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Sunset Ridge fluorite deposit, Fra Cristobal Range, Sierra County, New Mexico

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Introduction
The Sunset Ridge fluorite deposit was discovered by Tenneco in 1980 during mineral reconnaissance of the Fra Cristobal Range, Sierra and Socorro Counties, New Mexico (Fig. 1). The first documentation of fluorite in the Fra Cristobal Range was by Walker (1914). Peale (1949) explored the extensive vein systems in the range and identified many fluorite occurrences.

Sunset Ridge deposit
Sunset Ridge is the topographic expression of the West Vein, a thick, resistant, composite-quartz vein that occupies the north-trending West Vein fault (Figs. 2 and 3). The vein dips steeply westward and is partly exposed along the fault trace for a strike length in excess of 5 mi (8 km). Fissure zones in the West Vein fault have been opened repeatedly, mineralized chiefly with quartz, and brecciated. The planar orientation of minerals and breccia fragments in the fissure and subsequent weathering are responsible for the well-developed exfoliation joints that give the vein outcrop a platy appearance. The local true thickness of the West Vein is uncertain, but it is estimated to be at least 130 ft (40 m) at Sunset Ridge. Hanging-wall rocks remain unknown because they are covered by talus and alluvium and were not intercepted by the drill holes. The footwall is composed of fractured and brecciated Precambrian granitic rocks (Figs. 4 and 5).

Late fissures in the West Vein at Sunset Ridge are filled with tectonically remobilized, coarse-grained, fluorite-breccia fragments with a matrix of fluorite, milky quartz, and sparse hematite. The most prominent fluorite-filled fissure, or "main zone," is exposed along the crest of Sunset Ridge and is associated with abundant milky quartz veinlets. The remainder of the West Vein is mostly quartz with disseminated iron oxides. The main zone is preferentially eroded relative to the enclosing quartz vein. The zone ranges from 5 to 13 ft (1.5 to 4.0 m) in true thickness and is approximately 400 ft (120 m) in exposed strike length (Fig. 6). Rock-chip samples collected from across the main zone range from 37.67% to 62.5% equivalent CaF₂, as calculated from specific ion and distillation analyses for fluorine. Smaller fluorite zones are partly exposed for hundreds of feet along the strike of the main zone.

All three of the core holes intercepted the main zone up to 300 ft (90 m) downdip from the vein outcrop. The deposit remains open.
at depth and laterally. The known portion of the main zone averages 9 ft (2.7 m) in thickness and contains approximately 34% equivalent CaF₂. Additional fluorite zones were identified in all core holes. These minor zones range from 1 to 13 ft (0.3 to 4.0 m) in estimated true thickness and occur within both the West Vein and brecciated granitic footwall rocks.

**Structural setting**

Many major fluorite districts of the world are located along or near continental rift zones and lineaments (Van Alstine, 1976). The Rio Grande rift is one such zone. Many of the fluorite mines and prospects of New Mexico, Colorado, and, possibly, Mexico are distributed along this major north-trending system of Miocene to Recent grabens. These structural basins formed during regional extension and are bounded by faults that have normal displacements up to or exceeding 10,000 ft (3,000 m). The grabens are filled with thick, semi-consolidated, detrital material and exhibit high heat flow (Reiter and others, 1975). These conditions promote the convective circulation of geothermal solutions that may be favorable for epithermal mineralization. As a result, quartz, fluorite, barite, and base-metal sulfides have been deposited into open spaces and have replaced favorable host rocks along major boundary faults of the rift.

The north-trending West Vein fault is the most prominent of many subparallel faults that form the boundary between the Fra Cristobal uplift to the east and a graben in
Granitic rock fragments are locally abundant in the West Vein, and drill holes intercepted one major horse of silicified granite breccia. Numerous lesser-normal faults that are subparallel to the master fault occur in the granitic footwall rocks. These faults are filled locally with thin quartz veins that may contain minor fluorite or base-metal minerals. The faults are associated spatially with wide zones of variably silicified tectonic breccia. Major west-dipping, northwest- and northeast-trending normal faults also are common in the footwall rocks. Fluorite, barite, and manganese-oxide deposits are localized along faults of similar strike elsewhere in the Fra Cristobal Range. These structures are cut by the system of north-trending faults at Sunset Ridge. Minor east-trending Quaternary (?) normal faults displace the West Vein, granitic rocks, and perhaps some older alluvium. These small-displacement, steeply-dipping faults are subparallel to one set of joints in the vein.

**Footwall rocks**

The footwall of the West Vein fault at Sunset Ridge is composed of the Fra Cristobal pluton, a Precambrian, composite, granitic stock or batholith with inclusions of meta-sedimentary rocks. The dominant intrusive rock here informally named the Fra Cristobal granite, is of somewhat uncertain age. In 1982, a K-Ar age of the granite was determined to be 850 ± 29 m.y. by Geochron Laboratories, Cambridge, Massachusetts. The age date was obtained from a concentrate of partly chloritized biotite in granite core from a drill hole in protracted sec. 11, T. 11 S., R. 3 W. Similar rocks in south-central New Mexico have Rb-Sr whole-rock isochron and U-Pb zircon age dates that range from 1.2 to 1.65 b.y. (Condie and Budding, 1979). A chemical analysis of granite from the same core hole is provided in Table 1. The composition falls within the group of high-potassium Precambrian granitic rocks in south-central New Mexico (Condie and Budding, 1979).

The granite is lightly gneissic with a tendency for alignment of mica plates and elongated quartz crystals. The rock is medium- to coarse-grained, hypidiomorphic-granular. Minerals are quartz 22%, orthoclase 41%, microcline 26%, albite 9%, muscovite 2%, minor biotite, hornblende and magnetite. The granite is anhedral, 1-4 mm in diameter, strained and in part cloudy with inclusions. Feldspars are subhedral laths, 3-8 mm long, altered to sericite and kaolinite. Micas are in scattered flakes, less than 1 mm long; near hornblende crystals, they are concentrated in lenses. Hornblende is pleochroic from aqua to greenish yellow-brown, euhedral to subhedral, less than 1 mm long, altered in part to chlorite, iron oxide, and chlorite.

The Fra Cristobal granite is typically altered. Mafic minerals are converted mostly to chlorite or hematite. If magnetite originally existed at Sunset Ridge, it is now oxidized to hematite. A portable magnetometer failed to reveal significant differences in magnetic susceptibility among the Fra Cristobal granite, the West Vein, and alluvial cover. The granite is also variably altered by potassium metasomatism, but the Sunset Ridge area is not particularly affected. Elsewhere in the Fra Cristobal Range, small altered zones with brick-red microcline and minor muscovite occur within the granite. These mesasomites are similar to larger bodies in the Precambrian intrusive rocks of the Cabalo Range (Staatz and others, 1965).

The Fra Cristobal pluton contains large inclusions of partly assimilated chlorite schist, chlorite-feldspar gneiss, and amphibolite. These deformed inclusions were not observed at Sunset Ridge, but they are particularly abundant in the northern Fra Cristobal Range. Abundant, small, Precambrian (?) dikes and irregular granitic intrusives that are composed of simple granite pegmatite, monzonite, quartz monzomite, and alaskite cut the Fra Cristobal granite. The degree of gneissic banding in the late intrusives is the same as, or less than, that found in the older granite. The late dikes are devoid of mafic silicate minerals and have traces of specular hematite or limonite pseudomorphs after pyrite.

**Hanging-wall rocks**

The hanging wall of the West Vein at Sunset Ridge is concealed by at least 125 ft (38 m) of Quaternary talus and alluvium, and it was not intersected by exploration drill holes. The hanging wall may contain the Fra Cristobal pluton and portions of the approximately 5,000 ft (1,500 m) of overlying Paleozoic, Mesozoic, and Cenozoic sedimentary rocks. In probable order of abundance, these strata include carbonate rocks, shales, sandstones, evaporites, and conglomerates. Possible Paleozoic units are the Bliss Sand-
Paragenesis of the West Vein at Sunset Ridge, Fra Cristobal Range, Sierra County, New Mexico.

FIGURE 7—Paragenesis of the West Vein at Sunset Ridge, Fra Cristobal Range, Sierra County, New Mexico.

West Vein mineralization

The West Vein at Sunset Ridge is composed of fine-grained quartz, coarse-grained fluorite, and granitic rock fragments. Iron oxides, barite, and clays occur in minor amounts; traces of pyrite, "psilomelane," calcite, gypsum, galena, and copper minerals also have been identified. The weathered and partly covered surface of the West Vein is mostly quartz with disseminated iron oxides. The known minerals are listed in Table 2 according to their relative abundances. Vein-mineral paragenesis (Fig. 7) is complex, and our knowledge of it is likely to be modified with additional study. More than 95% of the volume of West Vein mineralization may be hypogene. Epithermal solutions deposited minerals into open spaces between breccia fragments and in fissures that formed during episodic extensional faulting. Minor, late-stage minerals were introduced into existing open spaces during a period of relative tectonic quiescence. This late mineralization may have originated from mixed hypogene and supergene (mesogene) solutions. Some of the earlier mineralization was altered by oxidation and dissolution, and was locally redistributed in the mesogene environment.

Quartz is the most abundant mineral in the West Vein. It was deposited in 12 or more distinct episodes of cross-cutting vein mineralization. Most quartz was deposited prior to the first fluorite mineralization. The earliest quartz deposit is barren and milky. Subsequent quartz deposits contain disseminated pyrite, commonly oxidized to limonite. The last quartz veinlets emplaced prior to the first fluorite mineralization contain disseminated red hematite. Continued faulting along the West Vein opened narrow fissures that were filled with barren, milky-quartz veinlets. Subsequently, wider fissures were filled with coarse-grained fluorite. Later faulting brecciated and mechanically remobilized the fluorite. Milky quartz and reddish hematite were deposited interstitially between fluorite fragments. The resulting fluorite breccia contains single-crystal fragments up to 1.5 inches (3.8 cm) across (Fig. 8). These fluorite fragments exhibit well-developed internal (111) cleavage and are generally transparent and colorless, purple, or green, if fresh. Weathered fluorite is commonly whitish and opaque. Traces of coarsely crystalline, beige to white barite in small breccia fragments are associated with fluorite and also occur elsewhere in the vein without associated fluorite.

The major period of fluorite mineralization was followed by two late periods of quartz mineralization. Primary base-metal sulfides were deposited in openings within the younger of these two quartz phases. Chalcopyrite, pyrite, and arsenopyrite (?) crystallized first. Galena commonly was deposited as overgrowths on chalcopyrite crystals. Quartz veins with base-metal sulfides generally occur in the fractured granitic footwall rocks without attending fluorite.

Minor late-stage minerals filled local voids in breccias, fractures, joints, and solution cavities. The late-stage minerals are not fractured and therefore appear to have formed after the cessation of major displacement along the West Vein fault. Some fluorite breccia contains solution vugs that are partly filled with later fluorite and associated minerals. Minor iron and manganese oxides occur as colloform coatings on fractures and around breccia fragments in the granite and vein quartz. Weathering has altered some pyrite to limonite, and chalcopyrite is partly converted to chalcocite and subsequently to malachite and chrysocolla(?)

Trace cuprite(?) also

FIGURE 8—Core and surface samples of fluorite breccia with fluorite, milky quartz, and hematite matrix from Sunset Ridge, Fra Cristobal Range.
may have formed from chalcopyrite. Late-stage barite crystallized as tiny laths in open spaces prior to malachite crystallization, whereas small, modified cubes of purple fluorite crystallized on the malachite coatings and in other voids. These unbrecciated fluorite crystals commonly have internal ghosts of limonite and may have formed by dissolution and redissolution of the earlier brecciated fluorite. Traces of chalcedony, finely crystalline quartz, white poker-chip calcite crystals, gypsum, and caliche were deposited sequentially after the last fluorite crystals.

**West Vein geochemistry**

Core and surface-rock samples from Sunset Ridge were submitted to commercial laboratories and assayed for fluorine by quantitative techniques, and 55 elements above atomic number 21 were analyzed by semi-quantitative x-ray fluorescence. Concentrations of up to 30.4% F, 7.8% Fe, 6.0% Ba, and 0.45% Mn were encountered. All other detected elements showed concentrations of less than 0.2%. A quantitative whole-rock analysis for the main fluorite zone is provided in Table 1. Forty-four stream-sediment samples from the prospect area were sieved to ~80 mesh and assayed quantitatively by commercial laboratories for fluorine, barium, and metals.

Geochemical data indicate that fluorite is negatively correlated with base-metal minerals, barite, and hematite. The greatest stream-sediment fluorite values, 4,000 ppm F, was determined in a sample collected about 640 ft (195 m) downstream from the main fluorite zone. Stream sediments derived chiefly from silicified footwall rocks contain the largest base-metal values: up to 72 ppm Ba. Similar barium values occur down the largest base-metal values: up to 72 ppm Ba. Similar barium values occur down the largest base-metal values: up to 72 ppm Ba. Similar barium values occur down the largest base-metal values: up to 72 ppm Ba.

The West Vein fault served as a major conduit for the circulation and possible mixing of meteoric waters. As indicated by multiple episodes of brecciation and complex mineral paragenesis, the fault was repeatedly reactivated and sealed with vein minerals. Fluorite and all other West Vein minerals probably were deposited under epithermal conditions (50-200°C). No high-temperature minerals or associated alterations are evident. Pervasive, periodic, brittle deformation (brecciation and fissuring) indicates that mineralization occurred at relatively shallow depths. The paragenetic association of the main-zone fluorite with hematitic quartz suggests that these minerals were deposited in a near-surface, oxidizing environment.

The most likely mechanisms for fluorite deposition are: increasing the pH, cooling, dilution, or mixing of hydrothermal solutions (Richardson and Holland, 1979). All of these factors contribute to the instability of the SiF₄⁻ complex. Acidic epithermal solutions may have mixed with cool, near-surface ground waters. Each successive motion of the West Vein fault would have dropped the possible limestone in the hanging wall. This would raise the activity coefficient of the calcium cation and increase the rate of the local ground waters. Quartz and, subsequently, fluorite then would be deposited from probable acidic epithermal solutions that circulated or stagnated along the West Vein fault and mixed with ground water or simply cooled. Minor, later fluorite may have been derived from earlier fluorite by local solution and redistribution.

**Summary**

The Sunset Ridge fluorite deposit (Miocene or younger) at the eastern margin of the Rio Grande rift in south-central New Mexico, is a classic fissure vein. Mineralization is controlled by open spaces within the north-trending, steeply dipping, West Vein fault. The greater part of the West Vein is composed of a quartz envelope around a main fluorite zone that averages almost 10 ft (3 m) in true thickness and ranges from 30% to more than 60% fluorite. Core drilling intersected the main zone and other fluorite zones at depths up to 300 ft (90 m) below the surface. Footwall rocks are composed mostly of fractured Precambrian Fra Cristobal granite. Hanging-wall rocks are concealed by surficial debris, but they may contain granitic or sedimentary rocks. Paleozoic carbonate rocks may occur in the hanging wall and are potential hosts for significant replacement-type fluorite deposits. Fluorite may have been deposited from fluorine-rich epithermal solutions that resulted from alteration and leaching of the Fra Cristobal platon by hydrothermal fluids that were generated and circulated during the development of the Rio Grande rift. Quartz and fluorite were deposited into open fissures as the epithermal solutions cooled or mixed with alkaline ground waters that contained calcium derived from local carbonate rocks.

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Lemitar Tuff (samples TS-5, TS-23, DB-108, all from south and southeast Magdalena Mountains) is a strongly and complexly zoned unit. The Lemitar Tuff is a moderately crystal rich rhyolite at the base (Fig. 7a) that grades normally upward into a quartz-poor quartz latite (Fig. 7b), which in turn grades upward into a very phenocryst rich rhyolite (Fig. 7c).

Figure 7a, from the lower rhyolite interval, contains approximately 12–15 percent phenocrysts consisting of sanidine (s), quartz (q), minor plagioclase, biotite and opaques, and traces of zircon and sphene. The groundmass in this sample is partly glassy and contains well-preserved shard structures. This lower interval grades upward over a few feet into a phenocryst-rich quartz latite (Fig. 7b).

Figure 7b contains abundant sanidine (s), plagioclase (p), biotite and minor quartz, opaques and pyroxene. This middle zone grades upward over several tens of hundreds of feet into a very phenocryst rich rhyolite (Fig. 7c).

Figure 7c contains abundant quartz (q), sanidine (s), plagioclase (p), and biotite (b). Very little groundmass is visible between the phenocrysts in figures 7b and 7c, but large pumice fragments in outcrop attest to the pyroclastic origin.

South Canyon Tuff (Samples JA-SC-1, Joyita Hills; 8-11-8, southeast Magdalena Mountains) is texturally zoned from phenocryst poor below to moderately phenocryst rich above; mineralogies are similar in both zones.

Figure 8a illustrates a glassy vitrophyre from the base of the lower zone. Small gray, irregularly curved shapes are undeformed glass shards. Note slight compaction around phenocrysts. Subequal amounts of sanidine (s) and quartz (q) make up the phenocrysts.

Figure 8b, from the upper interval of this unit, contains more abundant and larger phenocrysts of sanidine (s) and quartz (q) with minor biotite, but little preserved vitriclastic texture.

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