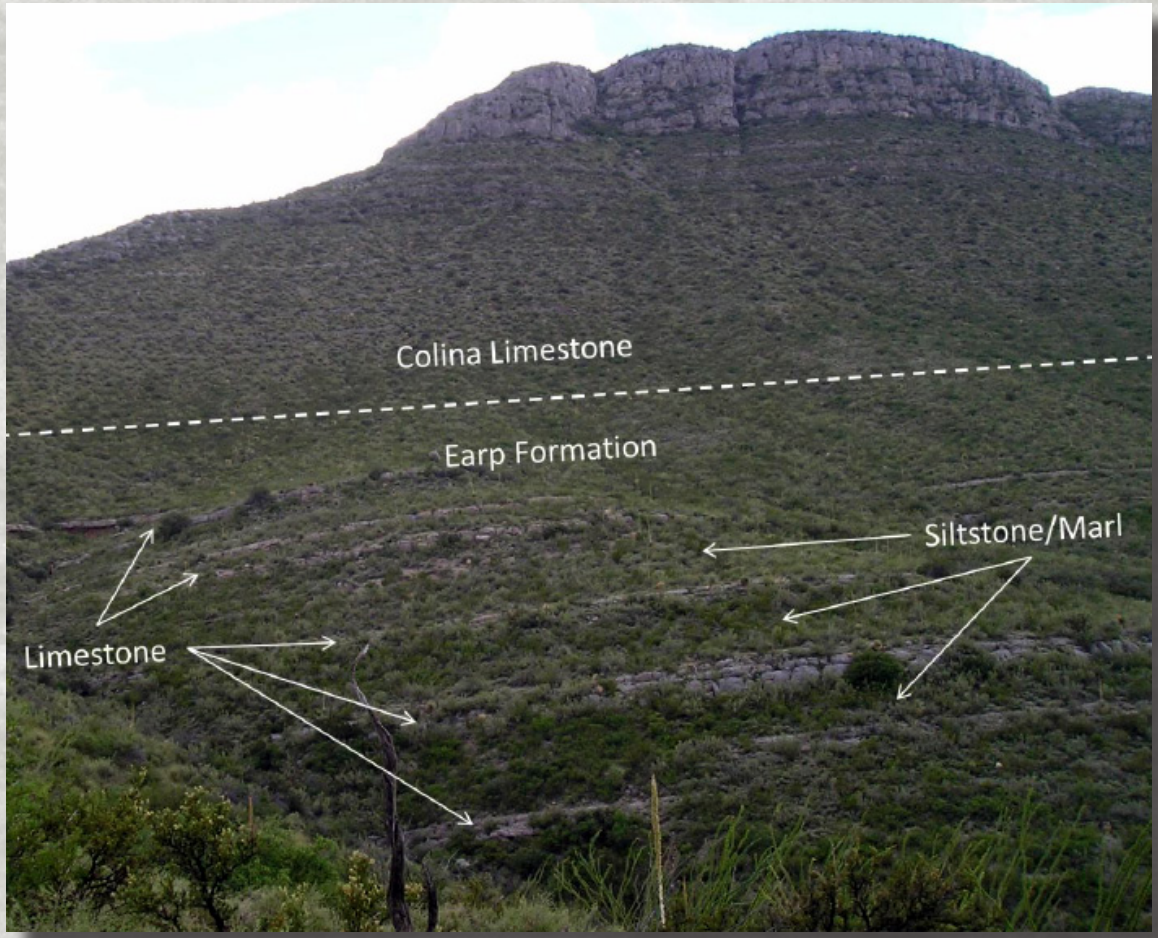
Stratigraphy of Lower Permian Skarn Protoliths, Southeastern Arizona

Richard P. Huebschman
Consulting Geologist



Earp and Colina Formations, eastern Whetstone Mountains, Arizona

CONTRIBUTED REPORT CR-13-B

June 2013

Arizona Geological Survey

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Manuscript approved for publication in June 2013
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Recommended Citation: Huebschman, R.P., 2013, Stratigraphy of Lower Permian Skarn Protoliths, Southeastern Arizona. Arizona Geological Survey Contributed Report CR-13-B, 27 p.

Arizona Geological Survey Contributed Report CR-13-B

Stratigraphy of Lower Permian Skarn Protoliths, Southeastern Arizona

June 2013

Richard P. Huebschman
Independent Research Geologist
Tucson, Arizona

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-Southern Whetstone Mountains Section
-Eastern Whetstone Mountains Section
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STRATIGRAPHY OF LOWER PERMIAN SKARN PROTOLITHS, SOUTHEASTERN ARIZONA

Richard P. Huebschman*

Introduction

Carbonate rocks of lower Permian age are important host to copper skarn mineralization, in the porphyry copper belt of southeastern Arizona, near Tucson. Early Permian sedimentation occurred on an unstable shelf with abrupt facies changes, resulting in diverse lithologies, repetitive depositional sequences and obscured formational contacts. Favorable carbonate protoliths are not necessarily confined to a given stratigraphic horizon, nor limited to a particular formation, complicating efforts to determine stratigraphic controls of skarn mineralization within a porphyry system. Since carbonate rock types are defined by their depositional environment, facies modeling may help to delineate important carbonate skarn protoliths, in altered section.

This study represents a synthesis of previous work, and adds new observations and stratigraphic interpretations of the lower Permian Earp, Colina and Epitaph Formations within the porphyry copper belt of present day Pima and western Cochise Counties, Arizona. Potentially favorable carbonate protoliths are described, utilizing stratigraphy and facies analysis as a means of determining their spatial distribution. For workers studying altered drill core associated with copper mineralization, important diagnostic features of lower Permian protoliths and marker beds useful in altered section are discussed here, along with their commonly associated skarn assemblages.

Early Permian Setting, Southeast Arizona

The late Paleozoic of southeastern Arizona consisted of a relatively stable carbonate shelf, on the western periphery of southeastern-trending Pedregosa basin, bordered by the Florida Islands to the northeast and the Zuni-Defiance uplift and Sedona arch to the north and northwest (Armin, 1987; Fig.1). Increased tectonism and continental erosion during onset of the late Pennsylvanian and early Permian resulted in deposition of clastic sediments of the Earp Formation onto an emergent Pedregosa shelf.

*Present Address:
425 N. Sedge Lane
Tucson, AZ 85748
huebschrp@cox.net

Butler (1969, 1971) and Lodewick (1970) interpreted the clastic-dominated portion of the Earp Formation as a southeastward-prograding delta extending from present-day northern Pima to southern Cochise County, Butler (1969) noting the pattern of clastic distribution (Fig. 2) as "that of a radiating distributary channel leading to a marine basin". Further evidence of deltaic sedimentation included primary sedimentary structures typical of deltas, and a thinning of the Colina Limestone over the Earp clastic tongue.

Armin (1987) completed a detailed study of a thin (5 meters) and widely-correlated chert clast conglomerate sequence of the Earp Formation in southeast Arizona, New Mexico and northern Mexico. His study recorded a middle Wolfcampian erosional event and deposition by southeastward-trending braided stream channels, on a cratonic "forebulge" peripheral to a subsiding Pedregosa foreland basin, caused by northward thrusting in the Chihuahua region during the Ouachita orogeny (Fig. 1). It can be reasonably inferred that the deltaic facies of the Earp Formation was thus formed by a more distal ephemeral braidplain and alluvial fan system migrating onto the distal Pedregosa carbonate shelf.

Gradual retreat of the Earp delta during the mid-Wolfcampian occurred along with deposition of the Colina and Epitaph Formations in restricted lagoonal and coastal sabkha (i.e., a coastal flat characterized by evaporite deposits) environments. Lodewick (1970) and Butler (1971) showed that clastic ratios (i.e.: silt-sized clastics /carbonates) of Colina and Epitaph Formations increase over the Earp clastic tongue (Fig. 3), likely the result of Earp deltaic silts being incorporated into flanking and superjacent environments of Colina and Epitaph Formations.

Permian sedimentation patterns display marked facies changes with a pronounced linear orientation, elongated to the northwest, which Titley (1981, 1982) attributed to a northwest-trending structural fabric, active during the late Paleozoic. Structural control of sedimentation is suggested in the southeast-trending Earp clastic tongue (Fig.2), and profound northwest orientation of the lower Permian evaporite facies (Fig. 4). Titley (1982) further suggested that the same structural fabric controlling late Paleozoic sedimentation patterns may have been reactivated during later geologic time, perhaps providing structural control for porphyry emplacement of deposits such as the Silver Bell-Mission-Twin Buttes-Rosemont trend that parallels the northwest-trending basin axis, along the southwest boundary of evaporites (Fig. 4).

Figure 1. Map showing late Paleozoic tectonic features mentioned in text, in portions of Arizona, New Mexico, and Northern Mexico. Modified from Armin, 1987

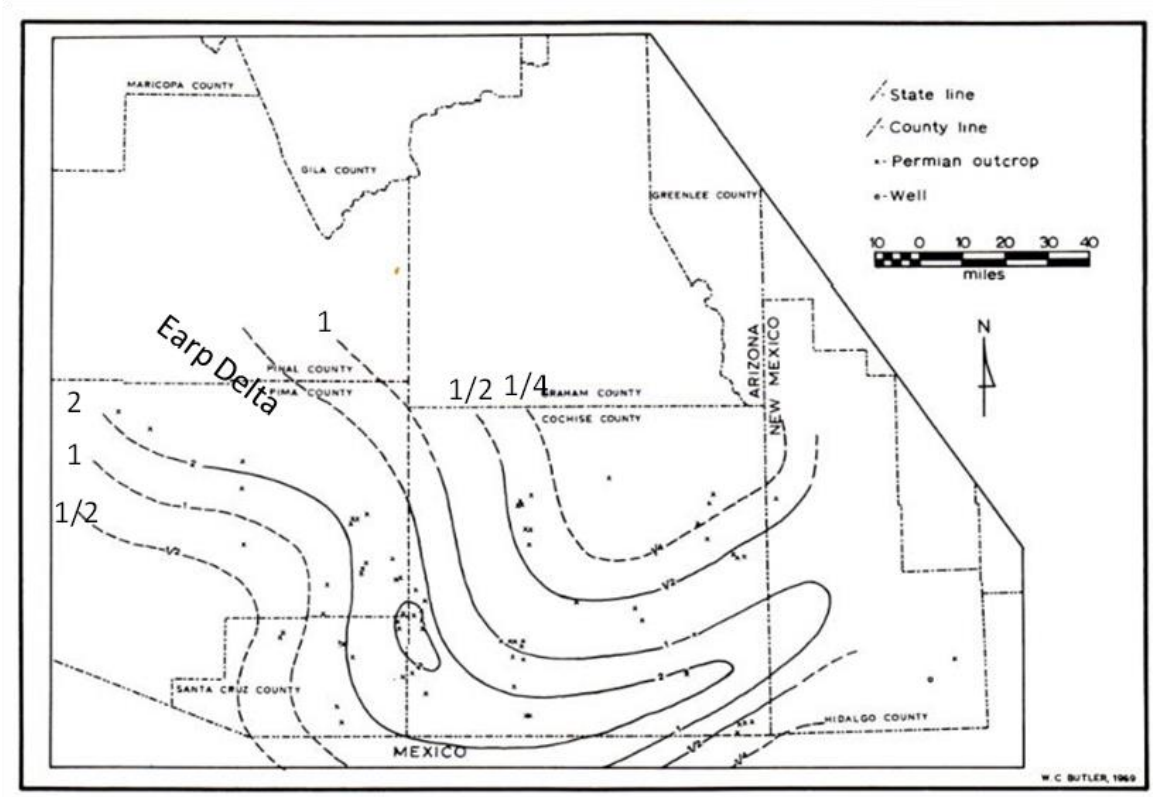

Figure 2. Contour ratios of clastic/carbonate rocks, Earp Formation.
Data from Butler (1971)

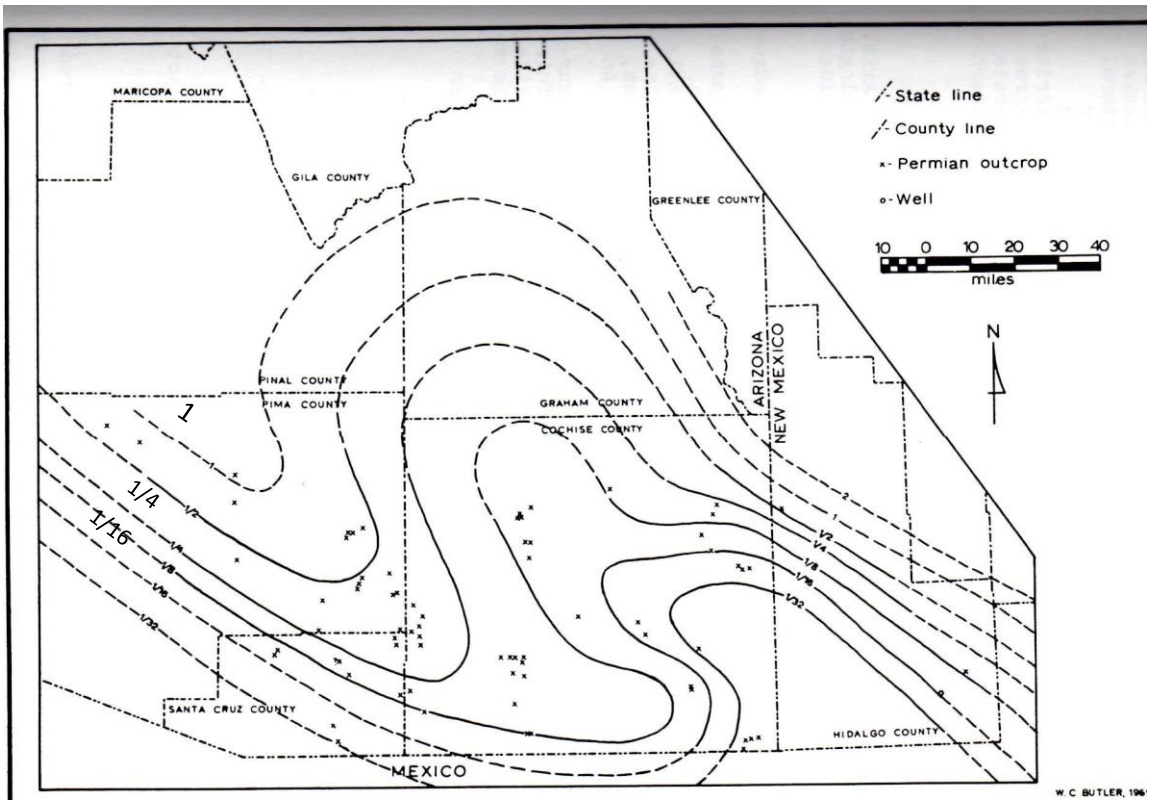

Figure 3. Contour ratios of clastic/carbonate rocks, Colina Limestone and Epitaph Dolomite. Data from Butler (1971).

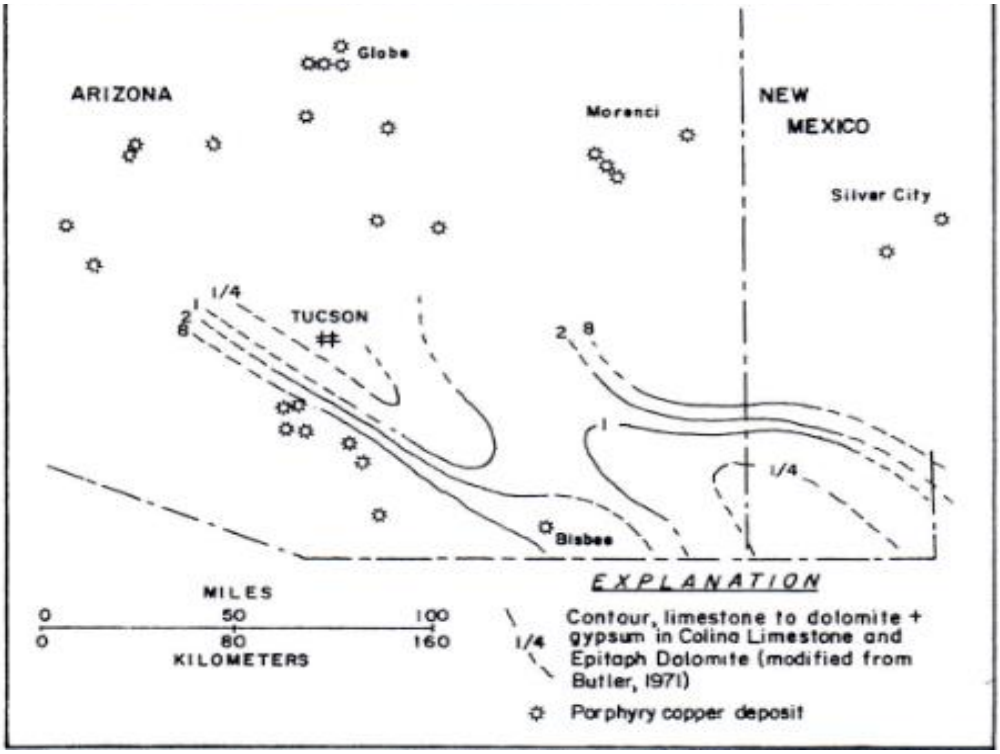

Figure 4. Contour ratios, limestone/ (dolomite+gypsum) in Colina and Epitaph Formations; showing porphyry copper deposits in relation to distribution of Permian evaporite facies, southeastern Arizona. Data from Butler (1971) and Titley (1982).

Sections, Descriptive Lithologies and Environments of Lower Permian Formations

Studies of Paleozoic stratigraphy in the Pedregosa basin of SE Arizona have been completed by Blakey and Knepp (1989), Butler (1969, 1971), Lodewick (1970), Creasey (1967), Ross (1973), among others. Data from published measured sections (locations shown on Plate 1) has been summarized in the appendix and is included in a regional cross section (Plate 2), of present-day Pima and Cochise counties (see location of study area, Fig.1). Barter and Kelley (1982), defined individual members within the Epitaph Formation at the Twin Buttes copper mine near Tucson, which are correlated here with other sections (Plate 2), allowing for construction of a regional facies model (Plate 3) of lower Permian environments.

Plate 1. Lower Permian Stratigraphic Sections Southeastern Arizona

Cross-Section Locations

- A. Sierrita Mountains (Twin Buttes)
- B. N. Santa Rita Mountains (Sycamore Canyon)
- C. Empire Mountains (Hilton Wash)
- D. Southern Whetstone Mountains (Sands Ranch)
- E. Eastern Whetstone Mountains (Dry Canyon)
- F. Tombstone Hills (Old Route 80)

Topographic Base Derived from U.S. Geological Survey

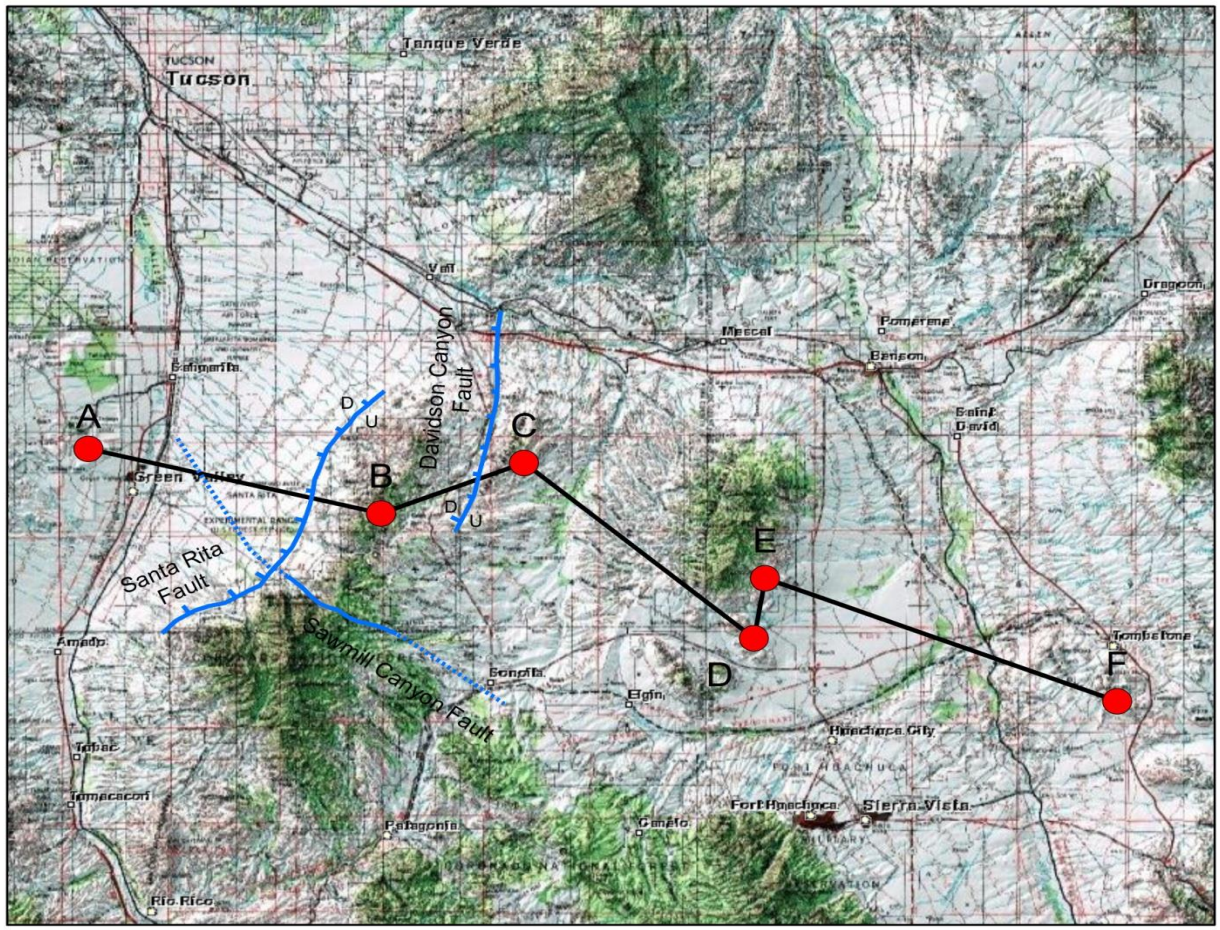

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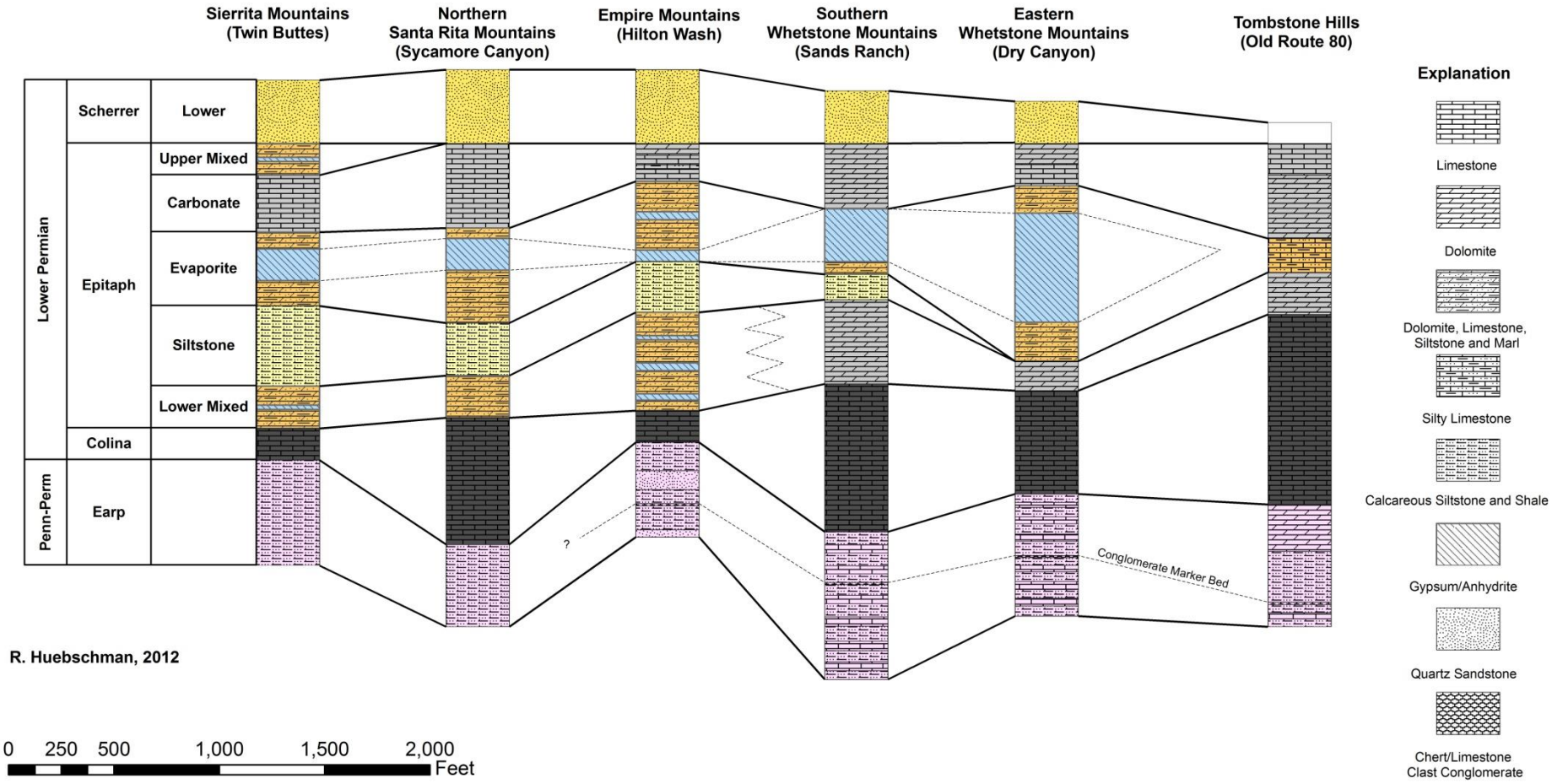
Plate 2. Generalized Stratigraphic Sections of Lower Permian (E. Pima and W. Cochise Counties, Arizona)



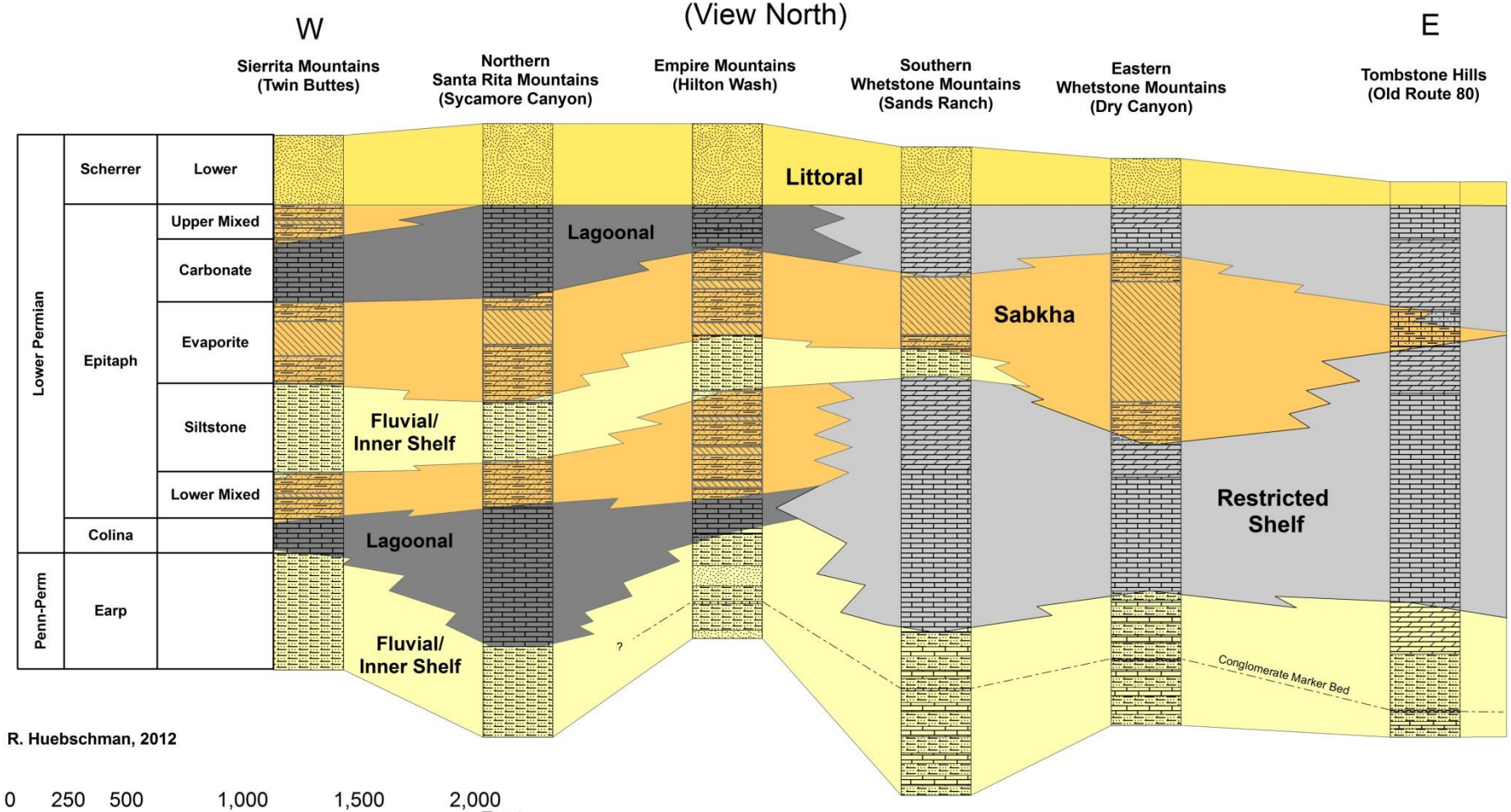
R. Huebschman, 2012

0 250 500 1,000 1,500 2,000 Feet

Vertical Scale (Horizontal Not to Scale)

Sources: Armstrong and Wrucke, Barter, Butler, Creasey, Graybeal, Lodewick

Plate 3. Lower Permian Facies Tract
E. Pima and W. Cochise Counties, Arizona
(View North)



R. Huebschman, 2012

0 250 500 1,000 1,500 2,000 Feet

Vertical Scale (Horizontal Not to Scale)

Sources: Armstrong and Wrucke, Barter, Butler, Creasey. Graybeal, Lodewick

Table 1. Key characteristics of lower Permian formations, Southeastern Arizona

Formation	Rock Type	Environment	Diagnostic features	Skarn minerals
Scherrer (lower to mid-Permian)	White to brown, low angle tabular-planar x-bedded, fine orthoquartzite/ sandstone. A middle member consists of limestone and dolomite.	High energy shoreline-shelf, reworked aeolian sands.	Predominant quartzite/sandstone formation of upper Paleozoic; color and cross-bedding are diagnostic. Directly overlies the upper Carbonate member of Epitaph formation.	Calcic=magnesian (garnet-diopside-chlorite).
Epitaph (lower Permian)	Primary rock types: thin-bedded to massive dolomite and gypsum, with subordinate amounts of limestone, siltstone and marl.	Supratidal-evaporite (coastal sabkha); locally fluvial-deltaic.	Four correlatable members: carbonate, evaporite, siltstone, and lower mixed. Bedded gypsum or anhydrite with dolomite is diagnostic of Epitaph Formation. Carbonate member strongly resembles Colina carbonaceous limestone , except more dolomitic. Evaporite member contains ubiquitous gypsum/anhydrite. Siltstone member makes a good marker unit in altered section.	Magnesian > calcic (diopside, garnet, diopside-garnet-chlorite, and chlorite-serpentine-magnetite).
Colina (lower Permian)	Massive to thin, dark-gray, black carbonaceous limestone; abundant fossil hash; local soft-sediment slump folds and breccia; locally pyritic.	Restricted shelf and lagoonal.	Large gastropods, some algal mats upper part. Black, strongly carbonaceous limestone with abundant fossil hash is typical, though not necessarily diagnostic of Colina. Becomes graphitic when metamorphosed.	Calcic > magnesian (garnet, diopside, and serpentine-magnetite).
Earp (upper Pennsylvanian-lower Permian)	Thin-bedded, wavy-laminated and ripple crossbedded, calcareous red, green and gray siltstone and sandstone; variable amounts of shaly, silty limestone and dolomite.	Fluvial-deltaic west, carbonate shelf east.	Red chert-pebble conglomerate, mid-formation; fusilinids.	Calcic = magnesian (garnet, and garnet-diopside-chlorite).

Earp Formation

The Earp Formation of late Pennsylvanian and early Permian age in southeastern Arizona consists of interbedded siliciclastic and carbonate rocks deposited in shallow-marine, fluvial-deltaic and local supratidal environments (Lodewick, 1970; Armin, 1987). It has extremely varied lithologies of sandstone, siltstone, limestone and shale but within the study area (Fig. 1) is predominantly a clastic-dominated, limy and dolomitic siltstone. Earp sections in the Empire Mountains and western Whetstone mountains are predominantly pink to orange weathered, calcareous siltstone and quartzose sandstone, commonly laminated, with small-scale ripple crossbeds (Fig's. 5, 6), with subordinate mudstone, the probable result of ephemeral streams and deltas. By comparison, Earp sections in the Eastern Whetstone Mountains and Tombstone Hills contain roughly equal amounts of interbedded pinkish-gray calcareous siltstone, shale, and gray limestone (Fig's. 7, 8), indicating an eastward transition to a shallow marine environment. Earp lithologies in the Santa Rita and Sierrita Mountains are obscured by metamorphism and faulting, but outcrop and subsurface observations show a familiar limy siltstone,

with subordinate limestone/dolomite. Because of its diverse lithology and relatively thin bedding, the Earp is one of the least competent Paleozoic units, thus more prone to structural deformation from tectonism.

Unique to the Earp Formation is the red chert-pebble conglomerate in the middle part of the formation (discussed above). This excellent marker bed can be correlated on a local and regional scale (see Plate 2). The red chert pebble conglomerate is commonly associated with a gray limestone clast conglomerate, and at locations where the red chert pebble conglomerate has not been noted, the limestone conglomerate has been recorded at the same stratigraphic position (Bryant, 1968). Though not noted in published stratigraphic sections from the Santa Rita and Sierrita Mountains (see appendix), the chert conglomerate has reportedly been observed in exploratory drill holes.

The Earp Formation is host to copper skarn mineralization in the porphyry belt south of Tucson. Earp siltstone usually alters to a dense, flinty, calc-silicate hornfels. Non-hornfels skarn varieties may occur as a soft, greenish "grit"; a diopside-garnet-chlorite-altered siltstone. Mineralization occurs selectively in carbonate-rich units, where copper sulfides occur in quartz-chlorite-calcite veinlets or as disseminations in garnet skarn or in garnet-diopside-chlorite skarn, with scattered and weak serpentine.

Figure 5. Laminated siltstone rock type of Earp Formation, with parallel and convolute laminations.

Figure 6. Sandstone in Earp Formation, Empire Mountains.

Figure 7. Earp Formation, Eastern Whetstone Mountains, consisting of gray limestone and pink siltstone/marl.

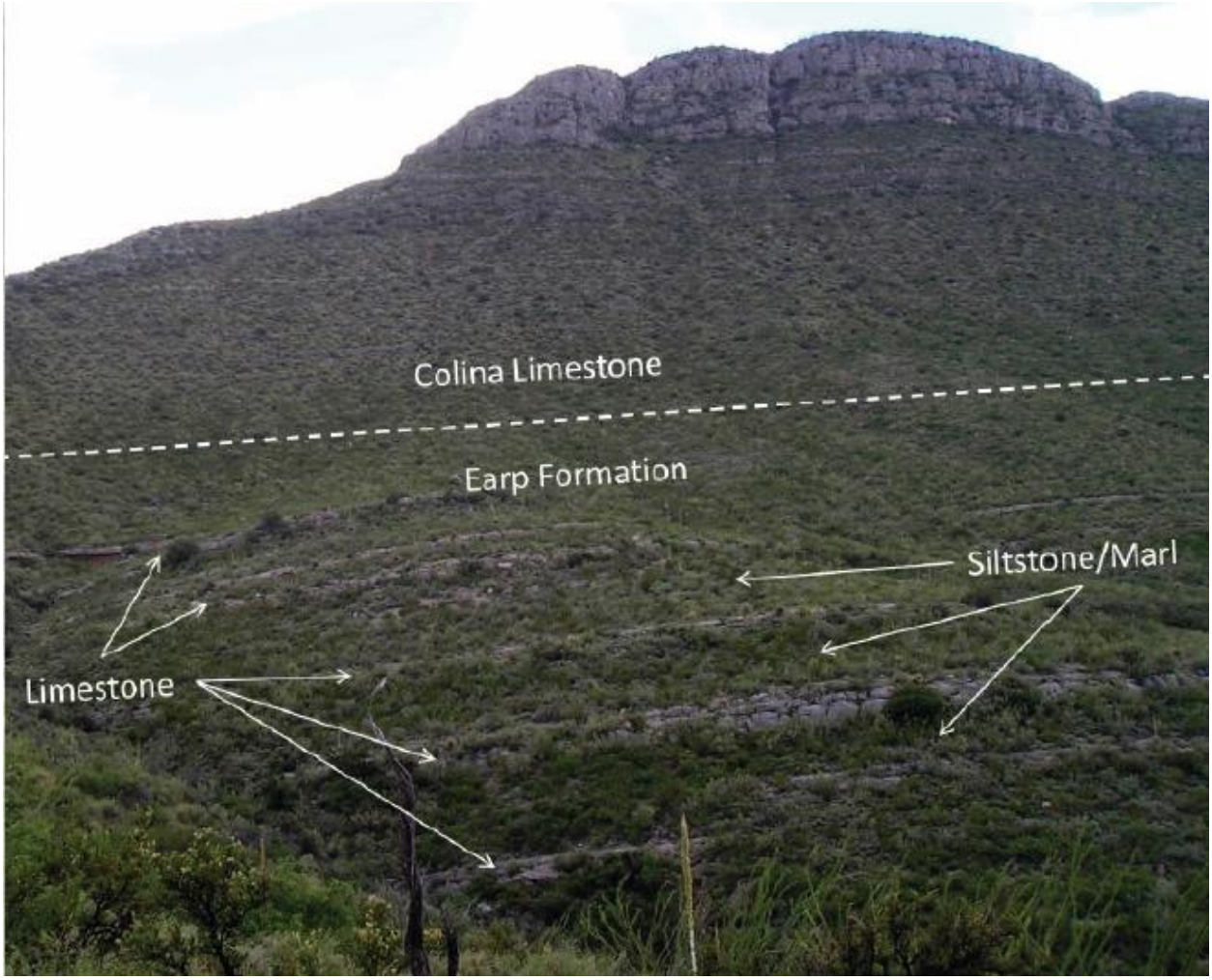


Figure 8. Earp and Colina Formations, eastern Whetstone Mountains.

Colina Limestone

The Colina Limestone lies conformably and gradationally on the Earp Formation. The lower contact with Earp is defined where dark colored limestone of Colina dominates over varicolored siltstone and mudstone of Earp. The upper Colina contact with Epitaph dolomite is more problematic, picked (at its type section in Tombstone Hills) where dolomite (Epitaph) dominates over limestone (Colina). However, Blakey and Knepp (1989) call this contact "of a chemical rather than sedimentological nature", consisting of "an irregular dolomitization boundary not confined to a given stratigraphic horizon", with limestones of the upper Colina often seen grading laterally into dolomites indistinguishable from the Epitaph. This may be attributable to seepage reflux diagenesis, a dolomite replacement process commonly occurring

in Permian basins, through the alteration of metastable limestones by hypersaline brines refluxing from evaporite lagoons (Adams and Rhodes, 1960). In sections west of the Whetstone Mountains, the Colina-Epitaph contact is more easily placed where distinctive dark gray Colina limestone grades into intercalated clastics, carbonates and gypsum of the lower Epitaph.

Colina Limestone (Fig's. 9, 10) is massive to thinly laminated, dark gray to black with abundant (3-5%) organic carbon, an H2S odor, and locally disseminated pyrite, indicative of reducing conditions. A common feature is an abundance of speckled light colored fossil hash (Fig. 10), attributed to bottom-feeding by scavengers, on restricted shelf and lagoonal environments with a lack of currents, at moderate depths (Wilt, 1969). Local occurrences of algal mats indicate near-shore conditions (Armstrong and Wrucke, 1987) were also present.

The Colina is 900 feet thick at its type section near Tombstone, thins westward to only about 100 feet in the Empire mountains (over "Earp delta"), thickens again abruptly to 500-600' in the Santa Rita Mountains and thins to about 150 feet at Twin Buttes. Pronounced thickening of Colina limestone in the northern Santa Rita Mountains (Plates 2, 3) accompanied by soft sediment slumping, visible in drill core (Fig. 11), could be the result of subsidence caused by structural collapse marginal to Earp delta, or possibly caused by growth faulting during early Permian tectonism and sedimentation.

Figure 9. Outcrop of Colina Limestone, Empire Mountains.

Figure 10. Dark gray to black limestone of the Colina Formation, with fossil hash (white specks).

The Colina Limestone is an important host to mineralization at Twin Buttes and other copper skarn deposits south of Tucson. Garnet skarn (green or brown) assemblages are common, along with some diopside and serpentine-magnetite, with copper sulfides as disseminations or in veinlets.

Figure 11. Soft sediment slumps and breccia, Colina Limestone, northern Santa Rita Mountains (Core photo by permission of Rosemont Copper Company)

Epitaph Dolomite

The Epitaph Dolomite intertongues with Colina Limestone, and is the dolomitized and gypsum-bearing, lateral facies equivalent of the Colina (Butler, 1969, 1989). The two formations are typically treated as a single depositional unit (Blakey and Knepp, 1989). The US Geological Survey interpreted the Epitaph section in the Whetstone Mountains as an enclosed inland shallow shelf in which evaporation exceeded influx of marine waters, resulting in saline intertidal and supratidal depositional environments similar to sabkhas of the modern Persian Gulf (Armstrong and Wrucke, 1987).

The Epitaph contains a diverse depositional package of carbonate rocks, fine grained clastics, and gypsum/anhydrite. At its type section in the Tombstone area, the lower 300 feet is dolomite and the upper 370 feet is limestone, siltstone and dolomite. Westward toward the Whetstone and Empire Mountains, the Epitaph includes much gypsum and interbedded dolomite/siltstone/marl, and mudstone. The lower dolomite unit found in the Whetstone Mountains and Tombstone sections (Plate 2) is absent west of the Whetstone Mountains, where it apparently pinches out (Creasey, 1967) within interbedded siltstone, evaporites and carbonates of the Epitaph lower mixed member.

The Epitaph is host to important copper skarn mineralization at Twin Buttes mine, where Barter and Kelley (1982) divided the Epitaph into four members (Pe1 through Pe4). Mineralization is strongly controlled by a dolomite-limestone-anhydrite member (Pe2) and an upper limestone member with subordinate dolomite (Pe3). Pe1, Pe2 and Pe3 members have been correlated regionally in this study (plate 2), as the “siltstone” (Pe1), “evaporite” (Pe2), and “carbonate” (Pe3) members. The widely correlated evaporite and carbonate members of the Epitaph have excellent exploration potential for skarn mineralization within the porphyry copper belt south of Tucson.

Pe4 member at Twin Buttes, a mixed unit of interbedded siltstone and limestone, definable by local presence of anhydrite, is not mentioned elsewhere in the literature, and may be present only in the Twin Buttes area (see description of Sierrita Mountains section, appendix). Also at Twin Buttes, Barter and Kelley (1982) included a sequence of thermally metamorphosed siliciclastics and anhydrite within the upper Colina Limestone, based on their alteration characteristics; but unaltered equivalents are better correlated to the “lower mixed” member of Epitaph (Plate 2), as described below.

Lower Mixed Member

In central Pima County, the lower mixed member consists of intercalated dolomite, limestone, interbedded silts, gypsum and marls (Fig. 12). Eastward toward the Whetstone Mountains and Tombstone Hills the member undergoes a facies change to predominantly dark gray dolomite (Plate 2), as land-sourced clastics and evaporites diminish eastward toward the restricted carbonate shelf. This member is host to copper mineralization in carbonate-rich units, most commonly in diopside and serpentine-magnetite skarn.

Figure 12. Lower mixed member of Epitaph Formation, Empire Mountains

Siltstone Member

The siltstone member consists of grayish green laminated to thinly bedded siltstone with calcareous to clay partings, which weathers reddish brown, and displays irregular to parallel laminations and ripple crossbeds (Fig's. 13, 14). Although not a significant host to mineralization, the siltstone member is a reliable marker unit (see Plate 2), readily identifiable in altered drill core at Twin Buttes and other copper skarn deposits near Tucson. It has the same lithology and sedimentary structures as Earp siltstone, probably the result of fluvial-deltaic fine clastics invading a coastal sabkha environment and nearby restricted carbonate shelf. Unlike Earp, the siltstone member has evaporite sequences above and below, key to its recognition as a member of the Epitaph.

Figures 13 and 14. Laminated siltstone with climbing ripple laminae, in siltstone member of the Epitaph Formation

Evaporite Member

The evaporite member, like the lower mixed member, contains an alternating assemblage of dolomite, marl, siltstone, some algal limestone (Fig. 15) and much gypsum/anhydrite. This member is about 900 feet thick in the Whetstone Mountains, thinning to a mere 100 feet near Tombstone, probably due to an eastward facies change from coastal sabkha to carbonate shelf; or perhaps due to tectonic displacement of Tombstone section (see Tectonic Restoration of Permian Sections, below). Ubiquitous presence of gypsum and/or anhydrite (Fig. 16) defines the evaporite member of the Epitaph, with individual gypsum intervals approaching 60 feet or more in thickness (Plate 2, cross-hatched blue).

This member is a notably important copper skarn host at Twin Buttes and other porphyry deposits south of Tucson. Due to a dominant dolomitic protolith, magnesian skarn assemblages are common to the member. Copper sulfides are found as disseminations in diopside skarn and finely concentrated in veins and stockwork veinlets of chlorite-serpentine-magnetite. Veinlets of chlorite-actinolite-tremolite are also locally present.

Figure 15. Algal limestone in evaporite member of the Epitaph Formation

Figure 16. Bedded gypsum, in evaporite member of the Epitaph Formation

Carbonate Member

The carbonate member of the upper Epitaph in Pima County is widespread, massive to thinly- bedded, dark gray to black, fetid limestone with fossil hash – by all appearances, the same rock type as Colina Limestone. Eastward in the Whetstone and Tombstone sections the member becomes dark to light gray, increasingly dolomitic, and locally cherty. The member was deposited in a restricted shelf and lagoonal setting, possibly the final transgression of the Pedregosa Sea in advance of the Scherrer littoral sands. In drill core studies, care must be taken to differentiate the carbonate member of upper Epitaph Formation, from Colina limestone. The carbonate member is readily identifiable as a dark-colored limestone sequence directly below the distinctive cross-bedded Scherrer sandstone, and above the gypsum-bearing and lithologically-varied evaporite member of Epitaph Formation (Fig. 17).

This member is an important host to copper skarn mineralization, which occurs in large sections of green or brown garnetite, with alternating diopside or diopside-garnet-chlorite skarn. Copper sulfides occur as disseminations or finely concentrated in veinlets of serpentine-magnetite.

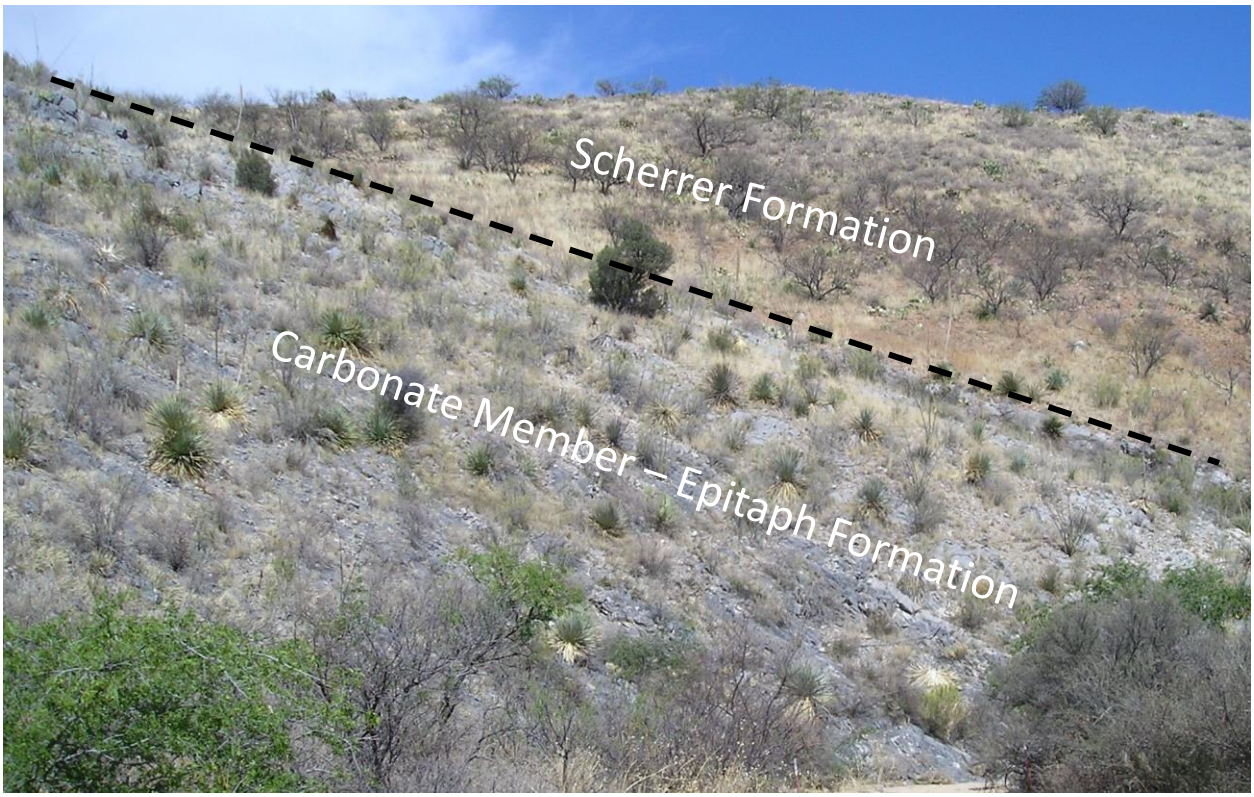


Figure 17. Contact of Epitaph and Scherrer Formations, Empire Mountains

"Upper mixed unit"

An upper mixed unit, noted only at Twin Buttes, is similar to the Epitaph lower mixed member in lithologies (i.e. interbedded limestone, dolomite and siltstone with minor anhydrite).

Scherrer (lower) Formation

The lower Scherrer Formation is readily identifiable as brownish sandstone or orthoquartzite, mostly fine grained, well rounded and well sorted, probably deposited in a high-energy nearshore littoral environment (Blakey and Knepp, 1989). Small-scale cross bedding is common. Small brown spots due to oxidation of an iron mineral, generally occurring as pits or nodes, are a common feature of the Scherrer throughout its area of outcrop. The Scherrer-Epitaph contact is picked where the uppermost

Epitaph carbonate grades into red siltstone of Scherrer. The distinctive features of Scherrer make it a convenient "marker" unit above the Epitaph carbonate member.

Facies Tract Interpretations and Problems

The facies model of Plate 3 depicts a restricted, shallow carbonate shelf bounded on the west by coastal sabkhas and lagoonal environments, with periodic influx from ephemeral streams onto a deltaic complex, similar to Permian (Leonardian series) environments of the western and northern Midland Basin of north-central Texas (Jones and Hentz, 1988; Handford, R.C, 1981). Partial modern day analogs might be the coastal sabkhas of the northwestern Gulf of California (Castens-Seidell and Hardie, 1984); an ephemeral stream delta (Wooramel delta) in Shark Bay, Australia; and Trucial Coast sabkhas of the Persian Gulf (Evans, et al., 1964)

The lower Permian sedimentary complex of southeastern Arizona contains favorable carbonate hosts for porphyry copper alteration and mineralization. Diverse and changing Permian depositional environments can complicate efforts to delineate favorable carbonate skarn protoliths and their stratigraphic controls. Facies modeling as defined by rock type and environment may be a helpful tool in targeting potential skarn protoliths in sedimentary rocks near porphyritic intrusive bodies. The Earp, Colina and Epitaph are a coeval package of multiple environments, or facies, represented by three basic rock types. Rock type 1 is thinly-laminated and ripple crossbedded, red and greenish gray, calcareous and dolomitic siltstone and sandstone (with subordinate mudstone and limestone) deposited as fluvial-deltaic and inner shelf sediments. Rock type 2 is massive to thin-bedded dark-gray to black, carbonaceous, restricted shelf and lagoonal limestone with abundant fossil hash. Rock type 3 is thin-bedded to massive dolomite and associated gypsum (with varying amounts of limestone, siltstone and marl) deposited in a coastal sabkha environment. Limestone and dolomite in restricted shelf/lagoonal and sabkha facies (see Plate 3) have proven to be the most favorable hosts for porphyry copper skarn mineralization, within the lower Permian depositional sequence.

Pronounced facies changes can be observed in lower Permian outcrops of the Empire Mountains, where sedimentation was dominated by Earp deltaic clastics, later superposed by coastal sabkha evaporites and flanking lagoonal and restricted shelf carbonates. The Colina Limestone, normally several hundred feet in thickness, thins markedly and is absent in parts of the Empire Mountains (Spencer, J.E., et al, 2001). However, the overlying Epitaph Formation contains Colina-like black limestone intercalated with gypsum and dolomite of the Epitaph evaporite member, resulting from interplay of lagoonal and sabkha environments. The Epitaph siltstone member was deposited by renewed influx of Earp deltaic clastics, onto the coastal sabkha environment. The carbonate member of uppermost Epitaph, which also looks like Colina, represents a transgression of restricted shelf carbonates onto the Pedregosa shelf. This diversity of lithologic sequences is evidence of shifting and interfingering depositional environments along an advancing, then retreating, Earp deltaic front. It complicates the task of delineating stratigraphic controls of favorable skarn protoliths where facies changes are encountered.

Tectonic Restoration of Permian Sections

The composite of Permian sections (Plate 2) is scaled for vertical thickness; but for ease of illustration, relative geographic positioning between sections is not shown to scale. Regarding potential tectonic displacement of Permian stratigraphic sections, discussions with Jon E. Spencer (2012) of the Arizona Geological Survey reveal the following:

There is no evidence of significant displacement of sections “B” through “E” (see Plate 1). The amount of extension along the Davidson Canyon fault is probably no more than a mile or two, and the Cienega basin occupies a synclinal warp with no significant faulting between the Whetstone and Empire blocks.

Evidence exists for seismogenic low angle westward extensional faulting (see Plate 1, Santa Rita fault) of about 10 miles along the west flank of the Santa Rita Mountains (Johnson and Loy, 1992). Restoration of Twin Buttes section eastward would place the Twin Buttes and Mission copper deposits about 10 miles closer to the Helvetia area porphyry systems in the northern Santa Rita Mountains, including the Rosemont copper skarn deposit, with host stratigraphy and alteration features similar to that at Twin Buttes copper mine (Anzalone, 1995). The Sawmill Canyon shear zone (Drewes, 2002) strikes northwestward across Santa Cruz valley between Twin Buttes and the Northern Santa Rita Mountains, but the amount of lateral displacement on this structure, if any, is unknown.

Geologists of the Arizona Geological Survey believe that eastward extensional faulting might have occurred in the San Pedro Valley, along a north-south line from the Rincon Mountains to the Huachuca Mountains, with potential displacement of section “F” (Plate 1) at least 15 miles northeastward. This would put a restored Tombstone Hills section somewhere near present-day Sierra Vista, relatively closer to the Whetstone Mountains sections. In summary, based on current knowledge, the geographic line of section on Plate 1 might be shortened through tectonic restoration by approximately 12-25 miles (from 70 miles to 45 miles) in an east-west direction.

Conclusions:

1) Late Paleozoic tectonism in southeast Arizona, possibly related to the Ouachita orogeny, resulted in an emergent shelf peripheral to a subsiding Pedregosa basin, with early Permian sedimentation controlled along a northwest-southeast structural grain; the most salient feature being a southeast-prograding fluvial-deltaic complex that interfingered with supratidal evaporite, lagoonal, and shallow shelf marine carbonate rocks.
2) Facies can play an important role in understanding complex stratigraphy of the lower Permian sequence-- a coeval package of 3 basic rock types: calcareous and dolomitic siltstone with subordinate carbonate rocks (fluvial-deltaic and shallow marine); carbonaceous and fossiliferous limestone (lagoonal and restricted shelf); and dolomite/gypsum (coastal sabkha); from which a regional facies tract has been modeled, which closely resembles Permian environments such as the Midland Basin of central Texas, and modern day environments such as the inner shelf and coastal sabkhas of the Persian Gulf and the Gulf of California.
3) The Epitaph Formation can be divided into four distinct members, providing important geologic controls for skarn mineralization: carbonate, evaporite, siltstone and lower mixed members; widely correlated along a southeast-trending extension of the Arizona porphyry belt.
4) Colina Limestone is also an excellent host to copper skarn mineralization. A thickened Colina section in the Santa Rita Mountains contains soft sediment slump features possibly attributable to local basin subsidence along the margin of the Earp delta, or to basin faulting.
5) In general, the best skarn hosts are limestone and dolomite protoliths from evaporite and restricted shelf/lagoonal environments.
6) Some displacement of stratigraphic sections may have occurred from east-west extensional faulting; however, with minimal effect on correlations and interpretations of this study.

Acknowledgements

I am indebted to geologist David F. Briggs and to my wife, Susan for their invaluable computer assistance in illustrating and formatting this report. I am also very grateful to Jon E. Spencer and Charles A. Ferguson of the Arizona Geological Survey, and consulting geologist Daniel M. Aiken, for their critique and constructive input to the manuscript.

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Appendix: Generalized Descriptions of Measured Sections

(Measured sections from previous workers, summarized by R. Huebschman, 2012)

Sierrita Mountains Section (Twin Buttes)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Scherrer	Lower	300	Sandstone	Fine grained, cross-bedded sandstone
Epitaph	Upper mixed unit**	90-150	Limestone,dolomite, siltstone and anhydrite	Interbedded limestone, dolomite and siltstone with minor anhydrite
Epitaph	Carbonate (Pe3 member of Barter and Kelly, 1982)	100-270	Limestone, minor siltstone and anhydrite	Limestone, minor siltstone and anhydrite
Epitaph	Evaporite (Pe2 member of Barter and Kelly,1982)	100-350	Anhydrite, dolomite, limestone and siltstone	Interbedded anhydrite, dolomite, limestone, siltstone
Epitaph	Siltstone (Pe1 member of Barter,Kelly,1982	150-380	Siltstone	Siltstone with minor anhydrite
Epitaph	Lower Mixed*	200	Limestone,dolomite, siltstone and anhydrite	Interbedded dolomite, limestone and siltstone with minor anhydrite
Colina		150	Limestone	Limestone
Earp		300-500	Calcareous siltstone	Siltstone and sandstone, partly limy and dolomitic; beds of limestone and shale

Modified from: Barter C. and Kelly J., 1982, Geology of the Twin Buttes Mineral Deposit; in Advances in Geology of Porphyry Copper Deposits, pp. 407-432.
* Lower mixed member of Epitaph was included into upper Colina Formation at Twin Buttes Mine by Barter and Kelly, 1982.
**Noted only in the Twin Buttes Mine area.

Northern Santa Rita Mountains Section (Sycamore Canyon)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Scherrer	Lower	350	Sandstone	Fine grained, cross-bedded sandstone and orthoquartzite
Epitaph	Carbonate	400	Limestone	Fossiliferous, black, thin-bedded to massive micritic limestone; bleached, with local marble; minor interbedded siltstone
Epitaph	Evaporite	50	Dolomite, limestone and siltstone	Interbedded dolomite, limestone and siltstone
Epitaph	Evaporite	150	Gypsum/anhydrite	Gypsum and anhydrite, with minor beds gypsiferous marl, dolomite, siltstone
Epitaph	Evaporite	250	Dolomite, limestone and siltstone	Interbedded dolomite, limestone and siltstone , marble and hornfels
Epitaph	Siltstone	250	Siltstone	Thin bedded siltstone
Epitaph	Lower Mixed	200	Dolomite, limestone and siltstone	Interbedded dolomite, limestone and siltstone
Colina		500-600	Limestone	Black to bleached, locally marbleized, thin to massive, micritic limestone, with fossil hash and local soft sediment slumps and breccia
Earp		390	Calcareous Siltstone	Limy and dolomitic siltstone, local marble and hornfels

Note: This section complicated by metamorphism and faulting; lithologies may be inferred and thicknesses estimated.

Sources:
1) R. Huebschman, stratigraphic field observations
2) Drewes, H., 1971, Geologic Map of the Sahuarita Quadrangle, Southeast of Tucson, Pima County, Arizona; USGS Map I-613
3) Ferguson, C.A.,etal, 2009, Geologic Map of Helvetia 7.5 min Quadrangle, Pima County, Arizona;
Arizona Geologic Survey OFR-09-06

Empire Mountains Section (Hilton Wash)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Scherrer	Lower	350	Sandstone	Fine grained, cross-bedded sandstone
Epitaph	Carbonate	180	Dark grey to black limestone	Black, fetid, thin-bedded to massive limestone with fossil hash; resistant weathering; dolomitic near top, silty near base and upper
Epitaph	Evaporite	325	Mixed dolomite, limestone, marl, gypsum, siltstone	Interbedded dolomite, limestone, marl, siltstone, gypsum and calcareous gypsum
Epitaph	Evaporite	55	Gypsum	Massive gypsum with marl interbeds; gypsum has hummocky and cavernous-like weathering; black, Colina-like limestone beds near base
Epitaph	Siltstone	240	Siltstone	Siltstone laminated to very thinly bedded, dense and non-porous, frequent calcareous clay partings, banded greyish green and light grey to greenish gray and greenish black; weathers reddish brown
Epitaph	Lower Mixed	450	Mixed limestone, dolomite, siltstone and gypsum	Interbedded silts, marl, dolomite, limestone, gypsum and calcareous gypsum; intraformational breccia and stromatolitic limestone near base
Colina		150	Limestone	Black, fetid, pyritic, fossiliferous, thin-bedded to massive limestone; occasionally argillaceous and dolomitic; contains 1-2 % disseminated pyrite, abundant fossil hash, gastropods
Earp		80	Siltstone, claystone and limestone	Intercalated orange to gray siltstone, claystone and limestone.
Earp		211	Siltstone and quartz arenite	Gray to orange, even and uneven thinly laminated to cross-laminated calcareous siltstone and quartz arenite sandstone with occasional gray calcareous mudstone. 3 feet greenish gray limestone pebble conglomerate at base. Sandstone and siltstone is light bluish gray on fresh surface, weathers red-orange, apparently due to presence of disseminated iron sulfide.
Earp		157	Quartz arenite, siltstone and claystone	Greenish-gray, thin bedded quartz arenite, siltstone and claystone

Adapted from:
1) Butler,William, 1969, The Upper Paleozoic Stratigraphy of Total Wreck Ridge; U of Arizona M.S.
2) Lodewick, R.E., 1970, Petrology and Stratigraphy of Earp Formation Pima and Cochise County; PhD U of Arizona
Note: Butler (1969) noted the presence of skarn alteration minerals in the Lower Mixed and Evaporite Members of the Epitaph Formation, in the Empire Mountains.

Southern Whetstone Mountains Section (Sands Ranch)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Scherrer	Lower	250	Sandstone	Fine grained, cross-bedded sandstone
Epitaph	Carbonate	310	Dolomite	Massive, cliff-forming dk grey to black dolomite
Epitaph	Evaporite	250	Gypsum	Massive gypsum with occasional marl, dolomite, silts
Epitaph	Evaporite	60	Dolomite, limestone and siltstone	Interbedded dolomite, limestone and siltstone
Epitaph	Siltstone	120	Siltstone	Thin-bedded red and grey siltstone
Epitaph	Lower Mixed	400	Dolomite	Black dolomite and buff siltstone
Colina		700	Limestone	Upper 400' massive dark grey limestone, becoming slightly dolomitic toward top. Lower 300' thin to medium beds dark gray limestone, lesser interbeds gray to red sandstone and siltstone, with buff dolomite.
Earp		700	Calcareous siltstone and limestone	Upper 380' red, pink, buff siltstone-marls and shale, with occasional 5- foot intervals of tan to light-gray, fossiliferous limestone, dolomitic limestone with ribbon-like algal tops. Limestone conglomerate 240 below top of unit, can be correlated with similar conglomerate in Tombstone hills. Lower 320' is gray limestone in more massive 10-foot thick units with thinner sequences of pinkish gray silts, marls and shales. Interfingering environments of terrigenous clastics with shallow-shelf marine.

Sources:
(1) Graybeal, Frederick T., 1961, Geology of the southern Whetstone Mountains; U of Arizona M.S.
(2) Lodewick, R.E., 1970, Petrology and Stratigraphy of Earp. Formation, Pima and Cochise County, Az; PhD thesis, U of Arizona.
(3) R. Huebschman, 2012 field observations

Eastern Whetstone Mountains Section (Dry Canyon)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Scherrer	Lower	200	Sandstone	Fine grained, white to pink and brown cross-bedded sandstone
Epitaph	Carbonate	100	Dolomite	Blue to light gray, massive dolomite, locally cherty, beds up to 3 ft thick
Epitaph	Carbonate	100	Limestone	Blue to light gray, massive limestone, locally cherty, 4 ft beds
Epitaph	Evaporite	130	Dolomite, limestone, siltstone and marl	Interbedded dolomite, limestone, siltstone and marl
Epitaph	Evaporite	517	Gypsum	Massive gypsum, marl, gypsiferous marl; much of interval covered.
Epitaph	Evaporite	184	Dolomite, limestone, siltstone and marl	Interbedded dolomite, limestone, siltstone and marl
Epitaph	Lower Mixed	140	Dolomite	Dark to light blue gray, laminated to thin bedded dolomite, minor marl and siltstone
Colina		490	Limestone	1-4 ft thick med-dk grey limestone and limey mudstone with subordinate olive green dolomite. Few black limestone beds with algal mats, stromatolites, mud chips/cracks.
Earp		578	Intercalated calcareous siltstone, shale, limestone and dolomite	Pale red to reddish brown, thin bedded, nodular, calcareous sandstone, siltstone, and shale, interlayered with light-to medium gray to pinkish-gray limestone and sparse, gray to tan dolomite. Limestone beds commonly occur throughout formation; dolomite beds mainly near the top, contain algal mats, stromatolites, dolomite pseudomorphs after gypsum and anhydrite, with mud cracks, suggesting supratidal environment. Chert pebble conglomerate 2 to 6 feet thick near middle of formation. Mainly an inner shelf environment with influx of terrigenous clastics.

*Note: Epitaph Siltstone Member not present this section

Adapted from:

(1)Creasey, S.C., 1967, Geologic Map of Benson Quad, Az; USGS Misc. Geologic Investigations Map I-470

(2) Armstrong, A.K. and Wrucke, C.T., 1987, Paleozoic Stratigraphic Section in Dry Canyon, Whetstone Mountains, Cochise County, Arizona; in Geological Society of America Centennial Field guide Vol 1, Cordilleran Section; pp. 29-34

Tombstone Hills Section (Old Route 80)

FORMATION	MEMBER	THICKNESS (FT)	LITHOLOGY	LITHOLOGIC DESCRIPTION
Epitaph	Carbonate	150	Limestone	Dark gray, thin to thick bedded limestone
Epitaph	Carbonate	300	Dolomite	Dark gray, massive dolomite
Epitaph	Evaporite	160	Silty limestone	Thin bedded silty to sandy limestone
Epitaph	Lower Mixed	200	Dolomite	Dark gray, massive dolomite
Colina		900	Limestone	Black, fetid, fossiliferrous, thin-bedded to massive limestone
Earp		222	Dolomite and dolomitic limestone	Thin to medium bedded dolomite and limestone with minor mudstone, algae and shell fragments.
Earp		247	Calcareous and dolomitic siltstone, quartz arenite and limestone-pebble conglomerate	Clastic units are reddish gray, thin-bedded with ripple laminations. Minor interbeds gray to pink thin-bedded limestone, mudstone. Pebbly units near the bottom are thin to thick bedded, grayish-red.
Earp		111	Calcareous siltstone, mudstone and limestone	Interbedded thin siltstone, mudstone and limestone, fossiliferous.

Adapted from:
(1) Gilluly, J., 1956, General Geology of Central Cochise County Arizona; US Geological Survey Professional Paper 281
(2) Lodewick, R.E., 1970, Petrology and Stratigraphy of Earp Formation, Pima and Cochise County, AZ, PhD Thesis U of Arizona
(3) Wilt, J.C., 1969, Petrology and Stratigraphy of Colina Limestone; M.S. Thesis, U of Arizona