Pecos diamonds–quartz and dolomite crystals from the Seven Rivers Formation outcrops of southeastern New Mexico

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Abstract

Pecos diamonds, also known as Pecos valley diamonds are colorful, doubly terminated quartz crystals that occur in scattered outcrops of the Permian Seven Rivers Formation (Permian) along the Pecos River valley in southeastern New Mexico. Although authigenic quartz is relatively common in evaporite sequences worldwide and throughout geologic history, Pecos valley diamonds are unique for their large size, variable color, and crystal morphologies. Single crystals of dolomite of variable morphologies also occur with the Pecos valley diamonds but are of much more limited distribution. Red pseudohexagonal aragonite crystals are also present near one locality, but they have not been found to coexist in the same unit.

Although the outcrop area encompasses an area 100 mi long by as much as 25 mi wide along the margins of the river valley, the distribution of Pecos valley diamonds is limited to specific depositional environments that resemble salinas and/or salt pans within a larger sabkha setting. Replacement features within the quartz indicate an authigenic origin with formation soon after dolomitization of the host rock. However, the large size and suite of inclusions may indicate a deep burial, late diagenetic origin for these crystals. The presence of organic matter, formation of dolomite, and the oxidation of sulfide appear to be important components to the ultimate formation of Pecos valley diamonds.

Introduction

Colorful and doubly terminated authigenic quartz crystals with variable crystallographic forms occur in and weathered from scattered outcrops of the Seven Rivers Formation in southeastern New Mexico (Fig. 1). In places, when the sun's rays are at low angles, the desert appears paved with diamonds. However, most sparkles are only broken or small and imperfect crystals. Only a small percentage of crystals are large enough to be of interest to the collector. Crystals in a matrix of gypsum are only rarely found, but at Locality 1, a 10-cm layer consists of a mass of quartz crystals.

A Spanish miner, Don Antonio de Espejo, first described these crystals in 1583 (Albright and Bauer, 1955). In 1929 Tarr described the occurrence near Acme in Chaves County (Locality 6) and followed that report with a description of pseudocubic quartz crystals from Artesia in Eddy County (Tarr and Lonsdale, 1929). The term "Pecos Diamonds" appears to have been first mentioned in print by Tarr and Lonsdale (1929), where they note that the crystals were described by that name by local collectors. Other names ascribed to the crystals include "Indian diamonds" and "Pecos valley diamonds," the latter term favored by collectors today. Practical uses for these objects are mainly decorative with present day uses confined to lapidary and jewelry. There is no evidence for their use, decorative or otherwise, by pre-European people.

Initial descriptions of euhedral authigenic quartz crystals noted the rarity of these minerals in evaporite sequences (Tarr, 1929). However, subsequent work has shown that euhedral quartz crystals are relatively common in ancient shallow marine carbonate and evaporite sequences (Folk, 1952; Grimm, 1962; Wilson, 1966; Zenger, 1976; Ulmer-Scholle et al., 1993). They are found throughout the Phanerozoic and exist in rocks as old as Proterozoic (Grimm, 1962). Other famous occurrences of authigenic quartz include Herkimer diamonds hosted by Cambrian dolomites in New York (Zenger, 1976). Large authigenic quartz crystals have been described in young Pleistocene carbonate-evaporite sediments in the Arabian Gulf (Chafetz and Zhang, 1998). One of the most comprehensive studies of worldwide occurrences of quartz crystals in evaporites was published by Grimm (1962). He noted over 150 localities that displayed similar geologic and depositional characteristics.

Personal collecting trips by the authors more precisely define the geological settings of the localities of Tarr (1929) and Tarr and Lonsdale (1929) in addition to documenting 10 other in situ occurrences along the Pecos River valley. These new localities highlight areas where authigenic quartz, dolomite, and/or aragonite crystals are relatively abundant, large, or morphologically unique. A discussion of color, crystal shape, and inclusion variations is provided for each occurrence. Ultimately, we will speculate on the origin of these minerals and their significance in sedimentological interpretations.

Distribution

Large, authigenic quartz and dolomite crystals appear to be confined exclusively to the Permian Seven Rivers Formation. Essentially all occurrences are confined to the back reef segment of the Guadalupe reef complex starting in the south at the "beginning of the gypsum facies" of Kelley (1971) near Dark Canyon and terminating near the De Baca and Guadalupe County line in the vicinity of Salado Creek to the north. In Pecos country, the back reef segment of the Seven Rivers Formation consists predominantly of gypsum with subordinate amounts of dolomitic limestone, red and gray gypsiferous shale, and fine-grained sandstone. East of the study area, anhydrite and salt become prevalent. Ward et al. (1986) documented two original depositional modes for the gypsum; these include subaqueous salina and subareal sabkha environments.

Meinzer et al. (1927) coined the term Seven Rivers gypsiferous member for the later discredited Chupadera Formation. Tarr (1929) referred to the authigenic quartz occurrence at Acme (Locality 6) as being in the Manzano series of red beds. In the same year, Tarr and Lonsdale (1929) continued to use the term Chupadera Group in describing the pseudocubic crystals near Artesia (Localities 1 and 2). These names were changed to Whitehorse, Chalk Bluff, and Bernal by various authors and petroleum geologists over the years. Subsequently, Tait et al. (1962) proposed the presently used stratigraphic names based on the nomenclature applied to the subsurface rocks of the Artesia Group.

Kelley (1971) mapped the surface outcrops of the study area. During his mapping, Kelley (1971, p. 18) reported, "in time it was noted that their [the Pecos diamonds] distribution is stratigraphically related. This is so commonly true that they might be used as a stratigraphic indicator. Most all occurrences are in part of a zone perhaps 100 to 200 feet thick from the upper part of the Seven Rivers into the lower part of the Yates." Of the 12 in situ occurrences of authigenic quartz crystals described in this paper, 10 are within a mapped area of Kelley (1971). Localities 12 and 13 also occur in the Seven Rivers Formation based on the mapping of Kelley

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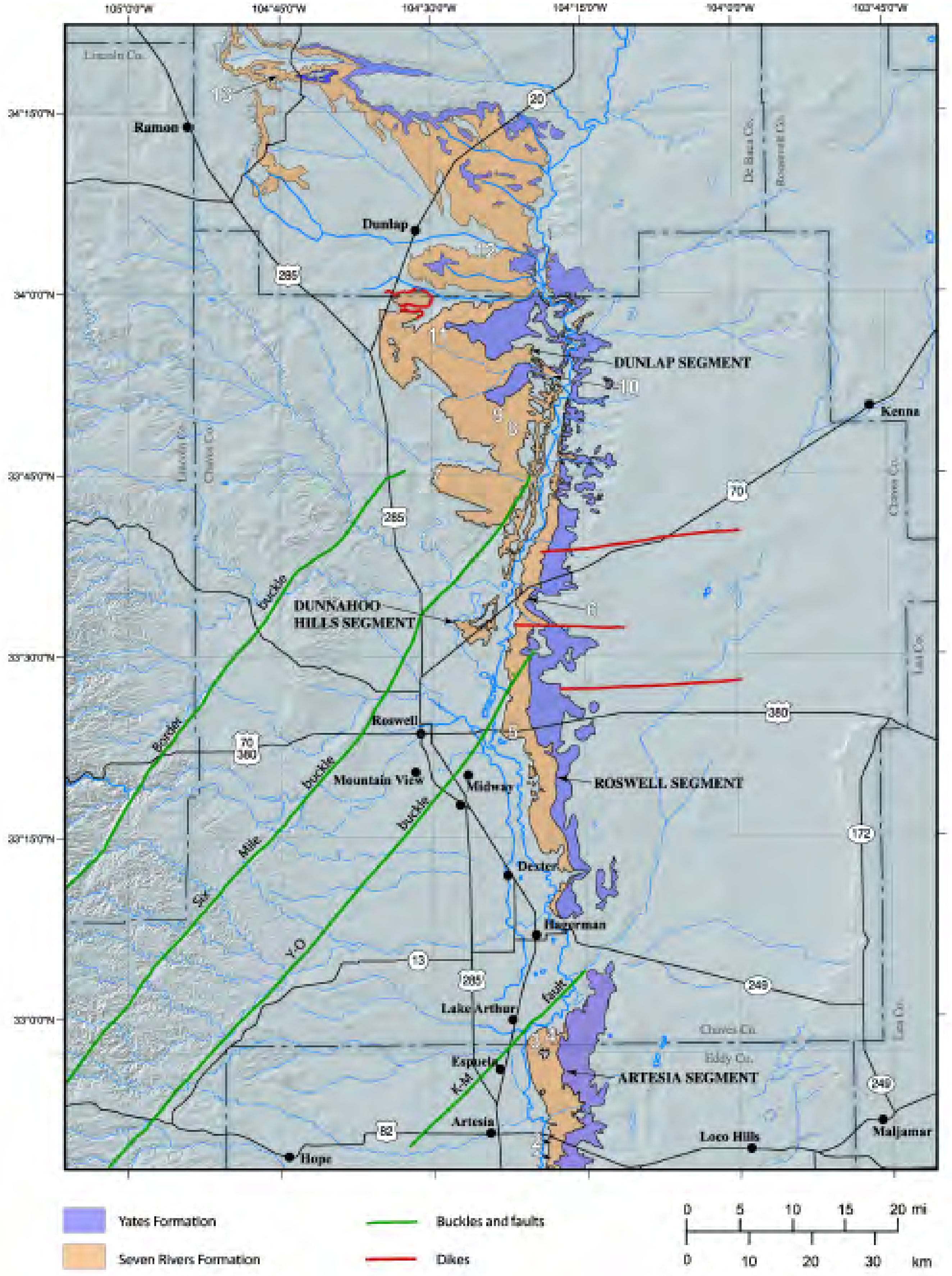


FIGURE 1—Location map illustrating the distribution of the Seven Rivers and Yates Formations in southeastern New Mexico. Numbers refer to Pecos diamond localities discussed in the text and presented in the appendix. Outcrop segments that contain Pecos valley diamonds are identified with arrows. Tectonic elements adapted from Kelley (1971).

(1972) on the Fort Sumner sheet. We have not been able to document any occurrences of Pecos valley diamonds in the Yates Formation during our study.

Outcrop segments

Both tectonic and geomorphic features along the Pecos valley control outcrop distribution of the Seven Rivers Formation (Fig. 1). Pecos diamonds occur sporadically within particular segments of an outcrop belt that is almost continuous. These outcrop segments, and gaps that separate them, are caused by specific tectonic and geomorphic controls that were imposed after Pecos valley diamond development. Descriptions of Pecos diamond localities within specific outcrop segments are presented in the appendix.

Seven Rivers segment

The Seven Rivers segment starts at the dolomite-gypsum transition near Dark Canyon north to the McMillan escarpment. The southernmost documented occurrence of Pecos diamonds was mentioned by Dake et al. (1938). They report, "at Seven Rivers, small doubly terminated crystals are found, averaging half an inch in length, which have a uniform red-brown color, and are quite perfect. The larger crystals from the same locality averaging 1½ inches in length are of a dirty brown color with faces as bright and perfect as the smaller ones...these crystals sometimes assume a cubical aspect." The original Seven Rivers townsite is now 1½ mi south-southwest of the present village along the transition zone from dolomite to gypsum facies. We have not been able to confirm the presence of Pecos diamonds at Dake's locality nor have subsequent studies in the area (e.g., Sarg, 1981). The segment is terminated by a 7½-mi gap in the outcrop near Lake McMillan caused by the presence of the Fourmile Draw syncline (Kelley, 1971). The downwarping of the syncline and subsequent Quaternary alluvial fill from a multitude of streams that drain the Seven Rivers embayment cover the outcrop.

Artesia segment

North of the Fourmile Draw syncline, the Seven Rivers Formation reappears on the east side of the Pecos River as the Artesia outcrop segment (Fig. 1). This outcrop segment, exposed by the Artesia–Lovington arch, is 17 mi long by approximately 3 mi wide. The northern margin of this segment is truncated in the vicinity of the K-M fault and covered by an embayment of alluvium deposited by drainages on both sides of the Pecos River. Tarr and Lonsdale (1929) published their early work on the southernmost occurrence of Pecos diamonds that we can document. Most Pecos valley diamond occurrences are limited to the upper benches of small bluffs on the east side of the Pecos River. Excellent exposures of matrix pieces can be found on the margins of drainages that dissect the bluffs.

Roswell segment

North of the K-M fault at the mouth of the Rio Felix, the Seven Rivers Formation reappears in the Roswell outcrop segment east of the Pecos River (Fig. 1). The Roswell segment is continuous over a north-south distance of 47 mi with an outcrop width varying from ⅙ to 3½ mi. The segment disappears in the north in the vicinity of the terminus of the Six Mile Buckle of Kelley (1971). Pecos diamond occurrences tend to be confined to the top of the bluffs in this segment except along the Pecos River cut bank at Locality 4.

Dunnahoo Hills segment

West of the Pecos, between Roswell and Acme, a triangular-shaped outcrop is present in the Dunnahoo Hills (Fig. 1). No authigenic quartz or dolomite has been found in this segment. The Dunnahoo Hills segment is surrounded by Quaternary terrace and alluvium deposits and not defined by tectonic elements, in contrast with the southern segments. The lack of Pecos valley diamonds in this segment may be due to the fact that this segment only exposes the lower portions of the Seven Rivers Formation.

Dunlap segment

North of Dunnahoo Hills and west of the Pecos River, the Dunlap segment of the Seven Rivers Formation forms an irregular fan-shaped outcrop covering over 165 mi^2 (Fig. 1). No tectonic elements, as defined by Kelley (1971), are apparent in this broad segment. Kelley (1971, 1972) noted an abundance of Pecos diamonds in the upper portions of the Seven Rivers Formation within this area especially south of Arroyo Yeso (Localities 8–12). The majority of Pecos diamond occurrences are found within this outcrop segment, particularly over broad areas in the southern part. The northernmost occurrence of Pecos diamonds is west of El Morro Mesa in De Baca County (Locality 13). The Seven Rivers Formation thins to the north (Kelley, 1972), and Pecos valley diamond occurrences decrease in that direction.

Salado Draw segment

The northernmost occurrence of the Seven Rivers Formation is confined to the drainage valley of Salado Creek at the De Baca and Guadalupe County line. Kelley (1972) notes that the Seven Rivers, along with the Yates Formation, pinches out beneath the Santa Rosa Sandstone under the pediment cap of Guadalupe Mesa. No authigenic quartz or dolomite occurrences are known from this segment.

Features of the authigenic quartz crystals

The authigenic quartz crystals from each Pecos valley locality are distinctive enough as to habit, size, color, and inclusions that they can be grouped into suites. Some suites are traceable for several kilometers, whereas others are restricted to a few square meters. Some localities contain specific forms and colors, whereas others may contain a diverse range.

Size

Crystals in the New Mexico Bureau of Geology and Mineral Resources Mineral Museum range from microscopic to a maximum of 6.5 cm (~2.5 inches) along the c axis. Median length for perfect crystal forms is approximately 2.5 cm (~1 inch); those larger tend to be distorted. The largest single crystals found thus far come from Locality 13, and the largest clusters are from Locality 3.

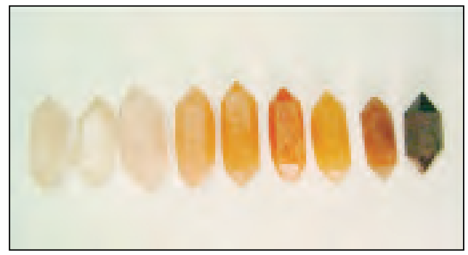


FIGURE 2—An example of color variation of Pecos Valley diamonds from Locality 9.

Color

Pecos diamonds take on a wide range of colors (Fig. 2). Perfectly transparent crystals are usually less than 4 mm (~⅛ inch) long. Larger crystals take on the color of the gypsum matrix, usually with a slight increase in intensity. Occasionally a bleaching of the host gypsum adjacent to the quartz crystals is observed. Color bands in the host rocks, present as laminations or along fracture joints, commonly cross the included quartz crystals without interruption. Opaque crystals are milky white, light to dark gray, red, pink, yellow, orange, light to dark hematite red to brown, and light to nearly black magenta. Translucent crystals tend to be white, white with pink or orange streaks, or light to medium honey brown. Nearly transparent crystals from Locality 7 contain cloudy gypsum inclusions along with greenish-black material possibly sapropel or hydrocarbon. Some crystals show color zonation. Very large prismatic crystals from Locality 12 are variegated creamy gray green with pink points.

Strikingly similar authigenic quartz crystals are common in the Triassic Keuper gypsiferous facies of Spain, where they are known as "Jacintos de Compostela"– literally, Hyacinths from Compostela, an allu-

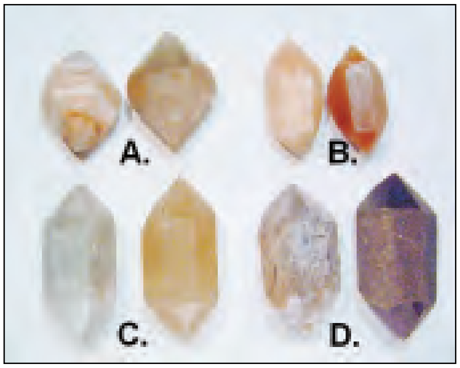


FIGURE 3—Color changes in Pecos valley diamonds after heating at 450°C. All samples illustrated as pairs with the heated sample on the left. Sample pairs **A** and **B** from Locality 2, **C** from Locality 12, and **D** from Locality 11. The upper left sample is 1 cm long.

sion to red-orange precious stones from that locality popular during the Middle Ages (Febrel, 1963; Rios, 1963). A comparison of Pecos diamonds from diverse localities cannot be distinguished from the Spanish Jacintos insofar as size, color, form, and inclusions.

Chaves (1896) observed that the Spanish Jacintos turned gray on heating and suggested that the pigments were in part organic. This heating experiment was repeated on representative Pecos valley diamonds by Abraham Rosenzweig (at the University of New Mexico) by raising the temperature in an electric oven to 450° C and maintaining the temperature for 12 hrs. All samples exhibited loss of color, with the least change in the hematite red varieties (Fig. 3). Loss of luster occurred primarily from fracturing of the crystal faces following decrepitation of fluid, hydrocarbon, or hydrous mineral inclusions.

FIGURE 4—Dark inclusions of organic material observed in some specimens. Note the quartz crystal clusters illustrating the tendency for subsidiary growth on the prism faces of the quartz crystal. Illustrated examples from Locality 3. The lower left crystal is 2 cm long.

Inclusions

In addition to color, many Pecos valley diamonds contain discrete inclusions of other minerals. Most common are included grains of gypsum in the outer portions of some crystals. Nissenbaum (1967) noted abundant anhydrite inclusions in Pecos valley diamonds and authigenic quartz crystals contained in evaporite clasts from Israel. The anhydrite inclusions are oriented along growth planes and are preferentially found in the cores of the crystals but absent on the rims. Anhydrite is notably absent in the surrounding evaporite in both the Pecos valley and Israel occurrences. Kelley (1971) noted gypsum pseudomorphs after anhydrite in places within the Seven Rivers Formation, however. Large (up to 3 mm, typically 1 mm) rounded, green-black inclusions are rarely noted in some crystals and may be of organic origin, although they do not fluoresce under UV light. These dark inclusions are always restricted to the outermost portions, and some intersect the surface of the crystals (Fig. 4).

FIGURE 5—Prismatic forms of Pecos diamonds showing rough prism faces (**m**) and smooth rhombohedron faces (**r** and **z**), even on secondary growths. Note the left and center crystals also show rough (**z**) faces. In contrast, both (**r**) and (**z**) rhombohedron faces on the crystal on the right are smooth. Quartz crystals illustrated are from Locality 11. The left crystal is 1.7 cm long.

Crystal surface features

Megascopic surface features include variations in reflectivity, growth lines, negative crystal pits, crystal mold impressions, and linear depressions. Tarr (1929) noted that the prismatic faces, when present, are typically rough, whereas the rhombohedron faces tend to be smooth (Fig. 5). Even among the rhombohedron faces, Tarr and Lonsdale (1929) noted in pseudocubic varieties that the negative rhomb (**z**) tends to be dull compared to the positive rhomb (**r**). When present, growth lines on the prism faces (**m**) tend to be subdued and broad compared with most common quartz. Negative crystal pits are common on prism faces and locally attain large sizes (7 mm [~¼ inch] on a 5-cm [~2-inch] crystal). These pits may be casts of dissolved dolomite or other evaporite minerals and represent mold impressions. Linear depressions are typically zones of crystal-growth overlap.

Crystal forms

One of the distinguishing features of Pecos valley diamonds when compared with other occurrences of authigenic quartz is the great variation in crystal forms (Fig. 6). The vast majority of quartz crystals are typically hexagonal prisms (Figs. 5, 6B) terminated on both ends by positive (**r**) and negative (**z**) rhombs (Grimm, 1962; Nissenbaum, 1967; Chafetz and Zhang, 1998). Tarr (1929) reported a sequential development of crystals from Acme (Locality 1). Based on size and morphology, he stated that initially the quartz precipitated as a pseudocube (**r**), afterwards the quartzoid (**r + z**) and, finally, the doubly terminated prism (**r + z + m**) (Figs. 6 B–D). Unequivocal development of any other crystal forms of quartz, although observed elsewhere in the Seven Rivers Formation in our study, was not observed from specimens in the Tarr (1929) study area around Acme. A basis for size and sequential development is rendered false at other localities, however. Some of the largest crystals found are pseudocube specimens (as long as 6 cm [~2.5 inches] along the c axis) at Locality 13 in association with large authigenic dolomite crystals.

Prismatic forms. The most common megascopic crystal habit in Pecos valley diamonds is the regular prism (**m**) pointed at both ends by hexagonal pyramids formed by equal, or near equal, development of both the (**r**) and (**z**) rhombs (Fig. 5). Grimm (1962) measured 1,000 authigenic quartz crystals that were associated with evaporite deposits from around the world (including the Pecos valley) and found that the axial ratios range from 1.5 to 3.0 in the majority of cases, the shortest being 1.1 and the most acicular being 5.5. Commonly the (**r**) rhomb is relatively large, even though the prism (**m**) faces are equal or nearly so. Most of the (**r**) faces have a bright luster, whereas the (**z**) faces tend to be dull. A significant portion of the prismatic crystals have prism faces that are alternately wide and narrow; thus, in cross section, the prism zone appears as if trigonal prisms are present (Figs. 7 and 6E–plan

FIGURE 7—Quartz crystals displaying partial development of a pseudotrigonal bipyramid habit from Locality 1. The crystal on the left is 2 cm long.

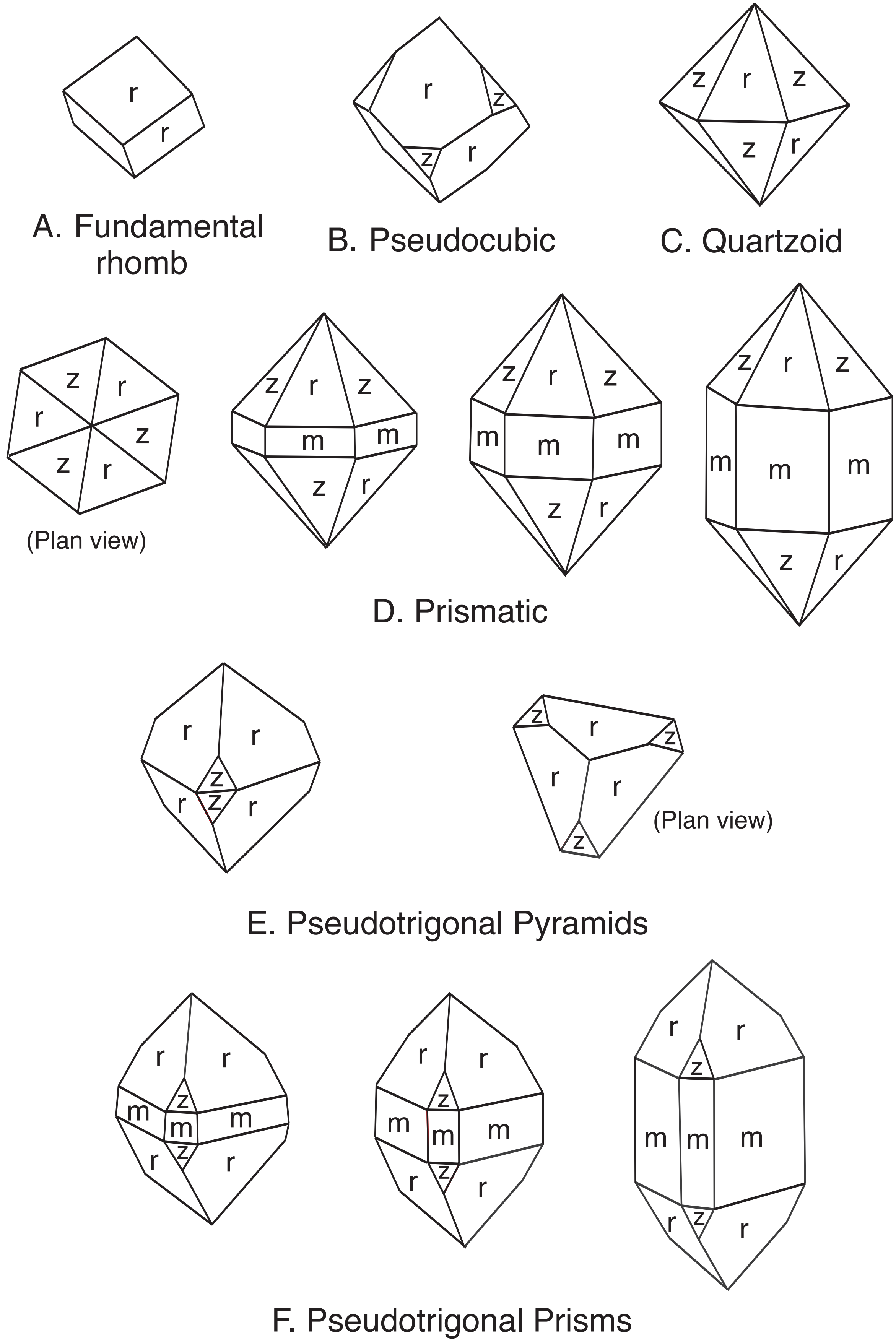


FIGURE 6—Crystal diagrams of the various forms of Pecos valley diamonds noted in the study area. Diagram modified from quartz crystal incremental growth concepts of Grimm (1962).

FIGURE 8—Equant pseudocubic quartz crystals from Locality 13, placed at various orientations. The large crystal on the top is 2.5 cm across.

view). The slanted (**r**) and (**z**) faces are also equally wide and narrow, forming matching trigonal pyramids at each end. Tabular crystals flattened parallel with a pair of coplanar prism faces (**m)** are rare. Only one such tabular Japan-Law twin has been found at Locality 12; however, normal prismatic Japan-Law twins are fairly common at Locality 11.

Equant forms. Equant pseudocubic habit results when the faces of (**r**) are developed to the exclusion, or near exclusion, of both (**z**) and (**m**). Because the interface angle is 85°46′, these crystals appear cubic to the unaided eye. Vestigial developments of (**z**) and/or (**m**) are nearly always present. Locality 1, first described by Tarr and Lonsdale (1929), yields pseudocubic crystals as great as 1 cm (~⅜ inch) in size. Pseudocubes as long as 2.5 cm (~1 inch) on an edge also occur at Locality 13 (Fig. 8).

Equal or near equal development of (**r**) and (**z**) to the exclusion or near exclusion of (**m**), simulates a quartzoid habit, which is more characteristic of high-temperature quartz known as beta quartz (Frondel, 1962). This form is best thought of as matching (**r**) and (**z**) faces at the ends of a very narrow prism zone. Localities 2 and 6, and especially at the latter, contain abundant examples of this form (Fig. 9). The obvious low-temperature environment required by the mineral assemblage in the Pecos valley suggests a high-temperature origin for beta quartz forms is not required.

FIGURE 9—Pecos diamonds exhibiting the quartzoid and pseudo-octahedral habits from various localities. Top crystal group represents a common twinning habit in beta quartz. Crystal bottom center is a pseudo-octahedral type. Note initiation of prism face growth on left and right quartzoid crystals. The crystal on the lower left is 2 cm long.

FIGURE 10—Trigonal prism form of Pecos diamonds from Locality 1. Note the color zonation in the upper portion of the crystal. Maximum dimension is 2.2 cm.

Pseudotrigonal bipyramids (Figs. 10, 6E) at Localities 1 and 13 are the result of the rare over development of (**r**) and diminution of (**z**), to the exclusion or near exclusion of the prism faces (**m**). These are also the localities with abundant pseudocubic types and may represent modification of previously formed pseudocubes (Albright and Krachow, 1958) in a manner similar to that described by Tarr (1929).

FIGURE 11—"Bent or twisted" appearing quartz crystals from Locality 1. These crystals tend to be more mottled than typical Pecos valley diamonds. Largest crystal is 4 cm.

Distorted crystals. The prism (**m**) faces are not always completely developed and may be rough and pitted, even when the rhombohedra (**r**) and (**z**) are bright and smooth. This is especially true when the axial ratio is greater than three. At Locality 1, tapered prismatic crystals of this type, as long as 3.5 cm (1⅜ inches) with axial ratios averaging 3.5, also give the illusion of being bent or twisted along the c axis (Fig. 11).

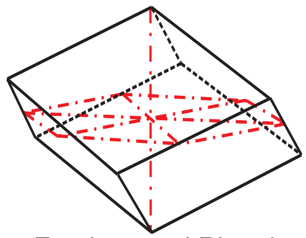
Clusters of quartz crystals are sometimes observed, especially at Localities 2 and 3. Interestingly, these clusters are composed of one large core crystal with smaller crystals growing from the (**m**) faces almost exclusively (Fig. 4). These smaller crystals tend to grow perpendicular to the prism (**m**) face. These subsidiary crystals radiate from the (**m**) faces parallel to the bedding planes within the host gypsum, a feature also noted in authigenic aragonite crystals found in the Grayburg–Queen Formation stratigraphically lower in the section at Locality 13. It is important to note, however, authigenic quartz is only found with dolomite and never observed with aragonite.

FIGURE 12—Examples of loose authigenic dolomite from the study area. Maximum length of the largest crystal is 2 cm.

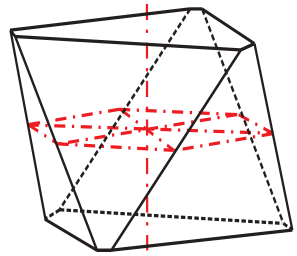
Features of the authigenic dolomite crystals

Euhedral, authigenic dolomite crystals also occur in the Seven Rivers Formation (Fig. 12). Sparse, light to medium honey-yellow crystals have been found at Locality 3. At Locality 4, medium to dark honey-brown crystals as great as 2 cm (~ ¾ inch) in size occur in and weathered from massive white gypsum slump blocks. These crystals do not withstand weathering and are difficult to free from matrix. Nevertheless, both fine matrix specimens and loose crystals from this locality are found in museums around the world. Small (5 mm), scarce, transparent to translucent, euhedral dolomite crystals occur in white gypsum with abundant medium to dark honey-brown prismatic quartz crystals that average 2.5 cm (~1 inch) in length at Locality 12.

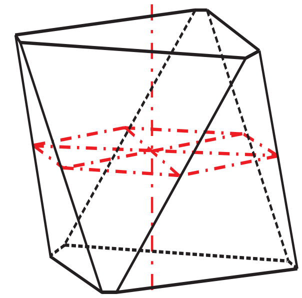
FIGURE 13—Crystal drawings of the variations in authigenic dolomite crystal morphology from the study area.



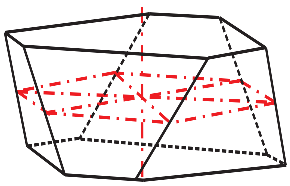
Fundamental Rhomb



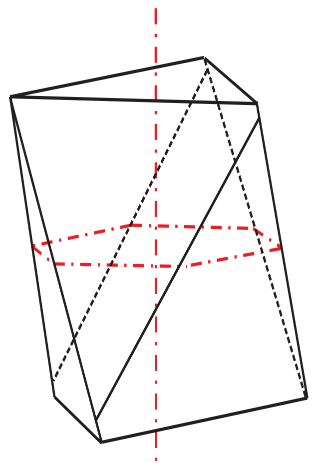
Type 2 c:a = 4/5
Medium Tabular



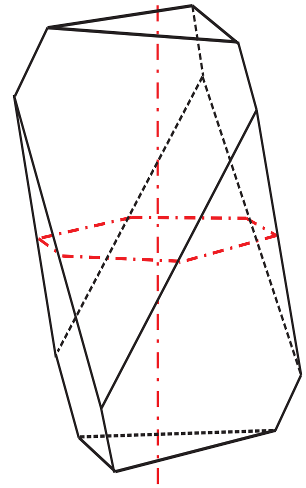
Type 3 c:a =1
Thick Tabular



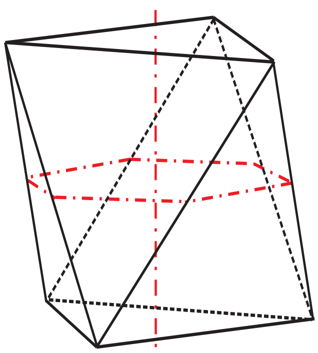
Type 1 c:a = 1/2
Thin Tabular



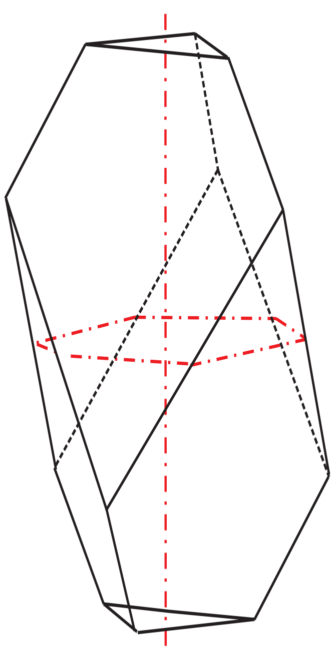
Type 5 c:a = 3/2
Octahedron-like



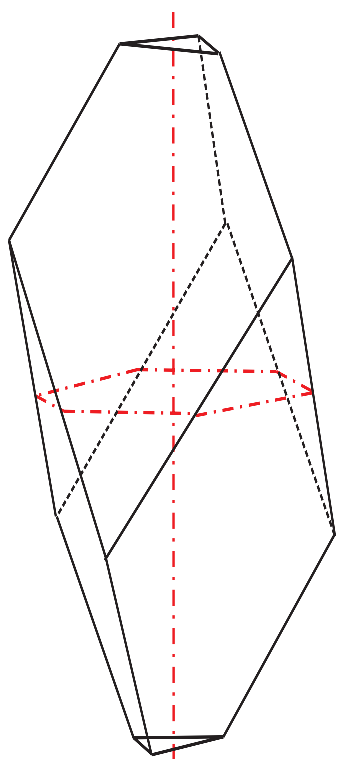
Type 6 c:a = 2
Truncated Rhomb



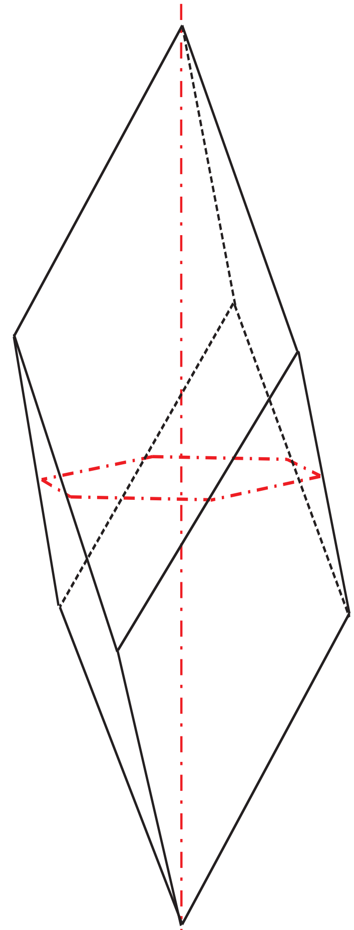
Type 4 c:a = 5/4
“Las Teruelitas”
Pseudo-octahedron



Type 7 c:a = 5/2
Truncated Rhomb



Type 8 c:a = 3
Truncated Rhomb



Type 9 c:a = 4
Postive Rhomb

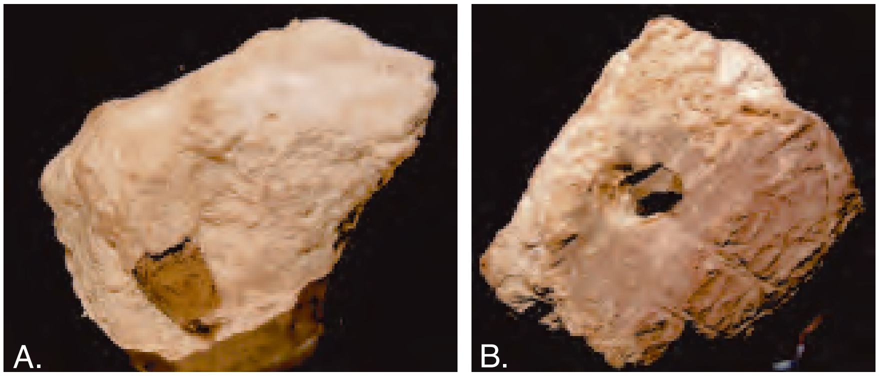


FIGURE 14—Authigenic dolomite (**A.**) and Pecos valley diamond (**B.**) in matrix from Locality 1 an 11 respectively. The dolomite crystal in **A**. is a Type 4 (Fig. 13), pseudo-octahedral shape. Note the rhombohedral shaped vug in sample **B** with quartz occupying only part of the space. A small rim of gypsum marks the extent of the original crystal that dissolved and left the vug later partially filled by quartz crystal with a pseudo-trigonal prism form. Both specimens are 7 cm in the longest dimension.

The geometry of the dolomite crystals is formed by combinations of the positive rhombohedron {4041} truncated by positive and negative basal pinacoids spaced at specific axial ratios (Fig. 13). Crystal Types 1 through 7 are found at Locality 3, including one specimen with hemimorphic truncations by Types 7 and 8 pinacoids. These crystals average less than 1 cm (⅜ inch) in length. Types 4 and 5 dolomite forms occur at Locality 4. Locality 12 contains Types 1 through 5, and they average 2.5 cm (~1 inch). No Type 9 dolomite forms have been recognized in the study area. Where gypsum matrix pieces are available, careful examination of vugs occupied by Pecos valley diamonds in a couple of locations (2 and 9) suggests that the space may have been originally a dolomite rhomb (Fig. 14).

Known as "las Teruelitas" in Spain, black pseudo-octahedral Type 4 dolomite crystals were first described by D. Amalio Maestra in 1845 from a similar geologic setting. At the type locality (Barranco de Solabral, northeast of Teruel in the province of the same name) the Teruelitas occur with black Jacintos de Compostela in a gray to black Keuper gypsum (Muñoz and Piñero, 1951). Chemical analyses of the Teruelitas show them to be calcian-dolomite. The black color results from a small iron and manganese content. Rogers (1949) first reported on the similarities of Pecos valley dolomite to Spanish Teruelitas.

Discussion

During his study of over 150 authigenic occurrences of quartz in evaporites, Grimm (1962) noted features that were common to all localities: 1) presence of saline facies; 2) evidence of euxinic environments; and 3) evidence of petroleum migration and entrapment. We will provide more information on these features in addition to specifying some of the details of the depositional environment, timing of the quartz formation, and speculate on the processes that may have led to the formation of the Pecos valley diamonds.

A fundamental question that remains unanswered is the timing of Pecos valley diamond precipitation. The presence of authigenic quartz in deeply buried evaporites and carbonates is well known (e.g., Ulmer-Scholle et al., 1993). However, the recent discovery of modern megaquartz in dolomite in the Arabian Gulf (Chafetz and Zhang, 1998) reveals the possibility of early diagenetic formation near the surface. The features exhibited by the Pecos valley diamonds and their host rocks have much in common with those described by other workers as characteristic of both near-surface and deep environments. These competing modes of formation will be discussed with regard to the possible origin of these fascinating quartz and dolomite crystals.

Depositional environment

Previous sedimentological studies of the Permian Seven Rivers Formation inferred the depositional environment to be similar to modern sabkha environments present in the Arabian Gulf today (Kendall, 1969; Till, 1978; Ward et al., 1986; Warren, 1989). The distribution of authigenic dolomite and quartz crystals appears to be related to a specific depositional environment within the Seven Rivers Formation. The crystals are not distributed uniformly throughout the evaporitic sequence stratigraphically or across the study area. The crystals tend to be concentrated near the top of the formation (Kelley, 1971) and are only sporadically distributed within the entire outcrop area. In general, their distribution pattern is typically circular to elongate.

The distribution patterns of Pecos valley diamonds, and their tendency to be most abundant stratigraphically adjacent to thin shale units, suggests they were confined to subenvironments of the sabkha, most likely shallow salinas or salt pans. The spotty distribution of Pecos valley diamonds is probably a function of the scattered nature of salinas or salt pans that served as catchments for meteoric water and perhaps fine-grained wind-blown sand and silt. The silty units could serve as a potential source for silica although other workers have cited a biogenic source of silica, mainly from sponge spicules (Ulmer-Scholle et al., 1993; Chafetz and Zhang, 1998).

Alternatively, the distribution of the Pecos valley diamonds may represent zones of diagenetic alteration or fluid migration in the deep subsurface. Fluid or hydrocarbon migration may have been confined to the upper portions of the Seven Rivers Formation, hence the absence of Pecos valley diamonds in the lower portions. The presence of anhydrite inclusions may be indicative of deeper burial, and the silica could be derived from diagenetic alteration of clays. The gypsum-rich outer zones observed in some Pecos valley diamonds may be linked to subsequent uplift diagenesis and the conversion of anhydrite to gypsum during final quartz growth.

The presence of dolomite and absence of aragonite are important indicators for the presence of Pecos valley diamonds. In evaporite units that underlie the Seven Rivers Formation (e.g., the Grayburg–Queen Formation) large and euhedral aragonites are fairly common and quartz is absent. Chafetz and Zhang (1998) also note an absence of quartz in aragonite and low-magnesium calcite units that overlie the quartz-bearing dolomites in the Gulf of Arabia. They suggest the aragonite low-Mg units were deposited in a marine environment, more similar to the Grayburg–Queen Formation. This relationship suggests that the Seven Rivers Formation may have undergone dolomitization and that the Pecos valley diamonds formed during or shortly after this process. The formation of the quartz in this environment would not require deep burial and is probably characteristic in portions of the sabkha environment. Nissenbaum (1967) also rejected a deep burial replacement origin for Pecos valley diamonds based on the presence of growth lines and zonal anhydrite found in the quartz crystals. He believed the quartz was formed during primary anhydrite precipitation on supratidal salt flats, consistent with the sabkha depositional model.

However, the very large size of the authigenic dolomite and quartz crystals are not common in low-temperature, sedimentary environments. Large crystal sizes in these minerals are more characteristic of the hydrothermal environment and may indicate deep burial and formation during diagenesis at higher temperatures.

The role of organic matter

Significant changes in oxidation and pH are required for the formation of dolomite and later formation of quartz. Stable isotope work has identified organic carbon as involved in the anaerobic bacterial reduction of sulfur to sulfide before chert formation in some chalk units (Clayton, 1986). Similar studies on authigenic quartz in karst settings (Palmer, 1995) noted an important contribution by organic carbon compounds in the formation of quartz. Bennett et al. (1988) also identified the ability of organic compounds to dissolve and later reprecipitate quartz.

Abundant organic matter is observed in partially aragonitized mats presently forming in the Macleod evaporite basin of Australia (Logan, 1987), another potential modern analog to the Seven Rivers Formation. This material forms a sapropel, a jelly-like ooze composed of algal remains macerating and putrefying in an anaerobic environment in shallow water. Other workers have noted periods of hydrocarbon migration and associated evaporite silicification in the Seven Rivers Formation south of the study area (Ulmer-Scholle et al., 1993). Regardless of the type of organic matter, it appears it had an important role in the reduction of sulfate to sulfide in parts of the study area and may have mobilized silica for later precipitation as Pecos valley diamonds.

Dolomite and quartz formation

Authigenic dolomites within the Seven Rivers Formation are unusually large and have a wide variety of morphologies not typical of sedimentary environments. These crystals are typically dark when compared to the matrix. This is in contrast to the similar colors exhibited between host rock matrix and quartz crystals. This dark coloration may be due to small amounts of manganese or iron like Spanish "Teruelitas," although the matrix in the Pecos valley is not dark like that in Spain (Muñoz and Piñero, 1951). Alternatively, they may be dark colored because of hydrocarbon or sulfide mineral inclusions indicative of reducing conditions during their formation. In contrast, authigenic quartz is typically associated with oxidized colors and mineral phases. We have not observed dolomite and quartz in the same sample or stratigraphic layer, although they can be found together at a particular locality. The mutually exclusive occurrence within a particular stratigraphic horizon may indicate an aspect of each mineral's formation that precludes the presence of the other. Accordingly, we speculate that the dolomite and quartz formed at different times based on the presence of rhomb-shaped vugs occupied by quartz.

Many of the features within the quartz crystals suggest that they formed by both open space precipitation and in situ replacement of gypsum and dolomite. Some of the Pecos valley diamonds are found in vugs with rhombohedral outlines similar in form to the authigenic dolomites (Fig. 14). Larger quartz crystals undoubtedly exceeded the space of the precursor minerals and further engulfed the evaporite minerals. Some quartz crystals appear to have grown entirely within the gypsum, especially those with abundant inclusions. If the quartz replaced earlier dolomite forms, some of the unusual quartz forms (e.g., pseudocubes, etc.) may actually be quartz pseudomorphs after dolomite. The presence of quartz in vugs with rhombohedral outlines, similar to dolomite, suggests the precipitation of quartz at least accompanied the dissolution of dolomite.

Tarr (1929) suggested hematite as the main coloring agent in the crystals and speculated that the coloration was induced from the outside of the evaporite unit after quartz formation. Later the same year, Tarr and Lonsdale (1929) noted that coloration of the rock preceded the formation of the quartz crystals as the color banding in the host rock was continuous through intervening quartz. They speculated that the source of the color was from adjacent red beds. Nissenbaum (1967) analyzed both authigenic quartz crystals from Israel and Pecos valley diamonds to find some crystals contained as much as 0.3% Fe_2O_3. We speculate an influx of meteoric water oxidized sulfides, creating locally acidic waters that dissolved the dolomite and led to the precipitation of quartz. Stable isotope work by Chafetz and Zhang (1998) documented periodic episodes of meteoric water flushing during in the modern megaquartz occurrence in the Arabian Gulf. A similar episode or episodes of oxidation would explain the near ubiquitous red coloration seen in many Pecos valley diamonds. Alternatively, migration of diagenetic fluids could also lead to changing fluid chemistry that would favor quartz stability over dolomite.

Suggestions for further work

The varied morphology of the quartz crystals, especially variations in crystal face luster and orientation of subsidiary quartz growth on (**m**) faces suggests that unique controls on crystal growth were present during quartz precipitation. Surface studies on these crystals may reveal features that lead to a better understanding of both internal and external controls on crystal morphology.

A fluid inclusion study on the dolomites and quartz would greatly help to constrain the origin of the quartz crystals. Homogenization temperatures and salinities could differentiate between crystals formed near surface and at low temperatures (e.g., Chafetz and Zhang, 1998) and those formed during deeper burial and at higher temperatures (e.g., Ulmer-Scholle et al., 1993). Perhaps the Pecos valley diamonds have components that suggest they formed initially near the surface and grew larger with diagenesis. Stable isotope studies of organic materials contained in inclusions within the Pecos valley diamonds and host rocks would be useful in testing the speculations presented in the discussion above. Variations in both carbon and oxygen isotopes should fall within values observed by other workers (e.g., Clayton, 1986; Palmer, 1995) and help identify the type and role of organic matter in this process.

Detailed mapping of quartz, dolomite, and aragonite occurrences may prove useful for delineating different depositional environments within the Seven Rivers Formation or pathways for diagenetic fluids, depending on the results of fluid inclusion analysis. The limited distribution of the Pecos valley diamonds suggests that they are unique to particular depositional/diagenetic environments within fairly monotonous evaporite units. Detailed petrography of the evaporites and associated silty units may also show evidence of quartz solubility within the host rocks (e.g., Bennett and Siegel, 1987).

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James Lofton Albright

James Lofton Albright was born in Kingwood, West Virginia, on December 26, 1922, to Charles and Hazel Albright. He developed an interest in minerals at an early age after seeing the amethyst crystals in a new railroad cut near his home. After graduating from high school at age 16, Albright spent a short amount of time at the University of West Virginia before the hard economic times of the depression caused him to leave school and seek employment in the naval shipyards in Orange, Texas. There he met his future wife, Carrie Willey, and they were married in June 1942. After spending 3 years in the South Pacific during World War II, Albright returned to Texas and enrolled at the Texas School of Mines, now the University of Texas at El Paso. There he earned a B.S. degree in mining engineering in 1949. In El Paso, Albright was able to practice his hobby of mineral collecting in earnest, soon amassing an impressive collection with emphasis on specimens from New Mexico, Texas, Arizona, and northern Mexico.

After graduation, Albright began a long and varied career in the oil and gas industry as a geologist and geophysicist. He worked for Pan American Petroleum in Roswell, New Mexico, from 1950 until 1959, and then for Pubco Petroleum in Albuquerque until 1966. After a short stint with a NASA project at the University of New Mexico, Albright and his family moved to Texas where he worked for Petty Geophysical in Houston and San Antonio. In 1971, Albright began work as an independent consultant in Houston. He retired to Canyon Lake, Texas, in 1993 where he passed away in September 2000.

Albright had a life-long passion for minerals and mineral collecting. Most of his collection he gathered himself, including a large collection of Pecos diamonds. He proudly displayed his most interesting and favorite samples in special glass cabinets at his home. Albright's minerals are now part of the collection at the mineral museum of the New Mexico Bureau of Geology and Mineral Resources at New Mexico Institute of Mining and Technology in Socorro. The donation represents one of the most significant in recent museum history consisting of many singularly unique and historic pieces. A review of Stuart Northrop's book, *The Minerals of New Mexico*, reveals many entries with described occurrences attributed to James L. Albright—many of them one of a kind. In his tradition of sharing mineralogical knowledge, this paper is his last work, most of it written shortly after retirement.

Appendix

Localities of authigenic quartz and dolomite crystals.

Artesia outcrop segment
Sample localities 1–4

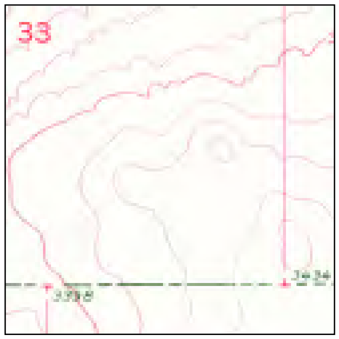
Locality no. 1
Artesia, NM
secs. 19, 30, 31
T17S R27E
Spring Lake 7½-min quad.
32°48′59″N
104°18′35″W

Tarr and Lonsdale's (1929) paper, as well as the fine crystals that can be found here, especially the pseudocubes, have made this locality the destination of collectors over the years. With a little work this locality can still yield good examples of authigenic quartz forms, both loose and in matrix.

Locality no. 2
Artesia, NM
sec. 18 T17S R27E
Spring Lake 7½-min quad.
32°49′39″N
104°18′35″W

Locality 2 is separated from Locality 1 based on a distinctive assemblage of attractive, small, medium to dark blood-red crystals that can be screened from loose silty sand in large numbers. These are mainly equant forms averaging 5 mm with rare pseudocubes. No bedrock is exposed.

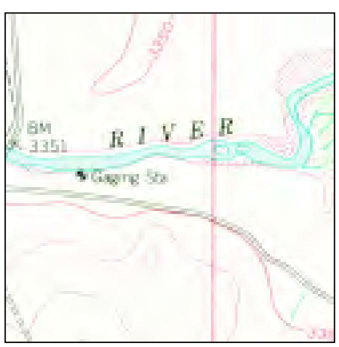
Locality no. 3
Lake Arthur, NM
secs. 33, 34 T15S R26E
Artesia NE 7½-min quad.
32°56′57″N
104°20′06″W



Deeply weathered Seven Rivers gypsite high on a topographic rise in the SE¼ sec. 35 T16S R26E along the Eddy–Chaves County line contains sparse light to medium honey-yellow euhedral dolomite crystals as large as 2 cm. These are combinations of the rhombohedron M{4041} truncated by a pair of basal pinacoids Types 1 through 7.

Sparse, poorly developed, brownish prismatic authigenic quartz crystals, as large as 2 cm along the c axis, also occur in and weathered from the gypsite.

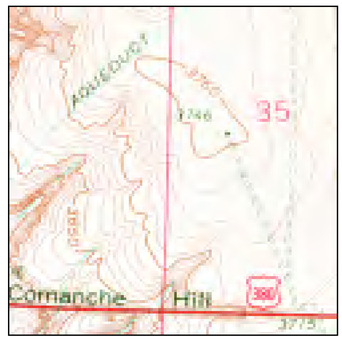
Locality no. 4
Lake Arthur, NM
secs. 26, 35 T15S R26E
Artesia NE 7½-min quad.
32°59′20″N
104°19′11″W



In secs. 25, 26, and 27 T15S R26E the Pecos River makes a sharp west-southwest turn for 2½ mi around large obsequent slump blocks of Seven Rivers gypsite. These slumps result from continuing erosion, augmented by solution, along the trace of the K-M fault. Near river level, especially in the vicinity of the gaging station, they contain abundant world-famous-euhedral Types 4 and 5 pseudo-octahedral dolomite crystals.

Roswell outcrop segment
Sample localities 5 & 6

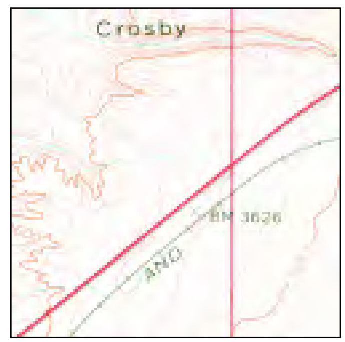
Locality no. 5
Roswell, NM
secs. 3, 10, 11, 14
T11S R26E
Bitter Lake, Bottomless Lakes, Comanche Spring, and South Spring 7½-min quads.
33°23′45″N
104°22′38″W



On Comanche Hill, 10 mi east of Roswell in the vicinity of Bottomless Lakes State Park, drussy, light to dark hematite-red quartz crystals were formerly abundant. The drussy faces are the terminations of prismatic crystals radiating about the center of a single short to long prismatic crystal. If short, the radiating cluster may approximate a sphere. If long, the drussy area is usually insignificant.

In the 1930s and 1940s drussy crystals from Comanche Hill were used to decorate cast gypsum ashtrays, book ends, etc. for the tourist trade. They are, or have been, so plentiful that this type has become synonymous with "Pecos diamonds" in the minds of most mineralogists.

Locality no. 6
Acme, NM
sec. 30 T8S R26E
Acme 7½-min quad.
33°35′18″N
104°20′48″W



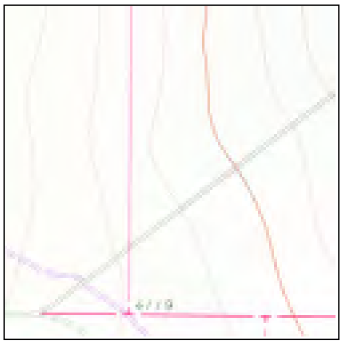
In the first professional paper published on in situ authigenic quartz crystals in the Seven Rivers Formation, Tarr (1929) describes white to pink drussy crystals "...one mile southwest of Acme along the highway to Roswell....The quartz crystals range from .075 millimeter to two centimeters in length."

Dunlap outcrop segment
Sample localities 7–13

Locality no. 7
Selmen Draw, Chaves County
sec. 4 T7S R24E
Coyote Draw, Shannon Draw and Marley Draw 7½-min quads.
33°44′21″N
104°31′34″W

Abundant, nearly transparent, prismatic quartz crystals, both loose and in matrix, occur in the SW¼ sec. 34 T6S R24E and SW¼ sec. 3 T7S R24E. These attractive crystals, averaging 2 cm along the c axis, contain cloudy-white inclusions of gypsum and greenish-black material resembling sapropel. Large, dry sinkholes in gypsite, comparable in size to those at Bottomless Lakes State Park, suggest original deposition in a salina environment.

Locality no. 8
Shannon Draw, Chaves County
sec. 2 T6S R24E
Cottonwood Draw, Coyote Draw and Eightmile Draw 7½-min quads.
33°49′10″N
104°26′13″W



Sparse pink, orange, red, and white prismatic crystals averaging 15 mm along the c axis occur loose and in white to pink gypsum matrix in sec. 36 T6S R25E.

Locality no. 9
Huggins Hill, Chaves County
sec. 36 T5S R24E
Cottonwood Draw and Shannon Draw 7½-min quads.
33°49′23″N
104°26′18″W

Sparse loose, white and dark-brown, almost black, prismatic crystals averaging 15 mm along the c axis have been collected in a shallow ravine in sec. 36 T5S R25E.

Locality no. 10
Huggins Draw, Chaves County
sec. 10 T5S R25E
Deering Place 7½-min quad.
33°52′45″N
104°18′13″W

Plentiful drussy, medium- to dark-orange, prismatic crystals occur in and weathered from light-orange gypsite bluffs on both sides of Huggins Creek in sec. 11 T5S R25E. Average size of these colorful crystals is 18 mm.

Locality no. 11
Old Cavel School, Chaves County
secs. 23, 24 T4S R23E
Dunlap Sill and Swallow Nest Canyon 7½-min quads.
33°56′43″N
104°29′21″W

Abundant dark-magenta to nearly black, short to long, stout, doubly terminated prismatic crystals occur in and weathered from medium- to light-magenta gypsite in sec. 13 T4S R23E south of the abandoned Old Cavel School. These crystals average 2 cm but may be as long as 4 cm along the c axis. A very few of these form normal prismatic Japan-Law twins.

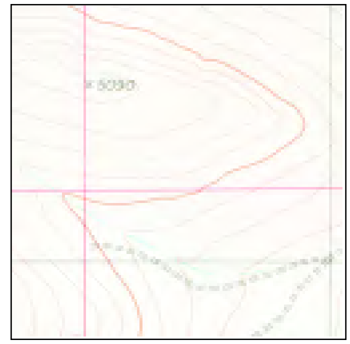
Southeast of the abandoned schoolhouse, plentiful handsome, opaque, medium hematite-red prismatic crystals as long as 3 cm occur loose in the soil. Approximately 5% of these form normal prismatic Japan-Law twins.

Locality no. 12
Gibbin Ranch
De Baca County
SW¼ sec. 10, T3S R24E
Lovelady Draw 7½-min quad.
34°03′05″N
104°24′32″W

On the Gibbin Ranch abundant very good, light to dark honey-brown prismatic quartz crystals occur in and weathered from light-gray to tan gypsite in sec. 10, T3S R24E. These crystals contain copious gypsum inclusions. Average size is 25 mm. Largest crystal found measures 50 mm (Albright and Bauer, 1955).

Scarce, small (5 ± mm), translucent, white euhedral dolomite crystals Types 1 through 5 are commonly embedded in the gypsum matrix along with the quartz crystals. These do not weather well and are easily overlooked. Very fine matrix specimens containing both authigenic quartz and dolomite crystals are easily obtained.

Locality no. 13
Overton Ranch
De Baca County
secs. 7, 8 T1N R21E
Yeso Mesa SE 7½-min quad.
34°18′50″N
104°46′11″W



Abundant prismatic quartz crystals as long as 70 mm and pseudocubes as great as 25 mm on an edge occur in and weathered from medium- to dark-gray gypsite in sec. 8 T1N R21E on the Overton Ranch. These crystals are accompanied by scarce pseudotrigonal bipyramids as long as 35 mm along the c axis that are formed by unequal development of the (**r**) and (**z**) rhombohedra and the absence or near absence of the prism (**m**) (Albright and Krachow, 1958).

The larger prismatic crystals are generally mottled reddish creamy gray or white with pink points, whereas the smaller crystals of all types are about evenly divided between white and light to dark pink.

All illustrations in the article and appendix with the exception of Figure 1 were created by Virgil Lueth.