GEM CORUNDUM IN ALKALI BASALT: ORIGIN AND OCCURRENCE

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Many deposits of gem corundum are associated with alkali basalt. Best known are the occurrences in Southeast Asia (especially Thailand) and Australia, which are responsible for much of the sapphire and fancy sapphire on the world market today. Yet alkali basalts are relatively uncommon, and corundum deposits are found only in those alkali basalts that occur in association with subduction zones involving ocean-continent plate collisions. This article offers a new hypothesis for the relationship between this rock type and gem corundum. It suggests that gem corundum is formed when certain rocks—such as shales, laterites, or bauxites, with aluminum-rich minerals—are subducted to depths of about 50 km, where metamorphism converts the minerals into corundum and other products that the alkali basalts later carry to the surface. The potential for new deposits is considered.

In 1992, more than 7.2 million carats of fashioned gem corundum were imported into the United States; of this amount, about 2.6 million carats were ruby and 4.6 million carats were sapphire (Austin, 1993). The total dollar value was almost US$153 million, second only to emerald ($213 million) for fine colored stones. These figures reflect the major role that gem corundums play in the jewelry industry.

The vast majority of gem corundums on the world market today, particularly blue and fancy sapphires, come from secondary deposits in Southeast Asia and Australia (figure 1). Although some of these deposits are associated with marbles, such as those in Burma (Mogok and Mong Hsu) and northern Vietnam, most are correlated with the occurrence of alkali basalt, a relatively uncommon type of volcanic rock. According to Olliver and Townsend (1993), until 1988 Australia supplied up to 70% by volume of the world's sapphires (mainly small dark stones); it now supplies about 25%–30%, owing to a large increase in production from Thailand. In both of these countries, the sapphires are recovered primarily from secondary deposits derived from alkali basalts. Yet while much has been published on marble-type deposits (again, as in Mogok) and those associated with peg-

Figure 1. The approximately 1-ct sapphire in this pendant is typical of some of the fine gem sapphires recovered from alkali basalts. Courtesy of Lindsay-Wasser, Toronto; photo © Tino Hammid.

matitic intrusions (e.g., Kashmir and the Umba River Valley of Tanzania), relatively little is known in the gem industry about the important alkali basalt source of commercial corundum. Thus, in this article we: (1) review various geologic aspects of this rock type and its relationship to gem corundum; (2) offer a theory for the origin of gem corundum in alkali basalts; and (3) apply the information gained to surmise, on geologic grounds, where additional gem corundum deposits of this type might be anticipated.

OCCURRENCE, CLASSIFICATION, AND MINERALOGY OF BASALTS

Basalt is a general term for a dark-colored, mafic (containing minerals with high contents of magnesium and iron), extrusive (volcanic) igneous rock. It is composed predominantly of calcium-rich plagioclase and calcium-rich pyroxene (mainly augite) plus other minerals, depending on the type of

basalt (see below). Basalts are by far the most abundant of the Earth's exposed crustal rocks. Not only do they cover essentially the entire ocean floor (usually beneath a thin veneer of sediments), but they also predominate in major "shield-type" volcanoes (which, on occasion, extend above the ocean surface, as is the case with the Hawaiian Islands). In addition, they occur extensively in certain continental settings, such as the Columbia River basalts of the northwestern United States. Basalts also occur abundantly on the moon and on the inner planets, including Mars. Basalts are discussed in all textbooks on igneous rocks (e.g., Williams et al., 1982; Philpotts, 1990).

Basalts can be classified into two broad types—tholeiite and alkali—based on their chemical characteristics and mineralogical composition. They can only be distinguished unequivocally by means of thin-section study with a polarizing microscope or by chemical analysis. Tholeiites constitute about 90% of all exposed basalts. Mineralogical (involving quartz, low-calcium pyroxene, feldspathoid minerals, and olivine) and chemical distinctions between the two types of basalt are shown in table 1.

Alkali basalts never contain quartz as a visible mineral or as theoretical "normative" quartz (a "norm" is a theoretical mineral composition of a rock calculated from the chemical analysis). They are characterized by the presence of silica-undersaturated minerals, including olivine, $(Mg,Fe)_2SiO_4$,

TABLE 1. Mineralogy and chemistry of tholeiite and alkali basalts.

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.%

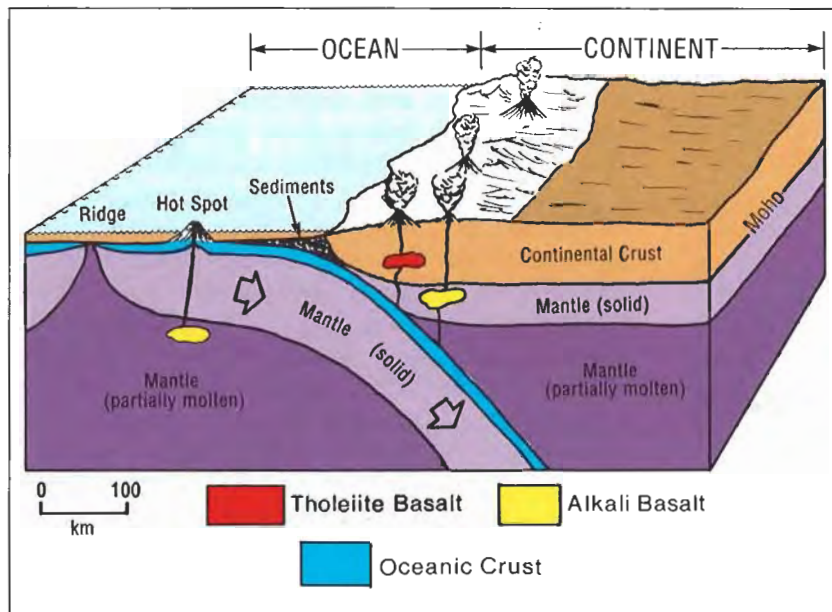[a]*Average of characteristic oxides; from Mysen (1987).*

Figure 2. The theory of plate tectonics explains how the Earth's solid outer portion (the lithosphere) is divided into a number of rigid thin segments (plates) which move in various ways. This includes downward movement at certain boundaries, particularly where continental and oceanic plates collide. This figure illustrates the process of subduction (as indicated by the arrows), in which a "conveyor belt" mechanism moves an oceanic plate, comprising mostly basalt with a thin veneer of marine sediment (shale, limestone, etc.), downward beneath a continent into the mantle. This figure also shows the source regions of magmas, which are generated by partial melting of material taken down the subduction zone, that may eventually rise to the surface and crystallize as tholeiite basalt and alkali basalt. Rhyolite and andesite magmas (not shown) would form at even shallower depths than tholeiite. These positions correspond in a general way with increasing depth (which is correlated with pressure) and temperature within the Earth. See text for further details. The Moho, the boundary between the crust and the mantle, is shown here at a depth of about 50 km beneath the surface of the continent. Corundum would form in the range of about 24 to 50 km below the continental surface, depending on the starting materials.

and certain minerals of the feldspathoid group such as nepheline, $(Na,K)AlSiO_4$, in which some of the characteristic alkali elements (Na, K) are found. Undersaturated minerals are those that would, under suitable conditions, react with free silica (quartz) if placed in contact with it to form more-silica-rich minerals. For example, there would be no nepheline in contact with quartz because this feldspathoid would react with quartz to form albite. Consequently, the presence of undersaturated minerals such as nepheline and olivine together identifies the basalt as alkali. Note that tholeiite and alkali basalts are always found in separate and distinct flows.

ORIGIN OF BASALTS

Basaltic eruptions are closely linked with plate tectonics, the generally accepted theory that the Earth's surface is divided into about a dozen large, thick (usually about 100 km) plates that are moving very slowly (about 2.5 cm—1 inch—per year), as illustrated in figure 2. Intense geologic activity, such as earthquakes and volcanism, occurs along the plate boundaries, and the process appears to have been in operation for most of geologic time. Typically, molten basalt (magma) rises from the Earth's mantle to the surface along zones of major rifting (i.e., crustal fractures)—primarily along mid-ocean ridges such as the Mid-Atlantic Ridge, at convergent plate boundaries such as are common along western South America and Japan, and above localized "hot spots" within the middle of plates such as Hawaii. Alkali basalts are found in all the above geologic environments.

To understand figure 2, it is essential to recognize that most rock types are composed of more than one mineral, and each mineral, or combination of minerals, has a specific melting temperature that is influenced by pressure, the amount of water present, and other factors. The process of "partial melting," in which minerals with the lowest melting points within a rock melt first as the temperature rises, allows the generation of various types of magmas (such as rhyolite, andesite, and tholeiite) from some minerals; other minerals with higher melting points (i.e., that are still solid) do not form magmas until they reach greater depths with higher temperatures (as is the case with alkali basalts). By virtue of their greater buoyancy in liquid form, the early-formed magmas tend to rise and become concentrated in locations closer to, or on, the surface where they eventually solidify. In a subduction zone (a long, narrow belt in which one plate descends beneath another), it is unlikely that

Figure 3. A dark blue sapphire xenocryst is seen here embedded in alkali basalt, as it was recovered from Fangshan, Shandong Province, China. Economic deposits with in situ corundum (i.e., primary deposits) in alkali basalt are rare. The yellow fragments adjacent to the sapphire are weathered ultramafic xenoliths from the mantle (from Guo et al., 1992b, who refer to the sapphire as a megacryst). Photo courtesy of J. F. Guo.

tholeiitic basalts will form in significant quantities until subduction processes have brought surface (oceanic crustal) rocks down to a depth of about 20–30 km; alkali basalts, however, are not likely to form at depths shallower than 50–60 km (Kushiro, 1987; Perchuk, 1987).

CORUNDUM IN BASALT

Many of the main commercial sources (e.g., Thailand, Australia) of gem sapphires are associated with the occurrence of alkali basalts. This does not necessarily mean, however, that corundum *crystallized* from the alkali basalt magma. This important distinction is explained by the fact that volcanic rocks, and particularly basalts because of the great depths from which they originate (at least 20 km in most areas), commonly carry to the surface xenoliths (rock fragments) and xenocrysts (crystals) of "foreign" origin. Thus, such fragments and crystals have no genetic relationship to the enclosing basaltic rocks (figure 3). For example, recent studies by Righter and Carmichael (1993) showed that all the inclusion-free and unzoned megacrysts (a general term used for large crystals of any type) of augite, feldspar, kaersutite, olivine, and biotite from eight alkali basalts in the western

U.S. and Mexico were xenocrysts. The xenocrysts are derived from broken-up or dissolved xenoliths that probably originated from several different rock types at pressures of 5–15 kbar (approximately 15–45 km depth) and were carried to the surface by the alkali basalt magma. Hence, the situation is analogous to diamonds occurring as xenocrysts in kimberlite or lamproite, except that diamonds originate at much greater depths (>110 km; Kirkley et al., 1991). Other gem minerals that are typically xenocrysts, as opposed to primary crystallization products, in alkali basalts include zircon, some garnet, and some spinel. In contrast, olivine (which occurs as the gem variety peridot), as well as some other garnet and other spinel, may be either a xenocryst or a primary crystallization product (Williams et al., 1982; Philpotts, 1990).

Most researchers (see, e.g., Schulze, 1987; Coenraads et al., 1990; Guo et al., 1992b) have concluded that corundum always occurs as xenocrysts in alkali basalts—and does not crystallize from the magma itself—on the basis of three key factors.

1. Experimental studies have shown that corundum cannot be grown from a melt of normal basaltic composition.
2. The surface features—e.g., rounding, etching, and corrosion—of the corundum crystals indicate that the crystals are partially resorbed by the alkali basalt magma (corundum is unstable in this magma, and if in contact with it for a long period probably would be completely resorbed).
3. Certain minerals found as inclusions in corundum, such as zircon and columbite, could not have grown from such a magma.

Significantly, all reported economic, and potentially economic, secondary occurrences of basaltic corundum are spatially associated with the alkali type of basalt. (Coenraads et al., 1990, mention two possible exceptions, in Nigeria and Southern China, but these are not well documented.) Further, most found so far are of Cenozoic age (66 million years or younger), although this may be a result of limited sampling. These observations apply to the occurrences in Chanthaburi-Trat, Thailand (Keller, 1982); numerous other localities in Thailand, Cambodia, and Kampuchea (Coenraads et al., 1990); New South Wales, Australia (Coldham, 1985; Coenraads et al., 1990); three areas of China (Keller and Keller, 1986; Wang, 1988; Guo et al., 1992b); and southern Vietnam (A. S. Keller, pers. comm., 1994). One exception is the little-known deposit in the Mercaderes-Río Mayo area of

Colombia, which is reportedly Cretaceous (66–144 My) in age (Keller et al., 1985).

ORIGIN OF CORUNDUM IN ALKALI BASALT

The main geologic question is: Why are gem corundum crystals found as xenocrysts only in alkali basalts, which represent a relatively small proportion (about 10%) of all basalts? We view the way in which corundum crystals are concentrated in alkali basalts as a two-stage process in the context of plate tectonics theory. The first stage relates to the formation of corundum (separate from the formation of the basalt) deep in the Earth; the second stage relates to the process whereby the alkali basalt magma brings the corundum to the surface.

Stage 1: Corundum Formation. We propose that there are two main mechanisms involving plate tectonics and metamorphism by which corundum can be formed; each involves different starting materials.

Mechanism 1. Aluminum-rich sedimentary rocks, particularly shales (which typically contain such aluminum-rich minerals as muscovite [illite] and kaolinite), are often carried to significant depths in areas of plate-margin interactions such as subduction zones (again, see figure 2). Once the sediments have reached an appropriate depth and sufficiently high temperature by this "conveyor belt" mechanism, they undergo conversion to other minerals that are more stable in the new higher temperature/pressure environment.

Corundum, Al_2O_3, along with potassium feldspar (orthoclase) and water, is a breakdown product of muscovite, a common micaceous mineral found in shales:

Equation 1
$$KAl_2(Si_3Al)O_{10}(OH)_2 \rightarrow KAlSi_3O_8 + Al_2O_3 + H_2O$$
(muscovite)   (orthoclase) (corundum) (water)
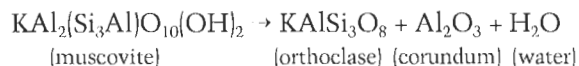
The above reaction must take place in the absence of quartz or else aluminum silicates such as kyanite (Al_2SiO_5) instead of corundum will form. Indeed, the fact that kyanite and related minerals are much more common than corundum in metamorphic rocks is evidence that quartz is usually present when muscovite breaks down. Further, if water is present above a certain pressure (about 4 kbar), muscovite will melt rather than form the reaction products shown. Notwithstanding the above restrictions, such reactions are well established. For example, Williams et al. (1982) state that certain aluminous minerals found in basalts, such as spinel, corundum, and cordierite (iolite), represent refractory (i.e., unmelted, unchanged) residues from fractional (partial) melting of shale.

Figure 4 illustrates a phase diagram of the systems muscovite-corundum and diaspore-corundum, which are discussed below. (A *phase diagram* is a graph in which two or more variables, in this case temperature and pressure, are plotted to show the boundaries of the fields, or areas, of stability of various phases; in this case, the phases are minerals. A *system* is that portion of the universe that is being studied, in this case, the mineral conversions of muscovite to corundum and diaspore to corundum.) These phase diagrams can be applied to the breakdown of muscovite and diaspore under conditions of high temperature and pressure, as would be encountered in a subduction zone.

With respect to the breakdown of muscovite, experimental studies have shown that the reaction given above can occur over a wide range of pressures (as indicated by the line separating muscovite from corundum + orthoclase + water in figure 4; pressure is comparable to depth in this case), but in only a relatively narrow range of temperatures (about 650°–725°C; Evans, 1965). Thus, corundum may be expected to crystallize at many different depths or pressures in the Earth's crust if the temperatures are high (*and* if quartz and water are absent). Such conditions occur at shallow depths (characterized by low pressure) in some contact-metamorphic areas where granitic (including pegmatitic) rocks are intruded into sediments, and at greater depths (>20–25 km, characterized by high pressure) in regionally metamorphosed rocks, such as gneiss. However, in a subducting plate, the conversion would take place at depths of about 42 km or greater. It should also be emphasized that the conditions required for this reaction to occur—for example, the absence of quartz, and the absence of water above a pressure of 4 kbars—may be rare in natural situations.

Mechanism 2. With fewer geologic restrictions, corundum could form from other starting materials, particularly hydrated aluminum oxides—such as gibbsite, $Al(OH)_3$, and diaspore or boehmite, $AlO(OH)$. For example, the equation for the formation of corundum from diaspore or boehmite would be:

Equation 2
$$2AlO(OH) \rightarrow Al_2O_3 + H_2O$$
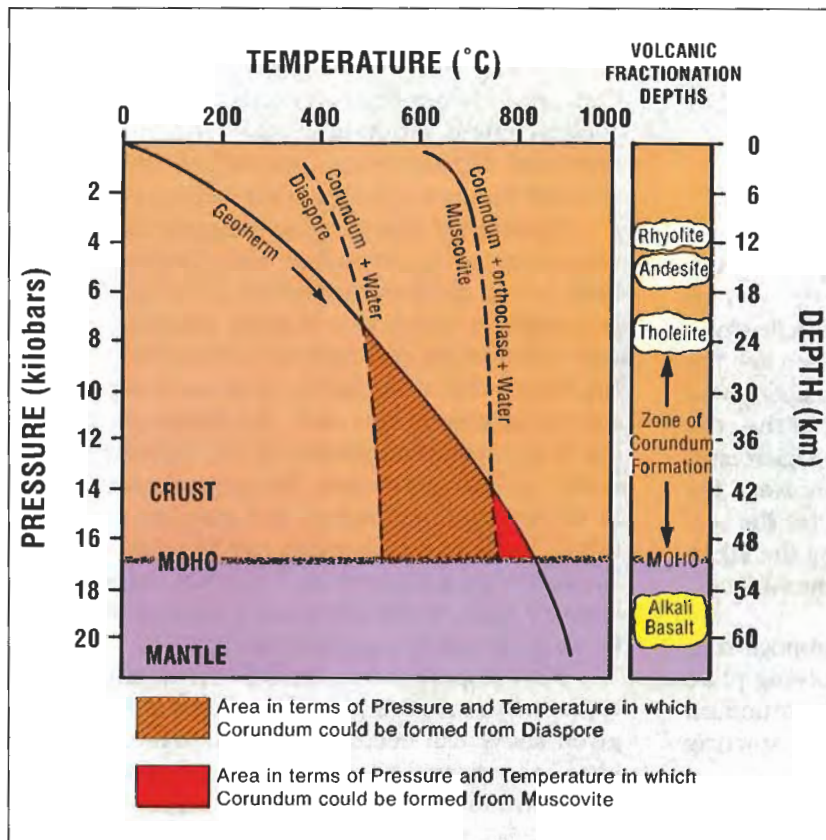(diaspore)   (corundum) (water)
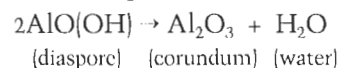
Figure 4. Phase diagrams are shown for conversion of muscovite to corundum (plus orthoclase and water), and diaspore (a constituent of lateritic and bauxitic soils) to corundum (plus water). Stability fields for the minerals are delineated by broken lines (solid where experimentally determined for muscovite), and a geotherm (temperature versus depth line) is plotted for the continental crust. Where the geotherm crosses the stability lines, conditions allow mineral transformation. Thus, corundum can only form from the breakdown of muscovite below about 42 km (cross hatching); however, it can form from the breakdown of diaspore as shallow as 24 km (slanted lines). Also shown are approximate depths of formation for various volcanic rocks. Only alkali basalt forms deep enough to migrate through the zone of corundum formation.

These hydrated aluminum oxides are typical of extensive laterite and bauxite terranes such as are found today in large areas of India, Africa, South America, Australia, and other tropical regions. The pressure and temperature conditions for the breakdown of gibbsite, diaspore, and boehmite also indicate that corundum might form from these minerals deep in the crust by mechanisms analogous to those discussed above for muscovite, except at depths as shallow as 24 km (see figure 4). Gibbsite, diaspore, and boehmite were suggested as possible starting materials for the formation of gem corundum, particularly ruby, in regional metamorphic environments such as at Mogok (Kammerling et al., 1994). Even though these latter deposits are in marbles rather than in alkali basalts, and the methods by which they reached the Earth's surface are distinctly different, the fundamental metamorphic reactions by which corundum is formed from aluminum-rich minerals (see equation 2) are still applicable.

Stage 2: Transport of Corundum to the Surface. The second stage of the process requires a method to bring the corundum crystals to the surface. Key factors in this process are listed below, and the entire process by which corundum forms and is transported to the surface in alkali basalts is illustrated in figure 5.

1. Basalt magmas typically migrate to the surface rapidly (sometimes explosively), in a matter of hours to days. During this short time period, alkali basalt magmas must: (a) incorporate the corundum-bearing xenoliths (figure 6), and then (b) disintegrate and dissolve the xenoliths, thus releasing the corundum and other refractory minerals (e.g., zircon) into the magma as xenocrysts. In most cases, there is at least some resorption of the corundum, as evidenced by characteristic rounding, etching, and corrosion of the surface. At the time it travels upward, the alkali basalt magma is at a temperature of 1100°–1300°C.

2. The depths at which alkali basalts form (> 50 km) require that—to reach the surface—they must pass through the uppermost mantle and deep part of the Earth's continental crust, where corundum crystals may have formed. This contrasts with other extrusives (such as rhyolite and andesite), which typically form at depths of only 10–25 km; this is too shallow to encounter any significant number of corundum crystals, which would have formed in the
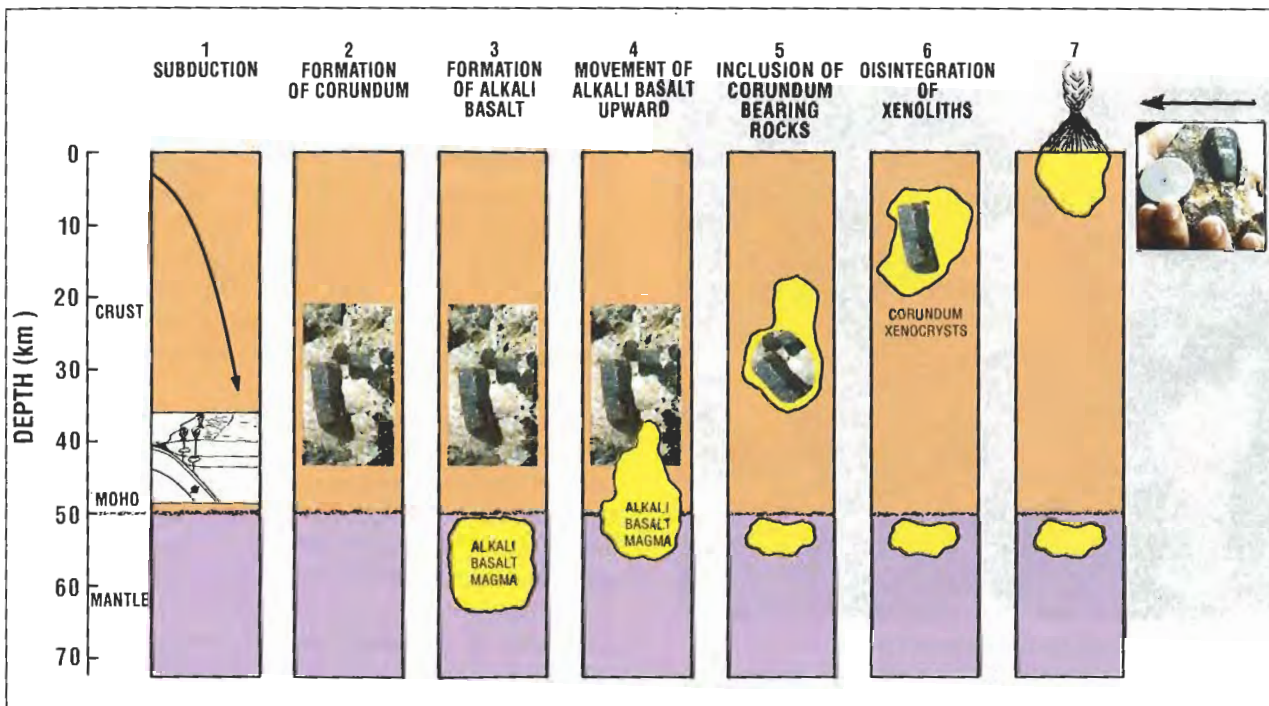
Figure 5. There are several main stages in the formation of corundums and their transport to the surface in alkali basalt: (1) subduction of appropriate starting materials (e.g., aluminum-rich sediments, laterites, bauxites; see figure 2); (2) formation of corundum in appropriate rocks (e.g., gneiss; see figure 6) deep in the crust by means of metamorphism of the starting materials (see figure 4); (3) formation of alkali basalt in the upper mantle by partial melting; (4) movement of alkali basalt upward; (5) inclusion of corundum-bearing xenoliths in alkali basalts (some alkali basalt remains in the mantle); (6) disintegration and resorption of xenoliths, the release of corundum crystals (xenocrysts), and continued transport upward; and (7) volcanic eruption brings corundum crystals to the surface (see figure 3).

Earth's lower continental crust. (Under some conditions of elevated temperatures in the lower continental crust, it might be possible for the geotherm [temperature versus depth line] of figure 4 to intersect the corundum stability field at shallower depths such that corundum could be formed at depths appropriate for transportation by tholeiite or andesite magmas. However, this would likely be rare.)

These various conditions are met, for example, in Southeast Asia (figure 7). Alkali basalts in Thailand, Cambodia, and Vietnam migrated through thick, fractured continental crust (Polachan et al., 1991) and occasionally carry corundum xenocrysts to the surface. Even in this area, however, corundum-bearing alkali basalts are not common.

We emphasize that the formation of alkali basalt magma may occur long after, and may even be unrelated to, the subduction that carried the aluminum-rich rocks to depth. In eastern Australia, for example, the sapphire-bearing alkali basalts are primarily younger than 55 million years, and subduction ceased about 200 million years ago (Veevers et al., 1991). In this region, alu-

minum-rich rocks may have been carried to depth by subduction and remained part of the lower crust until an alkali basalt magma, or other heat source in the general region, provided sufficient heat to effect conversion of some minerals to corundum. In the case of the alkali basalt magma, the same heat source could subsequently provide a mechanism to bring the corundum to the surface.

ALTERNATIVE THEORIES FOR ORIGIN OF CORUNDUM IN ALKALI BASALT

Only a few theories to explain the occurrence of gem corundum in alkali basalt have been proposed. Hughes (1990) briefly mentioned three: Two suggested that the corundum crystals were xenocrysts of unknown deep origin, whereas the third suggested that the corundum formed, as a primary mineral, in a basaltic magma generated at depths of 65–95 km by partial melting of mantle material.

Because so few corundum crystals have been observed *in situ* in (alkali) basalts in Australia, Pecover (1987) suggested that (alkali) basalt may not be the rock from which corundum is released, at least in that country. Rather, he suggested that

Figure 6. This hand specimen from Gallatin County, Montana, shows gray corundum crystals (longest is about 13 cm—about 5 inches, not of commercial quality) in contact with coarse-grained nepheline (white; a feldspathoid mineral) in a gneiss. The fine-grained areas of gneiss contain muscovite, feldspar, and sillimanite. This rock formed deep in the crust (at perhaps 20–25 km) and was brought to the surface by tectonic activity (not by alkali basalt magma). Although the exact conditions are not known, this rock could have been formed by the mechanism described in this article. Photo © GIA and Tino Hammid

basaltic "tuff" (a rock formed of compacted volcanic fragments), which may represent the surface expression of much deeper pipe-like bodies, may have carried the corundum to the surface.

Two distinctly different theories for the magmatic origin of corundum in alkali basalts, based primarily on the study of deposits in eastern Australia, have been developed: (1) by Coenraads et al. (1990) and Coenraads (1992); and (2) by Guo et al. (1992a, 1994). Both theories recognize that it is unlikely that corundum crystallized from its host alkali basalt and suggest different ways in which corundum may have crystallized from another magma, high in Al_2O_3 content, that is distinct from the alkali basalt that brought the crystals to the surface.

Both of these theories are based, in large part, on the importance attached to certain minerals found as inclusions in Australian sapphires that, like the corundum host, could not have crystallized from an alkali basalt magma. These include zircon, columbite, uranium pyrochlore, thorite,

ilmenite, alkali feldspar, and cobalt-rich spinel (the last only from Guo et al., 1994), as well as carbon dioxide–filled fluid inclusions. Thus, they concluded that the sapphires and their inclusions must have grown in an environment rich in "incompatible elements" (those elements, such as Zr, Nb, Ta, U, Th, Ti, and Co, that do not fit into the structures of the common rock-forming minerals), alkali elements (e.g., K and Na), and volatiles (e.g., CO_2).

On the basis of these and other data, such as the presence of iron-rich melt inclusions and the ages of included zircons, Coenraads et al. (1990) developed a model involving two magmas. Basically, this model involves: (1) the ascent from the mantle of a carbonate-enriched mafic magma (first magma) that also contained the incompatible elements; (2) crystallization of corundum and its inclusions within this magma; and (3) later volcanic eruption of alkali basalt (second magma) to entrain the corundum and bring it to the surface.

Guo et al. (1992a, 1994) developed a more complex, multistage model involving four magmas. Their model involves: (1) the ascent from the mantle of a carbonate-enriched mafic magma (first magma) containing the incompatible elements; (2) the interaction of this magma with an alkali-rich felsic (granitic) magma (second magma) in the lower crust; (3) the resulting hybrid magma (third magma) having favorable chemical characteristics (low SiO_2, high Al_2O_3) for the crystallization of corundum; and (4) later volcanic eruption of alkali basalt (fourth magma) to bring the corundum to the surface.

The mixing of two different magmas in the Guo et al. model to produce a third magma with distinctive characteristics is an accepted geologic process (e.g., Williams et al., 1982; Philpotts, 1990), and the mechanism they propose is theoretically possible and may well occur on a local scale. However, we believe that it requires too many special conditions to be applicable to the origin of the widespread corundum deposits of Southeast Asia and Australia. On the other hand, our metamorphic (as opposed to magmatic) model, which uses aluminum-rich sedimentary rocks such as laterite or bauxite as the starting material, provides a simpler explanation for the formation of corundum crystals and all the included minerals (e.g., columbite) that are so fundamental to both of the above models. In particular, our model requires only one magma (alkali basalt)—as a transport mechanism to bring corundum to the surface.
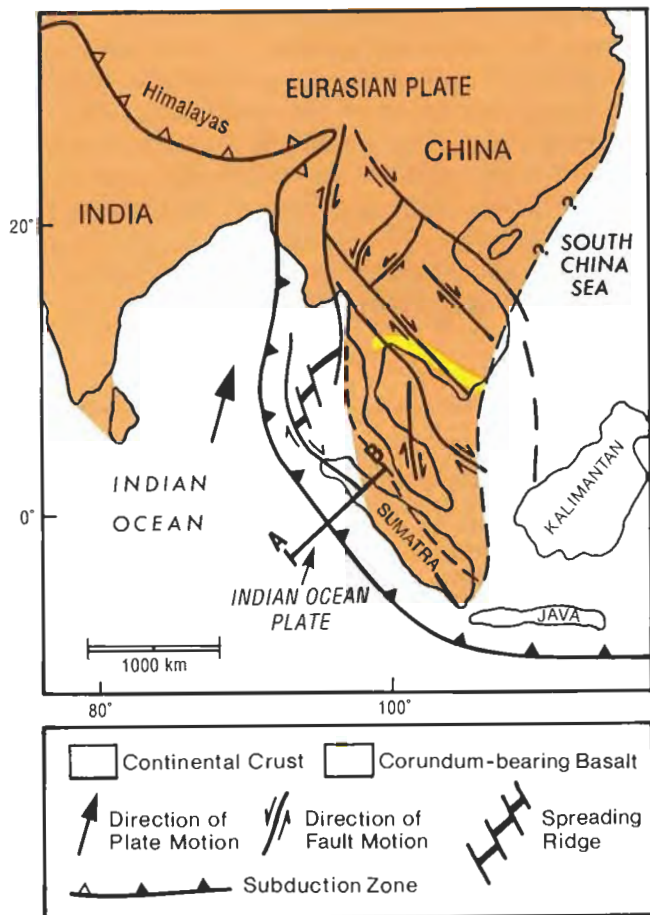
Figure 7. In this generalized tectonic map of Southeast Asia, alkali basalts (yellow area) are located in Thailand, Cambodia, and Vietnam. They occur in old (and probably thick) continental crust in a region that is presently undergoing active faulting associated with the subduction of the Indian Ocean plate beneath the Eurasian plate. A cross-section of the Earth through the crust and upper mantle (line A–B) might approximate the cross-section shown in figure 2. The corundum-bearing alkali basalts are located north of line A–B, where the crust may be thicker and where fractures produce zones of weakness through which the alkali basalt magmas rise to the surface.

Adding support to our proposed metamorphic model is the report by Koivula and Fryer (1987) on the discovery of an inclusion of sapphirine (not sapphire), $(Mg,Al)_4(Al,Si)_3O_{10}$, in a ruby from Bo Rai, Thailand (from alluvial deposits associated with alkali basalts). Sapphirine has also been reported associated with ruby and sapphire in one locality in eastern Australia (Sutherland, 1994). Sapphirine

only forms in a metamorphic environment, and Harley (1989) has shown that it crystallizes at pressures and temperatures appropriate for the lower continental crust.

During the formation of laterite and bauxite, certain trace and minor elements may be concentrated in these materials depending on the type of rock material from which they are formed by intensive weathering. For example, all the incompatible elements mentioned above are concentrated to some degree; some, such as Ti, Zr, and Nb may be enriched by as much as fivefold as compared to their parent material (Mason, 1966), which was probably a granite or a syenite. Some laterite deposits developed on mafic rocks—such as in New Caledonia, Australia, and Indonesia—have such large amounts of nickel and cobalt that they are economic to recover (U.S. Bureau of Mines, 1980). Depending on the presence of minor amounts of other minerals (e.g., calcite) in laterites, all other constituents emphasized in both the Coenraads and Guo models can be explained. Clearly, laterites and related weathering products contain the necessary minor and trace elements, in addition to large (or predominant) amounts of aluminum-rich minerals, to be a potential starting material for corundum formation. Not only are large areas of the world covered with laterites today, but it is also likely that equally large areas composed of laterite and similar materials (or weathered products derived from this material) have been subducted into the crust and mantle in the geologic past.

CONCLUSIONS

Although corundum is well known to gemologists, it is relatively rare compared to other minerals primarily because its formation requires an environment that has a low silica (SiO_2) content. Yet silica is one of the most abundant constituents of the Earth. The model presented in this article relates the formation of gem corundum deposits to subduction zones that carry aluminum-rich materials (i.e., quartz-free aluminous sediments, laterites or bauxites), which are naturally silica-depleted, below continental areas. At depths of about 25–50 km, these materials are transformed by metamorphic processes into corundum-bearing mineral assemblages. These assemblages are later brought to the surface by alkali basalt magmas, which form below 50 km. This metamorphic model is simpler than some previous magmatic models which, although they are theoretically possible and might well occur on a

limited scale, require numerous special circumstances. The effects of high temperature and pressure on corundum crystals during their transport in alkali basalt magmas are uncertain. However, it is interesting to speculate that they might influence the ultimate color and clarity of the corundum, analogous to some of the commercial enhancement processes currently employed.

At present, significant amounts of sapphire are obtained from secondary deposits derived from alkali basalts in Southeast Asia and Australia. We believe that additional sapphire deposits will be identified not only in the above-mentioned areas but also in other parts of the world where alkali basalts are, or will be, found. On the basis of this model for the origin of the corundum, and the mechanism by which it is brought to the Earth's surface, advances in geologic and geophysical knowledge should enable geologists to locate new areas worthy of exploration for gem corundum.

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