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FACIES DESCRIPTION AND EVOLUTION OF A WOLFCAMPIAN (EARLY PERMIAN) SHELF MARGIN: HUECO MOUNTAINS, WEST TEXAS

MICHELLE L. STOKLOSA[1], J. A. (TONI) SIMO[1], and GREGORY P. WAHLMAN[2]
[1]Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706;
[2]Exploration and Production Technology Group, Amoco Corp., P.O. Box 3092, Houston, TX 77253

Abstract—The Hueco Mountains of west Texas are situated at the eastern margin of the Late Paleozoic Orogrande Basin. A north-south trending series of outliers lie about 3 mi to the west of the range (19 mi east of El Paso) that are possibly faulted blocks associated with the Rio Grande rift-type graben structure of the present-day Hueco Bolson. The outliers are composed of primarily Upper Pennsylvanian-Lower Permian (Wolfcampian) carbonate strata. The southernmost outlier, which is the subject of this study, is approximately 1 mi in length and consists of about 500 ft of Wolfcampian shelf-margin limestones. Nine different limestone lithofacies have been recognized in this succession, and these have been further grouped into five facies associations, each of which can be placed in a carbonate shelf depositional model. From deepest to shallowest, the facies associations are: Deep Shelf-Basin, Outer Shelf, Buildup, Shallow Shelf, and Breccias. The strata in the outlier show an overall upward-shallowing trend with superimposed, higher-frequency, alternating landward- and seaward-stepping packages. The landward-stepping packages have an erosive base, and consist of the Breccias and the Shallow Shelf associations. A complete seaward-stepping package shows a succession from base to top of Deep Shelf-Basin, Outer Shelf, Buildup and Shallow Shelf associations. Four depositional sequences have also been recognized, each exhibiting a unique succession of landward- and seaward-stepping strata.

INTRODUCTION

This study is a detailed description of the facies associations, stacking patterns, and bioherms of a Wolfcampian shelf-margin complex exposed in the southernmost of the Hueco Mountains outliers (Fig. 1). This outlier is about 1 mi in length, 500 ft thick, and is composed almost entirely of Wolfcampian (Lower Permian) shelf-margin strata, where shelf-to-basin transitions can be seen (Fig. 2a). Emphasis was placed on the description of lithofacies and their relative distributions in order to construct a model that could be applied to subsurface Wolfcampian shelf-margin complexes in the adjacent Permian Basin and elsewhere.

Most published studies on Wolfcampian (Lower Permian) carbonate shelf-margin stratigraphic sequences are based on subsurface data from the Permian Basin region. For example, Dunham (1969) and Malek-Aslani (1970) described subsurface Wolfcampian shelf-margin reservoirs in the northern Delaware Basin, Asquith and Drake (1985) briefly described Wolfcampian bank and biohermal facies on the margin of the Eastern Shelf of the Midland Basin, Wahlman (1985, 1988, 1996) discussed the facies and evolution of Wolfcampian shelf-margin bioherms throughout the Permian Basin region, Mazzullo (1995) analyzed Wolfcampian stratigraphic patterns of shelf-margin strata in the northern Midland Basin, and Wagner et al. (1995) described the development of a Wolfcampian shelf-margin reservoir on the Central Basin Platform. Outcrop analog studies for these Wolfcampian subsurface reservoirs have been needed, but until recently suitable exposures were not known. Jordan (1975) described the general distribution of outcropping Wolfcampian facies in the Orogrande Basin area, but little has been done since. Wahlman et al. (1992a, 1992b, 1993) and Wahlman (1996) reported the Wolfcampian shelf-margin biohermal complexes in the western outliers of the Hueco Mountains and noted their significance, but they have only briefly described the shelf-margin facies and their stratigraphic relationships.

GEOLOGIC SETTING

Paleogeography

The Permian Basin refers to a series of north–south-trending platforms and basins in New Mexico and Texas. Uplift and subsequent basin formation occurred during the Paleozoic assemblage of Pangea as a result of the reactivation of older faults by compressive forces along the Ouachita and Marathon fold and thrust belts. Significant carbonate deposition occurred on the platforms and platform margins, and typically the basins were filled by siliciclastics. As suturing continued, the Permian Basin became more arid, as a result of both increasing continentality and its movement from tropical latitudes to more arid ones. Complete dessecation of the

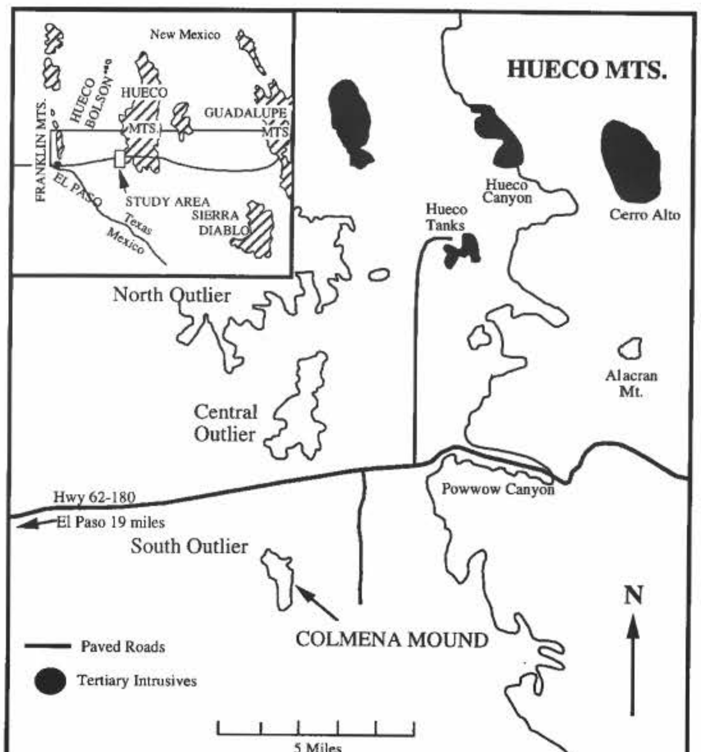

FIGURE 1. Regional map showing the location of the Hueco Mountains in Texas and New Mexico (inset, modified from Connolly and Stanton, 1983), and the location of the outliers and study area.

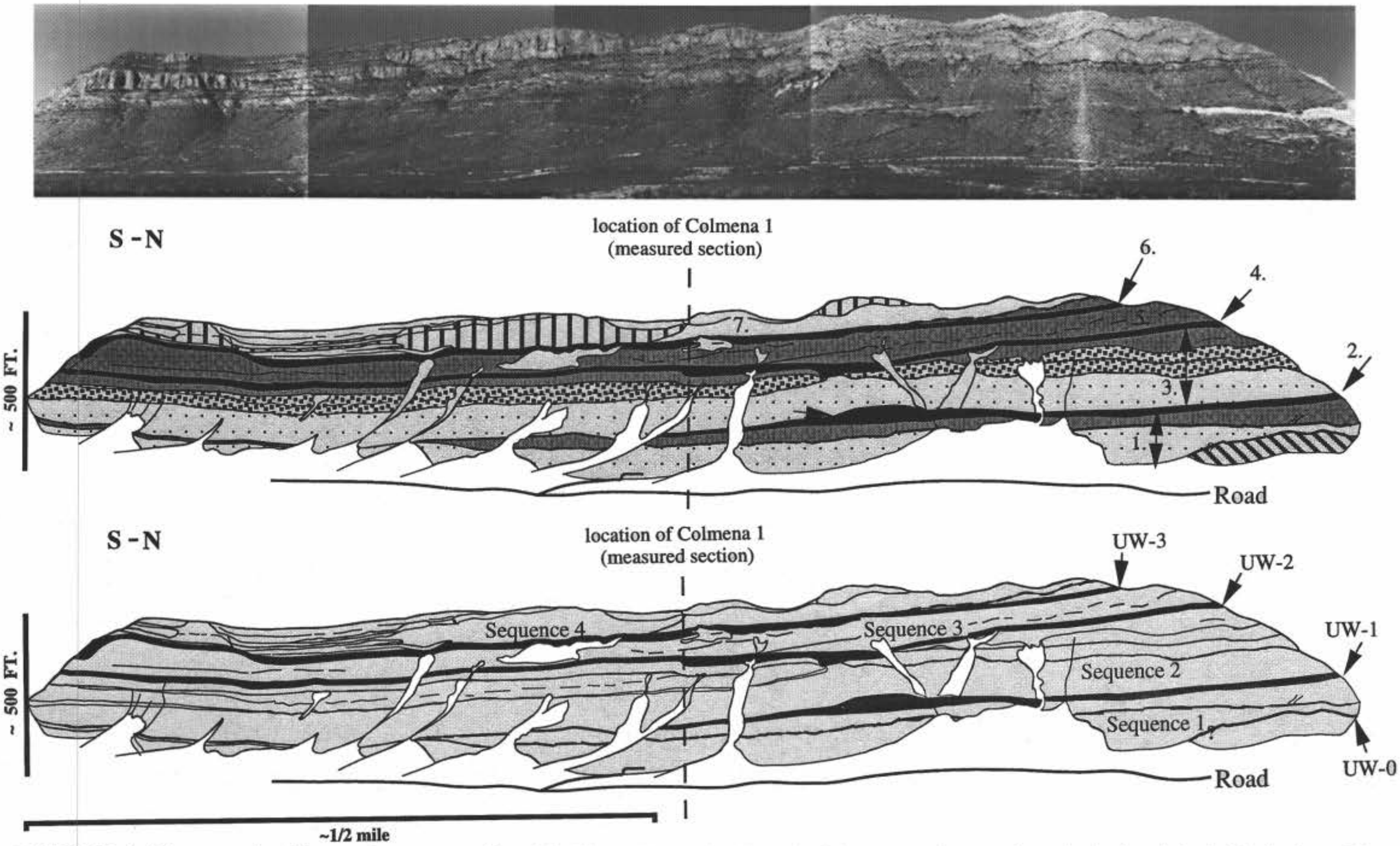

FIGURE 2. (a) Photomosaic of the southernmost outlier of the Hueco Mountains. Length of the outcrop is approximately 1 mi, and the height is about 500 ft. Schematic diagrams were traced from (a) and coordinated with field data to show (b) the stacking patterns of the facies associations and (c) the sequence stratigraphic framework.

basin was achieved at the end of the Permian period (Shepard and Walper, 1983).

The Late Paleozoic Diablo Platform and Orogrande Basin formed in the western part of the Permian Basin, in present-day west Texas and south-central New Mexico. Subsidence in the Orogrande Basin began in the Middle Mississippian and ended in the Permian (Pray, 1959; Jordan, 1975). The eastern shelf of the Orogrande Basin corresponds to the Precambrian Pedernal uplift in the north and Diablo Platform in the south. The western margin corresponds to the Burro-Florida uplift (Markello and Sarg, 1996). The Pedernal uplift on the eastern shelf was tectonically active during most of the Pennsylvanian and shed vast amounts of sediment into the basin. The Burro-Florida Platform was also uplifted during the Pennsylvanian collision of Laurasia and Gondwanaland (Markello and Sarg, 1996). Cyclic nonmarine and marine sedimentation in the region resulting from the different phases of uplift and erosion was common throughout the Pennsylvanian–Early Permian. In the Lower Permian, the regional lateral facies belts in the Orogrande Basin were nonmarine siliciclastic facies to the north (Abo redbeds), carbonate facies to the south (Hueco limestones), and a transitional zone between them (Jordan, 1975; Mack and James, 1986). Upper Pennsylvanian sediments account for the bulk of the fill of the Orogrande Basin, and the Lower Permian (Wolfcampian) sediments represent the final filling of this marginal cratonic basin (Jordan, 1975).

Tectonic setting

The Trans-Pecos region of west Texas and New Mexico, defined as the mountainous region between the Pecos River to the east and the Rio Grande to the west, is a tectonic terrain in which Paleozoic Permian Basin structural elements are overprinted with the Cenozoic Rio Grande structural styles (Markello and Sarg, 1996). Figure 3 shows the regional tectonic framework of this area during the Late Pennsylvanian and Permian periods. The Hueco Mountains are a 45-mi-long, north–south-trending range (Fig. 1) located in this overlap area of south-central New Mexico and west Texas. The strata are mildly folded from the Laramide compression of the late Mesozoic and early Cenozoic. Part of the Rio Grande rift, these mountains also record the effects of Cenozoic extension along their normal fault-bounded west side. The Hueco Bolson is a west-tilted graben separating the Hueco Mountains from the Franklin Mountains to the west. The normal fault-bounded western margin of the Hueco Bolson shows over 8000 ft of displacement at the Franklin Mountains, but the graben shallows to the east and vertical displacement is much less at the Hueco Mountains (Pol, 1985). The outlier studied here is the southernmost of a series of north-trending outliers 3 mi west of the main escarpment of the Hueco Mountains and are on the eastern side of the Hueco Bolson.

Stratigraphy and previous work

The first geologic map to include the Hueco Mountains was by Richardson (1904), but the more detailed map by King et al. (1945) is often considered to be the first geologic map of the entire mountain range. Included in this map is an expanded and updated version of stratigraphic units that had originally been proposed by Beede (1920). Williams (1963) published a detailed geologic map of only the Pennsylvanian–Lower Permian outcrop area in the north-central portion of the main range.

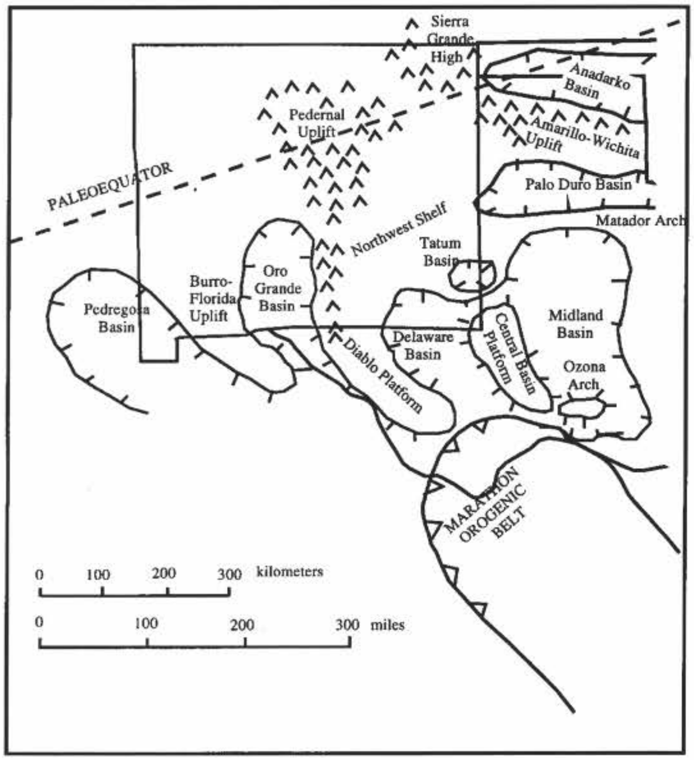

FIGURE 3. Regional tectonic framework of the Trans-Pecos region and Permian Basin during the late Pennsylvanian and Permian periods (modified from Markello and Sarg, 1996).

The strata of the Hueco Mountains typically dip to the north, with dips increasing southward and progressively older rocks exposed to the south. The stratigraphic section of these mountains contains a nearly complete succession of Paleozoic strata that rest on a base of Precambrian granite (Pol, 1985). The Pennsylvanian Magdalena Limestone and Lower Permian Hueco Group comprise the Hueco Mountains escarpment in the central to northern range, as well as the outliers to the west of that escarpment.

The Lower Permian Hueco Group is the youngest sedimentary unit exposed in the Hueco Mountains and it is separated from the underlying Pennsylvanian Magdalena Group by an angular, erosional unconformity that truncates progressively older formations southward (King et al., 1945). The Powwow Conglomerate Member lies on this unconformity at the base of the Hueco Group. The three mainly carbonate stratigraphic units overlying this conglomerate are, in ascending order, the Hueco Canyon Formation, the Cerro Alto Formation, and the Alacran Mountain Formation (Fig. 4) (Williams, 1963; Beard, 1983). Williams (1963) named these units and described the lithofacies in the Hueco Group stratotype. The Hueco Canyon Formation stratotype consists of 600 ft of thick-bedded, cliff-forming limestones that contain abundant stylolites and chert nodules. The Cerro Alto Limestone stratotype consists of 460 ft of typically undulatory medium-to-thin beds of dark gray limestone with decreased abundance of stylolites and chert. The Alacran Mountain Formation stratotype consists of 622 ft of limestones similar to those of the Hueco Canyon Formation, but it is divided by the Deer Mountain Member, which is a tongue of Abo redbeds extending southward from the Pedernal Uplift. Williams (1963) recognized distinct faunal assemblages in these three formations, and described the fusulinid biostratigraphy of the section. Based on Williams (1963) fusulinid correlations to the Wolfcampian stratotype of the Glass Mountains in west Texas, the Hueco Group is considered to be late Middle to Late Wolfcampian in age (Zone of Pseudoschwagerina), with the uppermost part possibly being earliest Leonardian.

Other significant studies on the Hueco Group in the Hueco Mountains and other nearby areas have been done by Seewald (1968), Kottlowski (1969), Jordan (1975), LeMone et al. (1975), Wollschlager (1975), Simpson (1976), Simpson and LeMone (1983), Cys and Mazzullo (1985), and Cys (1986). Seewald (1968) used the nomenclature of King et al. (1945) and Williams (1963) to describe the Lower, Middle and Upper Divisions of the Pennsylvanian Magdalena Group, as well as the three formations of the Hueco Group in the Powwow Canyon area of the Hueco Mountains. Kottlowski (1969) summarized the Upper Paleozoic strata in the El Paso border region, paying special attention to the Wolfcampian strata, and including a paleogeologic map. Jordan (1975) summarized characteristics of the Hueco Group in the Franklin, southern Sacramento, Jarilla, San Andres, Robledo, Florida, Tres Hermanas, and Hueco Mountains and outlined the Orogrande Basin depositional history during Wolfcampian time. Wollschlager (1975) studied and established the reference section for the Wolfcampian shelf strata in the Hueco Mountains. His detailed microfacies analysis of the Hueco Group resulted in an interpretation of the depositional environments backreef to lagoonal conditions, with shallow, warm water of varied salinity, and moderate to low energy. LeMone et al. (1975) and Simpson (1976) studied the paleoenvironment of the fauna of the Abo tongue and upper Hueco Limestone Member of the Hueco Formation in the Robledo and Doña Ana Mountains, New Mexico. These studies confirmed a late Wolfcampian age for the strata on the basis of its flora and fauna. The fauna were placed into the eight Wolfcampian megafaunal communities established by Stevens (1966), and two more communities were added. These communities are interpreted as deltaic-tidal flat, ostracod, euphemitid, nuculanid, Costellarina, chonetid, productoid-Composita, phylloid algae and coral, fusulinid, and palaeotextularid. Simpson and LeMone (1983) documented the fauna in the Hueco Formation in the Jarilla Mountains and correlated this to the Hueco Canyon Formation of the Hueco and Franklin Mountains.

Pennsylvanian and Late Permian biohermal communities have been a focus of stratigraphic studies in the Permian Basin region, but Wolfcampian buildups have received relatively little study because of the lack of adequate surface exposures. Most Wolfcampian bioherms have been studied using subsurface cores

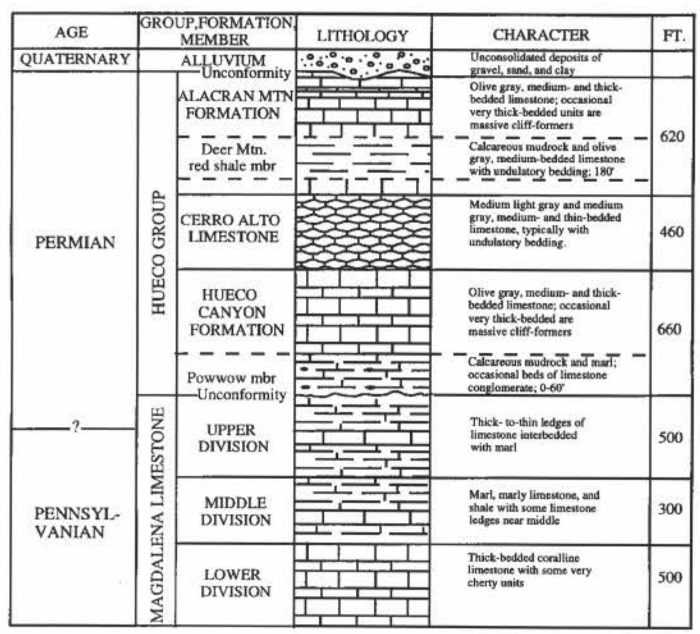

FIGURE 4. Pennsylvanian–Permian stratigraphy of the Hueco Mountains (modified from Williams, 1963).

from oil fields in the Permian Basin. Dunham (1969) and Malek-Aslani (1970) described Wolfcampian phylloid algal-*Tubiphytes* biohermal facies in subsurface cores from the northern shelf-margin of the Delaware Basin. Asquith and Drake (1985) described bryozoan-*Tubiphytes* boundstones in carbonate banks on the eastern margin of the Midland Basin. Cys and Mazzullo (1985) and Cys (1986) documented Wolfcampian phylloid algal bioherms and grainstones in Morton Field, Tatum Basin, southeast New Mexico. They claimed that those stacked phylloid algal bioherm complexes were on the intrabasinal shelf edge of the Tatum Basin and were correlatable to the Kemnitz-Townsend shelf-edge cycles to the south. Recently, Wagner et al. (1996) described a Wolfcampian shelf-margin biohermal bank reservoir on the eastern margin of the Central Basin Platform. Wahlman (1985, 1988, 1996) described Wolfcampian biohermal facies from cores throughout the Permian Basin in some detail. He recognized five upward-shallowing facies in the subsurface Wolfcampian shelf-margin complexes. He described shelf-margin biohermal facies consisting of phylloid algal-calcisponge bafflestone-boundstones rich in syndepositional radial fibrous cements and carbonate mud, which shallowed upward into *Tubiphytes* boundstones and crestal shelf-margin packstone-grainstone shoals.

Wahlman et al. (1992a, 1992b, 1993) briefly described the facies of the Wolfcampian shelf-margin complexes exposed in the Hueco Mountains outliers. In the northern and central outliers, they described shallowing-upward shelf-margin biohermal complexes consisting of, in ascending order: (1) phylloid algal-fusulinid bafflestone-wackestones with scattered fusulinids and composite brachiopods, and rare heliosponges; (2) phylloid algal-fusulinid bafflestone-packstone; and (3) *Tubiphytes* boundstone patch reefs intermixed with *Tubiphytes*-fusulinid-phylloid algal packstones and grainstones. However, in the southern outlier studied here, they described a bioherm of a more advanced character. The large bioherm at the top-center of the southern outlier, called Colmena Mound (Figs. 1 and 2a), was constructed by a more integrated biohermal community consisting of intermixed phylloid algae, calcisponges, heliosponges, *Tubiphytes*, and laminar encrusting red algae (*Archaeolithoporella*). Also in the same depositional sequence are smaller bioherms constructed predominantly of laminar encrusting red algae and bryozoans. Preliminary fusulinid biostratigraphic analyses of the Hueco Mountains outliers indicate that the shelf-margin complexes prograded to the south-southwest (Wahlman et al., 1993).

FACIES DESCRIPTIONS AND INTERPRETATIONS

Facies and associations

Table 1 describes the nine different facies documented in this study, and the facies associations into which they have been grouped (Stoklosa, 1997). The five facies associations are: (1) Deep Shelf-Basin, (2) Outer Shelf, (3) Buildup, (4) Shallow Shelf, and (5) Breccias. Delineation of these associations was based mainly on field observations. Grain size, fossil content, carbonate mud content, physical structures, and bedding style of the facies were used to make interpetations of depositional environments. These interpretations of the various lithofacies were incorporated with the lateral and vertical lithofacies distributions to construct paleoenvironmental associations and the depositional history of the stratigraphic succession. The depositional model that best fits these lithofacies associations based on their field occurrence is shown in Figure 5. The major facies tracts of the carbonate platform model are Deep Shelf-Basin, Outer Shelf, and Shallow Shelf, in order of decreasing water depth.

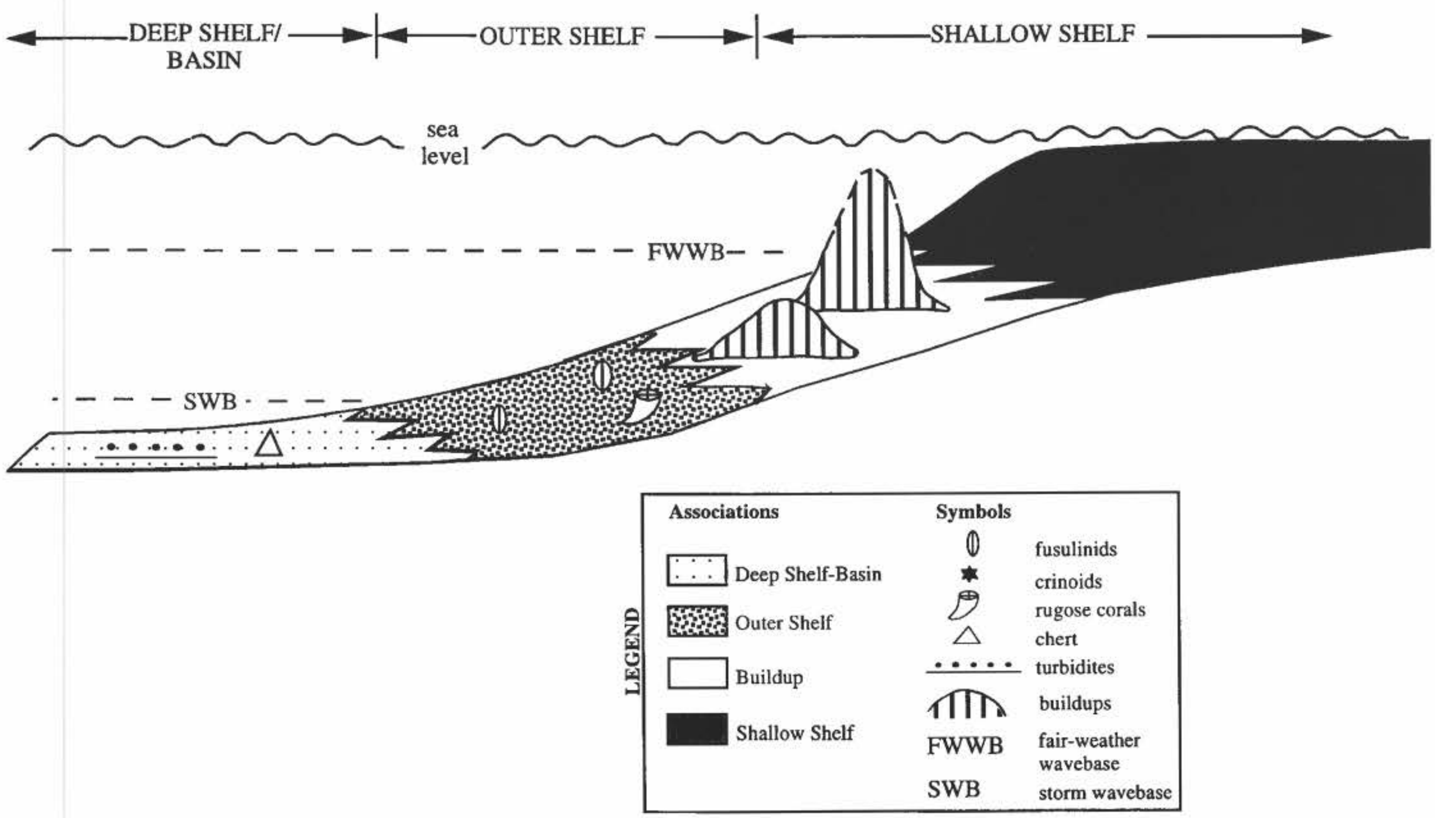

FIGURE 5. Depositional profile model of the southern outlier. Shown is a gently dipping carbonate platform, with a slight rimmed morphology where the buildups form. The three broad water depth zones are: Deep Shelf-Basin, Outer Shelf, and Shallow Shelf. Also indicated are the approximate positions of the storm wave base and fair-weather wave base. Note that during deposition of Sequences 1, 2, and 3 the shelf profile did not include buildups. The buildups do outcrop in Sequence 4, and are found both as rims separating the Shallow Shelf from the Outer Shelf, and as isolated masses in the more distal Outer Shelf.

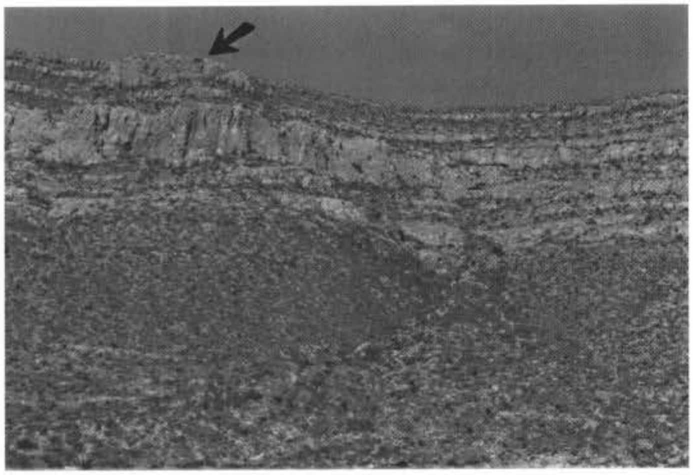

FIGURE 6. Photo of the southern portion of the eastern face of the outlier. A prominent bioherm is indicated by the arrow and its flanking beds are to the left, or south side of this feature.

Deep Shelf-Basin association

The facies grouped into the Deep Shelf-Basin association are *fine-grained spiculitic wackestones*, interbedded with both *fine and coarse turbidites*. *Fine-grained spiculitic wackestones* are medium-brown in color, thin-bedded (<0.4 in.) and in places fissile, and vary from a wackestone to mudstone texture, with rare interbedded shales and marls. Bioturbation is intense, though some beds retain planar laminae. The grains are mainly fine skeletal fragments, spicules, 1–2 in. bryozoans fragments, and some fine peloids. Abundant chert forms layers and nodules. *The fine and coarse turbidites* within the wackestone facies are medium-bedded (0.3–1.5 ft) and planar-laminated packstone to grainstone, which exhibit scoured bases and some normal grading. The coarse skeletal turbidites are composed of primarily fusulinids and crinoids, as well as some other forams and brachiopod fragments. The fine-grained turbidites are composed of both skeletal (crinoid and foram fragments) and peloidal grains. In both turbidite types, nodular and layered chert is abundant.

The Deep Shelf-Basin association is interpreted to be the deepest-water and lowest-energy setting of the all the facies associations. The fine-grain size, low density of fauna, and planar laminae characterizing the *fine-grained spiculitic wackestones* fit a low-energy depositional environment below storm-wave base. The normal grading, scoured bases and interbedded nature of the turbidites resulted from storm-wave action reworking a carbonate platform, and transporting the material basinward.

Outer Shelf association

The facies grouped into the Outer Shelf association are *fusulinid wackestones to packstones*, and *coarse skeletal* (including fusulinids, crinoids, rugose corals, brachiopods, gastropods) *wackestones to packstones*. Fusulinid wackestones to packstones are primarily

Table 1. Description of facies for each facies association. Texture was determined according to Dunham (1962), and grain size was determined according to the Wentworth (1922) scale. Only abundant (>35%) to moderate (5–35%) grain types are listed. Bedding description is defined by: thin = < 0.1 m; medium = 0.1–0.5 m; and thick = > 0.5 m.

ASSOCIATION	LITHOFACIES	TEXTURE	GRAIN SIZE	GRAIN TYPES	BEDDING	STRUCTURES	ENVIRONMENT
Deep Shelf-Basin	*fine-grained spiculitic wackestones	mudstone to wackestone	fine, some coarse, bryozoans can be 3 cm	sponge spicules, bryozoans	thin, fissile	bioturbated, occasional lamination, cherty	basin to deep shelf: below fair-weather wave base, turbidites transported from shelf
	*turbidites (fine and coarse)	cemented grainstones to mud-lean packstones	very fine/ fine or coarse/ very coarse	peloids, forams, crinoids, fusulinids	medium, planar	scoured bases, normal grading	
Outer Shelf	*fusulinid wackestones to packstones	wackestone to packstone	coarse and very coarse	fusulinids, crinoids, peloids	medium, wavy and planar	bioturbated, cherty	outer shelf: below fair-weather wave base, in photic zone
	*coarse skeletal wackestones to packstones	wackestone to packstone	very coarse, corals can be > 3 cm	fusulinids, crinoids, rugose corals, brachiopods	thick, wavy, not well-defined	bioturbated, cherty	
Shallow Shelf	*fine to medium grainstone	mud-lean packstone/ grainstone	fine and medium, occ. coarse	peloids, tubular forams, other forams	medium, planar	well-sorted bioturbated	shallow shelf: high energy, near fairweather wave base
	*medium to coarse grainstones	mud-rich packstones /grainstones	medium, coarse and very coarse	fusulinids, crinoids, Tubiphytes, tubular forams	medium to thick, planar	moderate to well-sorted; cross-bedding, normal grading	
Buildup	*boundstones	trapping, binding and encrusting boundstones	variable: greater than very coarse to medium	laminar alage, phylloid algae, Tubiphytes, fusulinids, crinoids, brachiopods	thick, massive, mound-shaped	massive, laminar binding, collapse structures	outer to shallow shelf: near to below fairweather wave base; flanking beds shed from proximal buildups
	*flanking beds	mud-rich to mud-lean packstones and breccias	medium to very coarse	fusulinids, Tubiphytes, crinoids	thick, planar	poor sorting	
Breccias	*breccia	fine to medium-grained grainstone clasts in a coarse skeletal packstone matrix	clasts 1-3cm in diameter, composed of fine and medium grains; matrix grains very coarse-medium	clasts: peloids, foram fragments, crinoids matrix: crinoids, fusulinids, tubular forams	thick, planar to convoluted	scoured base, poor sorting	shallow subtidal, high energy, following exposure

FIGURE 7. Photo of a typical breccia. The dark clasts are composed of fine-grained grainstones, and the surrounding matrix is a coarse skeletal packstone.

composed of very coarse fusulinid grains in a lime mud to fine peloidal matrix. Accessory biota include crinoids, brachiopod fragments and tubular forams. This facies is dark brown in outcrop, wavy to planar, medium-bedded, bioturbated and cherty. The *coarse skeletal wackestone to packstone* facies is composed of clusters of rugose corals (often >1 in. in length), large and small fusulinids, coarse crinoid stems as well as medium-grained crinoid fragments, and brachiopods in a lime mud, peloidal matrix. This facies is often cliff-forming and composed of thick (>1.5 ft), massive, wavy beds. Chert is abundant, and bioturbation is local.

The Outer Shelf association occupies a position on the platform between the Deep Shelf-Basin and Shallow Shelf association. The abundance of fauna and presence of substantial carbonate mud indicate deposition in an environment where carbonate production was occurring, and the energy was moderate to low, still below fair-weather wave base, where major reworking had not occurred. The presence of benthic fauna-like fusulinids and rugose corals also indicate that these strata were deposited in relatively shallow, clear water.

Shallow Shelf association

Two facies, *fine-to-medium* (forams, peloids) *grainstones* and *medium-to-coarse* (crinoid fragments and tubular forams or crinoid fragments and fusulinids) *grainstones* comprise the Shallow Shelf association. The *fine-to-medium grainstones* are composed of fine and medium peloids and skeletal fragments. The skeletal components are primarily crinoid, fusulinid, and tubular foram fragments. This facies is well-sorted, bioturbated locally, and medium- and planar-bedded. *Medium-to-coarse grainstones* are chiefly composed of very coarse to medium fusulinid, crinoid, and *Tubiphytes* grains. The rocks are moderately to well-sorted, and commonly contain dissolution seams. The bedding is planar and medium to thick, and chert is moderate to rare.

The Shallow Shelf association is interpreted to represent those rocks deposited in the shallowest setting of the platform, where wave energy is highest. The facies deposited here are well-bedded and often clinoformal or prograding. The absence of carbonate mud and good sorting of these grainstones indicate that a high degree of reworking occurred in near fair-weather wave base.

Buildup association

The Buildup association includes the facies termed *boundstones* and *flanking beds*. As noted previously, the biohermal community in Colmena Mound, the main buildup at the top-center of the outlier, represents a more advanced stage of reef community evolution than seen in other outlier buidups. It consists of intermixed phylloid algae, calcisponges, heliosponges, *Tubiphytes*, and *Archaeolithoporella* (laminar encrusting algae) (Wahlman, 1992a, 1992b, 1993). The internal sediment fill is composed of fusulinid, brachiopod, crinoid, gastropod, phylloid algae, and *Tubiphytes* fragments in a lime-mud matrix. Other mesopores of this boundstone have been filled by late diagenetic calcite. This facies is mound-shaped, massive, and can exhibit up to 50 ft of relief. These buildups are found as massive rim-like structures adjacent to Shallow Shelf association strata and as smaller, oblate bodies intermingled with *flanking* beds downdip. The *Flanking beds* facies refers to the bedded strata adjacent to the buildups (Fig. 6). These are packstones to conglomerates that contain fragments of biohermal fauna as well as clasts of the boundstones. The primary skeletal grains are fusulinid, crinoid, *Tubiphytes*, and phylloid algae fragments. This facies is poorly sorted, has many compaction features such as closely-packed grains and dissolution seams, and exhibits medium-to-thick, planar bedding. The Buildup association is only present in the uppermost depositional sequence of the southern outlier section.

The Buildup association was deposited in a position between the Outer Shelf and Shallow Shelf, where it may have created a more rimmed platform profile. The flanking beds contain reworked boundstone material and in some instances can be traced directly to a bioherm, which indicate that wave energy was substantial. In outcrop, the well-bedded, well-sorted Shallow Shelf grainstones are found updip and laterally equivalent to the Buildup association. Thus, this association was deposited in shallow water, near fair-weather wave base.

Breccias association

The Breccias association is composed of just one facies termed *breccias* that commonly drape surfaces that truncate the underlying Shallow Shelf association. The *breccias* are matrix-supported, and composed of fine-to-medium grainstone lithoclasts floating in a matrix of coarse-grained skeletal packstone (Fig. 7). The clasts are 0.4-1 in. in diameter, subrounded-to-angular, poorly to moderately sorted, and of the same skeletal material and texture as the fine-grained Shallow Shelf association facies defined above. The packstone matrix is composed of crinoid, fusulinid, *Tubiphytes*, and brachiopod fragments in lime mud. This facies exhibits thick bedding, which can be both planar or convoluted and slumped.

This association was deposited in a high-energy environment, at

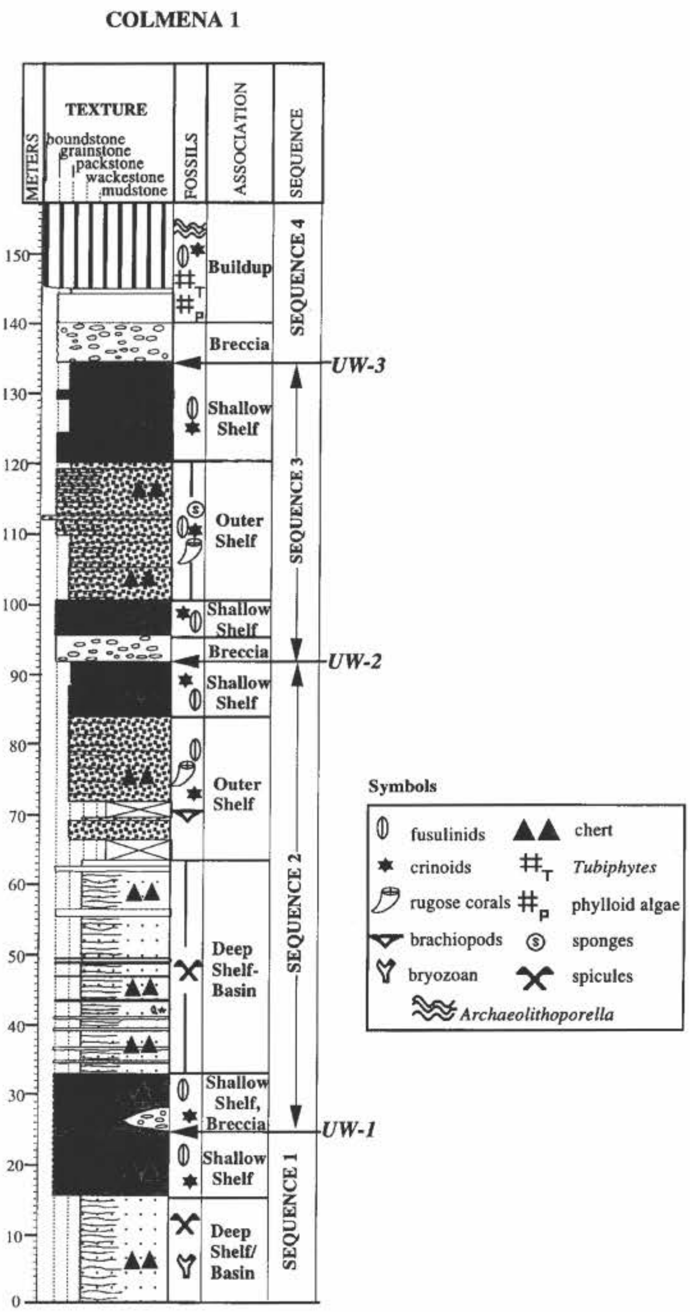

FIGURE 8. Stratigraphic column showing the facies associations, fossils and sequences of a section measured in the centermost part of the east face of the outlier. The location of this measured section is indicated in Figure 2b and 2c.

fair-weather wave base or shallower. The presence of a truncation surface and the obvious reworking of the underlying strata provide the best support of this interpretation.

Stacking patterns

The stratigraphic column of Figure 8 and the schematic of Figure 2b show the vertical and lateral distribution of the facies associations. Based on these lateral and vertical relations, two types of successions are recognized: landward-stepping and seaward-stepping. These two successions tend to alternate and represent transgressive and regressive packages, respectively. Landward-stepping packages exhibit a backstepping, retrogradational, upward-deepening pattern. A scoured, erosive base is overlain by Breccias and Shallow Shelf associations, commonly followed by strata of the Deep Shelf association. Seaward-stepping packages consist of progradational, locally clinoformal strata, of progressively shallower facies. A complete succession of seaward-stepping strata would exhibit a succession from base to top of Deep Shelf-Basin, Outer Shelf, Buildup, and Shallow Shelf associations, capped by an erosion surface. The landward-stepping packages are commonly thinner than seaward-stepping packages. The landward-stepping packages range from 3–50 ft thick, and the seaward-stepping packages range from 40–300 ft, with an average landward- to seaward-stepping ratio of 1:10. The composition and thickness of the alternating landward- and seaward-stepping packages vary through the succession.

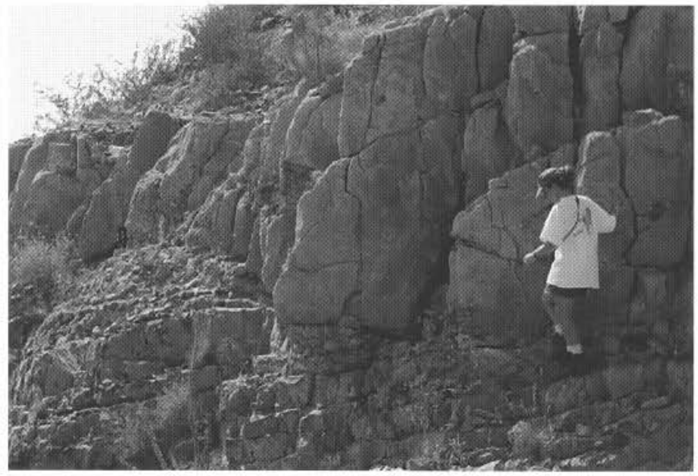

FIGURE 9. Photo showing the truncated clinoforms at the top of Sequence 1, and the draping of breccias and coarse grainstones on top of the erosional surface. Person in photo is standing at the sequence boundary and truncation surface.

An angular unconformity separates the shallow-water Pennsylanian Magdalena Limestone (diagonally-striped pattern in Fig. 2b) from the Wolfcampian Hueco Group, and represents both an erosional uplift event followed by a deepening event, and subsequent reestablishment of a carbonate platform. Beginning at this surface, the succession can be described in seven steps:

(1) The lowermost package of Wolfcampian seaward-stepping strata onlap the basal unconformity. This package is composed of Deep Shelf-Basin facies overlain by progradational, clinoformal Shallow Shelf association strata. Clinoformal dips reach a maximum of 11°S. The Shallow Shelf strata thin to the south and are capped by a scoured, irregular truncation surface.

(2) Next, a landward-stepping package toplaps against the truncation surface (Fig. 9). This package is composed of Breccias association strata followed by Shallow Shelf association grainstones. The fine-grained grainstone clasts of the breccia indicate reworking of the Shallow Shelf association of the underlying seaward-stepping package. This landward-stepping package thickens from 13 ft landward and forms some relief in the center of the outcrop. Bedded skeletal turbidites can be traced from this mounded feature (of primarily Shallow Shelf association grainstones) into the Deep Shelf-Basin association to the south, forming an apparent onlap .

(3) A thick unit of Deep Shelf-Basin association facies (105–164 ft) overlies the landward-stepping succession, followed by a seaward-stepping package composed of Outer Shelf and Shallow Shelf association strata. The Outer Shelf package is continuous along the outcrop, but is thickest to the north where it forms massive cliffs 130 ft in height and cliff-forming to the north. The overlying Shallow Shelf association strata are clinoformal (depositional dip

of 11°S), thinner than the Outer Shelf strata (range of 16–23 ft), relatively uniform in thickness along the outcrop, and have a scoured, truncated upper surface.

(4) The next landward-stepping unit is composed of Breccia and Shallow Shelf associations. Breccias, consisting of reworked Shallow Shelf strata, fill-in and drape the erosional topography of the truncated surface, and the Shallow Shelf strata overlie these breccias. The package as a whole is irregular in thickness, ranging from 2 to 40 ft, with a maximum thickness in the center of the outcrop.

(5) The next unit is a complex package. The base exhibits features of a gullied slope depositional environment, with channel morphologies and rapid facies changes from Deep Shelf-Basin to Outer Shelf to Shallow Shelf associations. Shallower facies are predominantly present in the northern portion of the outcrop, while a mixture of deep and shallow facies are found in the center and to the south. Depositional dip is probably to the west to southwest, but some channels are obliquely cut, making correlation difficult. Seaward progradation is demonstrated by a thick package (72 ft) of bedded, clinoformal Shallow Shelf association grainstones forming a massive cliff in the south of the outlier. The top of this seaward-stepping package is scoured, locally exhibiting significant relief (13–20 ft).

(6) The next and final landward-stepping package of this outlier is similar to the others, as it is composed of Breccias overlain by Shallow Shelf association strata. The breccias again fill in the erosional topography of the underlying seaward-stepping package, and are a consequence of the reworking of this package. This package, which is primarily composed of the Breccias association, ranges from 3 to 30 ft in thickness, and is thickest in the center and to the north of the outcrop.

(7) The final seaward-stepping package, which caps this outcrop, is unique as it is the only one to contain the Buildup association. The Buildup association forms the bulk of this package, ranges from 40 to 144 ft in thickness, and is primarily exposed in the middle and to the south of the outcrop (Fig. 6). A laterally equivalent unit of Shallow Shelf association grainstones comprises the northern component of this seaward-stepping package.

SEQUENCE STRATIGRAPHY

Based on the previous description, at least four sequences can be identified within the Wolfcampian strata of this southern outlier (Fig. 2c). The sequence terminology used follows that of Mitchum (1977) and corresponds to a relatively conformable succession of genetically related strata bounded by unconformities. Unconformities were recognized by scoured surfaces, truncation of beds, downlapping of strata, and brecciation (Figs. 7 and 9). In the following sections, each of these sequences is described in terms of designation of sequence boundaries, and the type and internal succession of lithofacies. Sequences are numbered from 1 to 4; 1 is the oldest and lowermost sequence described. Sequence boundaries are labeled by UW (meaning Upper Wolfcampian) and a number, in order of position, starting at 0.

Sequence 1

Sequence 1 is bounded below by a regional, erosional, angular unconformity (UW-0), classified as a second-order sequence boundary (Fitchen et al., 1995). This unconformity, also described in the Wolfcampian strata of the Sierra Diablo, has been tectonically enhanced and is easily recognized. In the main escarpment of the Hueco Mountains, this unconformity corresponds to the base of the Powwow Conglomerate. In this outlier, the unconformity marks the boundary between Pennsylvanian strata and Upper Wolfcampian strata; the southward-dipping Pennsylvanian limestone, exposed in the northern part of the outlier, is overlain by horizontally-bedded Wolfcampian basinal strata. UW-0 and the Pennsylvanian strata are dipping southward, and eventually disappear into the subsurface. The upper boundary of Sequence 1, UW-1, is a toplap surface.

The thickness of Sequence 1 ranges from 46 to 167 ft, and its average is 82 ft. The thickest portion is exposed in the center of the outcrop. The lithofacies associations documented in this sequence are the Deep Shelf-Basin association at the base, immediately followed by the Shallow Shelf association. The intermediate Outer Shelf association is not present. The Shallow Shelf association facies that cap this depositional sequence are clinoformal beds with a depositional dip of 11°S. The overall succession indicates a regional shallowing, which resulted in this abrupt progradation of finer-grained Shallow Shelf association grainstones directly over Deep Shelf-Basin strata.

Sequence 2

Sequence 2 is bounded below by a truncation surface (UW-1). Either Breccia and Shallow Shelf association strata toplap this surface (Fig. 9). The breccias draping the UW-1 surface are composed of fine-grained grainstone clasts and lenses of light tan siltstone. The Shallow Shelf association strata that overlie the sharp erosional surface of UW-1 are coarse-grained skeletal grainstones, which have few to no fine-grained grainstone intraclasts. Sequence 2 is also bounded above by a truncation surface (UW-2) that is toplapped.

Next is a succession of Deep Shelf-Basin to Outer Shelf to Shallow Shelf associations. The Deep Shelf-Basin is the thickest association in this sequence, and such thickness is not repeated in any other sequence. It is interpreted to represent the maximum transgression in the section studied. The Deep Shelf-Basin association shows alternations of burrowed and laminated thinly-bedded mudstone to wackestone lithologies, which appear to be amalgamated dysaerobic and aerobic facies, possibly representing a composite sequence in a shelfward direction. The Deep Shelf-Basin association is sharply overlain by Outer Shelf association lithologies. This fauna-laden association is thick and cliff-forming to the north, and thins to the south. Coarse fusulinid wackestones to packstones dominate the base, grading into a more diverse faunal facies of fusulinids, crinoids, brachiopods, and rugose corals. Pockets of solitary rugose corals can be found in this layer all along the outcrop. The Outer Shelf facies grade into Shallow Shelf facies of first coarse fusulinid-crinoidal grainstones, and finally into clinoformal fine-grained skeletal and peloidal grainstones. The Shallow Shelf strata are thinner than the Outer Shelf strata of this sequence, and no obvious thickening or thinning is evident. The range of thicknesses for Sequence 2 is 137 to 331 ft, and the average of 253 ft. Overall, the sequence thins to the south. The gradual nature of this vertical succession of Outer to Shallow Shelf strata indicates that it is a upward-shallowing package that eventually prograded seaward.

Sequence 3

Sequence 3 is bounded below by a toplap surface (UW-2), dividing the truncated clinoformal beds at the top of Sequence 2 from the more horizontally bedded strata above. These onlapping strata are primarily the Breccias association (containing fine-grained grainstone intraclasts reworked from below) overlain by a minor amount of coarse-grained Shallow Shelf association grainstones.

Again, this transgressive package fills in the topography of UW-2, and is irregular in thickness. Sequence 3 is bounded above by an exposure surface (UW-3).

The majority of the strata overlying the transgressive package of this sequence are composed of Outer Shelf and Shallow Shelf association facies; only a very minor amount of Deep Shelf-Basin strata are represented. As described in Step 5 in the previous section of this paper, most of these strata represent a gullied slope depositional regime, with only the shallower strata alternating in the north, and a mix of the three associations alternating in the middle to south of the outcrop. A cliff-forming unit of Shallow Shelf fine-grained grainstones overlies these gullied strata in the south. The range of thickness for Sequence 3 is 79–138 ft, and the average is 98 ft. No trend in thickness changes can be discerned.

Sequence 4

Sequence 4, the uppermost sequence of this outcrop, has no exposed upper bounding surface. The lower bounding surface, UW-3, is an exposure surface, recognized by the presence of irregular karst surfaces and the infilling of mud into the karst porosity created by dissolution.

Above this exposure surface is a minor transgressive package of Breccias and Shallow Shelf association strata, indicating that reworking of sediments during the subsequent gradual rise in relative sea level occurred, followed by a reinitiation of carbonate production in this locality. In the regressive, seaward-stepping package overlying this, the predominant association represented is the Buildup association, with a lesser amount of the Shallow Shelf association exposed. Sequence 4 ranges from 79 to 154 ft thick, and has an average thickness of 121 ft. In general, this sequence thickens southwards. Sequence 4 is unique in that it is the only sequence of this outlier in which the Buildup association crops out. This sequence is also exposed in such a way that a platform-to-basin transition can be easily visualized. To the north of the buildup masses is a laterally equivalent unit of Shallow Shelf strata, and to the south of the largest buildups are smaller oblate bioherms and conglomerates derived from the buildups, which have prograded to the south in a basinward direction. The massive Buildup association most likely graded seaward into the Outer Shelf association that would have been located to the south.

Summary

Each of the four sequences defined and described are unique in their facies types and succession, thickness, and boundaries. A similar pattern does exist, however, within these strata. Shallow-water facies are represented in all of the sequences, and are typically clinoformal, exhibiting progradation generally southwards. Another significant similarity is that these shallow-water facies are generally truncated and abruptly overlain by coarse grainstones with reworked clasts. This area of truncation and marked change in deposition corresponds to a sequence boundary, which represents the time when the platform stopped building basinward and began to migrate landward. The coarse-grained strata and breccias, topped by deeper water facies (Deep Shelf or Outer Shelf associations), are transgressive facies. Above the transgessive facies in each sequence, the succession shallows upward.

Overall there is a upward-shallowing trend, as Sequence 3 and 4 contain almost no Deep Shelf-Basin facies. Deep water facies are found immediately above the Pennsylvanian-Permian unconformity, and with the exception of the thin Shallow Shelf strata capping Sequence 1, the lower two-thirds of the section is dominated by strata deposited below storm-wave base (53%) and between storm-wave base and fair-weather-wave base (28%). The upper one-third of the outcrop is dominated by shallow-water facies, and an important change in this portion of the section is the appearance of buildups (Figs. 2 and 8). The change from a grainy ramp profile in Sequences 1, 2, and 3 to a rimmed-platform profile in Sequence 4 is abrupt; buildup facies drape the sequence boundary capping Sequence 3 and are resistant masses separating fine-grained grainstones landward from the brecciated flanking facies seaward. However, incipient buildups may have been present during the deposition of Sequence 3, as some facies compositions suggest buildup facies nearby, but these are not exposed in this outcrop. The occurrence of buildup facies in Sequence 4 may suggest a deepening trend, as buildup facies caught up with rising relative sea levels.

Equivalent rocks to the outcrop studied are late Wolfcampian in age (Williams, 1963). Similar age rocks in the Midland and Delaware Basins are interpreted as a landward-stepping part of the large-scale Leonardian transgression (Candelaria et al., 1992). However, the Late Wolfcampian in the Hueco Mountains is mostly progradational. This difference may be a reflection of the relative position in the basin, with the Hueco Mountains representing a leeward margin where abundant sediment transport off the Diablo Platform into the Orogrande Basin occurred.

The large-scale porosity that is characteristic of these bioherms is one incentive to use the sequence stratigraphic framework outlined for this outcrop to discern the stratigraphic relationships in the subsurface. The description of the nature of the sequence boundaries and the strata that occur above and below it could be used to identify such important depositional changes in cores where these relationships may not be obvious.

CONCLUSIONS

The southern outlier of the Hueco Mountains is an ideal field area for the study of vertical and horizontal facies patterns of a Wolfcampian shelf margin during sea-level fluctuations. The outlier strata are subdivided into nine facies types that are grouped into five facies associations. The character and distribution of these associations are best represented by deposition on a broad, shallow platform. This depositional model recognizes three broad water-depth zones: Deep Shelf-Basin, Outer Shelf, and Shallow Shelf (Fig. 5).

These strata exhibit an overall upward-shallowing succession, but with superimposed higher-frequency packages of landward- and seaward-stepping strata. The landward-stepping packages are composed of Breccias and Shallow Shelf associations; the seaward-stepping packages are composed of Deep Shelf-Basin, Outer Shelf, Buildup, and Shallow Shelf associations. These landward- and seaward-stepping patterns can also be viewed in a sequence stratigraphic framework. Four sequences have been identified within this strata, and each sequence is roughly equal to one succession of landward and seaward-stepping strata, bounded above and below by unconformities.

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