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SCANDIUM-BEARING ALUMINUM PHOSPHATE DEPOSITS OF UTAH

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Abstract

The continuing development of high-efficiency lasers that use gadolinium-scandium-gallium garnet crystals is creating an increased demand for scandium. Laser-grade scandium oxide currently sells for $15,000 per kilogram, roughly equivalent to the current price of gold. In Utah, scandium concentrates occur in a variety of geologic environments including a class of hydrothermal, scandium-bearing aluminum phosphate deposits containing variscite, crandallite, and related minerals. Bulk sampling of the best-known of these deposits, near Fairfield, Utah, yielded Sc_2O_3 concentrations of 0.10 percent. Factors controlling the localization of scandium-bearing deposits include (1) the presence of a brecciated carbonate host rock, (2) proximity to a gold-silver epithermal system, and (3) proximity to phosphatic shales.

Introduction

The recent increase in the demand for nearly pure scandium oxide (roughly equal in value to gold) stems from research and development in high-efficiency lasers and highlights the relationship between the fields of materials science and economic geology: discoveries of new materials generate demands for new commodities. Several recent discoveries, such as the high-temperature superconducting properties of certain metal-ceramic compounds, will revolutionize our current technology. Before these materials can make their way into our domestic markets, economic geologists must locate deposits of the raw materials necessary for their fabrication. The identification of potential supplies of new commodities needs to begin early in the development stage so that research can proceed uninhibited by concerns over commercial-scale supplies of raw materials.

Research and development of high-efficiency, high-energy lasers resulted in the discovery of a new laser crystal, termed the gadolinium-scandium-gallium garnet (GSGG) crystal, over 3.5 times more efficient than the widely used neodymium-yttrium-aluminum-garnet (Nd-YAG) crystal (Anon., 1987a). Scandium is critical in the growth of these crystals because it allows incorporation of chromium into the crystal structure with very uniform distribution (Personal communication, W. Krupke, Lawrence Livermore National Laboratory, 1987). The crystals contain 14 weight percent high-purity, laser-grade scandium oxide (99.999% Sc_2O_3). Potential uses of the new crystal include surgical lasers (laser-welding of tissue to replace suturing), lasers used to generate fusion reactions, and military applications. In 1986, fusion power researchers produced a fusion reaction using Nd-YAG lasers. To trigger the reaction, the lasers injected 100 trillion watts of energy into a tiny sphere of hydrogen fuel, producing a temperature of 30 million degrees Celsius (Hedrick, 1986). On a time-equivalent basis, the energy produced by the reaction was approximately twice that of the entire electric generating capacity of the United States. The development of high-efficiency lasers such as the GSGG laser may someday help to make fusion power a commercial reality.

Compounds used to make GSGG lasers include the oxides of gadolinium (a rare-earth element), scandium, gallium, chromium, aluminum, and silicon. Molycorp's Mountain Pass carbonatite mine in southern California produces gadolinium concentrate, the St. George Mining Company's Apex mine in southern Utah produces gallium, and all the other components except scandium are widely available. Sources of scandium in the United States are nearly non-existent and the majority of the world's supply comes from Russia and China. Minor (by-product) domestic sources are from fluorspar deposits in Montana, tungsten ores from Colorado, and uranium ores. A group at Iowa State University (Ames, Iowa) processes concentrates by ion exchange and solvent extraction methods to make laser-grade scandium oxide. The difficulty in processing scandium ore to make laser-grade material continues to be a major obstacle and is partially responsible for its high price.

Demand for scandium in research applications in 1987 drove the price of laser-grade scandium oxide (Sc_2O_3) to $15,000 per kg, roughly equal to today's price of gold ($467 per troy oz). Lesser grades of scandium sell for $6,500 per kg (90 percent Sc_2O_3) and $7,500 per kg (98 percent Sc_2O_3; personal communication, J. Hedrick, U.S. Bureau of Mines, 1987). The only free-world supplier of high-grade scandium oxide is Elkem Corporation of Norway. Elkem currently produces 10 kg Sc_2O_3 per month and is actively exploring for new deposits. Folldal Verk recently acquired a scandium deposit (discovered by the Geological Survey of Norway) located in the Finnmark province of Norway reportedly containing as much as 5 tonnes Sc_2O_3 (Anon., 1987b). Minor domestic production currently comes from small deposits containing 700 to 800 ppm Sc_2O_3.

Although the current consumption of scandium oxide is small (tens of kilograms per year worldwide) several factors suggest that it may become an economically viable commodity in the future. Its use in lasers for surgical applications may increase its consumption within the next few years. Research is underway to explore its possible use in high-temperature superconductors and, if successful, would greatly increase its demand. Identification of domestic sources of scandium oxide is important not only in terms of national defense but also in dispelling the current belief that it is too scarce to be commercially produced in the U.S. Already, research is in progress to find a substitute for scandium in laser crystals because of its prohibitive price (Personal communication, W. Elerman, University of Utah, 1987). The domestic scarcity of scandium probably reflects its newness as a commodity and the lack of a concentrated exploration effort. Potentially economic deposits of scandium oxide associated with variscite in western Utah may be an important supply of scandium.

Geochemistry of Scandium

Scandium is a lithophilic, dispersed, trivalent trace element that is a minor constituent in hundreds of minerals. Estimates of the average scandium content of the earth's crust range from 22 to 36 ppm (Schock, 1975), indicating that it is anomalously scarce considering its relatively low atomic number. In igneous rocks, scandium tends to concentrate in early formed ferromagnesium minerals. Mafic rocks, pyroxenites and gabbros, tend to have the highest scandium contents (as much as 80 ppm). Phosphatic shales, especially those from western Utah, contain as much as 500 ppm scandium (Ross and Rosenbaum, 1962), an order of magnitude more than other sedimentary rocks. The scandium ion is structurally analogous to yttrium and lanthanum and explains its frequent association with the rare-earth elements (Shcherbina, 1959). Scandium forms stable six-fold complexes with H_2O, SO_4, CO_3, and F (Frondel and others, 1968) and the phosphate ion (PO_4) appears to be the most effective precipitant of scandium from aqueous solutions. Scandium occurs naturally in oxides, silicates, titano-tantalo-niobates, and phosphates (table 1) and is immobile in the alkaline supergene environment.

Scandium enrichment occurs in several geologic environments. Late-stage pegmatite dikes and greisen zones with associated deposits of lithophile elements such as tin and tungsten commonly contain scandium. Scandium resides in wolframite (containing as much as 0.6 percent Sc_2O_3), cassiterite, and beryl in these deposits (Schock, 1975) and may be leached from wolframite in the supergene zone (Kalenov, 1958). Scandium also occurs in association with uranium and thorium deposits of the Colorado Plateau. Scandium content of these ores averages only 5 ppm, however, acid-leach uranium mills that use an organophosphate solvent extraction process sometimes produce an iron sludge that contains between 1000 and 2000 ppm scandium (Ross and Rosenbaum, 1962). Investigation of radiometric anomalies resulted in the discovery of Norway's new scandium deposit (Anon., 1987b) suggesting a possible relationship to uranium ores. Some heavy mineral sands and placer deposits may contain scandium, particularly if composed of monazite, euxenite, or zircon. Phosphatic shales in western Utah represent a tremendous low-grade reserve of scandium. The Phosphoria Formation contains only about 10 ppm Sc (Gulbrandsen, 1966), but other phosphatic shales contain as much as 500 ppm Sc. Topaz Mountain Rhyolite of the Thomas Range contains lithophysae minerals highly enriched in scandium. Frondel (1970) discovered that the late-stage minerals pseudobrookite, bixbyite, spessartite, hematite, and beryl (coating vugs in the rhyolite) contain between 0.16 and 0.74 weight percent Sc_2O_3, suggesting strong scandium enrichment during the terminal stages of crystallization. The last geologic environment where scandium occurs is unique to western Utah and Nevada and consists of a class of hydrothermal scandium-bearing aluminum phosphate deposits containing variscite, crandallite, and related minerals, which will be the focus of this report.

Table 1. Compositions of naturally occurring scandium minerals and scandium-bearing aluminum phosphate minerals. Data from Frondel and others (1968), Schock (1975), and Stoffregen and Alpers (1987).

Scandium Minerals	
thortveitite	$Sc_2Si_2O_7$
bazzite	$Be_3Sc_2Si_6O_{18}$
sterrettite or kolbeckite	$ScPO_4.2H_2O$
magbasite	$KBa(Al,Sc)Fe^{2+}Mg_5F_2Si_6O_{20}$
Sc-ixolite	$(Ta,Nb,Sn,Mn,Fe,Sc)_2O_4$
Sc-perrierite	$(Ce,La,Ca)_4(Fe_{2+},Sc)(Ti,Fe_{3+})Ti_2$-$[O_4/SiO_7]$

Scandium-bearing Minerals	
crandallite	$CaAl_3(PO_4)_2(OH_2)_5.H_2O$
variscite	$Al(PO_4).2H_2O$
millsite	$(Na,K)CaAl_6(PO_4)_4(OH)_9.3H_2O$
deltaite	$Ca_2Al_2(PO_4)_2(OH)_4.H_2O$(?)
wardite	$NaAl_3(PO_4)_2(OH)_4.2H_2O$
overite	$Ca_3Al_8(PO_4)(OH)_6.15H_2O$
gordonite	$MgAl_2(PO_4)_2(OH)_2.8H_2O$
montgomeryite	$Ca_4Al_5(PO_4)_6(OH)_4.11H_2O$
lehiite	$(Na,K)_2Ca_5Al_8(PO_4)_8(OH)_{12}.6H_2O$
goyazite	$SrAl_3(PO_4)_2(OH)_5.H_2O$

Scandium-bearing Aluminum Phosphate Deposits

In the late 1950s, two mineralogists, C. Frondel and M. Mrose, discovered that previous workers erroneously identified sterrettite (Kolbeckite), collected near Fairfield, Utah, as a hydrous aluminum phosphate. Their determinations showed instead that the mineral contains scandium as the sole cation. This discovery led Frondel to investigate other aluminum phosphate

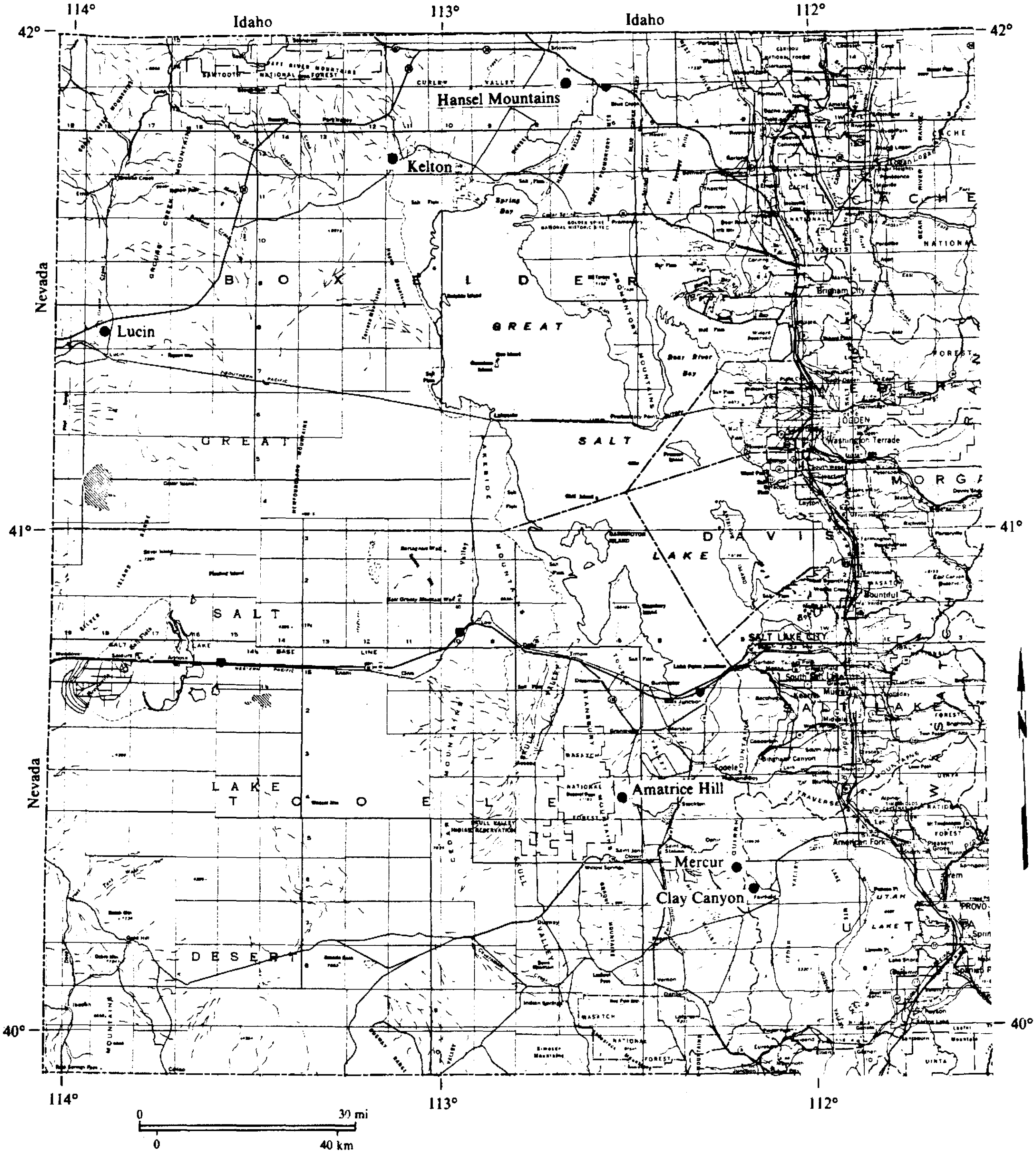

Figure 1. Location map of scandium-bearing aluminum-phosphate deposits in Utah. Locations of the Kelton and Mercur deposits approximate.

minerals from Fairfield and from scattered locations in Utah and Nevada (Frondel and others, 1968). Frondel found that both crandellite and variscite from the Fairfield deposit contain significant amounts of scandium and that other variscite occurrences in northwestern Utah also show scandium enrichment. Variscite, first discovered at Fairfield, was a popular gemstone between 1908 and 1910 and prospectors discovered many locations near gold and silver districts throughout the Great Basin (Sterrett, 1908; 1909; 1910; 1911). The following sections present descriptions of scandium-bearing variscite occurrences in Utah, located in figure 1, and table 2 contains the results of reconnaissance geochemical sampling by the UGMS.

Clay Canyon Deposits

Variscite occurrences in Clay Canyon, located near Fairfield, Utah, consist of three separate deposits, the Little Green Monster (also known as the Utahlite mine, Chlorutahlite mine, and Clay Canyon mine), and two unnamed deposits (figure 2). F.T. Millis first discovered variscite at the Little Green Monster in 1893, and from 1894 to 1911 Don Maguire mined variscite as a gemstone (Sterrett, 1908). In 1936, Edwin Over and Arthur Montgomery staked the Little Green Monster claim and obtained a patent in the late 1940s. Beginning in 1959, the Kawecki Chemical Company investigated the deposits as a possible source of scandium. In 1959 and 1960, miners produced two shipments of crandellite ore, weighing 330 and 4000 pounds, which contained

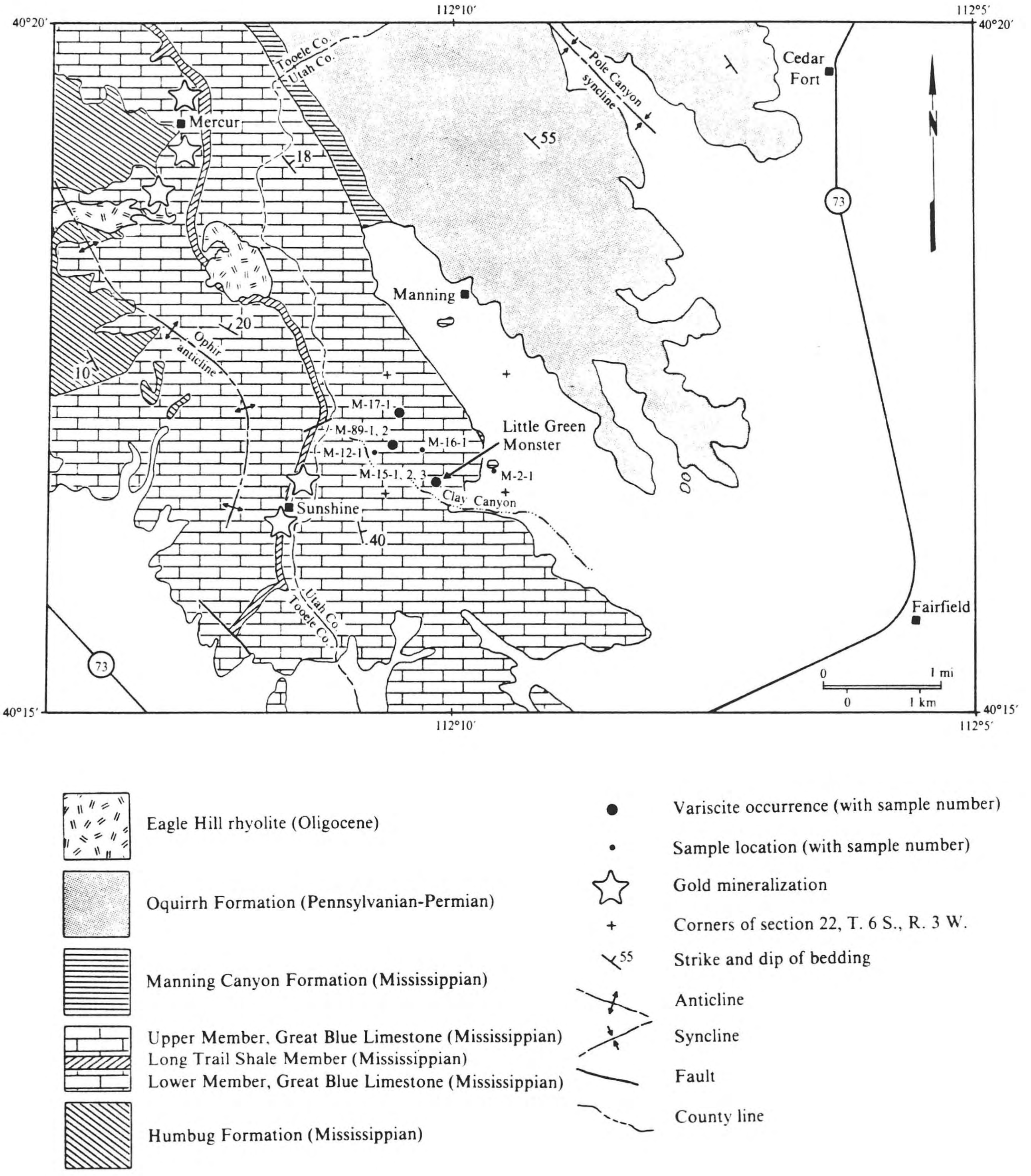

Figure 2. Geologic map of the Clay Canyon scandium-bearing aluminum phosphate deposits showing sample locations and areas of precious metals mineralization. Geology from Gilluly (1932).

0.14 and 0.10 percent Sc_2O_3 respectively (Frondel and others, 1968). At present, several mining companies are exploring for gold in the area.

Dark limestone and black shale of the Upper Mississippian Great Blue Limestone, stratigraphically above the Long Trail Shale Member, host the variscite deposits in Clay Canyon. Bedding dips 22° to the northeast and the area lies on the northwestern limb of the Ophir anticline (Gilluly, 1932). The nearest igneous rock is the highly altered Eagle Hill Rhyolite, dated at 31.5 Ma (Moore, 1968), located 2.2 miles to the northwest. At the Little Green Monster deposit, variscite nodules replace the limestone host along a north-trending, vertical fracture zone. Nodules lie within pipe-like bodies that plunge 25° to 30° to the north (Montgomery, 1970). Variscite and crandallite occur as aggregates of nodules in a highly altered matrix, as elongate replacements along fractures, and as fissure fillings (figure 3). Alteration products of brecciated and fractured limestone surrounding the nodules include limonitic clays, alunite, chalcedonic quartz, and calcite. At the northernmost variscite occurrence in Clay Canyon (figure 2), black chert nodules occur in the limestone but otherwise the surface expression of the deposit is identical to the Little Green Monster. At the westernmost deposit (figure 2), variscite occurs both as nodules in brecciated limestone and as vug fillings in jasperoid.

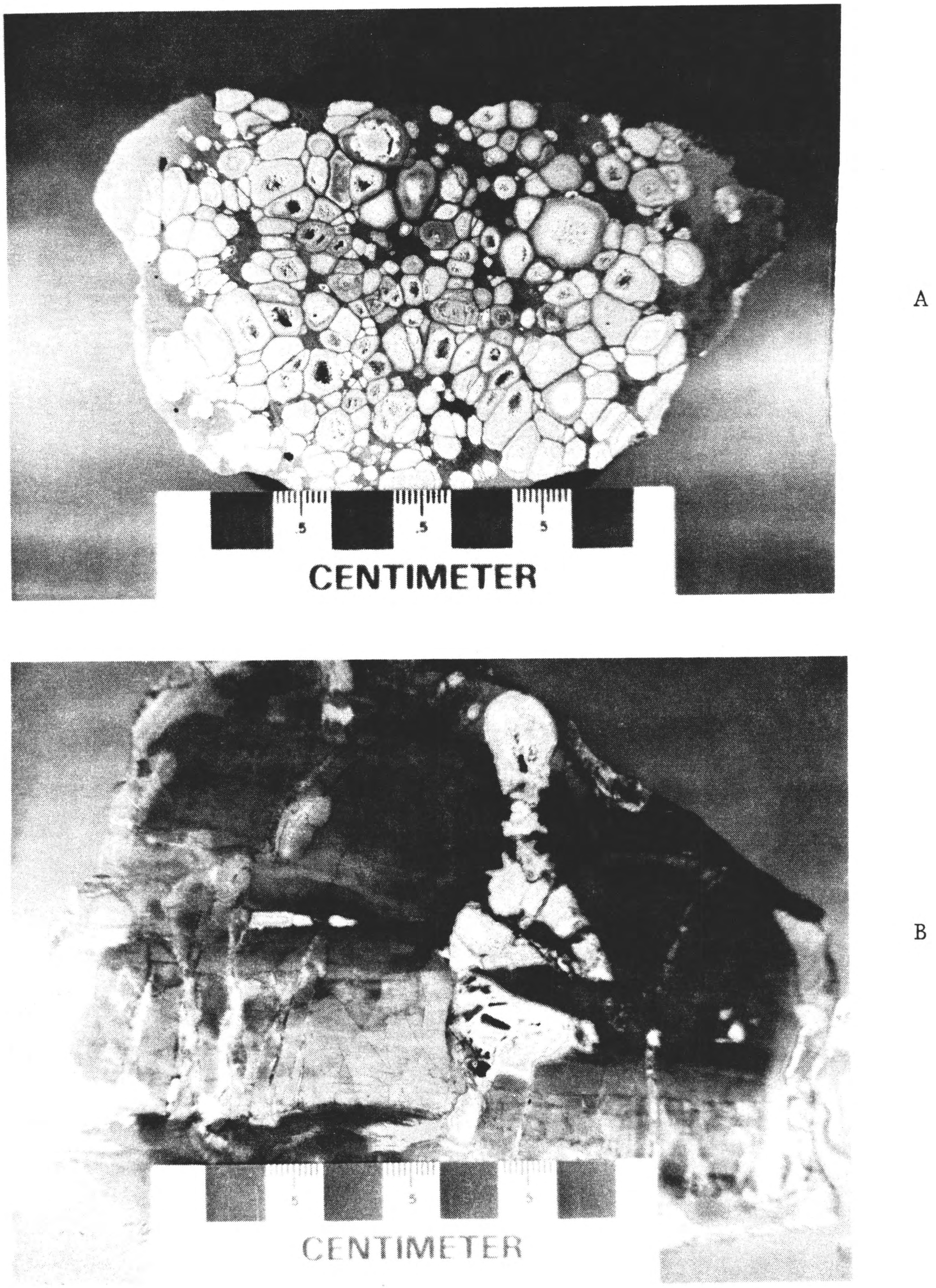

Figure 3. Scandium-bearing crandallite and variscite from the Clay Canyon area. A. Crandallite nodules (light colored) with sparse unaltered variscite (V) cores set in a highly argillized, limonitic matrix. B. Nodular crandallite replacing brecciated limestone along a small-scale fault, and crandallite filling fractures. Limestone host is variably argillized and limonitized.

Scandium-bearing aluminum phosphate minerals in all three deposits consist of crandallite, lesser variscite, and a variety of rare minerals (see lower half of table 1). A paragenetic sequence of scandium-bearing minerals determined by Larsen (1942, p. 365) for the Little Green Monster deposit suggests that the first event in the mineralization process was replacement of limestone by variscite. Next, crandallite largely replaced the earlier formed variscite. Precipitation of rare scandium-bearing aluminum phosphate minerals both accompanied and post-dated crandallite alteration. Quartz, calcite, and limonite precipitation followed the phosphate minerals.

Frondel and others (1968) showed that crandallite contains scandium oxide over a range of 100 to 8000 ppm and that wardite, deltaite, and goyazite contain as much as 5000 ppm Sc_2O_3. That study also determined that scandium enrichment accompanied alteration of variscite to crandallite and other late-stage minerals. As noted previously, bulk samples of crandallite ore contained over 1000 ppm scandium oxide. Trace elements associated with scandium mineralization include strontium, yttrium, gallium and vanadium (Frondel, 1968). In addition to these elements, sampling by the UGMS showed associated high values of gold (93 ppb).

Amatrice Hill Deposit

The Amatrice Hill deposit is 8 miles west of Stockton on the east flank of the Stansbury Mountains (figure 1). After its discovery in 1905, gem-quality variscite was produced for several years by the Occidental Gem Corporation under the trade name "amatrice." Production in 1908 was approximately 45,000 carats (Sterrett, 1908). Frondel and others (1968) analyzed two samples of variscite from the deposit and confirmed the presence of scandium.

Host rocks at Amatrice Hill include limestone, dolomite, calcareous sandstone, and quartzite of the Pennsylvanian Oquirrh Formation (Bissell and Rigby, 1959) that dip 60° to the west-southwest. Zalinski (1909) reported the occurrence of monzonite porphyry about a quarter of a mile southwest of Amatrice Hill and reasoned that variscite mineralization postdated intrusion. The deposit lies immediately west of a north-striking, high-angle fault juxtaposing Lower Mississippian and Upper Devonian rocks to the east (Moore and Sorensen, 1979). Two parallel, north-striking fracture zones cut the east side of Amatrice Hill, and variscite nodules locally replace brecciated carbonate rocks within these fracture zones. Hydrothermal alteration associated with variscite mineralization includes widespread replacement of carbonate rock by chalcedonic quartz (forming agate-like jasperoid) and pyrite, and later oxidation forming limonite. Variscite occurs both as nodules replacing carbonate rock and as fissure fillings. Locally, variscite and chalcedony veinlets cut variscite nodules, indicating syn-depositional deformation. Alteration of variscite to crandallite occurred at Amatrice Hill but to a much lesser extent than the Clay Canyon deposits.

Analyses of variscite and associated jasperoid collected by the UGMS from Amatrice Hill show geochemical enrichment in scandium, cerium, lanthanum, yttrium, vanadium, strontium, and chromium (table 2). Frondel and others (1968) analyzed two samples of variscite, one of which contained between 10 and 100 ppm Sc_2O_3 and the other between 100 and 1000 ppm Sc_2O_3.

Lucin Deposits

In 1905, Frank Edison rediscovered the variscite deposits of "Utahlite Hill", located 3.8 miles north of Lucin, Utah, in a shaft initially sunk by gold prospector C.J. Burke (Sterrett, 1910). Later, in 1909, Frank Edison and Edward Bird (discoverer of the Amatrice Hill deposit) located claims and produced variscite from the Edison and Bird mine until 1910. Exploration by the miners in 1911 resulted in the discovery of an additional variscite deposit located on the Sentinel claim. Analyses of variscite from the deposit by Frondel and others (1968) confirmed the presence of scandium.

Dolomite, limestone, quartzite, chert, and siltstone of Permian age underlie Utahlite Hill. Unpublished mapping by M.S. Tischler in 1960, as part of a mineral survey by Southern Pacific Railroad, shows that these rocks dip moderately to the northeast (figure 4). Miller (1985) identified similar rocks located 1.2 miles south of Utahlite Hill as probable equivalents

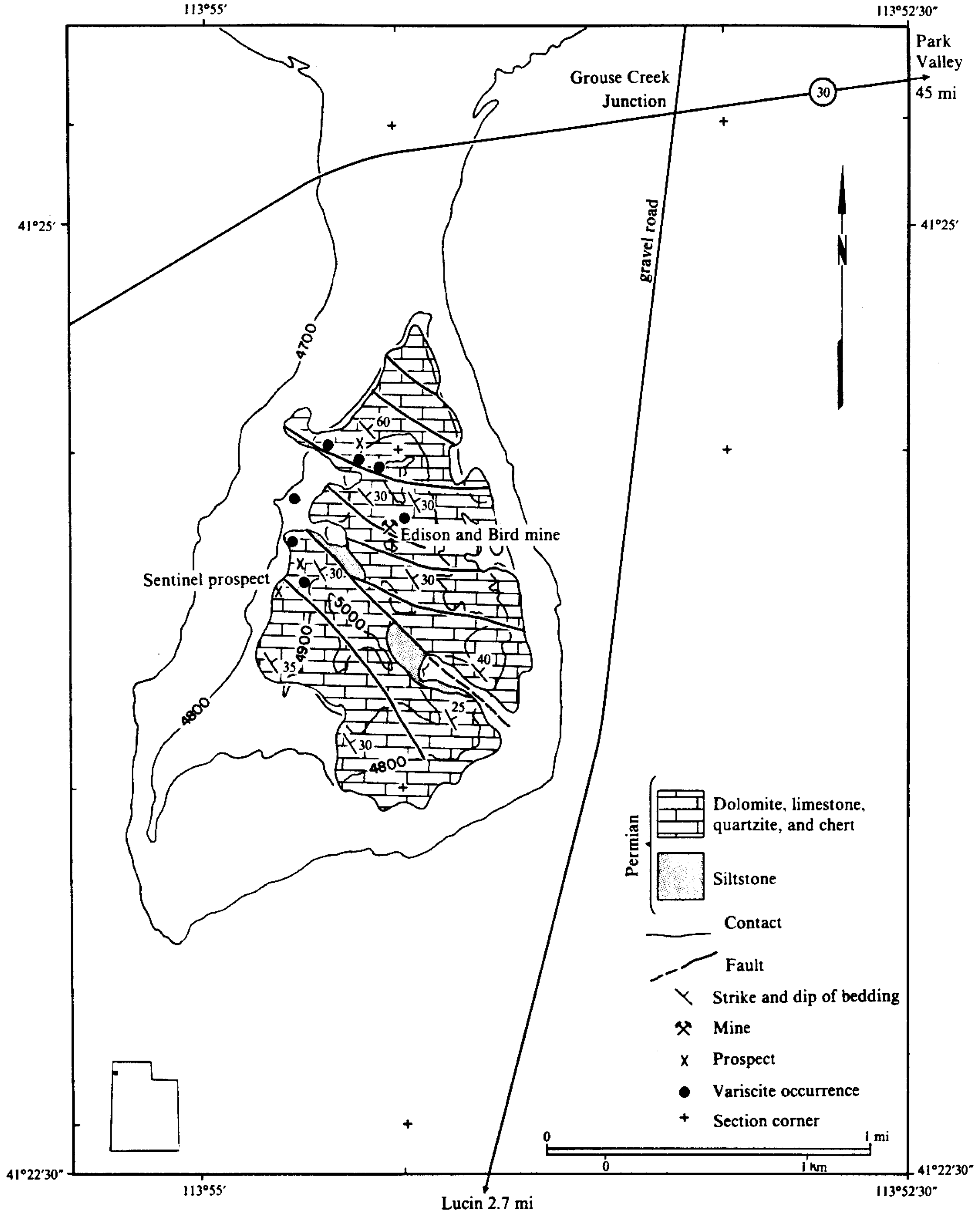

Figure 4. Geologic sketch map for the Lucin variscite occurrences. Reconnaissance geology mapped by Tischler (1960) for the Southern Pacific Railroad.

of the Grandeur Formation of the Park City Group. Numerous northwest-striking, high-angle faults mapped by Tischler cut the strata and appear to control the distribution of variscite occurrences. Miller recognized several pre-Oligocene bedding-plane faults south of Utahlite Hill and suggested that small bedding-plane faults are probably pervasive throughout Permian rocks in the area.

Sterrett (1910) described the variscite deposits at Utahlite Hill. Host rocks consist of chert and chalcedonic quartz with nodules and streaks of limestone. Sterrett characterized most of the rock as a "hard breccia cemented together by silica." This description suggests a history of tectonic brecciation followed by pervasive silicification. Variscite occurs as nodules, irregular masses, and less commonly as veins. Variscite both fills and replaces brecciated host rocks and typically has a concentric, banded texture. The dominant matrix associated with variscite is chalcedonic and crystalline quartz. Angular, white quartz breccia cemented by bright green variscite produced from the Edison and Bird mine has been quite popular. Sterrett mentioned the presence of other phosphates at Utahlite Hill but did not elaborate on their mineralogy. W.T. Schaller of the U.S. Geological Survey examined granular samples of variscite from the deposit in 1910, noting an orthorhombic symmetry and the presence of impurities of chromium (0.18% Cr_2O_5) and vanadium (0.32% V_2O_3). Frondel and others (1968) determined the scandium content of three variscite samples from the deposit, which fell into the

Sample No.	Deposit/Area	Description	Sc	Y	Ce	La	V	P	Cr	(ppb) Au	Ag	As	Sb	Mo	Zn	W	Ba	Sm	Eu	Tb	Yb	Lu	Th	U
M-2-1	Oquirrhs	Manning Canyon Shale	18.0	29	110	47	210	1060	98	<5	<5	31	28.7	<2	<200	<4	150	9.3	<2	<1	<5	0.8	15.0	3.7
M-12-1	Clay Canyon	Argillized black shale	13.0	*	24	21	143	3700	110	<5	5	43	61.0	18	<200	<2	<100	3.8	<2	<1	<5	0.6	2.2	12.0
M-16-1	Clay Canyon	Barren Black Shaley lms	1.5	<5	<10	5	34	670	<50	<5	<5	3	4.2	3	<200	<2	<100	1.0	<2	<1	<5	<0.5	<0.5	2.9
M-15-1	Little Green Monster	Grab sample, variscite + crandallite	101.0	*	34	5	1200	>2%	110	<5	<5	68	14.0	13	590	<7	<100	2.7	<2	<1	<5	1.9	0.6	42.0
M-15-2	Little Green Monster	Grab sample, variscite + crandallite	24.0	37	15	<5	385	19,750	78	<5	<5	15	11.0	5	580	<2	<100	2.8	<2	<1	<5	0.7	0.8	17.0
M-15-3	Little Green Monster	Barren lms host rock	2.2	<5	<10	7	45	1570	<50	<5	<5	7	6.3	2	<200	<2	<100	1.1	<2	<1	<5	<0.5	<0.5	2.1
M-17-1	Northern Clay Canyon	Grab sample, crandallite	98.3	*	16	9	1650	>2%	230	<5	<5	18	3.9	4	230	<7	<100	2.6	<2	1	<5	0.6	6.0	18.0
M-89-1	Western Clay Canyon	Variscite in jasperoid	67.7	*	<10	<5	1100	<2%	250	93	<5	74	10.0	10	220	<6	<100	1.5	<2	<1	<5	0.8	<0.5	16.0
M-89-2	Western Clay Canyon	Jasperoid with minor variscite	5.1	<5	65	24	315	3000	150	30	<5	68	3.6	6	<200	<2	190	5.1	<2	<1	<5	1.9	6.8	48.0
DPE-1	Amatrice Hill	Variscite in jasperoid	29.0	*	90	100	690	>2%	1100	<5	<5	66	0.3	<2	240	<2	830	12.0	<2	2	<5	1.0	11.0	17.0
DPE-2	Amatrice Hill	Variscite in jasperoid	76.0	*	<24	32	535	>2%	2300	<5	8	47	0.3	<2	<200	<6	690	2.7	<2	1	<5	0.8	7.2	220
S-4	Hansel Mtns occurrence	Variscite	40.0	*	21	27	235	>2%	580	<5	<5	184	10.0	17	1.2%	9	1000	3.5	<2	<1	<5	0.8	5.9	21.0

Table 2. Results of reconnaissance geochemical sampling by the UGMS. Neutron activation analyses performed by Bondar-Clegg, Lakewood, Colorado. "*" symbol denotes interference due to high strontium content. All values in ppm except where noted.

following ranges: 1 to 10 ppm Sc_2O_3; 10 to 100 ppm Sc_2O_3; and 100 to 1000 ppm Sc_2O_3.

Other Deposits

Frondel and others (1968) reported that the scandium content of variscite samples from near Kelton and Mercur, Utah contained between 100 and 1000 ppm Sc_2O_3. Accurate locations of these deposits are lacking, but figure 1 shows approximate locations. The Hansel Mountains variscite occurrence, located 5.6 miles south-southwest of Snowville, Utah, consists of minor amounts of broken nodules hosted by sheared, strongly argillized, and locally silicified carbonate rock (Personal communication, Bryce Tripp, UGMS, 1987). Doelling (1980) identified the host rock as the Pennsylvanian-Permian Oquirrh Formation. A sample of the Hansel Mountains variscite collected by the UGMS contained potentially anomalous values of scandium, chromium, zinc, strontium, and yttrium (table 2).

Discussion

Previous workers who studied the deposits in Clay Canyon (Frondel and others, 1968; Larsen, 1942) proposed a supergene origin for the scandium-bearing aluminum phosphate minerals. In their interpretation, descending, low-temperature, acidic (SO_4-bearing) ground waters leached scandium, yttrium, vanadium, phosphate, sulfate, and other trace metals from the Phosphoria

Formation (and other phosphatic shales), transported the metals as complex ions, and precipitated variscite and related minerals in brecciated limestone. New research on the geologic setting of aluminum phosphate-sulfate (APS) minerals, however, documents their occurrence as hypogene minerals in a variety of ore deposits. This information, coupled with mineralogical and chemical data from an active geothermal system in New Zealand (Krupp and Seward, 1987), and with field relations of variscite occurrences in Utah and Nevada, suggest that the scandium-bearing deposits described in this report originated as hypogene, hydrothermal deposits occupying the fringes of epithermal, locally precious-metals-depositing systems.

Stoffregen and Alpers (1987) documented the occurrence of APS minerals in three ore deposits including the epithermal Summitville gold deposit in Colorado. They define APS minerals as those conforming to the generalized formula $RAl_3(PO_4)_{1+X}(SO_4)_{1-X}(OH)_{6-X}\cdot(H_2O)_X$ and list crandellite and goyazite as end-member compositions. Compositions of APS minerals from Summitville include abundant strontium, lesser cerium, and variable amounts of light rare-earth elements. APS minerals in all deposits examined occur in the advanced argillic zone of alteration, indicating their stability in the acid-sulfate environment. In southwestern Utah, Mahin and Peterson (1987) discovered the APS minerals goyazite and crandellite in ores of the Apex gallium-germanium mine. They found early formed goyazite trapped within quartz grains that yielded fluid inclusion homogenization temperatures of 330°C. This data clearly documents the hypogene nature of goyazite at the Apex mine.

Krupp and Seward (1987) found that cerium and lanthanum, enriched in some of the scandium-bearing deposits described here (sample DPE-1, table 2), are constituents of minerals precipitating from the gold-rich Rotokawa geothermal system in New Zealand. One of the minerals is a cerium-lanthanum monazite ($(\mathrm{Ce},\mathrm{La})\mathrm{PO}_4$), and its presence in the Rotokawa system demonstrates the stability of this hydrothermal phosphate mineral in the acid-sulfate environment.

Field relations of scandium-bearing aluminum phosphate deposits in Utah and Nevada suggest a genetic relationship to epithermal, precious metals-mineralized systems. Deposits in Clay Canyon occur near the distal margin of a hydrothermal alteration halo extending from the Mercur district and including gold-mineralized rock in Sunshine Canyon (figure 2). K-Ar dating of clay minerals from the area indicate that no direct link between gold mineralization, alteration, and scandium mineralization can be made at this time because of the existence of a Jurassic hydrothermal event (Personal communication, Erich Peterson, University of Utah, 1987). The Lucin and Amatrice Hill occurrences do not occur immediately adjacent to precious metals deposits but do show hydrothermal alteration (pervasive chalcedonic silicification) characteristic of epithermal systems.

Variscite occurrences in Nevada occur in and adjacent to the Rock Hill, Candelaria, Gilbert, Silver Star, Eureka, and Manhattan districts and show a general spatial relationship to epithermal precious metals deposits.

The connection between scandium-bearing aluminum phosphate deposits and phosphatic shales is uncertain. However, the geochemical similarity between phosphatic shales and scandium occurrences, especially their Sc, Y, V, Sr, Ce, and La contents, suggests a genetic link.

Conclusions

Scandium remains an obscure element on the periodic table to most economic geologists, however, new advances in materials science may change this view and the deposits described in this report may serve as a starting point for future scandium exploration in Utah. Insufficient data on scandium-bearing aluminum phosphate minerals exist at present to formulate a genetic model, but several factors seem to be important in localizing deposits. These factors are the presence of a brecciated carbonate host rock, proximity to a gold-silver epithermal system, and proximity to phosphatic shales.

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