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New Mexico Geology, v. 9, n. 1 pp. 1-6,10, Print ISSN: 0196-948X, Online ISSN: 2837-6420.

<https://doi.org/10.58799/NMG-v9n1.1>

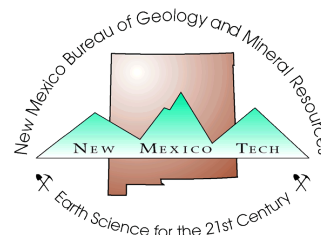
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A fluid inclusion study of the Waldo-Graphic mine, Magdalena district, New Mexico

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Introduction

The Magdalena mining district is located in Socorro County, central New Mexico, 30 mi west of Socorro and 1.5 mi southeast of Magdalena (Fig. 1). Replacement and skarn deposits of lead and zinc are hosted by Paleozoic limestones. The Waldo-Graphic mine, one of the principal zinc-lead producers of the district, was mined intermittently from 1881 to 1969. This deposit is now an experimental mine for New Mexico Institute of Mining and Technology.

Previous studies

C. H. Gordon (1910) described general geologic features of ore deposits from the Magdalena district. Lasky (1932) compiled production records for the district up to 1928. The most comprehensive study of the area was done by Loughlin and Koschmann (1942). They published a detailed study of the geology and ore deposits of the Magdalena district, including a petrological and mineralogical investigation and geologic maps of the mines. Titley (1958) studied the influence of silicate minerals on deposition of ore minerals at the Linchburg mine in the southern part of the district, and he concluded that both chemical and structural controls were important in the formation of the sulfide and skarn minerals. Park (1971) made a detailed study of the mineralogical and geochemical variations of the Anchor Canyon stock and concluded that it is a composite stock in which the composition varies from granite to gabbro. Iovenetti (1977) examined hydrothermal silicification (jasperoid) of the Kelly Limestone and made homogenization-temperature measurements of fluid inclusions in barite, calcite, quartz, and fluorite from vuggy cavities and fractures in the jasperoid. He concluded that the temperatures of deposition were in the range of 165–285°C and found no evidence of boiling. Blakestad (1978) used the concept of cauldron subsidence and stratigraphic nomenclature of Cenozoic volcanic rocks at that time to make a large-scale map of the district and a structural interpretation of the area.

Regional and local geology

The Magdalena mining district is located immediately south of the Colorado Plateau physiographic province, on the west side of



FIGURE 1—Index map of Magdalena mining district.

the Magdalena Mountains (Fig. 1). The mineralized areas are located near the structural margins of two overlapping cauldrons: the Socorro cauldron, which is located at the south end of the district; and the Magdalena-Sawmill Canyon cauldron, which is located south and west of the district (Fig. 2). The ages of the tuffs associated with the development of the two cauldrons have been estimated at 30–32 Ma (Weber, 1971; Burke et al., 1963) and 27–29 Ma (Blakestad, 1978), respectively.

Rock types

The oldest rocks exposed in this area are Precambrian; they crop out along the ridge tops and on the eastern side of the Magdalena Range. According to Loughlin and Koschmann (1942), the Precambrian rocks include argillite and schist, gabbro or diabase, felsite, and granite.

On the west side of the Magdalena Mountains sediments of the Carboniferous system were deposited upon a Precambrian surface of low relief. These are the Caloso and Ladron Members of the Mississippian Kelly Limestone and the overlying Sandia and Madera Formations of the Pennsylvanian Magdalena Group (Loughlin and Koschmann, 1942). In underground exposures of the middle part of the Ladron Member, there is a conspicuous marker bed of a dark-gray to black, dense argillaceous limestone. This bed is known as "silver pipe" or "indicator" because of its close association with ore shoots. The Ladron Member has been extensively

silicified in the southern part of the district (Loughlin and Koschmann, 1942; Iovenetti, 1977).

At the Waldo-Graphic mine, on level 9 between the Madera and Waldo faults, the Madera Limestone changes strike and dip chaotically. It has been interpreted as a zone of cauldron margin megabreccia (Fig. 2) by Blakestad (1978) and Chapin et al. (1978). However, reinterpretation of the location of cauldron margins suggests that the nearest cauldron margin is more than 3 mi southwest of the district (G. R. Osburn, pers. comm. 1986).

Cenozoic volcanic rocks of basaltic-andesitic, latitic, and rhyolitic composition range in age from 39 to 26 Ma (Blakestad, 1978). These rocks include Datil Group (39–33 Ma), Hells Mesa Tuff, and La Jencia Tuff (Loughlin and Koschmann, 1942; Blakestad, 1978; Eggleston, 1982; Osburn and Chapin, 1983). The

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thickness of Cenozoic volcanic rocks in the Magdalena area has been estimated to be 2,000 ft (Blakestad, 1978).

In the Magdalena district several dikes, stocks, and dike-like intrusive bodies are exposed with compositions ranging from granite to gabbro. The main intrusive bodies, which crop out on the surface, are Anchor Canyon stock (28.3 Ma), Nitt monzonite stock (28.0 Ma), and latite porphyry of Mistletoe Gulch. Additionally, four concealed intrusive bodies have been reported (Blakestad, 1978). The Linchburg porphyry quartz monzonite is exposed in underground workings of the Linchburg mine. A porphyritic monzonite body, which intrudes the Precambrian rocks, Kelly Limestone, and Sandia Formation, was discovered as a result of drilling at the North Baldy Peak area. A latite porphyry has been mapped on the 14th level and below in the Waldo-Graphic mine, which Chapin et al. (1978) reported to be similar to the latite porphyry of Mistletoe Gulch. A

porphyry granite or quartz monzonite body was also discovered (as a result of drilling during exploration work) 500 ft south of the Vindicator shaft (Fig. 2).

Other intrusive occurrences in the Magdalena mining district are mafic dikes, andesitic intrusive bodies, and white rhyolite dikes. All of these intrusive rocks are hydrothermally altered and some white rhyolite dikes show a spatial relationship with the mineralization (Titley, 1958; Blakestad, 1978). The white rhyolite dikes are considered to be younger than the emplacement of the stocks (Loughlin and Koschmann, 1942; Blakestad, 1978).

There is a spatial relationship between the main stocks and the mineralized zones (Fig. 2). The Nitt and Waldo-Graphic mines are located near the contact of the Nitt monzonite stock and limestones. For the most part this stock lacks conspicuous hydrothermal alteration in contrast to the concealed intrusions that show consistent alteration.

Waldo-Graphic mineralization

The Waldo-Graphic zinc-lead deposits are hosted by the limestones of the Pennsylvanian Madera and Mississippian Kelly Formations. The replacement and skarn bodies were localized by the intersection of north-trending fractures with favorable horizons within the limestones (Loughlin and Koschmann, 1942). The relative age of the mineralization is younger than the Nitt monzonite stock and latite porphyry dikes based on crosscutting relations seen in the field.

Mineralogy

A complete list of the primary and secondary minerals found in the Magdalena district, together with detailed macroscopic and microscopic descriptions, was published by Loughlin and Koschmann (1942); the reader is directed to it for details. In the Waldo-Graphic mine the gangue and ore minerals occur as open-space fillings and replacements in limestone. Loughlin and Koschmann (1942) reported that most mineralization was deposited by replacement of the limestones. That quantitative relationship cannot be confirmed because subsequent observations have only been made on remnants of the ore deposit.

The principal sulfide minerals consist of pyrite, sphalerite, galena, and chalcopyrite. Ore-associated gangue minerals include calcisilicate skarn minerals (diopside-hedenbergite and actinolite), iron oxides (specularite

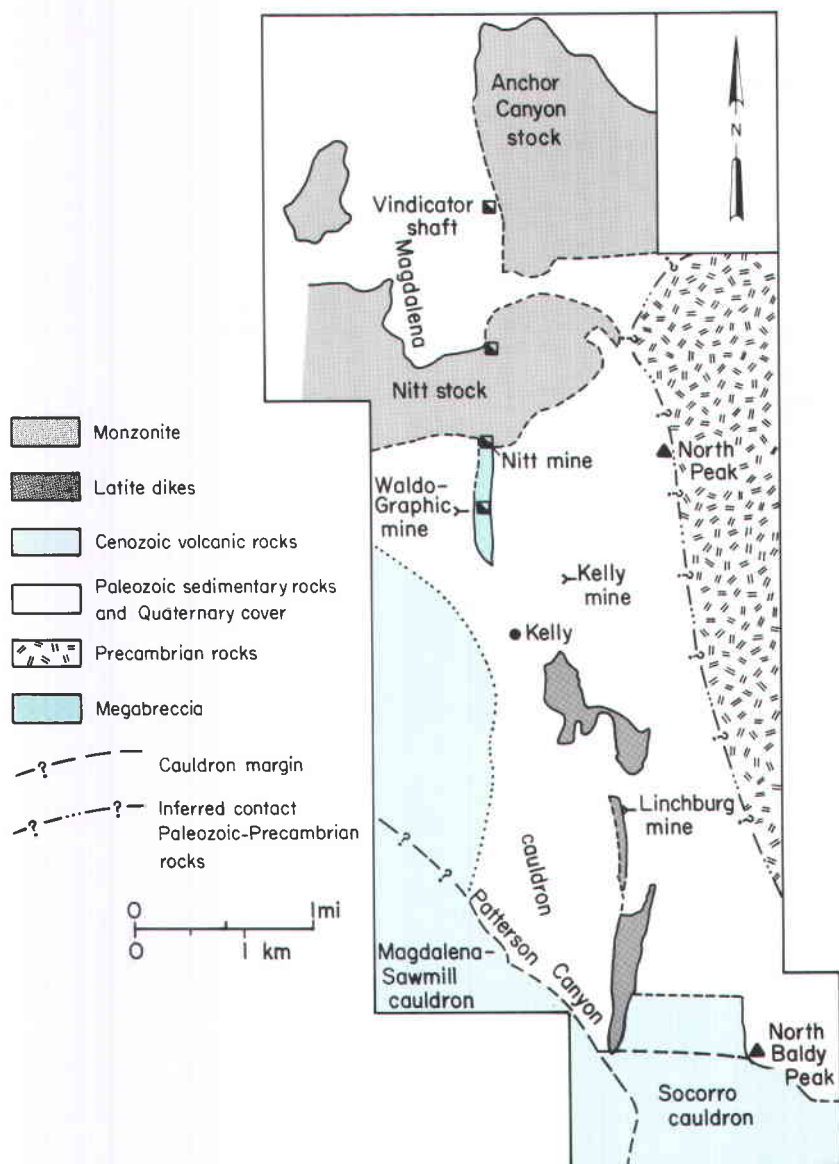


FIGURE 2—Structural map of Magdalena mining district and the major mines; modified from Blakestad (1978).

New Mexico GEOLOGY

• Science and Service
Volume 9, No. 1, February 1987

Editor: Deborah A. Shaw
Drafters: Cherie Pelletier and Becky Titus
Published quarterly by

New Mexico Bureau of Mines and Mineral Resources
a division of New Mexico Institute of Mining & Technology

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Circulation: 1,600

Printer: University of New Mexico Printing Plant

and magnetite), quartz, calcite, and minor barite.

The most common minerals of the oxidized zone are smithsonite, anglesite, cerussite, chrysocolla, malachite, chalcocite, and "limonite" (goethite-hematite). Silver minerals and native gold also have been reported (Loughlin and Koschmann, 1942).

Sulfides—In the Waldo-Graphic mine, pyrite occurs as: disseminations in the altered country rocks; veinlets and lenses in specularite-magnetite aggregates; pyritic bodies with minor associated interstitial chalcopyrite; crystalline masses associated with distinctive zones or bands of sphalerite and galena that have replaced limestone; and pyrite-bearing quartz and calcite veinlets that cut other sulfides, dikes, and wall rocks.

Most of the sphalerite in the orebodies of Waldo-Graphic mine is dark brown to black, shows little internal reflectance, and is probably iron rich. It occurs as aggregates of anhedral grains associated with specularite or other sulfides (galena-pyrite). In the northeast areas of the mine sphalerite reportedly forms massive orebodies with minor pyrite and galena. In the western portion of the mine sphalerite is light greenish to yellow and shows a distinctive color banding. In this area of the mine it does not appear to be associated with specularite. The dark-colored sphalerite contains chalcopyrite inclusions. This texture, known as emulsion texture or chalcopyrite disease (Barton, 1978), has been interpreted as a product of: 1) exsolution, 2) replacement or epitaxial growth, 3) mechanical mixing (Kojima and Sugaki, 1985 and references cited therein), or 4) a product of supergene processes (DeWaal and Johnson, 1981). Its formation may imply movement of copper within the sphalerite crystal itself or an addition of copper and iron from an external source. The effects of these processes on the fluids trapped at the time of sphalerite formation are unknown.

Chalcopyrite occurs as small interstitial grains in pyrite and as microscopic blebs enclosed in sphalerite. Galena is generally less abundant than sphalerite, and occurs as fine-grained, interstitial blebs between grains of sphalerite. Loughlin and Koschmann (1942) reported that the ratio of galena to other sulfides increased with the distance from the Nitt monzonite contact.

Skarn minerals—Diopside-hedenbergite and actinolite occur as replacement minerals in limestones and to a minor extent in intrusive rocks. These minerals occur as columnar sheaves, as much as 6 cm long, and as fine-grained masses. They have been partially replaced by calcite and quartz due to late hydrothermal activity.

Iron Oxides—Specularite is the most abundant of the hypogene iron oxides and occurs as micaceous aggregates and interwoven blade-like crystals. Most of this specularite is magnetic, probably due to the presence of microscopic or submicroscopic magnetite. In some polished sections magnetite was not observed, even though the specularite was

magnetic. Magnetite was found mainly in the Graphic zone as massive to fine-grained blebs and as specularite-magnetite aggregates.

Gangue minerals—Quartz grains are enclosed by skarn minerals and intergrown with sphalerite. Quartz veinlets crosscut dark sphalerite and larger veins at igneous rocks and recrystallized limestone.

Calcite occurs as long pointed crystals or scalenohedrons and as short prisms with rhombohedral terminations that fill vugs. Calcite has also been reported to occur as platy radial aggregates.

Barite occurs as white platy crystals, mostly in fractures bounding the "silver pipe" and away from the orebodies.

Paragenesis

The paragenetic sequence was determined on the basis of field relationships of the minerals and a limited study of polished sections. Because the orebodies above the water level have been mined out, observation and sampling were confined to remnants of the ore. Results from this study were compared with Loughlin and Koschmann's (1942) study, which was done when the mine was active. As a whole our observations are in agreement with the previous work.

Ore formation may be grouped into three major stages (Fig. 3). The first stage was the growth of skarn minerals, recrystallization and/or marbleization of the limestone, and deposition of specularite-magnetite and minor quartz. The second stage consisted of deposition of pyrite, dark sphalerite, chalcopyrite, galena, and quartz. The final stage was characterized by the deposition of carbonates, barite, and minor light-colored sphalerite.

The temporal relationship between specularite and magnetite was not determined conclusively in this study, but Loughlin and Koschmann (1942, pl. 2) suggested that magnetite was formed after specularite. Sphalerite was deposited in both the sulfide and carbonate stages of mineralization and

changed in color from dark in the sulfide stage to light in the carbonate stage. It is not known whether this is due to a continually evolving deposition or to two distinct episodes of deposition. As a whole, pyrite formed after the specularite-magnetite (Loughlin and Koschmann, 1942, pls. 24, 25) and, although it formed earlier than sphalerite, it was formed later than galena.

From textural relationships observed in this study, it is concluded that chalcopyrite formed later than pyrite and sphalerite, but the relationship between chalcopyrite and galena is ambiguous. However, based on the paragenetic sequence of Loughlin and Koschmann (1942), chalcopyrite is believed to have formed early with respect to galena.

Quartz and calcite were deposited throughout much of the paragenesis, but the calcite predominated in the final stages of ore deposition.

Fluid inclusion study

More than 50 doubly-polished thick sections of quartz, calcite, sphalerite, and barite were prepared; in most of them no useful fluid inclusions were found because of small size or poor optical characteristics.

The temperatures of phase changes in fluid inclusions during freezing and heating tests were measured on a Linkham TH600 dual-purpose heating/freezing stage. Reproducibility of the melting temperature (T_m) was $\pm 0.2^\circ\text{C}$. Measurements of homogenization temperature had a reproducibility of $\pm 1.0^\circ\text{C}$ except for inclusions in dark sphalerite, which, due to poor visibility, were only good to about $\pm 5^\circ\text{C}$.

Freezing and heating observations

During the freezing runs, inclusions exhibited different kinds of behavior: in some inclusions the size of the gas bubble decreased suddenly, but the inclusions remained relatively transparent; a second group showed similar behavior but turned "grainy" and dull gray; in a third group the gas bubble

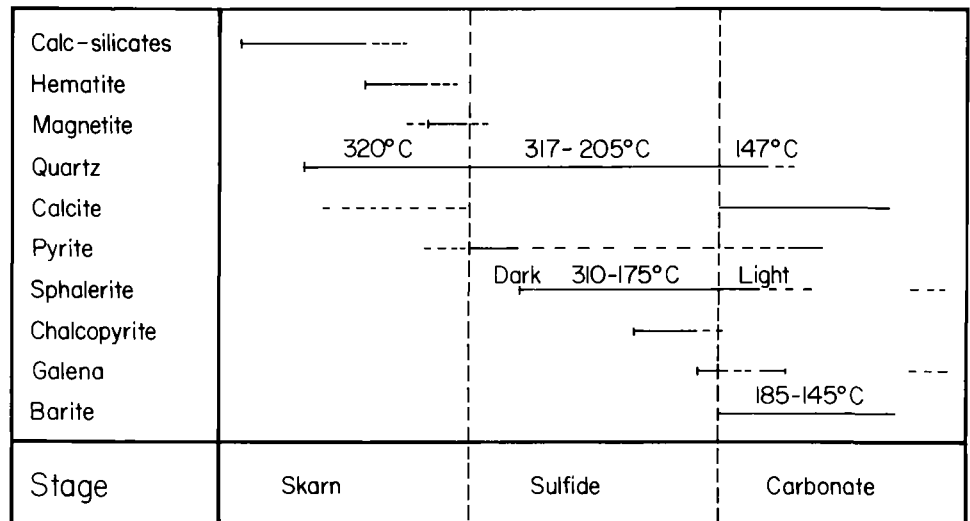


FIGURE 3—Paragenesis diagram with fluid inclusion temperatures.

disappeared. T_m was obtained by warming the inclusions slowly, especially above -30°C , and when the amounts of ice in the inclusion became small the warming up was stopped to ensure equilibration. The temperature at which the last ice melted (T_m) was recorded. The first appearance of liquid was not detected and, therefore, not recorded. Several fluid inclusions exhibited T_m above 0°C ; when this occurred and when freezing of the fluid inclusion was not observed, a careful check for the presence of CO_2 gas and for clathrate formation was performed by applying the techniques and criteria used by Collins (1979). However, CO_2 gas and clathrates were not observed. Each freezing run was performed at least twice in order to check the reproducibility of T_m . When T_m was not reproducible within the range stated, stretching upon cooling was assumed and the measurement was not recorded. The suspected stretching during cooling was detected only a few times in fluid inclusions in calcite and sphalerite.

After T_m was determined, experimental heating runs were performed for each mineral to determine the range of homogenization temperatures (Th). Each chip was heated at rates of 30°C per minute until temperatures near the range of homogenization were reached, then the rate of heating was slowed to rates of $1\text{--}2^\circ\text{C}/\text{min}$, and the temperature was registered when the gas bubble disappeared.

The fluid inclusions in sphalerite presented special problems in determining homogenization temperatures because the bubble disappeared in dark border areas of the inclusions. To obtain Th, the heating run was stopped as soon as the bubble disappeared in the areas of total reflection, and the temperature was dropped a few degrees centigrade. If the gas bubble immediately reappeared, then the temperature was raised $2\text{--}3^\circ\text{C}$ above the temperature at which the run was stopped. The cycles of raising and lowering the temperature were repeated until the vapor bubble reappeared only after the inclusion was supercooled. This indicated that the fluid inclusion had indeed homogenized during the previous heating.

Classification and description of fluid inclusions

According to phase relationships at room temperature, fluid inclusions of Waldo-Graphic mineralization may be separated into three groups. Type A [(L-V)L], the most common, are two-phase liquid-rich fluid inclusions in which the gas phase is less than 50% by volume and homogenized by vapor disappearance. Type B [(L-V)V] are gas-rich fluid inclusions in which the gas phase fills more than 95% of the volume of the cavity. In one type B inclusion, it was possible to observe that the inclusion homogenized to gas. Type C (L), are composed of one-phase liquid-rich fluid inclusions that exhibited no change when cooled or heated. No fluid inclusions were observed to contain daughter minerals.

TABLE 1—Fluid inclusion homogenization temperatures and salinities from the Waldo-Graphic mine; P = primary; S = secondary; * = number of measurements.

Sample	Salinity	Temperature ($^\circ\text{C}$) of homogenization (Th)	Observation
W910-SW (P)	7.44-1.73 (6)*	367-269 (17)*	Quartz in recrystallized limestone
-2W (P)	—	317 (1)*	
W900-50 (P)	5.4 (1)*	303-216 (4)*	Quartz intergrown with sphalerite
W600-25 (P)	4.48-4.32 (2)*	317-205 (5)*	Quartz hosted by skarn
W300-1 (P)	4.01-3.53 (3)*	341-209 (4)*	Quartz vein in intrusive
(S)	2.56-2.06 (3)*	270-205 (3)*	
W900-1 (P)	0.87-0.18 (7)*	270-147 (8)*	Quartz post-mineralization
W900-50 (P)	5.25-3.21 (3)*	362-232 (5)*	Sphalerite with quartz,
-10 (P)	2.40-1.90 (3)*	335-200 (5)*	hematite, and chalcocopyrite
W920-1 (P)	3.21-1.56 (6)*	185-110 (7)*	Sphalerite (light colored)
W300-3 (P)	0.70-0.18 (10)*	185-145 (10)*	Barite

Many inclusions located along fracture planes were interpreted to be of secondary origin. Isolated inclusions of large size, variable shape, and with no apparent relationship to fractures were assumed to be primary. In general, most of the samples contained few type A inclusions. The small size and/or the optical characteristics of many inclusions precluded observation of fluid behavior during cooling and heating.

Quartz—Only primary type A fluid inclusions were measured in quartz samples. However, sample 900-1 showed both type A and type B fluid inclusions. The coexistence of liquid- and vapor-rich inclusions suggests the trapping of immiscible fluids caused by boiling at the time of formation of this quartz.

Sphalerite—Primary fluid inclusions measured in sphalerite were type A. Most exhibited negative crystal shape in which inclusion borders were dark. In extreme cases, whole inclusions were almost completely dark because of the high internal reflectivity of sphalerite. It was possible to distinguish the bubble in several of these dark inclusions. Secondary fluid inclusions are related to fractures or as aligned arrays of negative crystal-shaped inclusions with no apparent relationship to actual fractures. Of this last group, some were measured and reported as T_m/Th of secondary fluid inclusions. Type C inclusions appeared dark and empty, and they were generally associated with fractures. These inclusions exhibited no change when cooled or heated.

Calcite—Fluid inclusions in calcite were type A with variable gas-liquid ratio and random distribution. In some inclusions the bubble appeared gray to dark and was conspicuously larger than the other group of inclusions with small, clear bubbles. In all cases, the bubble was not greater than 50% by volume. There was a general scarcity of type B fluid inclusions. Many areas appeared as clear

calcite without fluid inclusions. Secondary fluid inclusions in calcite were not abundant.

The presence of fluid inclusions with variable gas-liquid ratios may be interpreted in a variety of ways such as the trapping of an immiscible fluid, true boiling or effervescence, sequential trapping of different fluids at different times, necking down after formation, or leakage (Roedder, 1979). The variable gas-liquid ratio in calcite observed in this study is assumed to be the result of necking down for the following reasons: 1) no CO_2 was identified by optical means; 2) almost complete absence of gas-rich fluid inclusions; 3) lack of zonal distribution of fluid inclusions; and 4) no textural evidence of trapping of different fluids at different times. Therefore, Th is not representative of the temperature of trapping and, therefore, is not presented here.

Barite—Barite exhibited few clear areas that contained usable fluid inclusions. In general the fluid inclusions in barite were small and difficult to measure. In addition, many of the inclusions appeared to be secondary or to have leaked. Several type C secondary fluid inclusions were filled with a colorless solution. All the measurements were made in what were assumed to be primary type A fluid inclusions.

Fluid inclusion results

The homogenization temperatures and salinity measured from the Waldo-Graphic mine are summarized in Table 1.

Quartz—Because the fluid inclusion study was done with quartz samples from different stages of paragenesis, the range of homogenization temperatures was broad ($147\text{--}367^\circ\text{C}$). However, the data may be divided into three temperature populations that correspond fairly well with the paragenetic association of the quartz (Fig. 4). Temperatures of the highest group ranged from 280 to 380°C ,

with a peak of 320°C. Most of this data is from inclusions in quartz associated with recrystallized limestone and from primary fluid inclusions in vein quartz within an intrusive body. The intermediate temperature group ranged from 200 to 260°C. Inclusions in this group were mainly from quartz intergrown with sphalerite or skarn minerals and from secondary fluid inclusions from the intrusion-hosted vein quartz. Temperatures in the lowest group ranged from 140 to 200°C. These inclusions were in samples from the post-mineralization stage.

Fluid inclusion salinities ranged from 0.2 to 7.4 eq wt% NaCl. Figure 5 shows that early-stage quartz fluid inclusions have higher salinities than the salinities measured in samples of the later stages (post-mineralization).

Sphalerite—The range of Th of primary inclusions in sphalerite was 110–362°C. The distribution of Th values on a histogram shows two distinct populations (Fig. 4). The first ranged from 110 to 190°C and is composed of fluid inclusions from light-colored sphalerite. In this group Th values cluster around 150 to 190°C. The second population consisted of data from dark-brown sphalerite and ranged from 190 to 370°C with most temperatures grouped between 230 to 310°C (Fig. 4). Salinity values for both dark and light sphalerite are in the range 1.5 to 5.2 eq wt% NaCl (Fig. 5).

Barite—The fluid inclusions measured in barite have homogenization temperatures from 145 to 185°C (Fig. 4). Salinity values range from 0.2 to 0.7 eq wt% NaCl (Fig. 5). Again, the barite is thought to have formed in the last stage.

Discussion

The salinity values have been plotted versus homogenization temperatures in Figure 6. The data may be grouped in three populations: 1) inclusions in pre-ore quartz associated with recrystallized limestone and primary fluid inclusions from a quartz vein; 2) inclusions in dark- and light-colored sphalerite, inclusions in quartz intergrown with sphalerite or occurring in skarn, and secondary fluid inclusions in vein quartz; and 3) inclusions from barite and quartz thought to be post-ore minerals.

The salinity-homogenization temperature diagram (Fig. 6) shows a progressive cooling of the solutions through time, which began with early quartz and ended with late barite and quartz. Fluid salinity showed a sympathetic trend. Fluids trapped in minerals from the early stage had a higher salinity than those from later paragenetic stages. At the time of sphalerite deposition a decrease of the fluid temperature occurred, but there was no conspicuous variation of fluid salinity.

The combined analyses of the maximum and minimum temperatures of trapping of each mineral, the homogenization-temper-

ature histograms, the temperature-salinity diagram, and the paragenetic study suggest that the skarn stage was formed at temperatures greater than 320°C because the temperature of quartz formation associated with the recrystallized limestones ranges from 269 to 367°C, and most fluid inclusions homogenized at about 320°C. Most of the sulfide mineralization probably formed in the range from 175 to 310°C because all the homogenization temperatures measured in dark-colored sphalerite are in this range. The measured values below this range correspond to fluid inclusions in light-colored sphalerite. Minor sphalerite deposition occurred after the main stage of mineralization. The third (gangue) stage was deposited below 200°C. This interpretation has been plotted on the paragenetic diagram (Fig. 3).

Genetic model for ore deposition

The Waldo-Graphic deposit is typified by its association with shallow mid-Tertiary stock and volcanic cauldron-related sequences. Its primary mineralogy is specularite-magnetite, sphalerite, galena, and pyrite with subordinate chalcopyrite and barite. It forms replacements and skarn orebodies in the Kelly and Madera Limestones.

The fluids responsible for the mineralization in the Waldo-Graphic zone were H₂O-rich, low salinity (<7.4 eq wt% NaCl) with

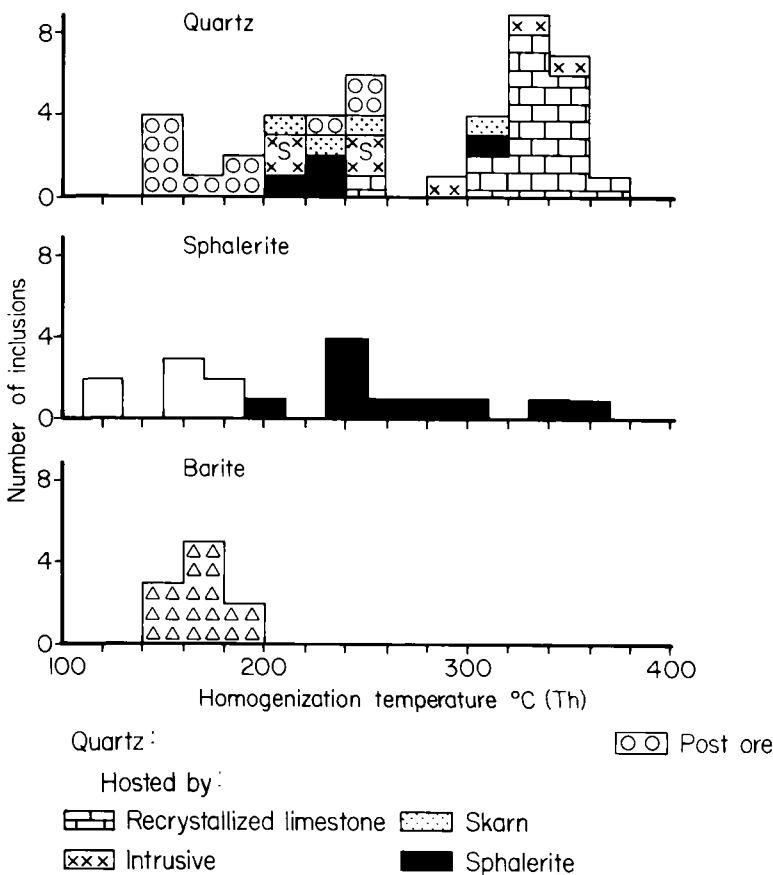


FIGURE 4—Histogram of homogenization temperatures.

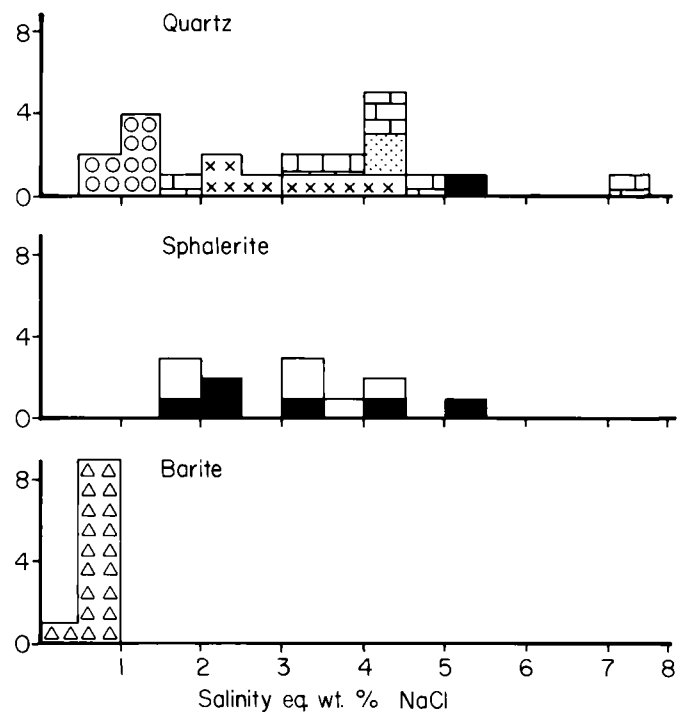


FIGURE 5—Histogram of salinity measurements.

temperatures in the range of 110 to 367°C. Boiling may have occurred but only in the final stages of quartz deposition.

To interpret the genesis of Waldo-Graphic deposits, it is necessary to build a hypothesis that explains the origin of mineralization on a district-wide scale. There is a spatial relationship between the fine-grained Nitt monzonite and the mineralization at Nitt and Waldo-Graphic mines, but the degree of hydrothermal alteration of the stock and the fluid inclusion study results suggest that the mineralization postdates the emplacement of the intrusive body. The spatial distribution of intrusive rocks (including those found in the subsurface) suggests that underneath the Magdalena district is a concealed pluton that

may be of regional dimensions. The exposed fine-grained intrusions would represent the earliest magmatic activity and the porphyritic phases, the latest.

In agreement with Elston (1976), the age of the Magdalena mining district mineralization is estimated to be between 28 Ma and 20 Ma because the ores were formed after cauldron collapse, after the intrusion of the Anchor Canyon and Nitt monzonite (28 Ma), and probably before the inception of basaltic volcanism into the region.

Tentatively, the ore deposit genesis is interpreted to be related to the episodic emplacement of a concealed pluton, which acted as a heat engine. This created episodic epithermal ground-water convection cells, lo-

calized by the structure developed during cauldron collapse. In this sense the skarn bodies are the result of the interaction of the limestones with fluids of appropriate composition and temperature. However, it is also possible that this deposit developed in two stages: 1) skarn formation associated with the Nitt monzonite intrusion as a ground preparation followed by; 2) an epithermal stage to which the sulfide ores were related.

With the present information it is difficult to determine the source of the ore metals. However, because we suggest that mineralization is related to epithermal activity and not directly related to igneous rock emplacement, derivation of the metals by leaching of plutonic and volcanic rocks seems more likely than a direct magmatic source. This is in agreement with the genesis postulated for the silica in the jasperoid (Iovenetti, 1977). In addition, Ewing (1978) proposed, as one of the possible sources of the lead, the leaching of Tertiary volcanic rocks based on the reinterpretation of the lead isotopic data from the mineral deposits of southern New Mexico. Nine of Ewing's lead isotopic analyses were from the Magdalena mining district.

ACKNOWLEDGMENTS—This paper has been improved from comments and suggestions made by David Norman, William Chavez, Jr., Ted Eggleston, and Bob North. The New Mexico Geological Society and the Latin American Scholarship Program of American Universities (LASPAU) provided funding for this research. We are grateful to all of them. Mr. Manrique thanks Tacpa University in Peru for leave of absence during this period.

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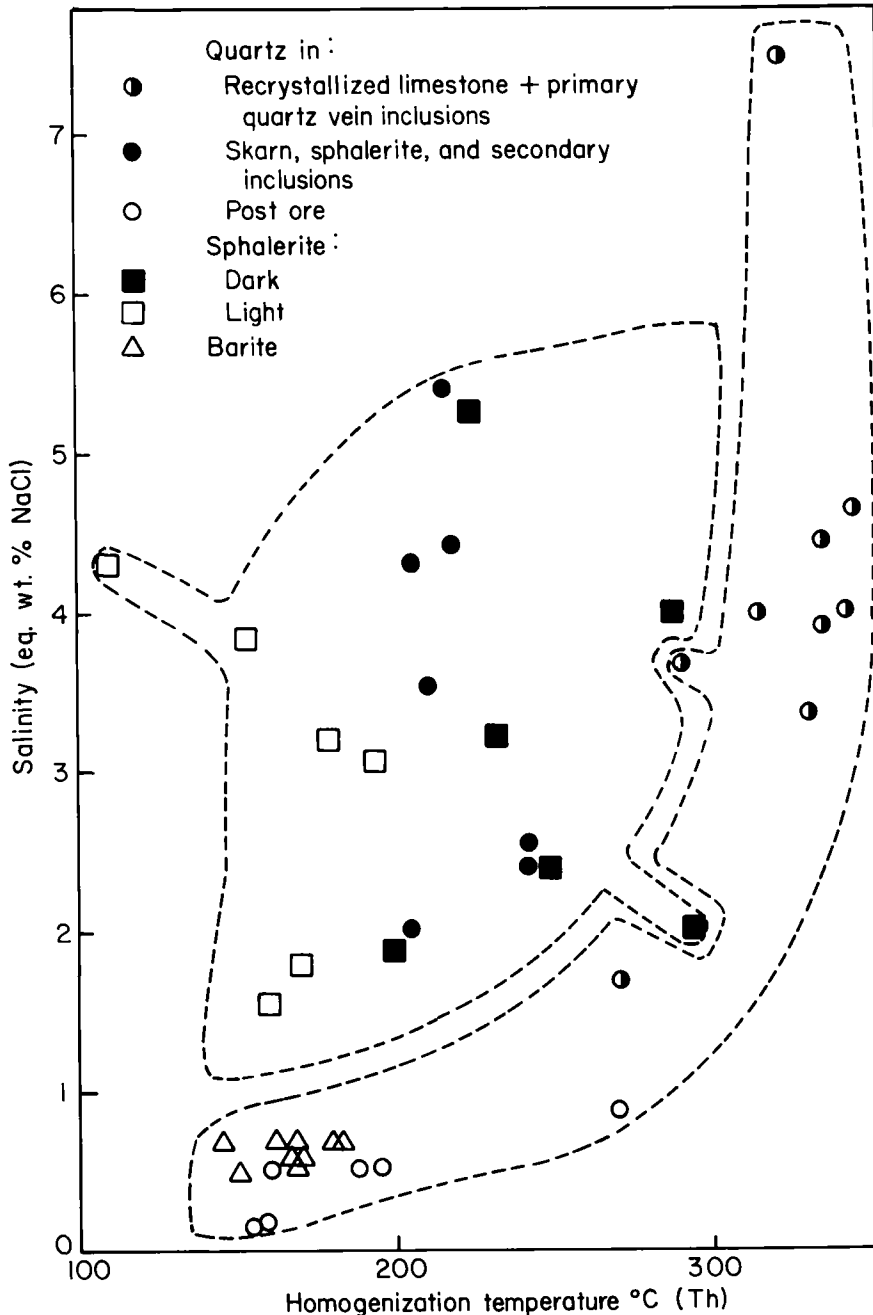


FIGURE 6—Salinity-homogenization temperature diagram.

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estimated a reserve base for the Salt Lake coal field of 347 million tons within 250 ft of the surface. Using sulfates as a factor, this reserve base can be recalculated as approximately 69 million tons of oxidized, lower rank coal and 278 million tons of unoxidized reserve base.

Conclusions

The formation of sulfates is due to an increase in the amount of oxygen-rich surface water reaching the coal. The oxygen then reacts with the sulfides, pyrite, and marcasite to form sulfates. Although the maximum depth at which sulfate is found is 180 ft, most of the sulfates are found within 50–60 ft of the surface. Coals containing sulfates that are deeper than this 50–60-ft interval are overlain by greater amounts of porous sandstones or alluvium. In either case, surface moisture, carrying oxygen, penetrated deeper than coals not overlain by the same thicknesses of these porous lithologies. Conversely, several coals that have no sulfate development, yet are within 50–60 ft of the surface, are overlain by impermeable materials such as mudstone and claystone. In this case, the impermeable nature of the overburden prevents oxygen-bearing water from reaching the coal. The shallowest coal in which no sulfate development occurs is 40 ft.

When analyzing the combustion characteristics and estimating the resources of a coal-bearing area, attention should be paid to the distribution of sulfate values in the coals. Coals in the Salt Lake coal field within 40 ft of the surface have sulfates, high moisture, low Btu, and increased oxygen values. The range of values for those parameters is much greater than for deeper coals. In the Salt Lake coal field all coals within 40 ft of the surface can be considered oxidized. None of these features is desirable for a steam coal. These data, if figured with the rest of the analyses, will tend to bias the

coal negatively. Likewise, excluding these data from an area-wide appraisal would bias the results positively. Reporting both sets of data and noting the maximum, minimum, and average depths of oxidation will allow a better assessment of area coals.

ACKNOWLEDGMENTS—I wish to thank Lynn Brandvold and William Stone for helpful comments and Orin Anderson, Louie Martinez, and Ralph Wilcox for reviewing a version of this paper.

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Review

PRECAMBRIAN AND PALEOZOIC ALGAL CARBONATES, WEST TEXAS–SOUTHERN NEW MEXICO, by Donald F. Toomey and Jack A. Babcock, August 1983: Colorado School of Mines, Professional Contributions No. 11, 345 pp., 53 figs., 97 plates. \$25.00

This book was published as the field guide for the 3rd International Symposium on Fossil Algae. It covers selected localities of Late Precambrian, Ordovician, Pennsylvanian, and Permian algal carbonates in westernmost Texas and south-central and southeastern New Mexico and is a significant contribution to knowledge of fossil algae and algal carbonate rocks. Many of the Paleozoic carbonate rocks of this region owe their origin directly to marine algae, and, most important, they continue into the subsurface as economically productive petroleum reservoirs.

Seventeen areas were selected as field localities. Beginning with the phylloid algal mound complexes of Late Pennsylvanian age in the Hueco Mountains, the localities visited include: Early Ordovician algal-sponge bioherms and stromatolites in the southern Franklin Mountains; Late Precambrian stromatolites and varied carbonate structures in the northern Franklin Mountains; Late Pennsylvanian phylloid algal mound complexes and Early Permian algal bioherms, miniherms, and biostromes in the Sacramento Mountains; and the

world-famous Permian reef complexes of the Guadalupe Mountains, where the algal-rich microfacies of these reefs are emphasized.

Each road log begins with a description of the general stratigraphy and geology of the mountain ranges and areas visited; then each stop that was made is explained in detail. Pertinent descriptions and comments on carbonate-rock and algal morphology are interspersed throughout the text. Visits to the gypsum sand dunes of White Sands National Monument and magnificent Carlsbad Caverns are also included.

The maps and sketches, along with outcrop photographs, show the detailed local and regional relationships of the algal-bearing carbonate rocks. The carbonate petrography as well as the algal descriptions and identifications are well illustrated by numerous photomicrographs.

Many field guides are of use mainly during the field trip when the trip leaders and other experts are present. This guidebook is actually a text. The descriptions of each site, along with sketches and photographs, allow anyone to utilize the book to revisit the outcrops and see the significant features of algal carbonates in the rocks.

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