GEM-BEARING PEGMATITES: A REVIEW

By James E. Shigley and Anthony R. Kampf

Many of the important gem minerals seen on today's market—aquamarine, tourmaline, and topaz, among others—come from an unusual type of rock known as a pegmatite. Gem-bearing pegmatites are crystalline igneous rocks that are distinguished by their large-size crystals, concentrations of certain chemical elements otherwise rare in the earth's crust, and various unusual minerals. Pegmatites are typically rather small bodies of rock that are found in particular geologic environments; the gem minerals occur in open cavities or "pockets" within the pegmatite. This article surveys our current understanding of pegmatites, beginning with a brief description of their characteristics and following with a discussion of the occurrence of gem minerals in them. The article concludes with a summary of the specific conditions necessary during pegmatite formation for the crystallization of abundant gem minerals.

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Aquamarine, tourmaline, topaz, kunzite, morganite—these are but a few of the gemstones found in the remarkable mineral deposits that geologists call pegmatites (figure 1). Of the many different kinds of rock exposed at the earth's surface, pegmatites contain the greatest abundance and variety of gem minerals. Pegmatite deposits in various parts of the world have yielded spectacular crystals of gem tourmaline (figure 2), topaz (figure 3), and beryl (figure 4), as well as a host of other minerals occasionally used as gems (see tables 1 and 2). Most of these minerals are only rarely found in other geologic environments in crystals suitable for faceting. In addition, pegmatites are a major source of certain rare elements of great economic importance.

This article briefly summarizes current knowledge concerning the nature and formation of these fascinating rocks and the occurrence of gem minerals within them. Individual pegmatite localities are not discussed in detail here. Rather, a broad overview is presented to demonstrate the remarkable similarities between gem-producing pegmatites in diverse parts of the world. Armed with this perspective, the reader should be able to better appreciate detailed reports of pegmatite occurrences such as those in Brazil that are discussed elsewhere in this issue.

WHAT IS A PEGMATITE?

The famous mineralogist Haüy first used the word *pegmatite* in the early 1800s to refer to a rock with a patterned geometric intergrowth of feldspar and quartz (now commonly termed *graphic granite*). Today it is applied to any crystalline rock that is, at least in part, extremely coarse grained. The term *pegmatite,* then, primarily refers to the texture of a rock, that is, the size, shape, and arrangement of mineral grains. In practice, it can be applied to a wide range of rocks of igneous or metamorphic origin that exhibit large crystals.

Figure 1. A selection of gemstones of pegmatite origin ranging from 5.87 to 11.25 ct. Minerals shown (from left to right, and from front to back) are as follows: tourmaline (elbaite), garnet (spessartine), chrysoberyl; topaz, feldspar (orthoclase), beryl (morganite); beryl (aquamarine), tourmaline (elbaite), tourmaline (elbaite); beryl (heliodor), spodumene (kunzite). Photo by Tino Hammid.

In reality, the vast majority of pegmatites are found to be chemically and mineralogically similar to ordinary granites and, hence, are called "granitic" pegmatites (as opposed to "gabbroic" pegmatites, "syenitic" pegmatites, etc.). Because gem minerals are, for the most part, found only in granitic pegmatites, these will be the focal point of the ensuing discussion.

Texture. Although pegmatites are commonly thought of as very coarse-grained rocks, they actually vary considerably in grain size. This variability is important in distinguishing pegmatites from most other crystalline rocks. For example, the mineral grains in a granite are quite uniform in size and only rarely exceed several millimeters in diameter. Those in a pegmatite are usually several centimeters across on average, but they can range from millimeters to meters in diameter (figure 5). Typically there is an increase in crystal size from the outer margins toward the interior of the pegmatite body.

The largest crystals ever found have come from pegmatites (see, for example, Jahns, 1953; Rickwood, 1981; Sinkankas, 1981). Outstanding examples include a 14-m-long spodumene crystal from the Etta mine in the Black Hills of South Dakota and an 18-m-long beryl crystal from a

Figure 2. Multicolored crystal of tourmaline with albite feldspar and quartz from a pegmatite in Afghanistan (14 × 9 cm). Photo © Harold & Erica Van Pelt. Specimen courtesy of David Wilber.

pegmatite at Malakialina, Madagascar. The famous Harding pegmatite in New Mexico contains spodumene crystals that are 5 m long (figure 6). Unfortunately, these and most other giant crystals are not of gem quality. There are, however, exceptions: for instance, a 300-kg transparent gem topaz from a pegmatite in Minas Gerais, Brazil, is now on display in the American Museum of Natural History in New York.

Mineralogy and Chemistry. The minerals that occur in any rock depend on the rock's overall chemistry and the pressure and temperature conditions under which it formed. Most granitic pegmatites are composed of the same minerals found in ordinary granites, that is, feldspars (microcline, plagioclase), quartz, micas (muscovite, biotite), and on occasion some common accessory minerals (table 3; also figure 5). As such these pegmatites have generally been of limited economic, scientific, or gemologic interest. A small percentage of pegmatites, however, contain additional minerals, such as beryl and tourmaline, which incorporate certain rare elements. This latter group of granitic pegmatites, which are the source of most gem rough, have been the principal objects of pegmatite exploration and mining.

Establishing the chemical composition of a rock provides important clues regarding its origin, geologic history, and relationships to other rock types. Relatively fine-grained rocks, such as granites, are easily sampled and analyzed to determine overall chemical composition; however, this is not generally the case for pegmatites. Their coarse and variable grain size, nonuniform distribution of minerals, and often poor surface exposure pose serious obstacles to accurate chemical analysis. Nevertheless, painstaking work at a number of

Figure 3. Topaz crystals with smoky quartz from a pegmatite in the Ural Mountains of the Soviet Union (9 cm wide). Photo © Harold & Erica Van Pelt. Specimen courtesy of David Wilber.

Figure 4. A superb crystal of morganite beryl with albite feldspar from the White Queen mine, Pala, California (4 × 5 cm). Photo © Harold & Erica Van Pelt.

Table 1. Occurrence of gem minerals in pegmatites.

Mineral	Relative abundance[a]	Pegmatites the major source?
Common		
Feldspar (gem varieties orthoclase, amazonite, moonstone)	A	no
Quartz (gem varieties rock crystal, amethyst, smoky, rose, citrine)	A	no
Unusual (containing rare elements such as Li, Be, B, P, F, Cs, etc.)		
Apatite	R	no
Amblygonite	C	yes
Beryl (gem varieties aquamarine, morganite, heliodor, goshenite)	C	yes
Beryllonite	VR	yes
Brazilianite	VR	yes
Chrysoberyl	R	no
Danburite	R	no
Euclase	R	yes
Garnet (spessartine)	R	yes
Hambergite	VR	yes
Herderite	VR	yes
Lepidolite	C	yes
Petalite	R	yes
Phenakite	VR	yes
Pollucite	VR	yes
Spodumene (gem varieties kunzite, hiddenite)	C	yes
Topaz	C	yes
Tourmaline (elbaite—gem varieties rubellite, achroite, indicolite; liddicoatite)	C	yes

[a]*Relative abundance in granitic pegmatites: A = abundant and widespread; C = common or locally abundant; R = rare or uncommon; VR = very rare.*

localities has yielded meaningful estimates of the chemical composition of granitic pegmatites (see table 3).

Figure 5. Small pegmatite body cutting through granite at the Fletcher stone quarry near Westford, Massachusetts. Both the pegmatite and enclosing granite are composed of feldspars, mica, and quartz, but within the pegmatite the crystals are much larger. In addition, the crystals near the center of the pegmatite are larger than those along the outer margins. Photo by Richard H. Jahns.

Common granitic pegmatites show little deviation from typical granite chemistry (compare columns 1 and 2 in table 3). In contrast, those that contain small amounts of unusual minerals exhibit marked enrichments in a variety of rare elements (table 3, column 3). Lithium, beryllium, boron, and fluorine, in particular, are essential constituents in several important gem minerals. Despite their small total amounts (seldom over 2 wt. %, expressed as oxides), the concentrations of these and other rare elements in some granitic

TABLE 2. 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

Figure 6. View of the Harding pegmatite in Taos County, New Mexico. Several internal zones are visible as colored bands with differing texture and mineral content. This large, complex pegmatite, approximately 80 m thick, is rich in lithium minerals and rare elements, but apparently crystallized at too great a depth in the crust to allow for the formation of gem-bearing pockets. The elongate, light-colored crystals are common spodumene reaching 5 m in length. Photo by Richard H. Jahns.

TABLE 3. Chemical and mineralogical comparison of granite and granitic pegmatites.

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 (Schneiderhöhn, 1961).*

pegmatites can exceed by several orders of magnitude the amounts found in other rocks. In fact, the mining of pegmatites for rare elements, or even for the common pegmatite minerals, has at times been of far greater economic importance than the mining of pegmatites for gemstones. For instance, the Harding pegmatite (figure 6) was an important wartime source of beryl for beryllium, of lepidolite and spodumene for lithium, and of microlite for tantalum.

DESCRIPTIVE CLASSIFICATION

Efforts over the past century to better understand granitic pegmatites and their distinctive features have led to numerous attempts to classify them according to some logical framework. Most early schemes were descriptive in nature, and were based on various observable features such as shape or key minerals (see Landes, 1933; Jahns, 1955; Vlasov, 1961; Černý, 1982). One of the most widely accepted of these descriptive classifications was summarized by Heinrich (1956). This scheme, which is still useful today, divides granitic pegmatites into three types on the basis of internal structure:

1. Simple (figures 5 and 7a)—lack any segregation of minerals; may or may not display a systematic variation in texture; consist mostly of common silicate minerals with accessory minerals on some occasions.
2. Zoned (figures 7b, 8, and 9)—possess distinct internal zones of contrasting mineral content and texture; often larger than the simple types; consist of common silicate

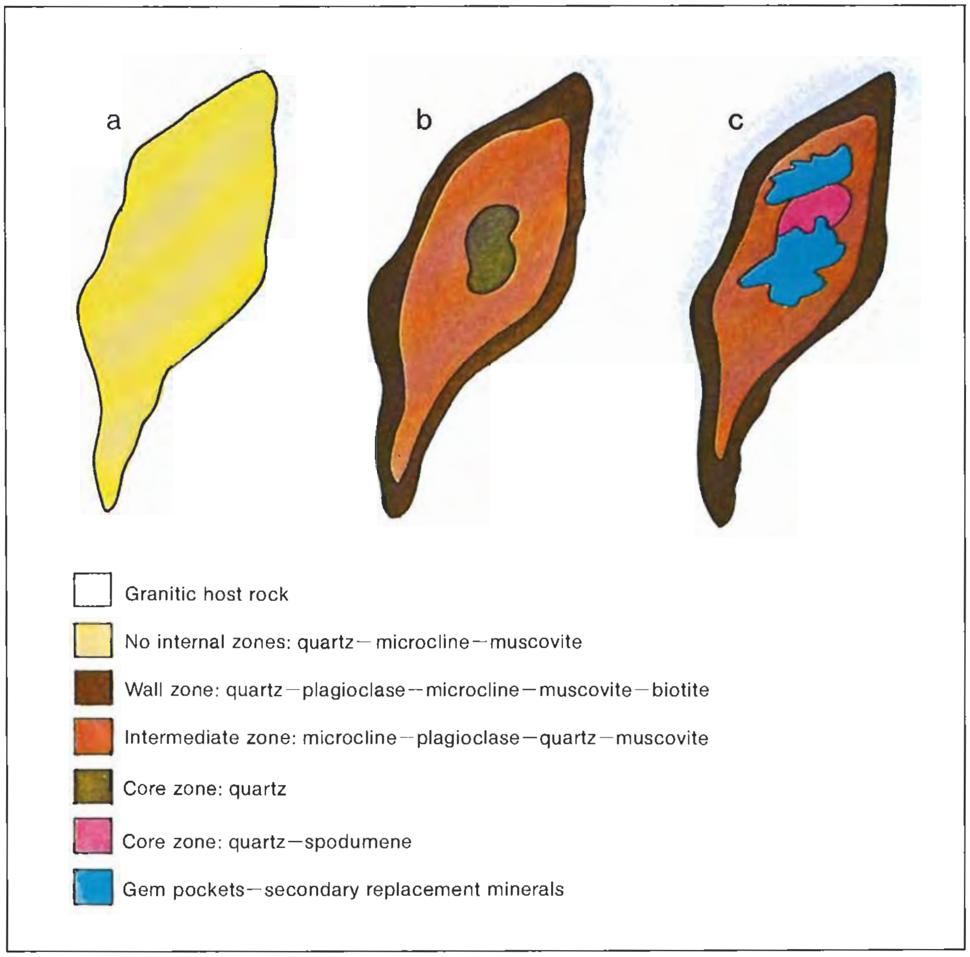


Figure 7. Idealized diagram showing internal structural relationships in simple (a), zoned (b), complex (c), pegmatites. Artwork by Christine Wilson; adapted from Jahns (1953).

minerals and various accessory species; minerals become more coarse grained toward the interior of the pegmatite.

3. Complex (figures 6 and 7c)—similar to the zoned types except also exhibit extensive mineral alteration and replacement; often contain high concentrations of rare elements and unusual minerals.

Simple pegmatites are by far the most numerous, while complex pegmatites are the least common but of greatest interest to the geologist and miner. Giant crystals, rare elements, and gem minerals are generally restricted to zoned and complex pegmatites.

Minerals found in the latter two types of pegmatites are arranged in layers or zones. As illustrated in figures 8 and 9, in an ideal situation these shell-like zones are concentrically disposed around an innermost core and tend to follow the exterior shape of the pegmatite body. Although the internal structure of many zoned pegmatites is rarely so uniform, and may be quite complicated, fieldwork at numerous localities has documented a basic internal arrangement of minerals in pegmatites that is generalized in table 4. In the field, recognition of this mineral arrangement in a pegmatite is of enormous help both to the student of pegmatites and to the miner (Sinkankas, 1970).

GENETIC CLASSIFICATION

Building on the earlier studies, more recent attempts to classify granitic pegmatites have emphasized the geologic environment of pegmatite formation rather than descriptive details. For example, an alternative scheme proposed by Ginzburg et al. (1979; summarized in Černý, 1982) uses the conditions present at various levels in the earth's crust to help explain observed differences in the nature of pegmatites. They recognized four classes of pegmatites:

1. Those formed at very great depth (more than 11 km), which are generally unzoned and possess little economic mineralization other than occasional concentrations of

Figure 8. View of the Oregon No. 2½ pegmatite in the South Platte pegmatite district, Jefferson County, Colorado. This zoned granitic pegmatite is a vertical, column-shaped body with an exceptionally well-developed internal arrangement of minerals. The feldspar-rich intermediate zones were removed during mining operations, while the central quartz core was left standing. The pegmatite body is approximately 70 m in diameter. Photo by William B. Simmons, Jr.

uranium, thorium, and rare-earth elements.

2. Those formed at great depth (approximately 7–11 km), which may be zoned, are generally rich in mica, but have few rare elements.
3. Those formed at intermediate depth (approximately 3.5–7 km), which are often zoned, may contain small crystal-lined pockets, and possess a number of rare elements.
4. Those formed at shallow depth (less than 3.5 km), which are zoned, and which sometimes contain rare elements and gem pockets.

Ginzburg et al. further contend that at very great depth pegmatites are formed largely through the partial melting or metamorphic recrystallization of existing rocks essentially in place, while at lesser depths pegmatite formation becomes more and more an igneous process involving the injection of a magma (molten rock) and its subsequent crystallization.

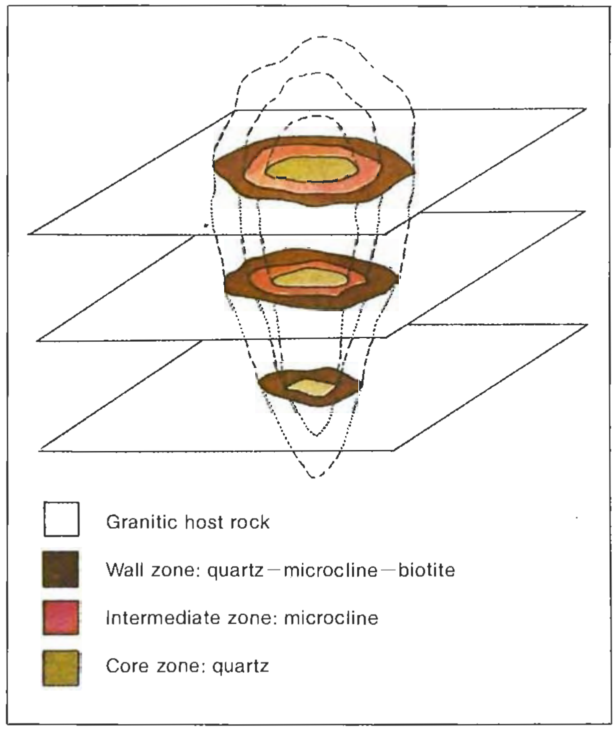


Figure 9. Idealized block diagram of a zoned granitic pegmatite similar to the one shown in figure 8. Note the horizontal and vertical zone structure and the apparent outcrop pattern resulting from the different levels of exposure possible. Artwork by Christine Wilson; adapted from Simmons and Heinrich (1980).

OCCURRENCE

Geologic Setting. Compared to most other rock types, pegmatites are relatively rare, yet they are widely scattered in the earth's crust and can be locally abundant. Pegmatites tend to be most common in particular geologic settings, generally where igneous or metamorphic rocks are exposed at the earth's surface (Jahns, 1955; Schneiderhöhn, 1961; Černý, 1982). Those pegmatites formed at very great depths are usually found in metamorphosed rocks that comprise the ancient cores of continents (e.g., the uranium–rare-earth pegmatites near Bancroft, Ontario). Those formed at deep and intermediate depths occur in folded and metamorphosed rocks in mountain belts (e.g., the mica pegmatites in the Soviet Union, and the beryl-spodumene pegmatites of the Black Hills, South Dakota). The shallow-depth pegmatites are associated with large, buried masses of intrusive igneous rocks, known as plutons or batholiths, that frequently underlie mountainous areas (e.g., the gem-bearing pegmatites of southern California, of the Hindu Kush region of Afghanistan, and of Minas Gerais, Brazil). Pegmatites in each of these depth-of-formation categories gradually become exposed at the surface over geologic time by either erosion or large-scale mountain uplift, and thereby become accessible.

Genetic Relationships. The close petrologic relationship that is sometimes apparent between pegmatites and plutonic igneous rocks has been taken as evidence that most pegmatites themselves result from the crystallization of silicate magmas. However, this connection is most obvious for the shallow pegmatites. As depth increases, metamorphic processes seem to play a greater role in pegmatite formation.

Age. The ages of pegmatites span much of the geologic time scale from 3.9 billion to less than 100 million years ago. As might be expected from their frequent occurrence in mountainous regions, pegmatites can often be correlated in age with the corresponding orogenic (mountain-building) periods.

Size. In general, pegmatites are rather small rock bodies, although quite large ones do occur. Outcrops of pegmatites have been observed to range from centimeters to meters in minimum dimension and up to several kilometers in maximum dimension (e.g., compare figures 5 and 6). Typically, pegmatite bodies are completely enclosed by other kinds of rocks. The actual dimensions of pegmatites are often difficult to estimate, not only because they are frequently irregular in shape, but also because very little of the pegmatite is exposed on the surface.

Shape. Pegmatites are among the least regular and most varied in shape of all rock bodies. This wide diversity can be attributed to a number of factors, including the depth of formation, the mechanical

TABLE 4. Some generalized features of internally zoned granitic pegmatites.[a]

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

[a]*Adapted from Cameron et al. (1949) and Norton (1983).*

Figure 10. Portion of an open gem pocket in the famous Himalaya pegmatite of Mesa Grande, California, with multicolored crystals of gem tourmaline up to several centimeters in length along with pale crystals of feldspar and quartz. Photo by Michael Havstad.

properties of the host rock at that depth, and the tectonic and metamorphic processes that took place at the time of formation. Shallow pegmatites often form sheet-like dikes, veins, or lenses that occur along faults or fractures in pre-existing host rocks. Deeper pegmatites, on the other hand, tend to be elliptical or ovoid as a result of the more plastic character of the enclosing rocks at depth.

OCCURRENCE OF GEMSTONES

Gemstones never constitute more than a small portion of any pegmatite body. Certain of the more common gem minerals, such as tourmaline, beryl, and spodumene, can occur as giant crystals in the intermediate or core zones of pegmatites. However, such large crystals are almost always highly fractured and clouded with inclusions, and consequently are of little or no gem value. The smaller, transparent crystals of these and other gem minerals are generally found only in pegmatite cavities, or "pockets."

Pockets are irregular openings in otherwise solid pegmatite (see figure 10). As found today, these pockets are usually filled partly or completely with clay, but during pegmatite crystallization they provided the necessary open space into which crystals could grow unimpeded, thereby attaining a very high degree of internal and external perfection.

Pockets are most common in the complex, internally zoned pegmatites, but even here they are infrequent. Although pocket-bearing granitic pegmatites are widespread in such regions as Minas Gerais, Brazil, and southern California, Jahns (1955) suggested that these cavities probably occur in less than one percent of all known pegmatites. Furthermore, few pocket-bearing pegmatites have the rare elements necessary for the formation of gem minerals in high-quality transparent crystals (figure 10). In fact, most contain only crystals of the basic constituents of the pegmatite itself, namely quartz, feldspars, micas, and schorl.

Even within the same pegmatite body, pockets can vary greatly in size and shape. Most are less than several centimeters in diameter, but a few several meters across have been reported. Nevertheless, the total volume of pockets is usually trivial in comparison to that of the enclosing pegmatite. There seems to be no particular relationship between the dimensions of the pegmatite and the number, size, or shape of its pockets. Even within the same pegmatite region, some pegmatites are remarkably rich in pockets (e.g., the Himalaya pegmatite shown in figure 11), while others have few if any.

Pockets are usually found within the central core or along the margins between the core zone and the enclosing intermediate zones. The mineral content from one pocket to another, even in a given pegmatite, is likely to vary considerably.

Figure 12, a diagram of an actual gem pocket found in a granitic pegmatite in southern California, illustrates several important characteristics of gem pockets. Pocket crystals are firmly rooted in the surrounding massive pegmatite, but in the open space of the pocket they are able to grow freely and thereby develop regular crystal faces. Crystals of feldspar and quartz are usually larger and more abundant than those of any gem minerals that may be present. Pocket crystals are often distributed nonuniformly, as is the case with the pocket in figure 12, where tourmaline was only found in place on the roof of the cavity. In some instances these crystals are etched or corroded as a result of chemical attack (see figure 13) and may exhibit replacement by secondary minerals. Broken crystals of feldspar, quartz, tourmaline, and other minerals that once grew from the walls are sometimes found scattered about in the pocket, usually embedded in clays that formed after the crystals had finished growing. Few gem species are

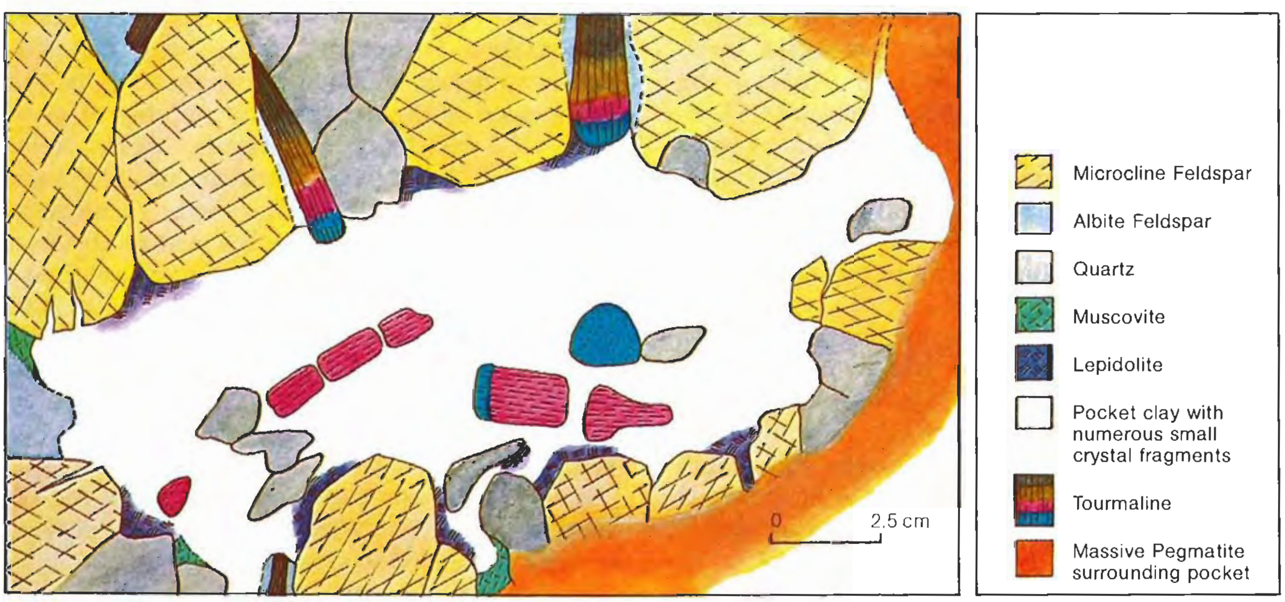
Figure 11. Underground mine view of the Himalaya pegmatite. The pegmatite, only about 1 m thick, is remarkably rich in gem pockets and has been a noted producer of gem tourmaline. The pegmatite consists of tan and grayish feldspars, grayish quartz, pink lepidolite, and black schorl. The light-colored areas along the central portion of the pegmatite are newly exposed but still intact gem pockets. Within the pockets, crystals of gem tourmaline are embedded in clays and other secondary alteration minerals. Photo by Michael Havstad.

found in any one pocket—in this case tourmaline was the only gem mineral present.

Some gem minerals exhibit compositional zonation to a varying degree within individual crystals. In an extreme example, such as tourmaline, this zonation is reflected in color zoning. That is, tourmaline crystals may have black, opaque (schorl) roots in the solid pegmatite and become pink, green, blue, etc. (elbaite) as they approach and project into a pocket.

Miners often use the color changes in tourmaline embedded in the massive pegmatite as an indication that a pocket area may be close by. Other indicators are the presence of lepidolite, the increased transparency of quartz, the black staining of the pegmatite by manganese oxides, extensive rock alteration, and the presence of clays. Miners quickly learn, however, that each pegmatite is

Figure 12. Diagram of a mapped, vertical cross section through a small, tourmaline-bearing gem pocket in the Stewart pegmatite, Pala, California. Crystal fragments of quartz and gem tourmaline, broken during the final stages of pocket formation, are embedded in the pocket-filling clay material. Artwork by Christine Wilson; adapted from Jahns (1979).



unique, with its own set of pocket indicators. They also learn that, despite careful attention to these clues, the location of productive gem pockets is still largely a matter of luck and hard work.

THE GENESIS OF GEM PEGMATITES

Although in the past there has been considerable disagreement among geologists regarding the origin of granitic pegmatites, there is a general consensus today that at least the shallower ones formed by crystallization from a magma. Numerous theories have been proposed to explain the formation of pegmatites via magmatic crystallization (see Landes, 1933; Jahns, 1955), but perhaps the most widely accepted general model is that of Jahns and Burnham (1969; also see Jahns, 1953, 1979, 1982). Their model is based on the work of many early investigators, notably Fersman (1931). The key points of this genetic model relevant to internally zoned granitic pegmatites containing gem minerals are described below.

Starting Materials. The starting material for a gem-bearing pegmatite is a volatile- and rare element–rich silicate magma derived from the final stages of crystallization of certain granitic magmas. Water is the most important volatile constituent of this pegmatite magma; however, other volatiles—such as fluorine, boron, lithium, carbon dioxide, and/or phosphorus—may be present. The rare elements include beryllium, cesium, niobium, tantalum, and tin, among others. Both groups of constituents may be present at much higher levels in pegmatite magmas than in the parent granitic magmas.

Figure 13. This crystal of gem green beryl from the Ukraine region of the Soviet Union (9 × 17.5 cm) displays intriguing surface features caused by chemical etching that took place subsequent to its formation in a pegmatite gem pocket. Photo © Harold & Erica Van Pelt.

Emplacement and Initial Crystallization. This pegmatite magma is injected into fractured rock in the upper portion of the crust; as the temperature falls, the magma begins to crystallize. Mineral formation begins at the outer margin of the pegmatite magma chamber at temperatures somewhat below 1000°C. Plagioclase feldspar, quartz, and muscovite mica crystallize first as the fine-grained border zone. Later, these are joined in the coarser-grained intermediate zones by microcline feldspar and additional minerals, such as common spodumene and beryl.

Concentration of Volatiles. The major chemical elements of the pegmatite magma determine the nature of the abundant, first-formed minerals such as feldspars, quartz, and micas. Because of their chemical and structural makeup, the early-formed minerals cannot, for the most part, incorporate the volatiles or rare elements present in the magma. As a result, these components are preferentially retained in the magma, where they become progressively concentrated. As crystallization continues with further cooling, the water content of the magma eventually reaches a saturation level. At this point, an aqueous fluid, rich in volatiles and certain rare elements, separates from the remaining pegmatite magma at between 750° and 650°C.

Nature of Aqueous Fluid. The physical properties of this aqueous fluid are markedly different from those of the magma and, therefore, the fluid greatly affects the subsequent crystallization of pegmatite minerals. The much lower viscosity of the aqueous fluid permits the rapid transport of chemical nutrients to the growing crystals, thereby promoting their growth in the innermost zones of the pegmatite. Its greater concentration of volatiles and many of the rare elements contributes to the partitioning of elements between magma and fluid, and thereby to the segregation of minerals in separate zones. In addition, vertical segregation of minerals has been attributed to the rise of the less-dense fluid within the pegmatite magma chamber. The aqueous fluid seems, in general, to be a superior solvent. Minerals crystallize from it at lower temperatures, and can grow to greater size, than from the magma. The fluid also tends to redissolve some earlier-formed minerals with which it comes in contact. This fluid is probably responsible for much of the secondary mineral replacement observed in complex pegmatites.

Intermediate Stages of Crystallization. The volatile-rich, aqueous fluid continues to exsolve from the magma as crystallization proceeds, and minerals in the inner zones of the pegmatite form in the presence of both the fluid and the magma. The last remaining magma eventually disappears at temperatures between 600° and 500°C. The innermost portions of the pegmatite are now occupied by large crystals of feldspar and quartz (and possibly common spodumene or beryl) with a few isolated, intervening "pockets" of trapped fluid.

Formation of Pocket Crystals. The formation of minerals in open pockets is the final stage in the primary crystallization of the pegmatite. With decreasing temperature (600° to 400°C) and rising internal pressure (resulting from the release of volatiles), crystallization continues from the fluid. Euhedral crystals of various minerals are able to form from the fluid within the open space of the pockets. At this stage, the concentrations of certain rare elements may reach sufficiently high levels for the crystallization of corresponding unusual minerals. In some instances, non-gem-quality crystals projecting into the pocket continue to grow and attain a more flawless, gemmy termination. This continued mineral growth is accompanied by changes in the chemical composition of the fluid which, in turn, are reflected in corresponding changes in some minerals (i.e., as exemplified by the color zonation of tourmaline). The occurrence of abundant liquid inclusions in many pocket crystals (and the gems faceted from them) attests to their growth from an aqueous fluid. The final temperature for mineral crystallization from this fluid may be as low as 250°C.

Evolution of the Pocket. Unfortunately, the changing fluid chemistry, coupled with decreasing temperature and increasing pressure, can eventually lead to the destruction of many pocket crystals. In addition, earlier-formed minerals may become unstable in contact with this highly reactive fluid. As a result, some pockets are found to contain only the remnants of what may have been gem-quality crystals altered to secondary minerals such as lepidolite mica and montmorillonite clay. Most of those pockets that ultimately produce gem minerals are thought by some to have undergone a final, very important step. This step involves the leakage of volatile fluids through breaks in the pocket walls that may have resulted from one or more of a number of possible mechanisms:

1. Increase in fluid pressure within the pockets that eventually exceeds the confining pressure or strength of the surrounding massive pegmatite.
2. Cooling and contraction of the pegmatite body.
3. Earth movements in the vicinity of the pegmatite body.

If the leakage of volatiles is gradual, the pocket crystals will remain intact. Unfortunately, evidence indicates that the pocket fluid often escapes rapidly, resulting in a very sudden drop in pressure and a consequent dramatic decrease in temperature. The resultant "thermal shock" is thought to be responsible for much of the internal fracturing often observed in gem crystals, as well as for the shattered fragments of crystals found on the floors of many gem pockets or embedded in the pocket clay. The fluid lost from the pocket is injected into fractures in the surrounding pegmatite where it results in the replacement of earlier-formed minerals.

Depth of formation is an important factor in determining whether pocket rupture will occur. It also seems to be a factor in determining whether pockets will form at all, because pockets are only found in the shallow and intermediate-depth pegmatites. It has been suggested that the separate, less dense, aqueous fluid phase, thought to be required for pocket formation, is only able to exsolve from the magma under the lower confining pressures experienced by pegmatites formed at shallower depths. This would explain the apparent lack of pockets in deeper pegmatites and the absence of pockets altogether from pegmatites in many parts of the world.

SUMMARY

Pegmatites are among the most geologically interesting and gemologically important types of rocks exposed at the earth's surface. They are crystalline rocks that are often characterized by highly variable texture, giant-size crystals, unusual minerals, and concentrations of rare elements. Pegmatites originate from residual magmas derived by partial melting of crustal rocks or as products of the final stages of igneous crystallization. Crystallization of these magmas, which are sometimes rich in volatiles and rare elements, gives rise to the distinctive mineral content and textural features of pegmatites. A small percentage of pegmatites contain well-formed crystals of gem minerals in pockets in their interiors.

With the increased demand for colored gemstones, the mining of pegmatites for gem material will continue to be an activity of small scale but great economic importance. This demand is leading to accelerated exploration of pegmatite regions for new sources not only in long-established areas such as Brazil and southern California, but also in newly discovered or recently accessible areas such as East Africa, Madagascar, and Afghanistan. Gem-bearing pegmatites are most likely to be found in geologic environments where the pegmatite magmas crystallized at shallow crustal depths. Pegmatites that form in other geologic settings hold less promise as sources of gemstones because physical and chemical conditions in these instances seem to preclude the formation of open pockets and, therefore, gem crystals.

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