



Th-U-REE quartz/fluroite veins, Capitan Pluton, New Mexico: Evidence for a magmatic/hydrothermal origin

Randall S. Phillips, Andrew R. Campbell, and Virginia T. McLemore
1991, pp. 129-136. <https://doi.org/10.56577/FFC-42.129>

in:
Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico, Barker, J. M.; Kues, B. S.; Austin, G. S.; Lucas, S. G.; [eds.], New Mexico Geological Society 42nd Annual Fall Field Conference Guidebook, 361 p.
<https://doi.org/10.56577/FFC-42>

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Th-U-REE QUARTZ/FLUORITE VEINS, CAPITAN PLUTON, NEW MEXICO: EVIDENCE FOR A MAGMATIC/HYDROTHERMAL ORIGIN

RANDALL S. PHILLIPS^{1*}, ANDREW R. CAMPBELL¹ and VIRGINIA T. McLEMORE²

¹Geoscience Department, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801;

²New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

Abstract—The Capitan Mountains, south-central New Mexico, contain several widely distributed Th-U-REE vein deposits near the western end and along the flanks of an east-west-trending Tertiary (26.5 Ma) granitic pluton. Mineralization associated with the Th-U-REE veins consists of quartz, fluorite, adularia, hematite, calcite, thorite, titanite, allanite, chortite and clay minerals. Fluid-inclusion microthermometry and optical microscopy of 638 fluid inclusions in quartz and fluorite from 14 vein systems indicates four main types. The most dominant type of inclusion is primary/pseudosecondary in origin and high-temperature, high-salinity (Th and Tm NaCl up to and greater than 600°C; bulk salinities as high as 84 eq wt% NaCl+KCl). Other types show a gradational trend from the high-temperature, high-salinity inclusions to low-temperature, low-salinity inclusions (Th as low as 110°C; salinities as low as 11 eq wt% NaCl). Most fluid-inclusion types define a trend when plotted on a Th vs. salinity diagram. The observed trends suggest evolution of the original parent fluid by cooling and crystallization of halite. $\delta^{18}\text{O}$ (from quartz) and δD (from inclusion fluids in quartz) of the fluids are 7.08‰ to 8.58‰ and -22‰ to -86‰, respectively. These isotopic data suggest that magmatic water was an important and possibly dominant source for the mineralizing fluids. Field relations, petrographic data, fluid-inclusion microthermometry and stable isotope data indicate that the fluids responsible for the Th-U-REE mineralized zones in the western half of the Capitan Mountains were of magmatic origin and were derived as a result of contraction and cracking of the Capitan pluton during cooling, followed by injection of the exsolved magmatic fluids into the brecciated zones. A late-stage, post-mineralization fluid, characterized by the lower temperature inclusions, may represent a mixture of an evolved magmatic fluid with meteoric water. This late-stage fluid appears to be restricted to the west end (apex) of the Capitan pluton.

INTRODUCTION

The Capitan Mountain thorium-uranium-rare earth element (Th-U-REE) deposits are located within the Lincoln National Forest, 5 km northeast of Capitan, Lincoln County, south-central New Mexico (Fig. 1). Access to the deposits is provided by graded dirt roads, jeep trails, pack trails and foot. The mineral potential of the Capitan Mountains consists of thorium, uranium, rare-earth elements, iron, manganese, feldspar and mineral specimens and is discussed elsewhere (McLemore and Phillips, 1991). Extensive prospecting for radioactive ore deposits was conducted during the 1950s and resulted in the discovery of Th-U-REE anomalies, most of which occur near the western edge of the Capitan Mountains.

Th-U-REE mineralization events in the Capitan Mountains provide an opportunity for direct investigation of the geochemistry of a mineralizing magmatic fluid. The Th-U-REE veins contain abundant primary and related pseudosecondary fluid inclusions in quartz and/or fluorite. Willis et al. (1989) initially described the primary/pseudo-secondary inclusions in quartz, worked on identifying daughter minerals and conducted preliminary microthermometric studies of 30 fluid inclusions in quartz from a single vein (Mina Tiro Estrella prospect—MTE). The purpose of this paper is to define the physical-chemical conditions responsible for the Th-U-REE quartz/fluorite veins. The methods of investigation include microthermometric studies of 638 fluid inclusions in quartz and fluorite from 14 different vein systems of the Capitan Mountains, oxygen isotope studies on vein quartz, and hydrogen isotope studies on fluid inclusion waters in quartz.

GEOLOGY AND MINERALIZATION

The Capitan Mountains consist of an east (core)–west (apex)–trending Tertiary (26.5 Ma, K/Ar, biotite; Allen, 1988) alkali granitic pluton approximately 35 km long and 5 to 8 km wide (Fig. 1). Elevations range from 1700 to 3100 m. The Capitan pluton is one of the largest Tertiary plutons in New Mexico and is a prominent feature of the Capitan lineament (Chapin et al., 1978). The Capitan pluton is one of at least eight Tertiary igneous complexes (referred to as the Lincoln County

porphyry belt by Thompson, 1972) in the region. The pluton has intruded carbonate, sandstones and shales of the Permian Yeso and San Andres Formations (Kelley, 1971). The Rio Bonito Member(?) of the San Andres Formation overlies the pluton on the west end, forming a roof pendant (Fig. 1; Kelley, 1971). The sedimentary rocks of the Yeso Formation are overturned or dip steeply away from the intrusive contact at the east end, suggesting a forceful intrusion (Allen, 1988). The Capitan pluton exhibits textural, chemical and mineralogical zonation trending west to east (Allen, 1988; Allen and McLemore, 1991).

The Capitan pluton is cut by several faults, and numerous brecciated and mineralized zones occur along the flanks and west end (Fig. 1). Four types of mineralization occur: (1) Th-U-REE enriched quartz and/or fluorite veins; (2) feldspar; (3) iron skarns near the intrusive contact and magnetite veins within the pluton; and (4) manganese veins. Only the first type of mineralization is discussed here. Th-U-REE analyses for some of the prospects are summarized by McLemore and Phillips (1991). The veins occur as fillings in brecciated zones and as joint or fracture fillings in the pluton. In most prospects, the brecciated zones lie parallel with near-vertical joints in the pluton. The veins vary from less than a few centimeters to several meters in width and can be traced for distances up to 300 m.

Based on field observations and hand sample identifications, the MTE prospect quartz vein (Fig. 1) consists of quartz, adularia, allanite, titanite, chlorite, epidote, magnetite, hematite and clay minerals. Actinolite and microlite were reported by Hanson (1989), but were not observed in the field by the authors. Quartz occurs as massive, somewhat transparent vein-filling material, as clear-to-smoky single crystals up to 3 cm filling open spaces, and as clear-to-smoky Japanese-law twinned crystals. Titanite occurs as reddish-brown, euhedral crystals up to 0.5 cm in length filling open spaces and as crystal aggregates within a massive adularia matrix. Allanite occurs as black, euhedral tabular crystals up to 1 cm in length filling open spaces. Allanite and titanite are the host minerals for REEs (see McLemore and Phillips, 1991, table 3) and both exhibit complex chemical zonation, as indicated by backscattered electron mapping (M. Willis, personal comm., 1989; Willis et al., 1989). The adularia is pink to white and occurs as massive intergrowths with quartz and as euhedral crystals filling open spaces.

*Present Address: Chemistry Department, Arizona State University, Tempe, Arizona 85287

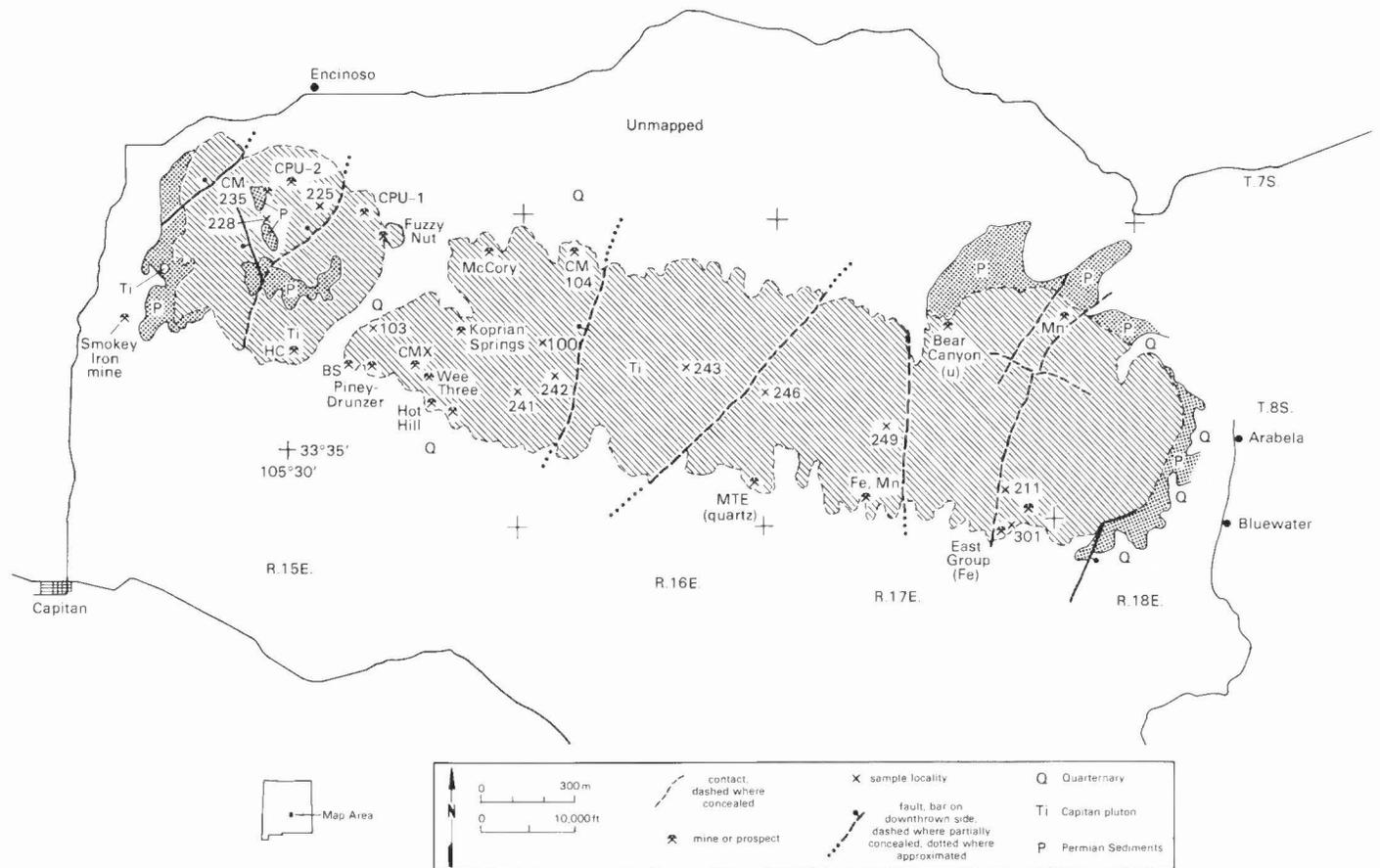


FIGURE 1. Generalized geologic map of the Capitan Mountains showing the location of the Capitan pluton, prospect localities and sample localities. Geologic map modified slightly from Kelley (1971). Sample localities refer to pluton samples (Allen and McLemore, 1991).

Clay minerals are present within the vein material and may be related to alteration of the feldspars.

Based on field observations and hand sample identifications, the quartz-fluorite veins (CM 235, Fuzzy Nut, CPU-1, CPU-2, HC, McCorry, Wee Three, Koprian Springs and Hot Hill prospects; Fig. 1) consist of quartz, fluorite, adularia, hematite/magnetite, thorite (identified by X-ray diffraction study of mineral separates) and possibly allanite. Quartz occurs as clear to smoky crystals up to 2 cm lining fractures and open spaces and as massive material filling brecciated zones. Fluorite occurs as green, blue, purple and colorless cubes up to 2 cm filling vugs and fractures and as massive, vein-filling material. Adularia generally occurs as pink to white, euhedral crystals up to 7 mm lining fractures. Primary hematite/magnetite occurs as specular plates coating fractured surfaces and as massive material filling brecciated zones. Th-U-REE prospects containing quartz, adularia, thorite and possibly allanite are CM 104, BS, Piney-Drunzer and CMX. Calcite was observed as a late-stage, fine-grained, vug-filling mineral at the Fuzzy Nut, HC, Hot Hill and Wee Three prospects. Apatite and garnet were found at the Fuzzy Nut prospect. Brown nodular to tabular masses up to a few centimeters were seen in veins at the CM 235, HC, Hot Hill, Wee Three and Fuzzy Nut prospects. For a more detailed description of the individual prospects, refer to Phillips (1990).

FLUID INCLUSION STUDIES

Sample selection and measurements

Samples for fluid inclusion microthermometric measurements were selected from vein quartz and fluorite. Forty doubly polished thick sections of euhedral quartz crystals, massive quartz within brecciated vein material and single fluorite cubes were prepared for microthermometric studies. Small cleavage fragments (0.1–0.5 mm thick) of fluorite were also used for microthermometric measurements.

Microthermometric studies of fluid inclusions were performed on a Linkham TH 600 heating/freezing stage. Calibration for heating measurements utilized various organic and inorganic compounds with melting temperatures 82°, 115°, 135°, 165°, 192°, 236°, 306°, 398°, 455° and 560°C. The precision for temperatures less than 150°C was $\pm 1^\circ\text{C}$, whereas for temperatures between 150 to 300°C it was $\pm 2^\circ\text{C}$, and for temperatures greater than 300°C it was $\pm 6^\circ\text{C}$. Calibration for freezing measurements was obtained using triply distilled/deionized water.

Fluid inclusion types

Optical microscopy of phase assemblages of 638 fluid inclusions in quartz and fluorite reveal four major types of inclusions.

Type 1 inclusions are multiphase inclusions [liquid (L) + vapor (V) + halite (H) + sylvite (S) + three or more other daughter minerals] that homogenize by either halite dissolution or vapor disappearance, the former being more dominant. Type 1 inclusions are the most abundant of the four types. The vapor phase constitutes 8 to 15% of the total fluid inclusion volume. Some of the daughter minerals in type 1 inclusions have been positively identified optically, by SEM and laser Raman spectroscopy (Willis et al., 1989), as halite, sylvite, anhydrite and hematite. Titanite, magnetite, barite (M. Willis, personal comm., 1989) and an unknown carbonate mineral (G. Wolf, personal comm., 1990) have been tentatively identified. Halite is the dominant solid phase and forms sharp to slightly rounded cubic crystals. Sylvite is the second most abundant solid phase, exhibits slightly lower relief than halite and forms subrounded crystals. Anhydrite occurs as elongated, slightly rounded rectangular prisms with moderate birefringence and generally does not dissolve at temperatures below 600°C. Hematite occurs either as a black opaque solid phase or as a yellow/orange to red thin plate, occasionally exhibits a hexagonal habit and never dissolves upon heating to 600°C. Phase-ratio observations of the daughter minerals in hundreds of type

1 inclusions within a given sample of quartz or fluorite show that the daughter minerals occur in similar ratios in the different inclusions, which suggests that the solid phases are not trapped minerals. Also, no solid inclusions were observed in the host quartz and fluorite.

Type 2 inclusions are multiphase inclusions [L + V + H + S] which generally homogenize by halite dissolution. The vapor phase accounts for 8 to 10% of the total inclusion volume.

Type 3 inclusions are three-phase inclusions [L + V + H]. The vapor phase accounts for 5 to 10% of the total inclusion volume. Type 3 inclusions may homogenize by either halite dissolution or vapor homogenization.

Type 4 inclusions are two-phase inclusions [L + V]. The vapor phase accounts for 5 to 10% of the total inclusion volume.

Origin, size and heating/freezing data

Vapor homogenization temperatures (Th), halite dissolution temperatures (Tm NaCl) and sylvite dissolution temperatures (Tm KCl) were measured on 638 fluid inclusions in quartz and fluorite from 14 different vein systems to determine the temperatures and pressures of vein formation and salinities of the vein-forming solutions. Table 1 summarizes the important fluid inclusion data. Fluid inclusion histograms illustrating Tm NaCl, Th and Tm KCl for quartz and fluorite from all of the veins examined in this study were presented in Phillips (1990). Histograms with all the quartz data combined and all the fluorite data combined are shown in Figs. 2 and 3, respectively. Due to a lack of adequate data for complex "salty" systems (type 1 and 2 inclusions), no pressure corrections have been applied to any of the measured temperatures. Fluid inclusions were also classified by timing relative to the host crystal formation as primary, pseudosecondary or secondary in origin according to the criteria of Roedder (1984).

Quartz

Type 1 inclusions are dominant in quartz from all prospects studied. The type 1 inclusions range in size from 150 to less than 5 μ, averaging

TABLE 1. Summary of fluid inclusion data.

Type	1	2	3	4
Phases	L+V+H+S + others	L + V + H + S	L + V + H	L + V
Th Vapor (C)				
Quartz	398 - > 600	343 - 480	119 - 461	113 - 208
Fluorite	329 - > 600	268 - 407	119 - 358	110 - 169
Bulk Salinity				
Wt% NaCl + KCl				
Quartz	65.8 - > 83.6	52.4 - 69.6	29.4 - 55.8	18.8 - 19.3
Fluorite	66.8 - > 80.8	45.6 - 56.5	30.8 - 42.7	10.6 - 20.7
K/Na Ratios				
Quartz	0.16 to 0.32	0.24 to 0.40		
Fluorite	0.21 to 0.33	0.21 to 0.43		
Number of Measurements				
Quartz	280	17	46	13
Fluorite	54	111	92	22

H = Halite, V = Vapor bubble, S = Sylvite, A = Anhydrite, O = Opaque, L = Liquid

10 to 30 μ. They are usually sub-oval to irregular in shape. They occur as isolated inclusions, as planes containing hundreds of inclusions along growth zones that do not cut through grain boundaries, as clusters, and as trails healing fractures that do not cut grain boundaries. Type 1 inclusions in quartz are primary or pseudosecondary in origin. Type 1 inclusions in vein quartz could not always easily be distinguished between primary and pseudosecondary. In cases where this distinction could not be made, a pseudosecondary origin was assigned. Type 1 inclusions account for greater than 90% of the total inclusions in quartz from the MTE, CMX, CM 104 and Wee Three prospects. For the remaining prospects, type 1 inclusions account for 75 to 90% of the total inclusion population. Two hundred eighty type 1 inclusions were measured in quartz. Th for type 1 inclusions range from 398° to >600°C. Tm NaCl for type 1 inclusions range from 483° to >600°C. Based on the size of the halite cube and/or vapor bubble still present at the 600°C limit of the heating stage, we estimate that complete homogenization would occur at temperatures less than 650°C, with the majority in the 610° to 620°C range. Tm KCl ranges from 145° to 313°C. There is a general increase in halite dissolution temperatures from west to east, with the westernmost CM 235 prospect having Tm NaCl up to 547°C and the easternmost MTE prospect having Tm NaCl >600°C.

Type 2 inclusions were only observed and measured from the CM

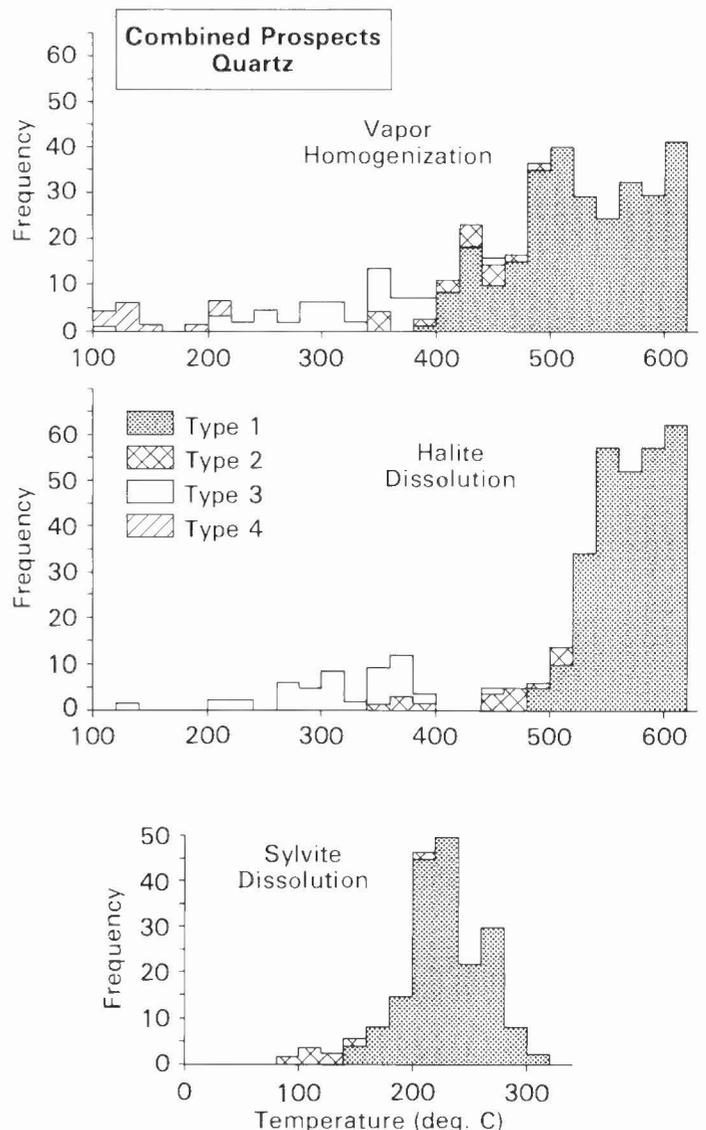


FIGURE 2. Histogram showing vapor homogenization, halite dissolution and sylvite dissolution temperatures for all fluid inclusions in quartz from all of the prospects examined in this study.

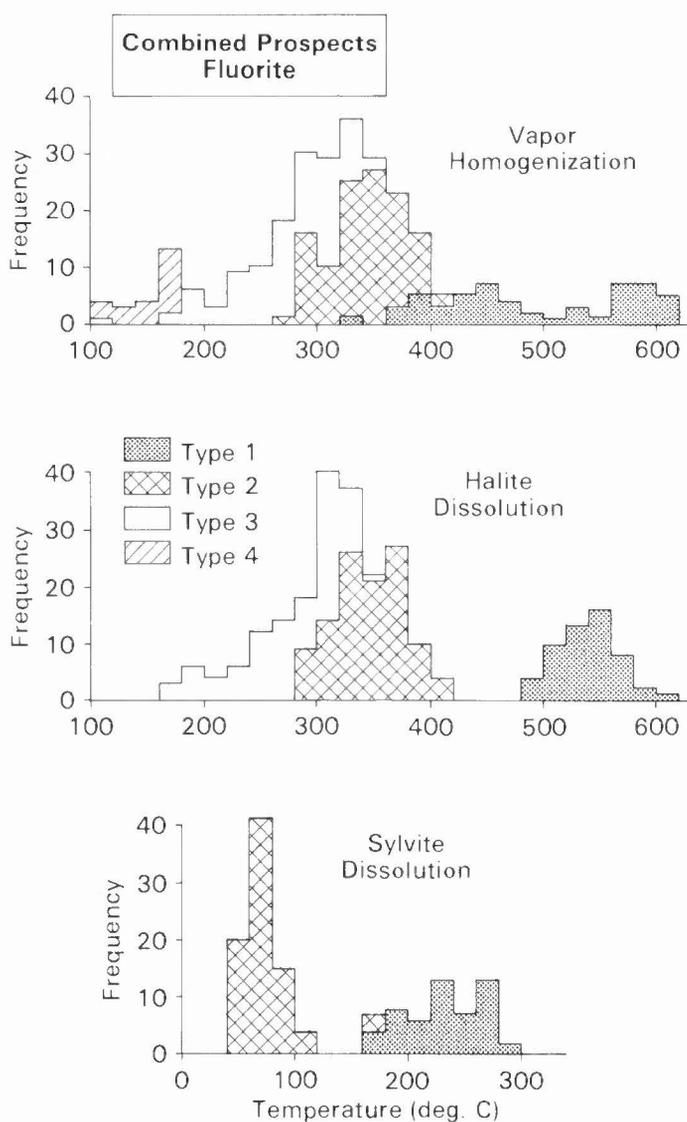


FIGURE 3. Histogram showing vapor homogenization, halite dissolution and sylvite dissolution temperatures for all fluid inclusions in fluorite from all of the prospects examined in this study.

235, Hot Hill, Fuzzy Nut, CMX and MTE prospects. They account for less than 1% of the total inclusions in the quartz. Sizes range from less than 5 to 15 μ . Type 2 inclusions occur as trails within healed fractures cutting across quartz grains and are classified as secondary in origin. Seventeen type 2 inclusions were measured in quartz. Th ranges from 343° to 480°C, Tm NaCl ranges from 363° to 509°C and Tm KCl ranges from 96° to 204°C.

Type 3 inclusions occur in all the quartz veins. They are less abundant in the MTE, CM 104, Wee Three and CMX prospects, accounting for less than 1 to 5% of the total inclusions. The other prospects contain 5 to 10% type 3 inclusions as part of the total inclusion volume. Type 3 inclusions are small, less than 20 μ , and generally ovoid in shape. They typically occur as secondary planes of inclusions cutting across mineral grains. Type 3 inclusions are classified as secondary in origin. Forty-six type 3 inclusions were measured in quartz. Th ranges from 119° to 402°C and Tm NaCl ranges from 139° to 389°C.

Type 4 inclusions are small, less than 10 μ , and generally subround in shape. Type 4 inclusions were observed in only a few prospects and account for less than 1 to 5% of the total inclusion volume. They generally occur as planes containing several inclusions cutting across quartz grain boundaries. Type 4 inclusions are classified as secondary

in origin. Thirteen type 4 inclusions were measured in quartz. Th varies from 113° to 208°C. Freezing point depressions for type 4 inclusions range from -15.8° to -14.1°C.

Fluorite

In general, type 1 inclusions are not very abundant in vein fluorite for most of the prospects. An exception occurs in fluorite from the CPU-1 prospect, which contains >90% type 1 inclusions. Most veins containing fluorite have type 1 inclusions accounting for 5 to 10% of the total inclusions. Type 1 inclusions range from less than 5 to 70 μ , averaging 10 to 20 μ , and are generally oval to irregular in shape. Type 1 inclusions are classified as primary when they occur isolated or in clusters, and pseudosecondary when they occur in trails healing fractures within mineral grains. Type 1 inclusions in fluorite have similar compositions and temperatures to those in quartz, which suggests that the quartz and fluorite are cogenetic. Fifty-four type 1 inclusions were measured in fluorite. Th for type 1 inclusions ranges from 329° to >600°C, Tm NaCl ranges from 483° to >600°C and Tm KCl ranges from 167° to 283°C.

Type 2 inclusions in vein fluorite were observed in all prospects, except the CM 235 prospect. They account for 0 to 25% of the total inclusions, are subround and elongate in shape and range in size from less than 5 to 30 μ . Type 2 inclusions generally occur as trails healing fractures that cut through grain boundaries and are classified as secondary in origin. One hundred eleven type 2 inclusions were measured in fluorite. Th ranges from 268° to 407°C, Tm NaCl ranges from 288° to 407°C and Tm KCl ranges from 51° to 162°C.

Type 3 inclusions were observed in all prospects containing vein fluorite, except the CPU-1 prospect. They account for 0 to 50% of the total inclusions, are oval to subround in shape and range from less than 1 to 30 μ in size, averaging 5 μ . They occur in planes cutting through grain boundaries and as trails crosscutting grain boundaries. Type 3 inclusions are secondary in origin. Ninety-two type 3 inclusions were measured in fluorite. Th ranges from 119° to 358°C and Tm NaCl ranges from 167° to 351°C.

Type 4 inclusions in fluorite were observed in most prospects. They account for 10 to 30% of the total inclusions, are rounded to oval in shape and range in size from less than 1 μ to 10 μ . They occur in planes containing hundreds of 1 to 2 micron-sized inclusions cutting grain boundaries, and are commonly stretched. They also occur within healed fractures cutting grain boundaries. Type 4 inclusions are classified as secondary in origin. Twenty-two type 4 inclusions were measured in fluorite. The inclusions have Th from 110° to 169°C. Freezing point depressions range from -17.7° to -7.1°C.

Fluid inclusion salinities

Salinities for type 1 and 2 inclusions, best represented by the NaCl-KCl-H₂O system, were obtained by measuring halite and sylvite dissolution temperatures and using the FORTRAN program SALT (Bodnar et al., 1989). Salinities for type 3 inclusions, best represented by the NaCl-H₂O system, were determined by measuring halite-dissolution temperatures and referring to FLINCOR [(Brown, 1989), a Microsoft Windows application (data from Brown and Lamb, 1989)], a computer program used to calculate salinities and densities for fluid inclusions with low to moderate salinities. Salinities for type 4 inclusions were determined by measuring the freezing point depression and using FLINCOR. Homogenization temperature and salinity data for all types of inclusions are summarized for quartz (Fig. 4) and fluorite (Fig. 5) from the different vein systems. The four types of inclusions describe non-overlapping separate fields. The origin of the observed fields is discussed in a later section. Salinity fields for type 1 and 2 inclusions in quartz and fluorite are shown on the NaCl-KCl-H₂O ternary plot (Fig. 6).

Quartz

Salinities for type 1 inclusions range from 49.3 to >66.6 wt% NaCl and 13.3 to 21.3 wt% KCl (Field A, Fig. 6). K/Na ratios for type 1 inclusions range from 0.16 to 0.32, with the majority in the 0.22 to 0.26 range. Bulk compositions of type 1 inclusions are more complex

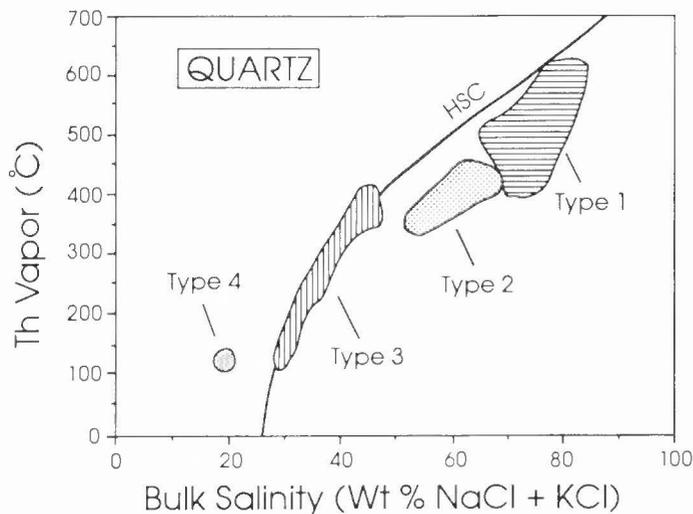


FIGURE 4. Plot of combined vapor homogenization temperature versus salinity data for type 1, 2, 3 and 4 inclusions in vein quartz from all prospects examined in this study. Salinities for type 1 and 2 inclusions are expressed as eq wt% NaCl + KCl. Salinities for type 3 and 4 inclusions are expressed as eq wt% NaCl. HSC is the halite saturation curve (from Sterner et al., 1988). All four types of inclusions plot in separate fields. Type 1 and 2 inclusions plot off the HSC because T_m NaCl is greater than T_h and/or HSC is not a good representation of the NaCl-KCl-H₂O system. Type 3 inclusions plot on or near the HSC. Type 4 inclusions plot off the HSC, suggesting a mixing trend between the evolved magmatic fluid and a meteoric water. Type 1 inclusions represent 186 measurements, type 2 inclusions represent 6 measurements, type 3 inclusions represent 43 measurements and type 4 inclusions represent 8 measurements.

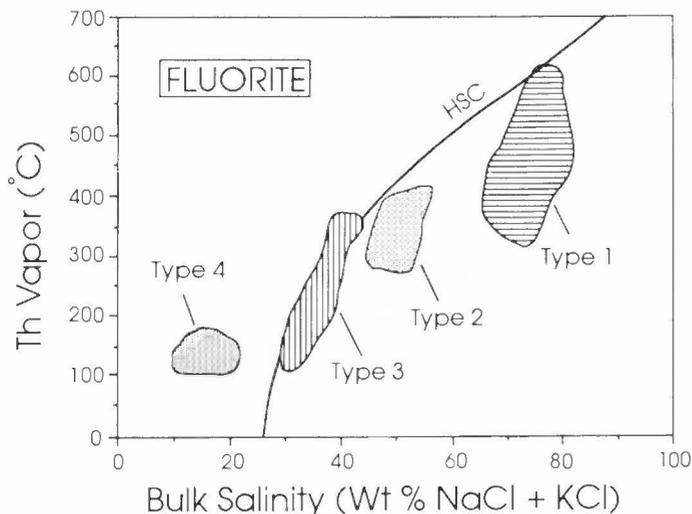


FIGURE 5. Plot of combined vapor homogenization temperature versus salinity data for type 1, 2, 3 and 4 inclusions in vein fluorite from all prospects examined in this study. Type 1 inclusions represent 53 measurements, type 2 inclusions represent 92 measurements, type 3 inclusions represent 92 measurements and type 4 inclusions represent 12 measurements. See Fig. 4 caption for additional comments.

than the simple NaCl-KCl-H₂O system. Daughter minerals in type 1 inclusions indicate additional components. The NaCl-KCl-H₂O system ignores the effects of these additional components. The additional components may alter the actual bulk salinities for the type 1 inclusions. Type 1 inclusions probably have higher bulk salinities and lower NaCl and KCl concentrations than reported above. Salinities for type 2 inclusions range from 35.4 to 49.8 wt% NaCl and 15.3 to 20.2 wt% KCl (Field C, Fig. 6). K/Na ratios for type 2 inclusions range from 0.24 to 0.40, with most falling between 0.26 and 0.30. Salinities for type 3

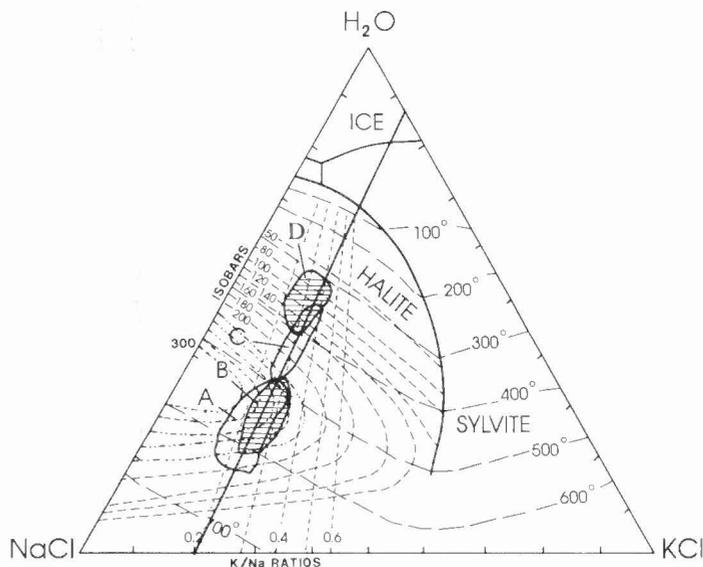


FIGURE 6. NaCl-KCl-H₂O ternary system (in wt%) showing compositional fields under vapor-saturated conditions for type 1 and 2 inclusions in quartz and fluorite from all the prospects. Figure is modified slightly from Cloke and Kesler (1979). Field A shows the composition of type 1 inclusions in quartz and represents 186 measurements. Field B shows the composition of type 1 inclusions in fluorite and represents 53 measurements. Field C shows the composition of type 2 inclusions in quartz and represents 6 measurements. Field D shows the composition of type 2 inclusions in fluorite and represents 92 measurements. Heavy solid lines are cotectics. Long dashed lines are isotherms (in °C), medium dashed lines are isobars (in bars), and short dashed lines projecting to the H₂O apex are lines of constant K/Na ratios. Dot-dash lines are extrapolated isobars from 200 to 300 bars. Fields A, B, C and D fall on a linear trend. This trend is similar to what Erwood et al. (1979) and Cloke and Kesler (1979) referred to as a "halite trend," interpreted to result from the separation and crystallization of KCl-bearing halite from the parent fluid prior to being entrapped in an inclusion (see text).

inclusions range from 29.4 to 55.8 eq wt% NaCl. Salinities for type 4 inclusions range from 18.8 to 19.3 eq wt% NaCl.

Densities for type 1 inclusions can be estimated from phase-volume measurements of individual inclusions. A typical type 1 inclusion contains roughly 30% halite, 39% liquid (saturated with 26.3 wt% NaCl), 15% water vapor, 7% sylvite, 2% anhydrite, 3% hematite and 4% unknown daughter minerals. Using densities (Klein and Hurlbut, 1977) of 2.16 g/cm³ for halite, 1.99 g/cm³ for sylvite, 2.89 g/cm³ for anhydrite, 5.26 g/cm³ for hematite, 0.001 g/cm³ for water vapor, an average density of 2.5 g/cm³ for the unknown daughter minerals (Roedder, 1971) and 1.2 g/cm³ for liquid (Roedder, 1971), the total density of the inclusion fluid is 1.57 g/cm³. According to Roedder (1971), such a fluid would be classified as a "hydrosaline melt" rather than a true aqueous fluid. A typical type 2 inclusion contains 72% liquid (saturated with 26.3 wt% NaCl), 14% halite, 12% vapor and 2% sylvite. The total density for such an inclusion is 1.21 g/cm³. Densities for type 3 inclusions were determined using FLINCOR and range from 1.07 to 1.15 g/cm³. Similarly calculated densities for type 4 inclusions average 1.08 g/cm³.

Fluorite

Salinities for type 1 inclusions range from 48.3 to >62.2 wt% NaCl and 16.6 to 22.2 wt% KCl (Field B, Fig. 6). K/Na ratios range from 0.21 to 0.33, with most in the 0.26 to 0.30 range. Salinities for type 2 inclusions range from 31.9 to 41.1 wt% NaCl and 11.4 to 16.9 wt% KCl (Field D, Fig. 6). K/Na ratios range from 0.21 to 0.43, with most falling between 0.28 and 0.322. Salinities for type 3 inclusions range from 30.8 to 42.7 eq wt% NaCl. Salinities for type 4 inclusions range from 10.6 to 20.7 eq wt% NaCl. Inclusion fluid densities for types 1-4 in fluorite are similar to those of quartz.

Pressure-depth estimates

Minimum pressures can be estimated for type 1 and 2 inclusions in quartz and fluorite, based on halite and sylvite dissolution temperatures and referring to the NaCl-KCl-H₂O system of Cloke and Kesler (1979). Extrapolating the isobars in Fig. 6 yields minimum pressure estimates for type 1 inclusions (Fields A and B, Fig. 6) of 190 to 300 bars. Assuming a lithostatic load and a rock density of 2.6 g/cm³, minimum depths for these pressures are from 0.74 to less than 1.18 km.

A reconstruction of the sedimentary thicknesses overlying the Capitan pluton during the mid-Tertiary can be approximated (B. Colpitts, personal comm., 1990) by using oil well log data and data from Kelley (1971) and Bodine (1956). Well log data south of the Capitan Mountains indicates approximately 640 m of Permian Yeso Formation above the Precambrian basement rock (B. Colpitts, written comm., 1990). Estimated thicknesses of sedimentary strata (Kelley, 1971; Bodine, 1956) that may have been present above the Capitan pluton during mid-Tertiary times are: 170 m of Permian San Andres plus Glorieta Formations (65 m of Four Mile Draw Member, 15 m of Bonney Canyon Member and 90 m of Rio Bonito Member), 110 m of Permian Grayburg Formation, 30 m of Permian Queen Formation, 180 m of Triassic Chinle Formation and Santa Rosa Sandstone, 40 m of Cretaceous Dakota Sandstone, 120 m of Cretaceous Mancos Shale, 150 m of Cretaceous Mesaverde Formation and 150 m of Paleocene Cub Mountain Formation. A total estimated thickness is 1590 m (1.6 km), corresponding to a lithostatic load of 400 bars.

The fine-grained nature of the alkali granite pluton, the presence of miarolitic cavities within the pluton and the presence of a limestone-sandstone roof pendant on the west end of the pluton, suggest that the pluton was emplaced at shallow crustal levels. From the fluid inclusion evidence and geologic evidence mentioned above, the depth of pluton emplacement and vein formation was estimated at between 1.2 km and 1.6 km.

STABLE ISOTOPE STUDIES

Oxygen-isotope ratios for vein quartz and hydrogen-isotope ratios for inclusion fluids from quartz were measured to constrain the source of the mineral-forming fluids. Sample descriptions, detailed experimental procedures and all experimental data were reported by Phillips (1990).

A silicate-extraction line employing a ClF₃ reagent in the stable isotope lab at the New Mexico Institute of Mining and Technology was used for extracting oxygen samples from quartz and adularia samples (technique from Borthwick and Harmon, 1982; modified from Taylor and Epstein, 1962). Oxygen-isotope ratios with respect to SMOW (Standard Mean Ocean Water, $\delta D = 0\text{‰}$) were measured on the CO₂ samples using a Finnigan Mat Delta E mass spectrometer. Precision for silicate samples using a National Bureau of Standards sample (NBS-28, $\delta^{18}\text{O} = 9.64\text{‰}$ vs. SMOW) was $\pm 0.07\text{‰}$ (actual values range from 9.59 to 9.84‰, averaging 9.71‰).

Hydrogen samples on inclusion fluids of vein quartz were determined by using 10 to 25 g of 0.2-to-1.0-cm-sized pieces of material, crushing the sample under vacuum in a steel tube, transferring the evolved water in a vacuum line to a hydrogen reaction vessel containing 0.3 g Zn and reacting the water plus Zn under vacuum at 500°C for 30 min (technique modified from Coleman et al., 1982). The hydrogen formed by this technique was measured to obtain the hydrogen-isotope ratio of the inclusion fluids on a Finnigan Mat Delta E mass spectrometer. Hydrogen-isotope values were corrected with respect to NBS water standards SMOW, GISP (Greenland Ice and Snow Precipitation, $\delta D = -189.7\text{‰}$ vs. SMOW) and SLAP (Standard Light Antarctic Precipitation, $\delta D = -428\text{‰}$ vs. SMOW).

Results of oxygen isotope analyses for quartz

Representative samples of vein quartz were measured for $\delta^{18}\text{O}$ (Table 2). $\delta^{18}\text{O}$ of quartz ranges from 8.73‰ to 10.16‰ with respect to SMOW. The isotopic composition of the waters in equilibrium with the quartz were calculated by using the highest halite-dissolution temperature for a type 1 inclusion in quartz for a given prospect and referring

TABLE 2. Oxygen isotopic values on quartz, and hydrogen isotopic values on fluid inclusion waters in quartz (values vs. SMOW).

Prospect	Description	$\delta^{18}\text{O}$ (o/oo)	FI Temp	$\delta^{18}\text{O}$ (H ₂ O)	δD (FI H ₂ O)
BS	clear qtz vein	9.12	549	7.23	
CM 104	clear qtz xls	8.86	577	7.16	
CM 235	clear qtz breccia	9.04, 9.46	559	7.22, 7.64	
CM 242	clear qtz vein	9.08, 9.62	n/m		
CM 301	clear qtz veinlet	9.07	n/m		
CMX-1	clear qtz xl	9.17, 9.14	610	7.68, 7.65	-50, -66, -67,
CMX-1	clear qtz xl		610		-73, -79, -80
CMX-2	smoky qtz xl	9.04, 8.82	610	7.55, 7.33	-86
CPU-2	clear vug qtz	9.11	568	7.35	
CPU-2	clear qtz vein	9.39	568	7.63	
CPU-2	smoky vug qtz	9.54	568	7.78	
CPU-2	smoky qtz xl	9.62	568	7.86	
Fuzzy Nut	clear vug qtz	8.82	570	7.08	-67, -75
Fuzzy Nut	clear qtz vein	9.42	570	7.68	
Hot Hill-8	smoky qtz xl	8.99	610	7.50	
Hot Hill-1	smoky qtz xl	8.73	610	7.24	
Hot Hill-2	clear qtz xl	9.43	610	7.94	
Kopr Spgs	clear qtz xl	9.22	541	7.27	
McCory	smoky qtz xl	9.59	610	8.09	
MTE-1	clear vein qtz	9.10, 8.99	620	7.67, 7.56	
MTE-2	clear qtz xl	8.81, 8.94	620	7.38, 7.51	
MTE-3	Jap-law qtz xl	9.21, 8.85	620	7.78, 7.42	-22, -25, -34
MTE-3	Jap-law qtz xl				-36, -49, -50
Piney	smoky qtz xl	9.05	n/m		
W3-3A	smoky qtz xl	9.06	610	7.57	-46
W3-3B	smoky qtz xl	9.01	610	7.52	-48
W3-3C	clear qtz xl	9.05	610	7.56	
W3-4	smoky qtz xl	9.16	595	8.58	

Samples W3-3,4 are from the Wee Three claims.

Oxygen and hydrogen isotopic values were determined on different pieces of similar quartz and are not "true" paired values. n/m = not measured

δ notation = a measure of the isotope ratio of sample with respect to the isotope ratio of a standard.

to the fractionation equation given by Matsuhisa et al. (1979). The $\delta^{18}\text{O}$ of the corresponding water values ranges from 7.08‰ to 8.09‰. There was no variation in the $\delta^{18}\text{O}$ values between smoky quartz and clear quartz from the same vein, indicating the two types of quartz formed from the same fluid. $\delta^{18}\text{O}$ values of massive quartz, vuggy quartz and Japanese-law twinned quartz from the MTE prospect are approximately the same, suggesting that all three forms of quartz originated from the same fluid.

Results of hydrogen isotope analyses from fluid inclusion waters

Data for hydrogen isotope ratio measurements on fluid inclusion waters in vein quartz from the MTE, Wee Three, Fuzzy Nut and CMX prospects are summarized in Table 2. δD values show a large range, from -22‰ to -86‰. The meaning of this large spread is uncertain. A plot of $\delta^{18}\text{O}$ water values versus the corresponding δD values from quartz samples is shown in Fig. 7. Samples from the MTE, CMX, Fuzzy Nut and Wee Three prospects fall within, above and slightly below the magmatic water box. A smoky quartz sample from the CMX prospect plots near the magmatic water boundary.

DISCUSSION OF FLUID INCLUSION DATA

Microthermometric and petrographic studies of 638 fluid inclusions in quartz and fluorite from the Th-U-REE deposits in the Capitan Mountains indicate that there are four main types of fluid inclusions (Figs. 4, 5). A detailed discussion of the origin of the four fluid inclusion types was presented by Phillips (1990). A general summary of the important results is presented here.

When type 1 and 2 inclusions are plotted on a NaCl-KCl-H₂O diagram (Fig. 6), the observed fields for both quartz and fluorite define a linear trend. This linear relationship implies that type 1 and 2 fluids are part of the same parent fluid, which may have undergone some type of fluid evolution. This linear trend has previously been referred to as the "halite trend" (Erwood et al., 1979; Cloke and Kesler, 1979), because the

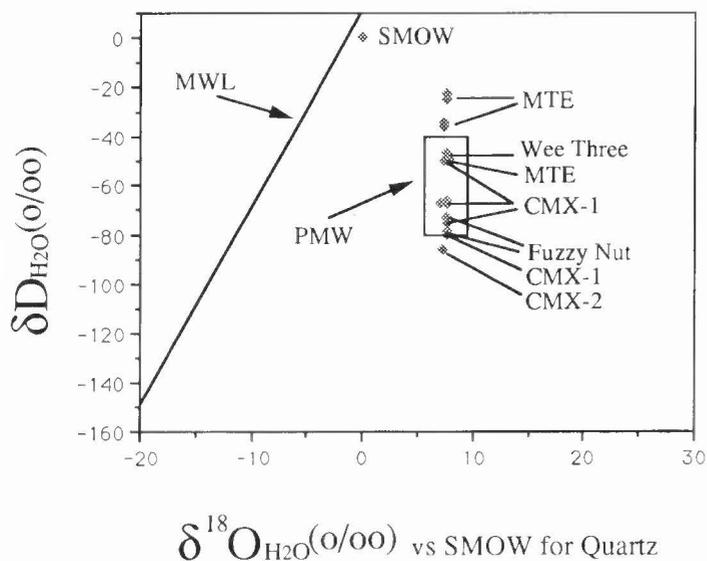


FIGURE 7. Plot of hydrogen isotope values of fluid inclusion waters in quartz versus oxygen isotope values of water in equilibrium with quartz at 600°C for samples from four prospects. MWL is the meteoric water line, PMW is the primary magmatic water box (Sheppard, 1977). SMOW is Standard Mean Ocean Water. Sample CMX-1 is clear vein quartz and CMX-2 is smoky vein quartz. Most quartz samples plot in the PMW box and are interpreted to have formed from magmatic fluids.

trend extends from (or near) the halite apex. The most likely model (other, less likely models were presented by Phillips, 1990) to explain the halite trend involves a mineralizing fluid saturated with respect to halite and subtraction (precipitation) of a KCl-bearing halite-rich solid from the high temperature-high salinity hydrothermal fluid prior to entrapment. When a line is drawn through the type 1 and 2 populations (Fig. 6), it intersects the NaCl-KCl solid binary at NaCl₈₀KCl₂₀ and not the NaCl apex. The initial fluid precipitated halite of composition NaCl₈₀KCl₂₀ and evolved from the NaCl₈₀KCl₂₀ binary along a linear trend toward the NaCl-KCl cotectic boundary. This interpretation is based on the NaCl-KCl-H₂O system; the presence of additional ions (Ca, Fe, Mn, SO₄) suggests a more complex situation.

The origin of type 2 and 3 inclusion fluids can be explained by continued cooling, with or without pressure drops, of the original saline parent fluid. For type 2 inclusion fluids, only halite and sylvite daughter minerals are present—the other daughter minerals (anhydrite, other chloride salts) are no longer saturated. For type 3 inclusion fluids, only halite daughter minerals are present; hence, the fluid can no longer be saturated with respect to sylvite.

Type 4 inclusions plot away from the cooling trend defined by types 1, 2 and 3 inclusions for both quartz and fluorite (Figs. 4 and 5). Type 4 inclusions represent the influx of a meteoric water (which may be slightly saline from percolating through evaporative-bearing Permian sediments) into the cooling pluton and mixing with some of the evolved type 2 or 3 fluids. The amount of meteoric water influx into the Capitan pluton is assumed to be small compared to that of a typical porphyry-copper deposit. The altered feldspars in the apex of the Capitan pluton also supports the presence of a meteoric water (McLemore and Phillips, 1991).

Based on the preceding discussion and the observed trends in Figs. 4 and 5, type 1 inclusions represent high-salinity, high-temperature brines exsolved from a crystallizing granitic melt, type 2 inclusions represent a cooling and evolved fluid from the original type 1 fluids, type 3 inclusions represent fluids derived from an even further evolved and cooled type 1 fluid, and type 4 inclusions represent a mixture between a meteoric fluid and an evolved type 2 or 3 fluid.

DISCUSSION OF STABLE ISOTOPE DATA

The calculated fluid $\delta^{18}\text{O}$ values of 7.08 to 8.09‰ in equilibrium

with vein quartz fall within the range of accepted values for magmatic fluids ($\delta^{18}\text{O}$ values of 5.5 to 9.5‰; Sheppard, 1977). The δD values on inclusion fluids in quartz, -22 to -86‰, also fall within or near the accepted values for magmatic fluids (δD values of -40 to -80‰; Sheppard, 1977).

The isotopic compositions of the fluids responsible for the Th-U-REE deposits are depicted in Fig. 7. The data for the MTE, Wee Three, Fuzzy Nut and CMX prospects plot within, slightly above and slightly below the magmatic water box. The isotopic data strongly imply that the vein quartz was deposited from fluids of magmatic origin. Similar $\delta^{18}\text{O}$ values on vein quartz (Table 2), and high temperatures and high salinities for the other Th-U-REE deposits examined in this study suggest that the fluids responsible for the mineralized zones were of magmatic origin.

SUMMARY AND CONCLUSIONS

This fluid inclusion and geochemical study on Th-U-REE deposits in the Capitan Mountains has shown that:

1. Four main types of fluids were evident, as determined by optical and microthermometric studies in quartz and fluorite. Type 1 inclusions are the most important of the four types and represent high-temperature and high-salinity fluids, with Th and Tm NaCl >600°C, and bulk salinities up to 85 wt% NaCl + KCl; type 2 inclusions represent high to moderate-high salinity fluids; type 3 inclusions represent moderate temperature-moderate salinity fluids; and type 4 inclusions represent lower-temperature and lower-salinity fluids.

2. Type 1 inclusions can best be explained as a high-salinity fluid that exsolved from a crystallizing granitic melt. Cooling of this highly saline fluid, followed by crystallization and subtraction of KCl-bearing halite from solution, will lead to the formation of the observed halite trend. Type 2 inclusions represent a cooling and evolved fluid from the original type 1 fluid. Type 2 inclusions also define the halite trend. Type 3 inclusions represent an even further evolved fluid from the original type 1 fluid. Type 4 inclusions represent the influx of a meteoric water into the cooling pluton and mixing with some of the evolved type 2 or 3 fluids.

3. Pressures and depths of pluton emplacement and vein formation are estimated to occur between 300 to 400 bars and 1.2 to 1.6 km, respectively.

4. Oxygen isotope analyses of vein quartz and hydrogen isotope analyses of fluid inclusion waters in quartz suggest that the fluids responsible for the associated Th-U-REE deposits were derived from magmatic fluids.

In conclusion, field relations, petrologic, fluid-inclusion microthermometry and stable-isotope data indicate that the Th-U-REE deposits in the Capitan Mountains were formed as a result of cracking of the outer carapace of the Capitan pluton during cooling, followed by the injection of exsolved high-temperature and high-salinity magmatic fluids from a crystallizing granitic melt into the brecciated and cracked zones. Type 1 inclusion fluids represent the main-stage, mineral-forming magmatic fluids. Type 2 and 3 inclusion fluids represent an evolved and cooling type 1 fluid. Type 4 inclusions represent a mixture of a meteoric water with an evolved type 2 or 3 fluid. These late-stage type 4 fluids appear to contribute little, if anything, to the Th-U-REE mineralization events.

ACKNOWLEDGMENTS

Financial aid for this study was provided by the New Mexico Institute of Mining and Technology Research Council, the New Mexico Geological Society and the Albuquerque Gem and Mineral Club. Special thanks are also given to the New Mexico Bureau of Mines and Mineral Resources, which helped support the project in the form of drafting figures, photography, providing transportation to the field, summer assistance and providing access to analytical instruments within the chemistry division. Also, thanks to Mike Allen who provided information pertaining to the petrology and geochemistry of the Capitan pluton. Quick reviews of the article by Richard L. Hervig and Paul Knauth are also greatly appreciated. This article represents a summary of a com-

pleted M.S. thesis in geochemistry by the senior author in 1990 at the New Mexico Institute of Mining and Technology.

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