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Sulfide/barite/fluorite mineral deposits, Guadalupe Mountains, New Mexico and west Texas

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Abstract

Sulfide/barite/fluorite mineral deposits in the Guadalupe Mountains are similar to those elsewhere in the Delaware Basin: (1) they are all mineralogically simple (containing pyrite and usually sphalerite, calcite, dolomite, and sometimes barite, fluorite, or galena); (2) most have sulfur-isotope values ranging from $\delta^{34}S \approx -9$ to $+5‰$; and (3) most have carbon–oxygen-isotope values ranging from $\delta^{13}C \approx -5$ to $-15‰$, $\delta^{18}O \approx -3$ to $-10‰$. The deposits are in structural and stratigraphic traps, occupying the same position as many of the caves in the Guadalupe Mountains. The sulfide/barite/fluorite deposits around the Delaware Basin are considered to be of the Mississippi Valley type (MVTs).

The origin of MVT mineral deposits in the Guadalupe Mountains may be related to the degassing of the Delaware Basin where H_2S moved from basin to carbonate-reef margin and accumulated there in structural and stratigraphic traps. Mineral deposition is believed to be Oligocene–Miocene in age, a time when these traps were still within the reduced zone. Later, in the Pliocene–Pleistocene, as the mountains uplifted and regional base level dropped, the trapped H_2S gas was oxidized to sulfuric acid at or near the water table, and the sulfuric acid dissolved out the large cave passages. Using the Delaware Basin as an example, I propose that the degassing of basins is a possible alternative model for the origin of other MVT deposits.

Introduction

The sulfide/barite/fluorite deposits in the Guadalupe Mountains, New Mexico and Texas, have been studied by King (1948), McLemore (1983), Thompson (1983), and North and McLemore (1986, 1988). Most of the mines and prospects in the Guadalupe Mountains probably were developed in the early 1900s (Thompson, 1983). The mineral deposits are small (probably only a few tens of tons) and of low economic potential. However, these mineral deposits are an important and integral part of the geologic history of the Delaware Basin and may be crucial to understanding the origin of all Mississippi Valley-type (MVT) deposits (Hill, 1993a,b).

Mineral deposits in the Apache and Glass Mountains, although more extensive than those in the Guadalupe Mountains, have not been economically profitable because of their small size, low grade, and remoteness. The Seven Heart Gap barite mine and the Buck zinc prospect in the Apache Mountains are located along Basin and Range fault zones (Wood, 1968). The Bird and Bissett mines in the Glass Mountains are associated with intrusive bodies (King, 1930). Despite variations in location (from Guadalupe Mountains to Fort Stockton; Fig. 1) and geologic association (igneous intrusions, faults, structural and stratigraphic traps), the mineral deposits around the margins of the Delaware Basin appear to be related. Mineralogy in all of the deposits is similar, and sulfur-isotope values of sulfide minerals usually fall within a fairly narrow range of values ($\delta^{34}S \approx -9$ to $+5‰$, CDT) regardless of location (Fig. 2). Carbon–oxygen-isotope values of gangue calcite also usually plot within a discrete isotopic field (ore-spar field, PDB, Fig. 3).

Description of mineral deposits

Mines, prospects, and other mineral deposits in the Guadalupe Mountains will be described from the vicinity of Carlsbad, New Mexico, southwestward toward Guadalupe Peak, Texas. In Fig. 1 mine localities are identified with letter symbols.

Golden Eagle mine (Lucky Strike, Lone Eagle, or Ammon)

The Golden Eagle mine (GE) is in SW 1/4 sec. 14 T21S R25E about 13 km (8 mi) northwest of Carlsbad, New Mexico. It is recorded in the files of the Eddy County Courthouse that H. H. Davidson and Ola Davidson sold a claim on the property on April 15, 1929, for \$200 to the Carlsbad Copper Company, a partnership consisting of Joe Morosi and others, who named the claim the Lucky Strike no. 1. Soulé (1956) used the names Lone Eagle and Ammon for the mine, but the name Golden Eagle appeared on Motts' (1962) map and is the name that is used in this report. McLemore (1983, pp. 1–91) described the mine as an "open pit 6 m deep with a 7.5 m decline (caved)."

The predominant mineralization at the Golden Eagle mine is copper, but the deposit also includes relatively high amounts of lead and uranium ($U_3O_8 = 0.004\%$, $Cu = 1.05\%$, McLemore, 1983; $Pb = 2590$ ppm, Table 1). Green malachite is distributed fairly uniformly as matrix material throughout the basal siltstone of the Yates Formation. The mine is located along an anticlinal (biohermal) feature trending approximately parallel to the reef front (Motts, 1962).

Rocky Arroyo prospect (Teepee mine, Pitts and Price, Jr.)

The Rocky Arroyo prospect (RA) is in SE1/4 sec. 26 T21S R24E along Walt Canyon ~1 km (~0.6 mi) south of NM–137 where the road crosses Rocky Arroyo. This prospect, unlike most of the other mineral deposits in the Guadalupe Mountains, is not a sulfide deposit. It is a uranium deposit where uranium (as much as 2.35%; Waltman, 1954; McLemore, 1983) as well as arsenic, barium, copper, molybdenum, and nickel (Table 1) are concentrated in hydrocarbon (thucholite) pellets disseminated in the dolomite of the Permian Seven Rivers Formation (not in the Yates Formation as stated by Finch, 1972). The distribution of the pellets seems to be controlled by a small, inclined fracture zone (Motts, 1962), along which a 2 × 2 × 20 m (6.5 × 6.5 × 65 ft) adit has been excavated in the dolomite. Hill (1989) reported a U–Pb age of 350–449 Ma for the hydrocarbon pellets and suggested that these pellets might possibly be derived from the uranium-rich Devonian Woodford shale in the subsurface.

McLemore (1983) reported two other uranium–petroleum sites in the Rocky Arroyo area: the W. H. Shaffer Ranch pits at sec. 27 T21S R24E and a roadcut site at NE1/4 sec. 24 T21S R24E. In the roadcut site anhydrite-nodule molds are filled with calcite; some also contain "dead oil." Uranium minerals in the "dead oil" have been dated radiometrically as Permian (Purvis et al., 1988, p. 97).

Little Walt prospect

Little Walt prospect (LW) is in SW1/4 sec. 2 T21S R24E. Motts (1962) speculated that the Little Walt was a copper mine like the Golden Eagle, but in actuality very little copper exists there (Table 1). Little Walt "mine" is a prospect about 15 m (50 ft) or so in diameter and 2 m (6.5 ft) deep. A 7.5-m-deep (24.6-ft-deep) shaft reported by McLemore (1983) was not observed at the site. The prospect is a slightly radioactive iron gossan (30 cps; McLemore, 1983). Thin veins of resinous sphalerite were found in mineralized rock scattered over the ground surface.

The Little Walt prospect has the same structural and stratigraphic position as the Golden Eagle mine: along a biohermal anticline (part of the Waterhole anticlinorium and Carlsbad fold complex) and at the base of the Yates Formation. The Little Walt anticline is the northern continuation of an anticlinal structure along which

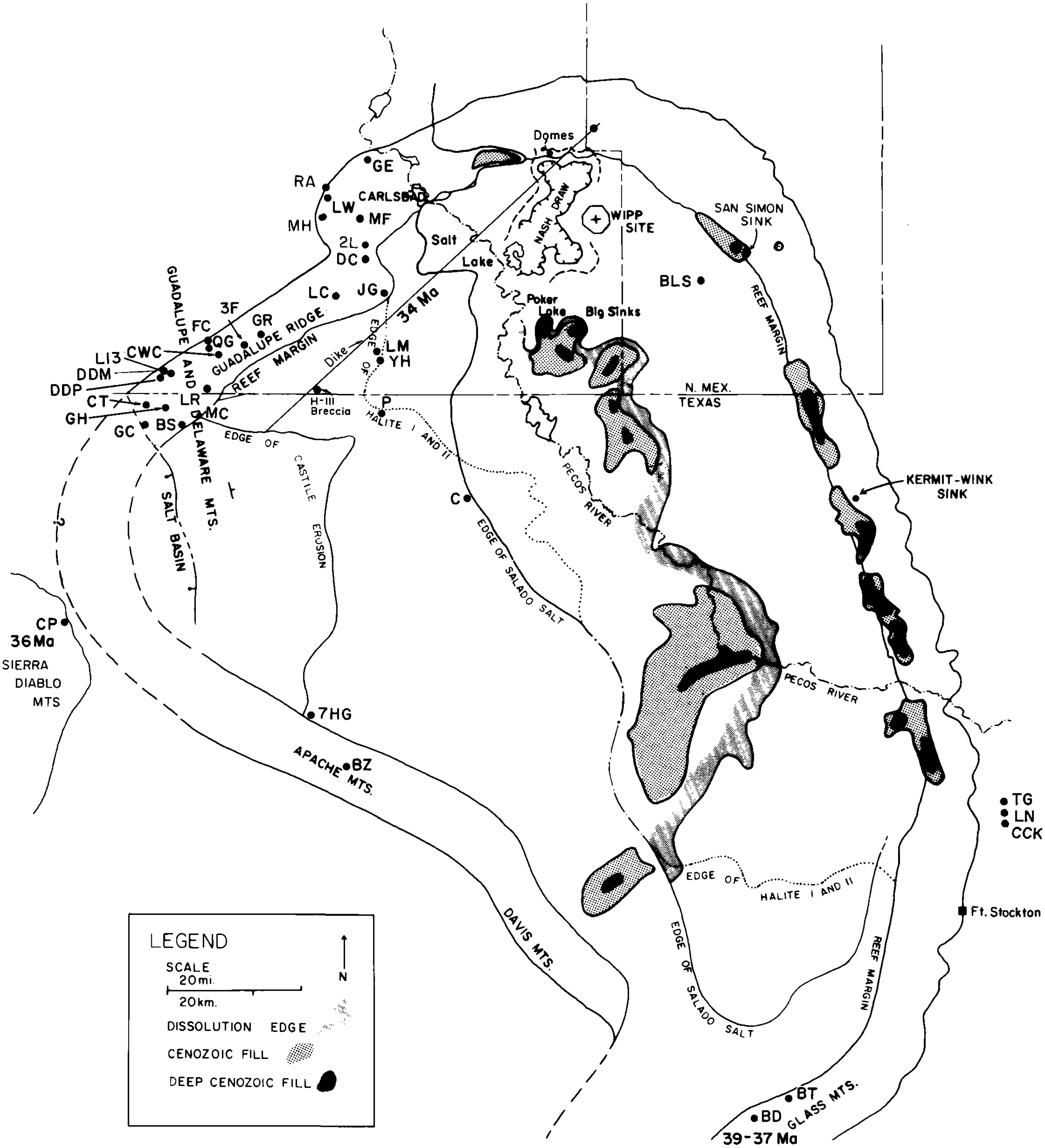

FIGURE 1—Location map of sites mentioned in the text, table, and other figures. Counterclockwise from Carlsbad, New Mexico, around and then within the Delaware Basin: GE = Golden Eagle mine, RA = Rocky Arroyo prospect, LW = Little Walt prospect, MH = McKittrick Hill pyrite, MF = Middle Fork Waterhole marcasite, DC = Dark Canyon pyrite/marcasite, 2L = Two Ladies prospect, JG = Jurnigan gossan, LC = Lechuguilla Cave, GR = Guadalupe Ridge pyrite, 3F = Three Fingers Cave Ridge pyrite, FC = Fir Canyon prospect, QG = Queen of the Guadalupes mine, CWC = Cottonwood Cave, LR = Lonesome Ridge pyrite, L13 = Lucky 13 prospect, DDM = Devil's Den mine adit, DDP = Devil's Den prospects, CT = Calumet and Tejas mine, GH = Grisham Hunter prospect, GC = Glori Cave fluorite, BS = Bell Springs prospect, MC = McKittrick Canyon pyrite, CP = Cave Peak fluorite, 7HG = Seven Heart Gap barite mine, BZ = Buck zinc prospect, BD = Bird mine, BT = Bissett mine, CCK = Comanche Creek, LN = Los Nietos, TG = Texas Gulf, C = Culberson sulfur mine, P = Pokorny sulfur deposit, LM = Leonard Minerals sulfur deposit, YH = Yeso Hills pyrite, BLS = Bell Lake sink. Base map from Anderson (1981). ☞

all of the McKittrick Hill caves are developed (Dry, Endless, McKittrick, Sand, and Little Sand; Hill, 1987). Pyrite collected from the area of the McKittrick Hill caves was analyzed by M. Buck (pers. comm. 1989) for its sulfur-isotope content (MH, Fig. 1; Fig. 2).

Middle Fork Waterhole marcasite

This site (MF) is in NE1/4 sec. 16 T22S R25E about 1 km (0.6 mi) north of the Middle Fork Waterhole and 1 km (0.6 mi) south of Boyd's Canyon. The iron-sulfide mineralization at this location has been identified as marcasite (P. Hlava, Sandia Laboratories, pers. comm. 1993). The marcasite is along or near the contact of the Yates and Tansill Formations and is apparently confined to a single sequence of thinly bedded dolomite (P. Sanchez, pers. comm. 1992). Despite its stratabound occurrence, the marcasite appears to be epigenetic, having been introduced into vugs and along mudcracks, fractures, and between bedding planes. In some places the bladed marcasite crystals (up to a few centimeters long) appear to be "smashed" on their upper surfaces where growth was confined by an upper rock bed. The Middle Fork Waterhole marcasite is in a biohermal anticline located ~6.5 km (~4 mi) west of the McGruder Hill anticline (Motts, 1962).

Dark Canyon pyrite–marcasite

A good exposure of pyrite–marcasite can be found in Dark Canyon (DC) in NE1/4 sec. 34 T23S R25E ~0.6 km (~0.4 mi) south of Dark Canyon and 0.5 km (0.3 mi) north of the Dark Canyon road. The pyrite forms cubes as much as 7.5 cm on a side, and the marcasite forms spears as much as 5 cm long. The mineralization is found as vein or vug fillings in the Seven Rivers Formation near the base of the Yates. The Dark Canyon pyrite–marcasite is located along an anticlinal structure considered by Motts (1962) to be of probable biohermal origin.

Two Ladies prospect

The Two Ladies prospect (2L) is in NE 1/4SE1/4 sec. 32 T23S R25E and was described by North and McLemore (1986, p. 4) as being a "replacement of carbonate and open-space filling in collapse breccia in dolomite of the Permian Yates Formation." According to R. North (pers. comm. 1993) the prospect is associated with a deep natural sinkhole and consists of ~30 m (~100 ft) of workings in brecciated limestone/dolomite and a surface shaft ~2 m (~6.5 ft) long. North found galena, smithsonite, and hemimorphite at the Two Ladies but no sphalerite. One assayed piece of "dry-bone" rock was 27% zinc (R. North, pers. comm. 1993).

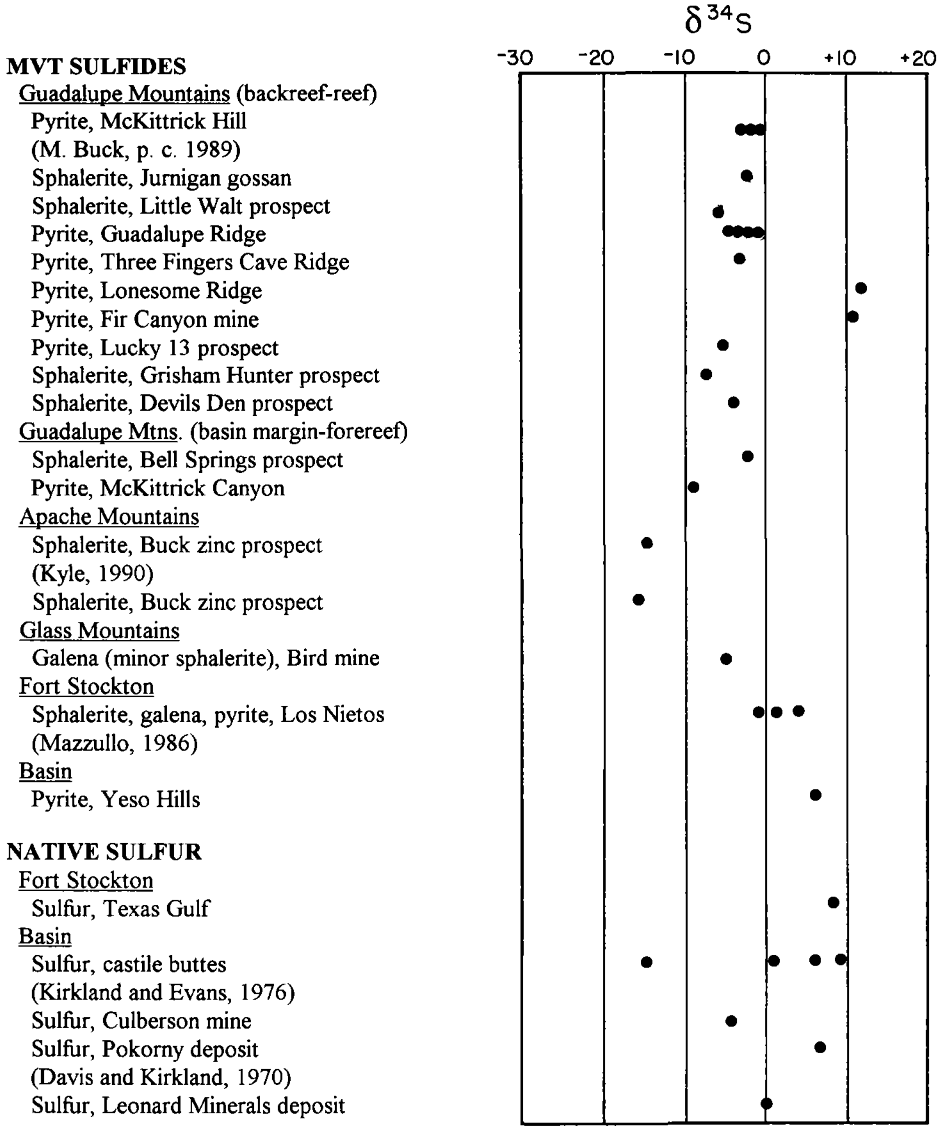

FIGURE 2—Sulfur-isotope values, various types of ore deposits, Delaware Basin.

Jurnigan gossan

Jurnigan gossan (JG) is in SW1/4 sec. 8 T24S R26E just north of Jurnigan Draw and 8 km (5 mi) north of White City at a point where the trend of the reef escarpment changes from a northeasterly to northerly direction (i.e., at the Cueva reentrant). The gossan is about 8 m (26 ft) in diameter, and there is a small prospect about 2 m (6.5 ft) deep dug into the mass. The gossan is located only a few kilometers from Doc Brito, Jurnigan #1, Jurnigan #2, and Wind (Hicks) Caves; all are located less than 1.6 km (1 mi) from the reef edge and along the Reef anticline.

Jurnigan gossan contains relatively high amounts of arsenic, copper, molybdenum, lead, and zinc (Table 1). Thin (0.5 cm) seams of dark-brown, resinous sphalerite are present in the gossan, and silicification of the mass has formed jasperoid. Iron mineralization takes the form of boxwork and cement; the goethite/limonite permeates the Tansill Formation, which is porous and spongy where mineralized. Owen (1983, p. 56) called the gossan a "mineralized dike" of "sandstone," but it is neither a dike nor sandstone.

Lechuguilla Cave barite

Exposed in the entrance sinkhole of Lechuguilla Cave (LC) is a small patch (~1 m^2; ~10 ft^2) of tabular barite intergrown with translucent, blocky calcite. The barite crystals are as much as 1 cm long and 0.25 cm wide. Sulfur-isotope analysis of the barite crystals shows a $\delta^{34}S$ value of +40.6. The entrance to Lechuguilla Cave is along a flexure superposed on the southeastern flank of the Guadalupe Ridge anticline (Jagnow, 1989). The barite is in the Seven Rivers Formation ~8 m (~26 ft) below its contact with the Yates Formation (D. Jagnow, pers. comm. 1992).

Guadalupe Ridge pyrite

Pyrite is concentrated at the base of the Yates Formation all along the crest of the

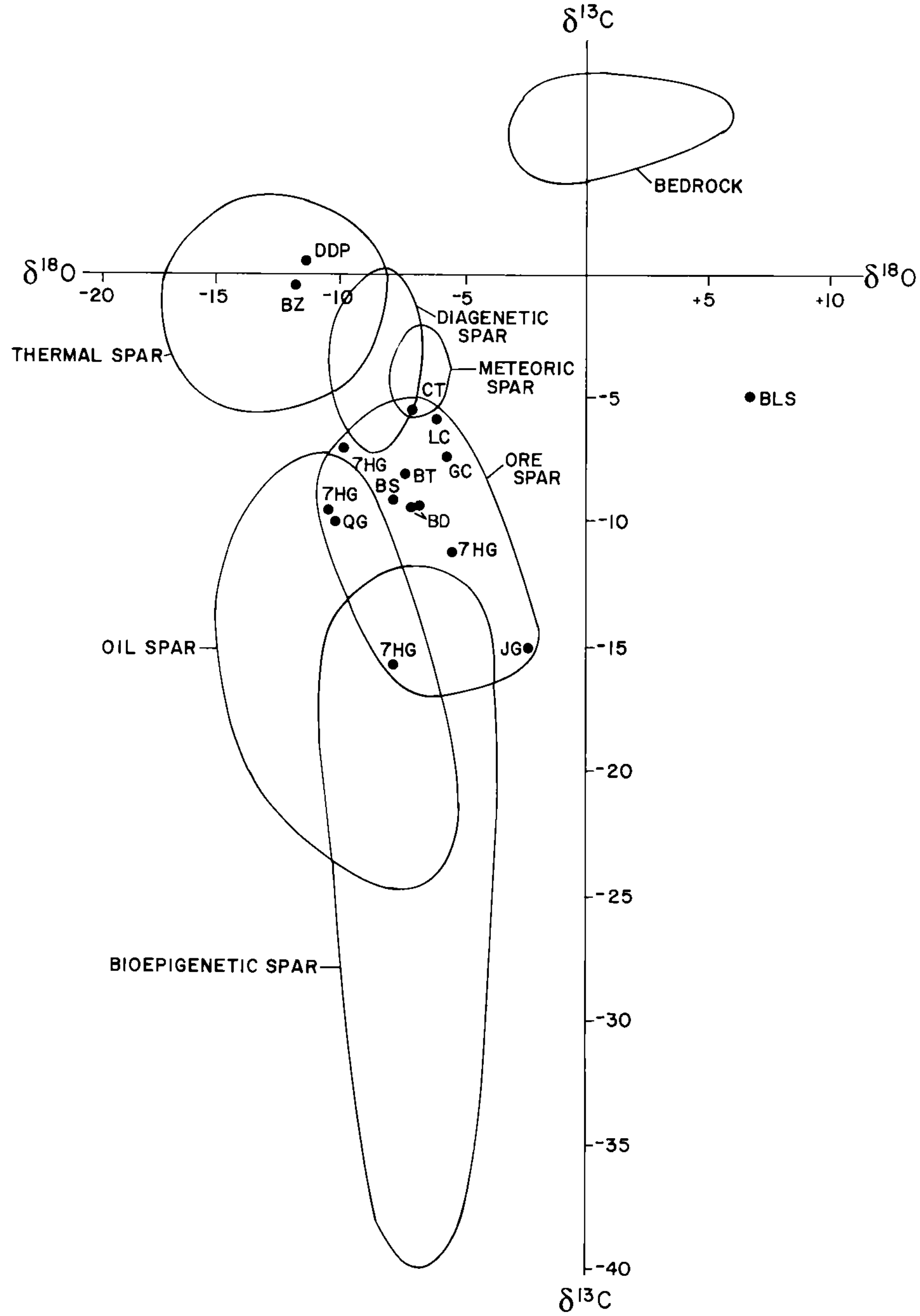

FIGURE 3—Carbon–oxygen-isotope values, various calcite-spar episodes, Delaware Basin. Symbols used are the same as those used in Fig. 1 caption.

Guadalupe Ridge anticline. Samples were collected at the GR locality along the ridge by Light and Domenico (1983), at Three Fingers Cave parking lot (3F) by C. Mosch, and at other locations along Guadalupe Ridge by D. Jagnow (Fig. 1). Sulfur-isotope analyses were performed on some of these samples where the pyrite had not completely altered to limonite (Fig. 2).

Fir Canyon prospect

Fir Canyon prospect (FC) is in NE1/4 sec. 36 T25S R21E approximately one-half the way down from the top of Fir Canyon and along the base of a cliff in the Seven Rivers Formation. It consists of a 2-m-long (6.5-ft-long) adit trending 245°. The prospect was briefly mentioned by Thompson (1983, p. 4) as "exhibiting slight iron-oxide staining." Two episodes of calcite mineralization are associated with the deposit: tiny (1 mm or so), drusy calcite crystals lining cavities, overlain by larger (~0.5 cm), milky, blocky calcite crystals partially or totally filling these cavities.

Queen of the Guadalupes mine

The Queen of the Guadalupes mine (QG) is in NE1/4 sec. 1 T26S R21E ~1.2 km (~0.7 mi) southwest of the Dark Canyon lookout tower. The mine is located in the Seven Rivers Formation directly beneath the Yates and along the crest of the Guadalupe Ridge anticline (Jagnow, 1977; Light et al., 1985). The mine is thought to have been developed by a Joe Weldy in 1934, although a note to this effect in the mineral claims office could not be verified by records in the Eddy County Courthouse. Early maps of the area called the gossan an "extinct volcanic crater" because the spongy, mineralized rock looks like lava (R. Turner, pers. comm. 1992).

The Queen of the Guadalupes mine is developed in an iron-oxide gossan underlain by the Queen of the Guadalupes Cave, a natural, 70-m-deep (230-ft-deep), vertical shaft complex (mapped by Jagnow, 1977, and Thompson, 1983). The gossan contains relatively high amounts of barium, molybdenum, lead, and zinc (Table 1). Minerals identified by Thompson (1983) include barite, azurite, malachite, bornite, and hematite; however, R. North (pers. comm. 1993) and this study (Table 1) found very little evidence of copper mineralization at this site. Sulfur-isotope analyses of the barite measured $\delta^{34}S$ values of +58.0 and +62.1. Gangue calcite (part of the ore-spar field, Fig. 3) is present within the gossan, and the host rock has been both dolomitized and silicified.

Cottonwood Cave

Cottonwood Cave (CWC) is located along the crest of the Guadalupe Ridge anticline 0.5 km (0.3 mi) southeast of the Dark Canyon lookout tower in NE1/4 sec. 6 T26S R22E. The cave is developed in the Seven Rivers Formation, just beneath the Yates Formation; the basal bedding plane of the Yates defines the cave ceiling.

The base of the Yates Formation above Cottonwood Cave is highly pyritic. Pyrite concretions collected directly above the cave show good epigenetic-replacement textures in thin section. Bedrock at the cave entrance (collected at the contact of the Yates and Seven Rivers Formations) contains anomalously high amounts of copper (5800 ppm), lead (4210 ppm), and zinc (2100; Table 1). This site is important because it shows that the base of the Yates is concentrated in metals even where a gossan is absent.

Lonesome Ridge

On Lonesome Ridge (LR), in NE1/4 sec. 13 T26S R21E, another zone at the base of the Yates Formation is abundant in pyrite (Light and Domenico, 1983; Light et al., 1985). Pyrite cubes as much as 3.5 cm across litter the ground (Fig. 4), and pyrite fills joints trending N60°E, parallel to the reef front. The rock surrounding the pyritized zone has been both dolomitized and silicified.

Lucky 13 prospect

The Lucky 13 prospect (L13) is in SE 1/4 sec. 15 T26S R21E just north of Forest

Service Road 531, where the road makes a sharp bend before reaching a drill pad. A claim was filed on the prospect in the Eddy County Courthouse by Seth McCollaum on March 16, 1940.

At the Lucky 13 minerals were deposited along a N5–10°W arcuate fault that roughly parallels the main Dog Canyon fault to the west. The prospect is located in the Seven Rivers Formation ~20 m (~65 ft) below the base of the Yates. The prospect is about 7 m (23 ft) deep and 1–2 m (3–6.5 ft) wide. Mineralogy consists of mostly iron and zinc enhancement (Table 1); sphalerite is present as both vein and vug fillings. No calcite or quartz was noted at this site.

Devil's Den prospects (Broken Horseshoe claim)

In sec. 21 T26S R21E, in the Devil's Den Spring area, are three separate prospects and one short adit. In the SW1/4 of this section two prospects have been dug directly beneath the Yates Formation, and another small (0.7 m deep and 1 m wide; 2 ft deep and 3 ft wide) prospect (DDP) has been dug about 10 m (33 ft) below the base of the Yates along the road leading to the remains of the old Devil's Den Spring house. Slightly to the north and west of this road prospect, in the NW1/4 of sec. 21, is an adit (DDM) known as the Broken Horseshoe claim (Thompson, 1983; Fig. 5). This adit is 14.6 m (48 ft) long and trends 160° before making a right-angle turn (maps by Thompson, 1983). The Devil's Den prospects lie close to the north-trending series of Basin and Range faults along which Dog Canyon has been downdropped.

Sphalerite found at the road prospect is reddish, reniform, and transparent to submetallic. In contrast, the nearby Broken Horseshoe claim area seems to be mineralized primarily with copper (Table 1). Glassy and drusy calcite can be found at the adit as crystals lining vugs within sucrosic dolomite; milky, blocky calcite coats the glassy, drusy calcite. Both types of calcite are intergrown with malachite and azurite. Specular hematite also has been reported from this locality (Thompson, 1983) but was not observed.

The Devil's Den Spring area is also the site of considerable pyrite/marcasite mineralization within highly fractured bedrock (Fig. 6). This mineralization is important because fracturing of the rock most likely took place during Basin and Range faulting, showing that the pyrite/marcasite were either contemporaneous with, or came after, at least some faulting.

Calumet and Tejas mine (Calumet and Texas mine)

The Calumet and Tejas mine (CT) is at latitude 31°58'40" and longitude 104°50'55" in Guadalupe Mountains National Park, Texas, along the Upper Dog Canyon trail and about 1.6 km (1 mi) northeast of Lost Peak. The mine is located in the Seven Rivers Formation, on a graben between the Dog Canyon and Lost Peak fault zones. According to King (1948, p. 160): "The mine was worked from time to time since about 1900 but the workings are small and were abandoned before our visit in 1934." Records show that in 1914 and 1926–27 approximately "66 tons of ore" containing "5256 lbs of copper" and "3 oz of silver" were mined from the Calumet and Tejas (Lasky and Wootton, 1933, p. 46). The Calumet and Tejas consists of four separate adits, 15–60 m (49–197 ft) in length, driven into the Seven Rivers dolomite (Thompson, 1983). Epigenetic deposits of copper and iron are found along thin joints and fault zones within these four adits.

Mineral deposits reported at the Calumet and Tejas mine include malachite, azurite, chrysocolla, beaverite, hematite, and possibly aurichalcite and bornite. Other metal enrichment besides copper includes arsenic, bismuth, lead, vanadium, tungsten, and zinc (Table 1). The deposits are in veins and along porous and fractured zones in the Seven Rivers Formation; silicification and dolomitization of the mineralized rock are conspicuous. As in the Devil's Den Spring area, pyrite/marcasite commonly are present along fine bedrock fractures in the area of the Calumet and Tejas mine.

Grisham Hunter prospect

Grisham Hunter prospect (GH) is at latitude 31°58'14" and longitude 104°48'00" in Guadalupe Mountains National Park, Texas. Price et al. (1983) gave an approximate location for the site and called it the "unnamed prospect." The Grisham Hunter consists of a shallow prospect about 7 m (23 ft) in diameter and 2 m (6.5 ft) deep. It is located at the base of the Yates Formation about 30 m (100 ft) south of the McKittrick Canyon trail just after the trail tops out on the Yates siltstone ridge. It also trends approximately along the axis of the Reef anticline. The prospect was dug into a highly silicified gossan. Drusy quartz, quartz veins, botryoidal opal, and yellow jasper can be seen at the prospect. The gossan is also enriched in arsenic, cadmium, lead, vanadium, and zinc (Table 1). Some sphalerite is present.

Bell Springs prospect

Bell Springs prospect (BS) is at latitude 31°56'37" and longitude 104°48'52". It is the only prospect in the basin-margin facies, although much pyrite can be found in this stratigraphic position along bedding planes dipping up toward the reef (e.g., McKittrick Canyon, MC, Fig. 1). The Bell Springs prospect is located at the contact of the Lamar Member of the Bell Canyon Formation with the forereef facies of the Capitan Limestone, where the Lamar pinches out on King's (1948) map, 1.6 km (1 mi) northeast of Bell Canyon. King (1948, p. 160) and Price et al. (1983) gave approximate locations for the prospect; during this study the site was relocated. The prospect is just inside of the wilderness area, Guadalupe Mountains National Park, Texas, at an elevation of ~1840 m (~6037 ft).

The Bell Springs prospect consists of two diggings: a 5-m-deep, 1-m-wide (16-ft-deep, 3-ft-wide) shaft on the northeast slope of a small ridge off of the main Radar Ridge and a 1-m-deep, 3-m-wide (3-ft-deep, 10-ft-wide) prospect on the crest of this small ridge. The deposit is predominantly an iron gossan containing rela-

FIGURE 4—Pyrite cubes littering the surface of the Seven Rivers Formation near the base of the Yates Formation, Lonesome Ridge, Guadalupe Mountains. Photo by Carol Hill.

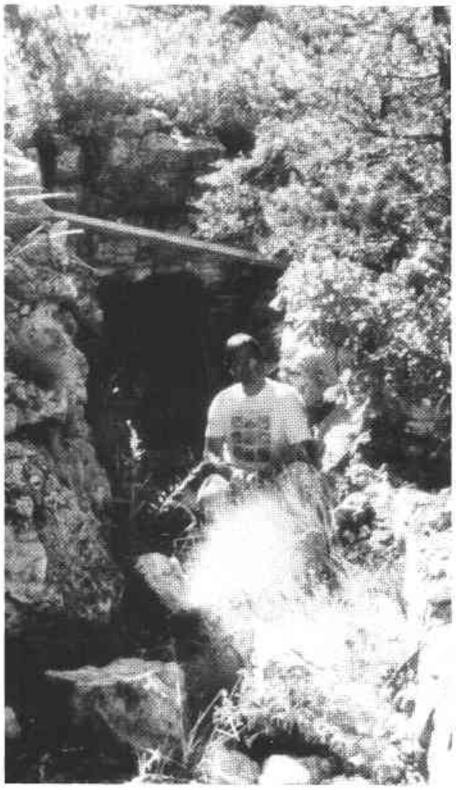

FIGURE 5—Entrance to Devil's Den adit (DDM) near the western Dog Canyon escarpment of the Guadalupe Mountains. Photo by Ransom Turner.

tively high amounts of vanadium and zinc (Table 1). Veins of black to red, resinous sphalerite are exposed in the shaft and are about 0.3 m (1 ft) wide and trend 350°. The whole area around the prospect is hematized, and rock textures vary from spongy to boxwork to densely massive. In some cases mineralization fills spaces between breccia fragments. Gangue calcite is common at this site (ore-spar field, Fig. 3).

Glori Cave fluorite

Fluorite is exposed in Glori Cave (GC) on the north side of upper Shumard Canyon along the western escarpment of the Guadalupe Mountains, Guadalupe Mountains National Park (latitude 31°53′30″, longitude 104°51′38″). Glori Cave is developed in the Victorio Peak Limestone of Leonardian age. Passages follow northeast- and northwest-trending joints and truncate the fluorite mineralization (i.e., cave-passage dissolution came after the fluorite).

Fluorite in Glori Cave occurs as veins 1–8 cm wide that follow joints and fractures in the limestone, as crystal linings 0.5 cm thick, and as small crystals disseminated in the limestone (Hill, 1988). The crystal cubes range from a few millimeters to 2.5 cm on a side. Fluorite crystals come in shades of brown and purple, but in general an earlier stage of transparent, resinous-brown fluorite seems to be overgrown by a later stage of opaque, light-purple fluorite. In thin section the fluorite can be seen to penetrate the limestone for as much as 2.5 cm. A fluorite sample collected for analysis was found to be enriched in chromium compared with other mineral deposits in the area (Table 1).

The fluorite exposed in Glori Cave is one of a few reports of this mineral in the Guadalupe Mountains. King (1948, p. 160) reported crystals of blue fluorite dispersed "here and there" in vugs of the Pinery (or Hegler) Member of the Bell Canyon Formation in the vicinity of Pratt Lodge, McKittrick Canyon. King's site was visited, but no fluorite could be found, possibly because this area has been badly hacked up by geologists over the years. Another report of fluorite along a roadcut 3.4 km (2 mi) west of the junction of US–180 with TX–54 on the Salt Flats (A. Kendall, pers. comm. 1989) was also visited, but no fluorite could be found.

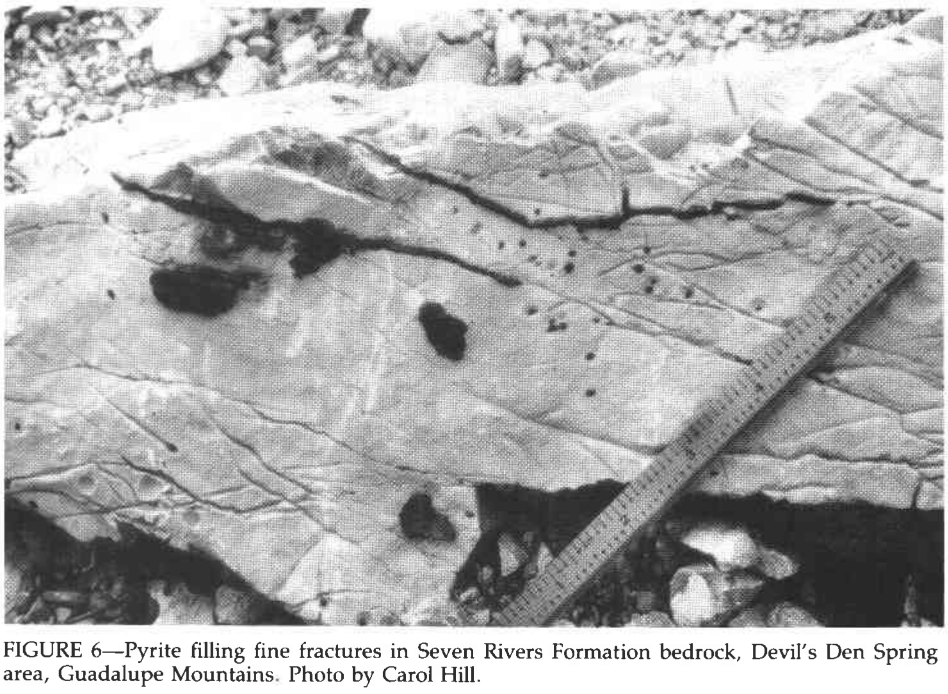

FIGURE 6—Pyrite filling fine fractures in Seven Rivers Formation bedrock, Devil's Den Spring area, Guadalupe Mountains. Photo by Carol Hill.

Results

Field relationships

Sulfide/barite/fluorite deposits in the Guadalupe Mountains are located primarily along structural (anticlines, faults) and stratigraphic (base of Yates Formation) traps. Of the 23 sites shown in the Guadalupe Mountain section of Fig. 1, 14 are located at the base of the Yates Formation, five are within the Seven Rivers Formation (not directly at the base of the Yates), two are in the Tansill Formation (one at the Yates–Tansill contact), two are where the basinal facies interfingers with the forereef facies (BS and MC), and one is in the Victorio Peak Limestone (GC). Of the 23 sites, 14 are located along some type of anticlinal structure, either a major anticline such as the Guadalupe Ridge and Reef anticlines or a minor anticlinal structure (the anticlines of the Waterhole anticlinorium and/or bioherms of the Carlsbad fold complex); five are along Basin and Range faults in the western escarpment part of the Guadalupe Mountains; and the remaining four sites seem unrelated to structure.

Mineralogy and trace-element analyses

Grab samples of the most mineralized-looking rock were collected from 16 of the 23 sites (Table 1). Usually only pyrite and sphalerite are identifiable as minerals within the deposits, with the exception of the Two Ladies prospect, which contains galena. Barite and fluorite are uncommon, and gangue calcite is common but not ubiquitous. Metal enrichment consists primarily of iron, zinc, lead, and copper; silver content is low (Table 1).

Sulfur-isotope analyses

Sulfur-isotope values of the sulfide minerals in the Guadalupe Mountains, as compared with other sulfide deposits around the Delaware Basin and with native sulfur deposits within the basin, are shown in Fig. 2. These deposits have a relatively narrow range of values ($\delta^{34}S \approx -9$ to $+5$) regardless of their geographic position within or around the basin. There is one exception to this rule: the sphalerite from the Buck zinc prospect, Apache Mountains, Texas ($\delta^{34}S = -16$ to -14).

The sulfur-isotope values of sulfide minerals around the Delaware Basin are within the same range as values of native sulfur deposits within the basin ($\delta^{34}S \approx -15$ to $+10$, Fig. 2). These depleted sulfur-isotope values are characteristic of biologically fractionated sulfur (Davis and Kirkland, 1970). In contrast to these light values ☞

TABLE 1—Trace-element analyses (parts per million) of selected grab samples. Delaware Basin. Chemical analyses performed by Chemex Labs using the aqua regia digestion method. Where values for a mine/prospect are from both this study and another study, the values in parentheses represent the other study.

Mine/Prospect/Occurrence	Symbol on Figs. 1, 3, and 7	Location	Ag	As	Ba	Bi	Cd	Co	Cr	Cu
		Trace-element detection limit (ppm)	0.2	2	10	2	0.5	1	1	1
Guadalupe Mountains										
Golden Eagle mine	GE	SW1/4 sec. 14 T21S R25E	1.4	<5	480	10	<0.5	7	17	(2.51%)
Rocky Arroyo prospect (thucholite pellets)	RA	SE1/4 sec. 26 T21S R24E	<0.2	250	150	2	<0.5	<5	15	270
Little Walt prospect	LW	SW1/4 sec. 2 T21S R24E	0.2	20	940	<2	<0.5	<1	<1	3
Jurnigan gossan	JG	SW1/4 sec. 8 T24S R26E	0.6	295	140	<2	8.0	3	70	263
Guadalupe Ridge (pyritic Yates sandstone)	GR	NE1/4 sec. 33 T25S R22E	–	5	150	–	0.3	5	100	<5
Fir Canyon prospect	FC	NE1/4 sec. 36 T25S R21E	<0.2	134	70	12	>100	10	54	1710
Queen of Guadalupes mine	QG	NE1/4 sec. 1 T26S R21E	0.2	70	860	<2	18.5	<1	72	45
Cottonwood Cave (pyritic Yates sandstone)	CWC	NE1/4 sec. 6 T26S R22E	0.4	10	10	<2	0.5	7	4	5800
Lonesome Ridge (pyritic Yates sandstone)	LR	NE1/4 sec. 13 T26S R21E	0.5	210	50	–	52.0	–	100	30
Lucky 13 prospect	L13	SE1/4 sec. 15 T26S R21E	<0.2	175	30	10	9.0	5	45	91
Devil's Den adit Broken Horseshoe claim	DDM	NW1/4 sec. 21 T26S R21E	<0.2	82	10	<2	<0.5	<1	30	828
Devil's Den road prospect	DDP	SW1/4 sec. 21 T26S R21E	<0.2	20	90	<2	6.5	10	119	49
Calumet and Tejas mine	CT	Latitude: 31° 58′ 40″ Longitude: 104° 50′ 55″	12.8	390	30	506	30.0	35	10	(8.85%)
Grisham Hunter prospect	GH	Latitude: 31° 58′ 14″ Longitude: 104° 48′ 00″	<0.2	660	20	<2	>100	<1	23	26
Bell Springs prospect	BS	Latitude: 31° 56′ 37″ Longitude: 104° 48′ 52″	<0.2	45	30	<2	32.5	<1	19	13
Glori Cave (fluorite)	GC	Latitude: 31° 53′ 30″ Longitude: 104° 51′ 38″	0.2	<10	120	4	1.0	8	158	172
Apache Mountains										
Seven Heart Gap barite mine (Main quarry)	7HG	Latitude: 104° 30′ 06″ Longitude: 31° 15′ 36″	2.0	<500	50%	<10	<50	<5	–	<2
Buck zinc prospect	BZ	Latitude: 104° 26′ 41″ Longitude: 31° 12′ 24″	0.4	20	40	42	(2%)	21	47	9
Glass Mountains										
Bird mine (north section)	BD	Latitude: 103° 30′ 51″ Longitude: 30° 20′ 42″	16.8	1000	2630	<2	>100	12	22	56
Bissett mine	BT	Latitude: 103° 25′ 09″ Longitude: 30° 23′ 25″	1.6	<5	30	<2	12.5	254	17	5120
Fort Stockton										
Los Nietos (core) (galena, sphalerite)	LN	Sec. 11 Block 26, University land	–	–	–	–	–	–	–	–
Texas Gulf (oil tar with chalcopyrite)	TG	Latitude: 102° 42′ 55″ Longitude: 31° 01′ 18″	24.0	3360	<10	<2	7.0	64	119	1805

are the very heavy values ($\delta^{34}S \approx +40$ to $+60$) of the barite at the Queen of the Guadalupes mine and Lechuguilla Cave entrance. Such values are typical of a closed system where the residual sulfate has become enriched in the heavy isotope of sulfur relative to the isotopically lighter sulfide minerals.

Carbon–oxygen-isotope analyses

Carbon–oxygen isotopes of gangue calcite intergrown with sulfide minerals are plotted in Fig. 3 relative to the other types of calcite spar in the Delaware Basin. Note that all but two of the calcites plot within the ore-spar field (as defined by Hill, 1992). The two exceptions are the Buck zinc calcite (BZ) and Devil's Den calcite (DDP), both of which are located within the thermal-spar field and along a Basin and Range fault zone.

Mississippi Valley-type ore deposits

The sulfide deposits in the Guadalupe Mountains are considered to be Mississippi Valley-type (MVT) deposits. The reasons for classifying these deposits as MVTs are:

(1) The mineralogy of the Guadalupe Mountains deposits is simple (pyrite, usually sphalerite, calcite, dolomite, and sometimes barite, fluorite, and galena). Pb–Zn enrichment is pronounced, but the concentration of silver is low (Table 1). This mineralogy and metal enrichment are typical of MVTs (Ohle, 1959).

(2) The mineralization is epigenetic not syngenetic. Probable time of mineralization is Oligocene–Miocene not Late Permian. Hill (1992) considered the mineral deposits around the Delaware Basin to be Oligocene in age (40–30 Ma), but based on the results of this study (some of the mineral deposits are associated with the thermal spar along Basin and Range fault zones), the mineral deposits are now considered to be from Oligocene to Miocene in age (<40–5 Ma).

(3) Mineralization occurs as open-space fillings (veins, vugs, breccia) and as a replacement of the carbonate host rock. This is also typical of MVTs (Ohle, 1959, 1980).

TABLE 1—continued

Mo	Ni	Pb	Sc	Sr	U	V	W	Zn	
Trace-element detection limit (ppm)									
1	1	2	1	1	10	1	10	2	**Reference**
5	3	2590	40	39	10	67	10	213	Soulé (1956) This study
130	165	310	<1	30	(2.35%)	<1	<5	30	Waltman (1954) This study
<1	9	40	2	49	<10	148	<5	100	This study
219	6	184	2	42	<10	233	<10	1665	This study
–	–	<10	5	300	–	30	–	15	Light & Domenico (1983)
70	82	8000	3	40	<10	33	10	3230	This study
134	24	242	<10	75	<10	92	<5	2100	This study
1	5	4210	<10	44	<10	27	<5	332	This study
20	20	30	–	300	–	50	–	2200	Light & Domenico (1983)
22	9	2370	5	–	<10	943	<50	5510	This study
2	1	30	1	45	<10	5	<10	70	This study
15	75	1275	5	–	<10	133	<50	7210	This study
13	36	(2.35%)	140	73	20	575	635	(>1%)	King (1948) This study
15	12	996	3	13	<10	486	<10	6210	This study
13	4	40	3	–	<10	292	20	3740	This study
14	24	62	2	510	<10	22	<5	310	This study
<2	<5	<10	–	7000	–	10	–	<200	Murray (1978)
2	4	1770	1	25	370	66	120	(34%)	Udden (1914) This study
80	3	>1%	1	485	<10	8	60	>1%	This study
2	206	152	1	57	<10	26	5	135	This study
–	–	6000	–	–	–	–	–	6.6%	Mazzullo (1986)
8690	1710	1990	1	409	70	211	<5	78	This study

(4) All of the sulfide deposits in the Guadalupe Mountains are located along the margin of the basin, within 20 km (12.5 mi) of the basin edge (Fig. 1). MVT deposits generally are found in carbonate rocks near the margins of sedimentary basins (Ohle, 1980).

(5) The sulfide deposits in the Guadalupe Mountains are in structural and stratigraphic traps. This is typical of MVT deposits, which are generally in structural and/or stratigraphic traps (i.e., as "manto" deposits below impermeable beds or along anticlines or faults; Ohle, 1980).

(6) Other workers have also considered these deposits to be of the Mississippi Valley type. Mazzullo (1986) found MVT sulfides in Lower Permian dolomites on the eastern, Fort Stockton, side of the Delaware Basin; sulfur-isotope values of these deposits match those in the Guadalupe Mountains (Fig. 2). North and McLemore (1986, 1988) classified the mineral deposits in the Guadalupe Mountains as MVTs based on their mineralogy, host rocks, form of deposits, tectonic setting, and genetic process.

Origin of sulfide deposits in the Guadalupe Mountains

Four pieces of evidence are crucial to understanding the origin of the MVT sulfide deposits in the Guadalupe Mountains:

(1) The sulfur- and carbon–oxygen-isotope values of the mineral deposits are relatively uniform (Figs. 2 and 3), no matter where the deposits are located in the Delaware Basin (Fig. 1). This strongly implies that these deposits are genetically related and have a common origin.

(2) Sulfur-isotope values of sulfides in the basin (e.g., Yeso Hills pyrite) are nearly identical to those in the basin–forereef margin (e.g., Bell Springs sphalerite and McKittrick Canyon pyrite) and to those in backreef structural and stratigraphic traps high in the mountains (e.g., Grisham Hunter sphalerite). This suggests a genetic connection between mineral deposits in the basin and those in the reef.

(3) Sulfur-isotope values of sulfides in the Guadalupe Mountains are similar to sulfur-isotope values of native sulfur in the basin (Fig. 2). This also implies a genetic connection between basin and reef.

(4) The structural and stratigraphic position of the sulfide mineralization in the Guadalupe Mountains is the same as that of the caves (Fig. 7). Because caves in the Guadalupe Mountains were dissolved by sulfuric acid derived from H_2S basinal degassing (Hill, 1987, 1990), it is not illogical to suspect that basinal H_2S may have also supplied the reduced sulfur necessary for the sulfide deposits in the Guadalupe Mountains.

The following scenario is proposed for the origin of sulfide mineralization in the Guadalupe Mountains. In the Oligocene–Miocene, as the Delaware Basin was being faulted, uplifted, and heated, hydrocarbon migration into Castile Formation evaporites in the basin produced H_2S gas that oxidized to native sulfur (e.g., the Culberson sulfur mine, Fig. 2) or ascended reefward where it accumulated in structural and stratigraphic traps (Fig. 7A). Metals moving as chloride complexes downdip from backreef evaporites formed sulfide minerals in the reduced zone wherever they came in contact with this trapped H_2S gas. Later, in the Pliocene–Pleistocene, as the water table dropped, H_2S migrating into these same traps became oxidized to sulfuric acid at or near the water table (Fig. 7B). The sulfuric acid then dissolved out the large cave passages in the Guadalupe Mountains.

This scenario is consistent with the four pieces of evidence listed above. The sulfides and native sulfur around and in the basin are isotopically similar because they have the same *source* of light gas—that is, H_2S generated from hydrocarbon reactions in the basin. Sulfur isotopes are similar from basin to basin margin to backreef because they also had this same source of light gas and because the migration path for the gas was from basin to basin margin to reef to backreef (Fig. 7A). Finally, the sulfides and caves occupy the same structural and stratigraphic position because in each case H_2S accumulated in the same traps—the sulfides at an earlier time when these gas traps were in the reduced zone and the

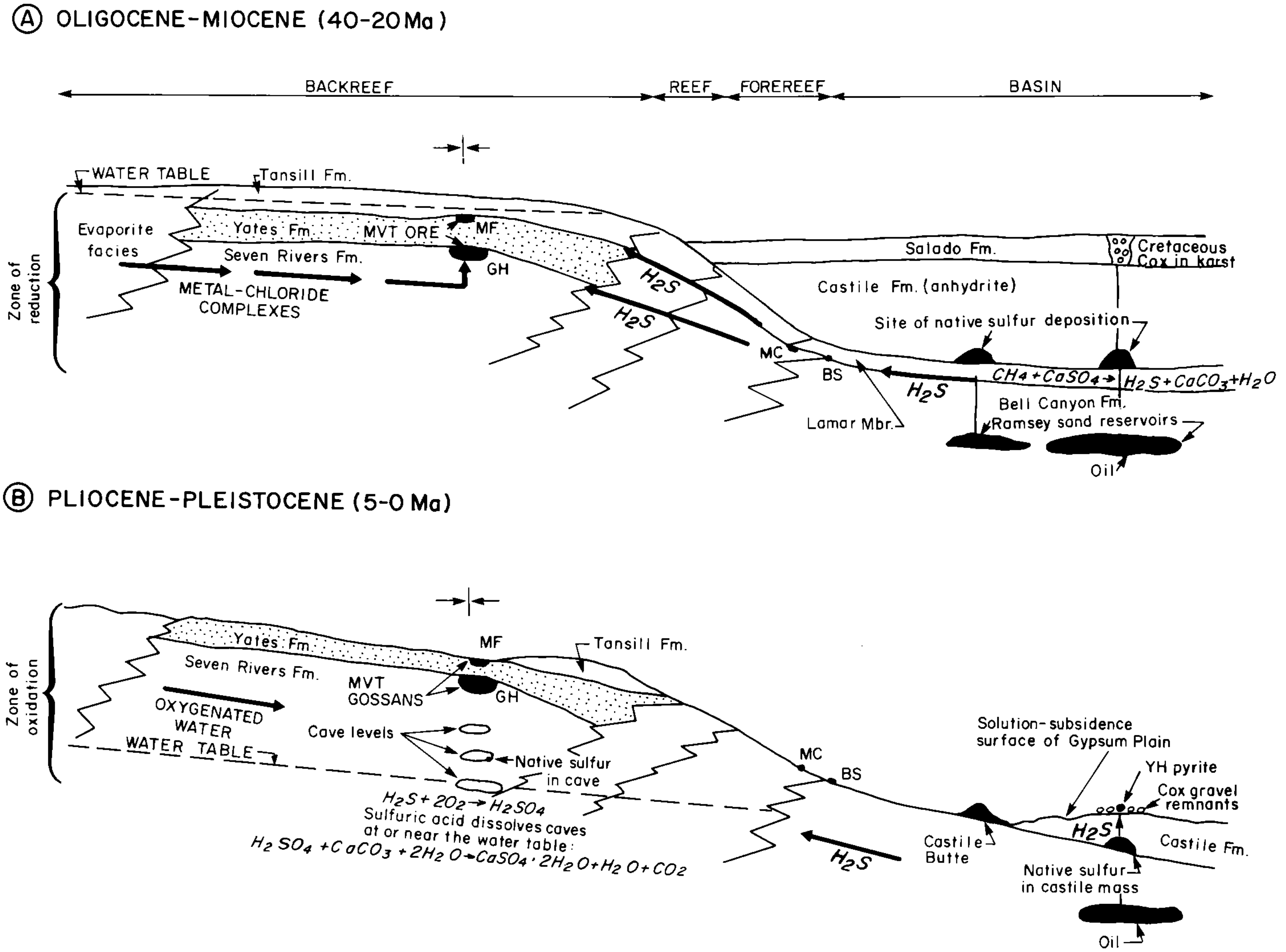

FIGURE 7—Idealized model for the formation of sulfide ore deposits, Guadalupe Mountains. This model proposes a genetic connection between hydrocarbons, native sulfur and pyrite in the basin, and Mississippi Valley-type (MVT) deposits and caves in the carbonate-reef margin. (**A**) In the Oligocene–Miocene, during the initial uplift of the Delaware Basin, H_2S was generated in the basin by reactions involving hydrocarbons and the Castile anhydrite. The H_2S oxidized to native sulfur in the basin and also migrated from basin to reef to accumulate there in structural (anticlinal) and stratigraphic (base of Yates) traps. Metals moved downdip as chloride complexes from backreef-evaporite facies, and where they met with the ascending H_2S below the water table in the zone of reduction, they formed MVT deposits. (**B**) In the Pliocene–Pleistocene continued uplift of the Guadalupe Mountains and basin caused increased H_2S generation and migration of gas from basin to reef. Cave dissolution occurred in the same structural and stratigraphic position as earlier MVT deposits; cave passages were dissolved where H_2S oxidized to sulfuric acid at or near the water table in the zone of oxidation. Cave levels correspond to a descending base level. Symbols used are the same as those used in Fig. 1 caption.

caves at a later time when these traps were in the oxidized zone (Fig. 7).

Summary

(1) The sulfide-mineral deposits in the Guadalupe Mountains are not extensive and have never been economically profitable. Mineral-assessment evaluation of the deposits is L/C—low potential with a level C of certainty (Hansen, 1991, pp. 95–97).

(2) The mineral deposits and the caves of the Guadalupe Mountains occupy the same structural and stratigraphic position. These caves were dissolved by sulfuric acid derived from H_2S migrating from basin to reef.

(3) Likewise, the sulfide deposits in the Guadalupe Mountains may have had as their source of reduced sulfur H_2S gas generated in the basin.

(4) Sulfur-isotope values support the concept that H_2S generated in the basin was the source of reduced sulfur for the native sulfur deposits in the basin and for the MVT mineral deposits around the margins of the basin.

(5) The sulfide deposits in the Guadalupe Mountains are considered to be of the Mississippi Valley type.

(6) The model of origin proposed for MVT deposits in the Delaware Basin may apply to other basins; i.e., MVTs may be related to the degassing of basins rather than the compaction and dewatering of basins (Hill, 1993a,b).

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