

GEOLOGY OF GEMSTONE DEPOSITS – EXPLORATION MODELS FOR WYOMING

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‘Bureaucracy is a giant mechanism operated by pygmies’ - Honore de Balzac

ABSTRACT

Much of Wyoming is underlain by Archean cratonic basement rocks and cratonized Proterozoic rocks that provide favorable geological environments for a variety of gemstones – notably diamond, iolite, ruby, sapphire, garnet, kyanite, andalusite, sillimanite, labradorite, jewelry grade gold, platinum and palladium nuggets, emerald, aquamarine, heliodor, tourmaline, spinel, clinozoisite, zoisite, apatite, jasper, specularite, etc. Thick Phanerozoic sedimentary rock successions with lesser Tertiary volcanic rock cover large portions of the basement terrain. Some of these Phanerozoic rocks provide favorable hosts for other gemstones including opal, placer diamond, placer gold, placer platinum, placer ruby, jasper, agate, emerald, varisite, etc.

Using traditional exploration and prospecting methods, dozens of gem and precious metal deposits were discovered over the past 3 decades including major discoveries and geological and mineralogical evidence for significant undiscovered deposits. Major swarms of mantle-derived kimberlite, lamproite and lamprophyre, many of which have proven to be diamondiferous, also host colored gemstones including pyrope garnet (Cape Ruby), spessartine garnet, almandine garnet, chromian diopside (Cape Emerald) and chromian enstatite. One lamproite also yielded peridot.

Favorable conditions for crystallization of metamorphogenic gemstones during regional amphibolite-grade metamorphism occurred during the Precambrian. In this terrain, metapelite in the central Laramie Range hosts kyanite, sillimanite and andalusite. These three minerals provide evidence of favorable pressures and temperatures needed for crystallization of aluminous gemstones including ruby, sapphire and kyanite. Cordierite (iolite) another aluminum-rich gemstone, formed during a later thermal event. This later event was responsible for deposition of world-class iolite (Water Sapphire) gemstone deposits.

Evidence for undiscovered gemstone deposits is predicted based on mineralogical anomalies detected during various research projects from 1977 until 2005. These include ruby, sapphire, gold and aquamarine found in stream sediment samples as well as favorable geological terrains that remain unexplored. Other anomalies include pyrope garnet (several with G10 geochemistry), picroilmenite, and some chromian diopside that provide evidence for hundreds of undiscovered diamond deposits. Elsewhere, detrital

diamonds reported by various prospectors provide direct evidence for undiscovered diamond deposits. Other geological and mineralogical evidence suggest the presence of additional undiscovered opal, cordierite (iolite) and kyanite deposits.

Wyoming could potentially become a major source for gemstones including diamond, gold, platinum, palladium, Cape ruby, Cape emerald, iolite and opal.

I dedicate this paper in memory of a friend and former colleague at the Wyoming State Geological Survey who greatly advanced the State's knowledge in industrial minerals and decorative stones. Ray E. Harris former Industrial Minerals and Uranium Geologist prematurely passed away – his passing was so unnecessary.

INTRODUCTION

Gemstones are timeless treasures of nature that not only represent objects of beauty and intrigue, but also represent some of the more valuable commodities on earth. The extraordinary and satiated colors of many gemstones enhance their aesthetic beauty, while others may produce extraordinary fire, birefringence or other unusual light display or interference. When Mankind first picked a stone from the ground for its innate beauty rather than as a tool or weapon, this symbolized an important event in evolution. Mankind visualized beauty. And when this stone was given to another as a gesture of friendship or love - a unique quality of the human soul was manifested in the sharing.

This evolution led Man to search for similar rocks and minerals. The recognition of certain characteristics in a particular stone and its association with nearby specific rock types, such as agate or jasper in distinct grey to white rock (limestone), or quartz crystals in vugs of milky white and pink rocks (pegmatite dike), etc., greatly enhanced the ability of early prospectors to find additional stones of similar quality. Recognition of such mineral and rock associations signaled the start of the science of prospecting. As time passed, these primitive prospectors exchanged ideas and concepts that ultimately led to the science of economic geology.

Recognizing rock and mineral associations and understanding regional geology is important in a search for new gemstone deposits. In this search, the successful geologist and prospector not only focus on the regional geology, but also the surrounding host rocks, mineral and rock associations, and past geological environments. Gemstones, like any other mineral grow or crystallize under specific physical and chemical parameters. Some gems have innate favorable characteristics that allow survival during weathering, erosion, stream transportation and placer concentration. Gems may be found in igneous, metamorphic, and/or sedimentary environments and are typically associated with specific rock types and mineral suites. Unlocking these characteristics and clues can lead geologist to the discovery of additional deposits.

Gemstones are sought for personal adornment and have become the prized possessions of men, women, Kings and Queens, worldwide. Some of the more exotic minerals and gems represent the most valuable commodities on earth based on size. Nothing on earth can compare a fabulous gemstone. For example, Walton (2004) describes a 62-carat royal

blue rectangular cut sapphire valued at \$2.8 million (\$45,000/carat) (>9,000 times more valuable than an equivalent weight in gold). In general, rubies are more valuable. In 1998, a Burmese ruby of 15.97 carats sold at a Sotheby's auction for US\$3.63 million (\$227,301/carat). More recently (2005), Christie's of New York sold a near perfect 8.01-carat Burmese ruby for US\$2.2 million - a record per carat price for a ruby (US\$274,656/carat)! Some jade specimens of unimaginable value have included a 1.4-inch long jadeite cabochon that sold for US\$1.74 million (Ward, 2001)! In 1999, a jadeite bangle of only 2 inches in length and 0.3 inch wide sold at a Christie's auction in Hong Kong for US\$2,576,600 (Hughes and others, 2000). Even more incredible was a 27-bead emerald-green jadeite necklace, known as the *Doubly Fortunate* that sold in Hong Kong for US\$9.3 million in 1997 (Hughes and others, 2000; Ward, 2001).

Many diamonds have attracted the desire of the affluent. Some of the more valuable are red and pink diamonds. A small 0.95-carat purplish-red diamond (the Hancock Red) sold for nearly US\$1 million. To put this in perspective, one carat weighs only 0.2 gram (0.007 ounce). At today's gold price, this diamond was valued at more than 200,000 times an equivalent weight in gold - a common value for flawless pink diamonds.

Other priceless treasures have been purchased by Royalty or donated to Royal treasuries. Most notable were those cut from the Cullinan rough, the largest diamond ever found at a whopping 3,106 carats. The extraordinary gems faceted from this huge rough were donated to the British royalty and reside in the British crown jewels.

Many gemstones have intrinsic properties that make them visually attractive: others stimulate our imaginations with unique qualities. The value of others has reached extraordinary heights due to ingenious marketing strategies such as a group of former industrial diamonds that are now coveted by the wealthy. These include brown and very light brown diamonds that were at one time considered to be almost worthless, but today are marketed as rare *cognac* and *champagne* diamonds of great demand. Yellow diamonds, also once considered low-value stones, are now marketed as Canaries. Others, such as zoisite, an alteration mineral, were brilliantly marketed as Tanzanite. For the economic geologist, it is important to note how valuable gems are in comparison to other commodities. This alone should provide incentive to search for these commodities and for some government agencies to transcend politics and personal agenda and instead support the interest of the public.

Tapping into geological knowledge allows geologists and prospectors to predict where gemstones will be found and what type of host rock they will occur. Such information can lead to significant discoveries, such as the extremely rich diamond deposits in the Canadian Shield in the 1990s (Krajick 2002; Hausel, 2006a, b), the discovery of major poly-gemstone deposits (iolite-ruby-sapphire-kyanite) in Wyoming, discovery of one of the largest opal deposits in North America in Wyoming (Hausel, 2005) as well as several other gemstones in the Wyoming Craton over the past 2 to 3 decades (Hausel, 2005a), predictions of very large iolite, ruby, opal and diamond deposits in Wyoming (Hausel and Sutherland, 2006) and predictions of new discoveries and new commercial host rocks of diamonds worldwide (Erlach and Hausel, 2002).

GEOLOGICAL SETTING

Rocks that form the Wyoming Craton include Archean (>2.5 Ga) basement rocks of the Wyoming Province that underlie Montana and much of Wyoming (Hausel and others, 1991). Along the southeastern margin of the province, cratonized basement rocks (Proterozoic schist and gneiss; <2.5 Ga) of the Green Mountain terrain abut against the Wyoming Province along the Mullen Creek-Nash Fork shear zone (Houston, 1983, 1993). The craton was fragmented during the Laramide orogeny: the style of deformation was brittle and non-thermal. The resulting uplift was accompanied by erosion and episodes of renewed uplift.

The basement complex of the Wyoming Province consists of Archean gneiss and schist with scattered greenstone belts and supracrustal terrains that have been intruded by granitic plutons. The supracrustal rocks include thin successions of metapelite mixed with metagraywacke, metavolcanic rock, amphibolites, schist and gneiss. Metamorphism was predominantly regional amphibolite-grade with isolated upper greenschist facies. The regional prograde events proved favorable for genesis of metamorphogenic gemstones.

Notable are metapelites. These include sillimanite-garnet-biotite-muscovite-quartz schist, kyanite-biotite-corundum-quartz schist, andalusite biotite schist, sillimanite-kyanite-biotite-muscovite-quartz schist, cordierite gneiss and schist, corundum-kyanite schist, etc. Corundum- and cordierite-bearing metapelite is interpreted to represent aluminous shale precursors. One corundum-serpentine in the Granite Mountains is interpreted as an aluminous ultramafic magma precursor of komatiitic affinity. Other aluminous serpentinites have been identified in the South Pass and Seminoe Mountain greenstone belts, although no corundum is reported in those (Hausel, 1991; 1994).

Estimates for burial depth of metapelite in the central Laramie Range are based on the aluminosilicate polymorphs (andalusite, kyanite, sillimanite). Along the edge of the Elmers Rock greenstone belt, Graff and others (1982) identified metapelite with andalusite and sillimanite. A few miles north at Palmer Canyon, kyanite-sillimanite-corundum-mica schist is found. The presence of polymorphs within a narrow region supports that the metamorphic grade increased to the north, with the highest-grade exceeding the polymorph triple point in the vicinity of Palmer Canyon. The data suggests these rocks were subjected to lithostatic pressures exceeding 3.8 kb (possibly as much as 5.5 kb) equivalent to a burial depth of 8 to 10.5 miles (12.8-16.8 km) and temperatures exceeding 500°C.

Reports of gem-quality cordierite, corundum and kyanite were rare until the discovery of the Palmer Canyon deposit, 5 miles (8 km) north of the Elmers Rock greenstone belt, in 1995 (Hausel, 2002). Since that discovery, other discoveries were made and the possibility of additional gem material in this region is highly probable. This paper focuses on some of the recent iolite discoveries.

DISCOVERIES

Several gemstone, lapidary, and precious metal deposits were found in Wyoming from 1975 to 2004. Some notable discoveries include diamonds (McCallum and Mabarak,

1976; Hausel, 1998a), labradorite (Norma Beers and Letty Heumier, personal communication, 2000), opal (Scott Luers, personal communication, 2002; Hausel, 2005a), variscite, minyulite (Bob Bratton, personal communication, 2002), sapphire, ruby, peridot, aquamarine, heliodor, iolite, pyrope garnet (Cape ruby), pyrope-almandine garnet, chromian diopside (Cape emerald), chromian enstatite, specularite, several varieties of jasper and agate (Hausel and Sutherland, 2000; Hausel, 2006a) and jewelry grade gold nuggets (Hausel, 1989). Decorative stone deposits also were found and/or identified (Harris, 1991, 1994) prior to 2004. Essentially all meaningful research related to these and related projects ended in 2004 due to bureaucratic failures.

Cratons are notable geological environments for hosting major diamond deposits associated with kimberlite, lamproite and lamprophyre. Archean greenstone and high-grade supracrustal terrains within cratons provide excellent targets for a variety of gems including diamond, ruby, sapphire, emerald, aquamarine, and jewelry grade gold nuggets. Younger rocks, such as those in the Absaroka Plateau and Yellowstone Caldera are fertile for opal, agate, jasper, gold and several varieties of cupriferous minerals and gemstones, and the Wyoming sedimentary basins including the Overthrust belt provide potential hosts for other gems including diamond, emerald, opal, jasper and agate.

Diamond, Cape Ruby, Cape Emerald, Peridot

In its simplest form, isometric diamond is equal-dimensional and produces six-sided cubes referred to as hexahedrons. However, a more common habit of diamond is that of a octahedron (Figure 1). Octahedrons form 8-sided bipyramids, although some octahedrons may develop ridges on the octahedral faces resulting in crystals of trisoctahedral and hexoctahedral habit. Partial resorption of the octahedron will produce rounded dodecahedrons (12-sided) with rhombic faces. Many dodecahedrons develop ridges on the rhombic faces resulting in a 24-sided crystal known as a trishexahedron. Four-sided tetrahedral diamonds are sometimes encountered, and these are probably distorted octahedrons. Another relatively common form of diamond is the macle, or twinned diamond. Many macles form flattened triangular crystals.



Figure 1. This parcel of diamonds from the Kelsey Lake mine, Colorado includes a flawless 14.2 carat octahedron (photo courtesy of Howard Coopersmith).

The surface of diamond may contain growth trigons, and less commonly pits, which further distort the habit of the crystal resulting in other habits. Diamonds have brilliant greasy luster likened to oiled glass. Gem quality diamonds can occur as translucent to transparent colorless, green, yellow, brown, and rarely blue or pink stones. Opaque and heavily included diamonds are used for industrial purposes and bort.

Diamond is brittle, extremely hard ($H=10$), has a specific gravity of 3.5, and perfect octahedral cleavage. Even though it is heavier than water, it is non-wettable (hydrophobic) and will float on water under favorable circumstances. Diamonds are grease attractive. Under ultraviolet light, many will weakly fluoresce pale blue, green yellow, and rarely red.

Since diamonds are extremely rare, it takes considerable effort and patience to find diamonds. It has been estimated, that diamond occurs in concentrations considerably <1 part per million in commercial diamondiferous kimberlite and lamproite. Diamonds have been found or reported at several locations in Wyoming, Montana, and Colorado.

Strongly mineralized lamproites host olivine such that there is a correlation between the amount of olivine and the presence of diamond. Most olivine in lamproites is typically serpentinized to produce a rock that is not resistant to erosion. As such, most diamondiferous lamproites lie hidden within fields of non-diamondiferous and more resistant leucite lamproites (Figure 2). Less commonly, olivine remains pristine in such rock. Thus, some lamproites may represent potential hosts for another gemstone in addition to diamond – peridot.



Figure 2. (a) Ellendale 9 lamproite in Western Australia is located within a field of more resistant lamproites that are barren of olivine. This commercial deposit, exposed in the bottom of the trench, was discovered by its magnetic signature as it lay hidden within a prominent field of lamproites much similar to the Leucite Hills in Wyoming. (b) A parcel of peridot gems from anthills near the Black Rock lamproite in the Leucite Hills. These are part of the >13,000 carat group collected from just two anthills. Note the excellent clarity of the faceted gems.

Kimberlites are essentially potassic-peridotites composed almost entirely of serpentinized olivine. Olivine is rarely preserved other than as serpentine pseudomorphs in kimberlite. Typically, kimberlites contain varying amounts of mantle material as cognate nodules, megacrysts, xenoliths and xenocrysts. Some of the more important are the kimberlitic indicator minerals – pyrope garnet, chromian diopside, chromite and picroilmenite (and of course diamond). In some kimberlites (and some lamprophyres), pyropes and chromian diopsides are such high quality that they are used to produce gemstones referred to as Cape Ruby and Cape Emerald (Figure 3).



Figure 3. (a) Kimberlite breccia from the Sloan Ranch kimberlite, Colorado, exhibits large gem-quality pyrope-almandine megacryst. (b) parcel of gemstones from anthills in

the Greater Green River Basin include red, pink, and purplish red pyrope, emerald green chromian diopside, light green olivine that surround a Cape Ruby faceted from a pyrope garnet. (c) Faceted Cape Ruby (pyrope garnet) from the Green River Basin shows why these Wyoming gems are some of the best in the world.

Several intrusive episodes of kimberlite, lamproite and lamprophyre occurred in the Wyoming Craton (Hausel, 1996f). Such magmas are potential hosts for diamond deposits (Erlich and Hausel, 2002) and it is significant that the two largest kimberlite districts in the US, the largest lamproite field in North America, some unconventional diamondiferous host rocks, scattered detrital diamonds, and hundreds of kimberlitic indicator mineral (KIM) anomalies have been identified in the Wyoming Craton (Hausel, 1998a; Coopersmith and others, 2003).

At least 50 kimberlites (Late Precambrian and Early Devonian) intrude Proterozoic basement rock and granite in the Colorado-Wyoming State Line district (Hausel, 1998a). Essentially all of the intrusives that have been tested yielded some diamonds (Hausel, 2006d). Bulk sample tests ranged from 0.5 carat per 100 tonnes (cpht) to 135 cpht (Waldman and McCallum, 1991) (commercial ore typically averages from about 15 cpht to 700 cpht). Diamonds from this district include microdiamonds to very high-quality gemstones >28 carats in weight (Coopersmith and others, 2003). One octahedral fragment from an estimated 90-carat diamond was also recovered indicating that larger stones remain to be found in the kimberlites and adjacent stream placers.

More than 130,000 diamonds were recovered during testing in the district. A commercial mine was developed on the KL1 and KL2 kimberlites at Kelsey Lake, Colorado in 1996, but operations terminated due to land issues. The recovered diamonds included >30% gemstones, many of which were excellent transparent white gemstones. Others included yellow, gray, light brown, green and even pinkish stones!

At the Iron Mountain district to the north near Chugwater, a large dike-pipe complex was mapped. Testing of KIMs from essentially all kimberlites (Early Devonian) in the district indicated that nearly all originated from the diamond stability field at depth. The only exception was a group of small, faulted, intrusive breccias along the southernmost edge of the district that have carbonatite affinity. Based on mapping, it was apparent that hidden kimberlites also lie within the district (Hausel and others, 2003). Only 3 small bulk samples were collected in the early 1980s by Cominco American and one yielded some microdiamonds along with a 0.3 carat macrodiamond (Coopersmith and others, 2003). The rest remain untested. Some structurally-controlled depressions lie on trend with the Iron Mountain kimberlites 6 miles (10 km) west in the Indian Guide area. Kimberlite being relatively soft typically erodes more rapidly than surrounding country rock often producing subtle topographic depressions devoid of trees. Such depressions often exhibit some type of structural control.

Kimberlite is one of two host rocks mined for commercial quantities of diamond. The other is lamproite (Erlich and Hausel, 2002) and the largest field of lamproites in North America, the Leucite Hills (3.1 to 0.9 Ma), provides a good exploration target

(Coopersmith and others, 2003; Hausel, 2006e). This field overlies a thick cratonic keel that is a favorable source for diamonds. Olivine is found in some lamproites in the northeastern portion of the field. The presence of olivine suggests possibilities for hidden olivine lamproites. The recovery of diamond stability chromites from two of the lamproites along with the olivine suggest that this region represents one of the better unexplored diamond targets in the US. Although no diamonds have been found, there has been no testing even though there is a strong correlation between diamonds and increased amounts of olivine in lamproites. With few exceptions, olivine lamproites are diamond-bearing.

During field reconnaissance and mapping another gemstone was discovered was discovered in the Leucite Hills in 1998. Olivine in this field has excellent transparency and color and is a source for gem-quality peridot. More than 13,000 carats of the gemstone was recovered from two anthills (Hausel, 1998c) (Figure 2b).

Cedar Mountain to the southwest of the Leucite Hills along the Utah-Wyoming border lies on the margin of a very large KIM anomaly covering a few hundred square miles (McCandless and others, 1995) (Figure 4). The geochemistry of the KIMs suggests that the source intrusives are not diamondiferous. Even so, a group of detrital diamonds had been reported in drainages along the southwestern flank of Cedar Mountain and also in Butcherknife Draw to the east.

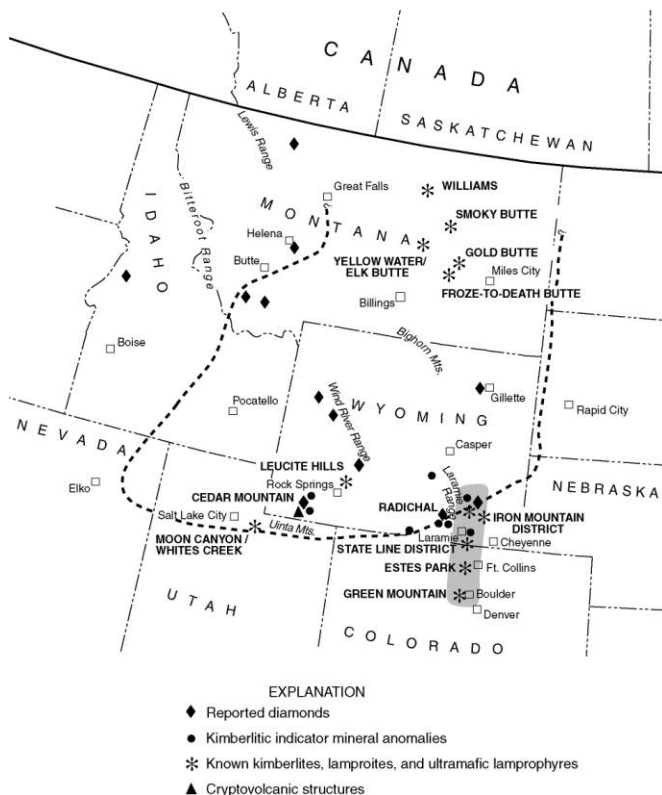


Figure 4. Location of some of the many anomalies related to diamonds. The heavy dashed line is the approximate boundary of the Wyoming Archean Province (the core of the Wyoming Craton). Cratonized Proterozoic rocks to the south are also considered good targets for diamonds. The geological setting of the Proterozoic terrain may also be favorable for fancy diamonds – particularly ‘pinks’, which are thought to have color lamellae related to deformation (see Hausel 2006d). The presence of a Proterozoic Benioff zone (the Mullen Creek-Nash Fork shear zone) suggests that the Proterozoic terrain to the

south could provide excellent hunting grounds for pink diamonds.

The discovery of a group of lamprophyre dikes and breccias along the flank of Cedar Mountain resulted in Guardian Resources and later Anadarko collecting bulk samples that yielded diamond (Hausel and others, 1999). This discovery represented a third rock type shown to be diamondiferous in this craton, and similar possibilities are likely elsewhere in Wyoming and Montana. The age of the intrusives is Tertiary (Oligocene). These do not show any distinct magnetic or conductivity anomaly, and were recognized only by following KIM trails to rounded boulders and cobbles on the side of a hill. The rounded stones are xenoliths hosted by the lamprophyre and represent partially assimilated crustal material. The matrix of the host rock is primarily brecciated Bishop Conglomerate containing mini-eclogite nodules and abundant chromian diopside, chromian enstatite, pyrope and pyrope-almandine, many of which are excellent gems with extraordinary color that blend into the surrounding country rock. In addition to the lamprophyres, hundreds of anthills scattered over hundreds of miles contain very high quality Cape ruby (pyrope garnet) and Cape emerald (chromian diopside). These represent some of the higher quality pyrope and chromian diopside gemstones found in the world (Figure 3c).

A similar KIM anomaly is recognized north of Thermopolis where hundreds of pyrope garnets (Cape ruby) occur in anthills. The source of these remains unknown. In the 1980s, >300 kimberlitic indicator mineral anomalies (KIMs) were identified in 1600 sample sites in the Laramie and Medicine Bow Mountains (Hausel and others, 1988). These and other results indicate that Wyoming is underlain by a major diamond province! Some of the sample concentrates collected in the search for diamonds, also yielded traces of native gold, aquamarine and corundum, and only a handful of the mineral trails were ever followed because of budget constraints. Later sampling projects identified dozens of gold anomalies in southern Wyoming (Hausel and others, 1994).

Detrital diamonds have been found at a number of places in Wyoming and Montana within the Wyoming Craton, and KIMs are reported in the Laramie, Medicine Bow, Seminoe, Bighorn and Hartville Mountains, and also in the Green River and Bighorn basins of Wyoming, and in the Sweetgrass Hills in Montana. KIMs are so common that during one public field trip in 2003, members of the general public were taught to pan gold in the Middle Fork of the Little Laramie River. Instead of gold, members panned out numerous pyrope garnets. KIMs were also recovered from gold placers along Douglas Creek and in paleoplacers north of the Seminoe Mountains surrounding the Miracle Mile. One gold miner found two excellent diamonds in Cortez Creek in 1977 and later exploration of the area by Superior Minerals Company identified a KIM anomaly to the south near Iron Creek in the Medicine Bow Mountains. This same company recovered diamonds from a Proterozoic age paleoplacers in this region during gold exploration (Tom McCandless, personal communication).

Ruby & Sapphire

Corundum (Al_2O_3) includes two gemstones: sapphire and ruby. These are chemically and physically the same mineral and only differ in color due to trace impurities. Corundum is found in rocks enriched in alumina and poor in silica: in particular aluminous schists and volcanic rocks that are silica-undersaturated. The principal habit of corundum is barrel-

shaped, six-sided (hexagonal) prisms and tabular prisms terminated by pinacoids. Corundum exhibits good basal and rhombohedral parting: twinning sometimes occurs parallel to the crystal base (Bauer 1968). Growth twins have been reported in corundum in Sri Lanka and in the Granite Mountains, Wyoming.

Corundum (H=9) has a hardness second only to diamond. Due to its extreme hardness, transparent to translucent corundum is highly prized as a gem. The mineral has relatively high specific gravity (3.94 - 4.08) (Bauer 1968), thus detrital corundum may be found in placers with other minerals of high specific gravity. But due to well-developed parting, it tends to disaggregate over short transport distances. Even so, corundum placers are reported along the Missouri River in Montana, along the edge of the Great Dividing Range in Australia, and in the Big Sandy opening of the Wind River Mountains of Wyoming. The author also identified excellent gem sapphire and benitoite in a placer at Poker Flat, California.

Rubies >5 carats in weight are uncommon and >10 carats are rare. One of the largest known rubies was recovered from the Dat Taw mine in Mogok, Myanmar: the stone weighed 1,743 carats (Gubelin and Erni, 2000). Kievelenko (2003) describes the Rajah Vijaya ruby of India to be 2,470 carats. One large red-corundum found in the Red Dwarf deposit of the Granite Mountains of central Wyoming by the author was the size of a hen's egg measuring 2.5 inches in length. However the specimen was stolen before it could be weighed (Hausel, personal field notes, 1995). Another specimen from the same locality was nearly 90% replaced by zoisite and fuchsite. The 5-inch pseudomorph weighed 7,150 carats and contained some preserved translucent ruby of excellent pigeon-blood red color. Thus the original ruby, prior to replacement, would have represented one of the largest, if not the largest ruby in the world.

Sapphires are typically small; even so, some very large stones have been discovered including a 63,000-carat sapphire found near Mogok. Another sapphire discovered in Madagascar in 1996 weighed 89,500 carats (Johnson and Koivula, 1996)! Sinkankas (1959) reports that an enormous corundum was found in Macon County, North Carolina that is believed to be largest found. The stone, which contained zones of transparency, weighed 707,600 carats (312 lbs)!

Corundum is found as an accessory in quartz-poor, aluminum-rich metamorphic rock such as mica schist, gneiss, and crystalline limestone. It is also found in silica-poor igneous rocks such as syenites, nepheline syenites, serpentinites, some lamprophyres, and alkalic basalts. The luster of corundum is greater than glass but less than diamond and is vitreous to sub-adamantine. Corundum's birefringence and dispersion is low compared to diamond, which is why faceted corundum has less 'fire' than diamond. Some may exhibit asterism and produce star rubies and sapphires when cut as cabochons. Asterism is either 6- or 12-rayed and a result of light reflecting off oriented, needle-like rutile inclusions in planes perpendicular to the *c*-axis.

Gemology

Trace elements (chromophores) responsible for color in ruby include Cr^{3+} , V^{3+} and Fe^{3+} and the trace elements responsible for color in sapphire are Fe^{2+} , Fe^{3+} and Ti^{4+} . Because

much corundum had been mined in the Orient in the past, the suffix '*oriental*' is attached to various colored sapphire gemstones. Modern descriptive terms are suggested (Table 1). Red gem-quality corundum is termed ruby; all other colors are sapphire.

Relatively common white gem corundum is referred to as white sapphire. Rare orange sapphire with a pinkish undertone is known as "*padparadsha*", meaning "*lotus flower*". All other sapphires are termed 'fancy' with a prefix to denote the color of the stone. The most desirable color for ruby is dark, purplish-red (pigeon blood red). The most attractive color for sapphire is velvety cornflower blue (Kashmir blue).

<i>Gemstone Color</i>	<i>Archaic Terminology</i>	<i>Modern Terminology</i>
red	oriental ruby	ruby
blue	oriental sapphire	blue sapphire
colorless	leuco-sapphire	white sapphire
light bluish-green	oriental aquamarine	bluish-green sapphire
green	oriental emerald	green sapphire
yellowish-green	oriental chrysolite	yellowish-green sapphire
yellow	oriental topaz	yellow sapphire
aurora-red	oriental hyacinth	aurora-red sapphire
violet	oriental amethyst	violet sapphire
pinkish-orange		padparadsha

Table 1. Varieties of gem corundum.

The color of ruby is of primary importance followed by transparency. A ruby may show different shades of red depending on origin. Even though gemologists refer to 'Burmese' ruby as top of the line, it does not necessary follow that the stone is from Myanmar (formerly Burma): the designation is only an indication of a shade of color similar to the famous pigeon-blood-red rubies. Kashmir blue sapphires are top of the line and have pure and intensive blue enhanced by a fine, silky gloss. Myanmar sapphire is also considered valuable and ranges from rich royal to deep cornflower blue.

A very large percentage of marketed rubies and sapphires are enhanced for clarity and color (Hausel and Sutherland, 2006) with thermal treatments. Such treatments have been used for centuries as Sanskrit texts show that such treatment was used as early as 2000 BC. As many as 90 to 95% of all sapphires and rubies are thermally treated (Ward, 1998).

Types of Deposits

Corundum is found in (1) magmatic, (2) marble-hosted, (3) metasomatic, (4) regional metamorphic and (4) placer deposits. Placer concentrations can be economically important due to natural beneficiation and ease of mining. Essentially all deposits found in Wyoming are either metamorphogenic or placer. Corundum found as an accessory in gneiss and schist is typically hosted by silica-poor rocks that were subjected to high pressure and temperature during regional metamorphism. At Palmer Canyon, Wyoming, the presence of alumino-silicates (kyanite and sillimanite) in the adjacent country rock, and andalusite and kyanite a short distance south, provide constraints indicating pressures

and temperatures necessary to reach the aluminosilicate triple point must have been about 4 kbars (14 km depth) and 500°C (Hausel, 1996).

Deposits

Corundum is described in Afghanistan, Australia, Cambodia, Burma, Thailand, Sri Lanka, Tanzania, and the US, Kenya, Madagascar and Vietnam. Less important deposits occur in Brazil, China, India, Laos, Malawi, Nepal, Nigeria, Pakistan, Switzerland, Russia, Rwanda, and Zimbabwe (Hausel and Sutherland, 2006).

A number of localities in the US have produced minor ruby and sapphire. The most productive is the alkalic province within the Wyoming Craton in Montana. Montana has been the source for considerable gem-quality sapphire from placers and a group of lamprophyres. Sapphires up to 0.5 inch have intermittently been recovered since 1865 (Voynick, 1987). According to Berg (2004), detrital corundum was traced to nearby ultramafic lamprophyre dikes, which yielded 18.2 million carats of raw sapphire at Yogo Gulch, 50 miles southwest of Lewistown on the northeastern flank of Little Belt Mountains.

Metamorphogenic corundum occurrences hosted in metapelite have been identified in Wyoming. Corundum was reported at a few localities in the Granite Mountains, central Wyoming. Some gem material was described in alluvium along the Sweetwater River both east and west of Jeffrey City. Pinkish red sapphires up to 0.25-inch in diameter were found in pelitic schist in NE section 31, T31N, R89W of the McIntosh Meadows Quadrangle in the northeastern Granite Mountains (Sutherland and Hausel, 2002). The corundum is very limited in extent. Deep- to purplish-red ruby was described near Sweetwater Divide. Some specimens were cut and produced star-rubies (Curtis 1943). The Red Dwarf deposit near Jeffrey City has produced several large rubies. Corundum was also found on the Robinson Claim in the Rattlesnake Hills of the northeastern Granite Mountains. One specimen of purple-red, opaque to translucent hexagonal corundum from the deposit was a little more than 1.25 inches (3.2 cm) in diameter.

Sapphires were recovered from the Abernathy deposit, 40 miles east of Lander. The pale-blue to white sapphires were described in N25°E-trending mica schist enclosed by gray-brown granite near Sweetwater Station. Abundant 1-inch (2.5 cm) diameter nodular 'sapphires' were found that were badly shattered and altered on the edges (Love, 1970). According to Hagner (1942) these are poor quality gray to dirty blue, cloudy corundum exposed in a prospect pit. The biotite-corundum schist is about 4 feet wide. Pale to bright-red rubies were found in mica schist north of the Abernathy deposit at the Marion prospect: some were cut into gems (Osterwald and others, 1966).

Other rubies were found as float in the Granite Mountains. According to Love (1970), soft green mica schist boulders with dark red rubies were found near Muskrat Creek in the Wind River Formation (Eocene) near Beaver Rim, west of the Gas Hills district, 12 miles (19 km) north of the Red Dwarf ruby deposit. These rubies were up to 1 inch (2.5 cm) in diameter and highly fractured.

A nearby placer with abundant, bright red (>1 inch in diameter), fractured rubies was reported (Osterwald and others, 1966). Chloritic schist float with rubies (similar to the Red Dwarf schist) was also found in the Crooks Gap Conglomerate (Tertiary), along the northern flank of Green Mountain, about 15 miles (24 km) to the southeast of the Red Dwarf (Hausel, 1986).

Red Dwarf. The Red Dwarf lies northwest of Jeffrey City (sections 13 and 24, T30N, R93W). The host rock is corundum quartzofeldspathic gneiss with a strike length of 5,000 feet (1560 m) and widths of 20 to 50 feet (6.25-15.6 m) (Hausel, 1997). The rock grades from gray quartzofeldspathic gneiss along its northern end, to chloritic schist along its southern end. It typically contains 1-10% corundum as porphyroblasts enclosed in fuchsite-zoisite reaction rims.

Some large specimens include one which measured >2.5 inches (6.4 cm) across. Another specimen was a large fuchsite-zoisite pseudomorph after corundum with small (0.25 to 0.5 inch) specs of preserved purplish-red ruby (J. David Love, personal communication). Only part of the original sample remained but measures more than 5 inches (12.7 cm) in length and 3 inches (7.6 cm) across. The other portion of the ruby was cut and removed and the original specimen was >7 inches in length (Figure 5a). Other Red Dwarf specimens were cut into cabochons, but none were faceted primarily due to the translucent to cloudy nature of the corundum. The fashioned stones are purplish-red. One yielded a 2.77 carat ruby cabochon that shows parting planes on the stone, but otherwise is an attractive gem. A few specimens of gem-quality ruby cabochons with excellent asterism were produced from this deposit in past years (George Devault, personal communication). Overall, lack of transparency of this material greatly diminishes its value and research in clarification processes (heat treatment) is needed.



Another corundum deposit identified in Palmer Canyon west of Wheatland includes pink to white sapphire in Archean age vermiculite schist (glimerite). Specimens weighing over 35 carats have been recovered with some faceted pinkish red sapphires weighing 3.5 carats. The raw stones are hexagonal prisms terminated by pinacoids with well-developed rhombohedral parting limiting the size of the faceted gems. The corundum occurs with iolite and kyanite (see Iolite section below). The percentage of gem-quality material has not been estimated, but could be 5 to 15%. Locally, some vermiculite has as much as 20% corundum, but the tonnage of high-grade rock exposed at the surface is limited. None of the corundum has been heat-treated.



Figure 5. (a) Large zoisite-fuchsite replacement of ruby from the Granite Mountains with preserved masses of excellent, high-quality ruby. Prior to replacement of the ruby, this may have represented the largest ruby in the world. (b) A 1.1 carat, reddish-pink sapphire from Palmer Canyon (photo courtesy of Chuck Mabarak), and (c) a large pink sapphire (>3 carats) from Palmer Canyon showing visible parting (specimen courtesy of Vic Norris).

The largest prism found by the author is a 1-inch (2.5 cm) prism with 0.3-inch (0.75 cm) diameter. The largest plate measured 0.4 inch in diameter. Larger specimens were later found by Eagle-Hawk mining (Vic Norris, personal communication, 2002) some of which has good translucency and a pleasing pink to red-pink color. The corundum typically averages 0.2 inch (0.5 cm) in diameter.

Three categories of gem and near-gem corundum were most common: (1) reddish-pink transparent to translucent sapphire, (2) light-pink translucent sapphire, and (3) white to light pink translucent to opaque sapphire. Microscopic examination of a limited number of specimens shows mineral inclusions to be relatively common.

Some corundum fashioned from this property included a brownish-pink opaque, 1.4-carat cabochon, and a near-perfect reddish-pink transparent, 1.1-carat marquise with few flaws (Figure 5b). Other faceted sapphires included gemstones of 0.75 to 3 carats in weight (Vic Norris, personal communication, 2002). Some cabochons yield pleasing, light-pink sapphires, but most faceted light-pink corundum is less attractive due to common, visible mineral inclusions and or parting (Figure 5c).

Similar deposits were reported to the north at Elk Park, to the south at Grizzly Creek and in the Platte River valley south of Encampment. Corundum is also found in the Big Sandy area of the Wind River Mountains (Hausel and Sutherland, 2000). At Big Sandy, hundreds of rubies and opaque corundum up to 90 carats were recovered from placers. The source remains unknown, and the placer lies at the base of outwash material from an alpine glacier. Some ruby-corundum schist with very nice translucent to transparent ruby was found north of the Big Sandy placer (B. Ron Frost, personal communication, 2004).

The close association of ruby vermiculite schist suggests that many of the Wyoming deposits are not only metamorphic, but also metasomatic. As such, the gemstones may be

related to desilication and potassic alteration. Corundum in vermiculite in the Platt River valley along the edge of the Medicine Bow and Sierra Madre Mountains in southeastern Wyoming includes Baggot's Rock, where specks of corundum with kyanite and vermiculite occur in biotite- and hornblende-schist (Osterwald and others, 1966). The deposit was mined on a small scale for vermiculite from 1937 to 1941 (Hagner, 1944).

A few miles south, an open cut dug for vermiculite in granite-gneiss in Homestead Draw contains scattered pockets of ruby. Some have reaction rims of green zoisite similar to those at the Red Dwarf ruby deposit in the Granite Mountains. Rubies were also found in another vermiculite deposit on the Platte Ranch to the southwest (Ralph Platt, personal communication, 1998). Corundum was initially reported in Wyoming by Aughey (1886) who described the mineral near the North Platte River in the Seminoe Mountains of central Wyoming, and in limestone. Unfortunately, the descriptions of these appear to be erroneous as there are no known corundum occurrences in the Seminoe Mountains, and no known ruby deposits in a Wyoming limestone.

Iolite (*Cordierite*, *Dichorite*, *Water Sapphire*)

One of the more exciting gemstone discoveries was that of gem-quality iolite in Palmer Canyon west of Wheatland. This also led to the discovery of the Grizzly Creek iolite deposit – considered as a world-class gem deposit, and also to the discovery of the Ragged Top iolite deposit that could potentially lead to the identification of one of the largest gemstone deposits in the world (Hausel, 2005b).

Gemologists refer to gem cordierite [$(\text{Mg,Fe}^{3+})_2\text{Al}_4\text{Si}_5\text{O}_{18}$] as *iolite* and geologists and mineralogists exclusively refer to the mineral as cordierite. The mineral has also been labeled as *dichorite* and *water sapphire* although these are less common terms. Cordierite is typically found in the vicinity of other alumino-silicates such as andalusite, kyanite and sillimanite. Host rocks include alumina-rich mica schists (metapelites) that have been subjected to amphibolite-facies metamorphism. In addition to being metamorphogenic, cordierite is also found as replacements in alumina-rich syenite-anorthosite complexes and shales.

Cordierite forms short prismatic pseudo-hexagonal crystals with rectangular cross sections as well as compact, granular masses and nodules of various shades of blue, bluish-violet, gray, or brown. Fresh cordierite has a hardness of 7 and specific gravity of 2.55 to 2.75. The hardness is favorable for durable gemstones and the specific gravity is unfavorable for placer concentration. Yet the principal deposits mined for iolite in the world are the Sri Lanka placers, where it is recovered with other gemstones.

Iolite exhibits strong pleochroism that varies from light gray, dark violet-blue, to light sapphire blue. Pleochroism is pronounced such that the gem may appear deepest blue when viewed down the c-axis and light blue to light grey in other orientations (Hurlbut and Switzer, 1979). These color variations are one of the attractive features of this gem. The gem is often enclosed by pinite, a reaction rim consisting of muscovite or biotite and chlorite (Dana and Ford, 1949). Iolite discovered by the author in Palmer Canyon and Grizzly Creek, often shows alteration to limonite and pinite (Hausel, 2002). Pinite rims

on the Palmer Canyon iolite are light-greenish due to the presence of chlorite, and typically less than a millimeter thick.

Gemology

Perfectly transparent iolite is suitable for gems. The luster of iolite is vitreous and when polished will become increasingly lustrous. Iolite of highest demand is deep, bright, vivid sapphire blue. Hematite inclusions that cause reddish aventurescence produce '*bloodshot iolite*'. Other inclusions may produce rare cat's eyes and stars.

Iolite is a low-priced gem marketed in the range of \$30 to \$150 for small, 1-carat stones. It typically costs <\$1/carat to facet in cutting centers in Sri Lanka. Larger gems of 5 to 10 carats may be valued at \$350 to \$1100, and flawless faceted stones in the range of 10 to 12 carats may be valued at \$1500 to \$1600. Gemstones >12 carats are unheard of on the world market. Rough material collected by the author at Palmer Canyon and Grizzly Creek represent the largest iolite gemstones found in the world. The value for iolite gems is relatively low due to a lack of marketing and a steady supply. The gem is rarely found in jewelry stores, but a large, steady, controlled supply of high-quality material along with marketing should lead to significant price increases.

Geology & Genesis

Iolite occurs as a metamorphogenic and magmatic mineral. It may crystallize as a direct product of magmatism since it is stable over a considerable temperature range. It has been identified in igneous, contact and regional metamorphic environments and in vitrified sandstones along contacts with basalt, and in shales altered by burning of coal seams (Dana and Ford, 1949). It is found in alumina-rich schist formed during regional metamorphism of shale and may occur with andalusite, sillimanite, kyanite, quartz, biotite and/or spinel in some granites, pegmatites, metapelites and anorthosites. In low- to moderate-grade schists, cordierite may exhibit xenoblastic to porphyroblastic habit with a groundmass of quartz, muscovite, and cordierite. In high-grade metamorphic rocks and pegmatites, cordierite may show well-developed pseudohexagonal habit.

Cordierite may form as a product of chloritization. In silica deficient rocks, it may be associated with corundum, spinel and alkali feldspar. However, in high temperature thermally altered rock, cordierite and corundum are incompatible and replaced by spinel and sillimanite (Deer and others, 1972; Spry, 1969). Where found, cordierite gneiss typically lacks garnet since garnet and muscovite are replaced by cordierite, potassium feldspar and spinel during metamorphism. In Wyoming, cordierite is found in gneiss with quartz and biotite and as large porphyroblasts with xenoblastic texture (Hausel, personal field notes, 1995).

Deposits

Iolite is known in Canada, India, Myanmar, Sri Lanka, India, Brazil, Tanzania, Finland, Germany, Norway and the United States. The highest quality iolite gems in the world are found as pebbles in Sri Lanka and as porphyroblasts in gneiss in Wyoming.

Large nodular masses of iolite were discovered in two separate deposits in Archean gneiss in Wyoming, and a giant disseminated deposit is described in the Laramie Range anorthosite-syenite batholith (Hausel 2002; 2004; 2006a). The Wyoming deposits represent some of the larger and better quality in the world, but these remain to be exploited (Sinkankas, 1959; Hausel, 2005b).

Two deposits (Palmer Canyon and Grizzly Creek) are poly-gem occurrences that include ruby, sapphire, kyanite and iolite in schist, glimmerite (vermiculite) and gneiss. The metapelites represent enclaves of aluminous schist and gneiss. A third deposit lies south in the vicinity of Sherman and Ragged Top Mountain and is hosted by anorthositic-syenitic rocks (1.5 Ga). This latter deposit remains unexplored for gems even though minor granular gem-quality iolite was recently identified, to date (Hausel, 2006a). Local enrichment of iolite at Palmer Canyon and Grizzly Creek is promising. It is not uncommon to find iolite gems of several hundred carats in both deposits with masses weighing several thousands of carats!

Palmer Canyon. Iolite was discovered in Palmer Canyon west of Wheatland during field reconnaissance (Hausel, 2002). This deposit lies along the eastern flank of the central Laramie Range of southeastern Wyoming 16 miles (26 km) west of Wheatland within Archean quartzofeldspathic gneiss, granite gneiss, pelitic schist, and biotite-chlorite-vermiculite schist north of the Elmers Rock greenstone belt. A shallow prospect pit was dug in vermiculite prior to 1944 in what is referred to as the Rolf vermiculite prospect. The schist also contains chlorite, kyanite and corundum. Hagner (1944) interpreted the deposit as a replacement of biotite by vermiculite under the influence of pegmatitic fluids. However, pegmatite is not found in the immediate area. Cordierite was not mentioned or identified and no descriptions were made of the corundum. In the 1930s and 1940s, vermiculite was sought for fire-resistant insulation.

Samples of vermiculite-chlorite-biotite-corundum schist collected from a small prospect pit contained as much as 10-20% corundum (the schist averages about 1-5% corundum). The cordierite was discovered nearby in quartzofeldspathic gneiss a short distance east of the Roff pit. Samples of the cordierite gneiss yielded many transparent cordierite grains including several >50 carats in weight. Gneiss collected from the property contained as much as 20% transparent cordierite.

The cordierite occurs as rounded to disseminated grains and large nodules: a few are intergrown with quartz. Foliation in the host rock parallels the margin of nodules and in some samples appears to terminate against the nodule boundary providing evidence that the cordierite formed post regional metamorphism. The host rock is dark to light gray cordierite-biotite-sericite-quartz gneiss. Kyanite and sillimanite may also be present, but as minor components. Some secondary calcite is found as crusts on some surfaces and many of the cordierite nodules exhibit a very thin (mm-size) alteration halo of chlorite and sericite.

The gneiss contains intercalated lenses of quartzofeldspathic gneiss, metapelite and biotite-chlorite-vermiculite schist with N80°W trending foliation. The quartzofeldspathic

gneiss is a primary host for cordierite and nearby kyanite schist contains 20 to 50% excellent, light to sky blue with lesser tawny, green and red gem-quality kyanite.

Six types of gems and near-gems were identified at Palmer Canyon: (1) high-quality violet to blue, transparent iolite, (2) dark-gray transparent iolite, (3) reddish transparent to translucent ruby, (4) white to light pink translucent to transparent sapphire, (5) white to pink translucent to opaque sapphire, and (6) sky-blue translucent kyanite. In addition, low quality, dark gray, translucent to cloudy mylonitized cordierite is present, as is corundum with prominent rhombohedral parting that tends to crumble. These latter two varieties are of little use as gems.

Transparent blue iolite occurs as large porphyroblasts, nodules and disseminated grains in quartzofeldspathic gneiss adjacent to corundum and kyanite schist. The iolite was traced over a strike length of 500 feet and continues under soil for an unknown distance. A handful of large nodules were initially found by the author at the time of discovery that include a raw, high-quality transparent gem known as the '*Palmer Canyon Blue Star*' of 342.8 grams (1,714 carats), which was believed to be the largest iolite gemstone in the world at the time of its discovery (Figure 6). Several thousand carats of fractured iolite were later exposed in backhoe cuts, and more than 100,000 carats of gem-quality and mylonitized material were recovered in about a cubic yard of material. In addition to clear, transparent, violet blue gem-quality cordierite, some black translucent cordierite ('*Palmer Canyon Black*') was recovered. The Palmer Canyon Black is not facet grade, but may produce cabochons.

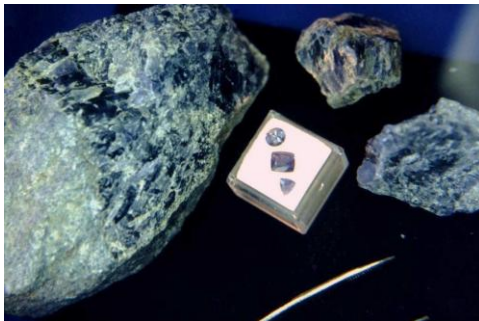


Figure 6. Large iolite porphyroblasts surround the first three faceted iolite gemstones from Wyoming. These three gems (0.5 to 1 carat) sit right of the Palmer Canyon blue star, a 1,714-carat, nearly flawless rough gemstone that was the largest found in the world at the time of its discovery.

Much of the high quality rough material ranges from pleasing violet to a very light-blue color with only a hint of cleavage and parting. Microscopic examination shows few mineral inclusions in these gems, which are for the most part invisible to the naked eye (Figure 7). Where found, the inclusions include white acicular grains (possibly sillimanite) and distinct pseudo-hexagonal biotite.

Gray to dark gray cordierite also exhibits good transparency. This variety has well-developed parting parallel to $c\{001\}$ and cleavage along $b\{010\}$. Many specimens exhibit rectangular cross sections and a few exhibit pseudo-hexagonal habit. A group of cabochons weighed 0.27 to 3.02 carats. These are dark-gray to black, translucent to opaque, near gems with distinct cleavage, parting and some fractures.

Another variety does not appear to be suitable for gem material as it has many flaws. Even so, two were faceted by Eagle-Hawk mining and yielded a 3.9-carat lozenge-cut

stone, and a 3.4-carat marquise. Both stones were extensively flawed with visible cleavage, parting, and some visible mineral inclusions. However, after mounting in gold necklaces, they produced surprisingly attractive jewelry (Chuck Mabarak, personal communication) (Figure 7). Some bluish gray to gray translucent to cloudy material represents rehealed myonlite that is poor-quality even though translucent. Due to the brittle nature of the stone and effects of deformation, portions of some iolite masses have cleavage and parting.



Figure 7. (a) Group of faceted iolites from Palmer Canyon ranging from 0.5 carat to about 6 carats (specimens courtesy of Vic Norris), and (b) a faceted, flawed cordierite (3.4 carats) that makes a surprisingly attractive gemstone dressed in a necklace (photo courtesy of Chuck Mabarak).

South of Palmer Canyon, is a world-class deposit. Grizzly Creek lies 4 miles south-southwest of Palmer Canyon (Figure 8). Rocks in the immediate area include quartzofeldspathic gneiss and kyanite schist, lesser corundum-biotite schist and cordierite schist. The Grizzly Creek deposit also has significant gem-quality kyanite along with incredible massive iolite replacements (Hausel, 2004).

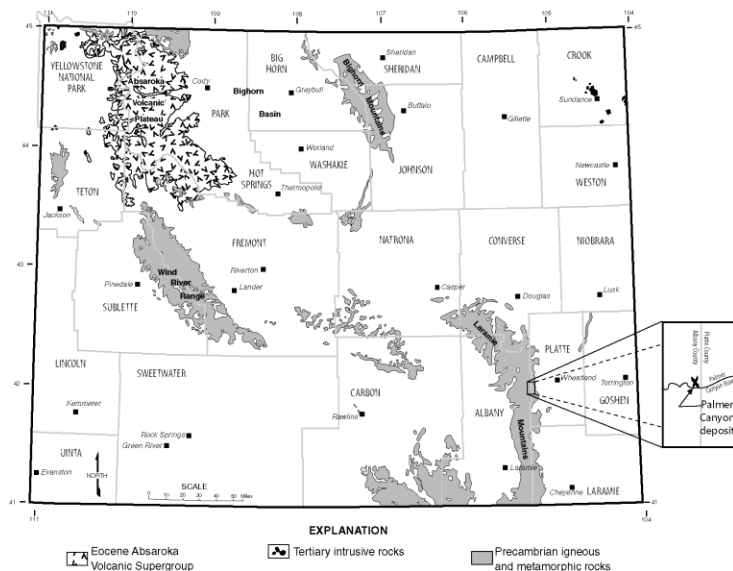


Figure 8. Location of Palmer Canyon gem deposit.

Grizzly Creek. Following discovery of the Palmer Canyon iolite (Hausel, 1998b), it became clear that similar deposits were likely. The later thermal metamorphic event responsible for the large cordierite porphyroblasts at Palmer Canyon appears to have been relatively widespread in the central portion of the Laramie Range.

The earlier prograde metamorphic event produced large porphyroblasts of kyanite in the adjacent rocks. The kyanite represents a good, indicator mineral in search for aluminosilicate and alumina gemstones in this region. Thus the search for similar metapelites resulted in another significant gemstone discovery south of Palmer Canyon – one that is likely a world-class discovery, but will need further exploration and research to fully appraise.

Grizzly Creek became a primary target for similar gemstones to those at Palmer Canyon because of its geology (Hausel and Sutherland, 2000). During the initial field investigation, it became clear that a major gem deposit had been discovered. Very large masses of gem-quality iolite were found with large quantities of gem-grade kyanite.

Cordierite at Grizzly Creek is surrounded by kyanite and sillimanite schists that contain minor corundum. The kyanite and sillimanite schist lies in a 300 by 5000 foot (94-1,560 m) belt of metapelite. During mapping by George Snyder of the US Geological Survey, a collector's quarry was identified that yielded a couple of nice specimens of ruby (George Snyder, personal communication) but the cordierite and kyanite was essentially overlooked as gem material.

Much kyanite appears to be cabochon grade and very pleasing, sky-blue color with some tawny and pink specimens (Figure 9). Iolite found nearby is massive and forms large replacements of the schist. This one deposit may represent the largest iolite occurrence in the world. During reconnaissance, specimens of massive iolite were collected including one football size transparent gemstone that weighed 24,150 carats – the largest iolite gem found on earth (Figure 9 b). However, this stone is dwarfed by masses of material that remain in place in Grizzly Creek. Some of the massive gem material will require quarrying operations to recover. It is very likely that gem specimens >1 ton (>4.5 million carats) in weight could be recovered and specimens as large as 2 to 4 tons are probable (Figure 9c)! In outcrop, the iolite is weakly iron stained and shows excellent light blue color and transparency on fresh surfaces (Figure 9d). But, it is not known how much if

any of this material has been destroyed by mylonitization. For example, several specimens collected at Palmer Canyon showed distinct mylonitic to ultramylonitic texture in thin section that resulted in a cloudy, light-blue and glassy material of poor quality.

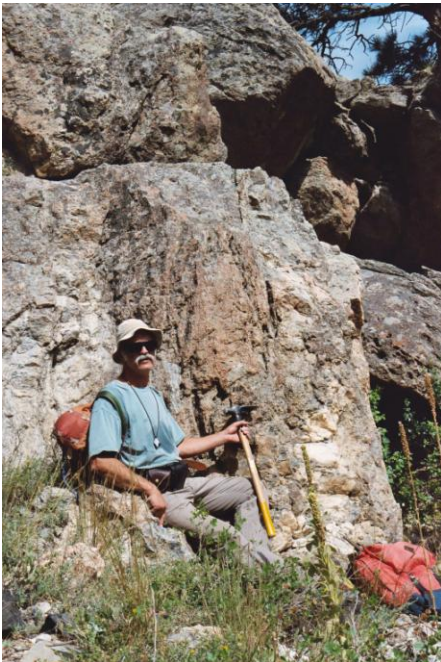


Figure 9. (a) Palmer Canyon kyanite with pink corundum. (b) The largest iolite gemstone in the world – a 24,150 carat giant. Although highly fractured, the gem material is high quality and could produce thousands of carats of gemstones. (c) Wayne Sutherland sits in front of a gemstone of potential weight of 1 to 4 tons (>4.5 million carats). The iolite forms much of the outcrop in the photo. (d) The iron stained outcrops yield excellent gem material on fresh surfaces.

Ragged Top (Sherman) Mountain. The first report of iolite in Wyoming was by Sinkankas (1959). A brief description indicated that iolite was a widespread constituent of schist and gneiss. In describing a deposit Sinkankas wrote, “...one estimate has placed the quantity available at thousands of tons. Specimens at this locality examined by the author are glassy broken fragments of rather light blue color, verging towards grayish, small sections are clear and suitable for faceted gems. It is entirely possible that important amounts of gem quality material will be produced from this locality in the future.” Unfortunately, Sinkankas did not mention the location of the deposit: its whereabouts remains unknown. At the time of writing (1959), only one cordierite deposit had been described in the literature. The deposit, known as the Sherman Mountains deposit, lies along the north fork of Horse Creek near Ragged Top Mountain northeast of Laramie 15 miles south of Palmer Canyon. In this region, Proterozoic (1.4 Ga) metanorite, syenite and syenite-diorite gneiss of the Laramie anorthosite complex intrude the Cheyenne suture (1.8-1.6 Ga) zone. Newhouse and Hagner (1949) and Osterwald and others (1966) reported widespread lenticular to tabular layers of cordierite in metanorite (hypersthene gneiss), gneiss and syenite along the southern margin of the anorthosite complex (1.5 Ga) in sections 13, 14 and 24, T 17N, R 72W and sections 17, 18, 19 and 20, T17N, R71W.

The host rock is described to locally have 50-80% cordierite (this deposit has not been investigated for gemstones, although based on its size it is possible that this is the deposit referred to by Sinkankas, 1959, 1964). The occurrence lies 0.5-mile west of Ragged Top Mountain in a belt 0.3 to 1.2 miles (0.5-1.9 km) wide and 6 miles (9.6 km) long. The host gneiss is highly foliated, intensely folded and contorted.

Howard (1952) described the weathered cordierite to have dark brown surfaces that yield to blue or bluish gray massive material on fresh surfaces. In thin section, the cordierite was described to form colorless, subhedral to anhedral grains ranging from a fraction of a millimeter to 1 mm across with a refractive index of 1.542 to 1.550. Well-developed polysynthetic twinning is common, but some cordierite is untwined.

The author was able to obtain small samples from the disseminated margin of this deposit. Although the material sampled was small and granular, all was gem-quality in grains typically <1 carat in weight. The massive portions of this deposit described by Newhouse and Hagner (1949) remain unevaluated for gems and may represent another world-class deposit. Cordierite is scattered over a few square miles in lenticular to tabular masses in metanorite in low ridges 5 miles long and 0.25 to 1 mile wide. Some exposures are described as having 60 to 80% cordierite. It was estimated that the combined deposits with strike lengths of 100 feet or more, contained >453,600 tonnes (500,000 tons) of cordierite (Newhouse and Hagner, 1949). In other words, a potential resource of 2.27 trillion carats! Sinkankas (personal communication, 2000) indicated that much of the material was gem-quality as suggested in his books (Sinkankas, 1959, 1964), although he could not remember the location. The cordierite is interpreted to have formed by replacement of metanorite during emplacement of diorite gneiss (Newhouse and Hagner, 1949). In contrast, Subbarayuda (1975) describes the cordierite in cordierite-hypersthene

gneiss that he interprets as contact metamorphosed sedimentary rocks. The formation temperature was estimated at 1000°C (Miyashiro, 1957).

Another iolite deposit in the northern Laramie Mountains is referred to as Owen Creek. Snyder and others (1989) report kyanite, sillimanite, cordierite and relict staurolite in pelitic schist in this region. Another occurrence was reported further north. Cordierite is also reported at South Pass (Hausel, 1991), Copper Mountain (Hausel and others, 1985), in the Sierra Madre, and in the Powder River Basin (Osterwald and others, 1966).

Exploration Model

Exploration for iolite in Wyoming should focus on regional metamorphic terrains with significant metapelite successions. Such successions were subjected to amphibolite- to granulite-grade metamorphism. The presence of nearby alumino-silicate polymorphs of kyanite and sillimanite signal distinctly aluminous rocks that have been subjected to pressures and temperatures favorable for crystallization of cordierite. Field examination of metapelites with alumino-silicates such as staurolite, andalusite, kyanite, sillimanite and/or chrysoberyl may lead to previously unrecognized gem discoveries. Anorthosite-norite-syenite complexes are also potential targets for magmatic iolite.

Opal

Opal [$\text{SiO}_2 \cdot n(\text{H}_2\text{O})$] is reported at a number of localities in Wyoming. Hausel and Sutherland (2005) suggest the following categories for jewelry-grade opal: (1) precious black opal, (2) precious white opal, (3) fire opal, (4) common opal, and (5) hyalite.

Precious opal is considered to be the most valuable because the internal color play (fire) producing a very attractive gem. The precious opal can have a white matrix or a dark matrix. Another category of opal, known as fire opal, may or may not have a play of colors. It may be translucent to transparent, red, orange-red, orange and/or yellow-orange. Common opal typically is translucent and milky white, but may also include specimens that are light-blue, gray, black, yellow, or tawny. Hyalite, a lower quality stone, is colorless, transparent opal that occurs as globules that resemble drops of water without color play. Hyalite often resembles glass or quartz but has a brighter surface and an almost greasy to waxy appearance due to the presence of water in the structure (Hausel and Sutherland, 2005).

The hardness of opal varies from 5.5 to 6.5 (Sinkankas 1959) and specific gravity 1.9 to 2.2 (Sinkankas 1959). Low specific gravity along with brittleness prevents opal from concentrating in placers. Common opal can be found in large deposits tens of feet thick measured in tons. However, precious opal is more restricted. Precious opal seams rarely exceed an inch or more in thickness. Schumann (1979) noted that most precious opal seams are less than 2 mm thick. Only a few of the world's largest opals exceed 10 cm thick, even so, some weighed as much as several tens of pounds.

The brilliant color play in precious opal results from light diffraction along submicroscopic orderly arrays of uniformly-sized amorphous silica spheres. A regular stacking of these spheres allows the pore spaces between them to diffract light. The pore spaces typically are filled with water, water vapor, or air (Darragh and others, 1966).

Opal is precipitated from silica-rich aqueous solutions associated with volcanic or sedimentary rocks. The water content varies between 6% and 10% in precious opal and the greater content equates to greater translucency, whereas lower water content results in increased opacity (Sinkankas, 1959). Water is bound loosely within the opal structure and is easily driven off by exposure to dryness or heat, which may cause the opal to turn opaque and white. When it loses water, the gem often cracks which is referred to as crazing. Common opal is generally more durable than precious opal, and will withstand greater temperature and humidity changes without crazing (Eckert 1997). Opals hosted by volcanic rocks often contain more water than opals found in sedimentary environments. Consequently, volcanic hosted opals (with the exception of Mexican fire opals) are generally less stable than opals mined from sedimentary rocks and have a greater propensity for crazing (Barnes and others, 1992). Opal is often associated with chalcedony and agate and the opal may grade into chalcedony in some deposits. Igneous-hosted opals are most often found felsic lavas. Sedimentary-hosted opals may be found with kaolinite, montmorillonite, bentonite, and concretionary iron in some areas (Keller, 1990).

Gemology

Opal is brittle, easily scratched, and sensitive to heat. However, it earns its place as a gemstone from the intense color play in precious opal. Some precious opals, because of their high water content (such as those from Virgin Valley, Nevada) are not cut, but instead displayed as specimens submersed in liquid to prevent crazing. It is primarily cut as cabochons to emphasize the play of color or opalescence in common opal. Some translucent material, particularly Mexican fire opal, may be faceted.

Doublet's are often manufactured. These consist of a thin slice of precious opal cemented to a base of common opal or other material. A *triplet* is a three layer gem where precious opal is cemented on a dark base and covered with a transparent top layer (quartz or glass).

Some of the larger raw pieces of precious opal include a 23,610-carat and a 13,381-carat stone found in Australia (Eckert 1997). Three large uncut common opals collected in Wyoming in 2003 and 2004 weighed 25,850 carats (11.4 lbs), 57,100 carats (25.18 lbs) and 77,100 carats (34 lbs) and represent some of the larger found in the world (Hausel and Sutherland 2006) (Figure 10).



Figure 10. Common opal from the Cedar Ridge deposit in Wyoming. Note the very large specimens adjacent to the opal cabochons.

Geology & Genesis

Much of the world's precious opal is produced in Australia where hosted by Cretaceous marine sediments of the Great Artesian Basin

in New South Wales, Queensland, and South Australia (Keller 1990). Opal is also found in joints in deeply weathered Proterozoic gneiss of the Musgrave-Mann Metamorphics in the Granite Downs of northwestern South Australia (Barnes and others, 1992). The Australian opal is generally thought to be a product of intense weathering and silicification.

Sedimentary-hosted opals are attributed to migration of meteoric silica-rich water but such waters can also migrate up and laterally. The source rocks must contain an abundant supply of readily soluble silica possibly from ash beds, diagenetic changes associated with bentonite, or *in situ* kaolinization of detrital feldspars. Deep chemical weathering of rocks such as pyroxenite and serpentinite, are also suggested to have resulted in the formation of precious opal (Eckert 1997).

Sedimentary-hosted opal in Australia is found down to depths of about 130 feet (40 m). Host rocks vary from conglomerates to sandstones, clay stones, and even bentonite beds. The opal typically is found in pore spaces, joints, fractures, shrinkage cracks, partings, bedding planes, and cavities or pore spaces (Barnes and others, 1992).

Darragh and others (1966) suggest that the opal formed in openings in the rock by slow evaporation of localized pockets of groundwater. Deeply weathered rock, combined with the arid climate in Australia's opal fields appear to be essential components for the formation of precious opal, and development of siliceous cap rocks. Stable tectonic conditions in a cratonic environment such as in Australia, provide an ideal situation for precious opal, especially where there is an abundance of silica-rich volcanic ash. These conditions exist in Wyoming and undoubtedly, some major opal deposits (in addition to Cedar Ridge) will be found. Exploration in that area may later result in the discovery of precious opal (Hausel and Sutherland, 2006).

Volcanic-hosted opal deposits appear to be related to post-volcanic hydrothermal activity, or to silica-rich waters derived from surface weathering processes similar to sedimentary-hosted deposits.

Deposits

Australia produces 95% of the world's precious opal. The world's largest opal fields, Coober Pedy and Mintabie, are found in South Australia. Precious opal is concentrated at the base of a deep weathering profile along contacts between porous kaolinized sandstone and underlying montmorillonitic claystone that lie beneath a silicified cap rock containing considerable common opal (Kievelenko 2003). Most Mexican opal is volcanic-hosted and mined from vugs, fractures, and openings in rhyolite, with a minority of material hosted by basalt. Mexican common fire opal exhibits a red to yellow-orange base color due to the presence of iron oxides.

Precious opal is found in the Bitterroot Range east of Spencer in northeastern Idaho 70 miles (112 km) west of Yellowstone National Park. This Spencer Opal Mine in this area contains precious opal in one or more thin (up to ¼ inch thick) layers within common

opal partially filling vugs within rhyolite. White to pink common opal and pink precious opal are produced at the mine (Eckert, 1997).

Opal was found in the Virgin Valley, Nevada. The opals are hosted by a 1.5 to 11.5 foot (0.45- to 3.5-m) thick layer of montmorillonite clay within a 1000 foot (305 m) thick sequence of volcanic sediments capped by basalt (Kievlenko, 2003; Eckert, 1997). Much of the opal replaces wood. Common opal varies in color from white to gray, yellow, green, tan, brown and black, and ranges from opaque to transparent. Some of the world's largest opals have come from the Virgin Valley. These include the 40 pound (18 kg), 10.4 pound (4.7 kg), and 8 pound (3.6 kg) cobbles (Eckert, 1997).

Precious opal is reported only from an isolated occurrence in the Tertiary Absaroka Volcanics outside the eastern border of Yellowstone National Park. Common opal is known at a few localities hosted by Oligocene White River and Wagon Bed Formations (Hausel and Sutherland 2000).

Cedar Rim Discovery.

Opal was reported at Cedar Rim south of Riverton by Sinclair and Granger (1911) as replacements of soft tuffaceous limestone at the top of the Oligocene sediments that cap Beaver Rim as well as on several buttes to the south. In places, the limestone formed a layer with masses of white chalcedony and opal nodules enclosed in calcareous crusts. The presence of cylindrical pipes of silica, cutting through some of the limy layers was noted. The source for both the limestone and silica was from underlying ash beds and the silica was thought to have been mobilized in percolating water in springs. Some chalcedony and opaline cement was also described in silicified arkose lower in the section (Wagon Bed Formation).

Van Houton (1964) described opal with chert and chalcedony in the Wagon Bed Formation, the volcanic facies of the Beaver Divide conglomerate member of the White River Formation (now the Wiggins Formation), and the Split Rock Formation. Numerous chert nodules and silicified zones in both the White River and Split Rock Formations include opal and yellowish-brown to light olive gray chert, in masses up to 3 feet in diameter in mudstone in the Wagon Bed Formation in the vicinity of Wagon Bed Spring and northeastward as far as the Rogers Mountain Anticline. Irregular chert masses up to 15 feet long are also found in the Kirby Draw syncline nearby.

The Wiggins Formation in this area forms a wide channel fill within the basal White River Formation characterized by debris from the Yellowstone-Absaroka volcanic field. This ranges from sand-sized material to boulders 8 feet long. Within this unit, sandy limestone lenses up to 5 feet thick have been partly replaced by irregular fibrous chalcedonic chert and massive gray opaline silica containing irregular tubes and pores: many of which are filled with calcareous montmorillonitic clay.

South of the Conant Creek anticline Van Houton (1964) described a prominent 160-foot high south facing escarpment. In the lower 50 feet of the upper part of the White River Formation are local layers of light blue to greenish-gray, limonite-stained, brittle opaline

chert containing rounded pellets up to 3 mm in diameter. Farther east, the lower greenish-gray tuffaceous mudstone of the White River Formation that contains several 2- to 4-inch thick layers of slightly calcareous opaline chert. It was noted that these mixed chalcedony and opal layers contained 1- to 2-mm diameter ellipsoidal to subspherical pellets. Both the opal/chalcedony pellets and the rock matrix contain abundant oololiths and round, structureless, thick-rimmed particles.

Van Houton (1964) reported irregular domal structures several feet in diameter that were formed of sand adhering to an opaline skeletal structure resembling tuffa or algal mats in the Split Rock Formation. These are in well-sorted calcareous sandstones southeast of Devils Gap. He also noted commonly occurring thin beds of chert, irregular concretions of opaline silica, and fibrous siliceous aggregates along Beaver Rim in the uppermost part of the Split Rock Formation, hosted within 2- to 6-inch thick light-gray limestone interbedded with equally thin calcareous tuffaceous sandstone.

Even with these descriptions, the opal lacked any genuine interest until investigated by the author. The deposit lies south of Riverton along Beaver Rim and consists primarily of vast amounts of white to very light-blue translucent to opaque common opal, with significant amounts of translucent to opaque yellow, yellow-orange to orange fire opal, and significant amounts of clear, transparent hayalite and agate (Figure 11).

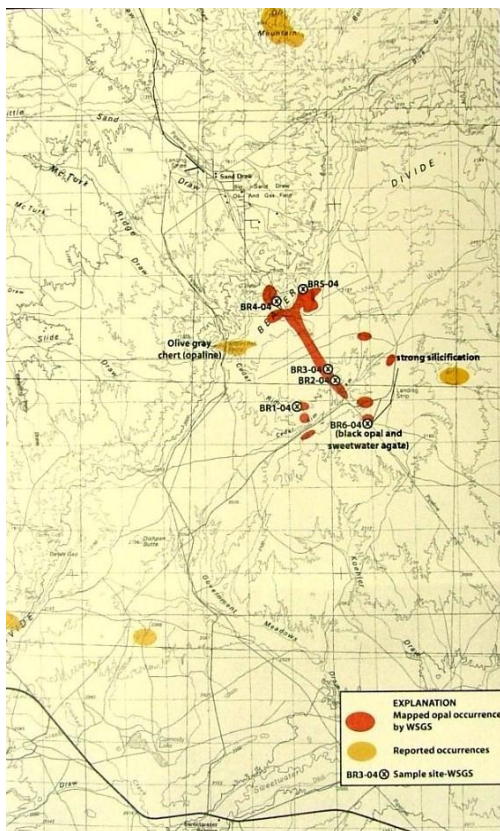


Figure 11. Location map of the Cedar Rim opal deposit.

The opal was found scattered within portions of 14 square miles. Locally, the opal beds are anywhere between a few to more than 50 feet thick and often found capping ridges. Exploration of this deposit at depth, will most likely lead to discovery of precious opal seams.

Numerous opal samples were collected during reconnaissance including three giant opals that weighed 25,850 carats (11.4 lbs), 57,100 carats (25.18 lbs) and 77,100 carats (34 lbs)! It is estimated that a vast field of opal exists in the Cedar Rim area potentially totaling tens of thousands of tons of opal. The opals range from small cobble size nodules to large boulders encased in caliche. The caliche appears to replace of opal as it weathers and devitrifies (Figure 12).



Figure 12. (a) Enormous nodular opal found in the Cedar Rim opal deposit represents some of the larger specimens from the world. The specimen adjacent to the rock hammer would be >100 pounds. (b) Fire opal collected south of the opal boulders, and (c) one of several specimens of precious opal. Where found, the rare precious opal occurs as fracture fillings and veinlets about 1 mm thick.

The following varieties of opal and chalcedony were found:

(1) Opaque milky white to translucent common opal with localized layers or fracture fillings with transparent clear opal. Some of this material includes very light blue opal with minor black dendrite-like inclusions. Some opal is perfectly transparent and much exhibits a very subtle color play with localized zones of stronger color plays. Many of fractured but also many form large consolidated, unfractured pieces weighing several hundreds of carats. (2) Translucent light-blue opal enclosed by milky opaque opal which in turn is enclosed by a narrow perfectly transparent and banded opal crust that exhibits a pleasant spectrum of color play (bands of blue-yellow-violet red) when natural light is reflected from the specimen. These are enclosed in a thin rim of tan to pink quartz. (3) Opal breccia consisting of milky quartz breccia clasts with some light gray to light blue translucent to transparent opal clasts and veins in a black opal to black chalcedony matrix. Some of the translucent to transparent opal and rarely the black opal exhibits some color play. (4) Gray black to black translucent opal and quartz. Some of these samples have a distinct appearance similar to the Sweetwater agates mentioned by Love (1970), and this is likely the original source bed of some of the Sweetwater agates. Very minor play of colors was observed in a couple of the specimens. Much of the color in these appeared as a surface sheen with uncommon, tiny distinct rainbow bands within the opal that may occur along fractures. (5) At one location in the opal field, varicolored opal

is common. This opal includes translucent fire opal as replacements and fracture fillings in silicified arkose. The opal includes milky white translucent to opaque opal, considerable opaque to translucent yellow opal, and lesser opaque to translucent orange opal comparable to the Mexican fire opal (Hausel, 2005a).

Much of this material is jewelry grade and large outcrops of the silicified cap rock containing zones of opal and agate, are excellent for decorative stone for tile and countertops.

Exploration Model

In Wyoming, key components in a search for opal would include a source for potentially soluble silica within, above, or adjacent to potential host rocks. In particular, Tertiary age volcanic ashes provide good sources. Exploration should focus on a search for distinct silicified cap rock and cobbles and boulders of opal within the ash beds as well as a bleaching of host rocks. Within these units, valuable precious opals should occur as fracture fillings, veinlets and seams. Areas of interest would be above impermeable zones or zones of reduced permeability (clay beds at depth) and beneath zones containing gypsum as well as in some bedding planes, fractures, and faults. Typically, the better deposits are found at depth, possibly as deep as 100 to 150 feet below the surface.

In volcanic rocks, such as those in the Absaroka and Yellowstone volcanic fields, precious opal may occur in vesicular felsic rocks that exhibit evidence of silica enrichment.

Other Gemstone Deposits

Several other gemstones have been identified in Wyoming in recent years. Some notable aquamarine beryl was found in pegmatites at Anderson Ridge at South Pass and also in the Copper Mountain area. Giant heliodor beryl was recovered from the Casper Mountain pegmatite. Some of these contain patches and zones of transparent facetable material.

Wyoming also hosts some very nice copper deposits that contain colorful cupriferous minerals. Some specularite found in some old mines in the Hartville uplift and Sierra Madre is gem quality and will produce excellent cabochons. Jewelry grade gold nuggets have been recovered for years from some of the State's gold districts. Most notable are those in the Lewiston district, the South Pass-Atlantic City district, and in the Crow's Nest within the South Pass greenstone belt (Hausel, 1991). Other good sources have included the Sierra Madre, the Douglas Creek district in the Medicine Bow Mountains and also Sand Creek at Mineral Hill in the Black Hills (Hausel, 1989, 1995).

Other areas of interest are the Seminoe Mountains along Deweese Creek (Hausel, 1995). Although unexplored for gold nuggets, some are anticipated in this area, especially due to the abundance of free gold in mines around Bradley Peak. Another commodity that is always overlooked is placer diamonds. The Colorado-Wyoming State Line district has several deeply eroded diamondiferous kimberlites that have released hundreds of thousands of diamonds downstream. But to date, place diamonds have not been sought and as a result, only a few have been found. These were recovered near George Creek,

Prairie Divide and in Fish Creek. The largest reported placer diamond (6.2 carats) was recovered from Fish Creek in Wyoming.

Many other possibilities exist. However, research funding for this and similar projects at the Wyoming Geological Survey has never been based on the merit of projects. Over the past 30 years, the success of finding gemstones, gold, and other metals on an unbelievably small budget (typically < \$5000/year) led to some of the more impressive discoveries by a government agency in the US. Anyone of these could lead to a major new industry in Wyoming. Support for this type of research essentially ended in 2004.

Wyoming is a gemstone-rich state – something that was unknown prior to research projects that began 30 years ago. Most notable are the Wyoming diamond deposits that potentially represent a major resource and potentially could result in a new multibillion-dollar industry, similar to that in Canada. Iolite deposits represent another discovery of significant proportions that could also lead to a new mega-industry in Wyoming.

ACKNOWLEDGMENTS

Robert Gregory and Wayne Sutherland of the WGS provided invaluable assistance on various projects related to gemstones. I would like to acknowledge Vic Norris of Eagle-Hawk mining for providing specimens of gemstones from Palmer Canyon and thank Robert Odell for access to his claims on the Red Dwarf ruby deposit. The late J. David Love provided information on various corundum occurrences in the state.

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