochemical expression of the Gachala emerald district in Colombia, Escobar (1978) reports that Na enrichment and depletion of Li, K, Ba and Mo 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 have anomalously low K/Na ratios when compared with those from background areas (Table 4.4).

	(a) Outside the mineralized tectonic zones (background)				(b) Within the mineralized tectonic zones		Concentration ratio (CR) b/a	
	Na		K		Na	K	Na	K
	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	$\bar{x}$		
Muzo	0.8	0.27	3.2	0.74	4.1	0.95	5.26	0.30
Gachala	0.6	0.25	3.9	0.89	2.9	1.18	4.76	0.30

$\bar{x}$ = arithmetical mean; S = standard deviation. Muzo — 38 samples outside and 50 samples within the mineralized tectonic zones; Gachala — 16 and 65 samples, respectively.

Table 4.3 Potassium and sodium distribution in the black shales (%)
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 4.4 Average values of some indicator elements in stream sediments in the Muzo area
From Beus (1979)

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 nebulous to narrow it down further within those blocks to find the actual emeralds - a difficult task in dense jungle terrain. Ringsrud (1986) reports that Colombian geologists were analyzing for Na, Li and Pb in soil samples collected from altered tectonic blocks to delineate emerald mineralization.

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

Paragenesis of the Emerald Deposits

The following section is a composite summary of the research described by Ottaway (1991), Ottaway et al., (1994), Cheilletz et al., (1994), Beus (1979) and Giuliana et al., (1995). The preliminary model described below is a relatively new one which favors emerald precipitation as the end product of a sequence of events triggered by the thermochemical reduction of sulphate-rich brines to hydrogen sulphide by interaction with the organic rich shales.

1. Depositional Setting

A thick sedimentary sequence consisting of organic material, mud, silt and limestone was laid down in an anoxic lagoonal setting in the shallow marine environment of the Eastern Cordillera. High salinity and reducing conditions inhibited decomposition of organic matter which accumulated in places to 1-2%. Streams draining into the lagoon area contained Be-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.

2. Burial and Deformation

The sedimentary sequence in the Eastern Cordillera basin reached thicknesses up to 12,500 m. At some point, the sedimentary package was buried at depths of 6,000 m. At this depth, the organic matter in the black shales transformed to impsonite (a partially crystalline, carbon-rich pyrobitumen) during thermal alteration.

3. Genesis of Brine Fluids

When the sedimentary package was buried or later, perhaps during Pleistocene uplift, heat and pressure on the block released water from the sediments. Where the water encountered evaporites in the sedimentary package, $NaCl\text{-}KCl\text{-}CaCl_2$ rich brines were generated. Giuliana et al., (1995) note that the brine fluids are remarkably similar to oil-field brines and brines involved in the formation of Mississippi Valley type lead-zinc deposits.

4. Structural Control on Brine Movement

The brines move through the sedimentary package along faults, unconformities and other structurally favorable sites.

5. Thermochemical Reduction of Sulphate to Hydrogen Sulphide

When organic material in the black shales cracks, H_2S gas is released and collects preferentially in the same faults and channelways favored by the brine fluids. A fascinating series of chemical reactions begins, cumulating with the deposition of emeralds at the end of the sequence.

Where there is sufficient concentration of H_2S in the shales, H_2S reacts with the SO_4 in the brine fluids to produce native sulphur. Then, the native sulphur reacts with organic matter to produce additional H_2S and CO_2. The two reactions are listed below:

$$SO_4{}^{2-} + 3H_2S = 4S + H_2O + 2OH$$
$$4S + 1.33(CH_2) + 2.66H_2O = 4H_2S + 1.33CO_2$$

This reaction is an exothermic one, that is, it may be self sustaining. As seen in the above equation CO_2 is produced, which would build up pressure in the reaction zone.

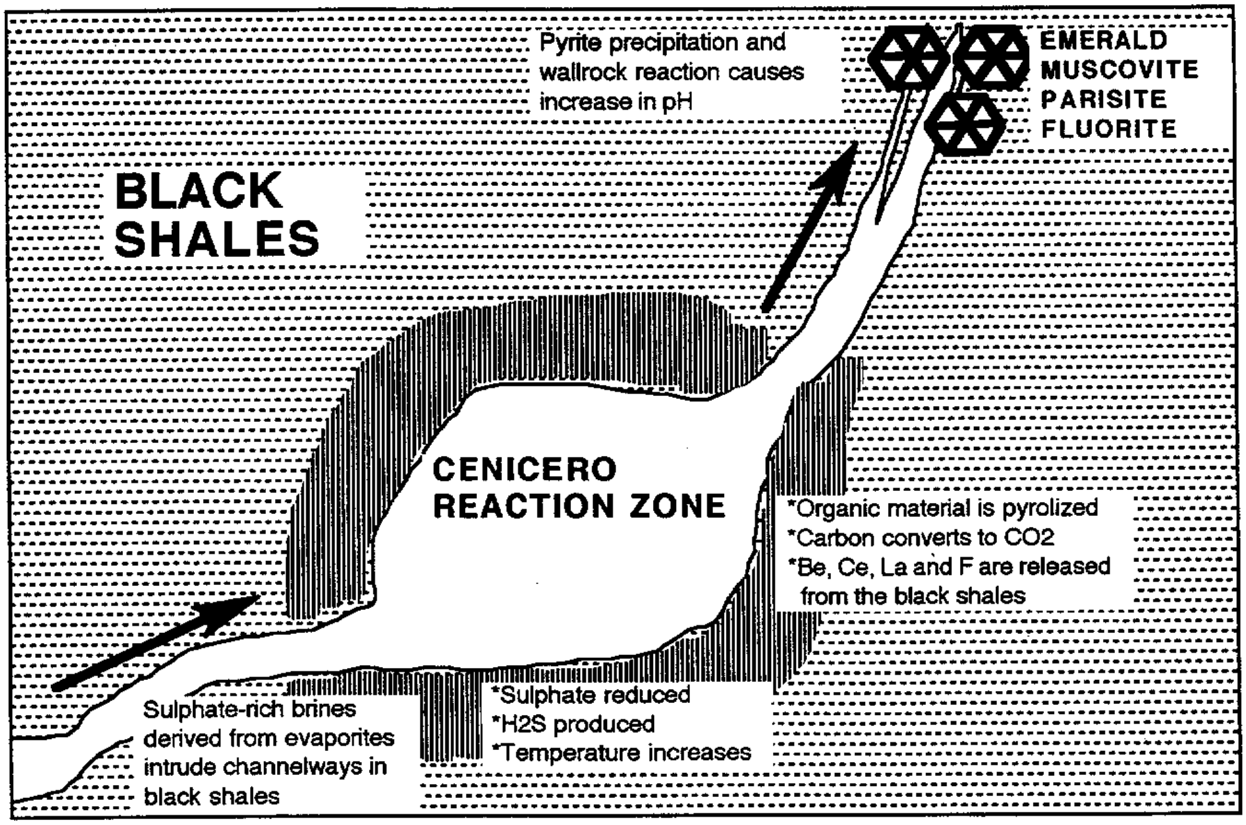


Figure 4.8 Model of emerald precipitation at Muzo
After Ottaway (1991)

The process of sulphate reduction, where sulphur is derived from evaporites is also responsible for high sulphur isotope values (Giuliana et al., 1995). Ottaway et al., (1994) note that carbon isotope values indicate that the organic matter was the probable source of CO_2.

6. Emerald Precipitation

Organically bound Be, Cr and V in the black shales are released as the exothermic reaction begins. Be is mobilized by OH- complexes in acidic H_2S brines. The build-up and subsequent failure of the wallrocks in response to CO_2 pressure injects the evolved fluid into newly developed fracture networks. Minerals crystallizing from the brines block the fracture passageways, the fractures are sealed, and the pressure builds up again. This cycle leads to repeated brecciation of the surrounding host rock.

Between the explosive events, fluids in the channelways stagnate, leaving abundant time for fluid-wallrock reactions. Precipitation of pyrite produces protons which make the fluid more acidic by combining H^+ with Cl to produce HCl. The HCl dissolves the wallrock which increases the pH of the fluid. Muscovite, albite, F-bearing minerals (fluorite and parisite) and eventually emerald precipitate (Figure 4.8). Emeralds formed in the *Cenicero* zone by hydrothermal fluids diffused into sediments rather than migrating into veins. The crystallizing emerald pushes away shale, until shale is trapped along the beryl's crystallographic axes producing a pattern (Figure 4.3).

Temperatures of emerald precipitation are given as 325°C (Ottaway, 1991) for the Muzo deposit and 290°C to 360°C for the Coscuez and Quipama-Muzo deposits (Cheilletz et al., 1994).

The crystallization process continues until the organic matter available in the black shales is consumed, leaving an ash-grey residue. Ottaway (1991) notes that not all products in the reactions may be produced, for example native sulphur.

Cheilletz et al., (1994) suggest that emerald mineralization in Colombia took place at depths of 4,250-4,500 m and at temperatures of 290 to 360°C. They linked time-pressure-temperature-age constraints of emerald mineralization to tectonic events in the Eastern South American Cordillera. The time of emerald precipitation was 31 to 38 million years ago. At this time, the large Eastern Cordillera basin was shortening, due to convergence between the Nazca and South American plates and sedimentation in the Eastern Cordilleran basin was undergoing transgressions and regressions towards a nonclastic depositional regime.

During late Miocene to Pliocene time, thrusting and uplift of the Eastern Cordillera took place in response to collision between the Caribbean arc system and South America. These tectonic episodes were responsible for inversion of the Cretaceous back-arc basin and emerald outcropping at the present day surface, a total of 6,000 m vertical displacement (Cheilletz et al., 1994).

The Color of Colombian Emeralds

The presence of iron in the beryl structure quenches a underlying red fluorescence. Colombian emeralds, which are noted for their vibrant, vivid emerald-green color due in part to this fluorescent effect, contain very little or no iron. The exothermic reaction responsible for generating emerald precipitation is also responsible for instigating pyrite precipitation which removes iron from the hydrothermal system (Ottaway, 1991). Miners at Muzo report that better quality emeralds are found in areas of abundant pyrite (Ottaway, 1991).

Comparison with other Ore Deposits

It is interesting for Canadian geologists familiar with the Pine Point lead-zinc deposit in the N.W.T. to note that the chemistry of the emerald fluids is the same as that observed in oil-field brines and in Mississippi-Valley-Type deposits (Giuliani et al., 1995). Indeed, Ottaway (1991) examines the Mississippi-Valley-Type Pine Point deposit in the N.W.T. as a lower temperature analog to the mesothermal Colombian emerald deposits.

The only other emerald deposit in the world associated with organic black shales is at Eidsvoll, Norway. The emeralds are within a quartz-feldspar-fluorite-topaz vein which has intruded Cambrian age aluminum-bearing bituminous shales (Kazmi and Snee, 1989).

Emeralds Associated with Pegmatites or Granites Interacting with Chromium-Bearing Rocks

Most emerald deposits fitting this category can be subdivided into two groups. The first group of deposits in Pakistan and Afghanistan is related to "recent" suture zones (Figure 4.9). The second group of deposits seem to 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. The deposits are hosted in what, in most cases, could be the remnants of very ancient suture zones, but the exact geological relationships are uncertain.

Emerald Deposits Related to "Recent" Suture Zones

Pakistan

In the Himalayas, Karakorams and Hindu Kush mountain ranges where rocks were compressed, deformed, metamorphosed and obducted, emerald precipitation took place. There could be no greater contrast than that between the relatively placid sedimentary basin setting for Colombian emerald formation and the most tectonically active area in the world (Kazmi, 1989).

Most of the following information is taken from the landmark study "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 Eurasia continent, the two continental masses were separated by the Tethys Ocean (Figure 4.10). 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 overriden by Kohistan island arc rocks. Metasomatic alteration at depths up to 12 km transformed the ocean-floor rocks to a talc-dolomite melange. The deep burial of the frontal part of the Indian plate also generated anatectic 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 favorable for providing the proper physio-chemical conditions for gemstone formation.

Without exception, all the emerald deposits in Pakistan are located within or closely associated with the Indus suture zone (Figure 4.11). The Indus suture zone is a complex zone of diverse rock assemblages including tectonic blocks of ophiolites, blueschists, greenschists, metavolcanics and metasediments in a matrix of sheared and variously metamorphosed fine-grained sediments and/or serpentinite. All the emerald deposits in Pakistan, except for one, are contained within the Mingora ophiolitic melange 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.

Emerald Mineralization

Descriptions of emerald mineralization are given by Kazmi et al., (1989). The best and largest emerald

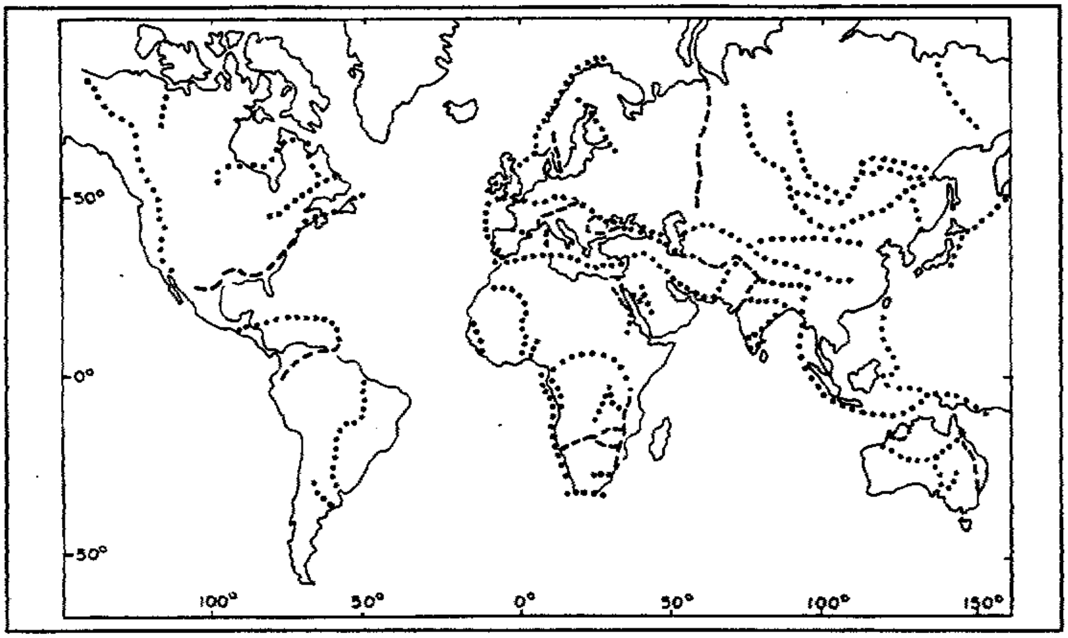
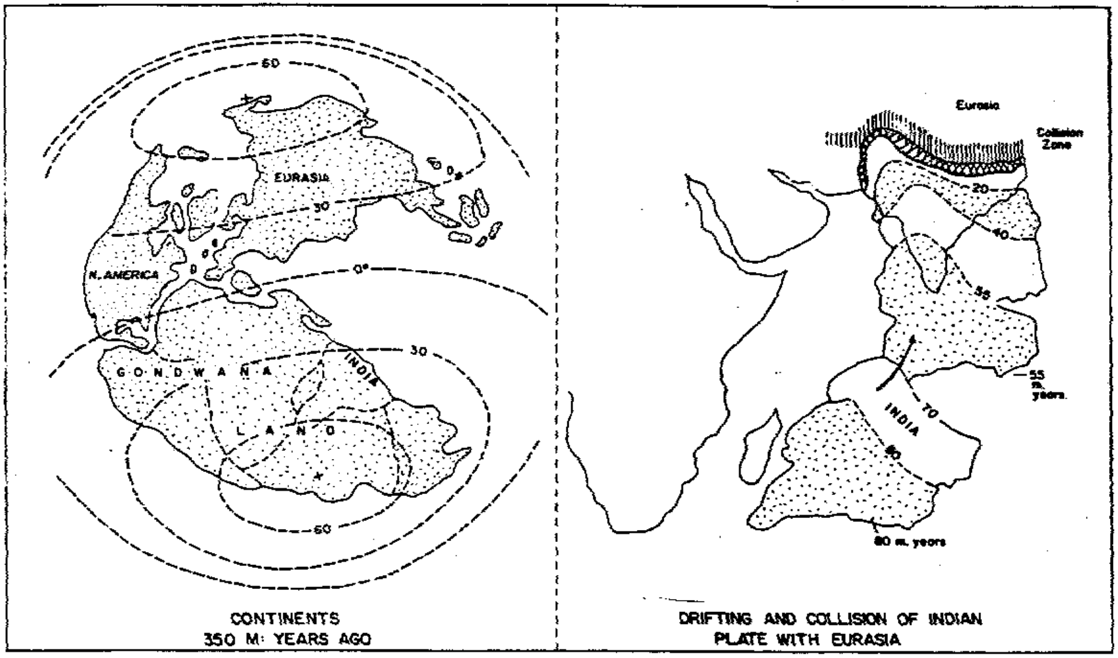


Figure 4.9 Distribution of major Phanerozoic and Proterozoic suture zones (dotted). Suture zones that are found near emerald deposits are shown as dashed lines. From Snee and Kazmi (1989)



CONTINENTS 350 M. YEARS AGO

DRIFTING AND COLLISION OF INDIAN PLATE WITH EURASIA

Figure 4.10 From Kazmi (1989)

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 melange containing tectonized clasts of serpentinite, dolomite, greenschist and graphitic schist up to hundreds of meters in size set in a fine to coarse-grained ductilely deformed matrix (Figure 4.12).

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 stockworks.
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. Color photographs of the deposit in Kazmi et al., (1989) and Bowersox and Anwar (1989) show it to be in a picturesque valley. The deposit is in a small triangular outcrop of ophiolitic melange which is barely 1.5 hectares across (Figure 4.13). Emeralds occur in a brown to yellowish green, medium-grain 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, metavolcanics, serpentinite, pyroxenite, peridotite and talc-chlorite-dolomite schist. This area is host to several emerald deposits (Figure 4.14)

As mentioned earlier, the Khaltaro emerald deposit differs from the other deposits because the emeralds occur within pegmatite dikes located near a major suture zone. The dikes intrude medium to coarse-grained amphibolite-grade biotite schist and gneiss with marble, calcsilicate gneiss and subordinate amphibolite. The deposit was discovered in 1985 by the Gemstone Corporation of Pakistan while exploring for gem pegmatites of 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 contains extremely rugged and complex terrain with the maximum relief (7,000 m a.s.l.) seen anywhere in the world. The uplifted area is at the junction of three major suture zones; the Indus suture zone, the Tsangpo suture zone and the Karakoram suture zone. In this tortuous terrain are not only emerald deposits, but also tourmaline, topaz, aquamarine and garnet.

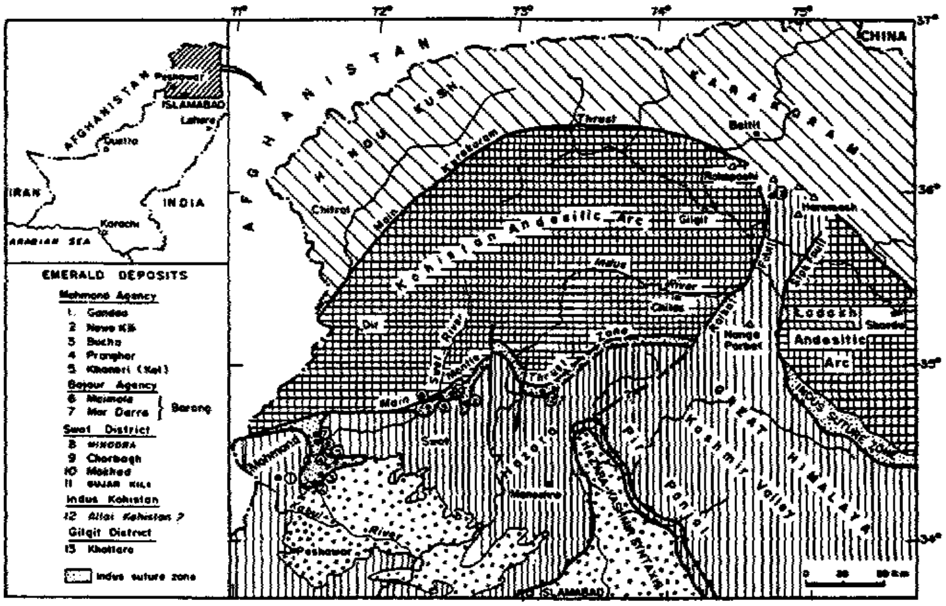
Although the Khaltaro emeralds are hosted by pegmatites, the deposit is located along a major suture zone.

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 color was provided by ophiolitic suture zone rocks.

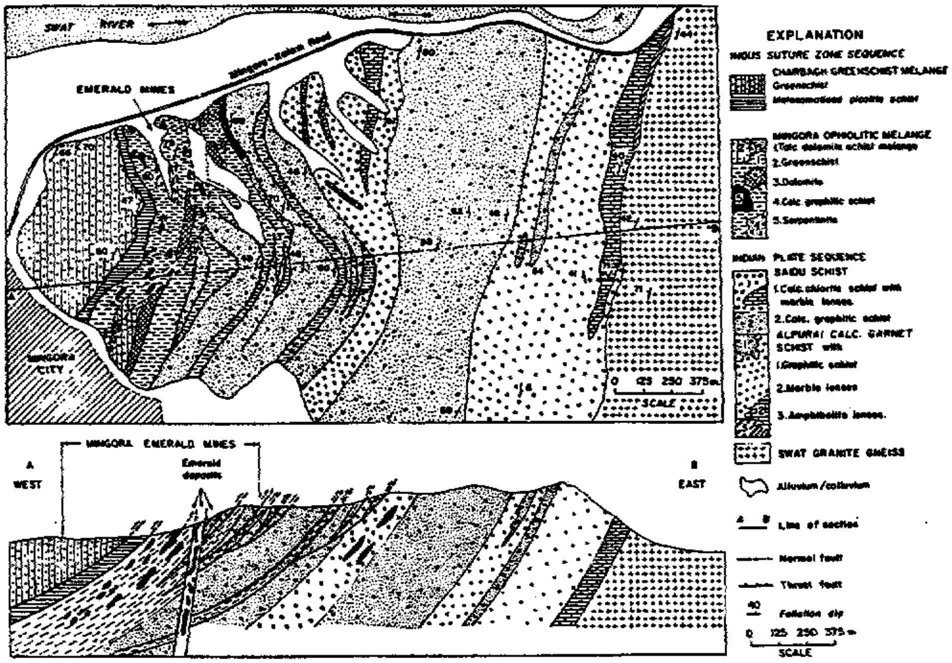
During the collision of the Indian plate to Eurasia, the ocean floor ophiolitic rocks were buried to an estimated depth of 12 km, and metasomatic alteration transformed the once ocean-floor rocks to a talc-dolomite melange. The deep burial of the frontal part of the Indian plate also generated anatectic 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 Be, Al and Si from the continental anatectic granites penetrated the soft, permeable chromium talc-dolomite melanges which were once the ocean floor rocks of the Tethys ocean, emerald precipitation took place.

An important criterion for the percolation of the Be-bearing fluids was the metasomatism of hard ultramafic ocean floor rock to soft, porous and permeable talc-dolomite melange matrix. It should also be noted that although the melange 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).



Emerald locations in northern Pakistan in relation to major tectonic subdivisions. Small circles indicate molasse of Murree and Siwalik Formations and sedimentary fill of the Peshawar Plio-Pleistocene basin. Vertical ruled lines indicate the Indo-Pakistan subcontinent-sequence of Gondwana-related, folded and thrust faulted shelf sediments, basement, and their metamorphosed equivalents. Crossed lines indicate the Kohistan andesitic arc sequence of amphibolites, layered mafic complex, arc volcanosedimentary units, and arc-related, calc-alkaline, I-type intrusions. Diagonal ruled lines indicate Karakoram microplate sequence. Indus suture zone and Main Mantle thrust zone are principal Cenozoic suture between Indo-Pakistan subcontinent and Asian mass and are occupied by the Indus suture melange group indicated by fine dots.

Figure 4.11 From Lawrence et al., (1989)



Geologic map and cross-section of the Mingora emerald mine area (after Kazmi and others, 1984).
Geologic map shows details of melange in Mingora emerald mine and imbricate interleaving of talc-carbonate melange slices with Saidu schist.
Cross-section shows melange structure and younger cross-cutting normal fault with which emerald mineralization is associated.

Figure 4.12 From Lawrence et al., (1989)

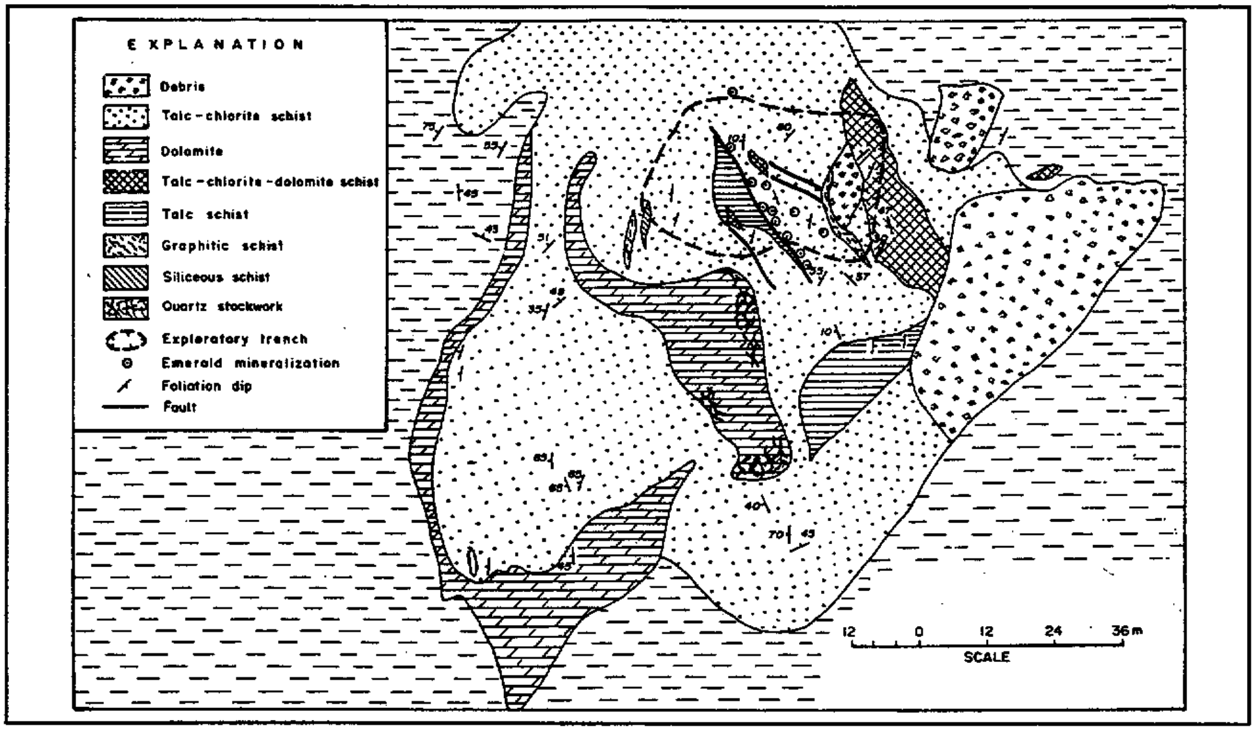


Figure 4.13 From Kasmi et al., (1989)

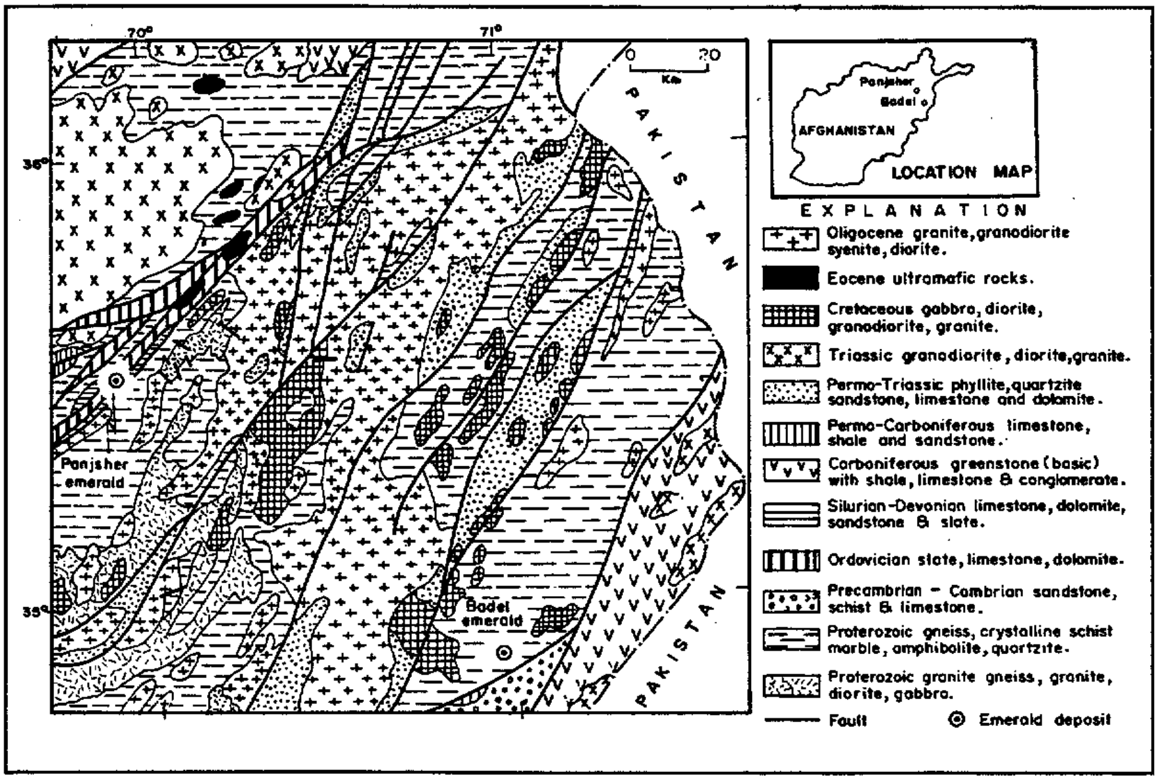


Figure 4.15 Regional geology of the Panjsher emerald deposit From Kazmi and Snee (1989)

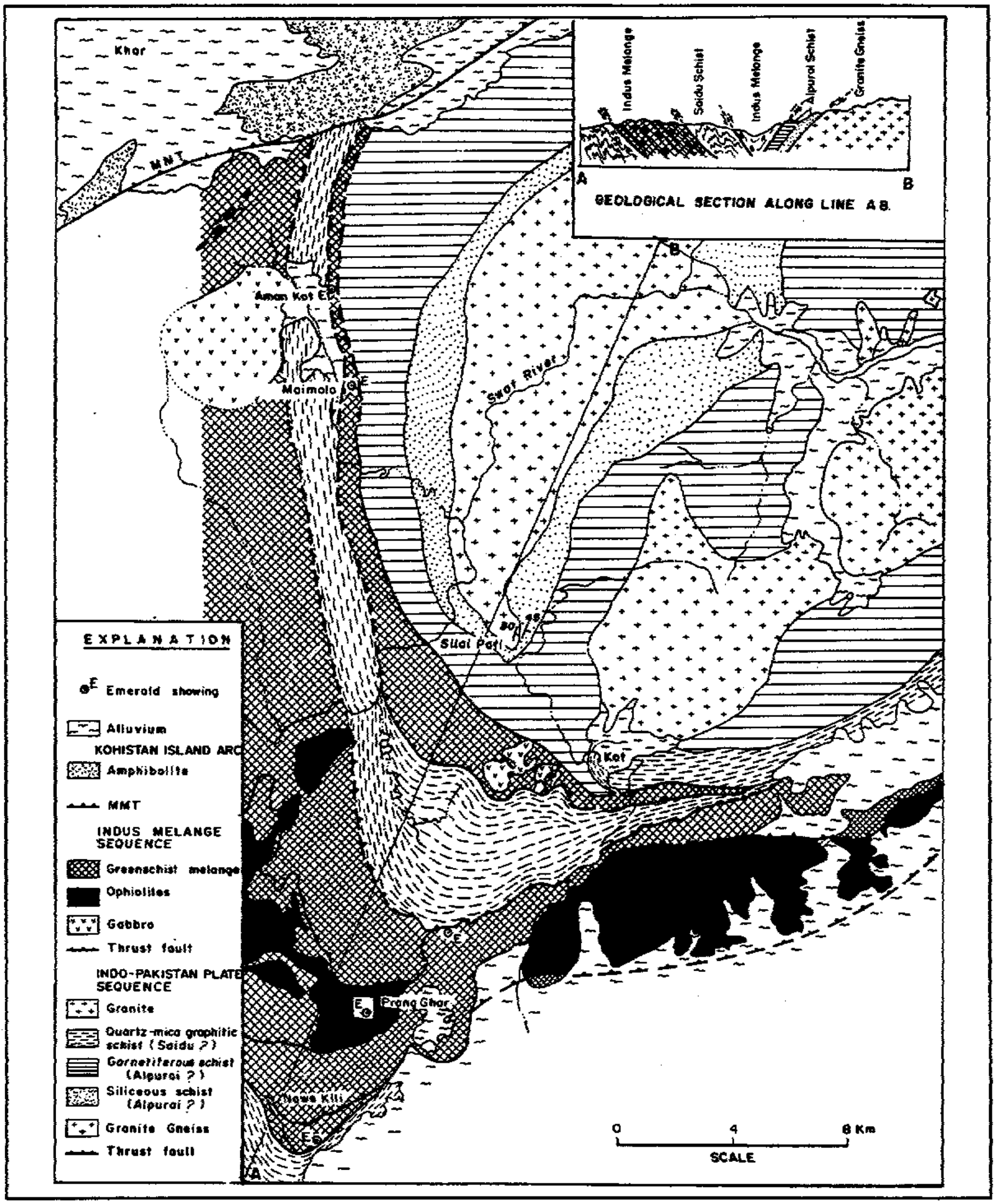


Figure 4.14 Geologic map of the Kot-Pranghar emerald mine area From Lawrence et al., (1989)

Afghanistan

Emeralds are found in a Cenozoic suture zone developed during collision between the Asia continent and a microcontinent known as Cimmeria. An estimated $10 to $12 million of rough emeralds were produced in 1990 (Bowersox et al., 1991). This area of the world, the Panjshir Valley in the Hindu Kush mountain range, was cut off from the world during the Soviet occupation of Afghanistan. With no Soviet troops to battle, former Mujahideen freedom fighters are concentrating on mining emeralds from these formidable mountains. Emerald mining is very treacherous because of the steep topography, landmines and tribal warfare. A description of the deposit and a mining update is given by Bowersox et al., (1991). The words "Occupational Health and Safety" obviously do not exist in the 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. Bowersox et al., (1991) note that there is no formal record keeping of property, so disputes over mining rights between various groups are complicated.

Emerald crystals are contained within small quartz-ankerite and dolomite veinlets in metasomatically altered diorite-gabbro, dolomitic marble, quartz-biotite schist and quartz-porphyry (Figure 4.15). Kazmi and Snee (1989) felt that the emeralds from the Panjsher valley are suture related, much like most of the Pakistan deposits.

Emerald Deposits related to Biotite Schists and Other Mafic/Ultramafic Rocks (Possible "Ancient" Suture Zones)

Sinkankas (1981) and Kazmi and Snee (1989) provide detailed summaries of the largest group of emerald deposits; those formed by chemical interaction between pegmatites and mafic to ultramafic rocks or their metamorphosed equivalents. Biotite schist, for example, is the most common host rock containing emerald mineralization. These deposits are found in several countries including Australia, Austria, Brazil, Bulgaria, India, Madagascar, Mozambique, Nigeria, South Africa, Tanzania, United Arab Republic (Egypt), Russia, USA, Zambia and Zimbabwe. Characteristics of some of the better-studied deposits are given below:

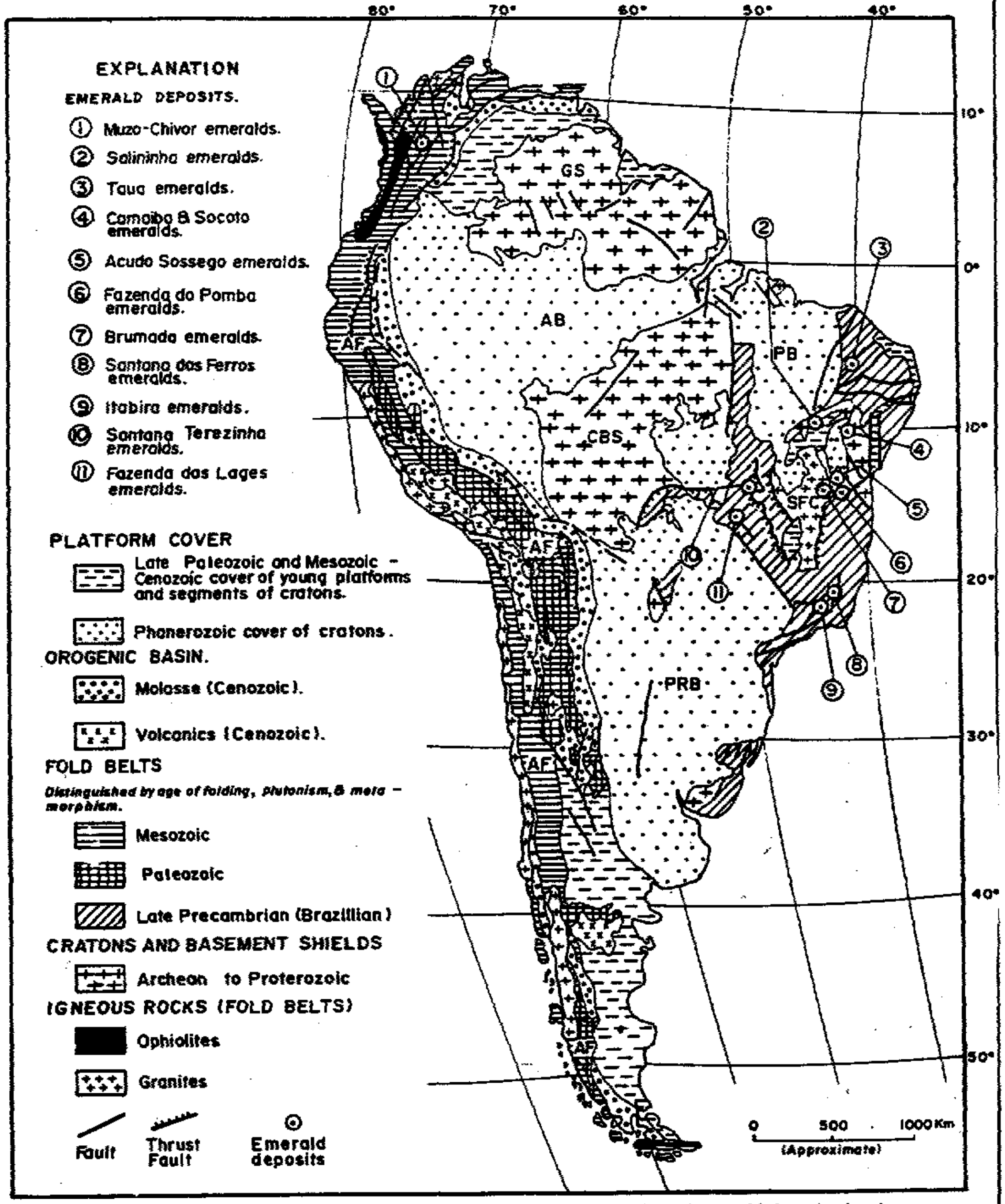
Brazil

As with most gemstone discoveries, the emerald deposits of Brazil were discovered accidentally, one by one, starting in 1963 when the Salininha deposit was discovered. The highly productive Santa Terezinha deposit was discovered in the late 1970's when, typically, 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-honored Brazilian fashion, an immediate tremendous staking rush resulted in the usual chaos, largely due to the small 4 m x 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.

During the 1980's, Brazil became a significant emerald producer. The Carnaiba mine continued production and several new deposits were discovered, including Santa Terezinha (Cassedanne and Sauer, 1984), Socoto (Schwarz et al., 1990), Belmont (Hanni et al., 1987), Taua (Schwarz et al., 1988), Carnaiba (Schwarz and Eidt, 1989), Fazenda Boa Esperanca (Schwarz et al., 1988), Ceara (Schwarz et al., 1988) and Capoeirana (de Souza et al., 1992). Summaries of Brazilian deposits are provided by Sinkankas (1981) and Kazmi and Snee (1989). The origin of emerald deposits in Brazil is discussed by Giuliana et al., (1990). The locations of the emerald deposits are shown in Figure 4.16.

Giuliana et al., (1990) examined the geology of Brazilian deposits and linked their geology, geochemistry and structure to a single genetic model. The host rocks are Archean basement rocks (tonalitic gneisses, migmatites, diatexites or granite gneiss), Proterozoic volcano-sedimentary sequences (intercalated iron formations, felsic and mafic-ultramafic horizons, cherts and quartzites) and granites or their magmatic or late-magmatic equivalents. The Proterozoic sequences sometimes form greenstone belts, imbricated structures or are intensely folded and deformed.

The geology, mineralogy and chronology of the different types of deposits are given in Table 4.5. The



Geological sketch map of South America showing location of emerald deposits (geology from Leonov and Khain, 1982). AB-Amazon Basin; AF-Andean fold belt; CBS-Central Brazillian Shield; GS-Guiana Shield; PB-Parnaiba Basin; PRB-Parana Basin; SFC-Sao Francisco Craton.

Figure 4.16 Location of Brazilian emerald deposits From Kazmi and Snee (1989)

	Deposits Occurrences	Type I			Type II	Type III		
		Carnaiba (1) Socotó (2) BA		Pirenópolis GO	Santa Terezinha de Goiás GO	Itabira MG	Tauá (1) Coqui (2) CE	
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	metasediments of Minas Supergroup	(1) Independencia complex (2) Caico and Nordestino complexes	
Intrusive rocks	Nature	pegmatitic veins		pegmatitic veins	–	pegmatitic veins	pegmatitic veins	
	Typical mineral association	beryl (molybdenite)		garnet	–	beryl aquamarine	columbite tantalite beryl aquamarine (2) cassiterite (2)	
	Related γ	(1) Carnaiba (2) Campo formoso		Quebra Rabicho				
	Age	Transamazonic 1.9 Ga		pre-Uruçuano (?)	–	probably Brazilian 0.5–0.7 Ga	Brazilian? (1) Brazilian (2) 0.5–0.7 Ga	
Emerald and metasomatic rocks	Nature	phlogopitite		phlogopitite	+phlogopitite +phlogopitite-talc carbonate schist +phlogopitite-carbonate schist	phlogopitite	phlogopitite	
	Typical mineral association	molybdenite alexandrite (1) scheelite apatite tourmaline phenakite (2)		tourmaline apatite (cassiterite)	pyrite chromite (Mg, Al) carbonate (Mg)	alexandrite chrysoberyl	apatite bismutite (1)	
	Emerald composition	(2)	(2)				(1)	(2)
	Cr_2O_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_2O	1.29	1.09	1.77	1.77	0.92	1.84	0.59

Table 4.5 Geology, mineralogy and chronology of the three main types of emerald deposits of Brazil. Ba-Bahia State; GO-Goias State; CE-Ceara State From Giuliana et al., (1990)

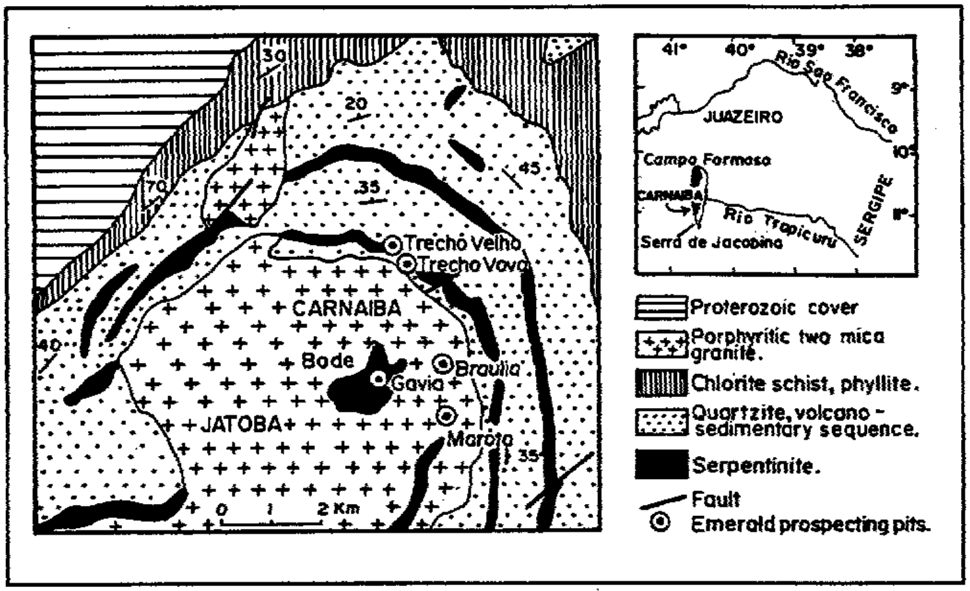


Figure 4.17 Geology of the Carnaiba emerald deposit From Kazmi and Snee (1989)

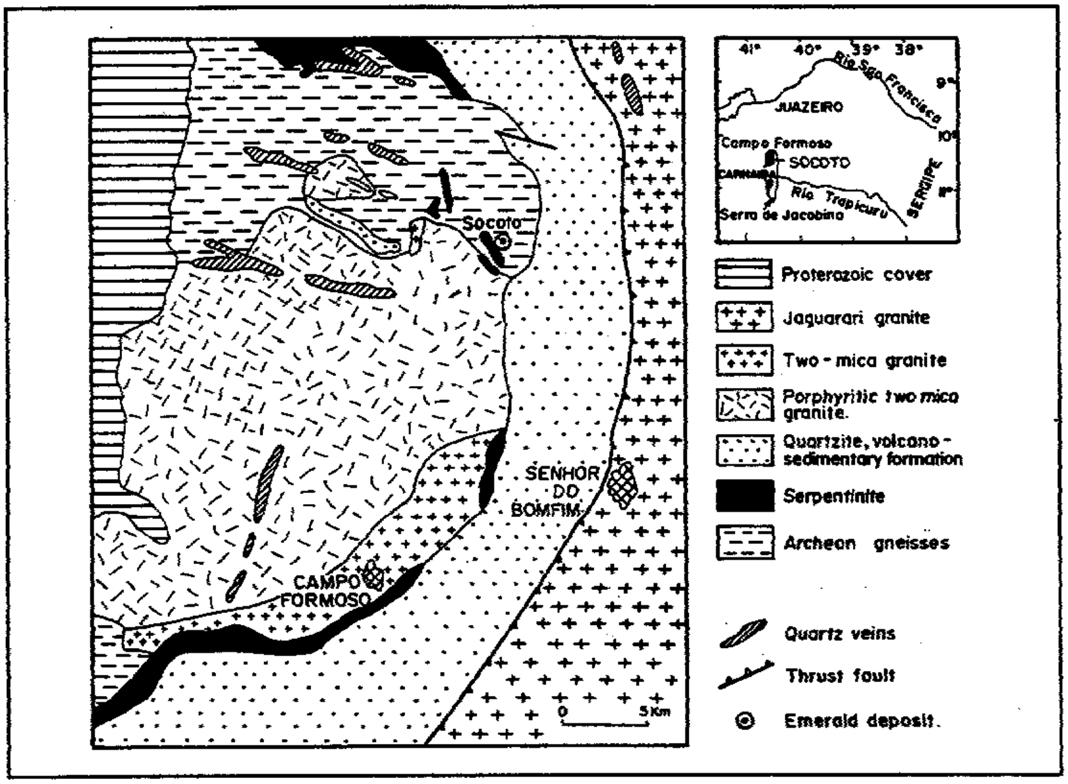


Figure 4.18 Geology of the Socoto emerald deposit From Kazmi and Snee (1989)

geology of the Carnaiba and Socoto emerald deposits are shown in Figures 4.17 and 4.18.

Giuliana et al., (1990) were able to divide the Brazilian deposits into three types:

Type I
Mafic-ultramafic host rocks, granitic proximal intrusives 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 Nb-Ta-cassiterite-bearing pegmatites of uncertain origin.

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 deposit, Mo and, to a lesser degree, W are good pathfinders
- 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, Sn, and Nb-Ta

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. To form emeralds, acid Be-bearing fluids also enriched in F, Cl, K and Al must penetrate mafic or ultramafic rocks rich in Cr. 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)

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 center in the mid 1880's), whereas the ruby deposits described in the previous chapter occur to the southwest. During the Late Paleozoic, Europe and Asia collided, resulting in the formation of the Ural Mountains chain which divides Europe from Asia. 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 one m in thickness and 25-50 m long and consist of 95-99% phlogopite. Emeralds are found 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 sized emerald crystals. Laskovenkov and Zhernakov (1995) report that an 11,000 carat crystal of grass green color was found in 1831 and, more recently, a 4,400 ct stone was faceted from a rough Uralian emerald in 1990.

Egypt

The famous "Cleopatra's Emerald Mine" is hosted in a district of Late Proterozoic metasediments, ophiolitic melange and associated intrusions (Figure 4.19). Younger tin and beryllium bearing granites intrude the package. Biotite schists associated with either quartz,

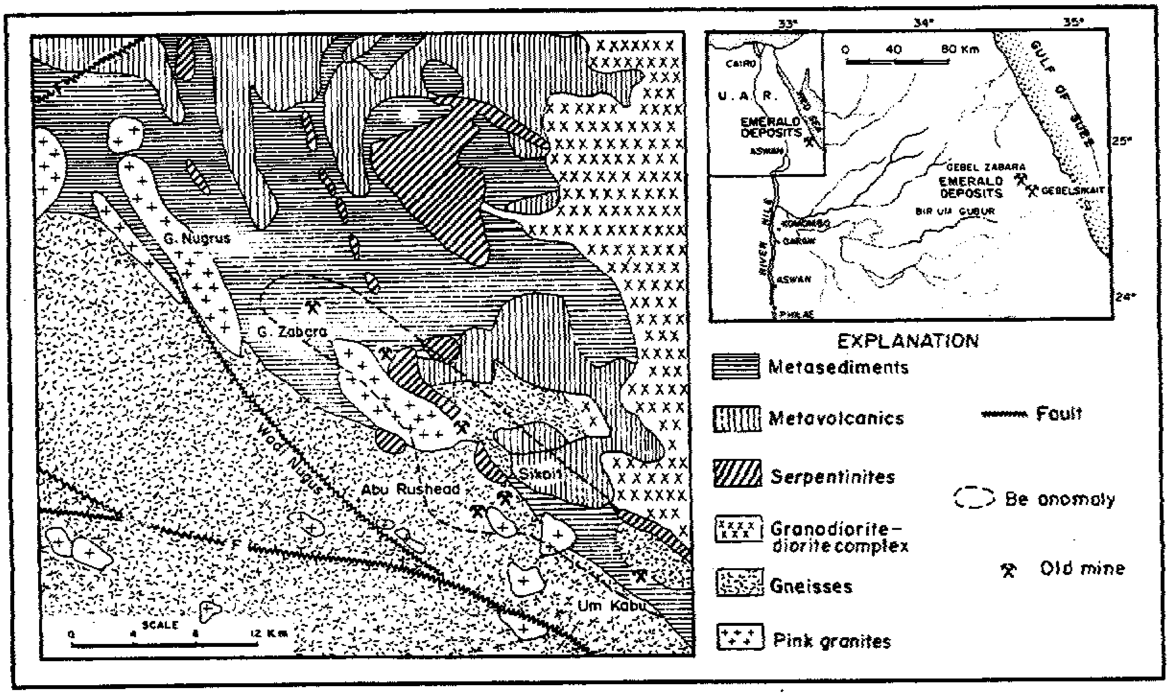


Figure 4.19 Geology of the United Arab Republic emerald deposits From Kazmi and Snee (1989)

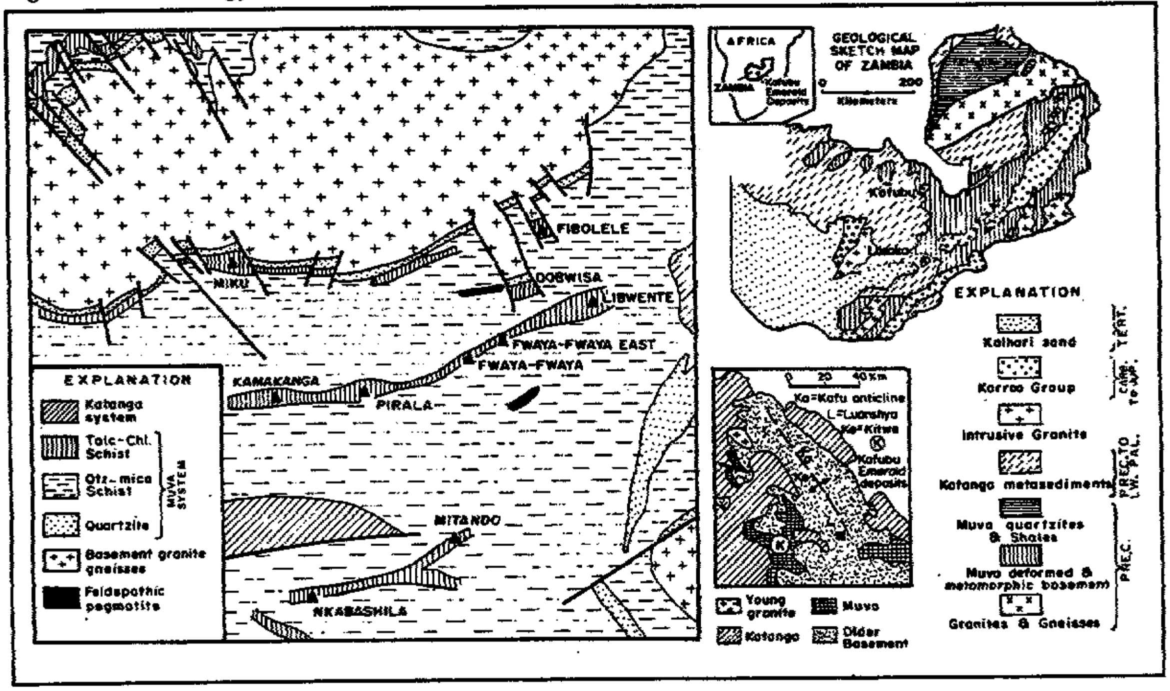


Figure 4.20 Geology of emerald deposit in Zambia From Kazmi and Snee (1989)

actinolite or tourmaline contain emeralds or intruded 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 melange unit and Sn, Nb, Be, W, Mo, Bi, B and F mineralization. A regional geochemical survey showed a Be-rich zone parallel to one of the deep-seated faults. The ultramafic melange serpentinites are strung out bead fashion along this beryllium enriched zone, which contains tin bearing granites and emeralds.

Zambia

Emeralds are found in a westerly striking talc-chlorite amphibolite and magnetite schist, which was derived from an ultrabasic igneous rock (Figure 4.20). The emeralds are hosted within smaller, dark colored bands and lenses consisting of biotite and phlogopite. The petrogenesis of the emeralds is given by Sliwa and Nguluwe (1984). Tourmaline-bearing pegmatites provided beryllium and ultramafic units provided chromium. During pegmatite intrusion, the wall rocks were altered to phlogopite-biotite schist and emeralds formed in response to pneumatolytic alteration.

Zimbabwe

The emerald deposits in Zimbabwe occur in some of the oldest rocks on earth. Associated pegmatite dykes have been dated at 2,650 million years old (Kazmi and Snee, 1989). The pegmatites intrude metamorphosed ultramafic rocks on the margins of greenstone belts. The mineralogy of the deposits is similar to that noted in the Urals, Brazil, and the Franqueira deposit in Spain.

South Africa

Emeralds occur in 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. Emerald occurs in biotite schist and sugary vein quartz, and is associated with fluorapatite, aquamarine, beryl, biotite, chalcopyrite, clinochlore, almandine-molybdenite, muscovite-sericite, nontronite, plagioclase, pyrite, quartz, scapolite and tourmaline.

Australia

The following description is taken from Kazmi and Snee (1989). Australian occurrences of emerald are associated with pegmatites intruding Archean greenstone terrains. At Poona, the pegmatite dykes contain biotite, muscovite, lepidolite, zinnwaldite, topaz, tourmaline, fluorite, cassiterite, manganocolumbite and monazite. The pegmatites intruded greenstones metamorphosed to amphibolites and hornblende-chlorite schist.

At Menzies, the emeralds are found in pegmatite dykes which have intruded metamorphosed ultramafic rocks. The chlorite schist is altered by contact metamorphism and pegmatitic hydrothermal processes to crenulated tremolite/actinolite-phlogopite/biotite schist with bladed spinifex texture.

Lake Manyara, Tanzania

The emerald and alexandrite deposit in Tanzania at Lake Manyara, is described by Gübelin (1974) and Keller (1992). The deposit was discovered in 1970 by a prospector who had been shown some emerald crystals. Over a million carats of emerald were mined in the first two years of production, then alexandrite (a variety of chrysoberyl, see Chapter 6) crystals were discovered when laborers were digging a hole for a swimming pool at the mine. The emeralds occur as aggregates with alexandrite in the contact zone between biotite-actinolite schists and pegmatites.

India

Emeralds are found in talc, biotite and actinolite schists which have been intruded by tourmaline granite and associated pegmatite veins. The minerals associated with emerald are beryl, tourmaline, apatite, quartz, feldspar, muscovite and biotite. The host rocks contain kaolin, sericite, chlorite, albite, tourmaline, vermiculite, calcite, talc, serpentinite, tremolite and anthophyllite.

Mozambique

Emeralds are found in the portion of the Proterozoic Mozambique orogenic belt which passes through

Mozambique. Emeralds occur at the contact between beryl-rich granitic pegmatites and amphibolite and talc-actinolite schist. The emeralds are associated with biotite, plagioclase and quartz. The pegmatites which contain emerald also host scheelite, apatite, stilbite, molybdenite, pyrite, fluorite and calcite.

Austria

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. Some authors believe that it formed as a result of regional metamorphism (Grundmann and Morteani, 1989).

North America

Although there are many occurrences of green opaque beryl and some gem quality aquamarine and morganite, gem quality emeralds have been found only in North Carolina, U.S.A. (Figure 4.21). The emeralds occur where older Precambrian mafic/ultramafic chromium-bearing schists have been intruded by younger granites.

There are many other schist-hosted emerald deposits. Figure 4.22 summarizes some of the geological and geochemical requirements (Figure 4.22).

Exploration Criteria for Emerald Deposits

Emeralds Associated with Bituminous sedimentary rocks (Colombian 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 (100's of meters) are:
  Enriched in Na, Mg, Mn, S
  Depleted in K, Al, Si, Li, Mo, Ba, Zn, Cr and V
- A host rock Na/K ratio of less than 1.1 was used in Colombia to separate altered blocks from unaltered blocks.

Regional Stream Sediment Geochemistry

- Na is the best single geochemical pathfinder for determining mineralized from unmineralized areas.
- Li, Mo and Pb may also useful to determine if an area has undergone leaching.

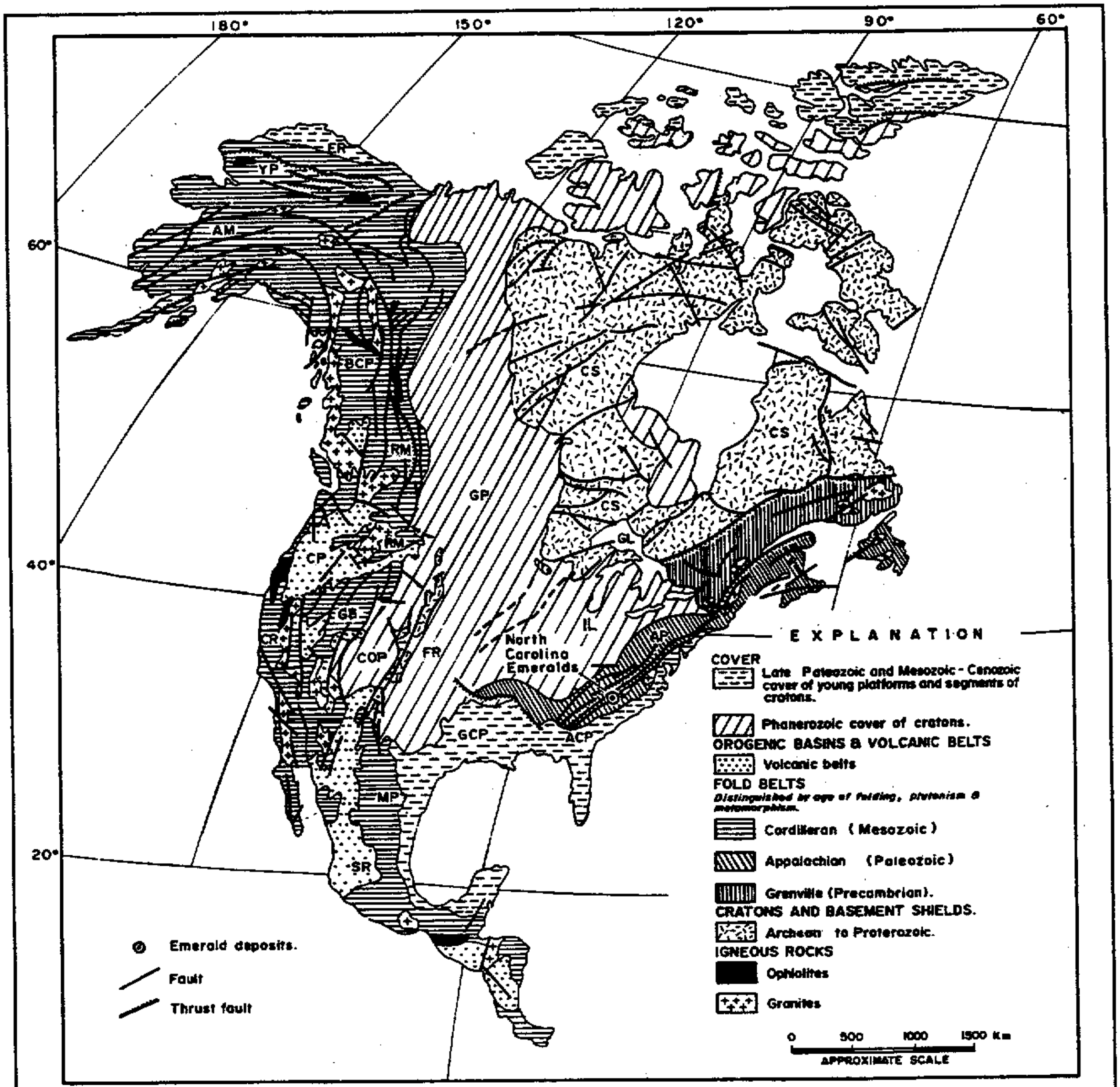
Structure

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

Ground Prospecting

In general, one should look for areas with calcite-albite-dolomite vein networks, fibrous calcite, bands of hematite, folded and brecciated sediments, 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 H_2S 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



Geological sketch map of North America showing location of emerald deposits (geology from Leonov and Khain, 1984). ACP-Atlantic Coastal Plain; AM-Alaska Mts.; AP-Appalachian Range; BCP-British Colombia Plateau; COP-Colorado Plateau; CP-Colombia Plateau; CR-Coastal Ranges; CS-Canadian Shield; ER-Endicott Range; FR-Front Ranges; GB-Great Basins; GCP-Gulf Coastal Plain; GL-Great Lakes; GP-Great Plain (Platform); IL-Interior Lowlands (Platform); MP-Mexican Plateau; RM-Rocky Mts.; SR-Sierra Madre; YP-Yukon Plateau.

Figure 4.21 Geology of North America showing emerald occurrence From Kazmi and Snee (1989)

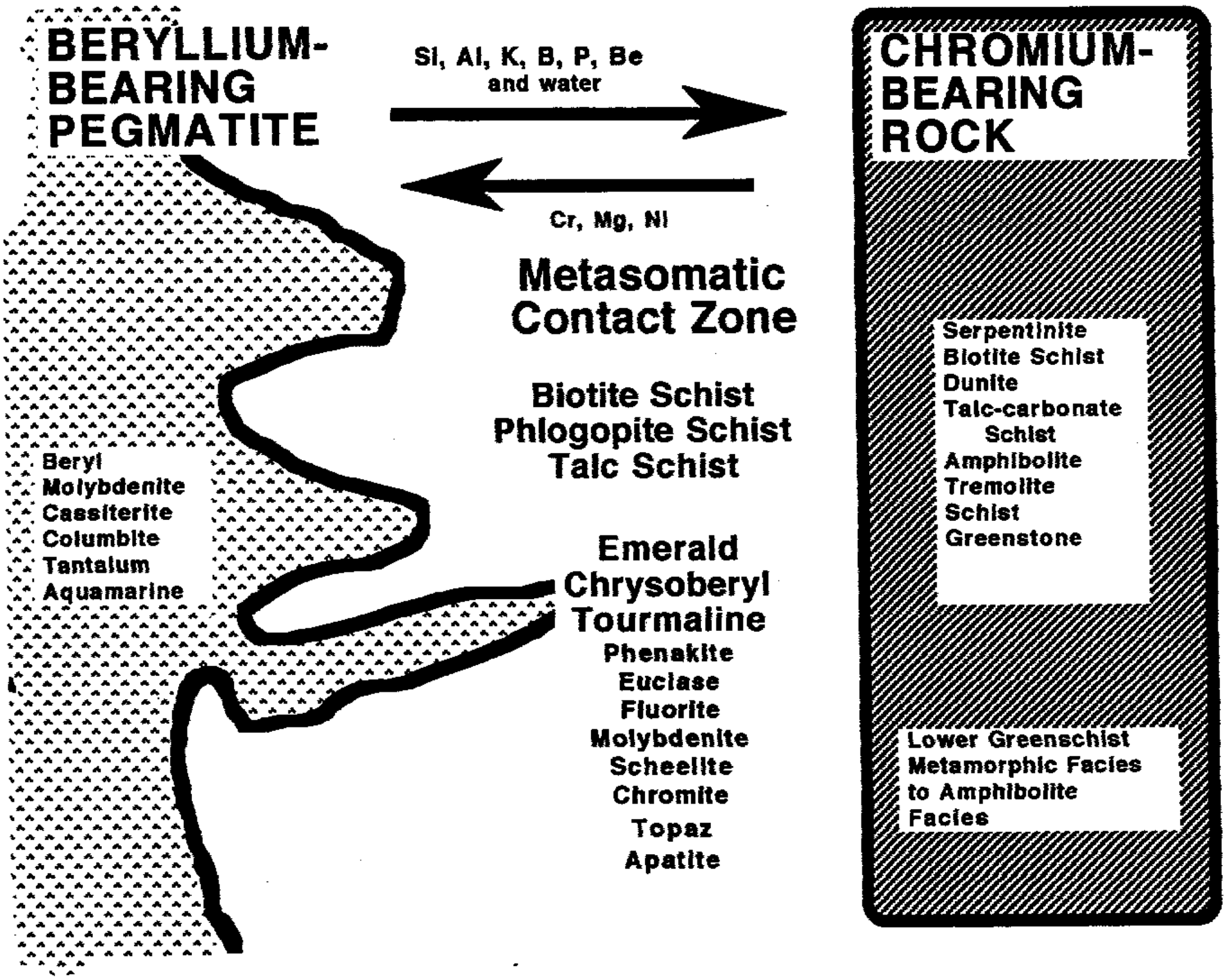


Figure 4.22 Schematic sketch of emerald precipitation model After Martin-Izard et al., (1995)

mineralization. The mineral parisite, which forms fudge colored stubby hexagonal crystals is another good indicator mineral.

As inspiration, it should be noted a single pocket of emeralds discovered in a calcite vein at Chivor had an estimated value of $6,000,000 U.S. (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 schists, serpentinites, peridotite, dunites, biotite schist, biotite-actinolite schists, phlogopite schists, tourmaline-biotite schists, talc schists or other metamorphosed ultramafic rocks

- associated pegmatites, especially beryl-bearing pegmatites, tourmaline-bearing pegmatites or anatectic granitic intrusion.

- pay close attention to the metasomatic contact zones between the pegmatites and meta-ultramafic. This is usually a zone of biotite-phlogopite schist.

- biotite schists, phlogopite schists, biotite-talc-carbonate schists and carbonate-biotite schists <u>without</u> intruded pegmatite veins. Hydrothermal fluids may carry Be from pegmatitic source rocks through fault conduits and channelways.

Structure

- areas of intensive tectonism, fracturing and folding are preferential hosts for emerald mineralization. This makes it easier for Be-bearing fluids to permeate Cr-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 Cr content.

- zones of beryllium enrichment coincident with biotite schists or other metamorphosed ultramafic rock.

- zones of beryllium enrichment coincident with Cr, F, Sn, Mo, W anomalies especially in areas containing meta-ultramafic rocks.

- areas hosting rare-element pegmatites intruding biotite schists or ultramafic rock

It would be interesting, to study, on a global scale the geochemical similarities between the Be source rocks and the Cr source rocks to determine:

1. Minimum Cr content needed to form emeralds
2. Minimum Be content needed to form emeralds
3. Geochemical signatures of these deposits from stream sediment studies draining the emerald-mineralized zones.
4. Amount of deformation needed before Be-fluid permeability is effective.

Pathfinder Minerals

- thin to thick selvages of biotite-phlogopite

- molybdenite, alexandrite, scheelite, apatite, chrysoberyl, tourmaline, phenakite, pyrite in the metasomatic contact zone

Geophysics

- zones of Be enrichment coincident with magnetic highs on aeromagnetic maps to locate meta-ultramafic rocks covered by overburden. This technique is used successfully in Africa.

CHAPTER FIVE

TSAVORITE GARNET AND TANZANITE

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 with the last 25 years.

"Tsavorite 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 the fifth largest selling gemstone in the United States, behind diamond, emerald, ruby and sapphire.

The proper mineralogical name for tsavorite garnet (the "t" is silent) is vanadium grossular garnet; however, ever since its discovery in the 1970's it is marketed under the more glamorous and exotic name of Tsavorite in honor of Tsavo National Park in Kenya. To date, the world's supply of tsavorite garnet has come from a handful of small mines on either side of the eastern border separating Kenya and Tanzania. 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 tsavorite mines (Figures 3.10, 3.11). Keller (1992) reports that 1,500 kg of gem garnet, mostly tsavorite, has been produced from Kenya between 1984 and 1988.

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 south-southwest of the Kilimanjaro International Airport (Figure 3.10). Tsavorite is also produced at this mine. Tanzanite rough is auctioned in the town of Arusha whose name may sound familiar for a sad reason; it is where the tribunals for the Rwandan genocide are taking place in 1996.

The Discovery of Tsavorite Garnet

It has been known for many years that garnets occur in all colors except blue. Besides the familiar red shades, there are also purple, pink, orange, orange-brown, yellow, yellow-green, and colorless garnets. Placer miners are familiar with garnets, since, as a heavy mineral they tend to show up in placer gold concentrate. Exploration geologists use the presence of certain types of pyrope garnets in exploration for diamond-bearing rocks. A yellow-green andradite garnet called demantoid from Russia enjoyed popularity in the early part of the century. Rare Cr-bearing uvarovite garnet that shows a beautiful, vivid emerald green color, 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 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.

This small area in East Africa hosts the only economic tsavorite garnet deposit in the world, although it has been reported as an accessory mineral in gem deposits in Pakistan. 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 1 carat stone, a bargain when one considers an equivalent Colombian emerald would be almost three or four times as much.

The Discovery of Tanzanite

Tanzanite is the popular name given to the gem-quality blue transparent variety of the mineral zoisite ($Ca_2Al_3Si_3O_{12}OH$). Tanzanite is not the only variety of zoisite used as a gemstone. Rare transparent green and transparent yellow zoisite has 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 in the Whitehorse Copper Belt. It is "thulite", a massive pink opaque variety of zoisite colored 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 current mining area is still relatively small, approximately 5 km long x 1 km wide (Barot and Boehm, 1992). Open pits are up to 100 m deep (Keller, 1992); however much of the mining is now taking place underground (Barot and Boehm, 1992). It is interesting to note that 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 color.

Political instability over the last 20 years led to uneven supply of this gemstone, especially when the Tanzanian government took over the mines in the 1980's. They lost control of the tanzanite mining area in the late 1980's 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 1990's tanzanite was gaining popularity as a colored 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 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 1980's. Tanzanite is still gaining recognition and popularity in the United States, but has not made a significant impression in the more conservative Canadian jewellery market. Reports in the latest gem trade magazines show that the price of tanzanite rough has been increasing steadily and that supply is short. Consumers can expect to pay $500 to $1,000 (CAN) for a one carat stone. A larger five carat fine tanzanite gemstone would cost between $1,000 and $2,000 per carat.

Physical and Chemical Properties

The physical and chemical properties of tsavorite garnet and tanzanite are given in Table 3.3.

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 colorless, 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. Translucent to opaque varieties of grossular garnet found in Tanzania ("anyolite") and in the Whitehorse Copper Belt ("thulite") are actually "hydrogrossular," meaning they contain up to 8.5% water. Pale green grossular garnets are named after their resemblance to the gooseberry.

Pure grossular garnet is colorless. 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 color results (Manson and Stockton, 1982). Light green tsavorite crystals contain 0.1% V, and dark green tsavorite crystals contain up to 1.5% V (Keller, 1992). It is reported that some vivid green grossular garnets, for instance those found at the Jeffrey Mine in Quebec, are colored mainly by Cr_2O_3 (Wright and Grice, 1982).

Well-crystallized tsavorite 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 tsavorite crystals of three carats or more are very rare. Spectacular well-formed tsavorite 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).

Well formed 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 color of tanzanite. It substitutes for aluminum in the zoisite crystal structure. There are minor amounts of chromium present.

Tanzanite crystals can grow very large. A 2,500 carat rough crystal was found in the late 1960's (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 grayish brown, grayish purple, brownish purple, bluish and greenish brown. After heat-treatment for two hours at 320° C or higher, the undesirable yellow-green-brown color is driven off, leaving a pretty violet-blue color.

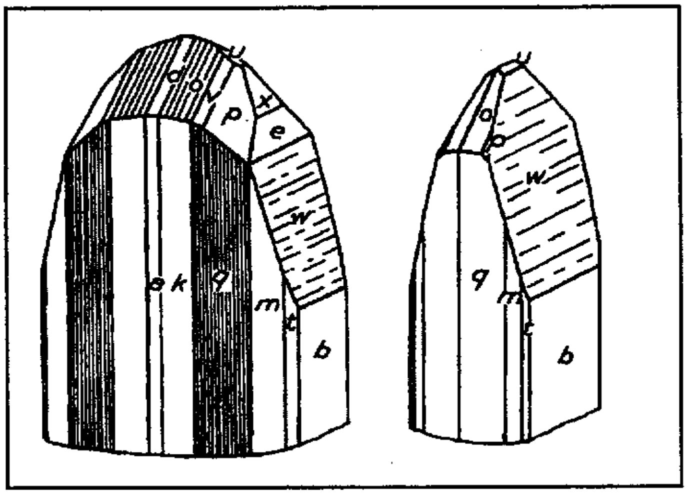


Figure 5.1 Tanzanite crystals
From Hurlburt (1969)

Transparent green zoisite has been discovered recently in the tanzanite mines at Merelani, Tanzania. Its color is caused by chromium and minor vanadium (Barot and Boehm, 1992), who report that local miners call the stone *Combat*, because it resembles the green of some military uniforms. Barot and Boehm (1992) estimate that 1,000 grams of green tanzanite have entered the global gem market.

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

Field Identification of Tsavorite Garnet and Tanzanite

Tsavorite Garnet

Usually tsavorite does not occur in 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 color 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 grayish 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 color change, depending on which direction the stone is viewed from. This is because tanzanite is so strongly pleochroic. A piece of transparent quartz held up to the sun and rotated will not show a color 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 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 3.10, 3.11). The Mozambique Orogenic Belt also hosts many other types of gem deposits, most notably the ruby deposits at Mangari described in Chapter Three. 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.

Tsavorite Garnet

All 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 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 gray and usually 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 (Figure 5.2, Figure 5.3) in one of the mines. 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 favorable 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 eluvial crystals are worked by hand-jigging and sorting. The ore shoots are opened by removing the hangingwall 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.

Genesis of Tsavorite Deposits

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 V content of graphitic gneisses is shown in Table 5.1.

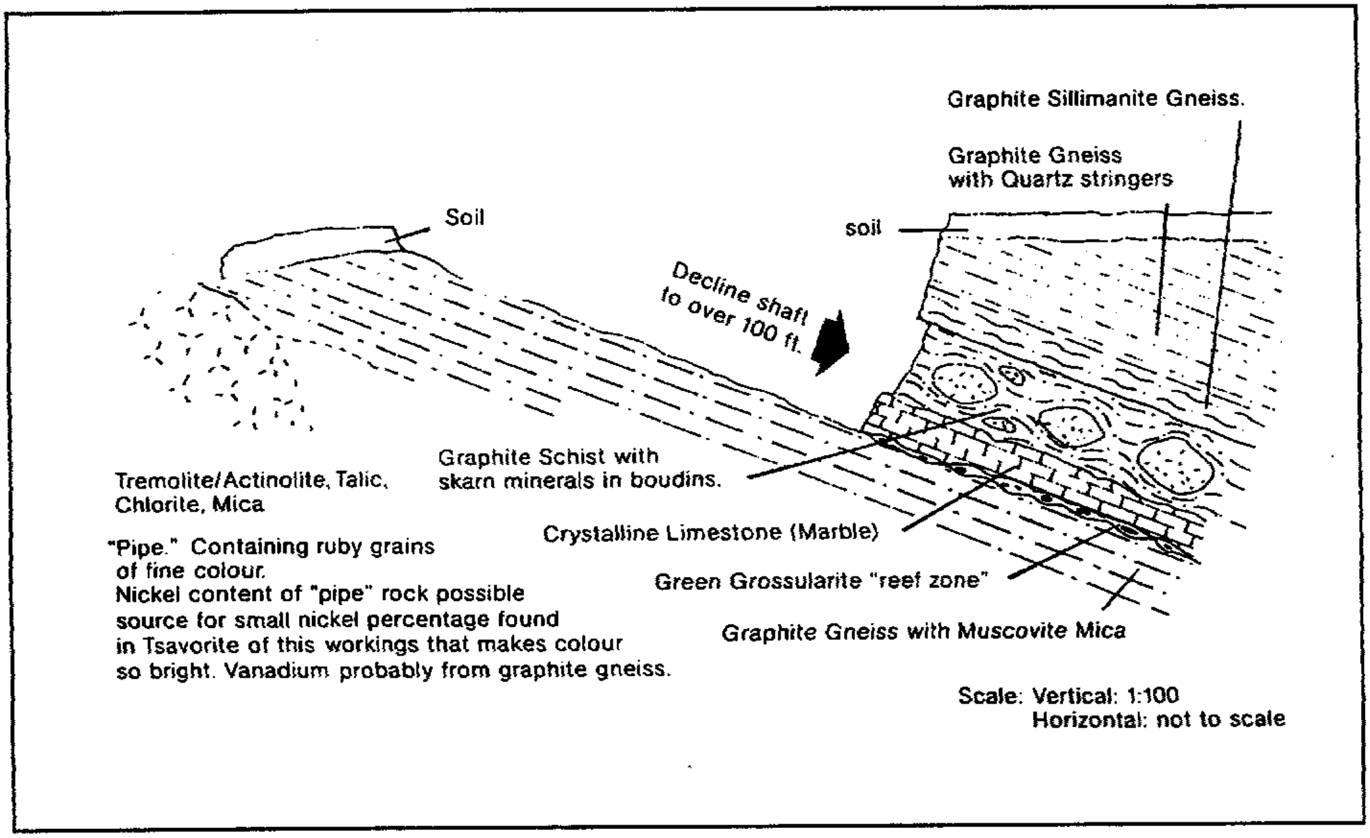
Vanadium is relatively immobile during high grade metamorphism (Key and Hill, 1989), so it would remain in the original host rock to enter new metamorphic assemblages. Marble provided Ca, gneiss provided Al, and Si came from feldspar and quartz. As mentioned above, V was supplied by graphite derived 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 CO_2 in garnet crystallization suggests that granulite facies conditions are 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.

Tanzanite

The world's only tanzanite deposit near Merelani in Tanzania is located 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 (Figure 5.4). 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.

Genesis of Tanzanite Deposits

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 (1990) suggests 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 V, Cr and other chromophores. Tanzanite preferentially precipitated from hot hydrothermal fluids in the fold crests and along fold hinges (Figure 5.4). The distinctive-looking alteration zone represents



"Pipe." Containing ruby grains of fine colour.
Nickel content of "pipe" rock possible source for small nickel percentage found in Tsavorite of this workings that makes colour so bright. Vanadium probably from graphite gneiss.

Scale: Vertical: 1:100
Horizontal: not to scale

Figure 5.2 Geologic cross-section of the GGI (Mindi South) Mine, Kenya From Bridges (1982)

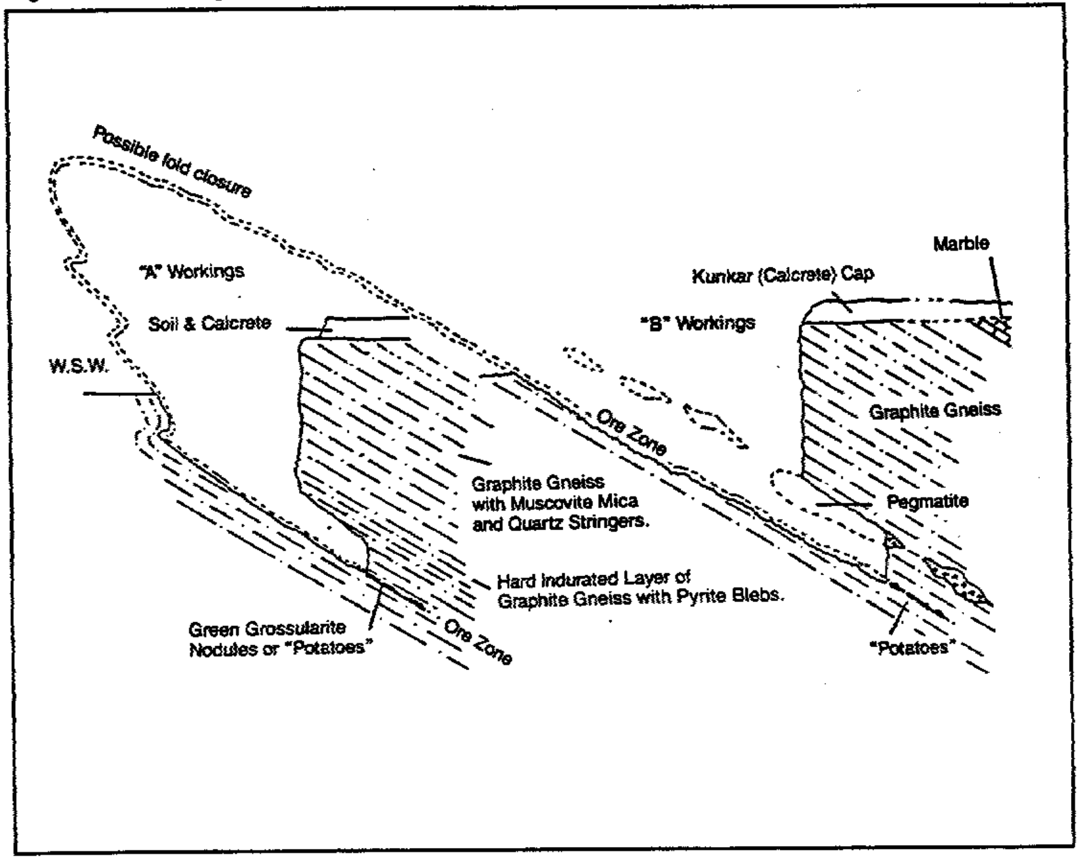


Figure 5.3
Section of G.G. 3B opencaste and underground workings.
Taita/Taveta District, "3B" workings
From Bridges (1982)

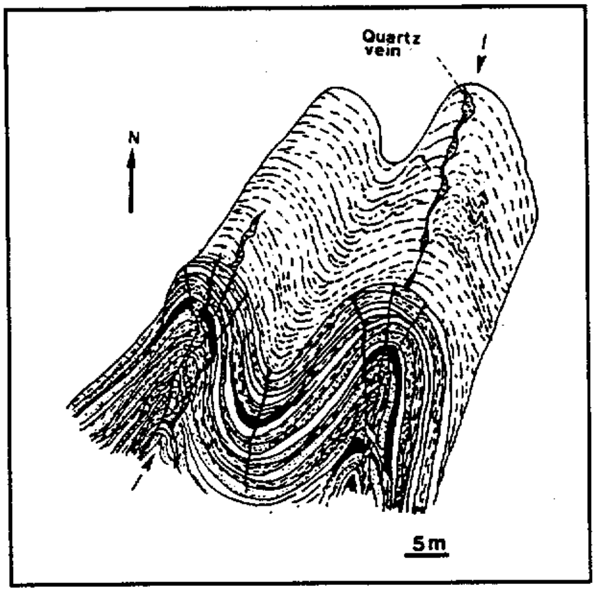


Figure 5.4 Occurrence of tanzanite veins
From Malisa (1990)

Locality	*V*	*Cr*	*TiO_2*
Kenya	(ppm)	(ppm)	(wt %)
Lualenyi	1259	732	0.78
Ol Doinyo Ng'iro – low grade	748	284	1.41
Ol 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

X R F analysis by David Bland as part of the BGS study of graphite resources of East Africa. Each analysis is of a single rock sample: 4 gms of powdered rock are mixed with 1 gm of elvacite binder and pressed into a disc. Note also that Sarbas *et al.*, (1984) record 1157 ppm V and 329 ppm Cr from graphitic schists from Lualenyi.

Table 5.1 V, Cr and TiO2 contents of graphitic gneisses from the Mozambique Orogenic Belt of East Africa
From
Key and Ochieng (1989)

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, according to the reaction:

grossular + 5 anorthite + $2H_2O$ - > 2 zoisite + quartz

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 Hills 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 Cr-bearing green zoisite crystals formed under the same geological conditions as the V-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:

1. 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).

2. Metamorphic Grade

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

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.

3. 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 V for Canadian shield rocks. Vanadium is the coloring 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.

4. Structure

Mineralization is concentrate 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.

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

CHAPTER SIX

CHRYSOBERYL

Chrysoberyl is a greenish yellow transparent gemstone of great hardness and durability. It is especially coveted by Brazilian people. Chrysoberyl was named after the Greek world "krisos" for golden and "beryllos" for beryl. Two well-known rare and very expensive varieties of chrysoberyl; alexandrite and cat's eye, display unusual optical effects.

In 1830, a color-change chrysoberyl associated with emerald and phenakite was discovered in the Ural Mountains of Russia and duly named after the heir-apparent to the Russian throne, Alexander II. Red and green, the two colors of the new gemstone, were the colors of the Russian Imperial Guard. Alexandrite is a transparent gem which shows a mysterious change of color effect. The finest examples of this exotic gem are emerald-green in daylight and raspberry red in incandescent light. Cat's eye, the other well-known variety of chrysoberyl is considered to be the most beautiful of all gemstones which show a "cat's eye" effect. Chrysoberyl is an extremely hard and durable gemstone, so it takes an excellent polish. The silvery color of the eye paired with the honey-color of the stone is a striking combination. Cat's-eye chrysoberyl, also known as cymophane (from Greek meaning "wave-like") is popular with Japanese men who like to display this gem in rings, cuff-links and tie-tacks.

Alexandrites and cat's-eyes are two of the most expensive gemstones in the world. A fine one carat alexandrite from Brazil or Russia will cost from $3,000 to $10,000. 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.

The author has noticed, partly due to the stone being featured on home-shopping TV networks, a profusion of synthetic alexandrite, or synthetic color-change corundum in jewellery, which is sometimes misrepresented or misinterpreted to be natural alexandrite.

Chrysoberyl and its varieties are not usually subject to treatment like oiling, heat-treating, dying or other enhancement before entering the global gem market.

Physical and Chemical Properties

The physical and chemical characteristics of chrysoberyl are given in Table 3.3.

Chrysoberyl, an orthorhombic beryllium oxide mineral is normally yellow, greenish yellow or brownish yellow. Alexandrite is the chromium-bearing variety of chrysoberyl. It is transparent green in daylight and red under incandescent light. Cat's-Eye is the variety of chrysoberyl which shows a sharp line on a honey golden-brown background.

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).

The Color-Change in Alexandrite

The remarkable color-change effect in alexandrite is caused by trace amounts of Cr replacing Al 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 color change.

Cat's-Eye Chrysoberyl

The cat's eye 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 it is cut into a cabochon.

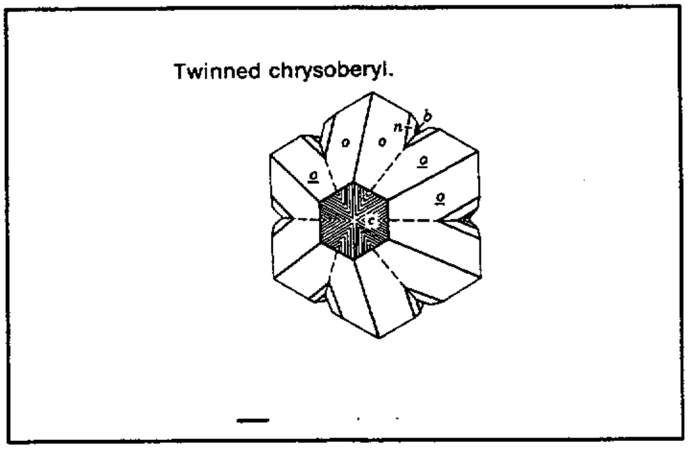


Figure 6.1 Chrysoberyl crystal
From Hurlburt and Klein (1977)

Chrysoberyl is trichroic, meaning that it shows three pleochroic colors. Yellow chrysoberyl shows colorless, pale yellow and lemon yellow pleochroic color. 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

Most gem chrysoberyl is generally found as waterworn crystals. It is an extremely hard and resistant mineral. Chrysoberyl which will show a cat's eye has a silky lustre. The "V-shape" characteristic of chrysoberyl twins is diagnostic, as is the "trilling" twin form.

Jacobson (1982) notes that chrysoberyl may often be unrecognized especially in pegmatites.

Geology of Chrysoberyl Deposits

Chrysoberyl is a rare mineral found in granitic rocks, pegmatites, and mica schists. Research on physio-chemical controls of chrysoberyl, alexandrite and cat's eye mineralization is scarce. Soman and Nair (1985) and Soman et al., (1984) 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 Be and F 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). Martin-Izard, et al., (1995) studied an occurrence of alexandrite, emerald and phenakite associated with metasomatism at a granitic pegmatite-dunite contact zone in Spain.

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.

Deposits of chrysoberyl, alexandrite and cat's-eye can be divided into three broad types:

1. Metasomatic chrysoberyl associated with pegmatites intruding ultramafic rocks.

2. Metasomatic chrysoberyl associated with pegmatites intruding aluminum rich rocks.

3. Chrysoberyl as a primary mineral of rare-element pegmatites.

Chrysoberyl associated with pegmatites intruding 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. These deposits are described in Chapter 4. The schematic model for emerald mineralization shown in Figure 4.20 also applies to chrysoberyl.

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 deposit was discovered during road construction in 1971 when a local school teacher noted emerald crystals. 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 (Figure 4.20). The Be content in the pegmatite is 18 ppm (Martin-Izard et al., 1995; Table 6.1). The dunite is composed mostly of olivine, some of which is partially serpentinized. Chromite is found disseminated through the dunite. Nickeline, maucherite, pyrrhotite and small quantities of pentlandite, westerveldite, millerite and chalcopyrite fill cavitites 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. The simply-zoned pegmatites with an aplite border contain quartz, albite, muscovite with rare K-feldspar. Apatite, tourmaline and zircon are accessory minerals. Alexandrite, emerald and phenakite occur in the phlogopite schist marking the metasomatic contact zone between the pegmatite and dunite. Accessory minerals are tourmaline, garnet, apatite and zircon.

The genesis of this deposit, as presented by Martin-Izard et al., (1995) resembles that of similar deposits in the Urals, Brazil and Zimbabwe although this interpretation includes fluid inclusion and geochemical data. Dunite and hornblende gabbro derived from obducted ophiolitc complexes are intruded by peraluminous heterogeneous two-mica granites and associated pegmatite bodies. The pegmatite fluids, rich in Be-B-P, intruded the dunite and flooded the dunite with water, Si, Al and K. In the metasomatic zone closest to the dunite, orthoamphibole (anthophyllite) and phlogopite crystallized. Tremolite developed further away from the dunite, incorporating Si and water introduced from the pegmatite. The dunite provided the Mg and Cr 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 phenakite. Precipitation of beryllium minerals took place at about 400° C.

REPRESENTATIVE WHOLE-ROCK COMPOSITIONS, FRANQUEIRA SUITE

ROCKS	Pegmatite	Phlogopitite	Tremolitite	Altered Dunite	Marum* Dunite	Gabbro
wt%						
SiO_2	74.80	44.18	56.87	40.22	39.8	47.26
Al_2O_3	14.40	14.99	4.75	3.07	0.04	21.75
Fe_2O_3	0.54	8.31	4.86	8.48	7.24	12.57
MgO	0.11	18.28	18.38	38.88	48.93	1.14
CaO	0.33	0.04	10.81	3.61	0.05	12.15
Na_2O	5.58	0.28	0.25	1.11	0.00	0.57
K_2O	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	0.08	0.10	0.12	0.11	0.24
P_2O_5	0.12	0.07	0.04	0.06	0.00	0.21
Cr_2O_3	0.00	0.21	0.41	0.36	0.42	0.01
LOI	1.80	1.40	1.10	2.20	2.52	1.90
Total	99.93	99.79	99.88	99.77	100.11	99.86
ppm						
As	5	151	6	1220	no data	10
Ni	10	600	383	1647	2520	12
Cu	2	29	3	4	4	24
Co	5	49	12	60	no data	5
Be	18	9	6	4	no data	20
Li	247	563	173	22	no data	49
Ba	135	1288	161	34	no data	159
Sr	32	41	66	29	0.00	434
La	18	5	13	2	no data	81
Zr	10	21	28	5	no data	386
Y	5	5	5	5	no data	120

Total iron as Fe_2O_3.

*Chemical composition of Dunite from the Marum Ophiolite (in Middlemost 1985) for comparison with Franqueira altered dunite.

Table 6.1 Representative whole-rock compositions From Martin-Izard et al., (1995)

Cassdanne and Roditi (1993) report that chrysoberyl and alexandrite in Brazil are a by-product of mining biotite-schist hosted emerald deposits.

Chrysoberyl associated with pegmatites intruding aluminum-rich rocks

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 sediments or in the contact zone of aluminum rich sedimentary rocks intruded by pegmatites.

In Sri Lanka, Rupasinghe et al., (1984) studied the geochemistry of Be and F in the gem fields and determined that Be-enriched pegmatitic fluids associated with charnockitic magmatism intruded and reacted with Al and Si in the highly aluminous metasedimentary country rocks.

Chrysoberyl in rare-element pegmatites

Cassedanne and Roditi (1993) document chrysoberyl deposits 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. 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. Chrysoberyl bearing pegmatites are found close to the base of the aquamarine-bearing pegmatite zone.

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 1900's. 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 gray or black clay and/or sands of various colors. 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.

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. 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 stones 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 keep news of their find quiet. The first five faceted stones, totalling only 11 ct, sold for $40,000 (U.S.) 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 garimpeiro's 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. 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 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 professional thieves who also invaded the area 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 gemmological community regarding the quality of these alexandrites, and whether they were more outstanding than the best material from the Ural's. The color change of alexandrites from these two deposits is truly outstanding. Under incandescent light the stones are raspberry red and under fluorescent light, the color changes to beautiful blue and blue-green.

Given the situation in the area (members of the International Gemmological 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 Cr-rich rocks.

Exploration Criteria for Chrysoberyl Deposits

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

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

CHAPTER SEVEN

GEM-BEARING PEGMATITES

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 with almost all of the gemstones discussed in this report. Gem tourmaline of all colors, aquamarine, chrysoberyl, kunzite, garnet, topaz and many other gems and rare minerals are found in the fabulous hardrock pegmatite deposits of Minas Gerais (Brazil), California, Pakistan, Madagascar and other places (Table 7.1).

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, under the proper pressure-temperature conditions, spectacular crystals of gigantic proportions. Proctor (1984) gives an account of the discovery and extraction of a 110.5 kg (244 lb) doubly terminated, hexagonal aquamarine crystal, which was so flawless and transparent that one could read through it from end to end. The crystal, which measured 48.5 x 38 cm, was discovered in the 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 meter 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 center 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 (U.S.). It was estimated that the crystal would produce 200,000 ct 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 (U.S.). 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 (U.S.).

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. Topaz rhyolite is discussed in Chapter Eight. 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 minerals such as mica and feldspars.

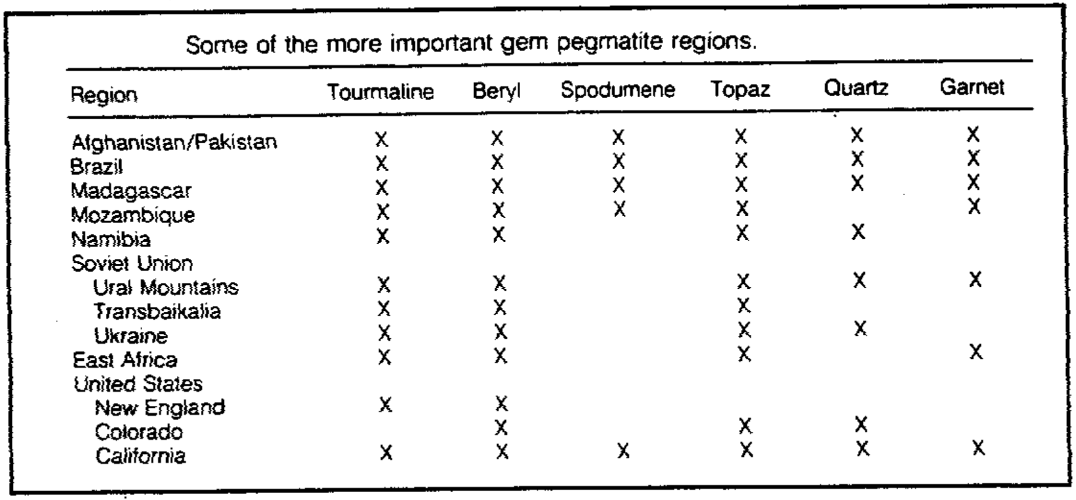
Pegmatite-related Gemstone Deposits

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

1. Gemstones that crystallize within a pegmatite (aquamarine, topaz, tourmaline)

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

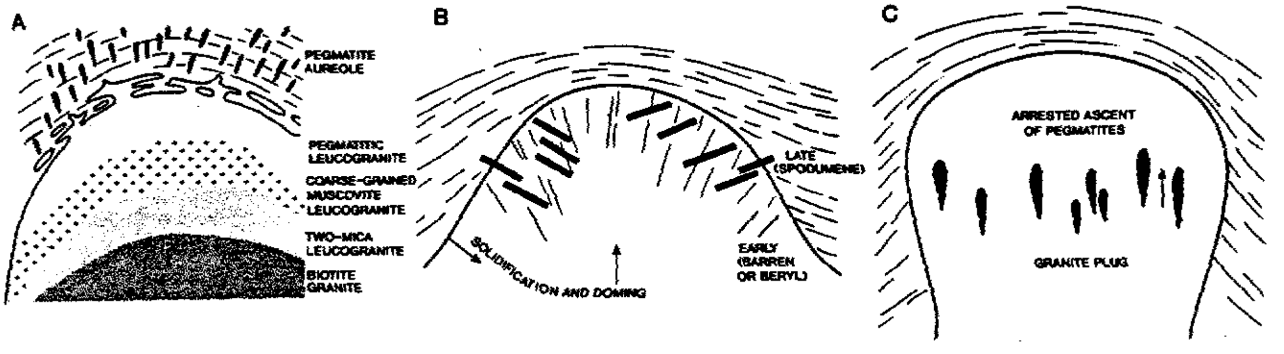
Metasomatism means "change in body or substance." For example, when a granitic body intrudes limestone or marble, calc-silicate minerals form a "skarn" along the contact zone. When carbonatites or silica-undersaturated magmas intrude limestones a "fenite" composed largely of sodic clinopyroxene and amphibole forms along the contact zone. When the intruding body



Some of the more important gem pegmatite regions.

Region	Tourmaline	Beryl	Spodumene	Topaz	Quartz	Garnet
Afghanistan/Pakistan	X	X	X	X	X	X
Brazil	X	X	X	X	X	X
Madagascar	X	X	X	X	X	X
Mozambique	X	X	X	X		X
Namibia	X	X		X	X	
Soviet Union						
Ural Mountains	X	X		X	X	X
Transbaikalia	X	X		X		
Ukraine	X	X		X	X	
East Africa	X	X		X		X
United States						
New England	X	X				
Colorado		X		X	X	
California	X	X	X	X	X	X

Table 7.1 Some of the more important gem pegmatite regions From Shigley and Kampf (1984)



Schematic representation of granite-pegmatite relationships. (A) Zoned outward-fractionated fertile granite with an aureole of exterior LCT pegmatites, typical of many fields of Kenoran and Hudsonian age (after Černý and Meintzer, 1988). (B) Interior to marginal LCT pegmatites in an inward-fractionated parent granite, located in fracture systems generated by upwarping of solidified upper crust of the intrusion (modified from Kuznetsov, 1977). (C) Turnip-shaped NYF pegmatites trapped during ascent through the parent granitoid mush

Figure 7.1 Relationship between granite and pegmatite From Cerny (1991b)

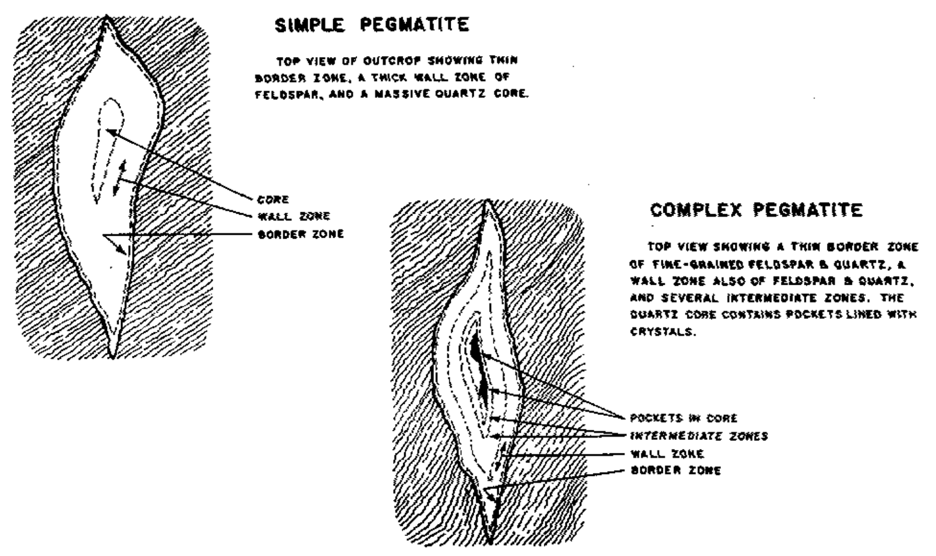


Figure 7.2
Simple pegmatite and complex pegmatite
From Sinkankas (1970)

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 Cr-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 Cr-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 Be, Bo, Li, Mn, Ph and F can combine with available Si, Al and O 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. Cerny (1991a) lists Li, Rb, Cs, Be, Ga, Sc, Y, REE (rare earth elements) Sn, Nb, Ta, U, Th, Zr and Hf as examples of rare-elements mined from pegmatites. A brief listing of the uses of rare-elements mined from pegmatites is as follows (from Cerny, 1991a):

Li	- used in storage batteries, ceramic ware and smelting of aluminum ores
Be	- beryllium alloys are used in aircraft, satellite and space-vehicle frames, Be metal is used in heat shields, rocket motors, aircraft and space-shuttle brake discs, inertial navigation systems and X-ray windows
Ga	- light emitting diodes, photodiodes, laser diodes and solar cells, fibre optics, computers
Ta	- computers, capacitors of solid-state circuits, chemicals, prosthetic devices

Downing (1993) provides interesting summaries of the uses of several minerals and metals associated with rare element pegmatites.

There is more information on exploration for rare-element pegmatites than for any other type of gemstone-bearing deposit (except, perhaps topaz rhyolites). Since gemstone-bearing pegmatites are a subclass of the rare-element group of pegmatites, 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 Cerny (1991 a,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 Cerny (1982).

Definition of Pegmatite

The term pegmatite, first used in the early 1800's, 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. As Keller (1990) mentions, these may have originally been granitic pegmatites that interacted with basic country rocks and were "desilicated".

Pegmatites form during the final stages of magmatic intrusion. They occur as swarms of dykes, veins or flat lenses within or at the margins of batholiths, stocks or other granitic intrusions.

Pegmatites can crystallize at the same time as the host magma; these are called syngenetic pegmatites. Syngenetic pegmatites usually form distinct segregations, lenses or veins within the granitic host. Epigenetic pegmatites form when late stage volatile-rich pegmatitic fluids are injected into a host rock during the late stages of granitic magma emplacement. Figure 7.1 shows the spatial relationship between pegmatites and their parent granite.

An essential process in pegmatite formation is "fractionation", which is the precipitation of successive crystal fractions from a residual magma.

Component/ phase	Granite[a]	Common pegmatite[b]	Gem-bearing pegmatite[c]
Chemistry			
SiO_2	72.34	74.2	70.22
Al_2O_3	14.34	15.0	17.20
$FeO + Fe_2O_3$	1.81	0.6	1.76
TiO_2	0.26	—	—
MnO	0.02	—	0.28
H_2O	0.36	0.6	0.39
MgO	0.37	—	trace
CaO	1.52	0.3	1.36
Na_2O	3.37	4.6	4.45
K_2O	5.47	4.2	2.85
Li_2O	—	—	1.49
P_2O_5	—	0.3	0.07
F	—	0.1	0.11
B_2O_3	—	—	0.18
BeO	—	trace	trace
$Rb_2O + Cs_2O$	—	—	trace
Total	99.86	99.9	100.36
Mineralogy			
Major phases	Microcline Quartz Plagioclase Muscovite Biotite	Microcline Quartz Albite Muscovite	Microcline Quartz Albite Muscovite
Minor phases		Beryl Tourmaline Apatite Garnet	Beryl Tourmaline Apatite 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).*

Table 7.2 Chemical and mineralogical comparison of granite and granitic pegmatites
From Shigley and Kampf (1984)

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 7.2).

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 (Figure 7.2). Zoned pegmatites which contain accessory rare-element minerals are far more interesting in terms of gemstone prospecting (Figure 7.3, Table 7.3). These pegmatites are often called "complex pegmatites" based on their mineralogy and texture.

Pegmatites can also be classified according to the geological environment in which they formed (Table 7.4). In this classification scheme, pegmatites which formed at relatively shallow depths beneath the earth's surface (rare-element and miarolitic in the above classification scheme) have the most potential for hosting gemstones and rare elements. These pegmatites contain rare-elements which do not fit into the quartz, feldspar or mica mineral structures. Pegmatites which form at depths less than 7 km are the best hosts of gemstone mineralization. These types of pegmatites are clearly igneous in origin, whereas deeper, simple pegmatites are thought to form through the partial melting of, or metamorphic recrystallization of, rocks essentially in place.

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

1. Pegmatites formed at great depths are usually found in metamorphosed rocks that form the ancient cores of continents
(U-REE pegmatites near Bancroft, Ont.)

2. Pegmatites formed at deep to intermediate depths are usually found in folded and metamorphosed rocks in mountain belts
(mica pegmatites in Soviet Union, beryl-spodumene pegmatites of Black Hills, South Dakota)

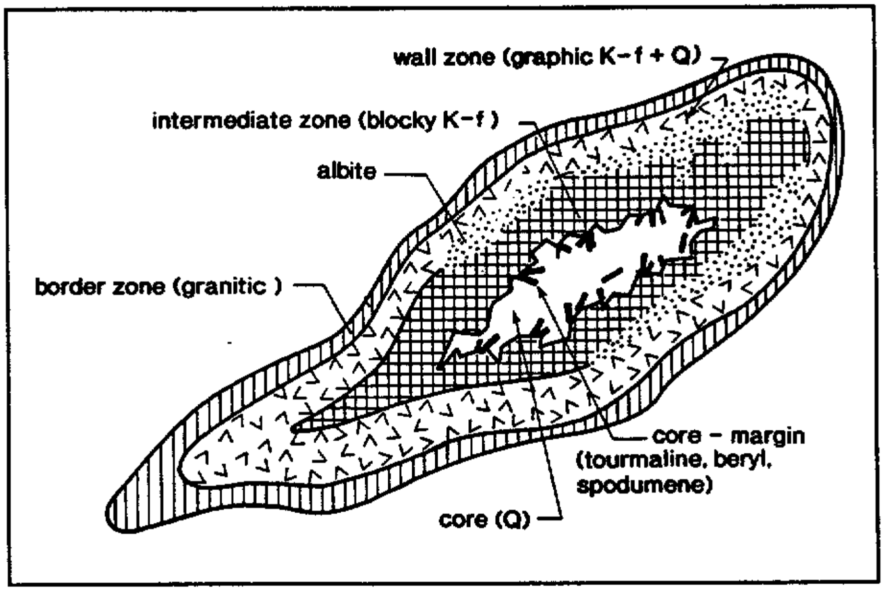


Figure 7.3 Cross-section of complex pegmatite From Cerny (1991a)

Zone	Thickness	Texture	Mineralogy (accessory phases)	Other comments
Border	Usually a few centimeters, but sometimes thicker	Fine-grained	Plagioclase-quartz-muscovite (garnet, tourmaline, other phases)	May or may not have sharp contacts with the surrounding host rocks
Wall	Usually on the order of several meters	Generally coarser than border zone	Plagioclase-microcline-quartz (muscovite, beryl, tourmaline, garnet, other phases)	May not be continuous or of uniform thickness around the entire pegmatite
Intermediate (possibly several zones)	Each zone may reach several meters in thickness depending on the size and shape of the pegmatite	Progressively coarser grain size proceeding inward; some giant crystals; innermost zones may contain some pocket-rich areas	Microcline-quartz-spodumene-amblygonite-muscovite-plagioclase (tourmaline, phosphate minerals, beryl, other phases)	May consist of a number of distinct zones of differing mineralogy; each may or may not completely enclose the central core; intermediate zones contain the giant crystals and comprise the bulk of the pegmatite; unusual minerals often concentrated toward core
Core	Up to several meters in thickness depending on the size and shape of the pegmatite	Variable—may contain both coarse- and fine-grained material; some giant crystals; may include pocket-rich areas	Quartz-spodumene-microcline (tourmaline, lepidolite, beryl, topaz, gem minerals, other phases)	Core zone may be composed of several segments; gem pockets often located on the contact between the core and the enclosing intermediate zones

Table 7.3 Some generalized features of internally zoned granitic pegmatites From Shigley and Kampf (1984)

3. Pegmatites formed at shallow depths are generally associated with large, buried masses of intrusive igneous rocks such as plutons or batholiths that frequently underlie mountainous areas.
(Southern California, Hindu Kush in Afghanistan, Minas Gerais in Brazil)

The important rare-element class can be subdivided further, into three petrogenetic groups (Table 7.5).

Pegmatite Pockets and Cavities

Gemstones in pegmatites are usually found in "pockets" which are irregular openings, usually towards the center of the pegmatite (Figure 7.4, Figure 7.5). In syngenetic pegmatites, the pockets often occur 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 meters across have been reported, most pockets are less than a few centimeters 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 between 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.

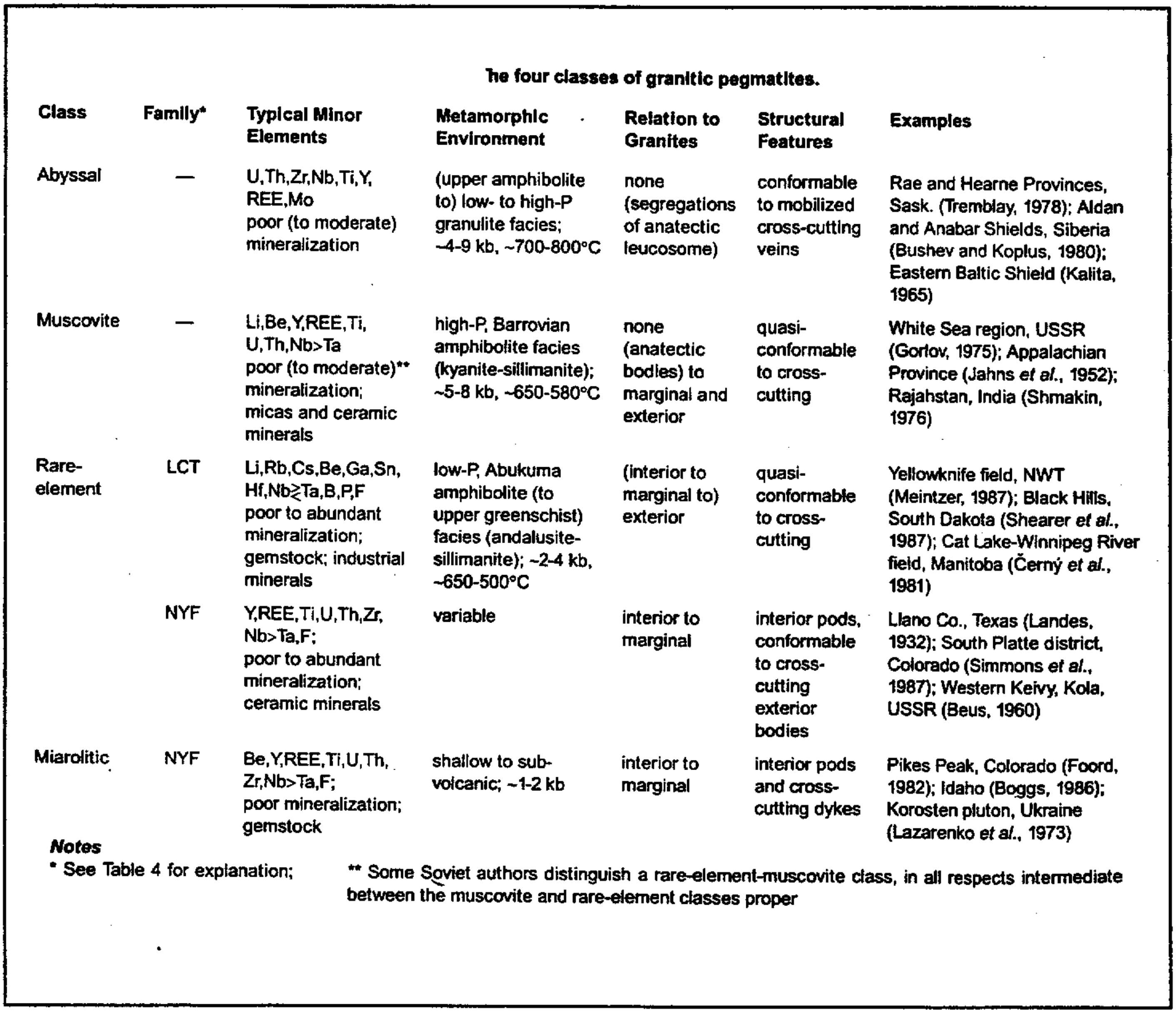
Pegmatite pockets are commonly filled or partially filled with clay minerals that formed after gemstone precipitation.

Pockets termed "miarolitic" 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 largest pegmatite gem pocket ever found, 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 1940's. 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 labor involving expensive blasting, Mr. Barbosa, who had noticed signs of pegmatite pockets (presence of lepidolite, etc.) eventually surrendered title on his Volkswagen to keep going for one more week. During the critical last days, as he was laboriously 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 usual going-ons 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 letting Brazilian Internal Revenue agents view the booty. The precautions worked, and the first crystals were offered for sale, starting at $9 million (U.S.) for the four largest. One of the crystals sold for $1.3 million (U.S.).

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



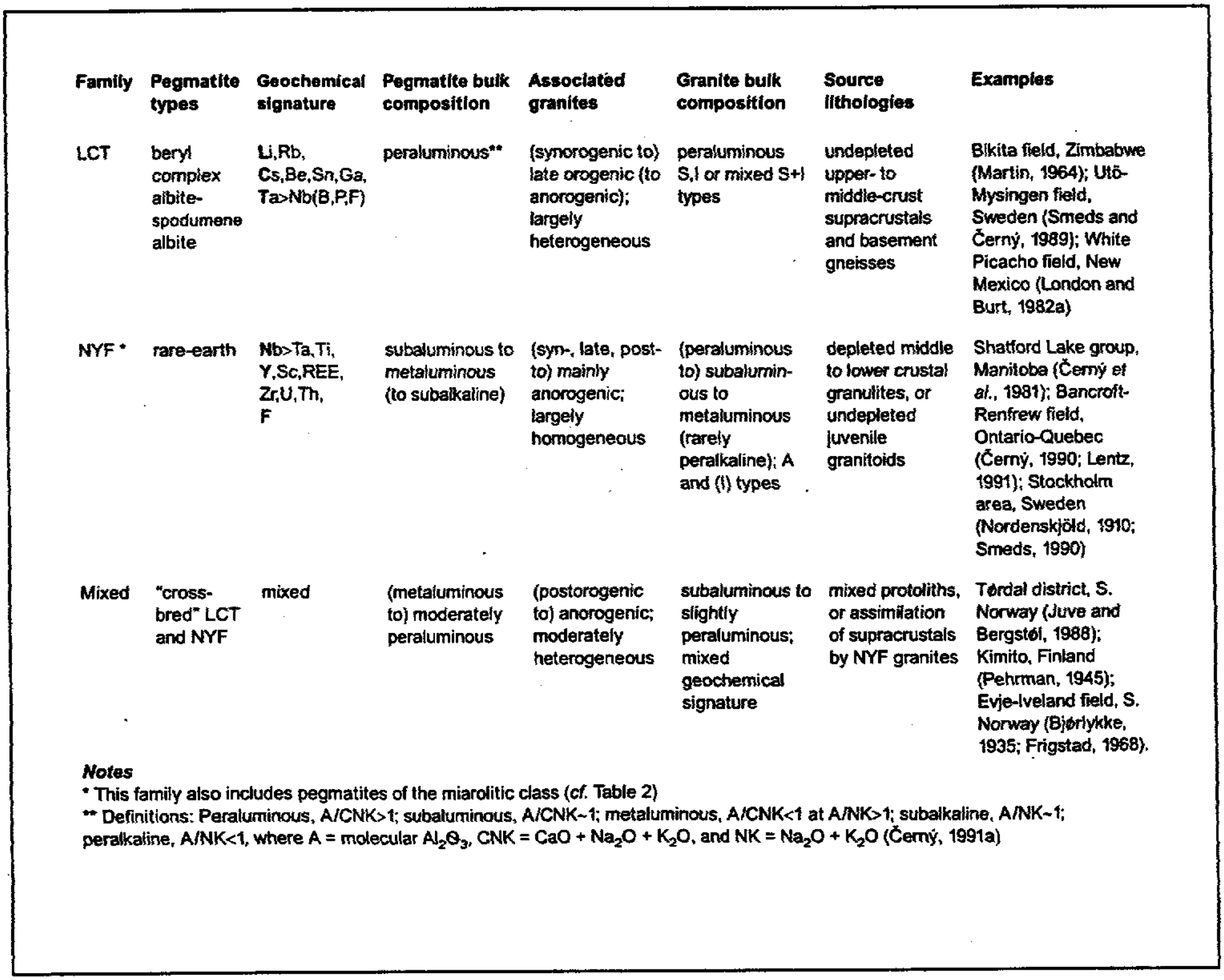
he four classes of granitic pegmatites.

Class	Family*	Typical Minor Elements	Metamorphic Environment	Relation to Granites	Structural Features	Examples
Abyssal	—	U,Th,Zr,Nb,Ti,Y, REE,Mo poor (to moderate) mineralization	(upper amphibolite to) low- to high-P granulite facies; ~4-9 kb, ~700-800°C	none (segregations of anatectic leucosome)	conformable to mobilized cross-cutting veins	Rae and Hearne Provinces, Sask. (Tremblay, 1978); Aldan and Anabar Shields, Siberia (Bushev and Koplus, 1980); Eastern Baltic Shield (Kalita, 1965)
Muscovite	—	Li,Be,Y,REE,Ti, U,Th,Nb>Ta poor (to moderate)** mineralization; micas and ceramic minerals	high-P, Barrovian amphibolite facies (kyanite-sillimanite); ~5-8 kb, ~650-580°C	none (anatectic bodies) to marginal and exterior	quasi-conformable to cross-cutting	White Sea region, USSR (Gorlov, 1975); Appalachian Province (Jahns *et al.*, 1952); Rajahstan, India (Shmakin, 1976)
Rare-element	LCT	Li,Rb,Cs,Be,Ga,Sn, Hf,Nb≳Ta,B,P,F poor to abundant mineralization; gemstock; industrial minerals	low-P, Abukuma amphibolite (to upper greenschist) facies (andalusite-sillimanite); ~2-4 kb, ~650-500°C	(interior to marginal to) exterior	quasi-conformable to cross-cutting	Yellowknife field, NWT (Meintzer, 1987); Black Hills, South Dakota (Shearer *et al.*, 1987); Cat Lake-Winnipeg River field, Manitoba (Černý *et al.*, 1981)
	NYF	Y,REE,Ti,U,Th,Zr, Nb>Ta,F; poor to abundant mineralization; ceramic minerals	variable	interior to marginal	interior pods, conformable to cross-cutting exterior bodies	Llano Co., Texas (Landes, 1932); South Platte district, Colorado (Simmons *et al.*, 1987); Western Keivy, Kola, USSR (Beus, 1960)
Miarolitic	NYF	Be,Y,REE,Ti,U,Th, Zr,Nb>Ta,F; poor mineralization; gemstock	shallow to sub-volcanic; ~1-2 kb	interior to marginal	interior pods and cross-cutting dykes	Pikes Peak, Colorado (Foord, 1982); Idaho (Boggs, 1986); Korosten pluton, Ukraine (Lazarenko *et al.*, 1973)

Notes

* See Table 4 for explanation; ** Some Soviet authors distinguish a rare-element-muscovite class, in all respects intermediate between the muscovite and rare-element classes proper

Table 7.4 The four classes of granitic pegmatites From Cerny (1991a)



Family	Pegmatite types	Geochemical signature	Pegmatite bulk composition	Associated granites	Granite bulk composition	Source lithologies	Examples
LCT	beryl complex albite-spodumene albite	Li,Rb, Cs,Be,Sn,Ga, Ta>Nb(B,P,F)	peraluminous**	(synorogenic to) late orogenic (to anorogenic); largely heterogeneous	peraluminous S,I or mixed S+I types	undepleted upper- to middle-crust supracrustals and basement gneisses	Bikita field, Zimbabwe (Martin, 1964); Utö-Mysingen field, Sweden (Smeds and Černý, 1989); White Picacho field, New Mexico (London and Burt, 1982a)
NYF *	rare-earth	Nb>Ta,Ti, Y,Sc,REE, Zr,U,Th, F	subaluminous to *metaluminous* (to subalkaline)	(syn-, late, post-to) *mainly* anorogenic; largely homogeneous	(peraluminous to) *subaluminous to* metaluminous (rarely peralkaline); A and (I) types	depleted middle to lower crustal granulites, or undepleted juvenile granitoids	Shatford Lake group, Manitoba (Černý *et al.*, 1981); Bancroft-Renfrew field, Ontario-Quebec (Černý, 1990; Lentz, 1991); Stockholm area, Sweden (Nordenskjöld, 1910; Smeds, 1990)
Mixed	"cross-bred" LCT and NYF	mixed	(metaluminous to) moderately peraluminous	(postorogenic to) anorogenic; moderately heterogeneous	subaluminous to slightly peraluminous; mixed geochemical signature	mixed protoliths, or assimilation of supracrustals by NYF granites	Tørdal district, S. Norway (Juve and Bergstøl, 1988); Kimito, Finland (Pehrman, 1945); Evje-Iveland field, S. Norway (Bjørlykke, 1935; Frigstad, 1968).

Notes

* This family also includes pegmatites of the miarolitic class (*cf.* Table 2)

** Definitions: Peraluminous, A/CNK>1; subaluminous, A/CNK~1; metaluminous, A/CNK<1 at A/NK>1; subalkaline, A/NK~1; peralkaline, A/NK<1, where A = molecular Al_2O_3, CNK = CaO + Na_2O + K_2O, and NK = Na_2O + K_2O (Černý, 1991a)

Table 7.5 The three petrogenetic families of rare-element pegmatites From Cerny (1991a)

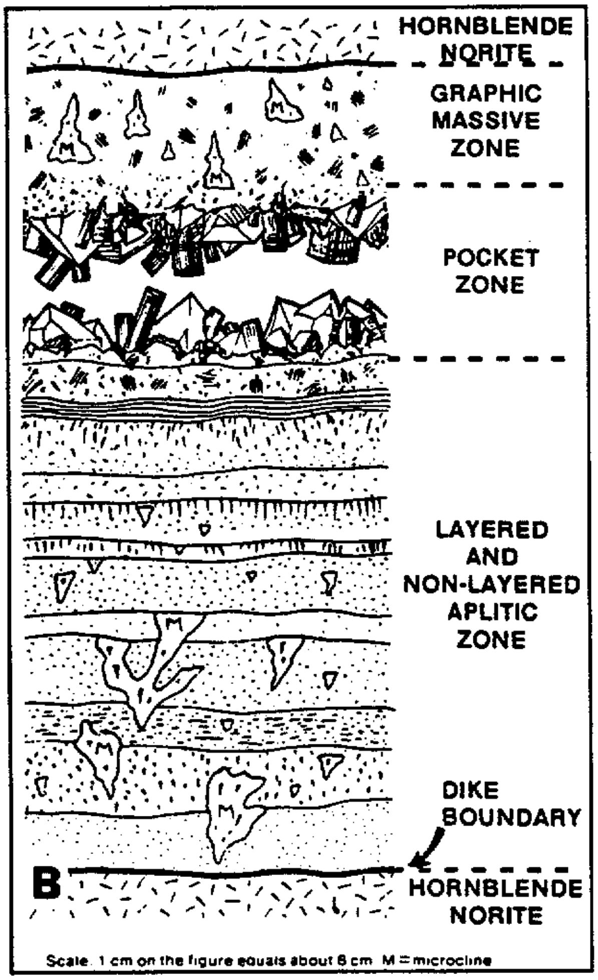


Figure 7.4 Schematic cross-section through tourmaline rich pocket in the Himalaya dike, San Diego, California
From London (1986)

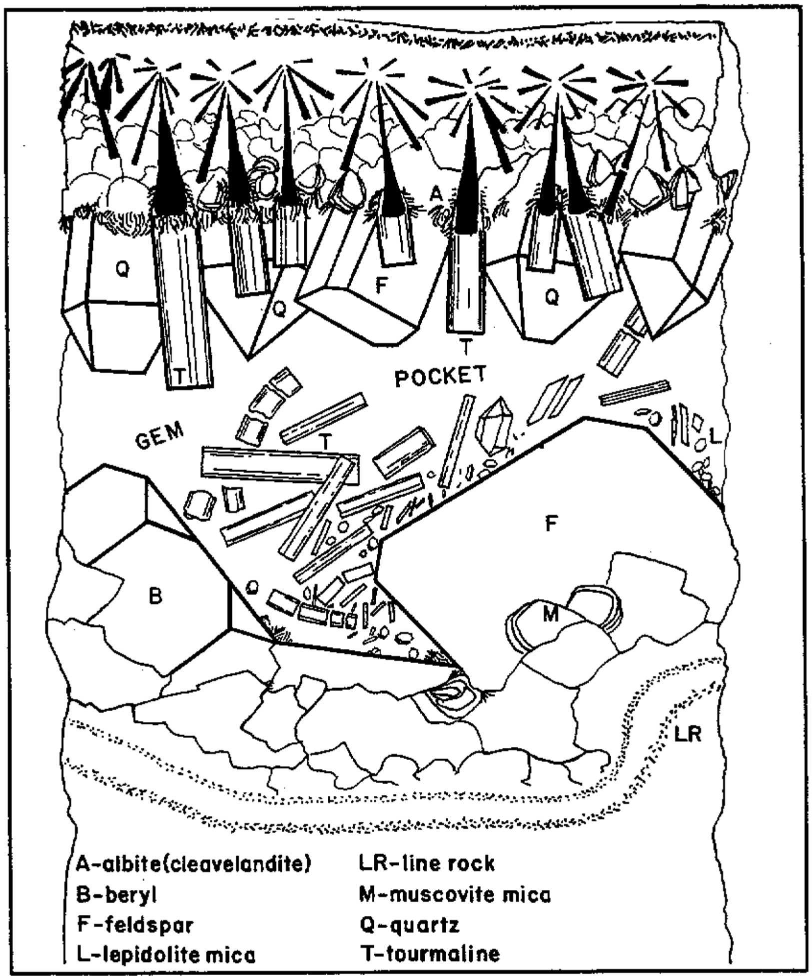


Figure 7.5 Schematic cross section of gem pocket in the Himalaya pegmatite dyke.
From Sinkankas (1970)

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 (1985) reports that the pegmatite which contained these magnificent gem pockets is 12 m wide and 200 m long. At the time of writing, only 30 m of it had been mined.

More often the gem crystals in pegmatite pockets are etched or corroded and may 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, exhibit a change in color, 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 as they approach and project into a pocket.

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 Cerny (1982) stress that this zoning can be irregular and depends on local structure. A typical zoning pattern is shown in Figure 7.6.

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. Figure 7.7 shows the regional zoning around a pegmatite field.

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), Cerny (1991b) and London (1986).

A silicate magma rich in volatile constituents such as H_2O, F, B, Li, CO_2 and/or K and rare-elements such as Be, Cs, Nb, Ta, Sn 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

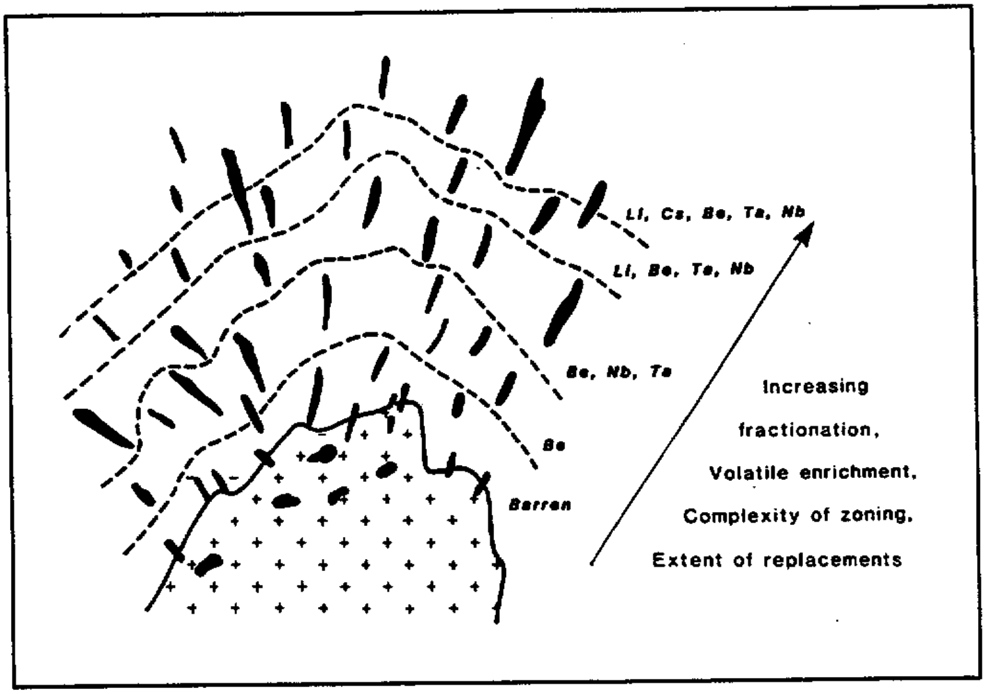


Figure 7.6 Schematic representation of regional zoning in a cogenetic granite and pegmatite group From Cerny (1991b)

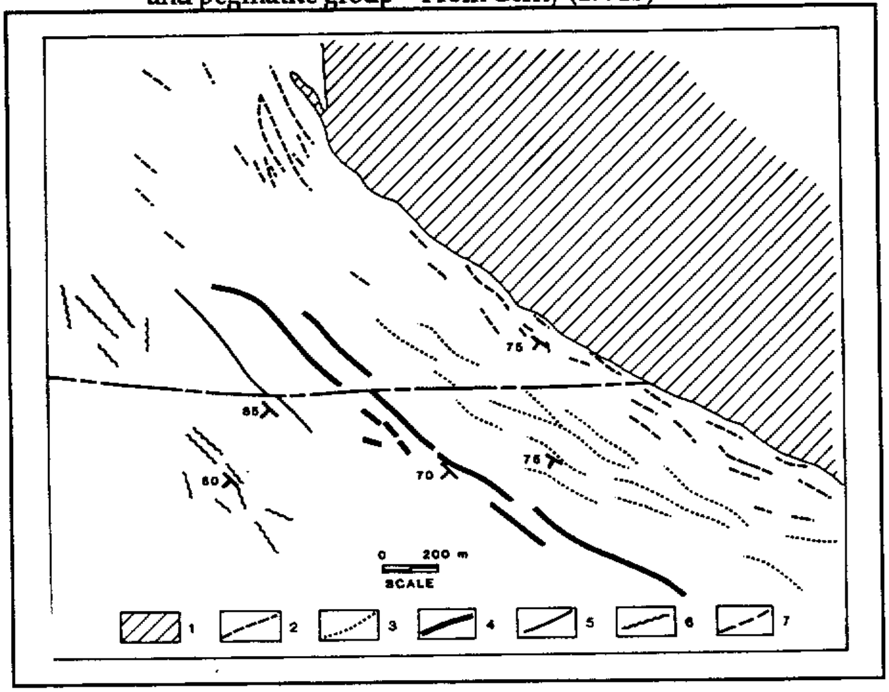


Figure 7.7 Regional zoning of a pegmatite group from Kazakhstan

1 - two-mica fine grained granite parental to the pegmatites
2 - barren and microcline pegmatites
3 - microcline+albite pegmatites with beryl and columbite-tantalite
4 - pegmatites transitional from the microcline+albite to albite type, with beryl, columbite-tantalite and altered spodumene
5 - albite pegmatite with low beryl and columbite content
6 - quartz veins with cassiterite and beryl
7 - fault

From Trueman and Cerny (1982)

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 center 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 center of the pocket. The crystals may become more "gemmy" (transparent) or change colors 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.

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 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) list three factors. Sometimes 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 gemstone forms distinctive slender crystals showing vivid color, or sometimes two or three colors in one stone. 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.

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).

The physical and chemical characteristics of tourmaline are listed in Table 3.3. Tourmaline crystals are usually slender, elongated crystals showing striations along the length of the crystal. Terminations on the ends of the crystals can be complex but usually consist of a rounded triangular habit. Crystals may be grouped in fibrous masses that appear to fan outward from a single crystal. As usual, exceptions to the usual 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 color and sometimes the same gem crystal can show two or even three vivid colors. Some of the more common colors, and the name given to that particular color of gem tourmaline are given below:

Red/Pink
This color 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-colored tourmaline
The change in color is a result of a change in supply of the elements which cause the color. Green/pink combinations either along the length of the crystal or from inside to outside are common. Sometimes the core of the tourmaline is one color and the outside rim is a different color, for instance "watermelon tourmaline".

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 a 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 electric charge that develops attracts dust.

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 earliest interpretation of the genesis of tourmaline crystals, as reported by Dietrich (1985) was in 315 B.C., where a gemstone, most possibly tourmaline, was reportedly "formed by the lynx urine, which the animal, as soon as it parts with it, hides by scraping the earth over it...... and the stones vary according to the sex and disposition of the animal." This brings to mind how our own geological theories might be looked at one or two thousand years from now.

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 are found in metasomatic zones in carbonate rock (Dietrich, 1985).

The gem tourmaline bearing pegmatites of Brazil are described by Proctor (1985a,b). Another pegmatite district famous for its gem tourmaline is the Pala district in San Diego County, California. It has been producing green and red tourmalines since its discovery in 1898. It is reported (Federman, 1990) that over 100 tons of gem and ornamental tourmaline came from the Californian Himalaya pegmatite mine between 1898 and 1914. One of that mines' best customers 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 1912 (Federman, 1990).

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 P-T conditions for massive (pegmatites which do not contain miarolitic cavitites) pegmatites 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. Stern et al., (1986) suggests that high F plus B contents enhance tourmaline crystallization by depressing the temperature of crystallization and by affecting the distribution of the alkali constituents.

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 labelled "topaz quartz" or brown, smoky quartz is sold as "smoky topaz". Other terms like "imperial" topaz, which originally identified rare pink topaz in Russia coveted by the Imperial family during the 19th century, are used for almost any color of topaz. The popularity of blue topaz during the late 1980's and early 1990's confused consumers even more.

Topaz was the featured mineral in a recent special issue of the *Mineralogical Record* magazine. The mineralogy, geology and occurrence of topaz is described in articles by Menzies (1995) and others. Abstracts of current research into topaz geology are included and full-color photographs of spectacular topaz crystals complement the articles.

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

Although natural blue topazes 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-1980's that the public really became aware of the gem. Suppliers began placing large amounts of natural colorless topaz from Brazil, Sri Lanka or Africa in nuclear reactors or linear accelerators where they are bombarded with neutrons or electrons to produce a blue color. The irradiated stones are heat-treated to stabilize the color and then released to the global gem trade, where they have become very popular low-cost alternatives to aquamarine or the more expensive colors 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 in impurity is often heat-treated in an attempt to produce the more desired pink color. Most of the sherry colored topaz from rhyolites and pegmatites fades gradually in sunlight.

The physical and chemical characteristics of topaz are given in Table 3.3. 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 7.8.

Topaz crystals can reach enormous size. Menzies (1995) reports a Brazilian topaz crystal measuring 3 x 5 x 10 meters 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% 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 7.9. The belts cover rift zones in continental crust and or collisions involving continental plates.

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 then "open systems" like a greisen or skarn where the hot fluid or magma seeps unhindered into the host rock (Table 7.6, Figure 7.10).

Fluorine-rich magmas are generated in long-lived, tectonically active zones. Menzies (1995) lists two tectonic regimes that are particularly favorable 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 Transbaikalia.

These regimes are illustrated in Figure 7.11. 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,

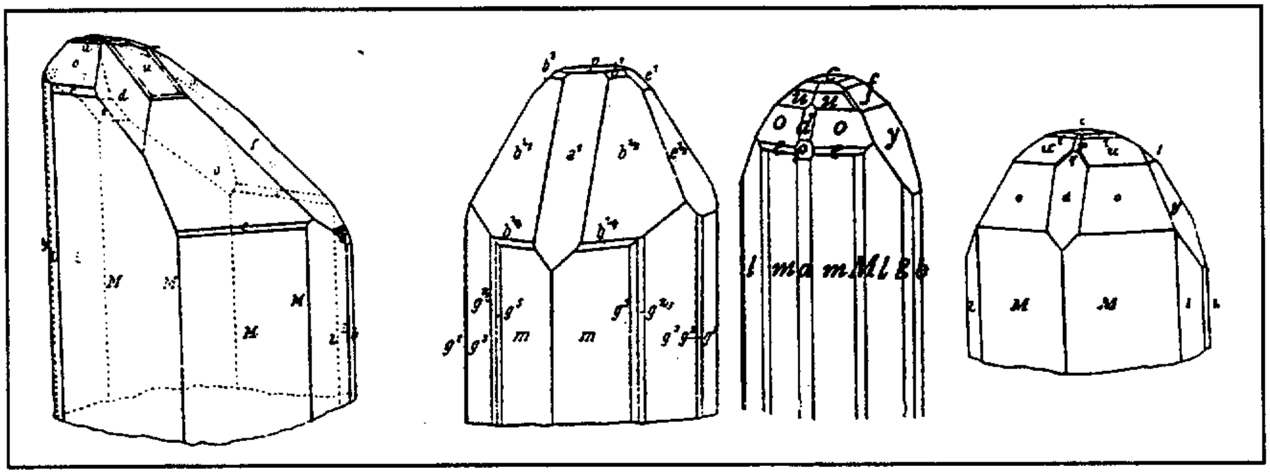


Figure 7.8 Topaz crystals From Menzies (1995)

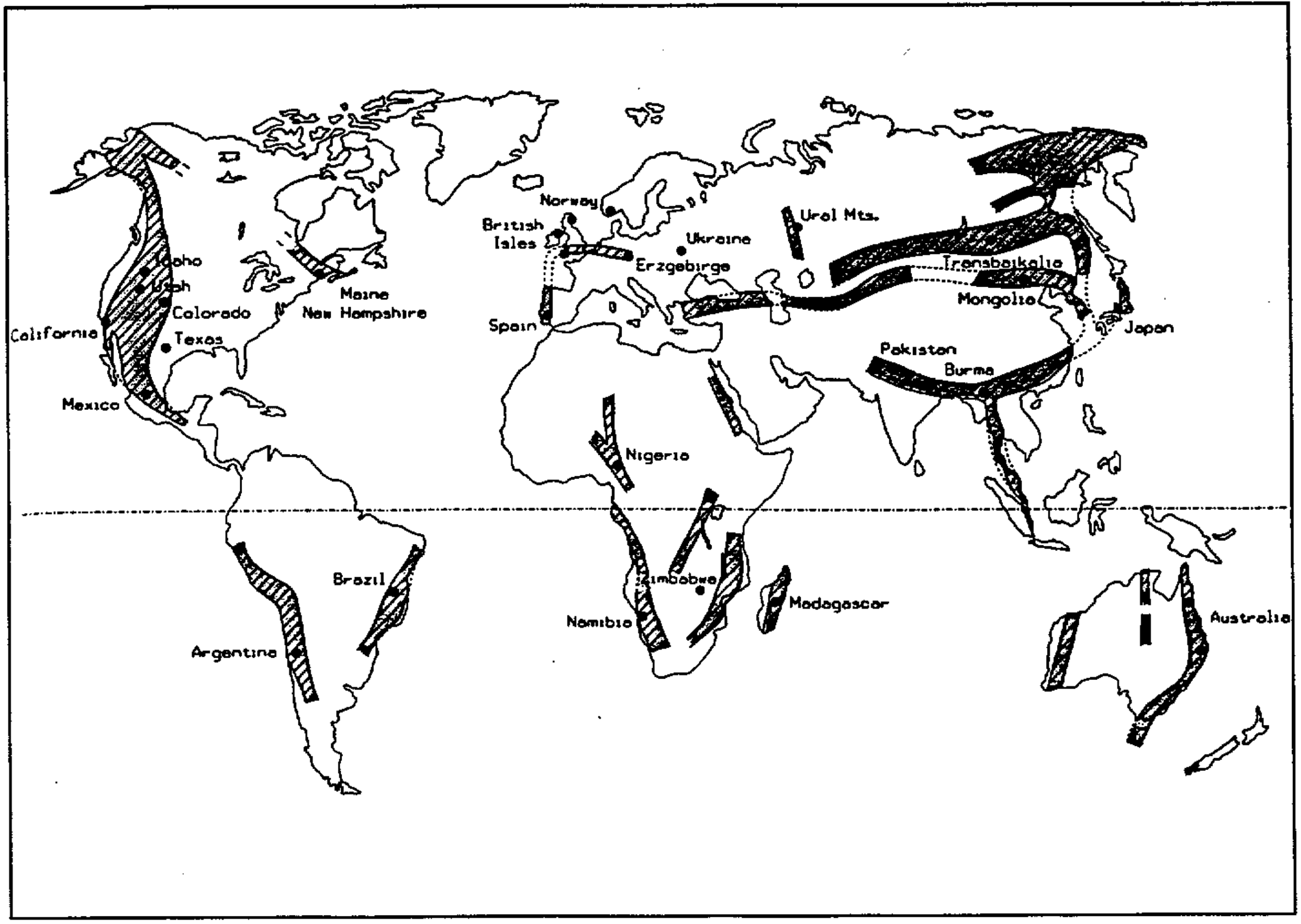


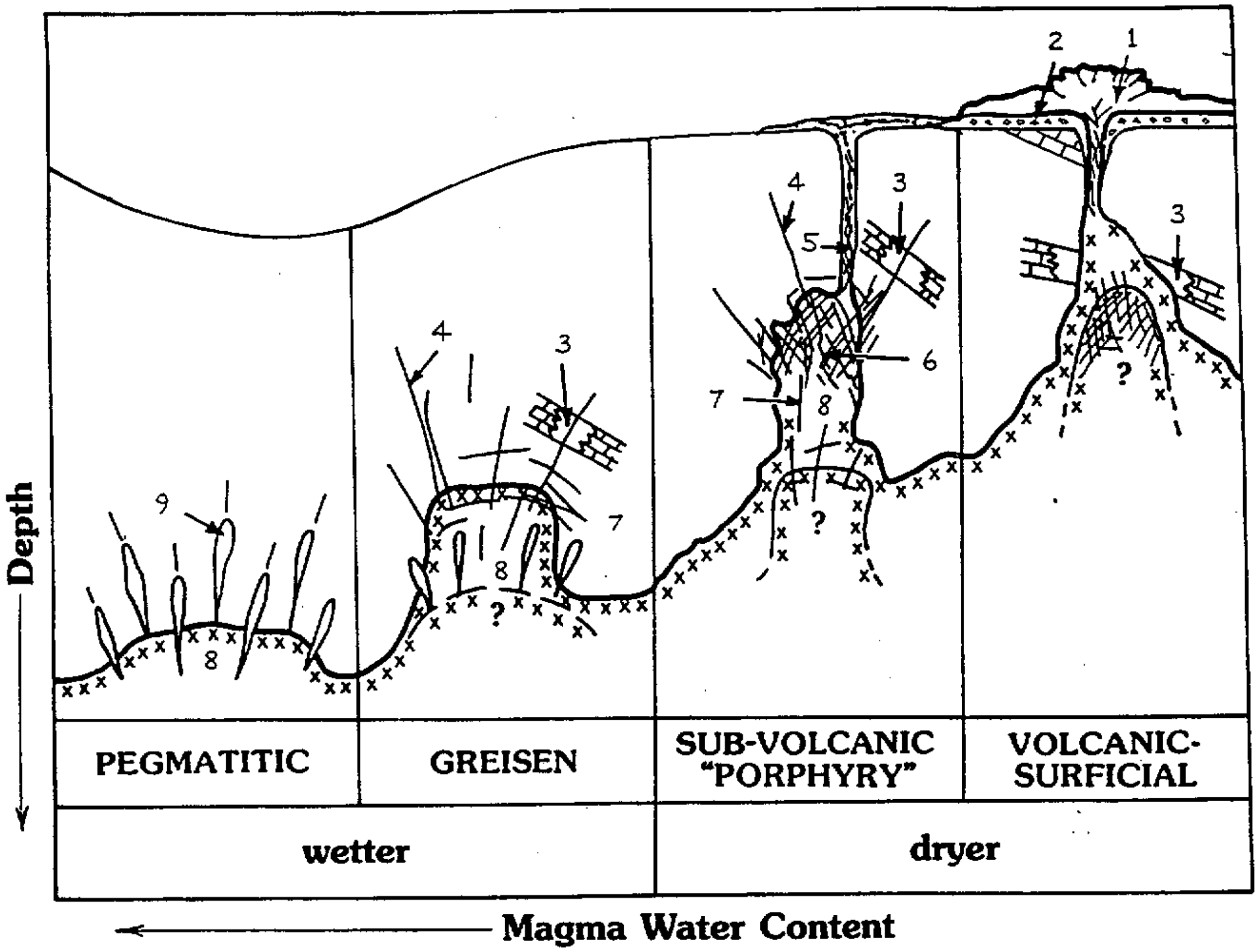
Figure 7.9 Rare-metals belt and major topaz deposits. The rare-metals belts are shown cross-hatched. Topaz deposits are marked with filled circles. From Menzies (1995)

Geologic Environment	*Deposit Type*	*Formation Temperature (Deg C)*	*Fluid Activity/ Replacement*	*% Fluorine in Rock*	*Typical Associated Species*	*Example Localities*	*Comments*
VOLCANIC	Gas cavities in Rhyolite	850–600	Deposition from gas phase	<1	Bixbyite, garnet, quartz hematite, Mn-beryl	Thomas Range, Utah Central Mexico	Fine crystals & groups
MAGMATIC	Ongonite	1000–600	Quenched magma	<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:		750–<300[1]		<1			
-NYF type[2]	Syngenetic Pegmatites in granite (simple cavities, zoning uncommon)	750–450	Localized, slight	Higher	Quartz, albite, microcline (incl. 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[2]	Epigenetic Pegmatites, intruded into country rocks (complex, zoned)		Extensive in inner zones	Lower	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							
	Greisens (in or associated with granites)	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)	>500–400	Extensive	Low	Calcium silicates, micas, tourmaline, fluorite, magnetite, cassiterite, sulfides	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, molybdenite	Eastern Australia	Good crystals in cavities, especially in nearer-surface deposits
Hydrothermal: lower temperature		400–<200					
	Quartz-Feldspar Veins		Intensive	Low	Quartz, cassiterite. Also euclase, hematite, rutile (Brazil)	Eastern Australia Ouro Preto, Minas Gerais, Brazil	Fine crystals, some of gem quality
	Sulfide Veins		Extensive	Low	Quartz, sulfides, fluorite	Cornwall, England	Rare occurrence for topaz
	Carbonate Veins and Alpine Clefts	ca. 200	Extensive along fractures	Low	Calcite, quartz	Brumado, Brazil Mardan, Pakistan Untersalzbachtal, Salzburg, Austria Val Lugnez, Grisons, Switzerland	Very rare occurrence for topaz
High-grade Metamorphic		High	Extensive	High	Quartz, sillimanite, kyanite	Tanzania Colorado South Carolina	Massive material
Sedimentary	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

[1] Pegmatite deposits listed in generally decreasing order of temperature

[2] Classification scheme per Černý (1991a)

Table 7.6 Topaz deposit types From Menzies (1995)



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 greisens**
7. **Greisens**
8. **Miarolitic cavities in granite**
9. **Pegmatites**

Figure 7.10 Schematic diagram of topaz deposit types From Menzies (1995)

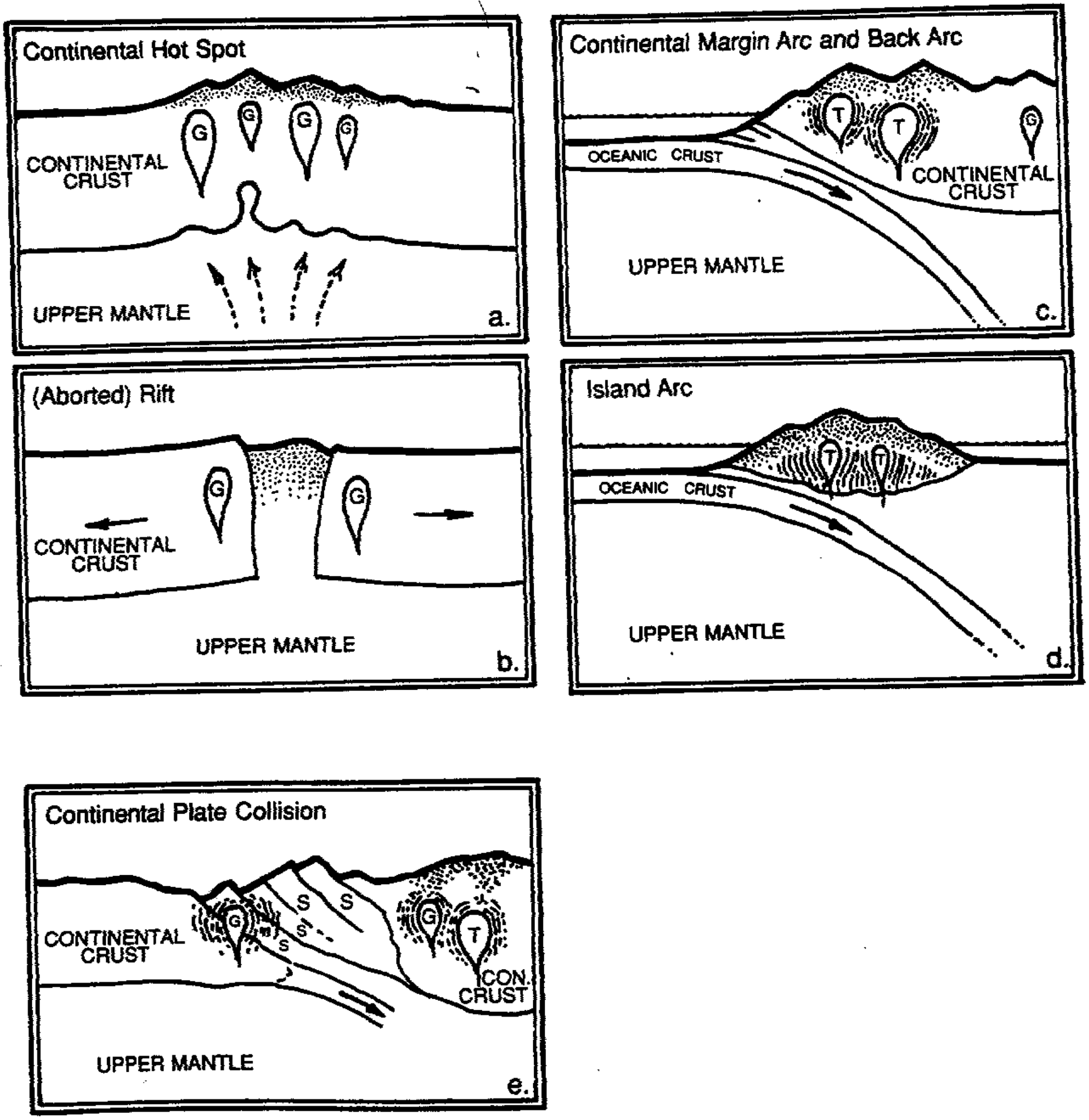


Figure 7.11 Tectonic regimes for topaz granites and rhyolites From Menzies (1995)

rare-element class, as described by Cerny (1991a) and can be further divided into syngenetic pegmatites (NYF - Niobium-Yttrium-Fluorine) as described by Cerny (1991a) and epigenetic pegmatites (LCT - Lithium-Cesium-Tantalum) pegmatites (Table 7.5).

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 cavitites 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 and less commonly beryl and phenakite and rarely spessartine and tourmaline may be present.

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 kilometers into the surrounding host rock. Typically, gem topaz crystallizes with lepidolite and albite pegmatites, which are usually the last to form furthest away from the parent granite. The pegmatites correspond to Cerny's LCT type (Table 7.5), 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 transparent green-blue variety of the mineral beryl, is named after latin for "the color of the sea". This gemstone was particularly favored not only by the ancient Greeks, but also in present history by Queen Elizabeth II. Possession of aquamarine was said to protect one against water-related disasters at sea. It was also said to bring courage to a wearer in times of war, help establish happy marriages and quicken a student's intellect.

The coloring 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 3.3. 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-quartz wall zone and project into the white quartz core.

Aquamarine is also found in miarolitic cavities found in A-type granites (anorogenic granites) described earlier in the section on topaz. 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. 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 meters 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 in the field 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 7.6 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 kilometers 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 Cerny (1982) provide a detailed listing of guidelines for the exploration geologist to help determine the potential of pegmatite field. The guidelines are based on studies of rare-element pegmatites in shield areas. Some of the relevant guidelines are summarized below:

1. Geochemistry

Stream sediment sampling is recommended as an initial approach. Trueman and Cerny (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.

2. Geology and Structural Control of Parental Granites

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

- generally small to moderate in size (5 to 150 km^2 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.

3. Composition and Texture of Parental Granites

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

4. Geochemistry of Parental Granites

(See Table 7.7, Table 7.8)

- highly silicic
- metaluminous to peraluminous
- low Ti, Fe, Mg and Ca contents
- high Na and K
- low Sr, K/Rb, K/Cs, Mg/Li ratios
- high Be, Sn, Rb/Sr ratios

	1 – Osis Lake			2 – Lac du Bonnet	
	biotite granite	coarse-grained leucogranite	pegmatitic leucogranite	leucogranite	pegmatitic leucogranite
SiO_2 (wt%)	73.15	75.40	72.72	76.56	75.75
TiO_2	0.12	0.06	0.04	0.10	0.03
Al_2O_3	14.40	14.33	15.36	12.36	14.07
Fe_2O_3	0.46	0.72	0.61	1.07	0.36
FeO	1.05	0.28	0.68	0.56	0.15
MnO	0.03	0.08	0.06	0.03	0.01
MgO	0.48	0.13	0.06	0.10	0.09
CaO	0.76	0.72	0.29	0.56	0.68
Na_2O	3.12	4.09	4.44	3.65	4.20
K_2O	5.42	2.83	4.78	4.65	5.24
P_2O_5	0.15	0.16	0.49	0.02	0.00
CO_2	0.03	0.08	0.11	0.05	0.03
H_2O^+	0.88	0.67	0.46	0.36	0.22
F_2	0.02	0.04	0.02	0.01	0.02
$-O=F_2$	0.01	0.02	0.01	–	0.01
total	100.07	99.57	100.11	100.08	100.85
A/CNK **	1.16	1.29	1.18	1.02	1.12
A/NK **	1.31	1.46	1.23	1.02	1.12
Li (ppm)	71	63	10	28	–
Rb	187	137	343	216	244
Cs	15.4	8.4	8.4	2.9	–
Be	0.7	0.8	0.8	2.9	–
Sr	83	26	44	30	33
Ba	287	8	14	398	103
Ga	28	48	43	32	47
Y	nd	28	nd	51	19
U	30	23	3.5	9.9	2
Th	nd	6.7	nd	39	8
Zr	78	38	13	196	9
Hf	1.63	3.05	0.34	7.4	1.8
Sn	4.8	13	20	7.9	5
K/Rb	237	132	117	194	178
K/Ba	162	5402	7010	492	422
Ba/Rb	1.53	0.06	0.04	2.2	0.42
Rb/Sr	2.25	5.3	7.8	9.5	7.6
Mg/Li	39.7	11.5	31	25.6	–
Zr/Sn	16.3	2.9	0.7	22	2.1
Zr/Hf	47.8	12.4	5.8	27.5	12.8
Al/Ga	2737	1674	1890	2087	1586
Th/U	0.1	0.3	0.1	2.75	2.75

Notes

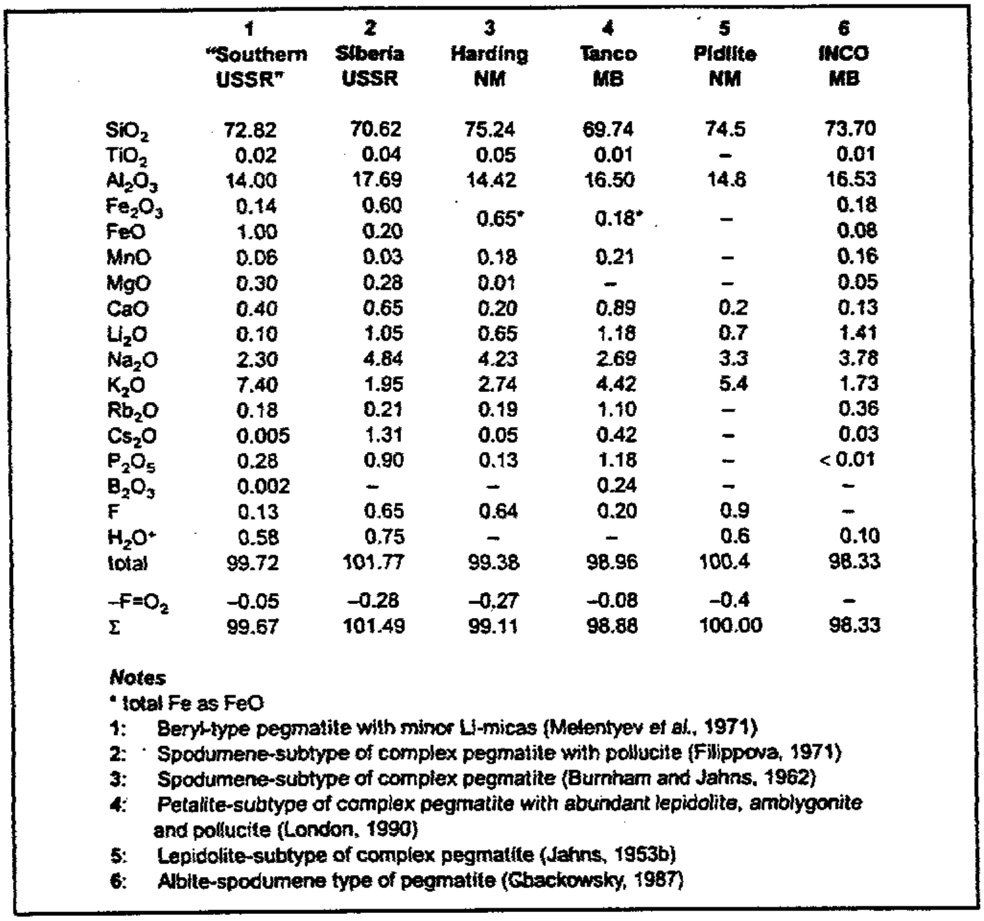
1 Peraluminous LCT granite grading from biotite through two-mica + garnet to muscovite + garnet + tourmaline types (from Černý and Brisbin, 1982)

2 Metaluminous NYF fertile granite with biotite and extremely rare garnet (from Černý *et al.*, 1987)

–, not determined; nd, not detected

** A = molecular Al_2O_3, CNK = CaO + Na_2O + K_2O, and NK = Na_2O + K_2O

Table 7.7 Composition of typical fertile granites From Cerny (1991b)



	1 "Southern USSR"	2 Siberia USSR	3 Harding NM	4 Tanco MB	5 Pidlite NM	6 INCO MB
SiO_2	72.82	70.62	75.24	69.74	74.5	73.70
TiO_2	0.02	0.04	0.05	0.01	–	0.01
Al_2O_3	14.00	17.69	14.42	16.50	14.8	16.53
Fe_2O_3	0.14	0.60	0.65*	0.18*	–	0.18
FeO	1.00	0.20				0.08
MnO	0.06	0.03	0.18	0.21	–	0.16
MgO	0.30	0.28	0.01	–	–	0.05
CaO	0.40	0.65	0.20	0.89	0.2	0.13
Li_2O	0.10	1.05	0.65	1.18	0.7	1.41
Na_2O	2.30	4.84	4.23	2.69	3.3	3.78
K_2O	7.40	1.95	2.74	4.42	5.4	1.73
Rb_2O	0.18	0.21	0.19	1.10	–	0.36
Cs_2O	0.005	1.31	0.05	0.42	–	0.03
P_2O_5	0.28	0.90	0.13	1.18	–	< 0.01
B_2O_3	0.002	–	–	0.24	–	–
F	0.13	0.65	0.64	0.20	0.9	–
H_2O^+	0.58	0.75	–	–	0.6	0.10
total	99.72	101.77	99.38	98.96	100.4	98.33
$-F=O_2$	–0.05	–0.28	–0.27	–0.08	–0.4	–
Σ	99.67	101.49	99.11	98.88	100.00	98.33

Notes

* total Fe as FeO

1: Beryl-type pegmatite with minor Li-micas (Melentyev *et al.*, 1971)

2: Spodumene-subtype of complex pegmatite with pollucite (Filippova, 1971)

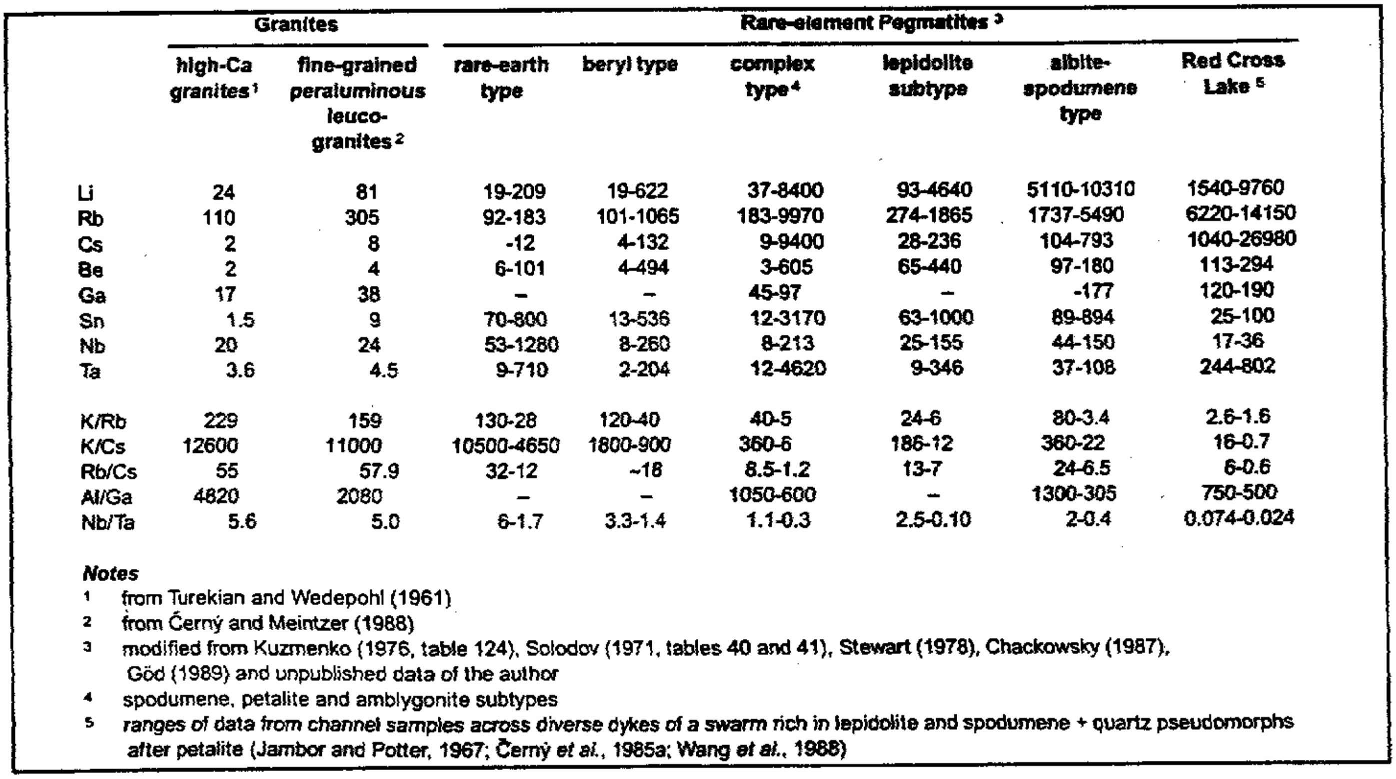
3: Spodumene-subtype of complex pegmatite (Burnham and Jahns, 1962)

4: *Petalite-subtype of complex pegmatite with abundant lepidolite, amblygonite* and pollucite (London, 1990)

5: Lepidolite-subtype of complex pegmatite (Jahns, 1953b)

6: Albite-spodumene type of pegmatite (Gbackowsky, 1987)

Table 7.8
Bulk composition of rare-element pegmatites
From Cerny (1991a)



	Granites		Rare-element Pegmatites[3]					
	high-Ca granites[1]	fine-grained peraluminous leuco-granites[2]	rare-earth type	beryl type	complex type[4]	lepidolite subtype	albite-spodumene type	Red Cross Lake[5]
Li	24	81	19-209	19-622	37-8400	93-4640	5110-10310	1540-9760
Rb	110	305	92-183	101-1065	183-9970	274-1865	1737-5490	6220-14150
Cs	2	8	-12	4-132	9-9400	28-236	104-793	1040-26980
Be	2	4	6-101	4-494	3-605	65-440	97-180	113-294
Ga	17	38	–	–	45-97	–	-177	120-190
Sn	1.5	9	70-800	13-536	12-3170	63-1000	89-894	25-100
Nb	20	24	53-1280	8-260	8-213	25-155	44-150	17-36
Ta	3.6	4.5	9-710	2-204	12-4620	9-346	37-108	244-802
K/Rb	229	159	130-28	120-40	40-5	24-6	80-3.4	2.6-1.6
K/Cs	12600	11000	10500-4650	1800-900	360-6	186-12	360-22	16-0.7
Rb/Cs	55	57.9	32-12	~18	8.5-1.2	13-7	24-6.5	6-0.6
Al/Ga	4820	2080	–	–	1050-600	–	1300-305	750-500
Nb/Ta	5.6	5.0	6-1.7	3.3-1.4	1.1-0.3	2.5-0.10	2-0.4	0.074-0.024

Notes

[1] from Turekian and Wedepohl (1961)

[2] from Černý and Meintzer (1988)

[3] modified from Kuzmenko (1976, table 124), Solodov (1971, tables 40 and 41), Stewart (1978), Chackowsky (1987), Göd (1989) and unpublished data of the author

[4] spodumene, petalite and amblygonite subtypes

[5] *ranges of data from channel samples across diverse dykes of a swarm rich in lepidolite and spodumene + quartz pseudomorphs after petalite* (Jambor and Potter, 1967; Černý *et al.*, 1985a; Wang *et al.*, 1988)

Table 7.9 Selected fractionation data on granites and rare-element pegmatites From Cerny (1991a)

- widely variable K/Ba ratios

5. Zoning of Pegmatite Swarms

Trueman and Cerny (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 sulphides.

6. Mineral Zoning

See Table 7.9

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 Be, Nb-Ta mineralized pegmatites including those with Li, Fe and Mn-phosphates.
- not found in spodumene-rich, rare-element or Li, F 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 Be, (Nb, Ta) bearing and spodumene pegmatites

Black Tourmaline
- boron is not related closely to the rare-metals
- found in barren and simple Be (Nb, Ta) bearing pegmatites
- becomes blue and green tourmaline with Sn, Nb and Ta mineralization in albitized pegmatites
- green, pink and colorless tourmaline indicate increased Li, Rb and Cs

Beryl
- appears as a primary coarse, columnar mineral of greenish, yellow or brownish color in simple, blocky pegmatites with negligible albitization.
- away from parental granites, the fluid is enriched in alkalis so the beryl becomes pale colored 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 Li, F-enriched type with Ta, Li, Rb, Cs mineralization

Columbite-Tantalite
- is the main Nb-Ta mineral in moderately fractionated pegmatites

Spodumene
- green spodumene indicates spodumene pegmatites with low Nb-Ta and Be potential but high Li content.
- white spodumene adjacent to quartz core is characteristic of rare-element pegmatites with diverse mineralization.

7. Minerals in Metasomatic contact zones

Biotite-Phlogopite

Trueman and Cerny (1982) note that this 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.

8. Trace Element Chemistry

Trueman and Cerny (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 Cerny (1982) list several types of geochemical indicators, usually 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.

Buried Rare Element Pegmatites

Geochemical halos have been discovered for rare-element pegmatites. The diagnostic elements are given below and their abundance in relation to different host rocks of rare-element pegmatites is also given below:

The authors caution that many variables affect the geochemical halos and the diagnostic background values should be well determined before using this technique.

9. Geophysical Methods

Trueman and Cerny recommend 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.

Pegmatites in the Canadian Cordillera

Groat et al., (1995) list characteristics of fertile pegmatites in the Canadian Cordillera as follows:

- late to 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 $^{87}Sr/^{86}Sr$ isotopic ratios are high
- K/Rb, K/Cs and K/Li ratios are low

Let us suppose that fertile granites were identified, stream sediment sampling was carried out and rare-element pegmatites showing signs or good potential for gemstone mineralization were found. How does one find the elusive gem pockets or cavities which are so randomly distributed and unpredictable? The following is a general listing of pocket-finding guidelines compiled from various sources.

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 color or increases in amount
- presence of lepidolite (purple 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 (color-zoned tourmaline) is found in pockets in the central zones of complex, Li-bearing pegmatites.

- tourmaline, especially schorl (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 Li-content of tourmalines is greater in albitized than non-albitized pegmatites and Rb and Cs, as well as Li, are apparently sequentially enriched in later generations.

- Li-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.

Muscovite is typically green colored in the nonpocket pegmatite portion of the dyke and is commonly colorless 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.

CHAPTER EIGHT

GEM TOPAZ ASSOCIATED WITH RHYOLITES AND GREISENS

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 sherry-brown topaz crystals which are found in the rhyolites, but instead the close spatial and genetic association of topaz rhyolite with volcanogenic Be, Sn, U and F mineral deposits. Topaz rhyolites may also serve as subsurface indicators of silver or fluorite (Mexican type carbonate replacement), 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:

1. "The Geology and Geochemistry of Cenozoic Topaz Rhyolites from the Western United States"
   -Geological Society of America Special Paper 205
   Christiansen et al., (1986)

2. "Topaz Rhyolites - Distribution, Origin and Significance for Exploration
   - Burt et al., (1982)

3. "Topaz"
   -Special issue of the *Mineralogical Record* focusing solely on gem topaz

Definition of Topaz Rhyolite

Topaz rhyolites are fluorine-rich alkaline silicic lavas and shallow intrusives that are characterised 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 Yukon, B.C, western United States and Mexico (Fig. 7.9). 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 gray 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 broken cavities are generally yellowish to pinkish brown; these colors 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 center. Other minerals which may occur in the cavities include red to black Mn-Fe garnet, black cubes of bixbyite, black acicular pseudobrookite and black platy specular hematite, colorless crusts of sanidine, tabular to prismatic, pink to red hexagons of beryl, colorless to purple fluorite and ruby red, stubby to platy cassiterite and opal.

Geochemistry

All topaz rhyolites contain high SiO_2 with elevated F, Na, K, Fe/Mg and low Ti, Mg, Ca and P. They are also enriched in incompatible lithophile elements (Rb, U, Th, Ta, Nb, Y, Be, Li and Cs). Elements compatible in feldspars (Sr, Eu, Ba), ferromagnesian minerals (Ti, Co, Ni, Cr) and zircon (Zr, Hf) 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 topaz-bearing rhyolites in the Thomas Range, Utah (Shigley and Foord, 1985). The red beryls are colored 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 contained preferential enrichment of beryllium as opposed to fluorine.

Greisens

Gem topaz crystals may form in greisen deposits, for example the 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. Typically, topaz greisens are formed when very hot, acid silica-rich and fluorine-rich fluids reacts with aluminum leached out of feldspars when the hot fluid invades a granitic rock. The sequence of mineralization is shown in Figure 7.10. When the original minerals are removed during the early stages of greisenization, there is room for topaz and other minerals to grow, particularly when there have been explosions (explosion breccia) leaving lots of open cavitites for topaz and other minerals to crystallize in.

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 pegmatites belong to the same group of granites which are 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 sulphides.

CHAPTER NINE

APPLICATION TO YUKON GEOLOGY

A general summary of Yukon geology is provided by Hart (1995). More detailed summaries are provided in Geology of the Cordilleran Orogen in Canada (Gabrielse and Yorath, 1991) and in publications released by Exploration and Geological Services of Indian and Northern Affairs Canada, and also by the Geological Survey of Canada.

The following are some general observations about Yukon geology in regards to gemstone exploration. A summary of exploration criteria is given in Table 8.1.

Alkali Basalt

Two recent papers by Francis and Ludden (1995) and Carignan et al., (1994) discuss mid-Tertiary to Recent alkaline volcanic complexes in the northern Cordillera (Figure 9.1). The alkaline basalt occurrences are listed as follows:

1. Alligator Lake
   (Eiche et al., 1987; Francis, 1987)
2. Watson Lake Area
3. Fort Selkirk Region
   (Francis and Ludden, 1986; 1990)
4. Southwest Dawson Map Sheet
   (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.

Although one can directly prospect the Yukon alkali basalt occurrences, 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 region.

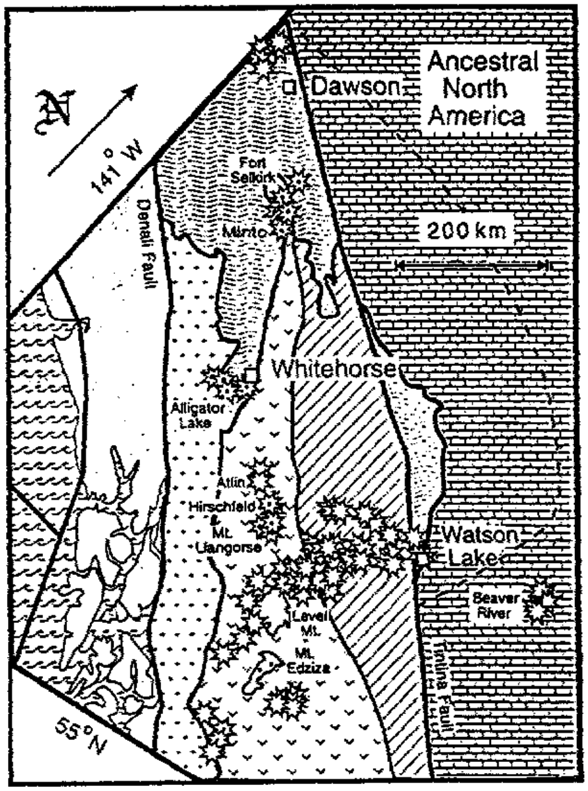
A possible exploration strategy for exploring for ruby and sapphire associated with alkali basalt in the Yukon is:

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.

2. If a suitable target is discovered, then heavy mineral stream sédiment sampling from streams draining the basalt field should be done using a cone seive 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.

	CORUNDUM	BERYL	CHRYSOBERYL	TANZANITE	TSAVORITE GARNET	TOURMALINE	TOPAZ
Major Occurrences	Thailand, Myanmar, Cambodia, Sri Lanka, Australia,India, Russia	Emerald: Colombia, Brazil, Pakistan, Zambia Aquamarine: Brazil	Brazil, Russia, Sri Lanka	Tanzania	Kenya, Tanzania	Brazil, U.S.A., Madagascar	Brazil, Russia, U.S.A., Pakistan
Typical Host Rock and Geological Environment	1. Alkali Basalt 2. Lamprophyre Dykes 3. Marble 4. Pegmatites intruding ultramafic rock, aluminum-rich rock or marble	Emerald 1.Organic-rich black shales interbedded with evaporites 2. Pegmatites intruding chromium-rich rocks (usually ultramafic) Aquamarine 1. rare-element pegmatites, 2. miarolitic cavities	1.Pegmatites intruding chromium-rich rocks (usually ultramafic) 2.rare-element pegmatites	Graphitic schists and gneisses interbedded with marble	Graphitic schists and gneisses interbedded with marble	Rare-element pegmatites	1. Rare-element pegmatites 2. Miarolitic cavitites 3."Topaz" rhyolites
Main Chromophore	Ruby: Cr Blue Sapphire: Fe and Ti Other colors of sapphire: Fe	Emerald: Cr, rarely V Aquamarine: Fe	Alexandrite: Cr	Vanadium	Vanadium, minor chromium	Various chromophores, mainly Fe	Various color mechanisms
Age of Host Rocks	Alkali Basalt Tertiary Others Paleozoic to Precambrian	Organic-rich black shale type: Cretaceous Other Teriary to Proterozoic	Proterozoic to Tertiary	Proterozoic	Proterozoic	Proterozoic to Tertiary	Proterozoic to Tertiary
Metamorphic Grade of Host rocks	Alkali Basalt Unmetamorphosed Others Med-High Grade	Organic Rich Black Shale: Unmetamorphosed Other: Low-High Grade	Unmetamorphosed to high-grade metamorphism	High-grade	High-grade	Variable	Unmetamorphosed, rare high-grade
Pathfinder minerals/ elements	Alkali Basalt Black spinel Black clinopyroxene Zircon Pyrope Garnet Ilmenite Magnetite, Olivine Granulite Facies Host Rock Rb/Sr ratio, Th, U. F, Ta, Nb, Y, REE	Organic-rich black shale type K/Na ratio Li, Mo, Pb in regional stream sediment and soil surveys Pegmatite-related Coincident Be and Cr anomalies, also tin-tungsten pathfinders including Sn, W, Mo, F	Same as Pegmatite-related emerald	Anomalous V	Anomalous V	Highly silicic, low Ti, Fe, Mg and Ca, High Na and K, low Sr, K/Rb, K/Cs, Mg/Li ratios, high Be, Sn, Rb/Sr ratios	Rare-element pegmatite Fluorine, and rare-element pegmatite suite Topaz rhyolites High Si, F, Na, K, Fe/Mg, Rb, U, Th, Ta, Nb, Y, Be, Li and Cs.
Exploration	Alkali Basalt type undersaturated alkali basalt, abundant spinel-lherzolite nodules, characteristic heavy mineral suite Other marble beds in high-grade metamorphic rocks, interaction of pegmatites with marbles, ultramafic rocks or Al-rich rocks	Organic-rich black shale type organic rich shales or sedimentary rocks associated with evaporites, sodium depletion in mineralized areas, Pb, Mo and Li anomalies in regional geochemical stream surveys Pegmatite-related Be-bearing rare-element pegmatite intruding any Cr-bearing rock. Coincident Cr and Be or magnetic anomalies	Same as Pegmatite-related emerald.	Anomalous vanadium, hydrothermal alteration, marble, graphitic rocks, high degree of deformation	Granulite facies regional metamorphism, interbedded marble and graphitic units, anomalous vanadium	Look for increasing complexity of pegmatite texture and mineralogy. Parental granites are typically two-mica, and show anomalous Na, K, Be, Sn and Rb/Sr ratios. Increased black tourmaline, lepidolite, muscovite, and transparency of quartz may indicate pegmatite pockets.	Highly evolved granites and rhyolites, emplaced at shallow depths. Topaz rhyolites are related to parental granites to rare-element pegmatites and tin-tungsten mineralization. Strong correlation between rhyolite-derived alluvial sherry-color topaz and cassiterite.

Table 9.1 Exploration criteria for gemstone deposits



Simplified map illustrating the regional geological context. Stars = Quaternary to Recent alkaline volcanic centres (dots = sampled localities). Terranes: Light grey = Insular Superterrane: plus signs = Coast Plutonic complex: V = Intermontane Belt: oblique shading = Omenica Belt: wavy lines = Yukon Crystalline Terrane; brick pattern = ancestral North America; dashed line = limit of the Omenica Belt.

Figure 9.1 Yukon alkaline volcanic centers
From Carignan et al., (1994)

Lamprophyre Dykes

Obviously, the occurrence of sapphires in dykes of lamproitic affinity from Montana and Scotland 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, the occasional single lamprophyric dyke is present. These dykes should be examined for sapphire content directly or by examining concentrate from creeks draining them.

Marbles and High Grade Metamorphic Terrains

High grade metamorphic terrains are host to several important gem deposits including ruby, sapphire, tsavorite garnet and tanzanite. Obviously, there are very little 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 most areas, the metamorphic grade in the Yukon does not reach the levels that seem to be needed for ruby, sapphire and tsavorite garnet formation during regional metamorphism. With this in mind, the Yukon-Tanana terrain shows 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 ratios have been used in Sri Lanka as an exploration tool; however, since the Rb/Sr ratio is a function of granulite facies metamorphism, it would be of little value in the northern Canadian Cordillera.

High Grade Metamorphic Graphitic 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 can be 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).

The vanadium content in stream sediments from regional geochemical surveys can be compared to that in Table 5.1. Target areas might include vanadium anomalies which correspond with graphitic schists or marbles in a highly metamorphosed sequence of rocks. In general, the highest vanadium values are concentrated along the Yukon/N.W.T. border (D. Brent, pers. comm., 1996).

Other Garnets

Garnets are one of the most common gemstones. Most exploration geologists and placer miners in the Yukon are familiar with red to reddish-brown almandine and pyrope garnets which occur in metamorphic and pegmatitic rocks and accumulate in placer concentrate. There is a large supply in the global gem trade of beautiful large garnets, many of them from East Africa, of all shades of red, orange-red and violet-red. Most Yukon garnets tend to be fractured, although some show attractive crimson hues. Unless one finds a large deposit of transparent garnet crystals greater than 2 cm in diameter with no visible flaws, it would be difficult to compete in the gem market, although selected individual gems look attractive when set with yellow nugget gold.

Organic Black Shale Sequences

Chapter Four in this report described 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 the western N.W.T. 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 color 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 the Colombian-type emerald deposits may produce a traditional reddish orange gossan.

Pegmatites

Pegmatites are intrinsic to the formation of many types of gemstone deposits.

Downing (1993) compiled information and updated a previously published report on industrial minerals and minor metals and their potential for development in the Yukon. Of particular interest to the gemstone pegmatite prospector are the summaries about and Yukon locations of rare elements and minerals that are typically contained in gemstone pegmatites. This includes cassiterite, fluorite, topaz (in the section on gemstones), mica, minor metals (Be, Ce, Cb, Nb, Ga, Gr, Li, Ta, Th, W, Yt), nepheline syenite and rare earth elements.

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 N.W.T. 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 N.W.T. of potential interest for rare element content or rare mineral species. The areas are listed and described below and the locations shown on Figure 9.2.

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 usually isolated and typically small (less than 30 km^2)
- These are S-type granites (derived from supracrustal source material)
- Usually mid-Cretaceous
- Peraluminous (ASI index 1-2), often megacrystic and leucocratic
- Show initial $^{87}Sr/^{86}Sr$ ratios greater than 0.7100 (often 0.7200 to 0.7400)

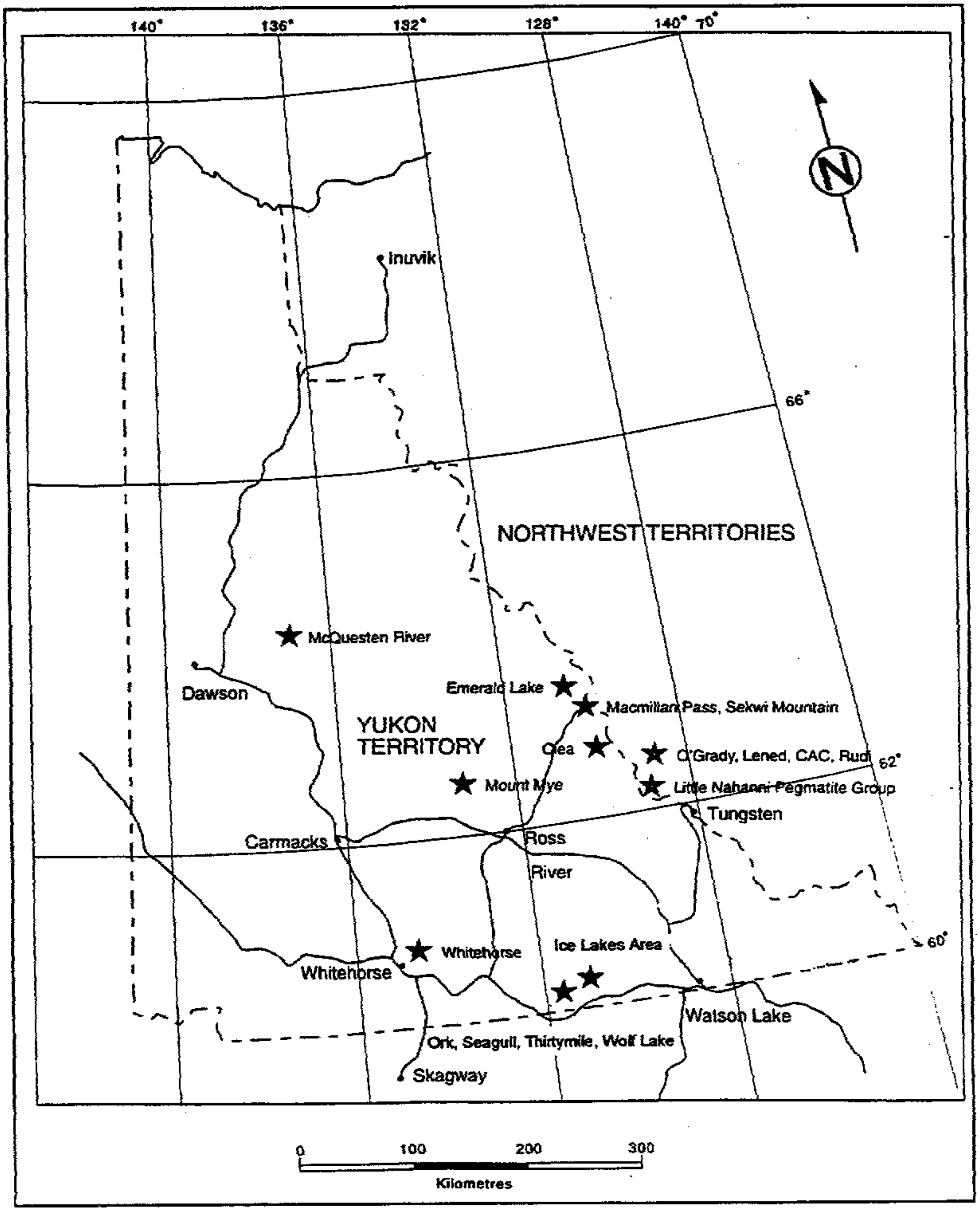


Figure 9.2 Potential areas for rare-element pegmatites From Groat et al., (1995)

- They often have a peraluminous accessory mineralogy (two-mica granite, garnet or andalusite-bearing) or rare-element bearing accessory mineralization (lepidolite = lithium)
- Their whole-rock geochemistry is rich in LILE and HFSE

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*
Little Nahanni Pegmatite Group* (on N.W.T. border)
O'Grady Batholite* (on N.W.T. border)
Seagull Batholith
Thirtymile Pluton and Ork Stock
Mount Mye Batholith, Anvil Plutonic Suite
Sekwi Mountain Area
Macmillan Pass
Whitehorse area, mid-Cretaceous suite
Emerald Lake

The localities marked with asterisks are ones visited and studied by Groat et al., (1995). The remaining areas have not been looked at.

The most interesting areas, the Little Nahanni area and O'Grady batholith are not in the Yukon, but are situated just across the border in the N.W.T. 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 tourmaline 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 is given by Sinclair (1986). 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 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 granites.

The Be Association

Light green, opaque beryl has been noted in many places in the Cassiar Batholith. Sinkankas (1981) documents locations of beryl and Groat et al., (1995) report on its presence in a zoned pegmatite field south of Ice Lakes on the Wolf Lake map sheet. They 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.

Gem-quality topaz in miarolitic cavititeshas been found in the Cassiar Mountains area east of Seagull Creek. This locality is described by Grice and Gault (1985). Sherry-color topazassociated with alluvial cassiterite is reported from the Klondike area from Germaine Creek (Yukon MINFILE, 1996).

Ultramafic Rocks

The ultramafic rocks associated with ruby deposits in Kenya are anomalous in Cr, Ni, Co and Co. Key and Ochieng (1991) 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 color is more obvious. One of the authors (Key, 1980) notes that the ultramafics have distinctive spectral signatures and are easily recognized on high resolution satellite images.

Any feldspar-rich pegmatites intruding ultramafic or basic rock would be a good target. The other good gemstone exploration target are aluminum rich metasedimentary rocks, perhaps originally derived from a bauxite deposit. 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.

The Be and Cr Connection

A primary gemstone exploration target would be those areas where rare-element pegmatites intrude or are close to any type of chromium-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 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 Be anomalies in areas showing geochemical Cr anomalies, areas of ultramafic rock or aeromagnetic anomalies which could represent buried ultramafic host rocks.

Gemstone deposits of any type are extremely rare compared with the more familiar and common precious metal and base metal deposits Yukon prospectors and geologists are familiar with. It is hoped that this report will generate interest in the exploration and identification of valuable gemstone deposits.

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APPENDIX A

EQUIPMENT SUPPLY COMPANIES

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