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New Mexico Geology, v. 12, n. 2 pp. 23-30, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v12n2.23

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Stratigraphy and structure of the Klondike Hills, southwestern New Mexico

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Introduction

The Klondike Hills are in southwestern New Mexico approximately 30 mi (48 km) southwest of Deming, at the northwestern end of the Cedar Mountain Range (Fig. 1). They are characterized by low relief and complexly faulted Paleozoic carbonate rocks, although brecciation, dolomitization, and silicification locally obscure primary lithologies. The stratigraphic section includes Precambrian granite, Upper Cambrian to Pennsylvanian carbonate and subordinate clastic rocks, locally derived Upper Cretaceous/lower Tertiary conglomerate, Oligocene ash-flow tuff and rhyolite, and Quaternary colluvial and alluvial deposits. Laramide-style structural features include a high-angle fault with dip-slip and probable strike-slip offset, low-angle faults with both elimination and repetition of stratigraphic units, small-scale folds, and localized extensive brecciation.

Darton's (1916) geologic map of Luna County was one of the first to show Paleozoic rocks in the Klondike Hills. Bromfield and Wrucke (1961) further defined the ages of the Paleozoic rocks in their reconnaissance map (scale 1:62,500) of the Cedar Mountains (now called Cedar Mountain Range). Armstrong (1970) focused on the stratigraphy of the Mississippian rocks that form the northwestern end of the Klondike Hills. Attracted by the structural complexity of the area, Corbitt et al. (1978) mapped (scale 1:50,000) the southern two-thirds of the Klondike Hills. Thorman and Drewes (1981) mapped the Klondike Hills as part of the Gage SW quadrangle at a scale of 1:24,000. The objective of this report, based on the work of Rupert (1986) is to illustrate the complex structural relations exposed in the Klondike Hills at an even more detailed scale (1:8,000). With this, elucidation of Laramide structural history is somewhat better.

Stratigraphy

Precambrian

Medium-crystalline granite occurs in the west-central part of sec. 22, T26S, R13W (Fig. 2). The rock is intensely shattered, deeply weathered, mostly covered by alluvium, and forms topographically low poor exposures. One sample of the weathered granite yielded an Rb/Sr age of 1390⁺ Ma (M. Shafiqullah, written communication, 1983).

Bliss Sandstone

An incomplete section of Bliss Sandstone crops out south of the granite in the west-central part of sec. 22, T26S, R13W (Fig. 2). The base is not exposed and the uppermost beds are faulted against the overlying El Paso Formation. The Bliss includes about 10 m of dark reddish-brown, fine- to medium-grained, crossbedded quartz arenite in this outcrop. Many of the grains are frosted and the sand is cemented by silica, calcite, and minor hematite. ☞

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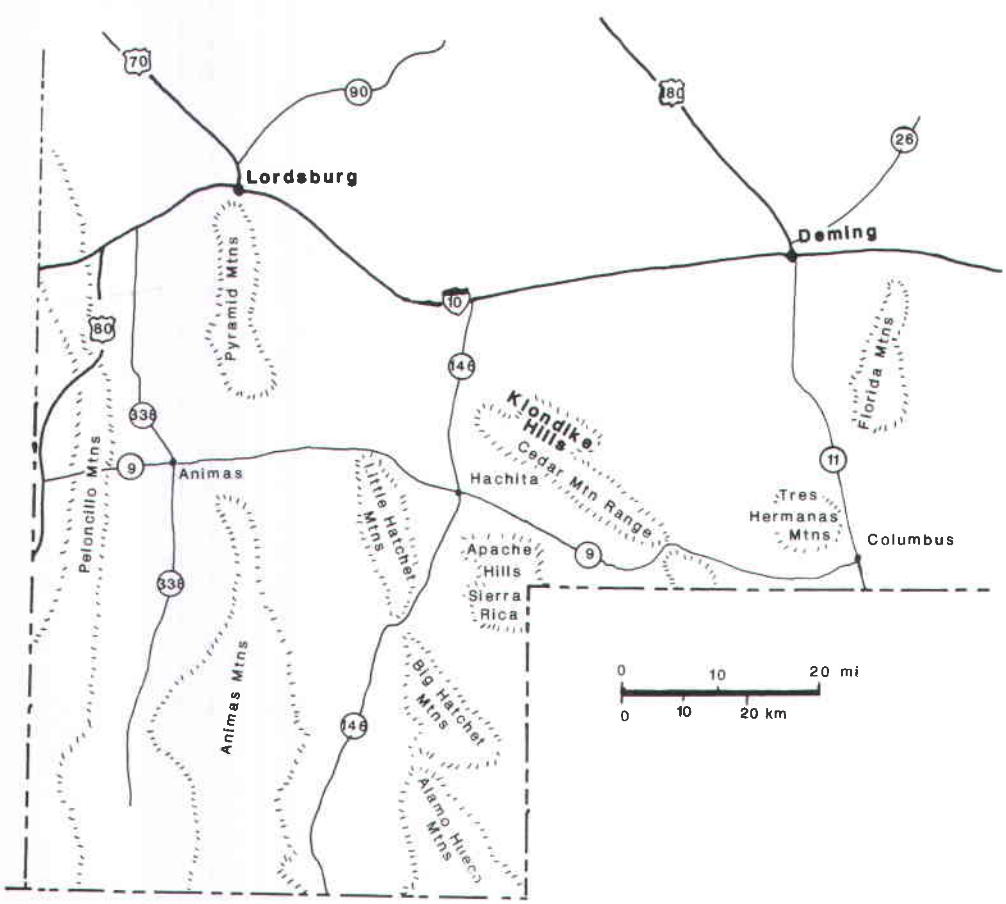


FIGURE 1—Location map of southwest New Mexico showing location of Klondike Hills area of Fig. 2.

El Paso Formation

The El Paso Formation crops out extensively in the southern part of the Klondike Hills. As a result of intense faulting, a complete El Paso section is not preserved but partial sections were measured by Rupert (1986). His sections indicate that the unit is a minimum of 300 m thick (Fig. 3) and includes all four members as defined by Hayes (1975) and Clemons (1988b, in press a, b).

The basal Hitt Canyon Member is thin- to medium-bedded, highly bioturbated, silty, light- to medium-grey limestone or dolostone. The silt and fine sand content decreases upward. The dolostone is believed to be mostly if not completely of hydrothermal origin (Clemons, 1988a). The limestones are interbedded wackestone, packstone, and grainstone. Allochems present in approximate order of decreasing abundance are intraclasts, peloids, echinoderms, trilobites, *Nuia*, spicules, gastropods, and brachiopods. Massive stromatolite mounds are common in the upper part of the Hitt Canyon. These mounds are complexes of narrow, columnar, stacked hemispheroidal heads (Fig.

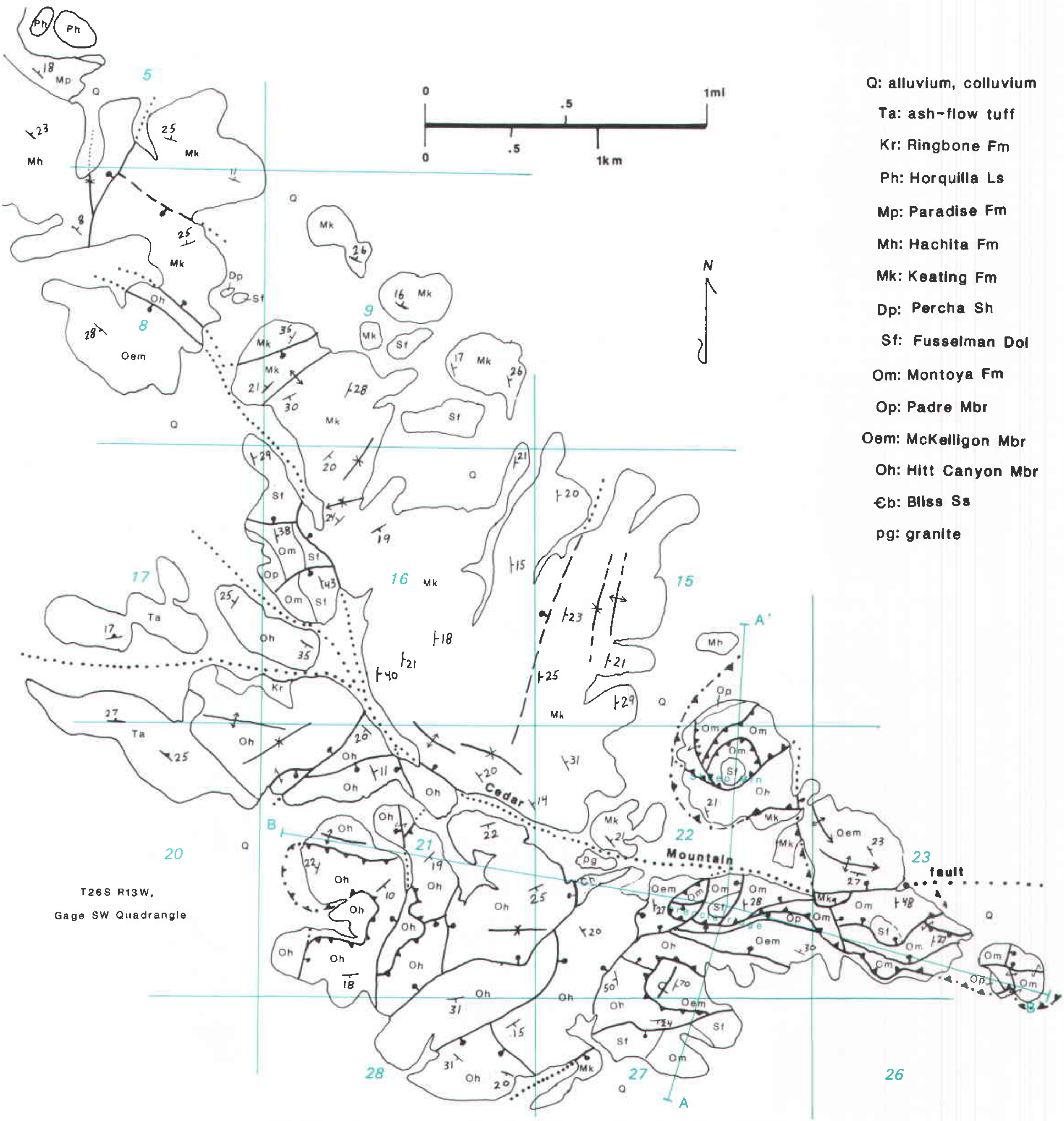


FIGURE 2—Geologic map of Klondike Hills generalized from Rupert (1986).

4) separated by distinctive channels. Oncolites (0.5 to 1.5 cm diameter) are locally abundant in the Hitt Canyon.

The overlying Jose Member is mostly thin-bedded, dark-gray to black, silty to sandy, oolitic limestone with a few interbeds of medium-gray limestone and orangish-gray dolostone. Most of the limestone is lithoclastic and bioclastic grainstones. Dedolomitized ooids with baroque and saddle-shaped calcite are quite common and locally concentric ooids are present. Bioclasts are mostly trilobites and echinoderms with minor gastropods and *Nuia*. All are rounded and typically have thick micritized rims.

The Jose Member is overlain conformably by the McKelligon Member which is medium- to thick-bedded, light- to medium-gray limestone or dolostone. The dolostone is probably a product of hydrothermal alteration common in the Klondike Hills. The limestones are interbedded wackestone, packstone, and grainstone. Allochems in the McKelligon beds include all those found in the Hitt Canyon and Jose Members except for the ooids, and siliciclastic detritus is notably absent even at the base of the McKelligon. Silicified cephalopod siphuncles appear to be more abundant in the McKelligon beds. A few, small (1 m high, 1–2 m long) sponge-*Calathium* mounds are interbedded in the lower McKelligon strata. The mound rock is predominantly spicular wackestone whereas the enclosing beds include packstone and grainstone.

The Padre Member conformably overlies the McKelligon Member in the Klondike Hills. Padre beds contain traces of siliciclastic silt and very fine sand, but the sandstone and sandy dolostone beds characteristic of lower Padre strata at Bishop Cap and in the Franklin Mountains (LeMone, 1969; Clemons, in press b) are absent. The Padre in the Klondike Hills contains thin-bedded, dark-gray, cherty limestone. A few beds have silty, cross-stratified laminations. *Nuia* is less abundant in the Padre than in the lower members; trace amounts of ostracods are present in the Padre.

SYSTEM	STRATIGRAPHIC UNIT	THICKNESS (m)	(ft)
TERTIARY	Ash-flow tuff	30	98
CRET.?	Ringbone Fm	15	50
PENN.	Horquilla Ls	20	67
MISS.	Paradise Fm	67	220
	Escabrosa Gp		
	Hachita Fm	90	295
	Keating Fm	213	700
DEV.	Percha Sh	30	98
SIL.	Fusselman Dol	152	500
ORD.	Montoya Fm		
	Cutter Mbr	66	216
	Aleman Mbr	18	59
	Upham Mbr	8	26
	Cable Canyon Mbr	3-6	14
	El Paso Fm		
	Padre Mbr	82	267
	McKelligon Mbr	107	350
	Jose Mbr	9	30
	Hitt Canyon Mbr	100	328
CAMB.?	Bliss Ss	30	98
PRECAMB.	granite		

FIGURE 3—Rock units exposed in the Klondike Hills.

Otherwise the Padre wackestones, packstones, and grainstones contain the same allochems as the lower strata.

Montoya Formation

The best exposures of the Montoya Formation are in the west-central part of sec. 16, T26S, R13W (Fig. 2). The Montoya also crops out on Sheep Mountain and along the crest of the long ridge south of Sheep Mountain but is extremely faulted and fractured in the latter two areas.

The basal Cable Canyon Member is a light reddish-brown, crossbedded, fine- to medium-grained, moderately sorted quartz arenite, which typically forms prominent ledges. The contact with the underlying Padre Member of the El Paso Formation is very sharp. The contact with the overlying Upham Member of the Montoya Formation is gradational over about 1 m and is marked by a change from quartz arenite to coarsely crystalline, dark-gray dolomite of the Upham Member. Petrographic examination of the Cable Canyon shows it contains mostly well-rounded, frosted, monocrystalline quartz grains, with undulose extinction and thin hematite rims, in variable amounts of silica and/or carbonate cement.

The Upham Member is a very dark gray, coarsely crystalline, massive dolostone, black to dark reddish-brown on fresh surface. It has much quartz sand at the base, but the sand fraction rapidly decreases upsection as the unit grades to a featureless and rather homogeneous dark-gray, coarsely crystalline dolostone. A few of the quartz grains in the Cable Canyon Member and lower Upham exhibit a characteristic blue tint when examined with a hand lens. No fossils were found in the Upham Member in the Klondike Hills.

The Aleman Member consists of light-brown to medium-gray, finely crystalline dolostone with abundant medium-gray chert as elongate nodules and lenticular beds. The chert constitutes 30 to 40% of the rock and weathers in a very characteristic contrasting relief. No fossils were observed in the Aleman Member exposed in the Klondike Hills. The contact with the overlying Cutter Member is gradational over approximately 1 m and is characterized by a decrease in chert and a change to the massive light-brown dolomite of the Cutter Member.

The lower three-fourths of the Cutter Member is chert-poor, medium-bedded, light-brown, finely crystalline dolostone with a few small, broken brachiopod fragments. The upper part of the Cutter Member is a slightly darker light-brown, finely crystalline dolostone with increasing amounts of nodular chert up-section, although the chert rarely exceeds 20% by volume. The uppermost beds are essentially chert-free, finely crystalline, light-brown dolostone. The contact with the overlying Fusselman Dolomite is an erosional disconformity and is marked by a notable upward decrease in nodular chert and a sharp change from the light-brown, finely crystalline dolostone of the Cutter to the medium dark-gray, slightly coarse crystalline Fusselman Dolomite. ☞

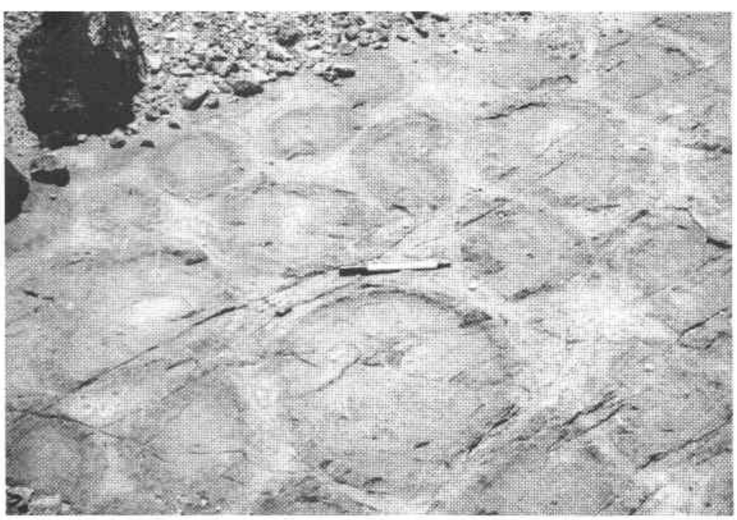


FIGURE 4—Stromatolites in the Hitt Canyon Member of the Klondike Hills.

FIGURE 5—Ringbone(?) conglomerate 3.75 mi (6 km) south of Klondike Hills.

Fusselman Dolomite

A complete section of the Fusselman Dolomite is not exposed in the Klondike Hills. The largest exposure is in the west-central part of sec. 16, T26S, R13W (Fig. 2). Most other exposures of the Fusselman in the Klondike Hills are highly brecciated to the point of total obliteration of any original bedding or texture. No fossils were observed in the Fusselman in the Klondike Hills.

The lowermost 17 m of the Fusselman Dolomite is a medium dark-gray, coarsely crystalline, medium-bedded to massive dolostone. This is overlain by about 7 m of dark-gray dolostone with very characteristic alternating light and dark, millimeter-thick banding (varve-like in appearance). Above this are 30 m of dark-gray, massive, coarsely crystalline dolostone with isolated lenses and knobby pods of chert and 15 m of medium dark-gray, massive, fine- to medium-crystalline dolostone with no chert. The top 83 m of Fusselman are coarsely crystalline, light-brown, massive dolostone.

Percha Shale

Armstrong (1970) mapped about 30 m of Percha Shale in the northwestern Klondike Hills. The only outcrop of Percha in the southern Klondike Hills is the east-central part of sec. 8, T26S, R13W (Fig. 2) where about 1 m of grayish-green, calcareous shale is poorly exposed in a small gully. A tailings pile in the north-central part of sec. 27, T26S, R13W also contains Percha. Thorman and Drewes (1981) reported that the nearby shaft is 18 m deep with Percha at the bottom.

Escabrosa Group

Armstrong (1970) mapped and described about 300 m of Escabrosa Group in the northwestern Klondike Hills. He subdivided the group into the lower, Keating Formation and upper, Hachita Formation. Outcrops of Escabrosa in the southern Klondike Hills are restricted to the north side of the Cedar Mountain fault. The one exception is the northwestern part of sec. 27. Furthermore, the Hachita Formation only crops out in secs. 5 and 8 to the northwest plus a small exposure north of Sheep Mountain in sec. 15. The Keating forms most of the outcrops north of the Cedar Mountain fault.

The Keating Formation comprises medium-bedded, light- to medium-gray limestones. The lower few meters are mostly echinoderm packstone with minor bryozoa and brachiopod fragments. The bulk of the Keating exposed is lime mudstone with abundant chert nodules and lenses. The Hachita Formation is mostly chert-free, massive-bedded, light-gray, crinoidal wackestones and packstones. Locally there are interbedded coated-bioclast grainstones.

Paradise Formation

The Paradise Formation is thin- to medium-bedded yellowish-gray silty limestone and interbedded shale and siltstone. It is only exposed in sec. 5 (Fig. 2), but Armstrong (1970) mapped and described about 67 m of more extensively exposed Paradise in the northwestern Klondike Hills. The limestones are typically ooid packstones and grainstones with some lime mudstones and wackestones.

Horquilla Limestone

Several small poorly exposed outcrops of Horquilla Limestone are mapped in the west-central part of sec. 5 (Fig. 2). Armstrong (1970) reported that about 20 m of Horquilla overlies the Paradise Formation in the northern Klondike Hills. He also reported that 2–3 m of sandstone are overlain by medium- to thick-bedded, cherty limestones. The limestones are peloid and ooid grainstones, packstones, and lime mudstones.

Ringbone(?) Formation

A small outcrop of clast-supported, cobble conglomerate, unconformable on El Paso Formation, in the southeast corner of sec. 17, T26S, R13W is tentatively correlated with the Ringbone Formation. Clasts include most of the lithologies of Precambrian and Paleozoic formations described in the Klondike Hills. This conglomerate is probably correlative with about 15 m of limestone conglomerate resting on Mississippian–Pennsylvanian beds mapped 6 km to the south by Bromfield and Wrucke (1961) and Varnell (1976). This southern exposure contains (Fig. 5) abundant rounded cobbles and boulders of rudistid limestones derived from the Lower Cretaceous U-Bar Formation. It also shows about 22 m of relief on the lower contact. Similar rocks in the Florida and Little Hatchet Mountains are the Lobo and Ringbone Formations respectively. The Ringbone and Lobo are considered to be syntectonic with Laramide deformation in southwestern New Mexico, Ringbone ranging from Late Cretaceous to Paleocene (Wilson et al., 1989), Lobo probably Paleocene to Eocene (Lawton et al., 1989).

Ash-flow tuff

Ash-flow tuff crops out in secs. 17 and 20, T26S, R13W on the southwest side of the Klondike Hills (Fig. 2). It is a pale-red to grayish-red to light brownish-gray, massive weathering, crystal-vitric, rhyolitic ash-flow tuff. Some zones contain pumice fragments as large as 15 cm. Phenocryst fragments include quartz, sanidine, plagioclase, biotite, and hornblende. Sphene and clinopyroxene are present in trace amounts. This tuff is about 30 m thick and forms gently northeast-tilted cuestas. Thorman and Drewes (1981) indicated a probable Oligocene age for this ash-flow tuff.

Structural geology

Cedar Mountain fault

The most prominent structure in the Klondike Hills is the Cedar Mountain fault (Fig. 2). This feature, named by Thorman and Drewes (1981), is a west–northwest-trending fault with a curvilinear surface trace (Fig. 6a). The fault dips 78° southward in the northeast part of sec. 21. In the west-central part of sec. 23, the fault zone forms a tectonic breccia 6–10 m wide with an approximately vertical attitude. Much of the Cedar Mountain fault is characterized by a breccia zone of variable width, locally only a meter wide but ranging upward to 10 m wide.

A striking aspect of Cedar Mountain fault is the contrast of tectonic styles on either side of the fault. The southern block comprises mostly Ordovician and Silurian carbonate rocks that are complexly cut by both low- and high-angle faults. Except for Sheep Mountain, the northern block is moderately deformed Mississippian Keating Formation. A small slice of Keating Formation near the west-central edge of sec. 23 is bounded by El Paso and Montoya strata. Apparently, this slice of Keating is a small horse incorporated along the Cedar Mountain fault zone.

Cedar Mountain fault displays more than 600 m of vertical stratigraphic separation in sec. 21 where Ordovician rocks to the south are juxtaposed against Mississippian rocks to the north. The small exposure of Precambrian granite in the west-central part of sec. 22 indicates that basement was involved in the faulting.

Cedar Mountain fault splits into three splays in the western part of the map area. The northern splay has a curvilinear trend with a large amount of stratigraphic separation that places mostly Ordovician rocks on the south and west against Mississippian rocks on the north and east. The middle splay separates Hitt Canyon Member on the south from uppermost El Paso, Montoya, and Fusselman Formations on the north. The southernmost splay has minor post-Oligocene normal movement, offsetting the ash-flow tuff by 10–30 m.

The most striking feature of the near-vertical Cedar Mountain fault is apparent drag folding (Fig. 6a), which suggests probable left-lateral slip (Fig. 6b). The strike of a plunging anticlinal axis exposed at the west-central edge of sec. 23 changes from almost due north to almost due east with increasing proximity to Cedar Mountain fault. In addition, strike of the Keating Formation exposed in secs. 16 and 21 changes from north to northwest with increasing proximity to the fault (Fig. 6a). No field evidence was observed to indicate the amount of left-lateral movement.

Low-angle faults

Two levels of low-angle faulting are exposed in the Klondike Hills (Fig. 7). The lower level places older strata on younger, thus repeating the section, with underlying beds locally overturned. The upper level of low-angle faulting is characterized by younger beds on older beds, with part of the section tectonically eliminated (Fig. 7). These faults are termed "low-angle" instead of "thrust" faults, because, for the upper level of fault-

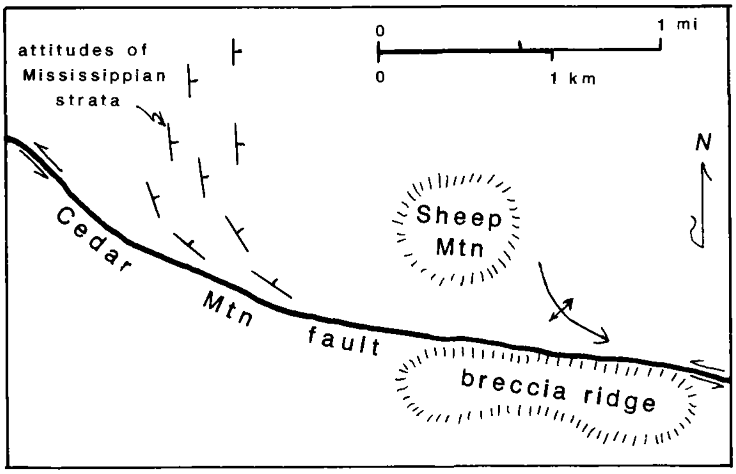


FIGURE 6a—Drag features along Cedar Mountain fault, Sheep Mountain, and breccia ridge (from Rupert, 1988, with permission from the New Mexico Geological Society).

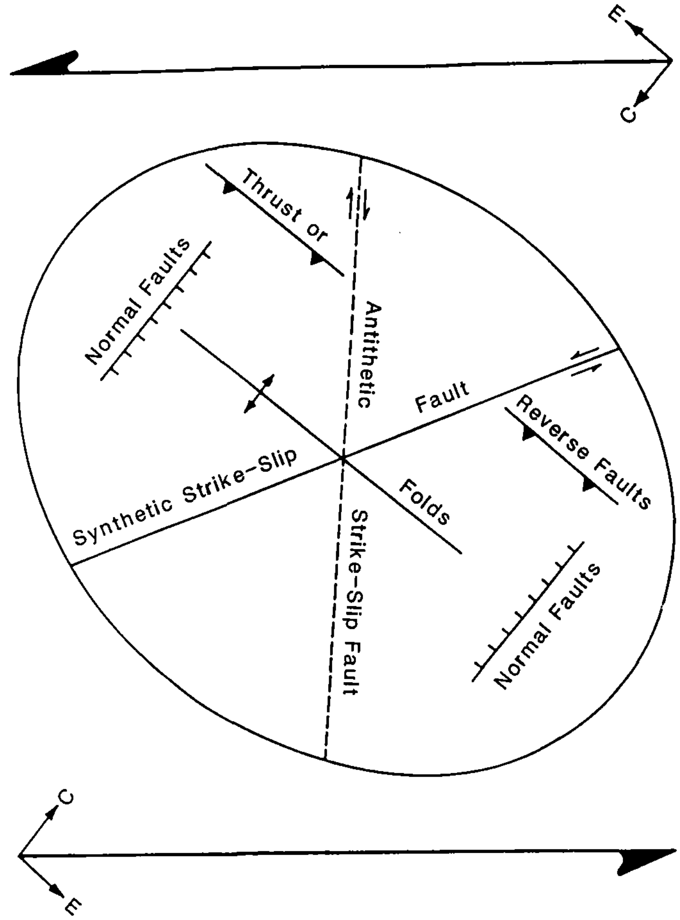
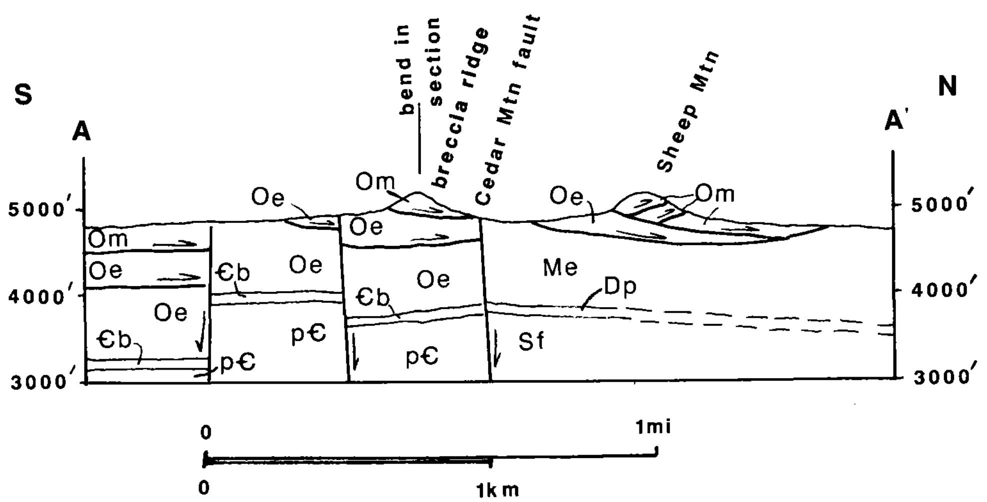


FIGURE 6b—Diagram showing possible features superimposed on strain ellipse resulting from left-lateral stress. Note orientation of normal faults. (After Harding, 1974, with permission from the Association of Petroleum Geologists.)



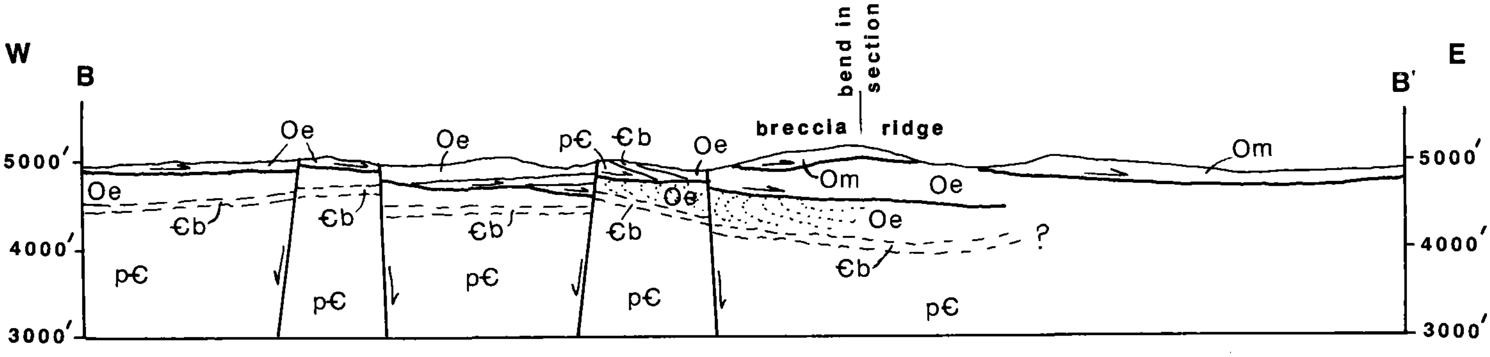


FIGURE 7—Cross sections showing two levels of low-angle faulting (from Rupert, 1988, with permission from the New Mexico Geological Society). See Fig. 2 for line of sections. Symbols same as Fig. 2 except **Oe** indicates undifferentiated El Paso Formation.

ing, it is unclear whether the faulting is low-angle normal faulting or thrust faulting with bedding at a steeper angle than the fault.

Faults showing older-on-younger relations are exposed in the SW1/4 sec. 21, along the south-central edge of sec. 22, and in the northeast corner of sec. 22 (Fig. 2). In the SW 1/4 sec. 21, the low-angle fault places lowermost thin-bedded Hitt Canyon Member of the El Paso Formation above the dolomitized uppermost part of Hitt Canyon Member with a stratigraphic separation of approximately 70 m. Beds of the upper plate are complexly folded, with highly variable orientation of fold axes. An older-on-younger low-angle fault places thin-bedded lowermost Hitt Canyon Member on top of McKelligon Member at the south-central edge of sec. 22 (Fig. 7, B–B'). Beds of the underlying McKelligon Member form an overturned syncline, which is exposed in a window in the allocthonous plate. In the northeast corner of sec. 22 an older-on-younger low-angle fault places Hitt Canyon Member on top of Keating Formation at the base of Sheep Mountain (Fig. 8). The Hitt Canyon Member is folded into a north-trending syncline.

Younger-on-older low-angle faulting exposed on Sheep Mountain (Fig. 8) places Montoya Formation on top of Hitt Canyon Member with Jose, McKelligon, and Padre Members missing. The upper plate is intensely deformed by both high-angle and low-angle faults. Many low-angle faults within this upper plate repeat various members of the Montoya.

Younger-on-older, low-angle faults are exposed in the south-central and eastern parts of sec. 22 and extending into the southwestern part of sec. 23, on a ridge herein called breccia ridge, for the pervasive cataclastic nature of the rocks forming the ridge (Figs. 7, A–A', 9). The younger-on-older faulting exposed on breccia ridge places Montoya Formation on top of El Paso Formation, with the Padre Member of the El Paso missing. This low-angle fault occurs just below the Cable Canyon Sandstone Member of the Montoya for the most part, presumably because the thin-bedded limestones of the underlying Padre Member act as a decollement surface between the overlying Montoya dolostones and underlying El Paso limestones. The upper plate is complexly faulted and brecciated.

High-angle faults

Relatively minor (less than 150 m displacement) high-angle faulting is common south of the Cedar Mountain fault. These faults appear to be high angle as suggested by their linear surface expression, but it is not certain whether they have reverse or normal displacements. Crosscutting relations, such as those exposed in the south-central part of sec. 21 and north-central part of sec. 27, suggest many of these faults postdate low-angle faulting.

Basin and Range faulting and tilting

The only faulting in the Klondike Hills that can be positively attributed to Basin and Range extensional deformation is in the west-central part of the map area. There, an ash-flow tuff, tentatively dated as Oligocene (Thorman and Drewes, 1981), has been tilted approximately 25° to the north–northeast. Laramide attitudes can be estimated by rotating the tuffs back to horizontal. When this is done, the Cedar Mountain fault still retains its near-vertical character, and both levels of low-angle faulting retain their low-angle orientation.

Discussion

Sheep Mountain (Fig. 8) and breccia ridge (Fig. 9) respectively north and south of the Cedar Mountain fault, have similarities indicating they may have been part of a once-continuous allocthon that has been eroded to its present form. These similarities include correlative structural features, sequences of rock units, and elevations of low-angle fault planes. Crosscutting relations suggest this allocthon moved subsequent to vertical movement on the Cedar Mountain fault.

The origin of the low-angle faulting is debatable because these faults could represent either low-angle, listric normal faults (Fig. 10) (Armstrong, 1972; Wernicke and Burchfiel, 1982; Reynolds and Spencer, 1985), or thrust faults with dips steeper than those of the underlying rocks (Fig. 11) (Brown, 1982). Resolution of this debate is not simple, as Dickinson (1984) has shown. Listric normal faulting has been documented on the flanks of Laramide uplifts in south-central New Mexico (Nelson and Hunter, 1986), with these uplifts presumably supplying the required slope. The intensely deformed character of the upper plate exposed on breccia ridge resembles that which would be expected in a listric normal fault environment. However, similar styles of faulting are exposed in the Florida Mountains, where Brown (1982) quite convincingly argued for thrust faulting. Development of a justifiable model in the Klondike Hills is limited by the low relief of the area. The Klondike Hills lack the exposure of a basement-rooted reverse fault, which would be necessary to prove thrusting similar to that seen in the Florida Mountains. The Klondike Hills area also lacks a topographic high, which would supply the necessary slope for normal listric faulting. If either of these features existed in the past, they presumably were located south or southwest of the Klondike Hills and have been obscured by subsequent Basin and Range faulting and volcanic activity.

Comparison of the Klondike Hills to the regional overthrust (Corbitt et al., 1978) and basement-cored block uplift models (Brown, 1982; Brown and Clemons, 1983) suggests

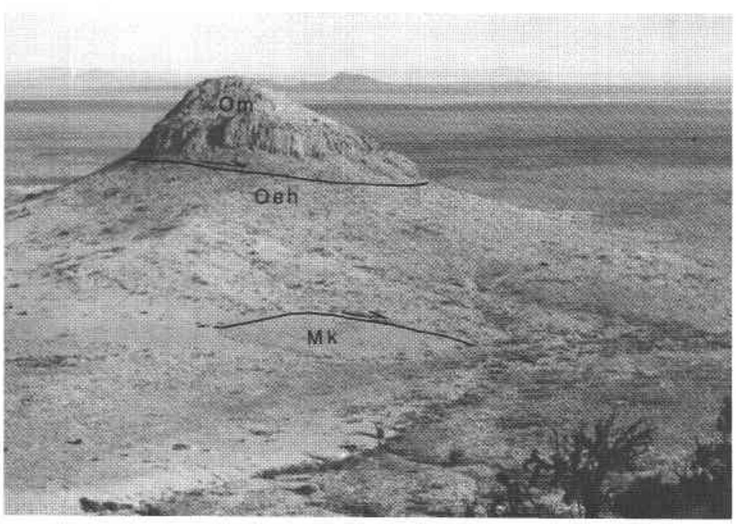


FIGURE 8—Looking north at Sheep Mountain. Younger-on-older, low-angle fault near top of mountain places Montoya Formation on top of Hitt Canyon Member with Jose, McKelligon, and Padre Members missing. Older-on-younger, low-angle fault at base of Sheep Mountain places Hitt Canyon Member on top of Keating Formation.

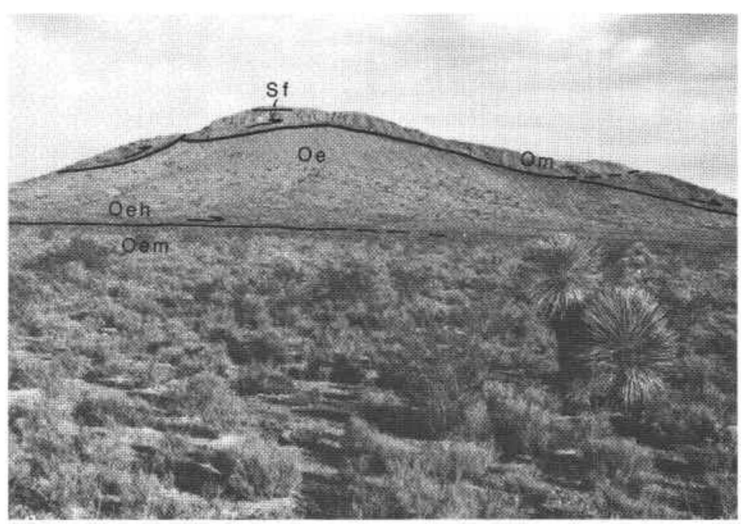


FIGURE 9—View north to breccia ridge. Younger-on-older, low-angle fault near top of ridge places Montoya Formation on top of El Paso Formation with a part of the El Paso missing. Older-on-younger, low-angle fault at base of breccia ridge places Hitt Canyon and McKelligon Members on top of McKelligon Member.

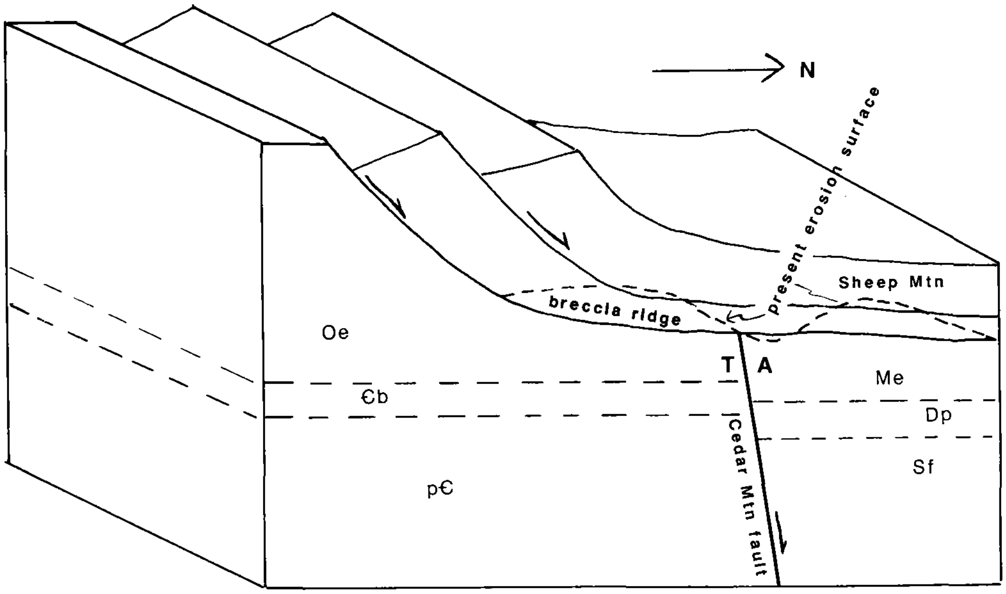


FIGURE 10—Listric faulting model for the Klondike Hills. Note multi-phase structural development with vertical movement on Cedar Mountain fault occurring first, followed by gravity sliding along low-angle normal faults from a topographic high to the south followed by left-lateral movement on Cedar Mountain fault (see Figure 2 for legend). Symbols same as Fig. 2, except **Oe** indicates undifferentiated El Paso Formation and **Me** indicates undifferentiated Escabrosa Group. **T** (toward observer) and **A** (away from observer) indicate left lateral movement on Cedar Mountain fault.

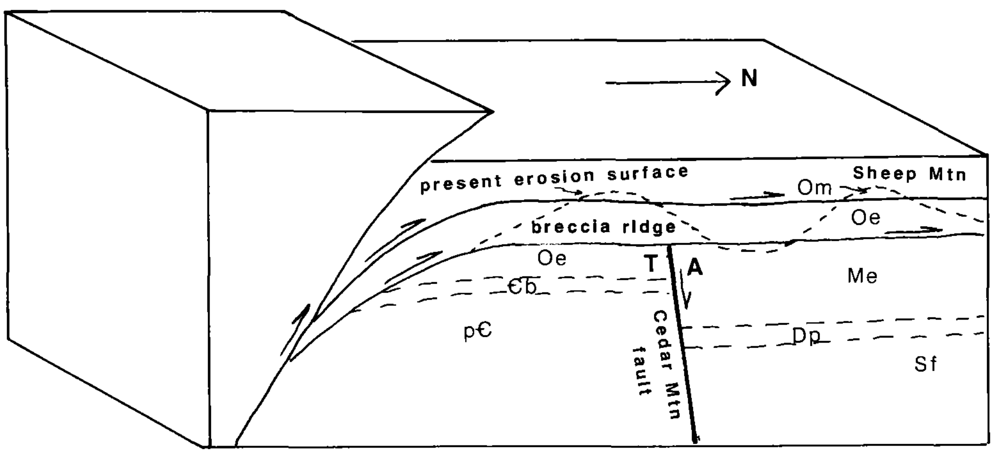


FIGURE 11—Basement-cored block uplift model for the Klondike Hills. Note multi-phase structural development with vertical movement on Cedar Mountain fault occurring first, followed by thrusting along low-angle faults rooted in a high-angle basement-cored reverse fault, and then left-lateral movement on Cedar Mountain fault. Symbols same as Figs. 2 and 10.

that the Klondike Hills more closely resemble the basement-cored block uplift model. Features associated with regional overthrusting include dominantly horizontal movement of a thick geosynclinal sequence along major décollement surfaces, with telescoped sedimentary sequences (Woodward and DuChene, 1981). Features associated with basement-cored block uplifts include dominantly vertical movements along high-angle, basement-involved faults through relatively thin cratonic sequences, with minor thrust faults produced from drag during uplift (Prucha et al., 1965; Seager, 1983). Features that suggest the Klondike Hills more closely match the basement-cored uplift model include the occurrence of both vertical and left-lateral strike-slip movement on a high-angle, basement-involved fault (Cedar Mountain fault), and localized, small-scale, low-angle faulting in close proximity to the Cedar Mountain fault. This interpretation is consistent with work by other authors in the area (Drewes and Thorman, 1980a, b; Thorman and Drewes, 1981; Brown and Clemons, 1983; Seager, 1983; Clemons, 1986).

Conclusions

The Klondike Hills exhibit Laramide-style deformation with 1) small scale, older-on-younger and younger-on-older low-angle faulting; 2) localized tectonic brecciation; 3) localized fold development; and 4) vertical and left-lateral movement on the Cedar Mountain fault. Involvement of the crystalline basement with the uplift along Cedar Mountain fault is suggested by 1) outcrop of the basement in one locality; 2) predominance of Lower Ordovician sedimentary rocks south of Cedar Mountain fault suggests that basement is close to the surface; 3) linear extent of Cedar Mountain fault; and 4) vertical displacement on Cedar Mountain fault. Left-lateral movement on Cedar Mountain fault is shown by drag folding of Keating Formation, drag of an anticlinal fold axis north of Cedar Mountain fault, and attitudes of high-angle faults south of Cedar Mountain fault. Strike-slip faulting is also implied by widespread, extreme brecciation and braided pattern of Cedar Mountain splay faults.

Crosscutting relations indicate the following sequence of events: 1) vertical motion on Cedar Mountain fault placing Keating Formation against El Paso Formation; 2) formation of two levels of low-angle faulting; 3) left-lateral movement on Cedar Mountain fault; 4) high-angle faulting that displaced low-angle faults; 5) high-angle faulting and tilting that offsets Oligocene ash-flow tuffs.

ACKNOWLEDGMENTS—This paper represents part of the senior author's MS thesis completed at New Mexico State University. The work was supported by a New Mexico Geological Society scholarship and a grant from the New Mexico Bureau of Mines and Mineral Resources. These funds made possible the extended field mapping. We also thank Glen Brown and Tim Lawton for their constructive reviews of the preliminary manuscript and Gus Armstrong for comments on the final version.

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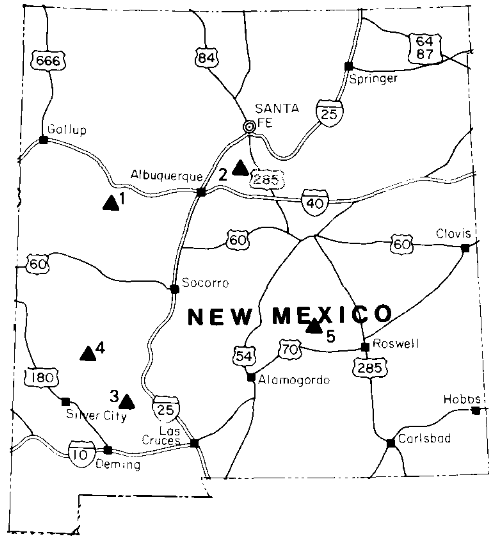
Abstracts

New Mexico Mineral Symposium

The Tenth Annual New Mexico Mineral Symposium was held November 11–12, 1989, at New Mexico Institute of Mining and Technology, Socorro. Following are abstracts from talks given at the symposium that concern New Mexico. The numbers in parentheses refer to locations on the map.



MINERALS AND ROCK FORMS IN LAVA TUBES OF EL MALPAIS NATIONAL MONUMENT, CIBOLA COUNTY, NEW MEXICO, by *Kent Carlton*, El Malpais National Monument, Grants, NM 87020, and *Christopher G. McKee*, New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801 (1)

El Malpais National Monument was established recently by Congress. One of the outstanding features of the monument is its lava-tube systems. The concentration of tubes is so high here that Hatheway and Herring (1970) chose El Malpais as a terrestrial analog to what are believed to be similar structures called "rills" that occur on the moon. The El Malpais tubes are also significant because of the length of many of the systems. For example, one tube system within the monument is reported to be 17.9 mi (28.6 km) long by Elston and Wohletz (1987). Such a considerable length is not believed to be typical of lava tubes in other locales. Further, the intact (cave) portions of El Malpais lava tubes are often noteworthy relative to tube lengths observed elsewhere. Four lava caves within the monument exceed one kilometer in length and one is two kilometers. Finally, the size of many of the El Malpais tubes appears to be uncommonly large. Tubes that exceed 50 ft in height and 60 ft in width are not uncommon. Kent Carlton collected cave minerals during a 1988 lava-tube inventory and submitted them to New Mexico Institute of Mining and Technology for identification. Chris McKee analyzed the samples by x-ray diffraction. The samples contain quartz, feldspar, calcite, thenardite, gypsum, trona, and burkeite.

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MINERALS OF THE CARNAHAN MINE, SANTA FE COUNTY, NEW MEXICO, by *Ramon S. DeMark* and *Judith L. DeMark*, 6509 Dodd Place, NE, Albuquerque, NM 87110 (2)

The Carnahan mine, located in the San Pedro Mountains (New Placers district) of Santa Fe County, New Mexico, has not been a major ore producer. Nonetheless, it has had a long, but intermittent, record of production of lead–silver, zinc, and manganese ores. Since 1968, the mine has been owned by the San Pedro Mining Corporation (Patrick Freeman, personal communication 1989). The mine workings consist predominantly of an inclined tunnel (5–20°) trending N75°E to N90°E with minor drifts and some stoping. Near the end of this tunnel another north-trending inclined tunnel proceeds approximately 500 ft before intercepting the water table. The geology and mineralogy of the Carnahan mine was looked at most extensively in 1903 (Yung and McCaffery). More recent studies have, in most cases, cited the mineralogical findings of Yung and McCaffery in reporting occurrences of specific minerals. Northrop (1959), crediting Dale Carson, cited a number of oxidized minerals including anglesite, cerussite, botryoidal hematite, limonite, possibly minium, pyrolusite, and native silver. Since 1985, however, a number of new species have been identified from the Carnahan mine, species that were either overlooked by earlier investigators or possibly misidentified. With the help of microprobe (Paul Hlava, personal communications 1989) and x-ray diffraction/SEM (Peter Modreski, personal communications 1989) analyses, 20 species new to the Carnahan mine have been confirmed. Two of the species (adamite and hetaerolite) are the first reported occurrences of these minerals in New Mexico. The new minerals are all secondary minerals resulting from the oxidation of primary iron, copper, zinc, and manganese sulphides. They include one native element (copper), oxides, carbonates, sulfates, arsenates, a molybdate (wulfenite), and silicates. Although galena and pyrite have been found in the oxidized zone, the predominant occurrence of primary sulphides is reputed by Atkinson (1961) to occur below the ground-water level approximately 400 ft below the surface. Most of the secondary copper minerals were found in a very restricted zone substantially down the tunnel. The arsenates, adamite, and agardite-(Y) were found in association with cuprite octahedrons that were partially or completely altered to rosasite, malachite, and chrysocolla. Native copper commonly occurs in the cores of the less altered cuprite octahedrons. Adamite most often occurs as transparent green spheres, but crystal morphology is evident on some of the balls. This adamite is cuprian, which accounts for the green color. Some individual colorless crystals to 0.5 mm are very low in copper content (Hlava, personal communication 1989). None of the Carnahan mine adamite is fluorescent. Aurichalcite and azurite, although scarce, were also found in association. Agardite-(Y) occurs in very fine acicular sprays and tufts. Linarite occurs as sky-blue, bladed crystals about 0.1 mm long and also as fine sprays of crystals about 0.3 mm across. They are found in association with pyrite, galena, and green spheres that appear to be a mixture of malachite and brochantite (Hlava, personal communication 1989). The pyrite in some cases is