Rocky Mountain Section of the American Association of Petroleum Geologists
59^{th} Annual Rocky Mountain Rendezvous
June 13-16^{th}, 2010

The Pennsylvanian Hermosa Formation, from Shelf to Basin,
Fieldtrip Guidebook for Pre-Convention Field Trip #1, June 11-12, 2010,
DAY 1

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Trip Description: This is a two-day trip comparing Pennsylvanian strata on the SE (active) margin of the Paradox Basin with deposits of equivalent age on the western (stable) margin. Recognition of reservoir facies and the correlation of outcrop units to producing intervals in the subsurface will be addressed. On Friday we will travel from north to south along the scenic Hermosa Cliffs Trend bounding the Animas Valley, north of Durango, Colorado. We return to Fort Lewis College that afternoon and board a tour coach to drive to Bluff, Utah. On Saturday we will float the San Juan River from Sand Island to Mexican Hat. We return to Durango that evening.

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Abstract

Although the interbedded clastic / carbonate character of the southeastern margin of the Paradox Basin has been recognized since Cross and Spencer (1900), the documentation of internal stratigraphic geometries along the cliff trend, and the interpretation of these patterns as progradational sequence sets, is new to this study (see Gianniny and Miskell-Gerhardt, 2009).

Participants on this fieldtrip will view the sedimentology and stratigraphy of the upper Desmoinesian Hermosa Group along a dip-oblique transect, from the upper shelf to the upper slope, which is dominated by progradation. The stratigraphy of the cliffs, as determined from measured sections and photo panoramas, can be carried 14km/8.7mi from Durango Mountain Resort on the north to Goulding Creek on the south. This trend exposes facies and depositional geometries that formed from the inner to the outer shelf. Geometries noted include the change from thin, updip, fluvial clastic beds to thick, downdip, progradational deltaic systems, both draped by biostromal (and rarely biohermal) carbonates. Depositional sequences are also seen to thin upwards in response to the loss of accommodation space.

From Goulding Creek south to Hermosa Mtn., a distance of 8km/5mi, the section is covered by vegetation, but four locations (Shalona, Elkhorn Canyon, Hermosa Mtn. and Steven's Creek) reveal a change from outer shelf to upper slope depositional environments in these correlative deposits. Deltaic sands and draping carbonates downlap southward into thin sandstones and calcareous shales separated by onlapping wedges of basinal lowstand evaporites or shallow tidal deposits.

Outcrop gamma ray measurements collected at the most downdip location (a composite measured section from Hermosa Mtn., Steven's Creek and Elkhorn Cyn.), and biostratigraphy derived from conodonts and fusulinids, enable a tentative correlation from the study area into the subsurface, a jump of 21 km/13 miles. This is not a simple correlation however because of the partitioning of sedimentation between basin and shelf with each sea level fluctuation. During glacio-eustatic lowstands, the margin was exposed and subject to erosion. Although several evaporite-carbonate-shale cycles may be recorded in the basin, if the highstands didn't flood the shelf, these cycles will be missing in that record. Alternatively, during transgressions and highstands there may be several sequences recorded on the shelf that are only seen in the basin as a thin layer of shale. In addition, tectonic events in the Ancestral Rocky Mountain uplifts immediately adjacent to the shelf may overprint eustatic signals.

With this caveat, the jump-tie indicates that Hermosa Cliffs sequences 10-12 (including the thick section of gypsum in the Animas Valley) correspond to the Upper Akah / Chimney Rock Shale. An onlapping wedge of shallow tidal deposits at the base of Sequence 13 correlates to the lower Desert Creek. This is overlain by an anomalously thick shale in the well log, corresponding to the sequence 13 transgressive deltaics and highstand carbonates. These limestones, still Desert Creek in age, were subaerially exposed.

The sequence 14 transgressive systems tract correlates to the Gothic Shale and highstand systems tract to the Lower Ismay. The initial Hovenweep transgression forms an onlapping wedge of shallow tidal deposits on the slope, overlain by calcareous shales of sequence 15. Sequence 15 late highstand systems track corresponds to the upper Ismay. Sequences 16-18 transition from alternating tidal clastics and silty lagoonal

carbonates (Hatch?) upwards into fluvial sandstones and paleosols with thin transgressive limestones (Honaker Trail). Porous sandstones in this interval on the nearest well log may roughly correspond to those in outcrop.

Introduction

During the middle Pennsylvanian, the continents of Laurasia and Gondwanna were colliding and forming the super-continent of Pangea. This suturing activated uplifts in the western United States, subdividing the western marine shelf into several sub-basins. The near-equatorial Paradox Basin was bounded by the passive Kaibob Arch on the southwest and the active Ancestral Rocky Mountain uplifts on the northeast (Blakey and Ranny, 2008). The study area is located on the active SE margin, on the seaward side of a sub-block (**figure 1**). In addition to tectonic influences, the basin was also subjected to multiple eustatic sea level changes caused by glaciation in the southern hemisphere. During sea level lowstands the basin shrank in size and evaporites were deposited, thickest to the NE against the uplift. During highstands the margins were flooded and carbonate bioherms grew.

A SW to NE cross-section across the basin (**figure 2**) shows the asymmetry of the depocenter. Evaporite deposition is immediately adjacent to the Uncompahgre Uplift and inorganic precipitation of hypersaline minerals was zoned from gypsum/anhydrite on the margin to halite in the thick. Coarse-grained fan-deltas are interbedded with halite. Outboard, on the thin, passive southwestern margin, carbonate build-ups and dolostones were deposited during highstands and exposed during lowstands.

Figure 3 is a stratigraphic column of the middle Pennsylvanian of the Paradox Basin with biostratigraphic zonation of conodonts from the Honaker Trail outcrop along the San Juan River (Ritter et al., 2002).

Figure 4 shows the locations of oil and gas fields in the Paradox Basin, which are mostly associated with carbonate bioherms encased in shale or evaporites. A new play concept is now being proven along the NE margin - shale gas from the Gothic Shale. Shale thickness contours (Moreland and Wray, 2009) are superimposed on the bioherm production map to clarify their respective locations. The Hermosa Cliffs study area is about 30mi/48km to the east of the shale gas play area near Dolores, Colorado. Moreland and Wray (2009) interpret the Gothic thicks as prodeltaic mudstones of the "Silverton Delta". The outline of the Gothic Shale thick and the Silverton Delta distributary system is overlain on **figure 1**, Blakey's paleogeographic map. If this paleogeography is correct, then the Silverton Delta drains to the NW off the same fault block that is the study area of the Hermosa Cliffs project. However, transport directions noted in the field for this study show drainage consistently to the SW, not feeding into the Silverton Delta thick.

The route for this field trip (**figure 5**, map) runs north from Durango up the Animas Valley along the eastern side of the Hermosa Cliff trend. **Figure 6** is this same topography as seen from the air, with measured section locations marked. Because of the necessity of avoiding afternoon thunderstorms in the mountains, this trajectory will be reversed, driving to the northernmost (and highest) stops first, then working back south to Durango. Stops will generally be from the most updip facies to progressively more downdip facies during the day.

Figure 7, the stratigraphic summary diagram of the Hermosa Cliffs trend, is drawn from geometries observed on photographic pans and facies recorded at the measured sections as shown. The photo pan, to big to reproduce in this guidebook, is published in Gianniny and Miskell-Gerhardt, 2009 and will be brought along on the field trip.

Figures 8-11 are an idealized block diagram of facies relationships during the early lowstand systems tract (LST) on the SE margin, and field facies pictures from three locations in the sequence 11 onlapping wedge. **Figures 12-15** are a block diagram of the late lowstand to early transgressive systems tract (TST) and field pictures of these clastic-dominated deposits. **Figures 16-18** are a block diagram of the late transgressive to highstand systems track (HST) and field pictures of the associated carbonate deposits. **Figure 19** is field pictures from mixed clastic-carbonate facies that occur in the upper shelf to intertidal zone.

Stop 1 – Lime Creek Burn Pulloff on highway 550 at mile marker 59.

The purpose of this stop is to gain familiarity with facies deposited in proximal (updip) environments, primarily coarse-grained fluvial sandstones and paleosols, that outcrop on the northwest side of the highway as near-vetical beds. Local variation in facies composition and bed thickness in the carbonates exposed here, at Molas Pass and at Coal Bank Pass (Engineer Mountain), are postulated to be controlled by syndepositional tectonics (Spoelhof, 1974). The carbonates are thermally altered here, in the San Juan Volcanic field, however, evidence of subaerial exposure in the form of breccias, rhyzoliths and karst features are preserved in limestones 3 and 5. A measured section (**figure 20a.b**) and the correlation of this section to the outcrop (**figure 21**) are provided for fieldtrip participants. Based on the current work of Gianniny's FLC research student Ned Perry, the outcropping interval is tentatively correlated to sequences 9 and 10 of the Hermosa Cliffs stratigraphic framework – stay tuned.

Stop 2 – Molas Pass Rest Area on east side of highway 550

The wheelchair ramp on the NE side of the rest area is cut into a well-preserved carbonate bioherm. At this stop participants will examine carbonate facies from the margins to the center of the mound (**figure 22**). Vertical zonation from phylloid algal-dominated packstones to framestones of *Chaetetes* and *Syringopora* capping the bioherm make this a classic exposure with similar zonation as the productive bioherms on the western margin of the basin. A remnant of onlapping, fine-grained micaceous sandstone is present on the south side of the buildup just beyond the base of the wheelchair ramp. These strata appear to be Spoelhof's (1974) Section 4 at 378-384m in the lower Hermosa Group. According to Spoelhof's correlations to Coal Bank Pass, which ties into our Hermosa Cliffs sequence stratigraphic and biostratigraphic framework, this bioherm is most likely the Barker Creek interval, in one of the lower sequences exposed at Castle Rock (Stop 5).

Stop 3 - View of Engineer Mountain / Coal Bank Pass measured section at gravel pulloff on west side of highway 550 at mile marker 56.

The upper Mississippian Molas Formation is exposed near the highway at Coal Bank Pass and the Permian Cutler formation forms the base of Engineer Mountain on the top of the plateau high above it. The peak of Engineer Mountain is an eroded Tertiary sill associated with the San Juan volcanic field. The Coal Bank Pass measured section up the side of the lower plateau covers much of the Hermosa Formation in this location (**figure 23**). At this time, only the upper "limey interval", or sequences 8-11, can be correlated with certainty southwards through the vegetated drainages and faulted blocks back to the Hermosa Cliffs (**figure 24**).

Within sequence 10, there is a dramatic change in facies within the highstand carbonates over this distance of 6mi/9.7km (**figure 24**). At the north end of the Hermosa Cliffs (Castle Rock), the highstand is divided into a lower and an upper packstone separated by carbonate mudstone. All units are highly fossiliferous, and the fauna of the packstones indicate open-marine circulation, whereas the mudstone has a more restricted fauna of brachiopods and crinoids suggesting a more stressed environment. In this same interval at Coal Bank Pass, there are only three, thin wacke- to packstones separated by reddish silt to vF sandstones, with tidal features overprinted by rhyzoliths. The shoreline must have oscillated between these two locations several times just during the highstand of sequence 10. The down-dip lateral extent of these exposure surfaces is currently being studied by an advisee of Gianniny at FLC, Amos Culbertson, using stable carbon isotopes.

Below the "limey section" are many interesting examples of very proximal facies illustrated by the field photos in **figures 19 and 25**. These include very coarse fluvial channel sands and angular conglomerates deposited over broad scour surfaces, tidal bars and bioturbated tidal flats, karsted carbonates and carbonate grainstones, rip-up clast conglomerates and thick, chaetetid boundstones.

Stop 4 – Fan Delta outcrop in lower parking lot of Durango Mountain Resort

The fluvial channel sandstones observed at stops 1 and 3 transition downdip (basinward) into progradational fan-deltas along the cliff trend. This stop is an opportunity to see fan-delta facies in outcrop including bottomsets, forsets and topsets. It is very similar to the progradational lowstand of sequence 10, seen farther downdip, although this outcrop is much older (just above the Pinkerton Trail). The coarse sand to conglomerate grainsize, angular grains, petrographically immature, arkosic composition and lack of fines are characteristic of this facies. **Figure 26**, a short measured section through the delta with outcrop gamma ray, is provided as a field aid.

Stop 5 – View of Castle Rock and J.E. Ravine measured sections from Needles Country Store

The section measured up the side of Castle Rock (**figure 27**) is continued to the north in J.E. Ravine (**figure 28**) on a downdropped fault block. Sixteen depositional sequences are exposed here. Of these, sequences 10-16 can be correlated 14mi/22km to Hermosa Mtn. Most of these sequences are interpreted to be examples of reciprocal sedimentation, i.e., clastic deposition during lowstands and carbonate deposition during highstands.

Typical Depositional Sequence: For the interval seen near the top of Castle Rock (sequences 8-11), a typical depositional sequence is dominated by upper shelfal deposits. During the early lowstand systems tract (LST, **figure 8**), sea level fell below the shelf margin causing widespread subaerial exposure of underlying highstand limestones at this updip location. The tops of the limestone beds are karsted and brecciated, marking each sequence boundary. There is minor evidence of fluvial bypass across the exposed shelf.

The exposed limestones are overlain by coarse-grained to conglomeratic, arkosic, planar and cross-bedded, channel sandstones of the late LST/ early transgressive systems tract (TST, **figures 12 and 13**). Because these sandstones develop southwestward into thick, clinoforming wedges, the entire clastic interval is interpreted as a transition from updip fluvial to downdip deltaic environments. Progradation of deltas within each sequence built extensive shallow platforms.

During the highstand systems tract (HST, **figure 16**), the topography created by the clastic apron was colonized by calcareous fauna, resulting in thick, draping, biostromal carbonates. Carbonate intervals are dominated by phylloid algae and a diverse, open-marine fauna indicating a normal, well-oxygenated, shallow, marine environment within the photic zone (**figures 17and 18**).

Above sequence 11 at J.E. Ravine, the percentage of non-marine redbeds, paleosols and very shallow tidal flat sediments in late LST / early HST increases (**figures 19 and 28**). These very thin sequences, identifiable by their late HST limestone caps, are correlated on the photo pan over 4 km downdip into fluvial/carbonate facies, which transition southward into deltaic/carbonate sequences.

Lower Sequences: Below sequence 8 at Castle Rock, the section is dominated by siliciclastics of fluvial, deltaic and restricted-marine environments. None of these sequences can be carried to the south because they are soon lost under cover.

Sequences 1-5 were dominated by fluvial systems, small deltas very shallow and possibly restricted, marine facies (the dark lagoonal mudstones of sequences 4 & 5) and a few open-marine limestone HST caps. Sequences 6 and 7 are preceded by a transgression to deeper water that is followed by a major regression. Starting at the base of sequence 6 there is a transition from distal pro-delta fines through delta front clinoforms (prograding from right to left on **figure 27**) into channelized stream mouth bar sands and shales (seen in strike view) which are truncated by thick fluvial deposits of sequence 7.

A flooding surface / sequence boundary above this (sequence 8) initiates the alternation between lowstand, clastic, fluvio-deltaic sandstones and highstand carbonates, as described above.

Stacking Pattern: The upwards thinning of sequences 11-16, as well as the dominance of paleosols (long term exposure) suggest that over time, accommodation space on the shelf filled in at this location and sediment accumulation shifted basinward. This conclusion, based on vertical stacking patterns here, is supported by lateral observations at later stops.

Age Control: Biostratigraphic ages based on conodonts extracted from highstand limestones at Castle Rock **(figure 27)** indicates that sequence 5 falls within the Barker Creek, sequence 8 in the lower Akah and sequence 11 in the upper Akah to basal Desert Creek. Sequence 16 contains the fusulinid *Beedeina megista* (pers. comm. Greg Wahlman, 2006), characteristic of the lower Honaker Trail Fm. This biostratigraphic marker lies just above the Ismay oil and gas interval in the Paradox Basin.

TOC Data: Total organic carbon measurements are all <1% for deltaic and calcareous mudstones. The highest value, 3.37%, is from a black, fissile shale which is interpreted as restricted marine, possibly lagoonal, based on a monospecific ostracode fauna. High T-Max (434-520) and very low HI (17-64) values from Rock Eval pyrolosis on these samples from Castle Rock show that the source rocks are mature to overmature for oil generation. Presumably original TOC levels would have been significantly higher. Nuccio and Condon (1996) noted the same trend at Hermosa Mountain (20km/12.4mi farther south) and remarked that this section is unique in the basin in that it's had the least amount of burial but is among the most thermally mature. They concluded that thermal maturity is due to the proximity to the San Juan volcanic field.

Sandstone Petrographic Data: Four thin sections made from sandstones collected from sequences 10 and 11 were point counted. All four are arkosic in composition based on ternary Quartz-Feldspar-Lithics plots (**figure 27**).

Stop 6 – View of Nary Draw section from Electra Lake Toll Booth

This location is 5km / 3mi south of Castle Rock. A "recon" section (lithologies tied to photos but not rigorously measured) was drafted here for sequences 10-13 (**figure 29**). This stop will examine progradational sequence sets and mounded carbonates.

Whereas sequence 10 at Castle Rock is definitely fluvial, the equivalent deposits here, visible at the base of the outcrop just above tree line, have progradational deltaic geometries. These geometries are first noted on the photo pan 5km / 3.1mi south of Castle Rock. This system prograded south to the Hermosa Mountain location (22km / 13.6mi) where it goes into the subsurface. The thick, highstand carbonates draping sequence 10 clastics are also continuous from Castle Rock to North Goulding Creek, retaining their tripartite character.

The overlying sequence 11 lowstand deltaic deposits, which also correlate back updip to fluvial channel sandstones at Castle Rock, are mostly covered by conifers at Nary Draw. The transition in sequence 11 from fluvial to deltaic, as noted on the photo pan, takes place slightly farther south, at 6km/3.7m south of Castle Rock. This offset of the depositional shelf break 1km basinward indicates progradational stacking of sequences 10 and 11.

The marked thinning of the overlying sequence 11 and 12 highstand limestones define the downdip margin of a carbonate bank. Across this thinning ramp, the overlying sequence 13 clastics expand from thin, updip fluvial facies on the right (north), to thicker, downdip, deltaic facies on the left (south), filling in the topographic low (**figure 30**). This association of a thin underlying carbonate (sequence 11 highstand) and thick overlying delta (sequence 13 lowstand) carry south to Goulding Creek. **Figures 13 & 14** show field photos of deltaic facies.

The sequence 16 carbonate, barely seen at Castle Rock because of erosion, forms distinct bioherms in the cliff above the carbonate ramp (**figures 29 & 31**).

Sandstone Petrographic Data: Two thin sections made from sandstone collected from sequences 10 and 11 were point counted. Both are arkosic in composition based on ternary Quartz-Feldspar-Lithics plots (**figure 29**), and plot in the same region as the Castle Rock samples.

Stop 7 – View of North and South Goulding Creek measured sections from Tamarron

From the north to the south side of Goulding Creek, in sequences 10-13, depositional paleoenvironments shifted subtly from outer shelf to upper slope. Please refer to the numbers posted on **figure 32a** in the following discussion. The Goulding

Creek South measured section was done by Fort Lewis College student Dan Bassett as a senior thesis project in 2008 (Bassett, D. A., Gianniny, G.L. and Miskell-Gerhardt, K., 2008).

The decrease in the angle of sequence 10 lowstand clinoforms (#1) from north to south is interpreted as change from more proximal delta front to more distal delta front. The abrupt thinning of the sequence 10 carbonate bank across Goulding Creek (#2) is similar to that seen at Nary Draw for sequences 11 & 12, and is interpreted as a bank edge, related to deepening in the inherited deltaic topography.

At the base of sequence 11 on the south side of Goulding Creek there is a wedge (#3) of dolostone, fissile black shale and laminated, mudcracked carbonate which onlaps the topography formed by the underlying carbonate bank edge. This interval correlates 9km /5.6mi downdip to gypsum deposits at Hermosa Mtn. and Elkhorn Canyon. These deposits are interpreted as early lowstand systems tract (LST, **figure 8**). Rapid sea level fall exposed the shelf (forming karst and breccias at Castle Rock) and caused a restricted, evaporitic, highly saline environment in the Paradox basin resulting in deposition of halite, anhydrite and gypsum. The small wedge present on the south side of Goulding Creek is the updip remnant of an upper Akah evaporite cycle. The facies assemblage seen here and at Shalona is referred to as "Evaporite Associated Facies" (EAF). See **figure 11** for field pictures.

Sequence 11 late TST/ early TST fluvio-deltaics expand across the creek into the accommodation space above the onlapping EAF wedge. Abundant organic matter, including logs, in this interval indicate that the arid climate of the evaporites did not persist. The thin sequence 11 limestone (fossiliferous packstone) that was the downdip remnant of the extensive carbonate bank at Nary Draw, is present on the north side of Goulding Creek, but thins to a minor wackestone on the south side.

Sequence 13, which transitioned from fluvial to deltaic at Nary Draw, thins across Goulding Creek by downlap, forming a new depositional shelf break. The overlying sequence 13 highstand carbonate (#4), visibly thins from N-S just on the north Goulding Creek side, and disappears altogether on the south side - where no shallow platform remained to support calcareous fauna.

Sequence 14 expands from thin fluvial deposits on the north to thick deltaic lobes on the south into the new accommodation space (#5) created by the downlap of sequence 13. Note the change in direction of progradation on the south side of Goulding Creek, interpreted as autocyclic lobe switching. Sequence 14 fills in all the available accommodation space at this location forcing a change from a shelf margin characterized by distinct depositional shelf breaks in the underlying sequences to a ramp margin in the overlying ones.

Above sequence 14, depositional geometries change from progradational fluvio-deltaics draped by thick, but limited, carbonate banks to flat-lying, extensive tidal, fluvial and paleosol deposits punctuated by thin, broad, shelf carbonates (#6-10).

Age Control: Conodonts extracted from limestones (**figure 32b**) confirm sequence 10 as Akah and sequence 11 as Akah to basal Chimney Rock Shale. They bracket sequence 13 as Chimney Rock to Hovenweep and sequence 16 as Gothic to lower Honaker Trail. Results from sequence 18 are not definitive.

TOC Data: TOC contents range from 0.5% to 3.19% in six samples from sequences 10 to 15 (**figure 32b**) . Lowest values (0.5 and 0.76) are from pro-delta mudstones at the bases of sequences 13 and 14. A thin, shaley, carbonate mudstone within sequence 15 yielded 0.78% TOC. The two highest values (3.19 and 1.27% TOC) come from thin shales at the base of the sequence 10 deltaics, although these might be associated instead with underlying sequence 9 carbonates. A black shale within the onlapping wedge of EAF sediments yielded a TOC of 1.10%. Presumably these TOC values are much lower than original because of the thermal maturity of the entire Hermosa Cliffs trend (see Stop 5 discussion).

Sandstone Petrographic Data: Six thin sections made from sandstones collected from sequences 10 through 14 were point counted. All are arkosic in composition based on ternary Quartz-Feldspar-Lithics plots (**figure 33**), and plot in the same region as samples from Castle Rock and Nary Draw.

Stop 8 – Pinkerton Trail outcrop on hwy 550 at entrance to Tamarron

WARNING – This outcrop is best viewed from the east side of the road as falling rock is common!

Gianniny and Miskell-Gerhardt measured a section through this outcrop in 2006. There is 18m of Pinkerton Trail exposed along the road, consisting of three to four sequences of fossiliferous, sub-tidal wackestones capped by silty fossiliferous packstones which grade into ten-centimeter thick beds of coal or carbonaceous shale. Marine flooding surfaces directly overlie the coals. Black shales and brachiopods are found within one centimeter of the top of the coals.

These sequences are overlain by a 25m-thick, siliciclastic package which grades upwards from alternating shales and fine-grained sandstones with abundant plant debris (? turbiditic) to coarse-grained fan-delta deposits. The siliciclastics are generally considered to be the base of the Hermosa Group.

The Pinkerton Trail Fm. contains Atokan fusulinids. In the oil and gas fields of the Paradox Basin, the Pinkerton Trail is overlain by the Desmoinesian Hermosa Group, which is subdivided into the underlying, producing, Paradox Fm. and the overlying Honaker Trail Fm. The Paradox Fm. is recognized by it's widespread evaporites separated by organically-enriched black shales. Here, on the southeastern margin of the Paradox Basin, the entire section above the Pinkerton Trail is called the Hermosa Group, undivided, because the general absence of evaporites defeats most attempts to recognize an equivalent to the Paradox Formation (Franczyk et al., 1995).

Stop 9 – View of Shalona measured section from hwy 550 / upper CR 250 intersection

This measured section location is in an intermediary position between the shelfal environments of Coal Bank Pass to North Goulding Creek and the upper slope environment of Hermosa Mountain. / Stevens Creek / Elkhorn Canyon. The Hermosa Cliffs terminate at south Goulding Creek. From there to Hermosa Mtn. abundant vegetation separates intermittant outcrops. The exposure across the highway from Shalona Lake is the only semi-complete section in the area. See **figures 33** (overview) **and 34** (close-up of sequences 10-15).

The sequence 10 delta is still present here and still prograding southwestward, but is much thinner than at Goulding Creek. The sequence 10 highstand carbonate cap is gone by downlap between South Goulding Creek and Shalona.

The basal sequence 11 wedge of LST evaporite associated facies (EAF), first noted at south Goulding Creek, is characterized here by dissolution breccias, black shales and interbedded wavy carbonate laminites (laminated on a centimeter scale) (see facies photos in **figure 10**). These laminates resemble the laminated gypsum beds found at Hermosa Mtn. and Elkhorn Canyon, farther downdip.

Deltaic deposition in the sequence 11 LST/TST seen at S. Goulding Creek is expanded here, where there was more accommodation space, and resolved into two thick parasequences. The thin carbonate HST cap, present at S. Goulding Creek, is gone by downlap here similar to sequence 10.

Above these deltaics (above the top of sequence 11), is a 15m-thick interval of very fine to medium-grained, wave and current-rippled sandstones (1-2m thick) which are overlain individually by stromatolitic limestones (1-2m thick) and interbedded with fissile, black shale. At first glance, such fine-grained sands seem ideal as down-dip toes of the sequence 13 deltaics seen at Goulding Creek. However, the presence of very shallow water carbonates and organically-enriched fines, probably related to a setting of restricted marine circulation, necessitates an alternative solution. This interval is proposed as a second onlapping wedge which is the early lowstand systems tract of sequence 13. The thinning and downlapping deltaics of sequence 13 at Goulding Creek are the following late LST/ early TST deposits which, together with the very thin limestone cap, are gone by downlap at Shalona.

A 16m section of calcareous shale with very rare brachiopods, followed by a 44m thick coarsening-upwards section of deltaic mudstones and sandstones, is interpreted as the continuation of the sequence 14 LST/TST prograding delta which initiated at South Goulding Creek. Downlap geometries to the southwest are seen in the face of the Shalona outcrop in the field (**figure 34**). In the summary diagram (**figure 7**), this interval is interpreted to also downlap to the north, connecting to the upper lobe at South Goulding Creek seen in **figure 32a**, forming a strike section through a system that prograded more westerly than southerly.

The succession of sequences and facies from sequences 15 through 18 at Shalona is very similar to Goulding Creek with two exceptions. First, within sequence 15, the shaley interval between the upper and lower pack- to grainstones expands to 11m of barren, silty, calcareous mudstone. Secondly, a slump along the ridge has removed the top of sequence 16 (the HST limestone) and all of sequence 17. The remaining outcropping fluvial, paleosols and lagoonal carbonates of sequences 18 and 19 correlate well back to the top of Goulding Creek and also to Hermosa Mountain.

Age Control: Conodont extractions were run on the same shales collected for TOC analysis in 2008. No conodonts were recovered. The sequence 15 limestones were sampled in 2010 and yielded indeterminate, long-ranging samples.

TOC Data: TOC values were measured on ten shale samples from Shalona (**figure 34**). Sequence 10 interbedded shale with deltaic sandstone measured the lowest, at 0.31%. Two samples of black, fissile, calcareous shale from the EAF at the base of sequence 11 measured 1.12% and 1.15%. Six samples were taken from the 16m of calcareous shale below sequence 14 deltaics. They ranged for 0.66%-1.38% and averaged 1.04% TOC. The final sample was taken from the barren, calcareous mudstone in sequence 15, of 0.63% TOC. The same over-maturation issue applies here as for previous stops. See Stop 1 for discussion.

Sandstone Petrographic Data: Eight thin sections made from sandstones collected from sequences 10, 11 and 14 were point counted. All are arkosic in composition based on ternary Quartz-Feldspar-Lithics plots (**figure 34**), and plot in the same region as previous samples from more updip locations.

Stop 10 – View of Elkhorn Cyn. measured section from CR250/CR 251 intersection

The sequence 11 LST evaporite section, usually viewed on the south side of Hermosa Mountain, is better-exposed on the east side of the Animas Valley in Elkhorn Canyon. Gianniny and Miskell-Gerhardt measured 117m of section here in 2007 and found 30m of evaporites (gypsum), minor black shales and recrystallized dolomitic breccias, overlain by 10m of (mostly covered) black shales **(figures 9, 35& 36**). The evaporites are divided into a lower unit of 6m and an upper unit of 8m (more may be present under cover), separated by black, fissile shale. The lower gypsum unit is massive at the base but composed of 0.5 cm-thick gypsum / dolomite laminations at the top. The upper unit has wavy banding throughout. This section correlates updip to the EAF seen at Shalona and South Goulding Creek.

These few gypsum outcrops along the Animas Valley are the only known outcropping evaporites from the southeastern side of the Paradox Basin (not including the deformed salt valleys near the state line). The gypsiferous interval seen here is generally assumed to correlate to the Akah oil and gas producing interval in the Paradox Basin, because that was the time of most widespread salt deposition. This assumption is now confirmed by biostratigraphic results from conodonts extracted from correlative updip locations.

The evaporite section is underlain by medium to coarse-grained, deltaic sediments of sequence 10 and overlain by medium-grained, deltaic sediments of Sequence 11 LST/TST.

TOC Data: TOC values were obtained on three black shales interbedded with gypsum and on one shale within the upper deltaic unit (**figure 35**). Values for the evaporite section were 0.59%, 1.66% and 1.62%. The deltaic fines, which contain abundant visible plant-derived, coaly organic matter, measured 2.41% TOC.

Sandstone Petrographic Data: Three thin sections made from sandstones collected from the sequence 11 LST/TST deltaics were point counted. All are arkosic in composition based on ternary Quartz-Feldspar-Lithics plots (**figure 35**), and plot in the same region as previous samples.

Stop 11 – View of Hermosa Mtn. / Steven's Creek composite measured section

The section exposed in a drainage on the east side of Hermosa Mtn. is generally regarded as the type section of the Hermosa Formation in this area. Prior to this study it was measured most recently by Franczyk et al. (1995) and Wengerd and Matheny in 1958. Miskell-Gerhardt measured 101m of section at Hermosa Mtn., and 184m at Steven's Creek. Together with the Elkhorn Cyn section, this form a composite downdip measured section of 393m (including the covered interval). Outcrop gamma ray measurements were also collected every 0.5m or less to enable a better correlation of lithology to log response, and later from the outcrop to subsurface well logs. The result is shown posted against Hermosa Mtn. in **figure 37**. The final section extends from the sequence 10 LST/TST deltaics at the base, up through the highest sequence present at

Goulding Creek and Shalona (sequence 18) and includes at least an additional two sequences.

Compared to updip locations, for the interval above sequence 10 and below sequence 16, the main features here are the lack of thick, biostromal carbonates or supporting deltaic platforms and the presence two thick, calcareous, black shales. Given the current interest in shale gas in the Dolores/Dove Creek area, 48km/30mi west, the possible correlation of these outcropping shales to the Chimney Rock, Gothic or Hovenweep Shales in the basin is a very relevant question. To answer it, the correlations both updip back into the Cliffs trend, where there is some biostratigraphic control, and downdip into the subsurface, must be correct. Although this paper attempts both ties, future biostratigraphic results may force revisions.

Correlation from Hermosa Mtn. to Shalona

The sequence 10 bench, with it's slumped evaporite interval above, forms a ridge which is identifiable on a photo pan connecting Hermosa Mountain to Goulding Creek. At the top of the section, the coarse-grained clastics, green silty calcareous mudstones and reddish paleosols of sequence 18 are easily correlated back to Shalona and Goulding Creek along the photo pan and by comparing the lithologic successions of measured sections and zoomed photographs.

However, the correlation of sequences 11 (above the evaporites) through 17, from Shalona to Hermosa Mtn., is not well constrained as of June 2010. The vegetated hillside and steep terrain defeats photo pan correlations or walking out bed boundaries. There is also a thick covered interval at the base of the shaley section. Two attempts at extracting conodonts downdip from both the calcareous shales (in 2008) and the limestones (in 2009) were unsuccessful (**figure 37**). The results yielded generalized *Idiognathodus* fauna, which are found through most of the Desmoinesian stage (**figure 3**). These results are similar to the earlier attempt by Franczyk et al., 1995 at finer correlations from Hermosa Mtn. to the Paradox Basin using macrofossils. The correlations updip to Shalona, shown in **figure 6,** are based on the following reasoning:

- The two, thick deltaic parasequences above the sequence 11 evaporite associated facies at Shalona correlate to the two thinner deltaic parasequences downdip (see Elkhorn Cyn. measured section, **figure 35**)
- The possible sequence 12/13 LST onlapping wedge at Shalona (wave & current-rippled, fine-grained sandstones capped with stromatolitic carbonates and interbedded with black shales) correlate to a very recrystallized limestone and the bottom of the covered interval downdip.
- The thick, progradationally stacked, sequence 14 deltaics at Shalona are interpreted to have prograded mainly westward, forming the lower wedge at South Goulding Creek, and bypassing the Hermosa Mtn. location. At the southerly site, the equivalent facies are pro-deltaic fines to distal marine calcareous shales.
- Above the lower calcareous shale at Hermosa Mtn. there is an 8m-thick wacke- to packstone with an open marine fauna. This carbonate is correlated to the capping HST limestones seen on top of the sequence 14 deltaics at Goulding Creek and Shalona.
- Downdip, overlying this robust carbonate, there are 17m of very fine to fine-grained, micaceous, calcareous sandstones followed upwards by 18m of black,

fissile, calcareous shale, overlain by 11m of wacke- to packstones interbedded with calcareous mudstones. The shale-to-upper limestone section is a good match to the lithologies of sequence 15 at Shalona, but with thicker shale. The sandstones below the shale, which do not occur at Shalona, are mainly enigmatic planar-bedded deposits with minor burrowing and current-ripples. However, mudcracks found in upper beds at both the Hermosa Mtn. and Steven's Creek outcrops, suggest a shallow water to emergent paleoenvironment. This anomalous unit is interpreted as the updip end of an onlapping lowstand wedge at the base of sequence 15, followed by the shaley TST and the biostromal HST.

- Correlation of sequences 16 & 17 from Hermosa Mtn. to Shalona is complicated by the slump at Shalona that removed this section, necessitating a comparison back to Goulding Creek instead. The green/red siltstones and calcareous channel sandstones of the sequence 16 LST/TST at Goulding and the very top of Shalona are interpreted as tidal facies. These correlate downdip to a fine-grained progradational sandstone that may be a tidal delta. A thin, fossiliferous limestone overlying this downdip is correlated to the sequence 16 HST limestone which is present all the way updip to J.E. Ravine. The sequence 17 silty carbonates at Goulding Creek (possibly lagoonal?) are not found at Hermosa Mtn. where the sequence 16 limestone is overlain by fluvial sands that correlate well to the base of sequence 18 at Shalona. It is possible that the sequence 17 deposits were removed by erosion beneath these fluvial sands.

Correlation from Hermosa Mtn. to Subsurface

South of Hermosa Mtn., the south-dipping Pennsylvanian strata enter the subsurface. The nearest well with log data that penetrates the middle Pennsylvanian is the Cayman Corp., Colorado-Federal 1 in T35N, R10W, S26, which is 21km/13mi to the S/SW (see **figure 38**). The strategy for determining if the shaley intervals at Hermosa Mtn. correlate to those of interest in the shale gas play area is twofold. First, correlate the lower Honaker Trail to upper Akah interval on a well-log cross-section from the shale gas area to the Cayman Corp. well. Secondly, correlate the Cayman Corp well to the downdip measured section using the outcrop gamma ray curve and the constraints of biostratigraphy and sequence stratigraphy developed in the Hermosa Cliffs stratigraphic study (**figure 7**). Please refer to **figure 38** (location map for well log cross section), **figure 39** (comparison of outcrop GR to Cayman Corp. log curves) and **figure 40** (Basin to Outcrop Cross-section) during the following discussion.

The well log correlation from the Dolores area to the Cayman Corp well is shown on the left side of **figure 40**. These correlations are fairly straightforward from Dolores over to the Miller, Shelly & LeClair, Karl Hauert #1. From this well into the Texaco, Long Hollow #1 there is a change in character in both the Gothic Shale and the Lower Ismay, and an expansion of the Hovenweep. From the Long Hollow #1 into the Cayman Corp. the lower Ismay and Gothic regain their characteristic curve shapes, but below the base of the Gothic (as picked on a small resistant bed) there is a thick section of shale that appears to correlate into the upper Desert Creek. This "Desert Creek Shale" is not seen anywhere else in the Montezuma County area.

The Cross-Section (**figure 40**) is datumed stratigraphically on a limestone in the lower Honaker Trail (base of sequence 16 HST) which (hopefully) is correlative. By hanging the section high, on a widespread marker which was deposited after the basin was mostly filled in, the paleotopography of the basin to shelf transition is shown more accurately.

The correlation of the subsurface well logs to the outcrop trend is as follows:

- Sequence 10, LST/TST deltaics, are bracketed by Akah conodonts below, in sequence 8 at Castle Rock, and Akah above in the sequence 10 TST/HST carbonates at north Goulding Creek. Therefore this deltaic system is correlated as downlapping out in a basinal direction into a shaley layer in one of the upper Akah cycles in the subsurface. (During a sea level highstand.)
- Sequence 10, TST/HST carbonates, were deposited during an even higher stand of sea level. Although the limestones themselves downlap out between south Goulding Creek and Shalona, this time period would still be represented as continuing black shale in the Akah.
- Sequence 11 early LST gypsum and onlapping EAF's. the top of the sequence 10 limestones are karsted at Castle Rock showing exposure of the upper shelf during the subsequent fall in sea level that is the sequence 11 sequence boundary. The onlapping wedge of gypsum and EAF's are traditionally assumed to correlate to a basinally-restricted evaporite deposit of upper Akah age. Now, Akah ages from conodonts below the gypsum (sequence 10 carbonates) and above (sequence 11 carbonates at Castle Rock) confirm this age.
- Sequence 11, LST/HST deltaics are recorded from Nary Draw to Elkhorn Cyn. Akah conodonts extracted from the overlying sequence 11 limestones make these clastics also Akah in age. They are correlated as downlapping out in a basinal direction into a shaley layer in one of the upper Akah cycles in the subsurface. (During a sea level highstand.)
- Sequence 11 to 12 TST/HST carbonates formed a very thick, composite, biostrome on the upper shelf, at Castle Rock, requiring a further rise in sea level. Conodonts from sequence 11 at Castle Rock are upper Akah in age, and those extracted from the thinner equivalent at N. Goulding Creek, downdip of the bank edge, range from Barker Creek to basal Desert Creek but are most likely upper Akah. Although the limestones themselves downlap out between south Goulding Creek and Shalona, this time period would still be represented as continuing black shale in the basin, of upper Akah to possibly lower Desert Creek (i.e. Chimney Rock Shale) age.
- Sequence 13, LST. The top of the sequence 12 carbonates are karsted, rooted, altered to terra rosa and reworked into black pebble conglomerates from Castle Rock to Goulding Creek, indicating a major fall in sea level. The anomalous shallow-water clastics, carbonates and black shales overlying the sequence 13 sequence boundary at Shalona are interpreted to be an onlapping wedge of evaporite associated facies (EAF), correlated to the lower Desert Creek evaporites in the basin (Hite cycle 5?).
- Sequence 13 LST/TST deltaics represent a rise in sea level over the karsted exposure surface. The clastic wedge spills out from a fluvial feeder into the accommodation space formed by the underlying carbonate bank edge at Nary Draw. The delta is capped during the TST/HST by a thinner carbonate biostromal cap. Fauna from this cap span Chimney Rock through Hovenweep in age. Both clastics and carbonates

downlap out between N. Goulding Creek and Shalona, but they would be represented in the subsurface by black shale. This shale is correlated into the anomalous "Desert Creek Shale" section of the Cayman Corp. well log.

- Sequence 14 – The top of the sequence 13 carbonate at N. Goulding Creek is reworked into black pebble conglomerate indicating another fall in sea level and subaerial exposure on the shelf. This may be represented in the Cayman Corp. log by the thin, resistant bed (limestone or anhydrite?) between the Desert Creek and the Gothic (Hite cycle 4 to 3 boundary?). The sequence 14 LST/TST deltaics indicate another rise in sea level, returning the shelf to a marine environment. The clastics prograde westward from Shalona, bypassing Hermosa Mtn. where the equivalent deposits are nearly barren, calcareous, black shales that are interpreted as pro-deltaic to marine slope. These shales are correlated to the Gothic Shale interval in the subsurface. Although many limestones and shales were sampled in 2008 and 2009, there is no further biostratigraphic control between sequence 13 (Chimney Rock through Hovenweep) and sequence 16 (Lower Honaker Trail) to constrain correlations to the subsurface.
- Sequence 14 TST/HST is a fossiliferous carbonate wacke- to packstone. Conodonts extracted from this interval are generalized *Idiognathodus* forms which merely confirm a Desmoinesian age without further constraining it. Based mainly on log character, this limestone is correlated to the Lower Ismay interval. The correlation of this shelf carbonate to similar facies in the basin implies that the topographic relief between the southeastern margin and the basin is largely filled by the end of sequence 14, and that the margin has evolved from having a depositional shelf break, separating a distinct shelf from a distinct slope, to a ramp margin with a gentler incline. This change was the result of the progradational sequence stacking which continuously filled in accommodation space as discussed earlier.
- Sequence 15 – The top of the sequence 14 HST limestone is karsted at JE Ravine indicating subaerial exposure in updip locations and another fall in sea level. The overlying sequence 15 LST is an onlapping wedge of fine-grained, calcareous sandstones with burrows, current ripples and mudcracks, which pinches out between Hermosa Mtn. and Shalona. These beds are interpreted as tidal deposits and are correlated to the lower Hovenweep Shale, where there appears to be several clastic parasequences, in the Cayman and State-1 wells. The tidal deposits are interpreted to develop into a tidal delta basinward, which downlaps out between the Davis, Allardyce Fed 1 and Allardyce Haycamp Fee 1. The sands appear to be porous on the Cayman Corp. GR/Density log.
- Sequence 15 TST is a 20m thick, dark gray, calcareous shale indicating a marine transgression. Although samples were collected and acidized, no conodonts were recovered. This section is correlated to the main body of the Hovenweep shale.
- Sequence 15 HST is a 12m-thick, fossiliferous, carbonate wacke- to packstone with abundant interlayers of calcareous mudstone. Conodont samples collected both from Steven's Creek and Shalona are again, generalized *Idiognathodus* forms which merely confirm a Desmoinesian age without further constraining it. This interval is correlated to the Upper Ismay producing unit in the basin based mostly on log character tie.

- Sequence 16 LST/TST is markedly different from the underlying sequences in that shelfal deposits are mainly tidal and paleosols – no fluvio-deltaics. The tidal-flat facies of Goulding Creek transition southward to a fine-grained, prograding sandstone interpreted as an (ebb) tidal delta at Steven's Creek. It is capped by a widespread, shallow-water, fossiliferous packstone (the datum). Fusulinids from this limestone are lower Honaker Trail in age. This section is correlated to the first shaley/LS cycle above the Upper Ismay, which may be the "Hatch". Sandstone in this section on the Cayman Corp log shows porosity.
- Sequence 18 LST/TST consists of coarse-grained to conglomeratic, fluvial sandstones ("Gurdy's Grit") with an intervening fine-grained, calcareous, rooted and burrowed zone. This is capped by a thick (15m) interval of green, silty, calcareous mudstone with brachiopods interpreted as lagoonal carbonates of the sequence 18 TST/HST. The carbonates are Honaker Trail in age at Goulding Creek. The base of the lagoonal carbonates is correlated to the limestone marker, "A" on the well log cross-section. Sandstones in the Cayman Corp. well log correlative with "Gurdy's Grit" show porosity.
- The remainder of the downdip measured section consists of three more sequences of alternating lowstand paleosols and highstand lagoonal carbonates. Fine-grained channelized sandstones occur locally but are not extensive. A porous sand interval in the Cayman Corp well may be of this type. These sequences have not been correlated into the well logs, but must correspond to known Honaker Trail cycles and are probably similar in facies.

Review of Petrographic Data

Twenty seven sandstones were sampled in outcrop for petrographic analysis from sequences 10 to 15. Three hundred points were counted per slide. Grain composition is dominated by quartz and feldspar (microcline, orthoclase and plagioclase) with minor rock fragments (sandstones and carbonates), micas and rare opaques. When plotted on a Quartz – Feldspar-Lithics ternary diagram, the samples overplot each other in the "Arkosic" field (**figure 41**), with quartz around 52%, feldspar around 43% and lithics up to 5%. This composition indicates a steady granitic source throughout deposition which is compositionally (and texturally) immature in the study area. The high percentage of feldspars is not favorable for reservoir quality in the subsurface unless mechanical transport away from the study area to the basin increased the relative quartz content. See **figures 42 a,b, and c** for thin section photomicrographs of grain types and matrix.

When reading the following paragraph about matrix composition, please remember that these samples were collected from weathered outcrops of known thermal over-maturity, adjacent to the San Juan Volcanic Field. Observations made on these samples, other than basic grain composition, may not hold in the subsurface.

The matrix is dominated by carbonate (calcite and dolomite) cements (0-80%), followed by intergranular porosity (0-28%), bitumen (? 0-30%) and fines formed by the breakdown of feldspars. Both quartz and feldspar grains are partially dissolved and replaced by carbonate cements. The matrix constituent identified as bitumen is present vertically in sandstones from sequences 10,11, 14 and 15, and laterally from Steven's Creek to Castle Rock. If this identification is confirmed by UV light analysis it would suggest that the Hermosa Cliffs are a breached oil field.

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