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Analyzing the Effects of Carbonate Mounds on Associated Stratal Geometry and Fracture Development, Sacramento Mountains, New Mexico, USA

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Analysis of the Effects of Carbonate Mounds on Associated Stratal Geometry and Fracture Development, Sacramento Mountains, New Mexico, USA

by

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Dedication

To my family, for your immense support, love, and guidance from the beginning.

Luciana, I owe the rest to you.

Acknowledgements

I would like to extend sincere appreciation to the Carbonate Reservoir Characterization Research Laboratory (RCRL) team at the Bureau of Economic Geology. Your advice, mentorship, lectures, and field trips throughout the last two years have been the catalyst to my finishing this work, and were immeasurably helpful in my personal and professional advancement. In particular, this study would have been unachievable without the field assistance, intellectual feedback, and guidance from my advisers Dr. Xavier Janson and Dr. Christopher Zahm, as well as from Yaser Alzayer, and Derek Tinker. Revisions, advice, and wisdom from Dr. Charles Kerans, Dr. William Fisher, Ben Smith, Andrea Nolting, and Dr. Greg Hurd were very beneficial. Support from Josh Lambert and Stephanie Lane ensured each field season was well-coordinated and well-equipped. Additionally, I would like to acknowledge the significant financial assistance of the Statoil Fellows program, the AAPG Grants-in-Aid fund, as well as the RCRL consortium and the Jackson School of Geosciences, without which this work would not have been possible.

To my fellow graduate students of the RCRL, the memories I made with you during our adventures over last two years are some of the most meaningful and impactful of my life, and have vastly improved both my geologic knowledge and strength of character. I am indebted to you, and will always look back at my graduate experience fondly. To my family, especially my Mom and Dad: thank you for your unfaltering love, support, and perspective. Family is everything. Finally, thank you to my wife and best friend, Luciana de la Rocha Tinker, my light in dark times.

Abstract

Analysis of the Effects of Carbonate Mounds on Associated Stratal Geometry and Fracture Development, Sacramento Mountains, New Mexico, USA

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The objective of this research is an integrated structural-stratigraphic analysis of compaction-related fracturing in carbonate mounds and associated cover strata. The influence of early-cemented carbonate mounds on subsequent sediment deposition (such as creation of hard substrates and topographic relief) is relatively well-understood. The effect of early-cemented carbonate mounds during burial, however, has not been studied in detail. Early marine cementation of mounds enhances mechanical rigidity, which reduces mound compaction during burial as compared to less-resistant sediments surrounding and overlying the mound. This rigidity difference facilitates differential compaction of sediments overlying the mound, which are warped over the inflection point created by the mound topography. This study hypothesizes that there is a measurable increase in fracture intensity associated with differential compaction above early-lithified carbonate mounds. Thus, this work analyzes and quantifies the effects of differential compaction on stratal geometry, mechanical stratigraphy, and fracture development in Mississippian strata overlying carbonate mounds which are well-exposed in the Sacramento Mountains in southeast New Mexico.

Methods employed in this study are drawn from structural geology, sedimentology, petrography, and remote sensing in an effort to adequately determine facies, examine fracture characteristics (e.g. size, orientation, and intensity), and to better understand which process(es) most directly control those characteristics (e.g. host rock facies type, diagenesis, bed thickness, mound proximity, mound size). Innovative methods of outcrop characterization such as high-resolution gigapan photography and unmanned aerial vehicle (UAV) photography were combined with photogrammetric techniques to create photo-realistic 3D outcrop models. The resulting models enabled a cost-effective, more detailed, less-distorted, and more comprehensive interpretation compared to previous methods, and improved understanding of the relationship between stratigraphy, rock mechanical evolution, and structural deformation in carbonate mound systems. Field work documented facies, stratal geometries, folds, faults, and fracture sets which validated observations and characterizations made using high-resolution field photographs and 3D outcrop models.

Results of this work show that paleotopographic relief which has been early lithified (in this instance, Mississippian carbonate mounds) directly controls fracture development and overlying stratal geometry, in that there is a significant increase in tension fracture (opening mode) intensity above pre-existing rigid structures and over-steepening of bed dips beyond an expected and reasonable angle of repose. Additionally, this work outlines a multi-stage tectonostratigraphic sequence of the development of the stratigraphically complex Teepee Mound assemblage based on field observations of facies, fractures, stratal geometries, and diagenetic effects (e.g. cementation, compaction, and chertification), which includes new evidence of late-Mississippian tectonic

compression. This result emphasizes the importance of understanding both syndepositional and post-depositional processes in outcrop characterization. Specifically, syndepositional processes establish the original mechanical stratigraphy and control the formation and propagation of early mechanical discontinuities, which in turn set up the fabric of weaknesses preferentially utilized by later fracture development. Post-depositional mechanical and diagenetic processes alter mechanical stratigraphy and rock brittleness, and thus influence fracture propagation through time.

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INTRODUCTION

Carbonate mud mounds are marine-cemented depositional structures that are rigid and undergo very little compaction when buried. Beds that flank and overlie the mounds are grain-rich and mud-rich carbonates which undergo compaction during burial. The distinct difference in rock strength between the flank beds and the mud mounds creates tension due to differential compaction and early fractures develop which create a heterogeneous permeability architecture around the mound that persists from early development through reactivated deformation. Describing the distribution, intensity and character of the fractures that develop is important for prediction in subsurface reservoirs, especially reservoirs associated with carbonate mounds. Despite this need for characterization, few studies have examined the effects of carbonate mounds on both syndepositional and post-depositional fracture development within mounds as well as in the strata encasing the mounds.

The Sacramento Mountains of southeast New Mexico contain numerous exposures of Mississippian carbonate mounds which have been a significant component of numerous geologic studies defining the sedimentology (Pray, 1959; 1961; 1977b), paleontology (Lane, 1974; 1975; Lane and Ormiston, 1982), stratigraphy (Laudon and Bowsher, 1949; Kottlowski, 1975; Bachtel and Dorobek, 1998; Dorobek and Bachtel, 2001), diagenesis (especially cement stratigraphy and carbonate compaction) (Meyers, 1974a; Meyers, 1974b; Meyers, 1975; 1977; 1980; Meyers and Hill, 1983; Shinn et al., 1983; Leutloff and Meyers, 1984; Meyers, 1988).

The tectonic development of the Sacramento Mountains has been shown by several workers to be the result of Ancestral Rocky Mountain (A.R.M.) activity,

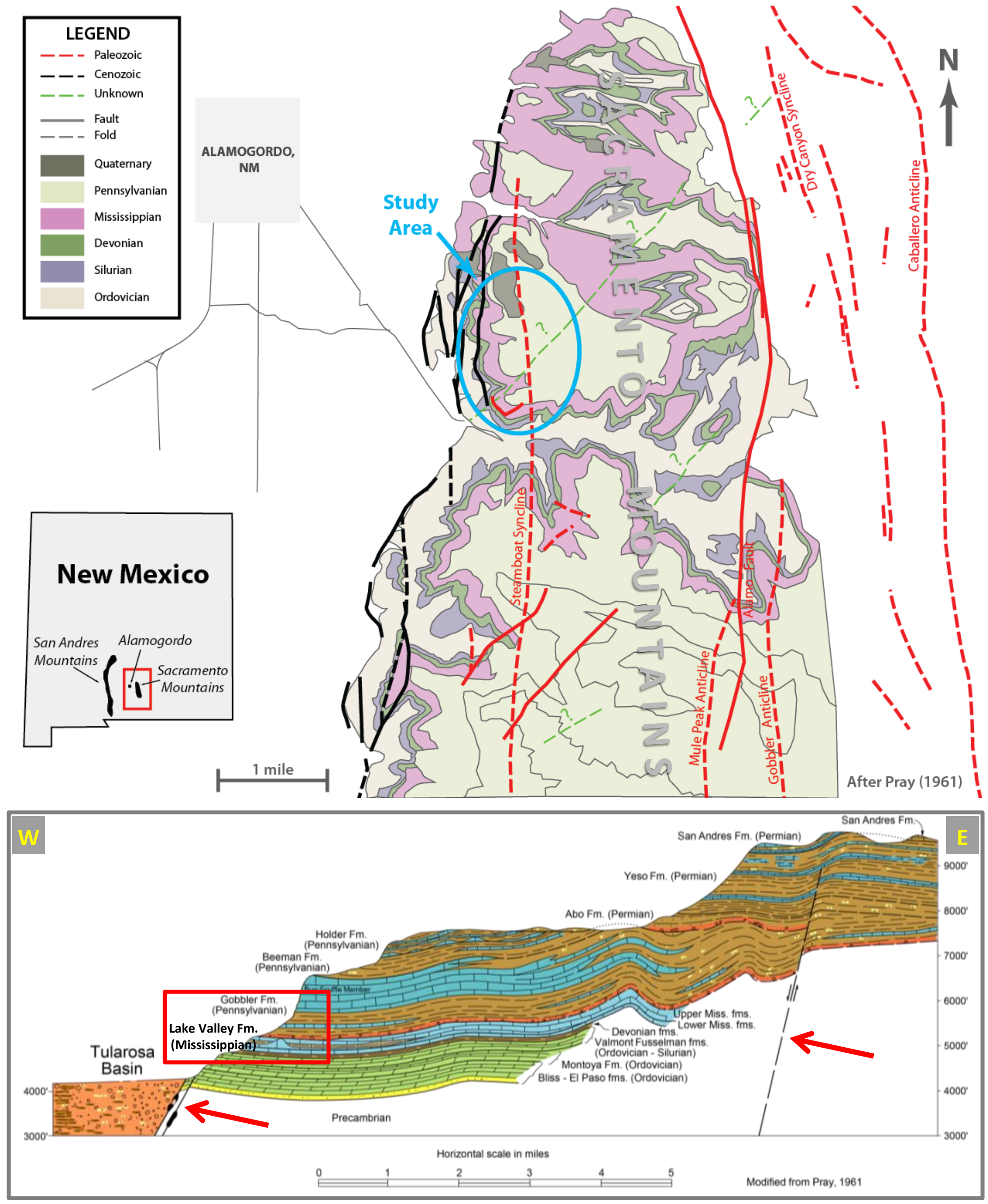

Figure 1. Above: Facies after Pray (1961), as well as north-south and NE-SW trending tectonic folds and faults of the surrounding region, separated into Paleozoic and Cenozoic groups. Below: Complete stratal succession of the western Sacramento Mountains modified from Pray (1961). Red arrows indicate Permian tectonic deformation and large-offset Tertiary normal faulting which affects the western margin. Extensive overburden is sufficient to generate stylolitization.

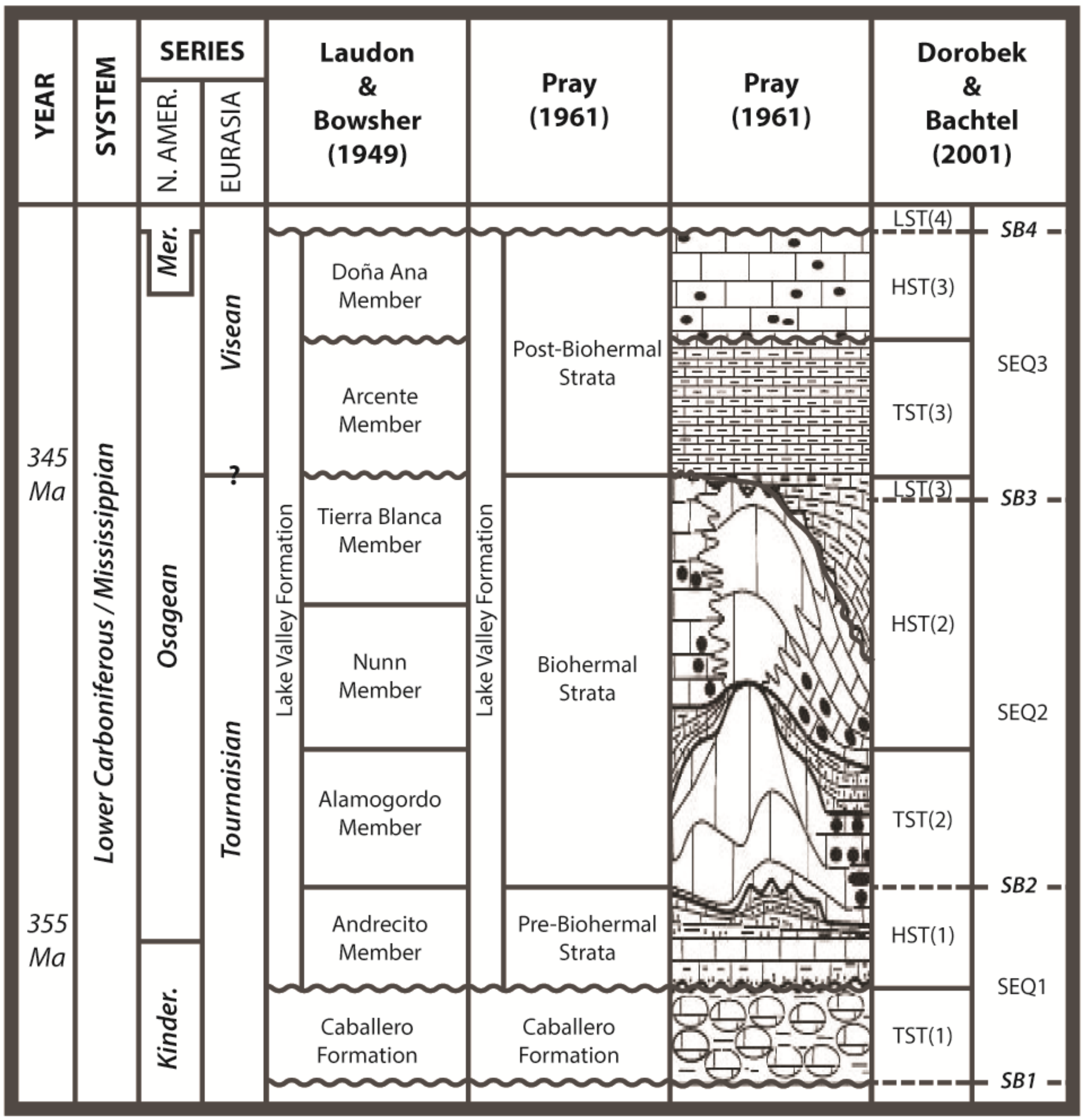

Figure 2. Composite stratigraphic column of the Lake Valley Formation, showing original member subdivisions by Laudon and Bowsher (1941), subsequent groupings and graphic representation by Pray (1961), as well as more recent sequence stratigraphic surfaces and divisions defined by Hunt (2000) and Dorobek and Bachtel (2001).

especially with the Pedernal Uplift (Late Mississippian – Early Permian) (Kottlowski, 1968; Kluth and Coney, 1981; Kluth, 1986; Ye et al., 1996), the Laramide Orogeny (80-30Ma) (Seager and Mack, 1986; Burchfiel and Lipman, 1992), as well as extensional stresses associated with the Rio Grande Rift, representing the eastern-most deformational limit of the Basin and Range province (Late Cenozoic to the present) (Brown and Phillips, 1999; Berglund et al., 2012).

This study hypothesizes that there is an increase in fracture intensity in strata directly above carbonate mounds associated with differential compaction. Relatively little has been published that specifically addresses the development of fractures in and around carbonate mounds. Frost and Kerans (2009) proposed differential compaction over early-lithified antecedent topography as a control on syndepositional fracture development. Characterization of this type of fracturing requires recognition of the multi-stage deformation history of the mounds and associated strata, including both syndepositional and post-depositional influences. Factors which most affect fracture development within the mound-flank complex include: (1) mound morphology and flank facies distribution; (2) diagenetic alteration of facies, including burial and associated compaction, and (3) tectonic deformation. Characterization of the interplay between compaction-driven deformation and subsequent tectonic deformation is complex and remains largely unresolved in the Sacramento Mountains. This study provides an introductory assessment of the relationship between early and late fractures, with specific insight on how fracture development evolves through burial and late uplift. Additionally, this study analyzes the fracture development around Teepee Mound by combining detailed mapping of the mound shape, associated flank facies and bed geometries, and the distribution of developed fracture sets in an effort to demonstrate that present-day outcrop contains a mixture of early and late structural elements, many of which are directly related to the original influence of rigid paleotopographic relief provided by early-lithified carbonate mounds.

GEOLOGIC BACKGROUND

Continuous exposures of Mississippian (Lower Carboniferous) strata occur along 30km of the western front of the Sacramento Mountains, and have been the focus of several stratigraphic, structural, diagenetic, and paleontological studies in the past century. Paleogeographic representations show that study area was likely south of the equator during Kinderhook and Osage periods at low paleolatitudes (5-10^{o}) (Armstrong et al., 1980; Lane and De Keyser, 1980; Gutschick, 1983; Byrd, 1989; Witzke, 1990; Scotese and Golonka, 1992; Blakey, 2006). The paleoclimate of the early Carboniferous was characterized by a transition from greenhouse to icehouse conditions, which was accompanied by high-amplitude, high-frequency relative shifts in sea level during that time (De Keyser, 1978; Kerans and Tinker, 1997). The tens of meters of eustatic fluctuation resulted in subaerial exposure of strata and associated meteoric diagenesis, including extensive cementation, which occluded intergranular pore space and elevated rock strength, making strata more brittle and susceptible to fracturing.

The Mississippian Lake Valley Formation comprises six members (Figure 2): the Andrecito, Alamogordo, Nunn, Tierra Blanca, Arcente, and Doña Ana, as established by Laudon and Bowsher (1941). It has been well documented that Lake Valley strata occurred on the lower portion of a south-dipping, distally steepened, homoclinal carbonate ramp below normal wave influence, and potentially below the photic zone (Hunt and Allsop, 1993; Dorobek and Bachtel, 2001). This interpretation is substantiated by a lack of photosynthetic green algae, absence of grain micritization, scarcity of aragonite constituents and cements, as well as the absence of shallow-water sediments (e.g. ooids or photozoans) (Pray, 1961; Laudon and Bowsher, 1941; Meyers, 1977).

The stratigraphic framework of the Sacramento Mountains was described as a "wedge-on-wedge" by Lane (1974), a description which captures the general relationship between the Caballero/Lake Valley sediment package and the subsequent Las Cruces/Rancheria/Helms stratal package. Mississippian strata are the preserved distal deposits (outer ramp to basin) of a much more expansive carbonate platform, the depositional effects of which provide an example of slope readjustment of the regional carbonate ramp profile (Bachtel and Dorobek, 1998). The slope readjustment model posits that the low-angle Mississippian carbonate ramp was steepened via deposition of sediment, until the angle at which erosion/bypass was equal to depositional gradient. This process was largely driven by deposition of three overall progradational sequences of fine-grained-carbonate-dominated transgressive systems tracts which are overlain by coarse-grained packstone to grainstone highstand progradational systems tracts, followed by a fourth basin-restricted onlapping sequence generated by the sediment bypass from the slope readjustment, which is interpreted by Bachtel and Dorobek (1998) down dip of the study area.

Teepee Mound, located 1km north of the entrance of Alamo Canyon (Figure 1), is a well-exposed example of a syndepositionally-lithified Mississippian (Osagean) age carbonate mound which was developed contemporaneously with well-preserved grain-rich (dominantly crinoidal) Mississippian flanking strata sourced both autochthonously (by numerous generations of on-mound crinoid communities), and allochthonously, via crinoid-dominated debris flows sourced from an updip crinoid factory. Teepee Mound and other mounds within the Lake Valley Formation display significant (10's of meters or more) synoptic relief on the ancient carbonate ramp, and their presence affected the deposition and geometry of the temporally-equivalent flanking strata. Indeed, the designations “Pre-biohermal”, “Biohermal”, and “Post-biohermal” (Figure 2) utilized in Pray, (1958; 1959; 1961) reflect the profound influence that carbonate mound growth imposed upon grain-rich flanking strata. Facies and stratal patterns around the Teepee Mound complex were documented by De Keyser (1978), and a more detailed interpretation of the strike-trending southwest exposure of the complex is included in Bachtel and Dorobek (1998). Stratigraphic work (Lane and Ormiston, 1982; Hunt et al., 1994; Jeffery and Stanton, 1996; Jeffery, 1997; 2000) better defined the relationship between the mound cores and flank facies by constraining mound growth phases utilizing a detailed lithostratigraphic framework. Hunt and Allsop (1993) segregated the Mississippian platform into 15 depositional sequences which span from Tournasian through Visean time, and Kirkby and Hunt (1996) recognized five unique stratal units within Muleshoe Mound (Msu I-V), the boundaries of which were interpreted as recolonizations of antecedent topography, and were then tentatively correlated to the Alamogordo Member development in the present study area.

More recently, work by Bachtel (1995), Bachtel and Dorobek (1998), and Dorobek and Bachtel (2001) contributed a third-order sequence stratigraphic interpretation for the Carboniferous (Figure 2). The present study is primarily focused on Alamogordo, Nunn, and Tierra Blanca members surrounding and including Teepee Mound, which formed during the transgressive systems tract to early highstand systems tract of Sequence 2 from the framework of Bachtel and Dorobek (1998). Maximum flooding surfaces are defined at sharp facies transitions, such as the top of the Alamogordo Member, which represents the transition from dark gray mudstone to much coarser chertified crinoid-rich grainstone, and sequence boundaries chosen at interfaces of high angular discordance, erosional truncation, and rapid facies change (see Bachtel and Dorobek, 1998).

Finally, differential compaction of strata surrounding relatively non-compactible antecedent relief is a dynamic and influential process which can shape stratal geometries by increasing accommodation space adjacent to the relied, act as a key driver of fracture formation, and influencing the location and accretion of later mounds or reefs by generating positive topographic relief on the sea floor (Hunt et al., 1996; Kirkby and Hunt, 1996). Certainly, compaction of both mud-supported and grain-supported carbonate fabrics is complex, and has been empirically and theoretically studied for many decades (Meyers and Hill, 1983; Shinn and Robbin, 1983; Goldhammer et al., 1985; Bathurst, 1987; Clari and Martire, 1996; Hunt et al., 1996; Goldhammer, 1997; Vajdova et al., 2004; Rusciadelli and Di Simone, 2007; Croizé, 2010).The primary variables controlling amount of compaction are initial thickness, lithology, maximum effective pressure, and the rate of pressure application (loading rate) (Gretener and Labute, 1969). With respect to the Mississippian Lake Valley Formation, mechanical and chemical compaction significantly reduced the pore space (up to 50-75%; Meyers, 1980) and were facilitated primarily by grain breakage and rearrangement, reduction of intergranular volume, and dissolution, as evidenced by thin sections created from this study (Figure 8) as well as from previous documentation by Meyers (1980), Meyers and Hill (1983), and others.

Structural and Tectonic Framework

The study area has been affected by multiple tectonic events following the deposition of the carbonate mounds and associated flank beds. With respect to southeast

New Mexico, the collision of Gondwana with Laurasia caused deformation throughout the Carboniferous, including folding, uplift, subaerial exposure, and erosion (Soreghan and Giles, 1999). Events which most influenced deposition and development of deformation elements around Teepee Mound include orogenic compression during the Pennsylvanian-Permian A.R.M. tectonic activity, compression associated with the Laramide Orogeny in the Late Cretaceous to early Tertiary, and Neogene extensional faulting during the Basin and Range and Rio Grande Rift events (Seager and Mack, 1986; Soreghan and Giles, 1999). Additionally, periodic uplifts of the NE/SW-trending Transcontinental Arch, a tectonic element with positive topographic relief during most of the Paleozoic, likely influenced erosional thinning in the region around Teepee Mound (Lane and De Keyser, 1980; Bachtel and Dorobek, 1998). Pre-Pennsylvanian "epeirogenic tilting and warping" was noted in Pray (1961), a study which also presents disconformities as evidence of late Devonian and early Mississippian deformation likely the result of tectonic uplift associated with basement block movement (Johnson, 1985; Ahr, 1989). These events are evidenced by dominantly N/S- and NE/SW-trending faults and folds (Figure 1) (Pray, 1961), which are documented within the study area in this work. Furthermore, Pray (1977b) noted the intensely deformed pre-Permian strata, with tectonic deformation culminating in the late Pennsylvanian/Wolfampian time, as well as subsequent and more subtle folding and faulting affecting Permian strata. Moreover, Kluth and Coney (1981), Jeffery (1997), and Soreghan and Giles (1999) described late Pennsylvanian/Permian structural activity associated with the Pedernal Uplift, a highland along the eastern edge of the Orogrande Basin.

The Sacramento Mountains represent the far eastern margin of the Basin and Range structural province, and deformational events have continued up to the modern, including local Tertiary igneous intrusive bodies present above Pennsylvanian beds in the study area (Figure 1), and numerous Quaternary fault scarps (Pray, 1958; 1959; 1961; Seager et al., 1984; Ahr, 1989). Pray (1961) and Pray (1977b) described the current state of the mountain range as a slightly east-dipping asymmetric fault block which is the final product of late Cenozoic uplift which was more intense in the center of the range than on the north and south margins. In their present state, the mountains form the footwall of a high-angle, west-plunging Tertiary normal fault system (Pray, 1949; 1961; Stanton et al., 2000), which truncates the western margin of the range with approximately 2,100 m of vertical displacement (Pray, 1958; 1959; 1961; Ahr, 1989).

DATA & METHODS

The data and methods used to characterize the fractures and strata around the Teepee Mound complex represent a hybrid approach which combines well-utilized classic field mapping methods with more innovative techniques using modern technology such as unmanned aerial vehicles (UAV's), GPS, digital compass/clinometer, and HD cameras. This hybrid strategy was utilized in an attempt to address the wide area and large number of fractures to be interpreted, numerous inaccessible areas of the outcrop which were critical to understanding fracture intensity above the mounds, as well as outcrop curvature issues which would be not well-resolved using sketches or panoramic photographs alone.

Facies, stratigraphy, and deformation data were acquired using standard field mapping techniques including direct field measurement, vertical measured sections, hand sampling, fracture scanlines, as well as analysis of relative timing relationships witnessed in beds and diagenetic features. Forty-six hand samples were gathered from key structural and stratigraphic locations around Teepee Mound, from which twenty-three thin sections were made with vacuum impregnation of fluorescent blue-dyed epoxy. Thin section petrography revealed more detailed facies information and diagenetic features, and substantiated various paragenetic events and relative timing relationships interpreted at the outcrop scale.

High-resolution, GPS-referenced outcrop imagery was captured using a telephoto lens mounted to a ground-based Gigapan unit, as well as with an unmanned aerial vehicles (UAV) (Bemis et al, 2014; Casini et al., 2016; Zahm et al., 2016). Image acquisition using UAV's is a cost-effective method of providing interpretable image data from optimal vantage points (e.g. orthogonal to steep and/or inaccessible cliff faces, or directly above an exposed rock pavement to be mapped) as well as high-quality basemaps of the study area which greatly exceed the quality of publically-available satellite imagery. More than 1,000 UAV-acquired georeferenced photographs were captured above Teepee Mound, taken with a gyroscopically stabilized 12 megapixel camera.

The set of images was stitched into a photomosaic, which was photogrammetrically processed to generate a dense point-cloud in three dimensions (longitude, latitude, and elevation). The point-cloud was subsequently draped with a polygonal mesh and then colored using the true-color pixel data from the original photo set, resulting in a decimeter-scale 3D outcrop model of Teepee Mound and the surrounding fractured strata. Combining the georeferenced 3D model with GIS software enabled more extensive fracture mapping coverage around the Teepee Mound complex. Additionally, the GPS-referenced photomosaics were integrated with pre-existing LIDAR datasets, and used to interpret fractures and stratal geometries, which were ground-truthed via field observations. The resulting images and models eliminated many of the typical perspective and curvature issues in panoramic photographs and allowed better interpretation of stratal relationships, bed thicknesses, dips, and other structural elements directly from the digital data.

Hundreds of fracture counts were manually collected via outcrop observations and measurement with a compass-clinometer tool on well-exposed rock faces, scanlines which quantified fracture characteristics (e.g. aperture, fill, spacing, and intensity), as well as via digital interpretation of outcrop imagery and models which greatly increased the number of samples utilized in subsequent statistical analysis and geologic interpretation. Fractures were evaluated with respect to horizontal distance from mound center and major faults, and were classified into three categories: bed-bound, through-going (flank), and through-going (mound). Fracture intensity values were calculated in one dimension (P_{10} = N/L = number of fractures intersections / length of scanline) using straight, bed-constrained scanlines in the field and via digital image interpretation, as well as in two dimensions (P_{21} = N/L = length of fracture traces / area of exposure) using digital interpretation of outcrop faces captured by spatially-referenced imagery. Potential sampling bias arises from any deviations from a perfectly planar rock interpretation surface, as well as from shadows, cover, snow, and inaccessible portions of outcrop. These sources of error occasionally prohibited fracture measurement and introduced anomalously low fracture intensity areas into the dataset which were manually filtered based on field ground-truthing. Fracture intensity data are summarized in figures created utilizing workflows employing GlobalMapper, ESRI's ArcMap 10.1, Adobe Illustrator CS6, and MS Excel 2013.

RESULTS

The results of this field study are subdivided into discussions on observed facies and stratal development, description and qualitative analysis of post-depositional deformation features observed and interpreted from outcrop and thin sections, as well as mechanical discontinuities observed at both the outcrop and regional scale. Field data are summarized in a geologic maps (Figure 3) as well as subsequent figures which show facies, structural information, and contacts between mound core and flank, as well as Mississippian versus Pennsylvanian outcrop.

Facies and Stratal Development

The study outcrop is primarily composed of Mississippian (Osagian) Lake Valley Formation strata, especially the Andrecito, Alamogordo, Nunn, and Tierra Blanca members (Figure 2). Field observations show that underlying the Teepee Mound complex are the nodular limestones and calcareous shales of the Caballero Formation, which grades into the relatively flat-lying thin-bedded fissile crinoid-brachiopod mud-dominated packstones, wackestones, and silty shales of the Andrecito Member. Further upsection, separated by a gradational contact, the cherty skeletal lime wackestones and mudstones of the Alamogordo Member are observed to exist coevally with the initial stage of Alamogordo Member crinoid-bryozoan-micrite carbonate mound facies, the development of which continued through subsequent Tierra Blanca sedimentation. The recessive, shallow-dipping argillaceous packstones of the Nunn Member are poorly exposed in the study area, except where it onlaps the edges of the mound core.

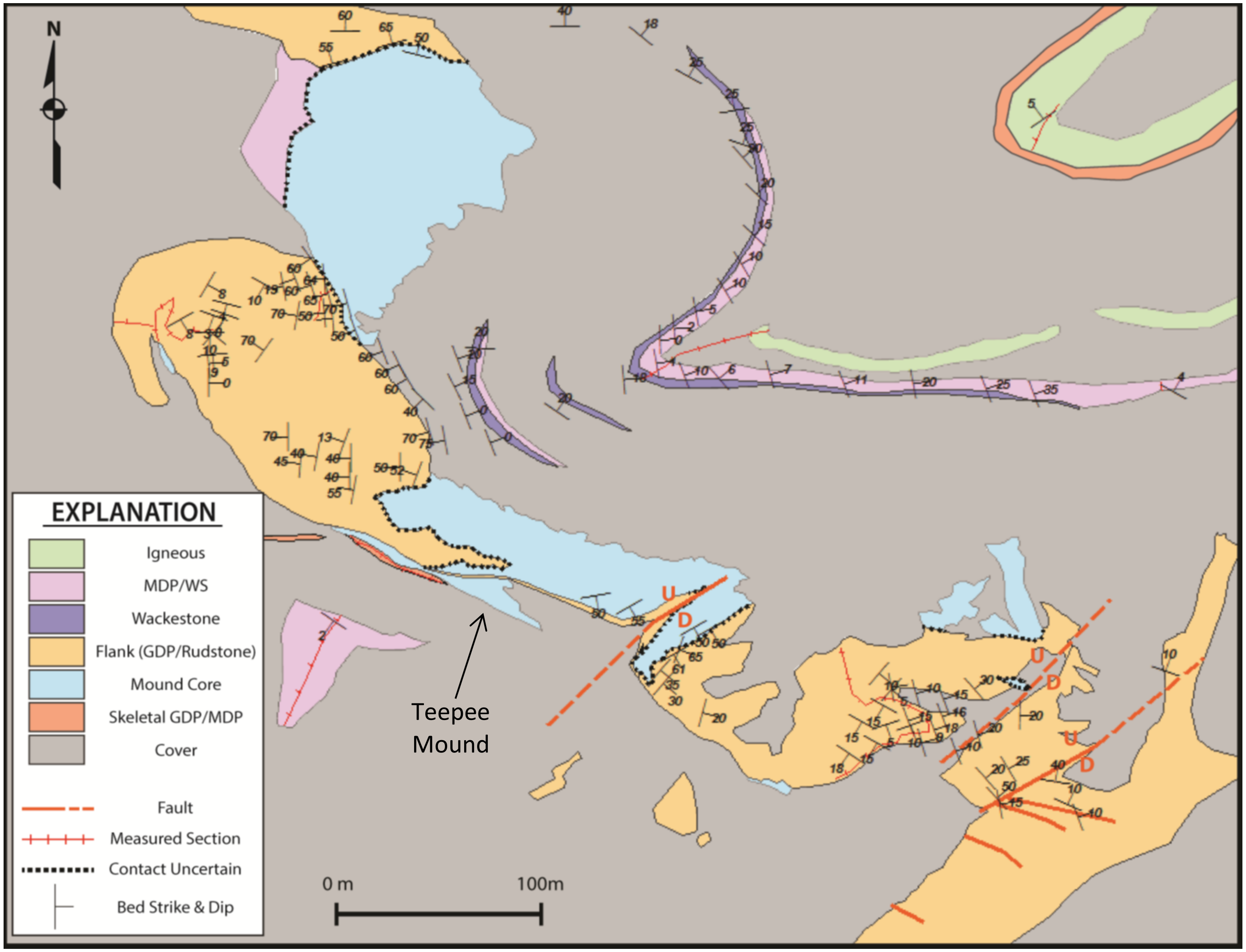

Figure 3(A): Geologic map of study area.

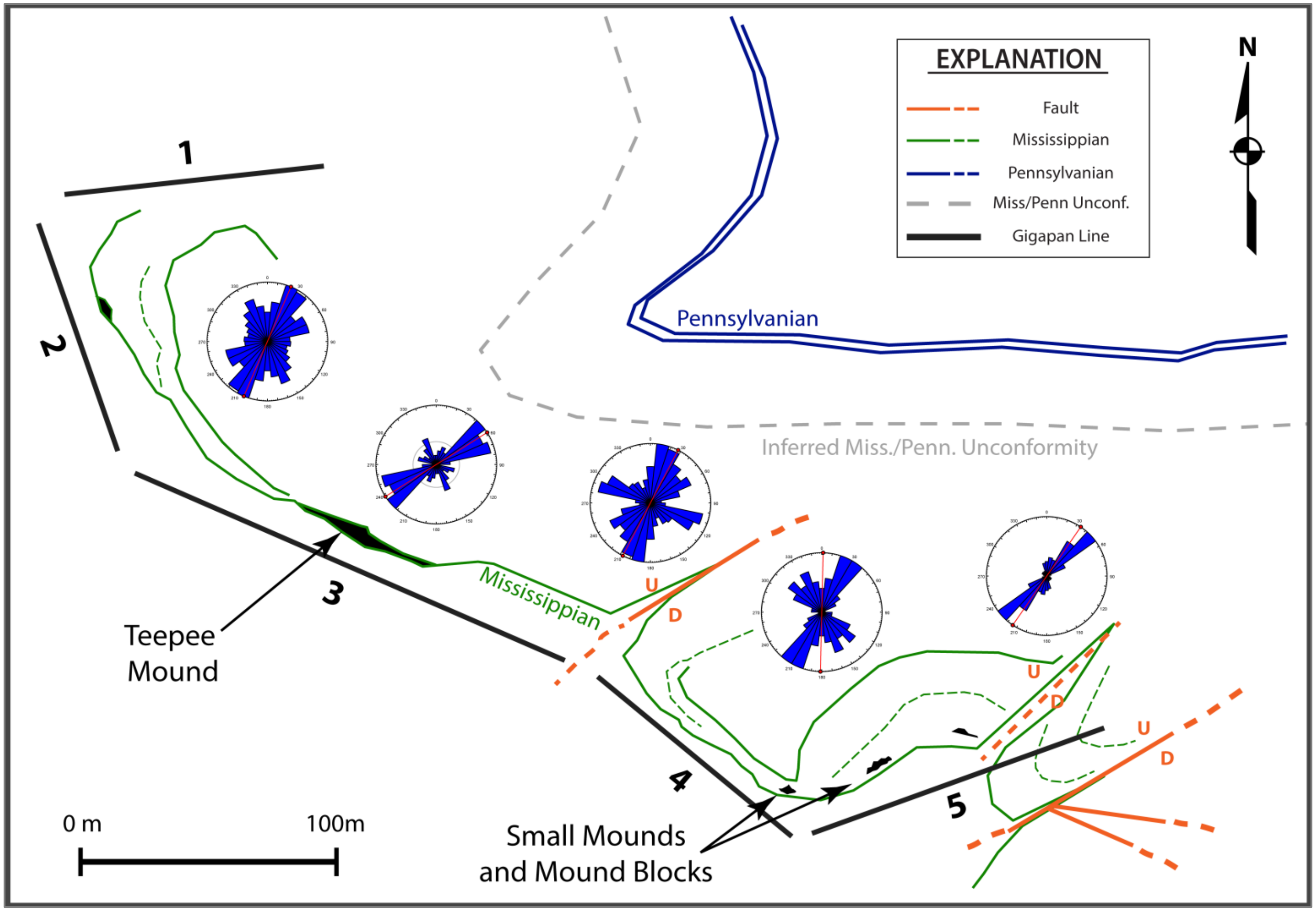

Figure 3(B): Formation map of study area with fracture rose plots, faults, and photopan lines.

Figure 3. (A) Geologic map of Teepee Mound, with extensive cover in grey. Dips of beds show significant over-steepening near and over mound cores. The top of the highest local hill was mapped as Tertiary (Pliocene to Eocene) mafic intrusive basalt-andesite dykes and sills. **(B)** Framework map showing Mississippian strata (dark green lines) undivided from the Andrecito Member through the Doña Ana Member. The Pennsylvanian Gobbler Formation (blue lines) overlies the entire area at the crests of local hills in laterally extensive and traceable bedsets. Dashed grey line denotes the inferred Mississippian/Pennsylvanian unconformity mapped in adjacent canyons. Black numbered lines delineate high resolution photopans acquired and used for stratal and fracture interpretation. Distinct triangular outcrop of Teepee Mound is captured in Line #3. Interpreted fault traces shown in oragne, as well as length-weighted rose plots (in blue) of ~1500 fractures interpreted from UAV and field study above the mound and flank beds.

The dominant portion of the outcrop is composed of beds of the Tierra Blanca member, represented by voluminous deposition (>50m present thickness) of laterally discontinuous layers of crinoid-brachiopod-bryozoan grainstones and rudstones, intercalated with mud-rich skeletal packstones, and extensively cemented by coarse sparry calcite. Sparse silty mud-dominated packstones and wackestones form infrequent recessive beds between the grain-supported layers. Within the studied area, Lake Valley strata are unconformably overlain by ledge-forming laterally continuous exposures of massive, dark gray, cherty grain and mud-dominated packstones of the Pennsylvanian Gobbler Formation (Pray, 1961; Lane, 1974). Extensive cover obscures many contacts between the mound core and flank beds, as well as the Mississippian/Pennsylvanian unconformity (Figure 3), which is documented in adjacent canyons in the Sacramento Mountains by Lane (1974) and others.

For this study, the various members and formations which comprise the Teepee Mound complex and surrounding strata are consolidated into three general facies: mound core, flank, and the mud-dominated lower-energy units which underlie and overlie the region (Figure 4). The mound core facies is massive to very faintly bedded micrite-dominated fenestrate bryozoan-crinoid boundstone with sparse brachiopods and ostracodes, and is best observed via the well-exposed triangular eroded edge of Teepee Mound (Figure 4). However, this study mapped several other patchy outcrops of mound core on the northern and the southern boundaries of the area, suggesting that the upper portion of the Teepee Mound core is larger and more domal in structure than previously interpreted. The flank facies comprises 5-30cm Nunn and Tierra Blanca bedsets, which dip from 0-15o and are laterally discontinuous (the outcrop expression of many beds discontinue after less than 20 meters). However, around carbonate mounds and

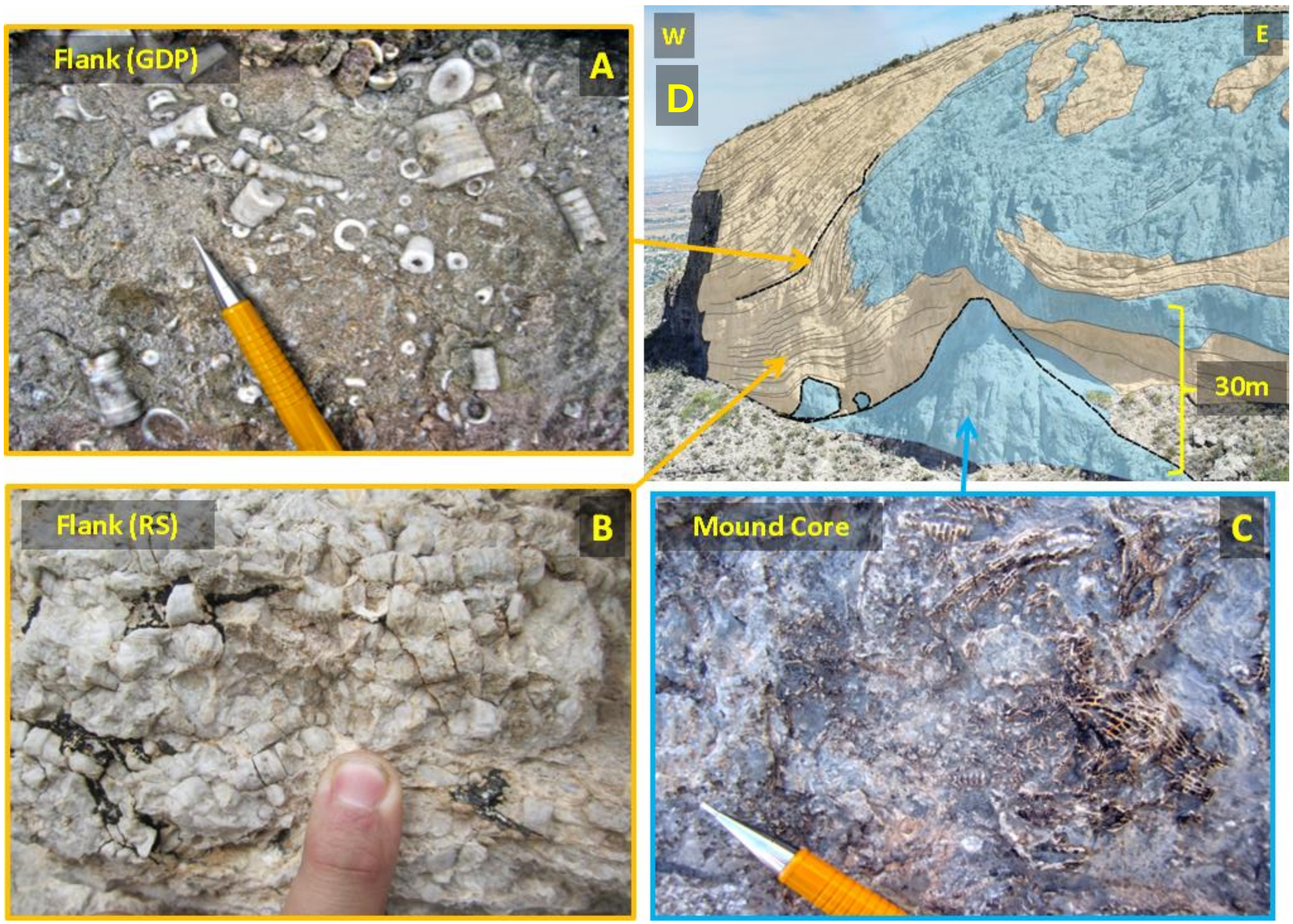

Figure 4. Examples of primary facies found around the Teepee Mound complex. (A) Less prevalent calcite-cemented skeletal grain-dominated packstones and wackestones; (B) skeletal-dominated crinoid rich calcite-cemented grainstones/rudstones; (C) crinoid-fenestrate bryozoan bafflestone mound core. (D) Teepee Mound (light blue) and surrounding flank strata (light orange. Orientation of D is Line #3 in Fig. 3b.

mound-derived olistoliths, flank beds dip well beyond the angle of repose, up to 80-85^o in some zones of the outcrop.

Post-Depositional Deformation Features in Outcrop

The results of both local and regional post-depositional processes such as fracturing, folding, faulting, and diagenesis were documented in the outcrop study, and were important in understanding and sequencing the general tectonostratigraphy of the Teepee Mound complex and surrounding region.

Temporally distinct episodes of folding are observed throughout the study area at multiple scales. At the meter to decameter scale, compaction drape-folding is ubiquitous above small (sub-meter to meter height) mound core developments, meter-scale mound-derived olistoliths, and eroded blocks. Folding of flank facies was observed above and below olistoliths, versus only above in-situ mound cores. Olistoliths are evidenced by the compacted and contorted beds below the blocks, in contrast with meter-scale mound developments which sit conformably on top of underlying flat-bedded strata. Other small-scale cylindrical folds are visible in steeply dipping flank strata, often with non-planar axial surfaces. Most folds documented consistently showed layer-parallel slip slickenlines developed on the tops of fold-associated bed surfaces, which are especially visible when calcite is present. Later deposition of Tierra Blanca grain-rich sediments clearly level out the localized folding within a few meters upsection above each early-cemented paleotopographic feature described above (Figure 7; Figure 5), which evidences the inter-Mississippian genesis of these folds.

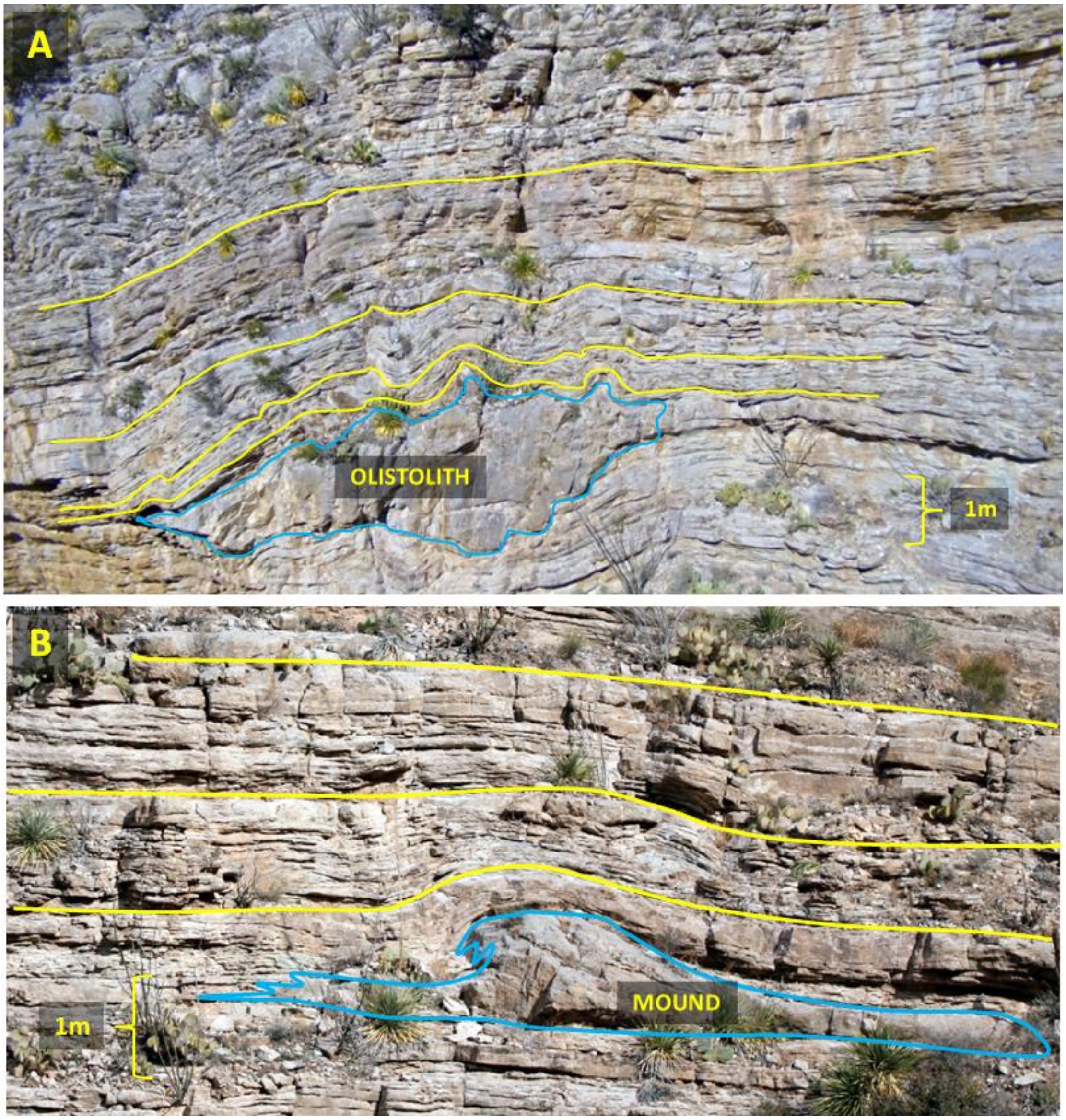

Figure 5. Skeletal-dominated Tierra Blanca flank beds (yellow lines) warped over both mound-derived olistolith (A) and meter-scale in-situ mound core (B), both outlined in blue. Beds below olistolith are impacted and warped, whereas the flat and level base of the mound rests conformably over strata below it. Subsequent flank bed sedimentation causes the geometry of overlying flank beds to re-flatten, suggesting that compaction occurred almost syndepositionally (inter-Mississippian.) Orientation is within Line #5 in Figure 3b.

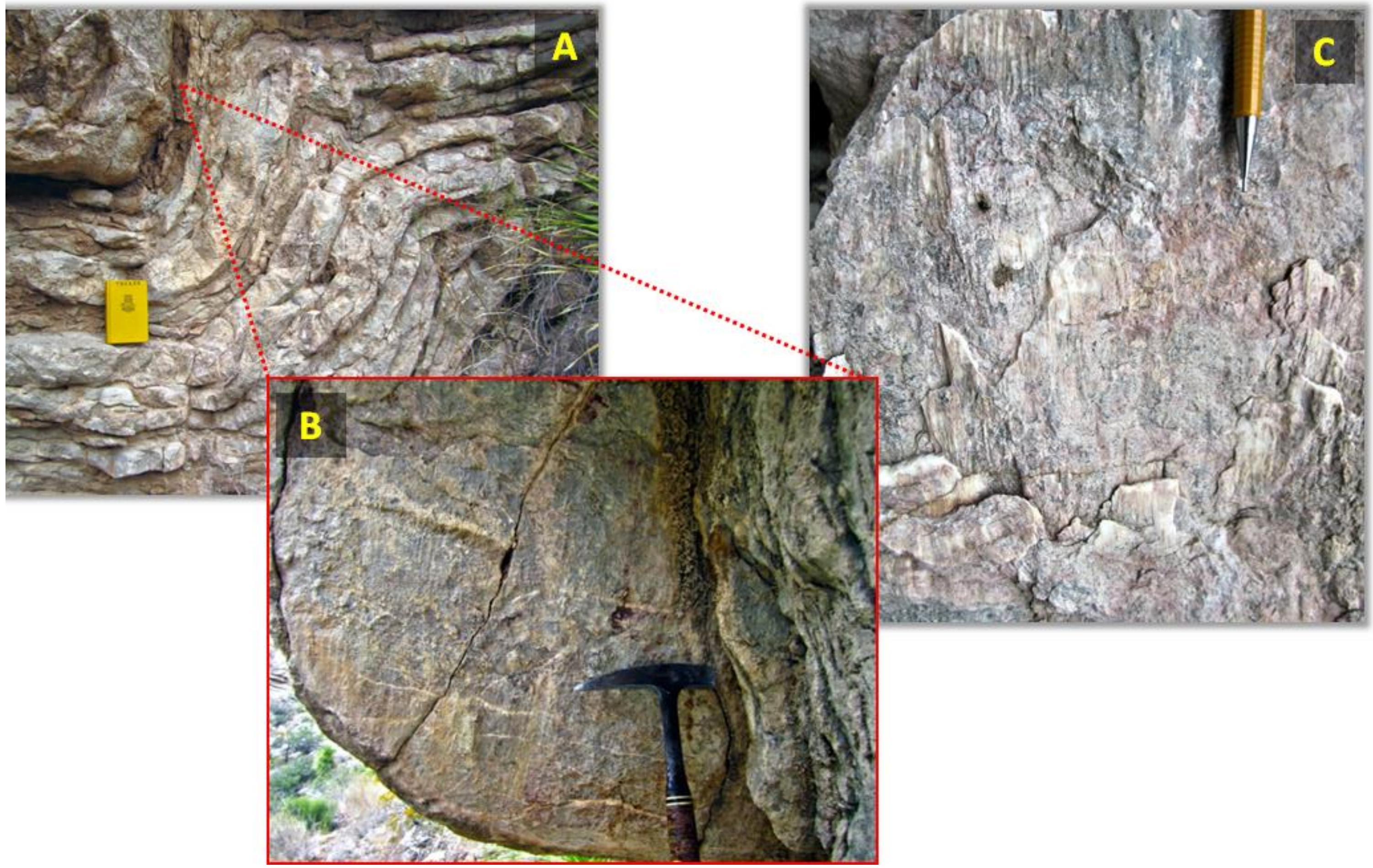

Figure 6. (A) Tight, local early slump folding generates fold axis parallel calcite veins (B) and is accommodated by layer parallel slip (evidenced by slickenlines; C) between flank beds, which are more visible when calcite mineralization is present between layers.

Folding exists at decameter and larger scales as well. The small canyon on the south margin of the outcrop (Figure 3b; Line #5) contains Tierra Blanca flank strata folded into a anticlinal form with limbs which dip up to 20^{o} (Figure 3a). Directly overlying the Teepee Mound complex, the Pennsylvanian Gobbler formation is flat-lying, but to the east dips increase as distance from the mound complex increases, until the beds are folded back to flat-lying in the off-mound area (Figure 3) within 20m lateral distance. Additionally, 750m north of Teepee Mound, folded Mississippian (Tierra Blanca Member) beds are overlain by flat-lying beds of the Gobbler Formation (Figure 14). In the same area, decameter-scale fault-propagation folding is present within Mississippian flank facies resulting from thrust faults (Figure 15).

In addition to the multiple types of folding observed, thin sections of flank facies show the results of multiple diagenetic processes which occurred at various times in the outcrop's history, including pressure solution seams, sutured grain boundaries, blocky calcite-filled veins and intergranular pore space, close grain packing, and grain breakage (Figure 8; Figure 16). These features also formed during multiple stages of the outcrop history, indicating a complex post-depositional story involving both local and tectonic stresses and diagenesis which pre-dates the overprint of the most recent tectonic episode. Additionally, chert lenses and nodules were observed throughout both the Mississippian and Pennsylvanian sections, and seem to be especially pervasive in mud-supported lithologies. In the Lake Valley succession, chertification is not fabric destructive: it essentially freezes the existing rock fabric at the time of chert development (Meyers, 1975). Understanding the timing of this process within the tectonostratigraphic development is important because chertification greatly impedes any further cementation and compaction.

Figure 7. UAV photo (Line #3 in Figure 3b) of Tierra Blanca flanking beds adjacent to and onlapping Teepee Mound, highlighting early deformation features: (1) flank beds draped around mound-derived 10m high olistolith in addition to folding, which is flattened out upsection, (2) inter-Tierra Blanca syndepositional normal faults, which are buried to flat upsection, (3) sub-vertical flank beds truncated by subsequent flank bed deposition, the dip of which were enhanced via compaction and tectonic compression around early lithified mound core. (4) mound-

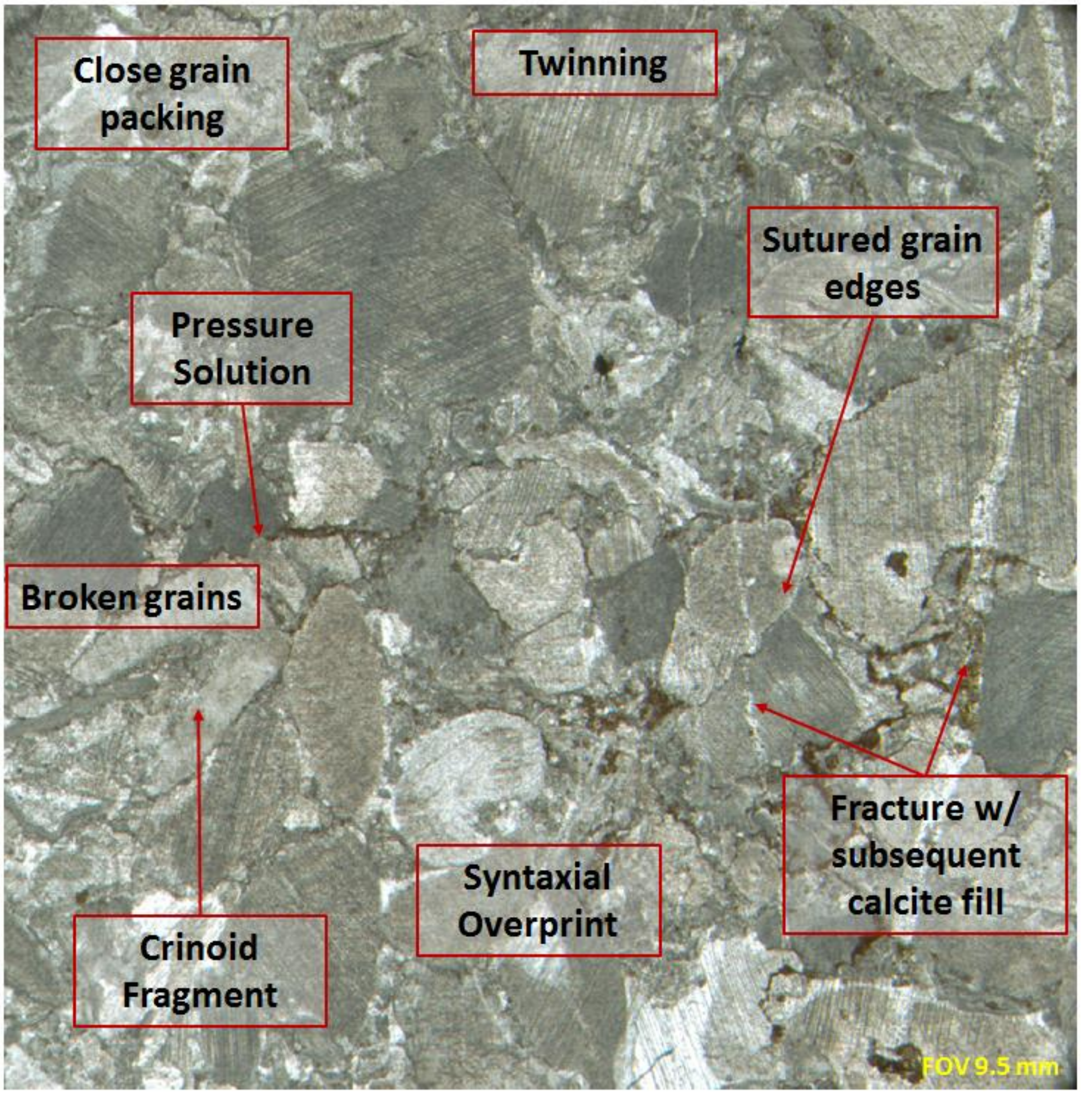

Figure 8. Thin section of brachiopod-bryozoan-crinoid grainstone/rudstone from Tierra Blanca flank beds, which reflects the cumulative result of numerous structural and diagenetic processes which deformed and overprinted the outcrop in various stages through time.

Fracture Observations and Analysis

Individual fractures were described and measured directly in the field around the Teepee Mound complex, as well as on high-resolution images captured with UAV and a ground-based Gigapan unit. Several styles of fractures were observed around Teepee Mound in both bed-bound and through-going type. The styles, grouped by abundance/prevalence in outcrop, are: (a) fold-axis-parallel blocky calcite-filled veins and tension fractures, especially concentrated at inflection point of maximum curvature of meter-scale folds; (b) mm to cm aperture calcite-filled veins; (c) decimeter to meter-length open joints; (d) opening-mode sediment-filled fractures in mound cores; and (e) faults, some of which are constrained to the lower Tierra Blanca flank beds, and others which cross-cut the entire outcrop.

Fracture style within the mound core facies is characterized by meter-scale opening mode joints filled with skeletal and silty sediments, meter-scale sub-vertical mound-bound joints, and decimeter scale elongate lenticular veins filled with blocky calcite (Figure 13). These fractures are spatially organized in *en echelon* swarms of 1-3mm aperture 5-15cm length lenticular calcite veins on the western upper edge of the Teepee Mound core. Additionally, meter-scale joints exist in the mound, with 310^{o} average strike, and cross-cut from the mound core into overlying flank beds. The fracture style of the grain-supported flank facies is primarily characterized by systematic bed-bound open joints and blocky calcite filled veins, typically vertical with respect to bedding planes, and meter-scale sub-vertical through-going joints which cross cut multiple beds. Chert nodules within flanking strata showed a distinct and ubiquitous fracture style which is very intense and chaotic as compared to the surrounding matrix.

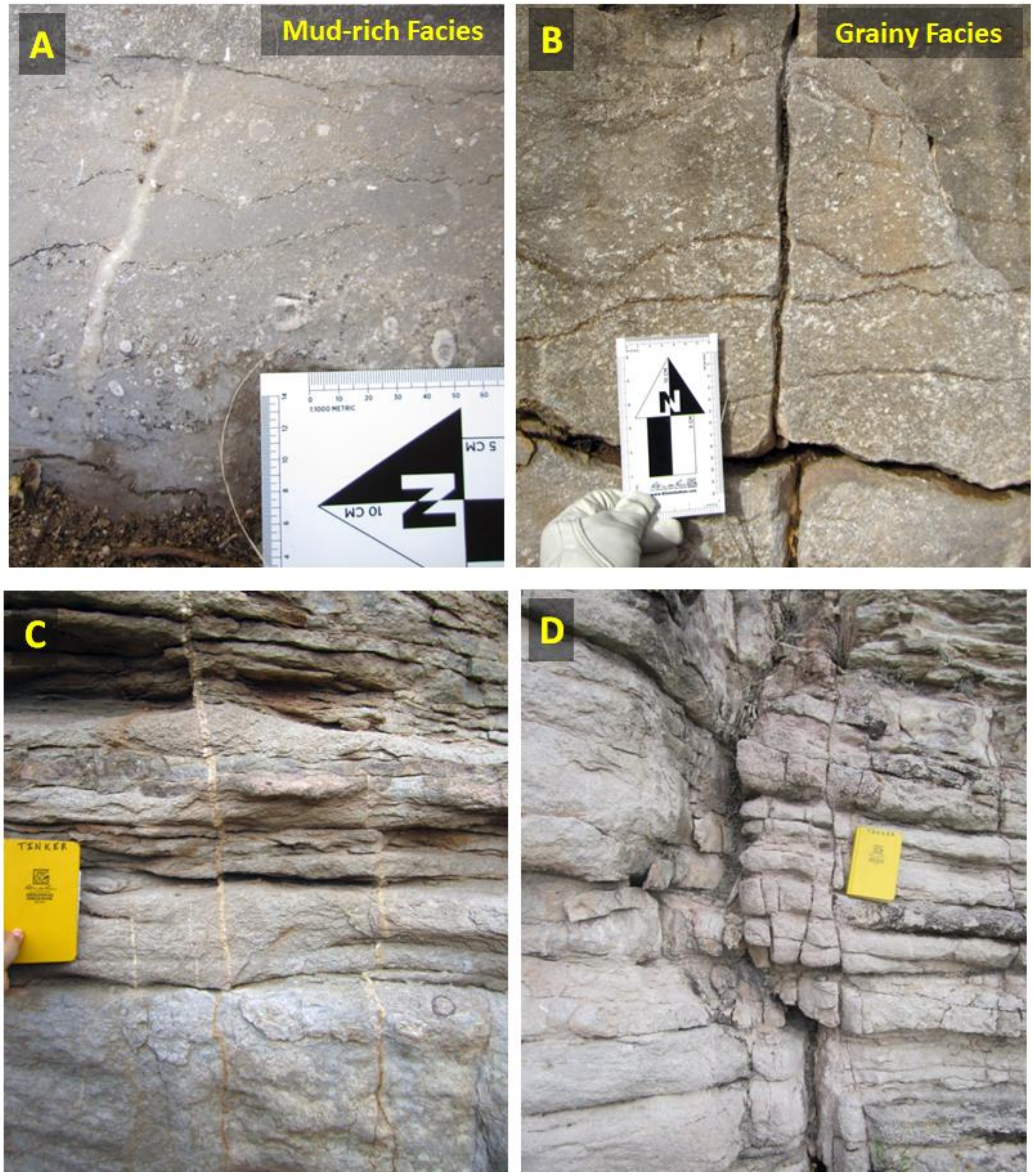

Figure 9. Subhorizontal stylolite development in both (A) mud-supported and (B) grain-supported facies, cross cut by later generations of both blocky-calcite filled veins and sub-vertical open fractures. Stylolite development requires significant overburden, which was likely achieved as a result of more than 4000 feet of Paleozoic sedimentation. (C) Blocky-calcite-filled veins cross-cut both resistant crinoid grainstone and less-resistant crinoid MDP/GDP bed-boundaries, as well as inter-Mississippian tabular chert nodules. (D) Open joints and fault with decimeter normal offset crossing numerous Tierra Blanca flank beds.

Fractures within the chert rarely propagate from the chert into the bed in which the chert is encased. However, these wispy sub-mm aperture chert-contained fractures are distinct from numerous instances of meter-scale calcite veins cross-cutting the chert nodules and chertified beds, which indicate the relative timing for at least one generation of fracturing and calcite fill with respect to timing of chert genesis (Figure 9). Additional cross-cutting relationships were documented such as subhorizontal stylolites cross-cut by either blocky-calcite veins (typically in mud-supported beds) or open joints (more prevalent in skeletal grainstones and rudstones), as well as various sets of fractures and joints cross-cutting one another (Figure 9; Figure 16).

The well-sorted crinoid grainstone flank beds on the southern margin of Teepee Mound contain fractures characterized primarily by bed-bound, sub-vertical, open and calcite-filled joints. Scanlines within the crinoid rudstone benches of this member show low fracture intensity as compared to equivalent facies directly above mound cores, and fractures usually striking N/S to NE/SW. Interpreted fractures, joints, and veins along the top face of the Tierra Blanca mound development show a distinct coalescing NE-SW trend near the main fault which cuts through the full Mississippian outcrop, and a more bimodal to random trend above the mound core itself (Figure 3b). Rose plots were generated from both field and digital interpretation of fractures above Teepee Mound (n=1396), which ranged in length from 0.2 - 48m. Fractures longer than 2 meters were binned by length to show the dominant fracture sets. Strike values for fractures greater than 2 meters in length (n=1045; 75% of dataset) have a mean strike orientation of 13^{o}. Strike values for fractures with lengths of more than 5 meters (n=348; 25% of dataset) have a mean orientation of 24^{o}. Strike values for fractures longer than 10 meters (n=85; 6% of dataset), have a mean strike orientation of 50^{o}. Although the fracture strike orientation is systematically increasing, the increase is nominal (occurs within 37^{o} range), and thus is treated as one fracture group. The fracture data generally follow a semi-lognormal distribution, as shown by a cumulative distribution function overlying the histogram of fracture lengths. Average strike of fractures generally coincides with the orientation of regional faulting and compression, implying that tectonically-generated fractures could be intermingled with local differential compaction related fractures.

Fractures mapped in the approximately 80 meters of vertical section of Lake Valley strata (Figure 10; Figure 17) show a stratification in which bed-bound fractures are more abundant than those which cross-cut multiple bed sets, both of which are more abundant than larger-scale fractures which cross-cut the entire outcrop. Based on digital interpretation of the southwest face of the outcrop, strata surrounding the early-lithified Alamogordo and Tierra Blanca mound cores are more intensely fractured than flank beds in inter-mound regions (Figure 10, Figure 11). The exceptions to this observation were in portions of the outcrop proximal to faults, in addition to the upper exposed edge of eroded cliff faces, where an increase in fracture is likely a result of recent freeze-thaw weathering, and thus not included in fracture intensity comparisons. Flank strata contain an increased abundance of both bed-bound and through-going meter-scale fractures above both mound cores and mound-derived blocks (Figure 10). The interpretation of the bed-bound fracture type was challenging directly above the main portion of Teepee Mound due to outcrop curvature and partially eroded flank beds. To address this issue, bed-bound fracture analysis was also conducted on imagery of areas above smaller local mounds and validated using scanlines measured in the field. Figure 11 shows that the summation of both mound and flank throughgoing fractures increase in intensity above the mound, as do the bed-bound variety.

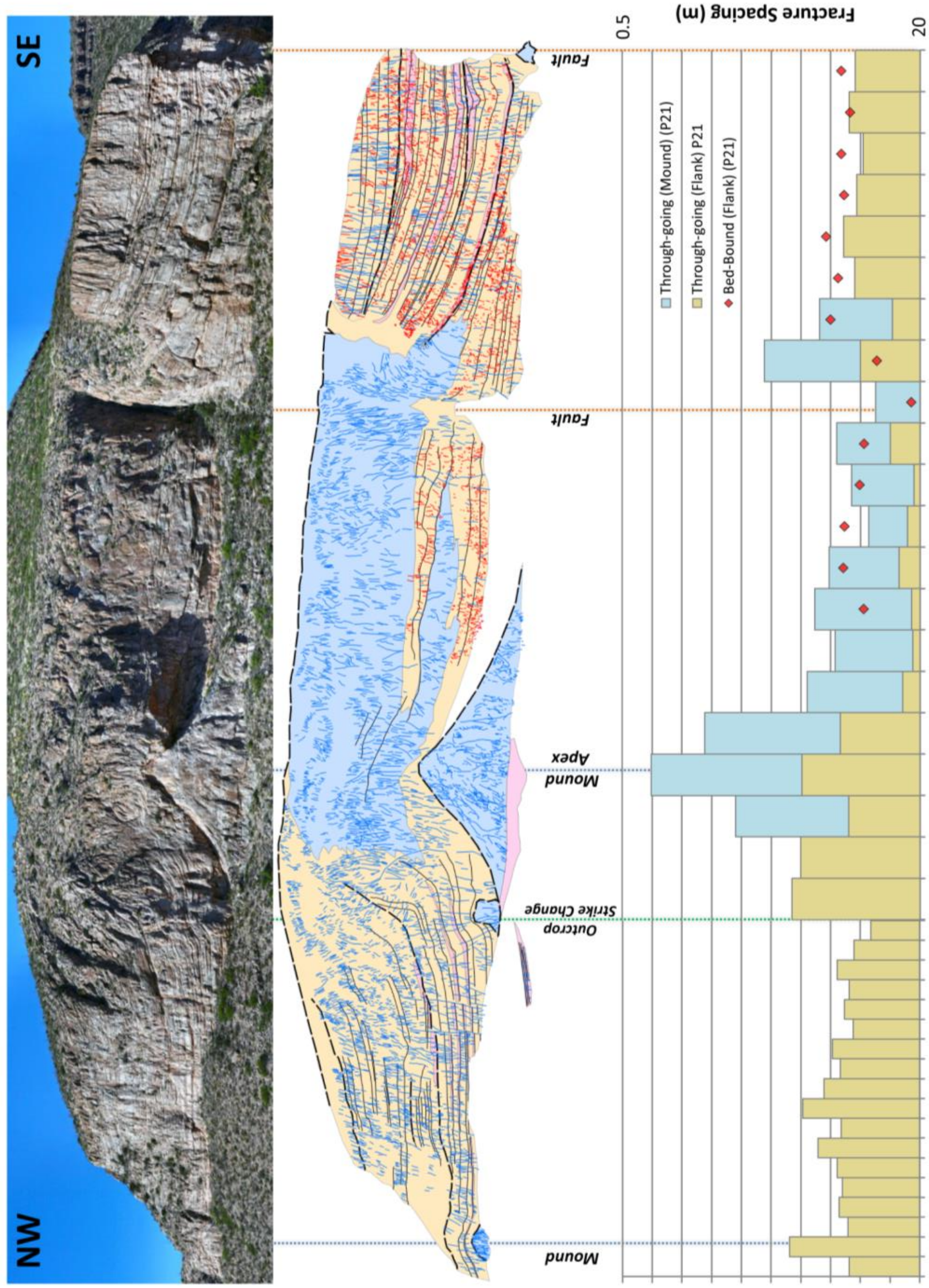
Fracture Intensity With Respect to Teepee Mound
NW
SE
Mound
Outcrop Strike Change
Mound Apex
Fault
Fault
Through-going (Mound) (P21)
Through-going (Flank) P21
Bed-Bound (Flank) (P21)
Fracture Intensity (#/m)
Fracture Spacing (m)
Distance from Mound Apex (m)
210 m
190 m
170 m
150 m
130 m
110 m
90 m
70 m
50 m
30m
20 m
10 m
0 m
10 m
20 m
30 m
40 m
50 m
60 m
70 m
80 m
90 m
100 m
110 m
120 m
130 m
140 m
150 m
160 m
170 m
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.5
20

Figure 10.

Figure 10. Strike view composite figure of Teepee Mound complex including crinoid-dominated flank beds which comprise the majority of the southwest face of Teepee Mound (Line #3 and #4 in Figure 3b). Blue indicates mound core facies, orange is skeletal grain-dominated flank facies, and pink color represents mud-dominated flank facies. Interpreted fractures from photo pan show a hierarchical fracture distribution and a distinct fracture intensity increase above the mound (center of figure, as well as right side above sloping mound edge). Fracture intensity increase above Teepee Mound (Line #3 in Figure 3b). Steep-angled flank facies (orange) overlie and interfinger with mound facies (blue). Bed-bound fractures (red) are typically subvertical with respect to bedding planes, versus through-going fractures (dark blue lines) which cross cut beds often in different orientation. Mound-derived blocks to the left of the triangular-shaped portion of Teepee Mound core are buried by flank beds which are later compacted over the initial topography.

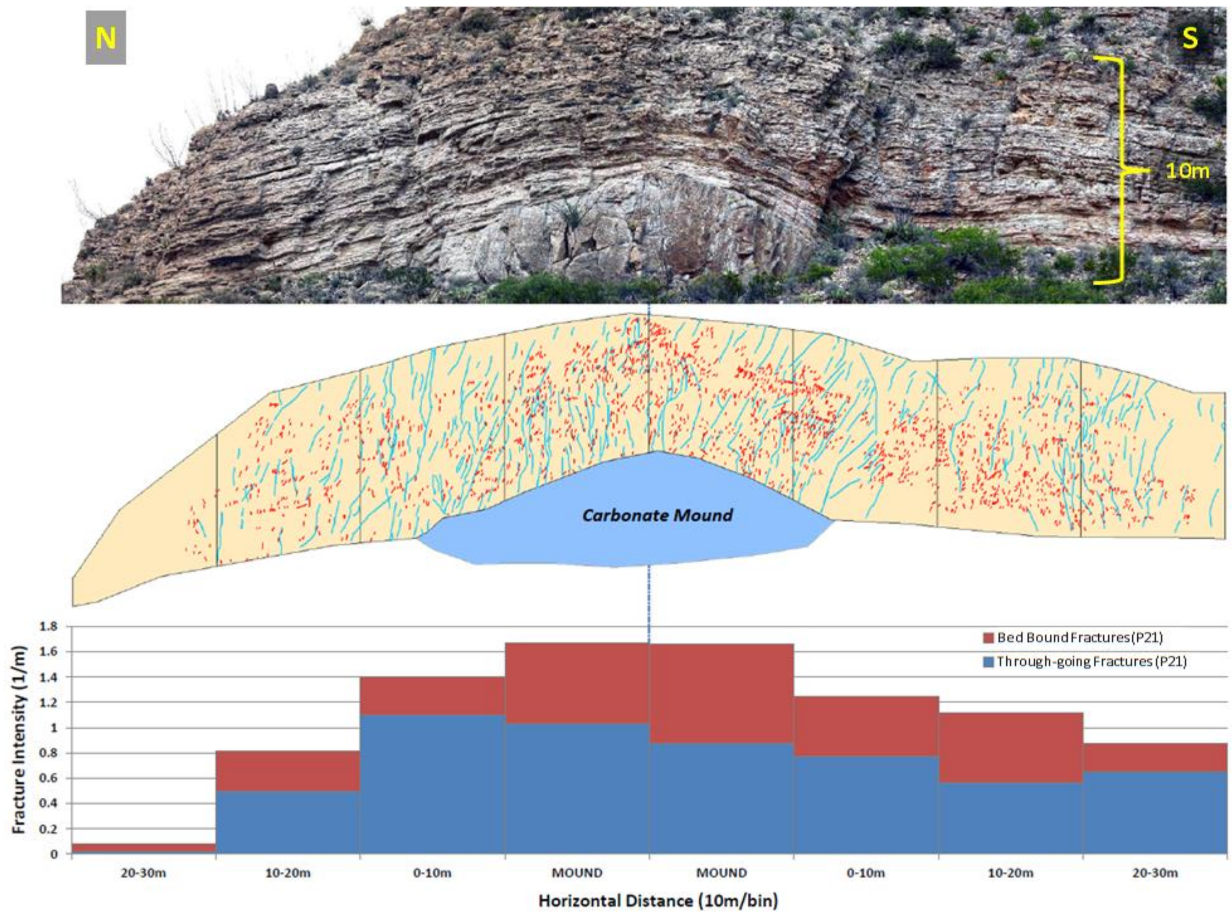

Figure 11. Fracture Intensity over Small Mound. Tierra Blanca grain-rich flank beds steepened as a result of differential compaction folding around early lithified mound core. (Line #2 in Figure 3b) Red lines are bed-bound fractures, and blue lines are fractures which cross-cut multiple beds and bedsets. Fracture intensity increases above the mound core, where tension is most focused.

Bed-bound fractures range in intensity from 0.1 – 0.6 per meter in flank beds away from both mound cores and faults, and increase to 0.7 - 0.9 per meter intensity above mound cores. Mound and flank through-going fractures showed a fracture intensity range of 0.3 - 0.5 per meter in well-exposed areas away from the mound, which increases to a range of 0.6 – 1.1 per meter above the mounds and near large faults. Additionally, fractures mapped in the field which were not as readily visible on aerial and photopan imagery showed a localized higher intensity immediately adjacent to the two primary faults shown on Figure 10, an intensity reduction between the fault and the mound core, and then increased yet again in outcrop areas above the mound core.

This study interpreted faults around Teepee Mound based upon (1) clear linear traces/break in outcrop and on UAV and satellite imagery, (2) bed offset (either vertical, rotational, or a combination), (3) a significant increase in fracture intensity around the interpreted fault plane. Faults primarily show a NE/SW orientation with a minor set striking NW/SE, and cross-cut the entire Mississippian and Pennsylvanian profile. Syndepositional faults were interpreted from the clear linear trace on the outcrop face as well as measureable bed-offset within early Tierra Blanca flank strata, the magnitude of which diminishes up section as later Tierra Blanca flank strata buried the fault tip and re-flattened the bed geometries (Figure 7). Finally, low-angle thrust faults were interpreted to the north and south of the study area, evidenced by fault-propagation folding and reverse-motion bed offset along the visible shear plane (Figure 15).

DISCUSSION

Tectonostratigraphic Development of Teepee Mound Complex

Field observations and fracture analysis show that the present configuration of the Teepee Mound complex and surrounding stratigraphy is the result of several deformation and diagenetic episodes. The simultaneous accretion of Teepee Mound and the deposition of adjacent flank beds created a stratigraphically complex relationship, characterized by flank-mound interfingering and laterally discontinuous strata. A conceptual model of the growth phases of Teepee Mound is interpreted in Dorobek and Bachtel (2001), which describes an early lenticular segment of mound growth, a secondary more aggradational phase, and a final lateral accretion stage. With slightly finer resolution, Hunt (2000) interpreted three inter-Tierra Blanca stratigraphic surfaces (TB1, TB2, and TB3) separated by erosional unconformities, which were correlated through Teepee Mound complex and into surrounding canyons (dashed black lines in Figure 10; Figure 17). See Hunt (2000) for justification and description of each surface. Combining these frameworks with the observations of this study facilitated the development of a general tectonostratigraphic sequence of the Teepee Mound complex, which is schematically represented in Figure 12. This sequence is useful in understanding timing of fracture formation as well as the most influential variables which affect fracture propagation through time.

The first depositional event observed was the undeformed, thin-bedded, fissile shales and wackestones of the Andrecito Member, interpreted to have been deposited in a low energy outer-ramp to basinal setting, which provided a substrate for the initial

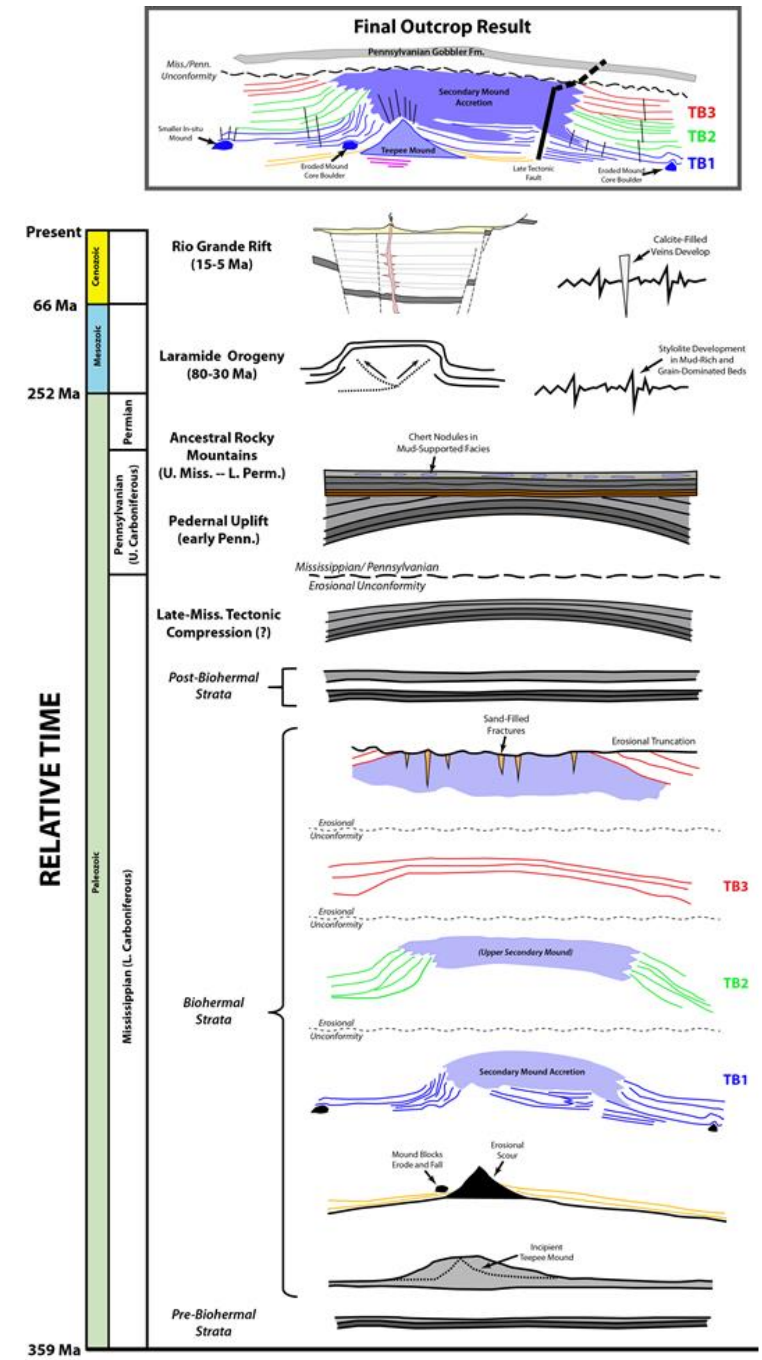

Figure 12. Schematic of the generalized sequence of Teepee Mound development and subsequent tectonic deformation. Deformation and diagenetic processes influenced various stages of development, and are represented. Ages of tectonic episodes averaged from literature (see text for discussion). Non-uniform timescale utilized.

lenticular phase of mound development. Subsequent mound aggradation and lateral accretion by localized shedding of autochthonous skeletal debris on mound flanks and inter-mound areas deposition occurred during the Alamogordo Member time (Figure 12). Pervasive synsedimentary marine cementation (Shinn et al., 1983) increased the rigidity and strength of the mounds early on without burial, making mound cores susceptible to early erosion by allochthonously-sourced crinoid debris flows as well as mound margin gravitational failure and early tension fracturing (Figure 7). Outcrop observations suggest that early open fractures within the mound core were infilled after by local crinoid and other skeletal debris via autochthonous sedimentation of on-mound crinoid and bryozoan communities (Figure 13). The distinct triangular outcrop expression of Teepee Mound, onlapped by Nunn and Tierra Blanca flank strata at the edges, indicates that the mound was post-depositionally contoured by submarine erosional processes which were caused by gravitational collapse and/or erosive effects of allocthonous gravity flows (Dorobek and Bachtel, 2001) (Figure 7).

The Nunn Member pinches out against the side of Teepee Mound (Figure 10). During this time, the system was transgressed, which resulted in all but the largest Alamogordo carbonate mounds to be draped and buried by muddier outer ramp deposits (Bachtel, 1995; Bachtel and Dorobek, 1998). The TB1/TB2 erosional surface is interpreted at the end of this interval, with the massive and laterally-accreting mound development capping the unit (Hunt, 2000).

Above the poorly-exposed Nunn Member, the Tierra Blanca member comprises allochthonous and autochthonous units of relatively grain-rich flank deposits that are laterally discontinuous and separated by localized minor erosional surfaces. The upper laterally-accreting portion of the Teepee Mound core accreted throughout this time period, interfingering with adjacent flank beds (Figure 12). In addition, some smaller minor mound developments occurred adjacent to the larger mound. Compaction caused flank bed flexure around these early-lithified mound cores, which generated bed-bound tension fractures which are especially concentrated above the features (Figure 11). As documented via field observation, localized slump folds feature fold-axis-parallel fractures which are filled by blocky calcite, and then cross-cut by later generations of open joints with different orientation. In addition, some portions of the flank beds were early-lithified and syndepositionally faulted, before further deposition of more flank beds which bury the fault tips in the outcrop. Furthermore, early bed-bound fractures were formed, which later reactivated and extended during subsequent tectonic episodes (Figure 17; Figure 18). During the final stages of Tierra Blanca time, skeletal dominated flank bed deposition continued contemporaneously with lateral mound core accretion, until the mounds were buried and encased by deposited sediments.

The entire Teepee Mound complex was subsequently buried by dark calcareous shales and argillaceous limestones of the Arcente Member, which serve as a potentially important mechanical boundary for further deformation events such as fault propagation. Although almost entirely buried under eroded alluvim in the study area, the Arcente Member represents the final stages of Lake Valley sedimentation above Teepee Mound, above which lies the Mississippian/Pennsylvanian unconformity (covered in the study area), and initial deposits of the much more flat-lying Pennsylvanian Gobbler Formation (Figure 14), an extensively chertified lower-energy unit comprising skeletal mud-dominated lower packstones, wackestones, and shales, adjacent to spase course clastic material eroded from the Pedernal Uplift. The Gobbler Formation is continuous, low-angle in most places except in the area above the Teepee Mound complex, and dips with

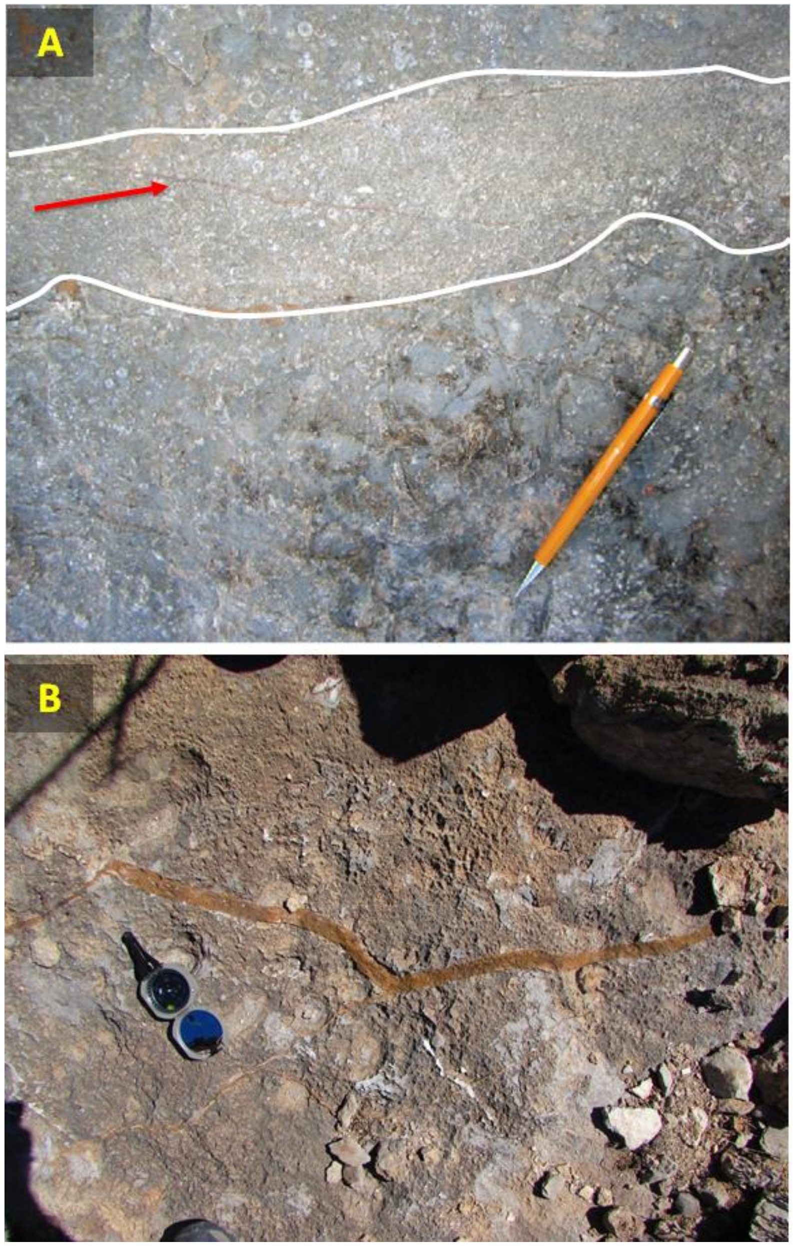

Figure 13. (A) Crinoid sediment and skeletal hash infill an early-formed, decimeter aperture mode-1 fracture (Neptunian dike, *sensu* Pray (1961)) in late Tierra Blanca mound core. Silicified rusty-brown fenestrate bryozoan debris is visible next to pencil for scale. Red arrow indicates where the early-cemented fracture is later cross-cut by thin reddish calcite-filled vein with different orientation. (B) Oxidized clastic silt fills fracture in the late Tierra Blanca mound core, possibly indicating subaerial exposure. Black metal tip of Brunton compass oriented north.

much lower angle in comparison to the deformed and discontinuous Mississippian strata underneath. In both the Alamogordo and Tierra Blanca exposures of Teepee Mound, Neptunian dykes occur (*sensu* Pray (1961); Bachtel and Dorobek, 1998)). The skeletal sediment infill suggests early fracture formation followed soon after by infill of debris sourced from local crinoid and bryozoan communities, and silt-filled fractures imply subaerial exposure of the cemented Teepee Mound core was between the late Mississippian and Pennsylvanian. Additionally, Meyers (1975) showed that the Lake Valley succession contains evidence (via detailed chert and cement petrography) for both pre-Morrowan and pre-Meramecian subaerial unconformities, and Bachtel and Dorobek (1998) also mention the possibility of a pre-Doña Ana subaerial exposure surface.

Tectonic Deformation

Pray (1961) grouped the structural features of the Sacramento Mountains into two general categories: structures that formed during the Paleozoic prior to the Sacramento Mountain range uplift, and Late Cenozoic structures related to uplift of the range during basin-and-range block faulting. During these periods, the Sacramento Mountains large-scale anticlines and synclines developed in response to tectonic processes (Figure 1). Detailed discussion in Pray (1961) and Pray (1977b) documents the significnant (more than 150m dip-slip displacement) pre-Abo N-S trending high-angle Fresnel, Alamo, and Bug Scuffle faults which are proximal to the study area (Figure 1). These features are truncated by the basal Abo unconformity, and related to Cenezoic uplift of the mountain range.

Late Mississippian Tectonic Compression

Field evidence interpreted in this work which supports late Mississippian tectonic compression includes: (1) considerably folded Mississippian strata underneath relatively undeformed Pennsylvanian beds (Figure 14), and (2) dominantly grain-rich Mississippian flanking beds dipping at 70-80^{o} around the mound core (Figure 7), which is much steeper than the depositional angle of repose for originally unconsolidated grain-rich sediments. Based on these observations as well as empirical data acquired in other studies of Mississippian sediments around the Sacramento Mountains (e.g. Meyers and Hill, 1983) such high-angle dips could not be a result of compaction alone. Meyers and Hill (1983) document that depositional intergranular porosities in Lake Valley formation coarse-grained echinoderm-bryozoan grainstones and cement-rich packstones can be as high as 42%, whereas modern intergranular space is only 12-41% (27% on average). Importantly, Meyers and Hill (1983) show that 90% of Mississippian grainstones in the Sacramento Mountains lost an average of 38% original porosity due to compaction prior to cementation. Given these values, it is unlikely that compaction was the sole driver of bed oversteepening (Figure 6), and was likely enhanced by the influence of inter-Mississippian tectonic compression. Such steep bedding angles are interpreted to be the combined result of depositional dip, subsequent differential compaction of the flank debris around the early-cemented mound core, and later tectonic compression.

Ancestral Rocky Mountains (A.R.M.)

It has been shown that ARM tectonic activity affected the Sacramento Mountains from the Pennsylvanian to early Permian time (Kottlowski, 1963; Kottlowski, 1968; Howell et al., 2002; Mack et al., 2003). Howell et al. (2002) conducted kinematic analysis on the N-S striking Fresnel, Alamo, and Bug Scuffle faults in the area, and links Pennsylvanian deformation to Ancestral Rocky Mountain tectonics, citing deformed Pennsylvanian strata overlain by undeformed or weakly deformed Permian strata. The Fresnal and Alamo faults are high-angle normal faults with significant (>150m) of dip-slip displacement, truncated by an unconformity of Abo time (Pray, 1977b). At Teepee Mound, evidence for late Mississipian Ancestral Rocky Mountain compression is supported by: (1) the distinct, laterally-continuous, ledge-forming Pennsylvanian Gobbler Formation with less than 5^{o} dip overlying $15\text{-}25^{o}$ dipping limbs of Lake Valley strata folded into antiformal geometry (Figure 14), and (2) skeletal-dominated Tierra Blanca flank beds were measured to have $70\text{-}80^{o}$ dips (Figure 7). Based on detailed measured sections showing the total thickness of grain-dominated beds versus the total thickness of mud-rich beds, this dipping angle cannot be explained by differential compaction alone based on empirical studies of carbonate compaction (e.g. (Goldhammer, 1997). Instead, it is more likely that the steep dip angles were achieved through a combination of differential compaction and inter-Mississippian tectonic compression.

Laramide Orogeny

Laramide Orogeny (~80-30Ma) compressional stresses affected the western margin of the Sacramento Mountains from Late Cretaceous to early Paleogene time (Seager and Mack, 1986; Burchfiel and Lipman, 1992), and early-formed fractures were likely reactivated and further propagated in response to this tectonic episode. Problematically, many Laramide-induced structures were subsequently buried beneath later volcanic and clastic strata, and cut by Basin and Range normal faulting (Seager and Mack, 1986). In the study area, Laramide compression is evidenced by low-angle thrust

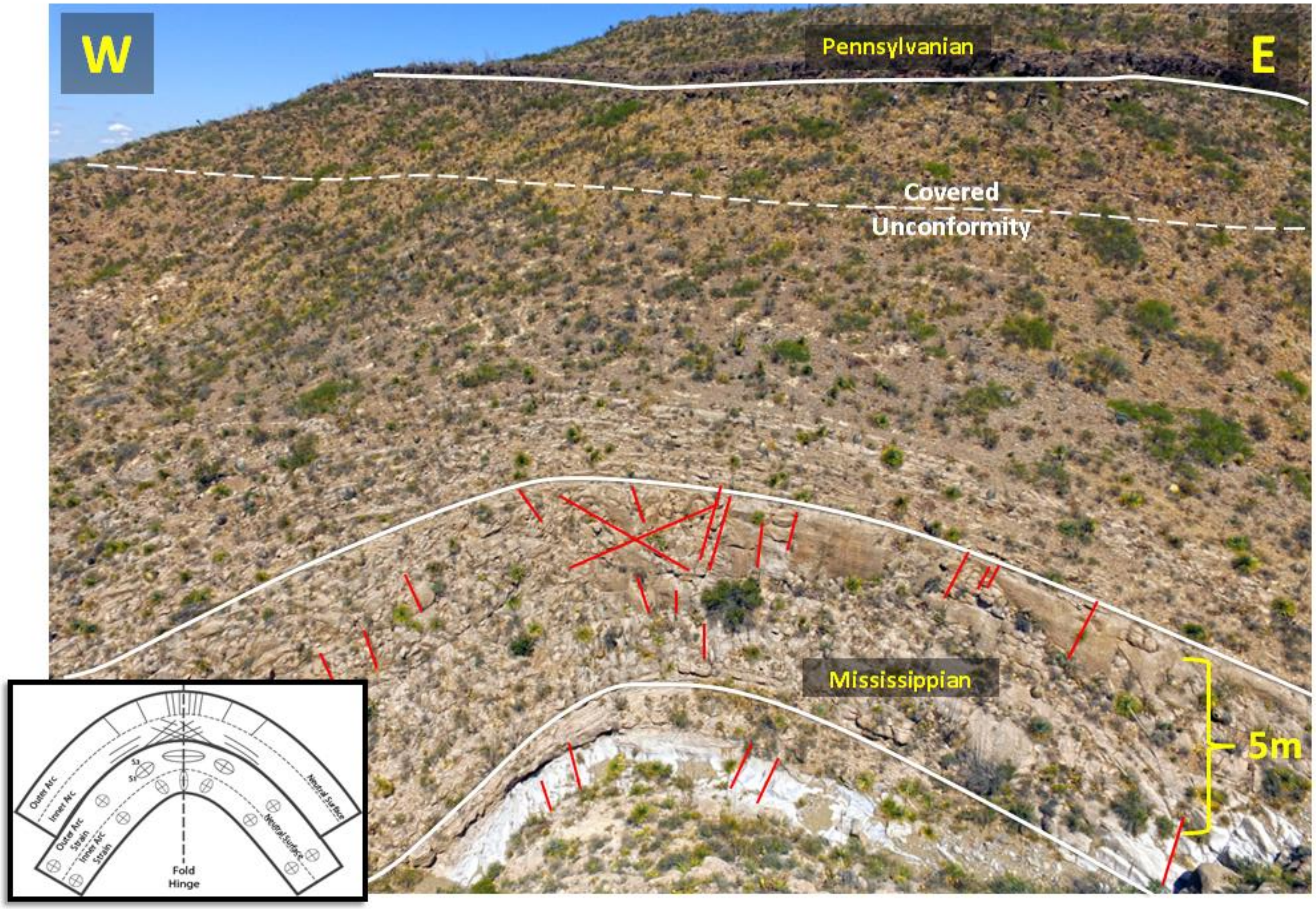

Figure 14. Folded Mississippian strata underneath flat-lying Pennsylvanian outcrop, evidencing Late Mississippian compression (possibly by Ancestral Rocky Mountain tectonics.) Idealized fold inset showing more intense fracture development above the fold axis and strain ellipses elongated in zone of increased tension.

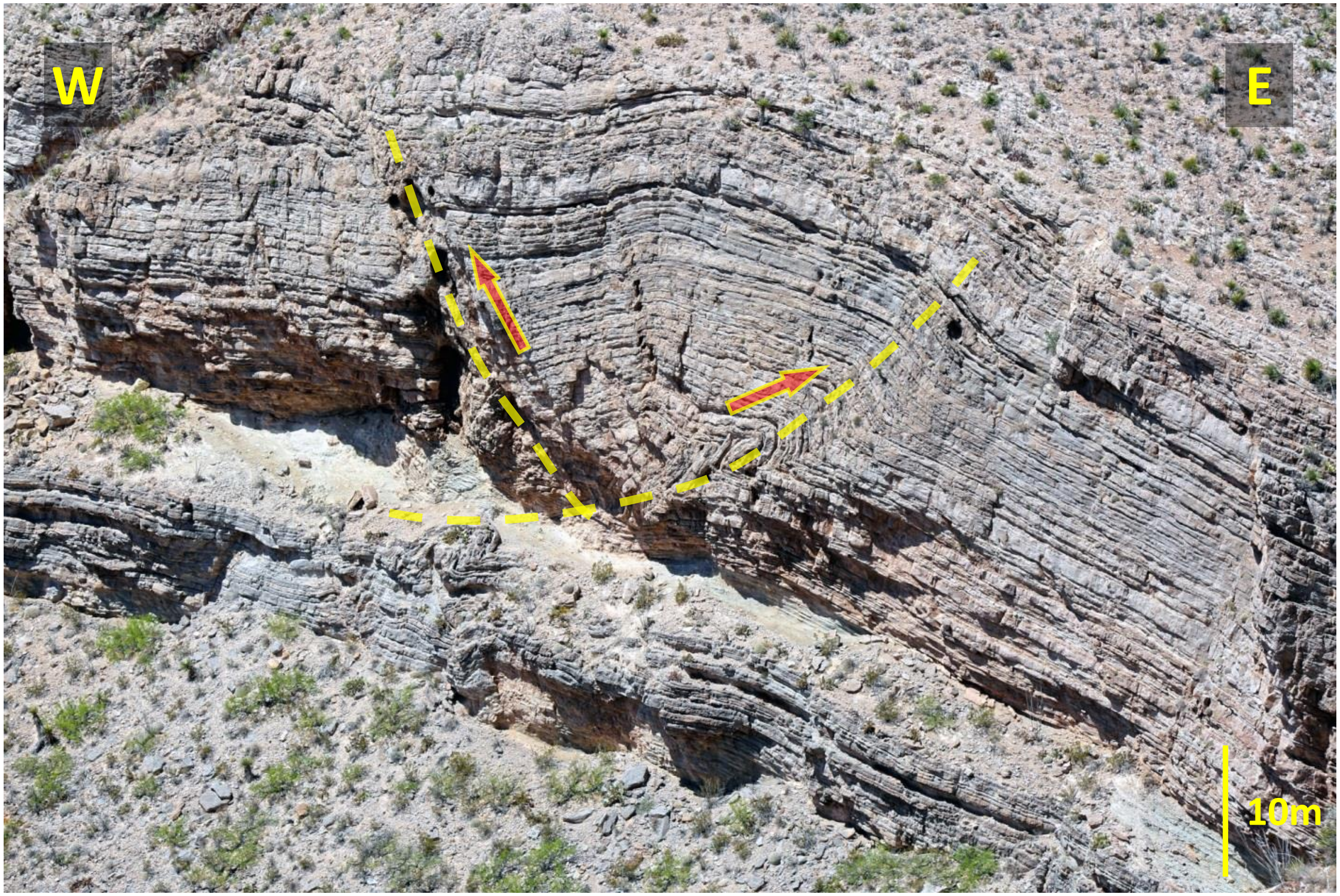

Figure 15. Mississippian sediments folded by thrust faulting probably related to the Laramide Orogeny, 1km northwest of study area. Early formed fractures were likely reactivated and further propagated during this event.

faulting resulting in fault-propagation folding in Mississippian strata (Figure 15), in addition to normal bed offset along a clear linear lineament in the cliff wall to the south of the Teepee Mound complex as well as in Alamo Canyon to the south.

Rio Grande Rift (Basin and Range)

The Rio Grande Rift (the eastern-most margin of the Basin and Range province) subjected the Sacramento Mountains to extensional stresses (Seager and Morgan, 1979; Brown and Phillips, 1999; Berglund et al., 2012), resulting large-offset normal faulting which bounds the western margin of the mountain belt (Figure 1), and as well as over-steepened bed geometries in the Paleozoic strata in the region. Pray (1961) and Seager (1981) attribute the present low-angle, eastward dip of the central Sacramento Mountain fault block to Tertiary Rio Grande Rift extension. Additionally, volcanism during this episode generated dark greenish gray igneous sills which cap some local hills above the Teepee Mound complex.

Deep burial during the Mesozoic is evidenced by stylolite development in both mud-dominated and mud-free strata throughout the study area, with subsequent uplift and exposure in the Cenozoic (Scholle and Halley, 1980) (Figure 9; Figure 12). Meter-scale joints and calcite-filled veins which cross-cut stylolites, erosional surfaces, mound/flank interfaces, and numerous bed sets are an overprinting from the Cenozoic extensional stress regime. The tectonic-scale anticlines, synclines, and faults interpreted throughout the Sacramento Mountains by Pray and other previous workers (Figure 3) were supported by observations from this study. For example, Tertiary faults cross-cut both Mississippian and Pennsylvanian beds in the study area with a N/S and NE/SW trend (Figures 1; 3; 6; 13), which matches the interpreted large-scale faults and folds of Pray and others. Pray, (1977a) mentions the enigmatic increase in east dips of strata to the south of the study area, as well as the prominent low angle thrust faults (dips 20-30^{o} with 200 ft. displacement in places) exposed just south of the study area which pre-dates the Cenozoic uplift of the mountain block.

Diagenesis

Throughout the development of the Carboniferous profile, compaction and cementation were important influences on stratal geometry, bed thickness, and fracture development. A significant lack of porosity is clear from the numerous thin sections taken from flank facies in this study (Figure 8). Post-depositional subaerial exposure events (Kirkby and Hunt, 1996) would have likely expedited meteoric cementation and occluded much of the primary porosity of the grain-dominated packstone, grainstone, and rudstone flank strata, with any remaining pore space filled by later generations of cementation. Such extensive cementation during Tierra Blanca deposition homogenized the mechanical strength differences from bed to bed, which in turn influenced fracture networks development by allowing fractures to cross cut boundaries which separated beds with originally distinct competencies.

Meyers (1977) and Meyers (1980) discussed important timing relationships between cementation, compaction, and stylolite development in the Lake Valley formation, claiming that compaction was initiated following very shallow (10-100's feet of overburden) completed under less than 6500 feet (2000 meters) of overburden. Most mechanical and chemical compaction occurred pre-Pennsylvanian (Morrowan), as early as mid-Mississippian time (pre-Meramecian, pre-Doña Ana). Meyers (1980) documents that some chemical compaction took place during cementation, providing dissolved calcium carbonate for cements. Some mechanical compaction must have occurred before chertification, as evidenced by skeletal grain breakage and skeletal fragments being entirely replaced by and encased in chert. Once a rock is chertified, it provides extreme resistance to compaction. Since most chert developed pre-Pennsylvanian (Meyers, 1977), almost all non-stylolitic compaction likely ceased before the Permian (Meyers, 1980). Using the same reasoning, mechanical compaction likely pre-dates cementation of Mississippian strata, a claim evidenced by field observation of cemented broken grains. Finally, this study documented stylolites which cross-cut cements, implying that they post-date cementation, in addition to stylolites which are themselves cross-cut by a late Cenozoic set of open joints and blocky calcite veins (Figure 9).

Fracturing and Mechanical Stratigraphy

Characterization of fracture development can be challenging, especially in carbonate outcrops, because existing outcrops reflect current rock properties and very rarely those of the ancient, due to various factors which affect mechanical strength and thus response to fracturing through time (Shackleton et al., 2005; Laubach et al., 2009). For example, progressive and episodic diagenetic processes significantly affect fracture development, because original mechanical properties, including brittleness, are altered via compaction, cement formation, and dissolution of unstable components. In the Teepee Mound outcrop, the fracture network developed within the mound and the surrounding grain-dominated flanks appears to be controlled predominantly by: (1) differences in original mechanical strength in grainy versus mud-dominated beds; (2) proximity to pre-existing early-lithified paleotopographic relief, and (3) diagenesis (specifically,

Figure 16. Showing chaotically and intensely fractured chert nodules within a much less fractured mud-dominated packstone host rock of the Tierra Blanca member, cross cut by at least three distinct generations of late fractures, one of which was subsequently infilled by blocky calcite.

syndepositional marine cementation of the mound core, post-depositional meteoric pervasive blocky calcite cementation of grain-dominated flanking strata, and compaction due to post-Mississippian burial.) For example, coeval grain-dominated facies adjacent to the mound would have undergone early cementation promoted by periodic subaerial exposure, which would have reduced their porosity via cementation, increased their brittleness, and increased their susceptibility to fracturing.

The modern Teepee Mound outcrop and the surrounding grain-rich strata show a distinct temporal change in mechanical stratigraphy through time, primarily due to cementation and compaction. Fracture development in the grain-rich flanking strata is hierarchical. An early set of bed-bound fractures (Figure 18) is vertical with respect to bedding planes, even when the beds are steepened due to local differential compaction around the mound. These early fractures are bed-bound because they respected the original rheological and mechanical strength differences between the mud rich and mud-free flanking layers. A second fracture set with markedly longer sub-vertical fractures cross-cuts both grainy and muddy beds in the outcrop, typically in *en echelon* form, ignoring bedding planes and interfaces. This fracture set likely developed as a response to post-Mississippian stresses directly related to burial, after mechanical strength of the entire outcrop was homogenized due to pervasive blocky calcite cementation (Figure 17), and/or from faulting and folding during the primary tectonic episodes which followed (Figure 12).

As an example of this type of mechanical stratigraphic hierarchy, Figure 18 shows a closer view of the two initially different mechanical units: a resistant, thick crinoid rudstone and the thinner bedded mud-dominated packstone. An earlier generation of fractures (shown in white) terminated at bed interfaces due to mechanical strength

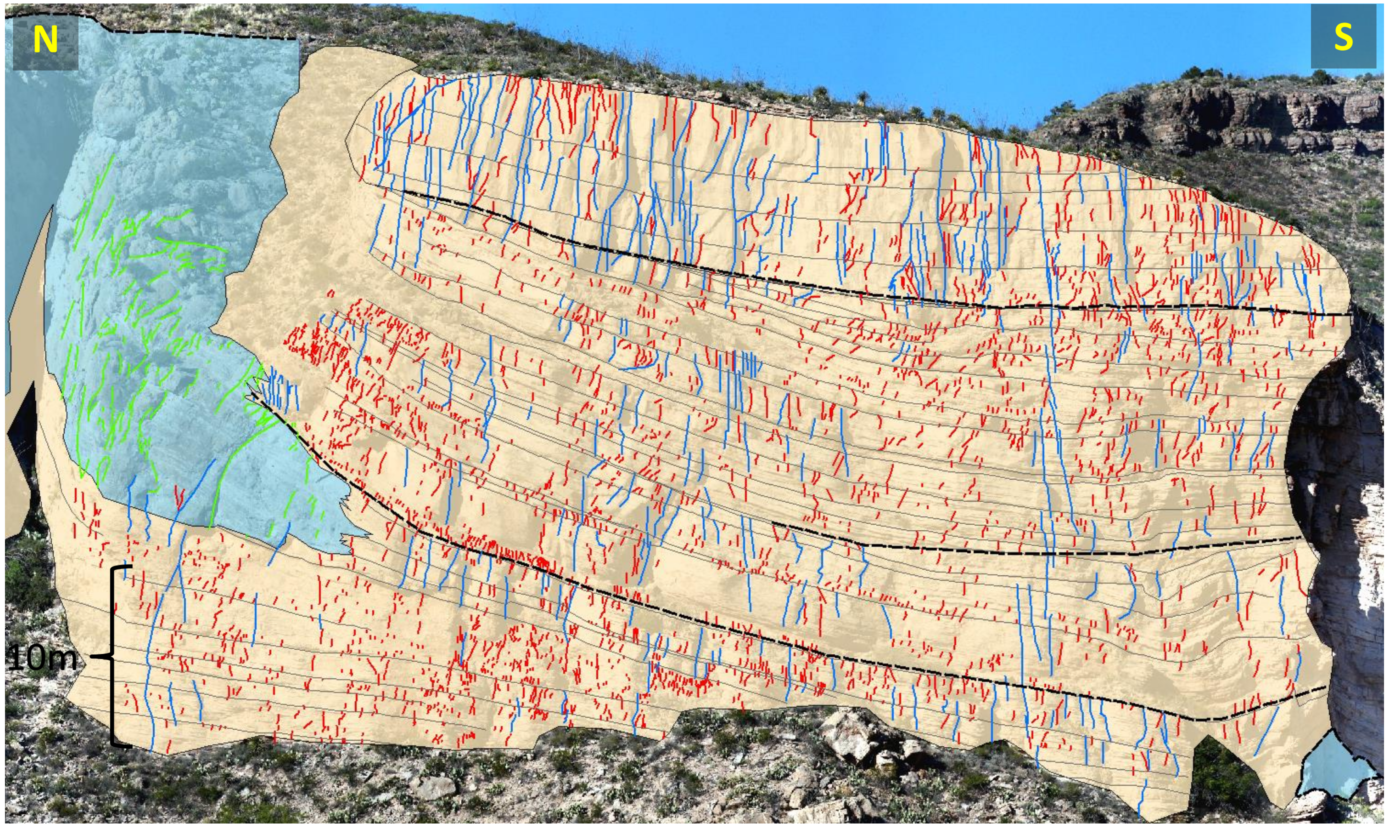

Figure 17. Close view of Tierra Blanca flanking strata (Line #4 in Figure 3b), showing bed-bound fractures in red, through-going fractures in blue, and mound-bound fractures in green, and interpreted erosional surfaces in black dashed lines (this work; Hunt, 2000). Early facies heterogeneity establishes original mechanical stratification, which later homogenized as a result of extensive and pervasive cementation and compaction. Early bed-bound fractures seed later through-going fractures. Early bed-bound fracture intensity increases as beds become progressively more steep above the mound. Through-going fracture intensity might be artificially elevated on the upper few meters of outcrop due to freeze-thaw weathering effects.

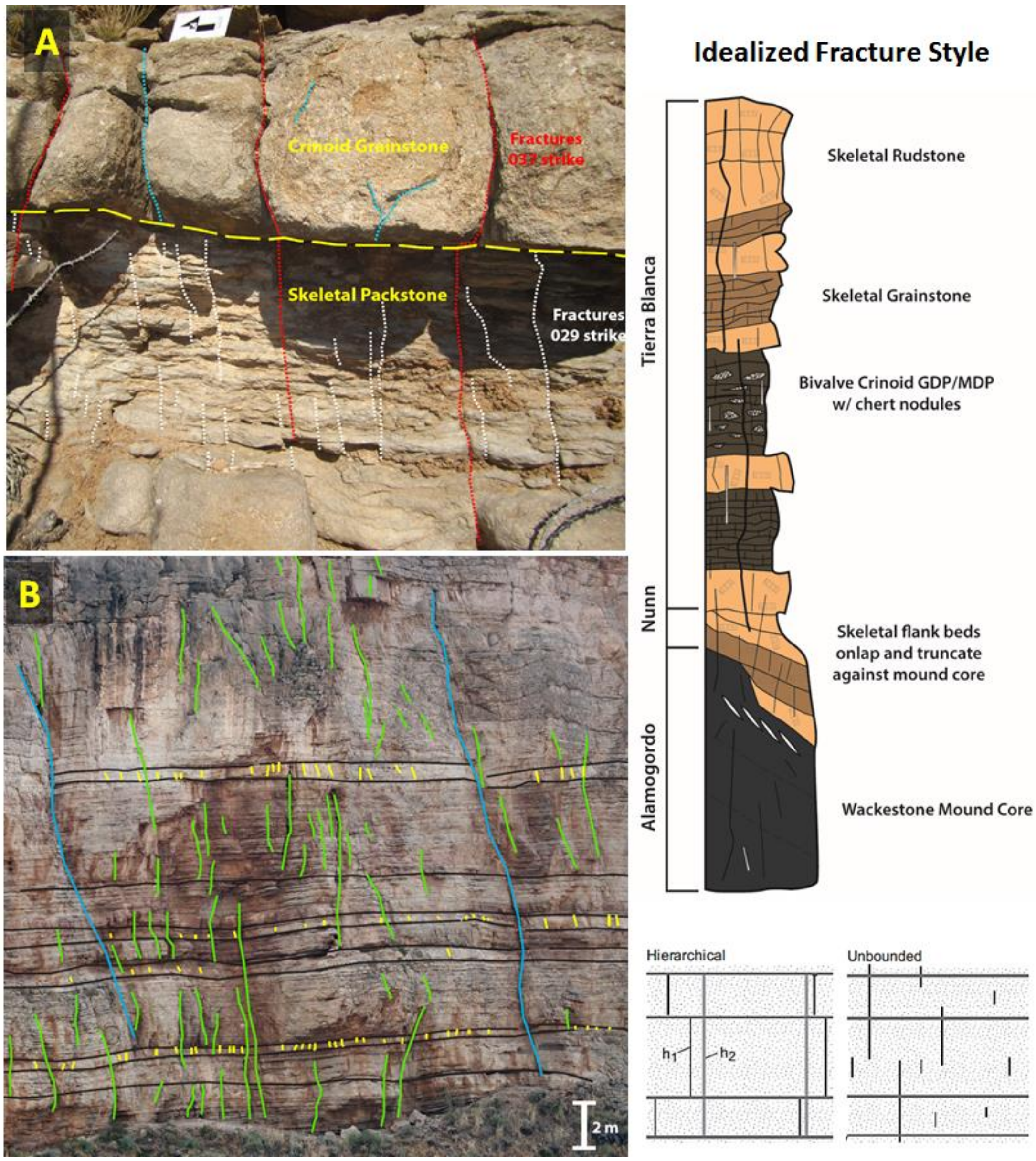

Figure 18. (A) mechanical stratigraphy displayed within the grain-rich Tierra Blanca flank facies (10cm card for scale). Early fractures respect depositional facies strength variation from bed to bed. Later through-going fractures cross-cut both grainstone and muddier beds, ignoring bed-boundaries, due to pervasive blocky calcite cementation which homogenized the mechanical strength of the outcrop. (B) Similar fracture stratification interpreted at the outcrop scale within Lake Valley succession. Schematic classification of fracture bed-boundedness (after Laubach, 2009). Flank beds style is “Hierarchical” to “Unbounded”.

differences between the layers. As a result of later episodes of pervasive blocky calcite cementation, the outcrop mechanical strength was homogenized, allowing a late set of through-going fractures (shown in red) to propagate and cross over all bed interfaces. Thinner beds seem to contain more bed-bound fractures than thicker, originally competent grainstone/rudstone beds. This can be misleading, however, as facies and extent of cementation likely exert more of a control than bed thickness. Although the idea that bed thickness can be used to approximate fracture spacing has been shown in some cases (e.g. Ladeira and Price, 1981; Verbeek and Grout, 1983; Nelson and Serra, 1995), this relationship is not always straightforward in carbonate strata (e.g. Hanks et al., 1997; Di Cuia et al., 2004; Wennberg et al., 2006; this study), where fracture intensity can depend more upon the Dunham texture than mechanical layer thickness. Specifically, beds with significant primary porosity and permeability (such as grain-supported crinoid rudstone flank strata prior to cementation) facilitate fluid flow and thus cementation processes, which strengthens strata early in the burial history. Hanks et al. (1997) shows how tens of percent of strain can be accommodated by calcite twin lamellae in coarse grained carbonates (Wiltschko et al., 1985), whereas mud-supported fabrics with less calcite content must respond to stress via multiple generations of fracturing.

Influence of Antecedent Topography on Fracture Development

The southwest facing triangular exposure of Teepee Mound gives a false impression of the true morphology of the mound. In agreement with the interpretation of Bachtel and Dorobek (1998), the triangular shape visible today is an erosional remnant of mound margin failure due to oversteepening and erosion via skeletal -dominated debris

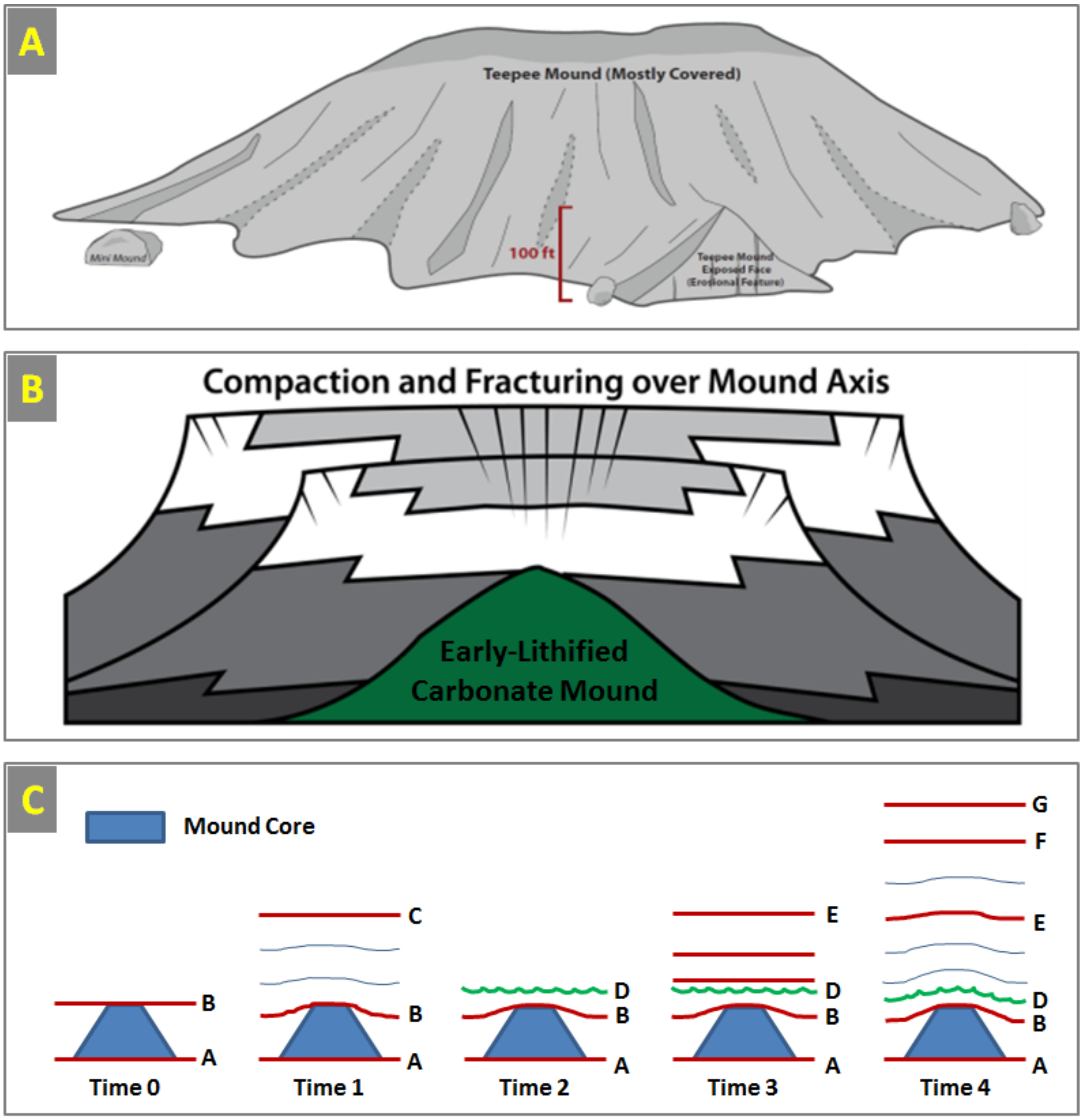

Figure 19. (A) Schematic of main body of Teepee Mound during aggradation. Much of the mound body is buried within the modern hillside and Quaternary alluvium. The distinct triangular geometry in the southwest well-exposed outcrop is shown as an eroded limb of the main mound. (B) Schematic representation of tension developed in strata overlying carbonate mound (green), resulting opening-mode fractures with increased intensity over the mound. After Frost and Kerans (2009). (C) Temporal progression of differential compaction over early-lithified antecedent topography in the presence of an unconformity. After Labute and Gretener (1969)

flows sourced updip (Figure 19). Thus, the southwest exposure of Teepee Mound is interpreted to be an eroded limb of a larger mound body buried within the hillside, with associated eroded mound blocks and temporally-equivalent smaller mound developments existing adjacent to the primary mound core (Figure 19). The small zones of exposed mound core to the north and south of the study area are parts of the domal, laterally-extensive upper Tierra Blanca mound core (Figure 3a). Supporting this idea, the dips measured on the overlying Gobbler Formation directly above the Mississippian mound core suggest that the beds gently curve over the underlying core. Topographic relief provided by the early lithified mound core affected fracture formation by providing an inflection point over which subsequent beds were flexed, generating a higher fracture intensity in the zone above the topographic feature. This process occurs at multiple scales around the outcrop, from the main body of Teepee Mound (Figure 10) to the early localized compaction of grain-rich deposits over meter-scale mounds and olistoliths (Figure 11; Figure 5), and is interpreted as an "early" process because subsequent Tierra Blanca sedimentation clearly flattens out bed dips within a few meters upsection.

The mechanical framework was initiated early in the flank facies development, which established planes of weakness which were preferentially utilized during subsequent tectonic events by later fracture generations. The outcrop is interspersed with bed-bound syndepositional joints related to early compaction. Just as facies typically control early diagenesis, these early generations of fractures established weakness heterogeneities which influenced the loci of formation of later fracture sets. This interaction is also interpreted utilizing evidence from the body of the Teepee Mound core: immediately following early marine cementation (Shinn et al. 1983), the mound core likely acted as one mechanical unit, facilitating early opening-mode mound-bound tension fractures and erosional failure at the mound margins. Subsequent flank bed deposition, lithification, and compaction over the mound cores generated the early flexure-related joint and fracture style described above, which was more intense above the mound. Even later formed fractures propagated across the mound-flank interface by utilizing the distinct sets of pre-existing fractures in the mound core as well as the bed-bound flexure-related fractures in the flank beds. The final result of this multi-scale process is witnessed in multiple locations in the outcrop around Teepee Mound (Figure 10; Figure 11; Figure 5).

CONCLUSIONS

The Teepee Mound outcrop is the final result of a complex history of deposition, diagenesis, and tectonic activity, and showcases the strong link between evolving rock properties and fracture generations. This study demonstrates that early-lithified carbonate mounds influence subsequent fracturing by enabling differential compaction of strata around the mound, which increases fracture intensity above mound cores. Moreover, carbonate mounds exert a strong control both early contemporaneous deposition of flanking strata as well as on fracture response to subsequent tectonic deformation. The Teepee Mound complex contains a mixture of both early and late formed structural elements which evidence changes in mechanical stratigraphy and stress through time, and is not simply an overprint of the most recent tectonic episode. Temporally evolving mechanical stratigraphy affects fracture characteristics such as intensity and length, and controls fractures propagation, especially across bed-boundaries. Early features at Teepee Mound include opening-mode mound-bound fractures, erosion-truncated edges and mound derived olistoliths, overlying sediment onlap with draping bed morphology due to early compaction, and an array of smaller, bed-bound fractures which were a response to early differential compaction over the mound. These early-seeded fractures provide preexisting zones of weakness which are preferentially utilized and reactivated by later features, which developed due to the changes in rock strengths via cementation, compaction, and other diagenetic processes through time.

Importantly, fracturing in mound-associated subsurface reservoirs typically adds complexity via secondary and tertiary porosity and permeability systems, because non-mineralized natural fractures in reservoirs establish preferential permeability anisotropy. Thus, fracture analysis which yields intensity and orientation information is of first-order importance for reservoir characterization efforts. To best define these attributes, it is imperative to understand deposition, mechanical stratigraphy, timing of diagenesis, fracturing, and tectonic history. It is challenging but necessary to distinguish the relative timing of those elements in order to correctly characterize the mechanical stratigraphic progression and fracture development through time, in order to understand potential fluid flow pathways and reservoir quality. Future work must integrate micro-textural information with rock mechanical studies, in order to better clarify the relationship between mechanical stratigraphy and fracture attributes.

REFERENCES

Ahr, W. M., 1989, Sedimentary and tectonic controls on the development of an Early Mississippian carbonate ramp, Sacramento Mountains area, New Mexico. Controls on Carbonate Platform and and Basin Development. p. 2003-2012.

Armstrong, A. K., B. L. Mamet, and J. E. Repetski, 1980, The Mississippian System of New Mexico and southern Arizona. Paleozoic Paleogeography of West-Central United States. SEPM. p. 82-99.

Bachtel, S. L., 1995, Sequence stratigraphic analysis of Mississippian limestones in the San Andres and Sacramento Mountains, south-central New Mexico, Master's Thesis, Texas A & M University.

Bachtel, S. L., and S. L. Dorobek, 1998, Mississippian carbonate ramp-to-basin transitions in south-central New Mexico: Sequence stratigraphic response to progressively steepening outer-ramp profiles: Journal of Sedimentary Research, v. 68, p. 1189-1200.

Bemis, Sean P., et al. "Ground-based and UAV-based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology." Journal of Structural Geology 69 (2014): 163-178.

Berglund, H. T., A. F. Sheehan, M. H. Murray, M. Roy, A. R. Lowry, R. S. Nerem, and F. Blume, 2012, Distributed deformation across the Rio Grande rift, Great Plains, and Colorado plateau: Geology, v. 40, p. 23-26.

Blakey, R., 2006, Global Paleogeography, mollewide plate tectonic maps-Mississippian (340), Available at http://jan.ucc.nau.edu/rcb7/340moll.jpg.(accessed 15 June 2015).

Bosence, D., and P. Bridges, 1995, A Review of the Origin and Evolution of Carbonate Mud-Mounds: Carbonate mud-mounds: their origin and evolution, p. 1-9.

Brown, C. D., and R. J. Phillips, 1999, Flexural rift flank uplift at the Rio Grande rift, New Mexico: Tectonics, v. 18, p. 1275-1291.

Burchfiel, B. C., and P. W. Lipman, 1992, The Cordilleran orogen: conterminous US, Geological Society of America.

Byrd, T. M., 1989, Facies analysis of the Caballero Formation and the Andrecito Member of the Lake Valley Formation(Mississippian): implications for Waulsortian bioherm inception, Alamo Canyon area, Sacramento Mountains, New Mexico, Texas A&M University College Station, Texas.

Cope, E., 1881, Geology of the Lake Valley mining district: American Naturalist, v. 15, p. 831-832.

De Keyser, T. L., 1978, The early Mississippian of the Sacramento Mountains, New Mexico: an ecofacies model for carbonate shelf margin deposition. Oregon State University,

Di Cuia, R., C. Gout, L. Bazalgette, and P. Masse, 2004, Are Fractures, in a Carbonate Sequence, Facies-Controlled?-The Maiella Mountain (Southern Italy), a Key for Complex Reservoir Modeling: 66th EAGE Conference & Exhibition.

Dorobek, S., and S. Bachtel, 2001, Supply of allochthonous sediment and its effects on development of carbonate mud mounds, Mississippian Lake Valley Formation, Sacramento Mountains, south-central New Mexico, USA: Journal of sedimentary research, v. 71, p. 1003-1016.

Frenzel, H., R. Bloomer, R. Cline, J. Cys, J. Galley, W. Gibson, J. Hills, W. King, W. Seager, and F. Kottlowski, 1988, The Permian basin region: Sedimentary cover—North American craton: US: Boulder, Colorado, Geological Society of America, The Geology of North America, v. 2, p. 261-306.

Frost, E. L., 2007, Facies heterogeneity, platform architecture and fracture patterns of the Devonian reef complexes, Canning Basin, Western Australia. The University of Texas at Austin.

Frost, E. L., and C. Kerans, 2009, Platform-margin trajectory as a control on syndepositional fracture patterns, Canning Basin, Western Australia: Journal of sedimentary research, v. 79, p. 44-55.

Giles, K. A., and T. F. Lawton, 1996, Control of Pennsylvanian facies distribution by coeval transpressional folding, Orogrande Basin, New Mexico: Geological Society of America Abstracts with Programs, v. 28.

Gretner, P. E., & Labute, G. J., 1969. Compaction—a discussion. Bulletin of Canadian Petroleum Geology, 17, 269-303.

Goldhammer, R., 1997, Compaction and decompaction algorithms for sedimentary carbonates: Journal of sedimentary research, v. 67. p. 26-35.

Gutschick, R. C., 1983, Mississippian continental margins of the conterminous United States. The Society of Economic Paleontologists and Mineralogists SEPM. p. 79-96.

Hanks, C. L., J. Lorenz, L. Teufel, and A. P. Krumhardt, 1997, Lithologic and structural controls on natural fracture distribution and behavior within the Lisburne Group, northeastern Brooks Range and North Slope subsurface, Alaska: AAPG bulletin, v. 81, p. 1700-1720.

Hoffmann, M. F., 1996, Sedimentology, sediment dispersal patterns, and stratigraphic architecture of progradational carbonate sand bodies, lower Lake Valley Formation (Mississippian), Sacramento Mountains, south-central New Mexico (Doctoral dissertation, Texas A&M University).

Howell, A. W., E. A. Erslev, and S. M. Cather, 2002, Evidence for Pennsylvanian transpression from preliminary kinematic fault analyses in the Sacramento Mountains, New Mexico, 53rd Annual Field Conference Guidebook: New Mexico, New Mexico Geological Society, p. 103-106.

Hunt, D., 2000, Platform architecture and sequence stratigraphy of the Lake Valley Formation, in R. Stanton Jr, ed., The Carboniferous Geology of the Sacramento Mountains, New Mexico, v. Field Guidebook: New Mexico, p. 36.

Hunt, D., and T. Allsop, 1993, Mississippian strata of the Sacramento Mountains, New Mexico: Sketches of stratal patterns, palaeogeography, and some preliminary interpretations, Unpublished Field Guide and Notes, University of Manchester.

Jeffery, D. L., 1997, Tectonic control on sea-floor relief and the localization of Lower Mississippian Waulsortian mounds, New Mexico: Geology, v. 25, p. 1011-1014.

Johnson, M., 1985, Pennsylvanian-Permian deformation at 1,000-5,000 feet of overburden: Sacramento Mountains, New Mexico [MS Thesis]: College Station, Texas A&M University, 116p.

Kenter, J. A., 1990, Carbonate platform flanks: slope angle and sediment fabric: Sedimentology, v. 37, p. 777-794.

Kirkby, K. C., and D. Hunt, 1996, Episodic growth of a Waulsortian buildup: the Lower Carboniferous Muleshoe Mound, Sacramento Mountains, New Mexico, USA, in P. Strogen, I. D. Somerville, and G. L. L. Jones, eds., Recent Advances in Lower Carboniferous Geology, v. Special Publication v.107: London, Geological Society, p. 97-110.

Kluth, C., 1986, Plate Tectonics of the Ancestral Rocky Mountains: Part III. Middle Rocky Mountains. p. 353-369.

Kluth, C. F., and P. J. Coney, 1981, Plate tectonics of the ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Kottlowski, F. E., 1963, Paleozoic and Mesozoic strata of southwestern and southcentral New Mexico, State Bureau of Mines and Mineral Resources, New Mexico Institute of Mining & Technology.

Kottlowski, F. E., 1968, Influence of the Pedernal Uplift on sedimentation. P. 21-40

Kottlowski, F. E., 1975, Stratigraphy of the San Andres Mountains in south-central New Mexico: Las Cruces Country, New Mexico Geological Society Annual Fall Field Conference Guidebook, v. 26: New Mexico, 376 p.

Labute, G. J., & Gretener, P. E., 1969. Differential Compactions Around a Leduc Reef--Wizard Lake Area, Alberta. Bulletin of Canadian Petroleum Geology, 17(3), 304-325.

Ladeira, F. L., and N. J. Price, 1981, Relationship between fracture spacing and bed thickness: Journal of Structural Geology, v. 3, p. 179-183.

Lane, H., and A. Ormiston, 1982, Waulsortian Facies, Sacramento Mountains, New Mexico: Symposium on the Paleoenvironmental Setting and Distribution of the Waulsortian Facies. El Paso Geological Society and University of Texas at El Paso, International Field Seminar Guide, p. 115-182.

Lane, H. R., 1974, Mississippian of Southeastern New Mexico and West Texas--A Wedge-on-Wedge Relation: AAPG Bulletin, v. 58, p. 269-282.

Lane, H. R., 1975, Correlation of the Mississippian rocks of southern New Mexico and west Texas utilizing conodonts. p. 87-97

Lane, H. R., and T. De Keyser, 1980, Paleogeography of the late Early Mississippian (Tournaisian 3) in the central and southwestern United States. Rocky Mountain Section SEPM. p. 149-162.

Laubach, S. E., J. E. Olson, and M. R. Gross, 2009, Mechanical and fracture stratigraphy: AAPG bulletin, v. 93, p. 1413-1426.

Laudon, L. R., and A. L. Bowsher, 1941, Mississippian formations of Sacramento Mountains, New Mexico: AAPG Bulletin, v. 25, p. 2107-2160.

Laudon, L. R., and A. L. Bowsher, 1949, Mississippian formations of southwestern New Mexico: Geological Society of America Bulletin, v. 60, p. 1-88.

Lawton, T. F., and K. A. Giles, 2002, Origin of the Orogrande basin by strike-slip faulting: evidence from subsidence patterns and facies distribution, AAPG Search and Discovery, AAPG Hedberg Conference, AAPG, p. 2.

Leutloff, A. H., and W. J. Meyers, 1984, Regional distribution of microdolomite inclusions in Mississippian echinoderms from southwestern New Mexico: Journal of Sedimentary Research, v. 54.

Mack, G. H., M. Leeder, M. Perez-Arlucea, and B. D. Bailey, 2003, Early Permian silt-bed fluvial sedimentation in the Orogrande basin of the Ancestral Rocky Mountains, New Mexico, USA: Sedimentary Geology, v. 160, p. 159-178.

Meyers, W., 1978, Carbonate cements: their regional distribution and interpretation in Mississippian limestones of southwestern New Mexico: Sedimentology, v. 25, p. 371-400.

Meyers, W. J., 1974a, Carbonate cement stratigraphy of the Lake Valley Formation (Mississippian) Sacramento Mountains, New Mexico: Journal of Sedimentary Research, v. 44. 837-861.

Meyers, W. J., 1974b, Chertification and carbonate cementation in the Mississippian Lake Valley Formation, Sacramento Mountains, New Mexico. Rice University.

Meyers, W. J., 1975, Stratigraphy and diagenesis of the Lake Valley Formation, Sacramento Mountains, New Mexico. p. 45-65.

Meyers, W. J., 1977, Chertification in the Mississippian Lake Valley Formation, Sacramento Mountains, New Mexico: Sedimentology, v. 24, p. 75-105.

Meyers, W. J., 1980, Compaction in Mississippian skeletal limestones, southwestern New Mexico: Journal of Sedimentary Research, v. 50. P. 457-474.

Meyers, W. J., 1988. Paleokarstic features in Mississippian limestones, New Mexico, Paleokarst, Springer, p. 306-328.

Meyers, W. J., and B. E. Hill, 1983, Quantitative studies of compaction in Mississippian skeletal limestones, New Mexico: Journal of Sedimentary Research, v. 53. p. 231-242

Nelson, R., and S. Serra, 1995, Vertical and lateral variations in fracture spacing in folded carbonate sections and its relation to locating horizontal wells: Journal of Canadian Petroleum Technology, v. 34. p. 51-56

O'Connor, M. J., & Gretener, P. E., 1974. Quantitative modelling of the processes of differential compaction. Bulletin of Canadian Petroleum Geology, 22(3), 241-268.

Pray, L., 1965, Clastic limestone dikes in Mississippian bioherms: New Mexico: Geological Society of America, Special Paper, v. 82, p. 154-155.

Pray, L., 1977a, Alamogordo to Alamo Canyon and the western Sacramento Mountains Escarpment, field guide and road log" A: Geology of the Sacramento Mountains, Otero County, New Mexico, West Texas Geol. Soc. Publ, p. 1.

Pray, L. C., 1949, Pre-Abo Defrormation in the Sacramento Mountains, New Mexico: Geological Society of America Bulletin, p. 1914-1915.

Pray, L. C., 1958, Fenestrate bryozoan core facies, Mississippian bioherms, southwestern United States: Journal of Sedimentary Research, v. 28. P. 261-273

Pray, L. C., 1959, Stratigraphic and structural features of the Sacramento Mountains escarpment, New Mexico: Guidebook of the Sacramento Mountains: Roswell Geological Society and Permian Basin Section SEPM, p. 86-130.

Pray, L. C., 1961, Geology of the Sacramento Mountains Escarpment, Otero County, New Mexico, New Mexico Bureau of Mines and Mineral Resources Bulletin, v. 35: New Mexico, New Mexico Bureau of Mines and Mineral Resources, p. 111.

Pray, L. C., 1977b, Stratigraphic and Structural Features of the Sacramento Mountain Escarpment, New Mexico: Geology of the Sacramento Mountains, Otero County, New Mexico: Field Trip Guidebook, Oct. 21-22, 1977, p. 73.

Scholle, P. A., and R. B. Halley, 1980, Upper Paleozoic depositional and diagenetic facies in a mature petroleum province (a field guide to the Guadalupe and Sacramento mountains), sn].p. 193.

Scotese, C. R., and J. Golonka, 1992, Paleomap paleogeographic atlas: Paleomap progress report, v. 20.

Seager, W., and G. Mack, 1986, Laramide Paleotectonics of Southern New Mexico: Part IV. Southern Rocky Mountains. p. 669-685.

Seager, W. R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico, New Mexico Bureau of Mines and Mineral Resources.

Seager, W. R., and P. Morgan, 1979, Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua: Rio Grande Rift: Tectonics and Magmatism, p. 87-106.

Seager, W. R., M. Shafiqullah, J. W. Hawley, and R. Marvin, 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87-99.

Shackleton, J. R., M. L. Cooke, and A. J. Sussman, 2005, Evidence for temporally changing mechanical stratigraphy and effects on joint-network architecture: Geology, v. 33, p. 101-104.

Shinn, E. A., D. M. Robbin, B. H. Lidz, and J. H. Hudson, 1983, Influence of Deposition and Early Diagenesis on Porosity and Chemical Compaction in Two Paleozoic Buildups: Mississippian and Permian Age Rocks in the Sacramento Mountains, New Mexico. The Society of Economic Paleontologists and Mineralogists (SEPM). p. 182-222.

Singleton, D. S., 1990, Depositional environments and tectonic significance of the Bar B Formation (Virgilian), Sierra County, New Mexico.

Soreghan, G. S., and K. A. Giles, 1999, Facies character and stratal responses to accommodation in Pennsylvanian bioherms, western Orogrande Basin, New Mexico: Journal of sedimentary research, v. 69. P. 893-908.

Stanton, R. J., SEPM, and I. A. o. Sedimentologists, 2000, Field Guide to the Carboniferous Geology of the Sacramento Mountains, New Mexico: Platforms and Mounds of the Lake Valley and Holder Formations, Alamogordo, New Mexico, May 12-14, 2000, SEPM (Society for Sedimentary Geology).

Verbeek, E. R., and M. A. Grout, 1983, Fracture history of the northern Piceance Creek basin, northwestern Colorado: Proceedings of the 16th Oil shale Symposium, p. 26-44.

Wennberg, O., T. Svånå, M. Azizzadeh, A. Aqrawi, P. Brockbank, K. Lyslo, and S. Ogilvie, 2006, Fracture intensity vs. mechanical stratigraphy in platform top carbonates: the Aquitanian of the Asmari Formation, Khaviz Anticline, Zagros, SW Iran: Petroleum Geoscience, v. 12, p. 235-246.

Wilson, J., and C. Jordan, 1988, Late Paleozoic–early Mesozoic rifting in southern New Mexico and northern Mexico: controls on subsequent platform development: Basin to shelf transition of the Wolfcampian stratigraphy of the Orogrande basin: SEPM Permian Basin Section, Guidebook, p. 88-28.

Wiltschko, D. V., D. A. Medwedeff, and H. E. Millson, 1985, Distribution and mechanisms of strain within rocks on the northwest ramp of Pine Mountain block, southern Appalachian foreland: A field test of theory: Geological Society of America Bulletin, v. 96, p. 426-435.

Witzke, B. J., 1990, Palaeoclimatic constraints for Palaeozoic palaeolatitudes of Laurentia and Euramerica: Geological Society, London, Memoirs, v. 12, p. 57-73.

Woodward, L., O. Anderson, and S. Lucas, 1999, Late Paleozoic right-slip faults in the Ancestral Rocky Mountains: Albuquerque geology: New Mexico Geological Society Guidebook, v. 50, p. 149-153.

Yang, K. M., and S. L. Dorobek, 1995, The Permian Basin of west Texas and New Mexico: tectonic history of a "composite" foreland basin and its effects on stratigraphic development, Stratigraphic evolution of foreland basins: Society of Sedimentary Geology Special Publications, p. 149-174.

Ye, H., L. Royden, C. Burchfiel, and M. Schuepbach, 1996, Late Paleozoic deformation of interior North America: the greater Ancestral Rocky Mountains: AAPG bulletin, v. 80, p. 1397-1432.

Zahm, C. K., and C. Kerans, 2014, Unmanned Aerial Vehicles (UAVs) and Digital Outcrop Models of Carbonate Reservoir Analogs, AAPG Annual Convention and Exhibition.

Zahm, C., J. Lambert, and C. Kerans, 2016, Use of unmanned aerial vehicles (UAVs) to create digital outcrop models: An example from the Cretaceous Cow Creek Formation, Central Texas: Gulf Coast Association of Geological Societies Journal, v. 5, p. 180–188.

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