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Sequence Stratigraphy of the Dakota Group and Equivalents from North–Central Colorado to Northeastern New Mexico: Down–Dip Variations in Sequence Anatomy: A Field Trip Guide for the 1996 GSA Annual Meeting

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SEQUENCE STRATIGRAPHY OF THE DAKOTA GROUP AND EQUIVALENTS FROM NORTH-CENTRAL COLORADO TO NORTHEASTERN NEW MEXICO: DOWN-DIP VARIATIONS IN SEQUENCE ANATOMY: A FIELD TRIP GUIDE FOR THE 1996 GSA ANNUAL MEETING

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FIELD TRIP OVERVIEW AND OBJECTIVES

This field trip is designed as a three-day excursion to examine Lower Cretaceous, Dakota Group rocks along the northern Colorado Front Range and to compare and contrast these rocks with similar-age rocks along the northern Colorado Front Range and northeastern New Mexico (Fig. 1). An additional caveat of this trip will be an examination of the Capulin Mountain basaltic cinder cone and a review Tertiary-Holocene volcanism in the high plains of northeastern New Mexico. The first day of the excursion will consist of stops in the Fort Collins, Loveland and Lyons area of north-central Colorado to examine the entire Lower Cretaceous section. At Horsetooth Reservoir, west of Fort Collins our emphasis will be on the recognition of surfaces, sequences and systems tracts, and a discussion of depositional environments in the Plainview and Muddy sandstones and the intervening Skull Creek Shale. At Carter Lake, west of Loveland Colorado, we will examine the nature of the lower contact of the Dakota Group and discuss depositional environments and lateral and vertical variation in the Lower Cretaceous, Lytle Formation. On Highway 36, south and east of Lyons, CO we will contrast the upper portion of the Dakota Group, including the Muddy Sandstone and upper Skull Creek Shale with exposures seen earlier along Horsetooth Reservoir. Day one will end with a drive south to Pueblo, CO. On day two we will examine lithofacies architecture and sequence boundary relationships within the Muddy valley-fill succession near Pueblo, CO, the Capulin Mountain, basaltic cinder cone, and a well-preserved dinosaur trackway at Clayton Lake, northeast New Mexico. Day two will end in Clayton, NM. Day three will involve an examination of down-dip, Muddy-equivalent sandstones at three locations in the Dry Cimarron Valley, northeast New Mexico. These exposures will afford an opportunity to contrast sequence boundary morphology and architecture in the down-dip area with that observed at locations along the northern Colorado Front Range on day one. The field trip will end in Denver Colorado.

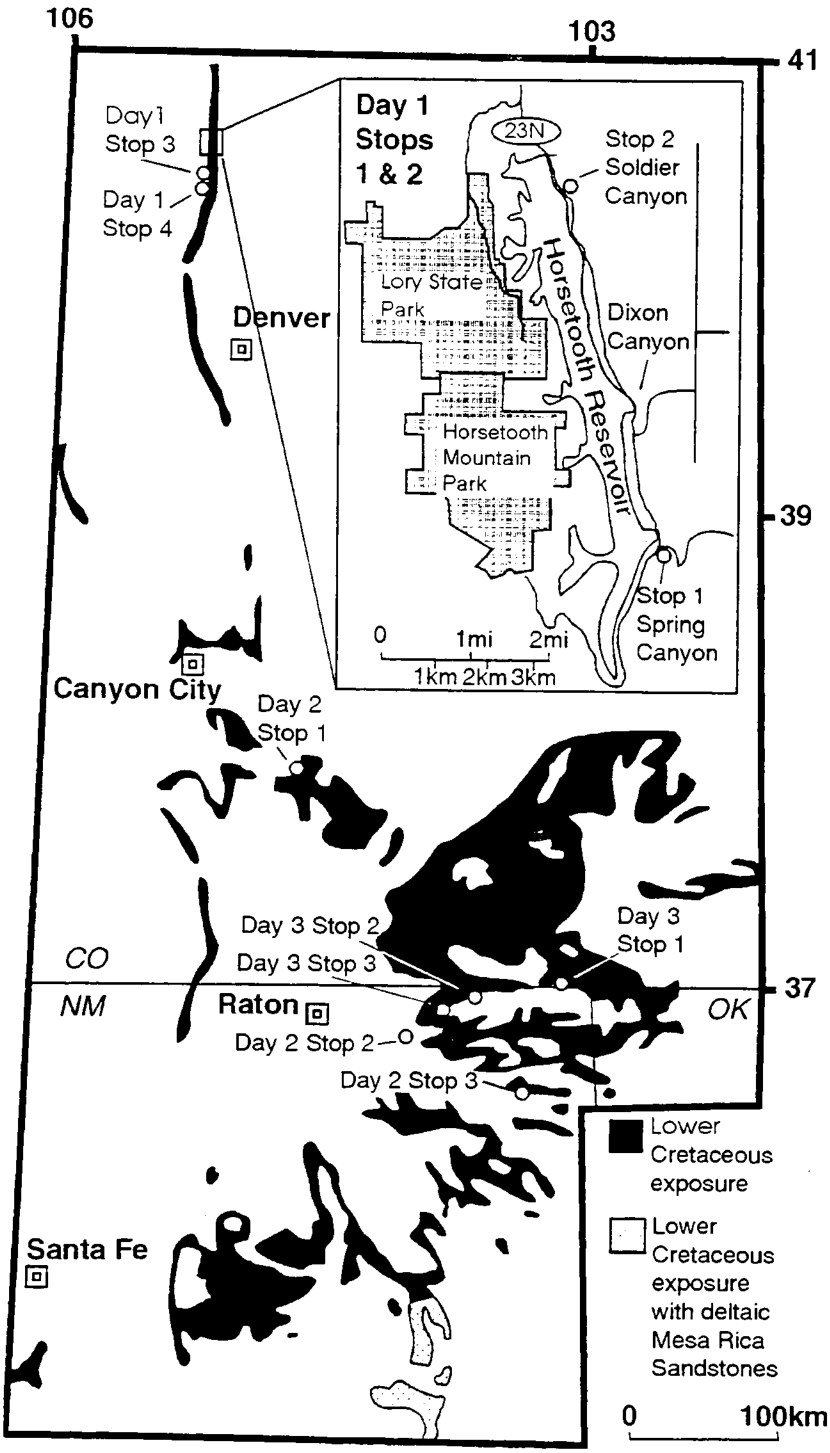

Figure 1. Location map of stops for days 1, 2, and 3 of the field trip. Stop 1 Day 1, NW1/4, SE1/4, SEC.32, T7N, R69W; Stop 2 Day 1, NW1/4, NE1/4, SEC.7, T7N, R69W; Stop 3 Day 1, NE1/4, SEC.10, T4N, R69W; Stop 4 Day 1, T3N, R70W; Stop 1 Day 2, NE1/4, SW1/4, SEC.12, T24S, R64W; Stop 2 Day 2, SW1/4, NW1/4, SEC.4, T29N, R28E; Stop 3 Day 2, SW1/4, NE1/4, SEC.15, T27N, R34E; Stop 1 Day 3, NE1/4, SW1/4, SEC.8, T35S, R52W; Stop 2 Day 3, SW1/4, SW1/4, SEC.8, T31N, R31E; Stop 3 Day 3, SE1/4, NW1/4, SEC.20, T31N, R29E.

DAY I - LOWER CRETACEOUS, NORTHERN COLORADO FRONT RANGE

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Rock outcrops along the eastern side of Horsetooth Lake, west of Fort Collins, CO, Carter Lake, west of Loveland, CO and along Highway 36, southeast of Lyons, CO provide excellent two-dimensional views of sequences and related unconformities in Lower Cretaceous rocks of the Dakota Group (Fig. 2). During day one of this field excursion our efforts will be concentrated on the sedimentologic characteristics, inferred depositional environments and sequence stratigraphic relations, and hydrocarbon trapping in these Lower Cretaceous rocks. Well developed valley networks are preserved in several of these lithostratigraphic units which are bounded by unconformities. These unconformities include lowstand surfaces of erosion (LSE) and transgressive surfaces of erosion (TSE). Most of these surfaces contribute to hydrocarbon trapping with the Denver Basin and also in foreland basins to the north in Wyoming and Montana (Dolson and Weimer, 1992; Dolson, et al, 1994).

The Rocky Mountain Foreland, in which we are located, has a complex Phanerozoic history driven by regional plate motions. In the simplest terms this history can be divided into four phases (Gries et al, 1992).

- Pre-Jurassic passive margin, disturbed by a brief orogenic event that produced the Ancestral Rocky Mountains during the Pennsylvanian.
- Development of the Cretaceous Interior Seaway (foreland basin) during the Sevier orogenic event (mid Jurassic to late Cretaceous) resulting from subduction along the western margin of the North American craton.
- Breakup and development of separate basins and ranges during the late Cretaceous to Eocene Laramide orogeny, resulting from a period of flat-plate subduction.
- Epirogenic uplift and erosion in late Tertiary to Quaternary producing the basic topography that we see today.

The bulk of the hydrocarbon production comes from Cretaceous rocks because of the thick shales and coals of this period that have generated large reserves (Grieves et al, 1992) during the third of the four phases mentioned above.

Stop 1 — Spring Canyon Dam Section, Horsetooth Reservoir

The Spring Canyon Dam Section (Sec. 32, T7N, R 69W) has been a reference section for the Lower Cretaceous stratigraphy in the northern Front Range Foothills since the initial work of MacKenzie (1963 and 1971). At this stop we will review Lower Cretaceous stratigraphy and regional correlations and discuss formations, members, lithofacies, ichnofacies, depositional environments, and key surfaces and sequences. The vertical sequences of textures, structures, and trace fossils are shown in Figure 3. A key to symbols used in stratigraphic columns for each stop is given in Figure 4.

Three major unconformities are recognized in Lower Cretaceous sediments; the K-0, K-1, and K-2 (Fig. 2; <u>NOTE</u>: these surfaces are roughly equivalent to the SB-1, SB-2, and SB-3 surfaces discussed later in this guide by Holbrook). These unconformity surfaces are traced westward by McGookey (1972) and Weimer (1984), and north into Wyoming and Montana by Dolson et al (1991), Dolson and Weimer (1992), and Weimer (1992). Uncertainty exists regarding the dating of these unconformities and other surfaces from radiometric age dates and faunal zones (Obradovich and Cobban, 1975; Obradovich, 1991 & 1992a & b). Obradovich (1992b) suggests a date of 98.5 to 99 Ma for the Albian/Cenomanian boundary, which is normally placed at the top of the Mowry. Weimer (1992; his figure 6) uses a date of 96 Ma for this surface and a date of 99 Ma for the middle Thermopolis (Skull Creek) Shale. Obradovich suggests a date of 111 Ma for the Aptian/Albian

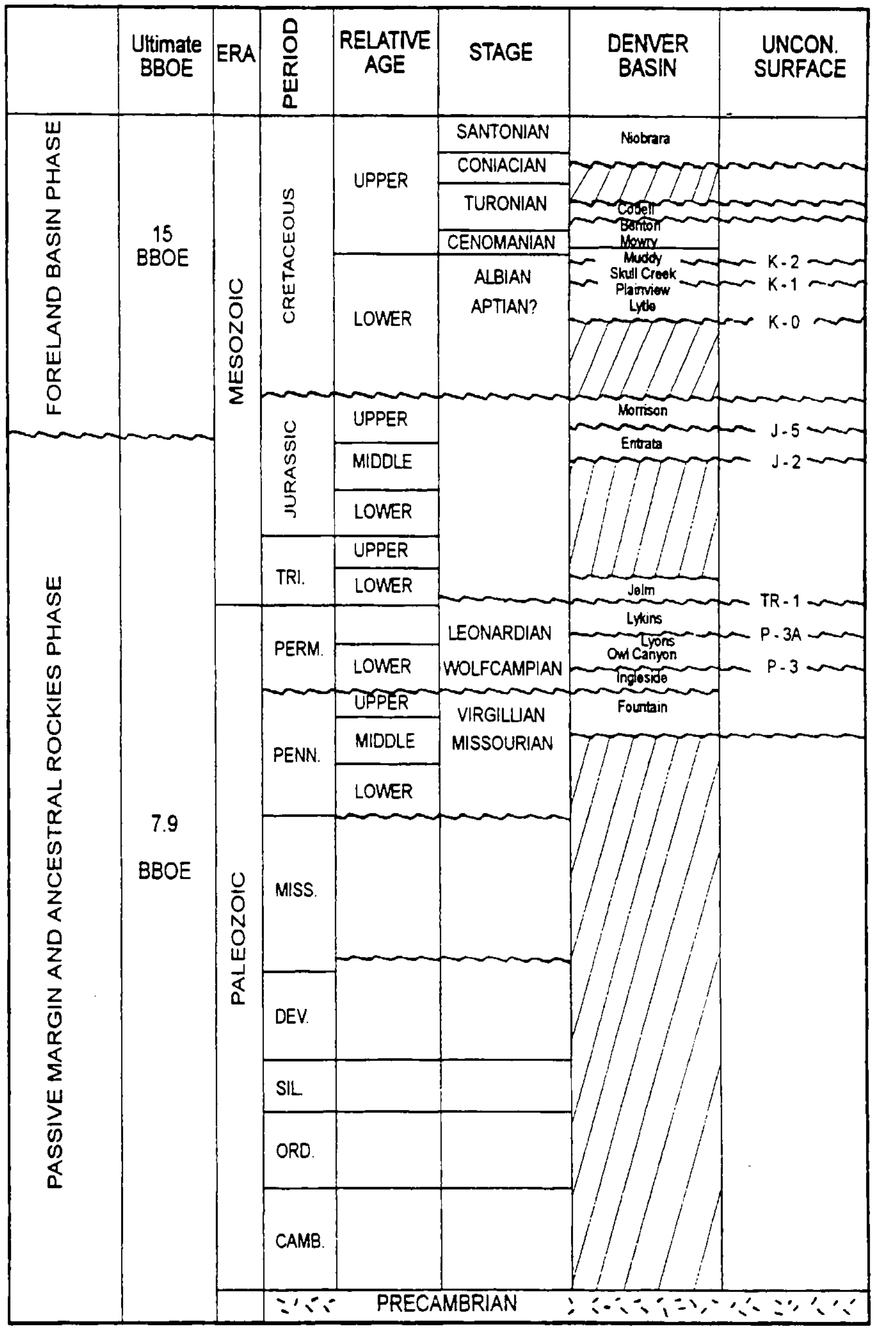


Figure 2. Generalized stratigraphic column showing stages, formations, and major unconformities in the northern Denver basin for rocks ranging in age from Precambrian to Upper Cretaceous. (NOTE: Not all Upper Cretaceous rock units are shown; foreland basin phase includes Upper Jurassic to Paleocene deposits; ultimate BBOE in Rocky Mountain Region from Gries et al, 1992). Column modified from Dolson and Weimer (1992).

boundary. Scott, et al (1994), using marine and nonmarine palynomorphs from a continuous core in western Kansas, near the Colorado border, and the graphic correlation method, date the three unconformities at 103, 98 and 94 Ma respectively. Correlation of theses surfaces in western Kansas with Front Range outcrops is, however, tenuous at best. Within the Dakota Group, along the northern Colorado Front Range, two sequences and one partial sequence are recognized (Fig. 5). Figure five also shows lateral relationships of units within the Dakota Group along the Colorado Front Range uplift from north of Fort Collins to Turkey Creek, west of Denver. Basic biostratigraphic data used by Dolson et al (1991) and Weimer (1992) for their interpretations and correlations of Lower Cretaceous strata are presented by Eicher (1960, 1962, and 1965). Criteria for recognition of unconformities in siliciclastic strata are reviewed by Weimer (1992) and Dolson et al (1994).

The Dakota Group section exposed at Spring Canyon Dam begins with the K-0 unconformity at the Lytle-Morrison boundary (Fig. 3). This unconformity marks the lowstand surface of erosion (LSE) at the base of sequence one (Figs. 3 & 5). The Lytle is composed of coarse grained, conglomeratic sandstones, with chert and clay clasts, which grade up into medium- to fine-grained sandstones in the middle and upper portions. Siltstone to mudstone units are present near the middle and at the top of this unit. The fine-grained units of the Lytle have oxidized red and green colors and lack carbonaceous material and hydrocarbon source beds. Sedimentary structures include trough and planar cross bedding, horizontal beds, and ripples. Scour and fill structures are also present. The fine-grained unit at the top of the Lytle is interpreted to be a paleosol based on the lack of sedimentary structures, the mottled appearance, and the presence of root casts. The bulk of the Lytle was probably deposited by a low-sinuosity fluvial system that flowed within an incised valley. At Horsetooth Reservoir and at the Bellvue Dome section north of Fort Collins, the Lytle Formation was interpreted as deposits of both a Donjek-type and a South Saskatchewan-type braided stream (Wescot,1979; Dolson, 1985). The uppermost portion of the Lytle at Bellvue Dome was interpreted as point bar, crevasse splay and well drained swamp deposits (Dolson, 1985). The K-1 unconformity at the top of the Lytle marks the LSE at the base of sequence two (Figs. 3 & 5).

The Plainview is composed of thinly bedded, medium- to very fine-grained sandstones interbedded with shale or siltstone laminae (Fig. 3). It contains wave ripples, horizontal laminations, herringbone cross-stratification, and flame structures. Bioturbation includes root structures, and *Rhizocorallium jenese*, *Planolites montanus*, and *Arenicolites sp.* burrows. In general this ichnofacies is characterized by a low diversity and a high density of burrows. All of these features suggest a general coastal plain/shoreface interpretation for the depositional environment. North of Fort Collins, at the Bellvue Dome section, the Plainview has a somewhat different vertical succession of lithofacies, which are interpreted as deposits of a transgressive barrier island (Dolson, 1985). Wescott (1979) interpreted the Plainview Formation along Horsetooth Reservoir as a subtidal, mixed sand and mud flat deposit. To the south, in the area west of Denver, the Plainview is interpreted as tidal flat and small channel deposits (Weimer, et al, 1990).

The basal portion of the overlying Skull Creek Shale is covered; however, it is clear from work by Dolson (1981 & 1985) to the north and Weimer (summarized in his 1992 overview paper) that the top of the Plainveiw along the Colorado Front Range uplift is a transgressive surface of erosion (TSE) with a sudden deepening from coastal plain/foreshore deposits to offshore claystones and shales of the lower portion of the Skull Creek. At the base of the exposed Skull Creek outcrop, the section consists of dark-grey marine shales, which contain bentonite beds and several thin, discontinuous bioclastic limestones. The shales are essentially unborrowed and this section is interpreted as a condensed section (CS). Samples from the shales from this part of the section have the highest total organic carbon (TOC) values observed in the Skull Creek. Previous interpretations of the Skull Creek Shale to Fort Collins Member interval suggested a gradational succession of facies from neritic shale to middle delta front sandstone (Weimer et al, 1990; Dolson and Weimer, 1992). However, the presence of gutter casts at the base of a hummocky to swaley cross-stratified lower shoreface succession suggests a previously unrecognized progradational event that resulted from a relative sea-level fall (i.e., a forced regression; Posamentier et al, 1992; Graham and Ethridge, 1995). Similar sharp-based, shoreface sequences have been documented from Upper Cretaceous shelf clastics in the Alberta foreland basin (Plint, 1991; Walker and Plint, 1992).

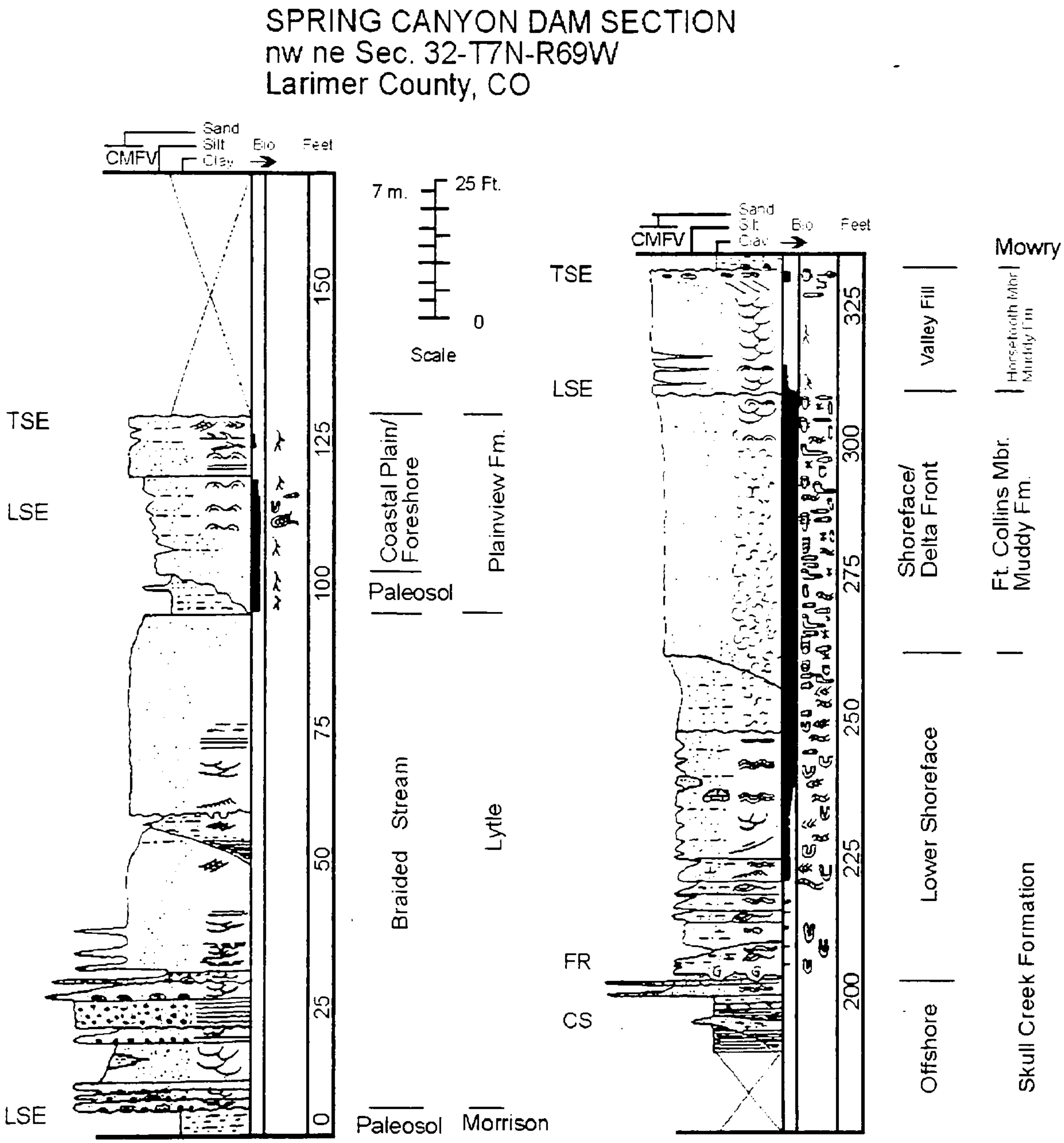


Figure 3. Detailed stratigraphic column at Spring Canyon Dam section, southeast side of Horsetooth Reservoir, Larimer County, Colorado, showing thickness, trace fossils, sedimentary structures, and grain size variation within the Lower Cretaceous Dakota Group. See Figure 4 for key to symbols (from Ethridge, et al, 1994b and Graham and Ethridge, 1995).

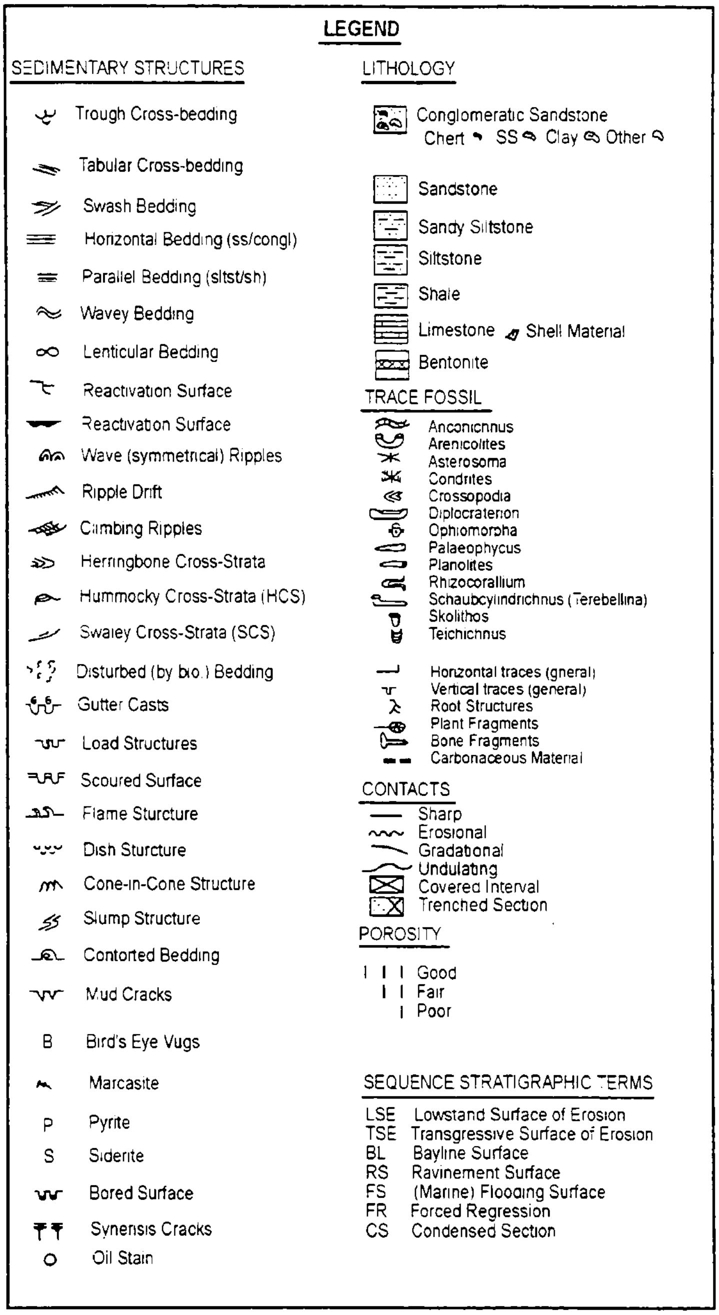


Figure 4. Key to symbols used in stratigraphic columns for day one of this field guide (from Ethridge, et al, 1994b and Graham and Ethridge, 1995).

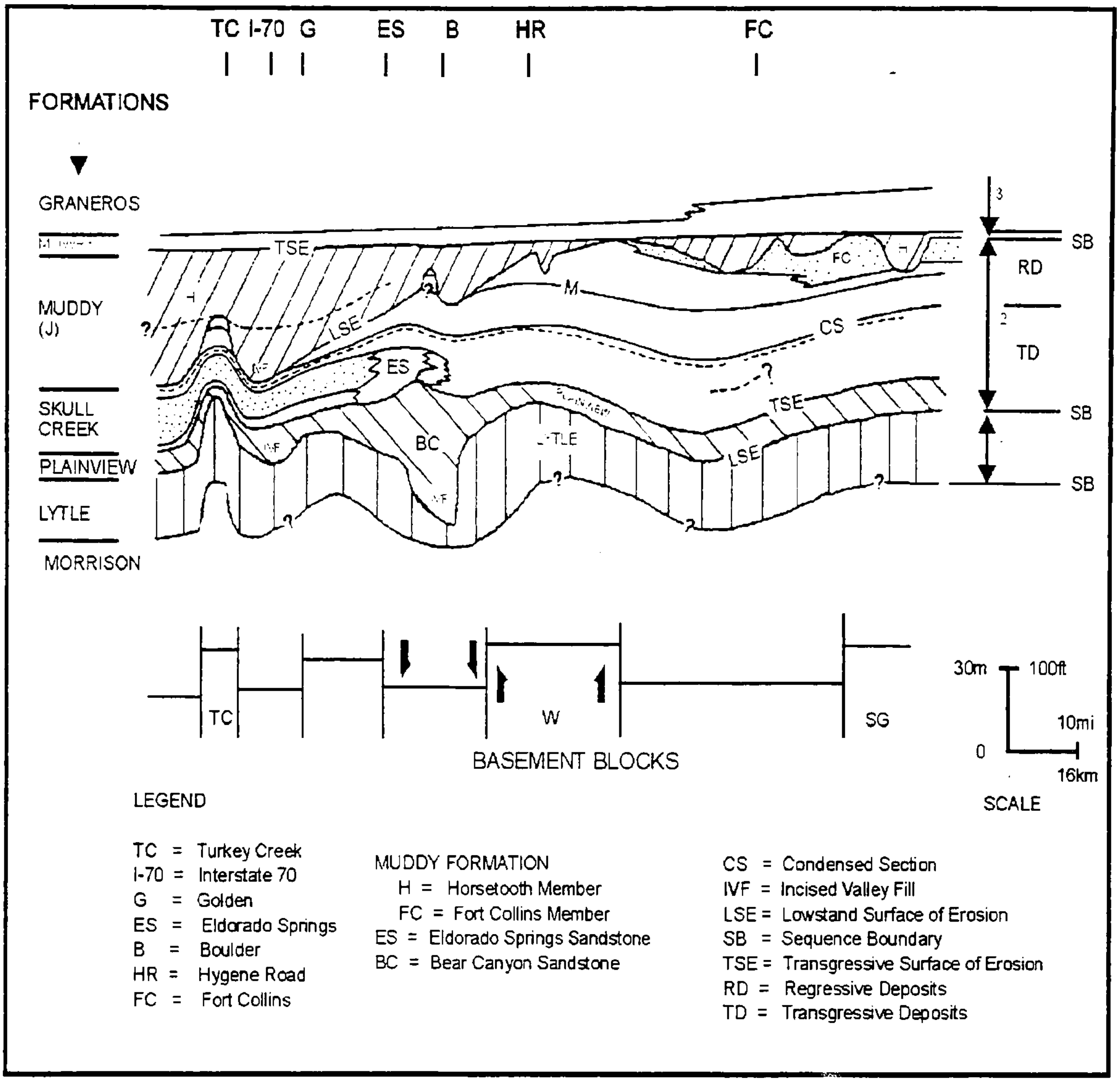


Figure 5. Restored stratigraphic section of Dakota Group (Albian) along the Front Range uplift from Colorado-Wyoming state line to south of Morrison, Colorado. Section was compiled from outcrop sections and nearby subsurface control. Modified from MacKenzie (1971), Weimer (1984), and Weimer et al (1990). From Weimer (1992).

Above the forced regression in the Skull Creek, thin interbedded sandstones and shales contain a low diversity and low density ichnofacies comprised of small U-shaped *Arenicolites sparsus* and small, grain-lined *Palaeophycus herberti* burrows. These are followed upward by a normal shoaling-upward succession of deposits characterized, in general, by a high diversity and a high density of burrows. The lower portion of this succession contains mostly *Asterosoma zoned*, *Anconichnus horizontalis*, *Schaubcylindrichus coronus*, vertical composite tubes, *Planolites beverlyensis*, and *Teichichnus rectus*. The upper sandstones are burrowed, mostly by *Asterosoma zoned*, *Ophiomorpha irregularis*, and vertical composite tubes. The succession from middle Skull Creek to Fort Collins Member of the Muddy Sandstone (Fig. 3) is characterized by an increase in the degree of bioturbation and by a change from ripple-drift, wavy and flaser bedding to a complete lack of sedimentary structures. The uppermost part of the Fort Collins Member is characterized by wave ripples and medium-scale, low angle trough cross-stratification. This succession is characteristic of first the *Cruziana* and then *the Skolithos* ichnofacies (Pemberton et al, 1992; MacEachern and Pemberton, 1992), and records the progradation of a sandy, shelf-phase delta. The Fort Collins Member is interpreted as a late highstand delta front deposit (Dolson and Weimer, 1992). Similar highstand, shoreline sandstones produce gas (Wattenberg field) and oil (Bell Creek field) in some of the largest Lower Cretaceous fields in the Rocky Mountain region.

The K-2 unconformity at the contact between the Fort Collins and Horsetooth Members of the Muddy Sandstone marks the LSE at the base of sequence three (Figs. 2 & 3). Both an increas in grain size and a change in sandstone character is observed as this boundary is crossed. Sandstones of the Horsetooth Member are tabular to trough cross-stratified in sets that range up to 2 feet (0.6 m) in thickness. Other than small rhizoliths (root molds 1 mm in diameter) the Horsetooth Member contains no ichnofauna. The Horsetooth sandstones are interpreted as fluvial and estuarine deposits that filled an incised valley (IVF) in the lower portion of sequence three (Dolson & Weimer, 1992). To the north and south along the Front Range (Fig. 5), other exposures described by Dolson (1985), Chamberlain, et al (1976 & 1985) and Weimer, et al (1990) provide ample evidence from trace-fossil and sedimentary-structure suites to support an estuarine interpretation for the upper portion of the Horsetooth valley-fill succession. Inferred drainage patterns, drainage divides, lowstand basins, and the maximum extent of the Skull Creek highstand seaway are shown in Figure 6 for the Rocky Mountain Region. Amalgamated fluvial-estuarine sandstones in some of these drainages produce hydrocarbons in the subsurface of the Denver basin (Ethridge and Dolson, 1989) and throughout the central and northern Rocky Mountains (Dolson et al, 1991). The top of the Horsetooth Member, at this stop, is characterized by a lag deposit consisting of chert pebbles and clay clasts along with bone and wood fragments. The uppermost portion also contains a low diversity and high density ichnofacies. Theses sandstones are thoroughly burrowed by *Ophiomorpha nodosa* and *Planolites beverlyensis*. The burrow *Ophiomorpha nodosa* extends from the upper surface down one meter into fluvial sandstones of the Horsetooth Member, and coarse grains and shell fragments have been piped into the sandstone. Some *Ophiomorpha* have paired surface tubes. The upper surface of the Horsetooth Member is interpreted as a TSE and is overlain by relatively deep-water deposits of the Mowry Shale.

Note that the Horsetooth Member is oil saturated at Spring Canyon dam while the Ft. Collins Member is not. This situation is typical of many localities in the Rockies. Deposits below the LSE are often too bioturbated or kaolinite cemented to be effective reservoirs. Exceptions are Amos Draw field (10 MMBO) and Bell Creek (125 MMBO) in the Powder River basin of Wyoming and Wattenberg gas field (1 TCF) in the Denver basin.

Stop 2 — Soldier Canyon Dam Section, Horsetooth Reservoir

Evidence for the TSE at the contact of the Plainview and Skull Creek, and the forced regression and a major slump structure within the Skull Creek are developed at the Soldier Canyon dam section (Sec. 7, T7N, R69W: Fig. 7). In the Plainview, thinly bedded, very fine to fine grained sandstones containing root structures and poor horizonation suggestive of protosols (Mack et al, 1993) are overlain by rippled and swaley cross stratifiied (SCS) sandstones with *Skolithos* and *Cruziana* ichnofacies trace fossils (Fig. 7). The SCS sandstones are sharply overlain by the Skull Creek Shale. The contact between the two represents the TSE. The lowermost portion of the Skull Creek, which is covered at the other two sections, consists of thinly laminated dark grey mudstones with

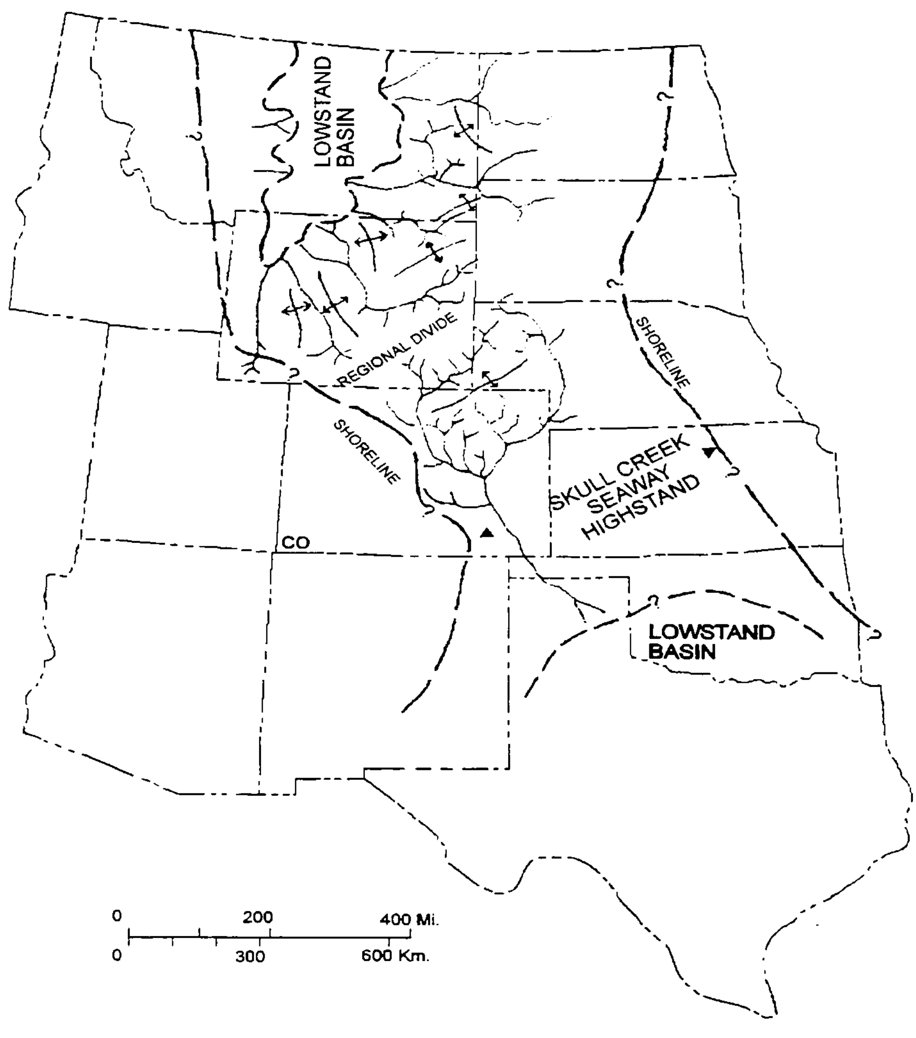


Figure 6. Map showing inferred drainage pattern for Muddy valley-fill deposits and maximum extent of Skull Creek seaway (modified from Dolson et al, 1991, Weimer andSonnenberg, 1982, and Weimer et al, 990).

occasional horizontal burrows immediately above the Plainveiw. The remainder of this exposed section is devoid of bioturbation, probably reflecting the fact that it was deposited under anaerobic conditions, below storm wave base and in water depths exceeding 100 feet (Weimer, 1992; Unit A of the Skull Creek, Fig. 5).

Like those within the Skull Creek at Spring Canyon, the gutter casts within the Skull Creek at Soldier Canyon Dam stratigraphically overlie thin limestone beds of bioclastic debris, thin bentonite beds, and dark gray shales of the condensed section, and overly hummocky cross stratified (HCS) sandstone. Limestone beds above and below the layer with gutter casts are petroliferous. The gutter casts mark a surface developed during a forced regression and above which the succession mimics the progradation seen in the upper Skull Creek - Ft. Collins ember rocks at Spring Canyon. Unlike the section exposed at Spring Canyon, the Skull Creek at this locality contains a major slump feature within an interbedded sandstone and siltstone succession that is dominated by hummocky to swaley cross-stratification. The slumped section contains large- and small-scale deformed beds including a large-scale recumbent fold. The overlying section of interbedded sandstone and siltstone with HCS appears to onlap onto the inclined top of the slump feature. To the best of our knowledge, no slumped sections of comparable magnitude have been found in any other outcrops of the Skull Creek and none have been reported in the literature from outcrop or core. Above and below the slumped interval, interbedded sandstones, siltstones, and shales show fining- and thinning-upward and coarsening- and thickening-upward successions over thicknesses of several feet to tens of feet. The remainder of the Dakota Group section exposed at this dam section (above about 125 ft; Fig. 7) is similar to that reported for the Spring Canyon Dam and Dixon Canyon Dam sections (Graham and Ethridge, 1994 & 1995).

Analog Stratigraphic Trap Production

The Dakota Group has produced over 1.7 BBOE hydrocarbons from the Northern and Central Rocky Mountains. Over 1.2 BBOE of this amount is from the Muddy Sandstone, which is sourced and sealed by the Skull Creek and Mowry shales. A complete review of regional stratigraphic relationships within the Dakota Group is given by Dolson and Muller (1994).

Figure 8 (Dolson et al, 1991) summarizes regional patterns of Muddy Sandstone production. Most of the production comes from stratigraphic traps located within paleodrainage basins which were buried sufficiently in Eocene time to expel commercial hydrocarbon quantities. Valley fills (first recognized by Harms, 1966, in the Nebraska portion of the Denver basin), buried hills and transgressive shoreline reservoirs form the most common pools, usually with a strike orientation with respect to regional structural dip. Strike oriented reservoirs are most common since hydrocarbon columns are generally short due to poor lateral seals (Fig. 9).

The Plainview Sandstone seldom produces, but its slightly younger equivalent, the Fall River Formation of Wyoming has produced over 250 MMBOE, primarily from incised valley-fill deposits which may have formed at about the same time as the LSE exposed at the top of the Lytle Formation. An example of an oil field that produces from Fall River valley-fill sandstones is discussed by Ethridge et al (1994b). These valley-fill deposits incise into a younger tongue of the Skull Creek Shale to the north. Like the Muddy Sandstone these deposits are encased in source rock and seals of the Skull Creek Shale.

The Lytle and equivalent formations seldom produce except on structural traps, due to poor lateral seals and lack of indigenous source rock. An exception is the giant Cutbank accumulation of Montana (175 MMBOER), where the Lower Cretaceous Cutbank sandstone reservoir oil was generated from the Devonian Bakken Formation. Juxtaposition of the Lower Cretaceous unconformity across an upper Mississippian migration path containing these oils allowed charging of the oils southward from Alberta to the Cutbank valley-wall trap (Dolson et al, 1993).

Stop 3 — Quarry on east side of Carter Lake

Exposures of the basal Dakota Group Lytle Formation are found in an abandoned quarry and in a road cut along the eastern side of Carter Lake west of Loveland where it unconformably overlies the Jurassic, Morrison Formation (Sec. 10, T4N, R69W). A major unconformity at the base of the Lytle Formation is based on data from Cobbin and Reeside (1952), Hills and Kottlowski (1983) and Scott et al (1994). Hills and Kottlowski dated Lytle equivalents as Aptian and the Morrison as Kimmeridgean. Scott et al in western Kansas date the basal Cretaceous as 103 Ma and the

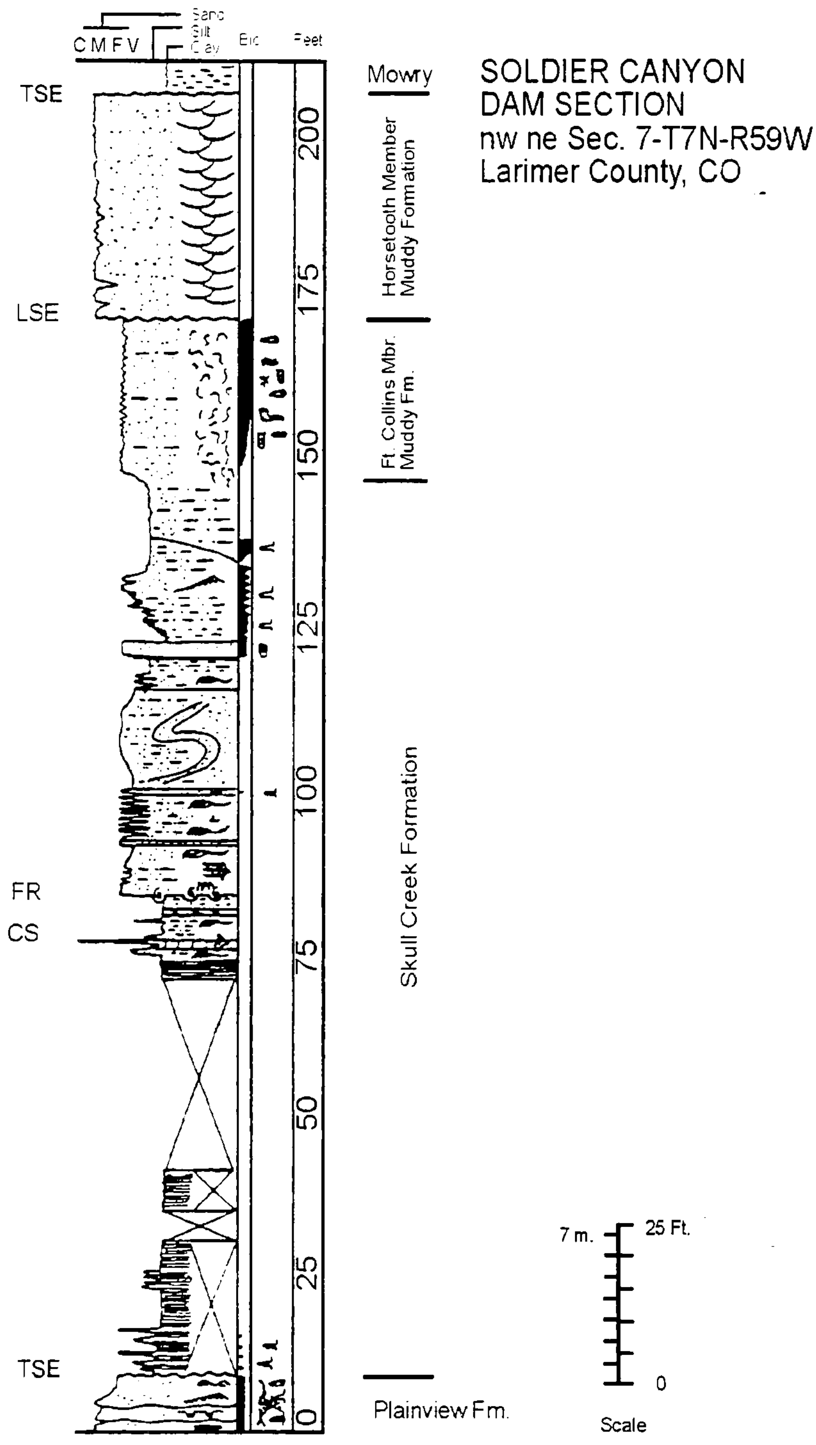


Figure 7. Detailed stratigraphic column at Soldier Canyon Dam section, northeast side of Horsetooth reservoir, Larimer County, Colorado, showing thickness, trace fossils, sedimentary structures, and grain size variation within the Lower Cretaceous Plainview, Skull Creek and Muddy formations. See Figure 4 for key to symbols (from Ethridge, et al, 1994 and Graham and Ethridge, 1995).

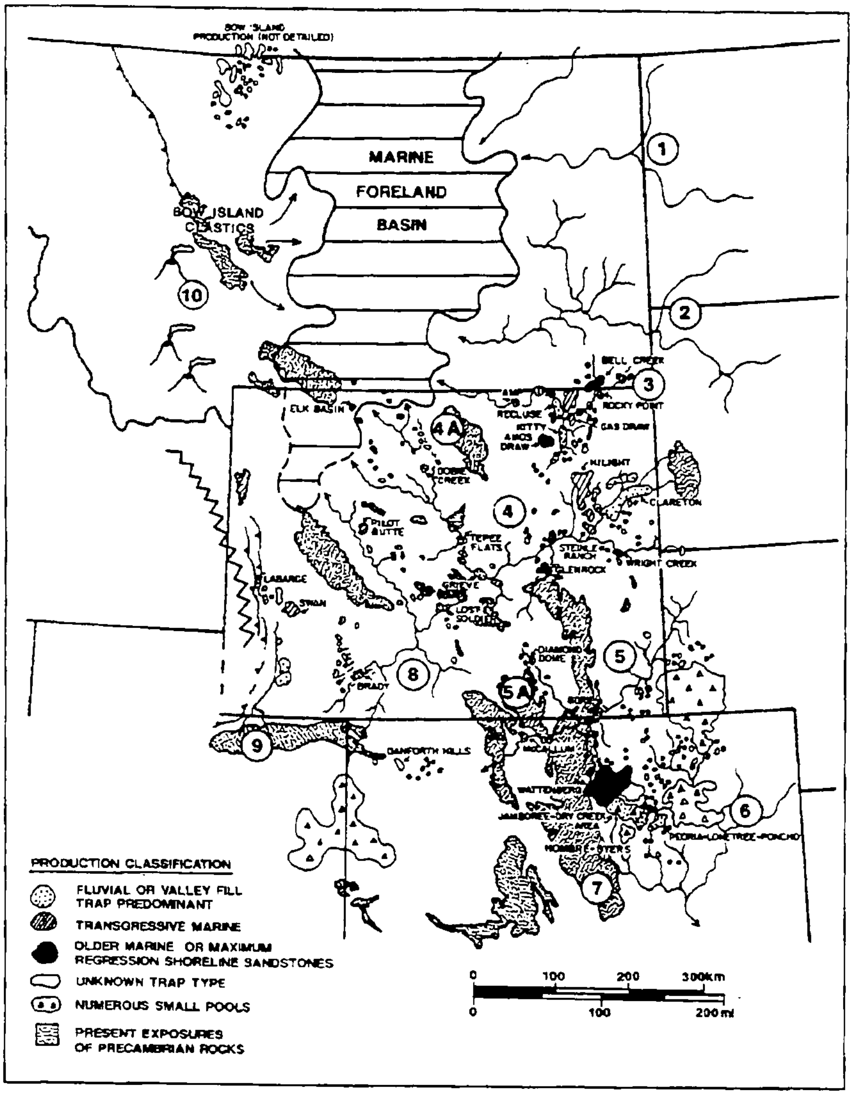


Figure 8. Regional patterns of production in the Muddy Sandstone (from Dolson et al, 1991). Unproductive paleodrainage basins are beyond the limits of oil migration or were never buried deep enough to generate hydrocarbons.

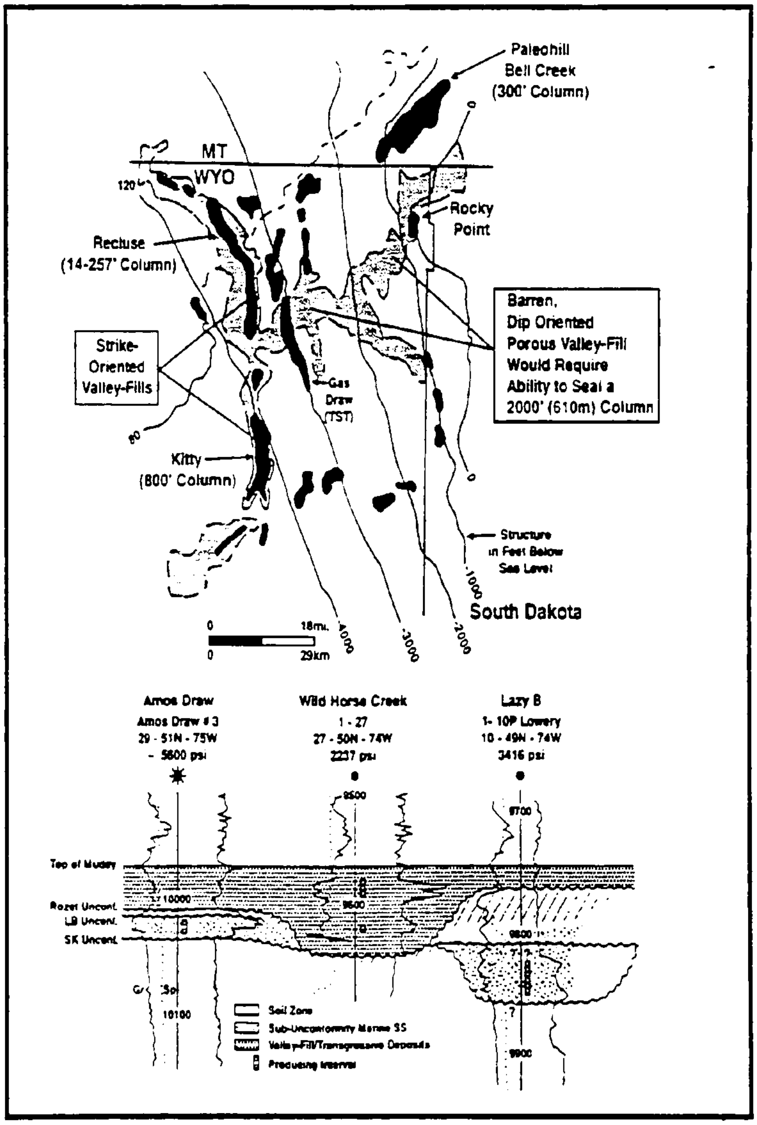


Figure 9. Typical strike oriented nature of many Muddy Formation stratigraphic traps. Poor seals caused by complex juxtaposition of reservoirs related to unconformities generally can only hold 50-200 foot (16-60 m) hydrocarbon columns. Traps oriented in steep structural settings or perpendicular to structure generally fail to seal commercially extensive hydrocarbon columns. Map is from Dolson, et al (1994). Stratigraphic cross-section shown is from Martinsen et al, 1994 from an area west and southwest of Kitty Field.

upper Morrison as >140 Ma. In their subsurface section, well to the east of the Colorado Front Range, the Lytle Sandstone is missing and the Plainview Sandstone rests unconformably on the Morrison Formation. There appears to be ample evidence to refute the conclusion by Johnson (1991) that the basal contact with the Morrison is conformable. Both a eustatic sea-level drop and regional uplift have been proposed to explain the widespread erosion of the Morrison Formation and the coarse grained conglomerate sandstone at the base of the Lytle at many locations (see Dolson, 1981 and 1985).

This stop will give us an opportunity of examine the inferred fluvial deposits of the Lytle in more detail and to review some of the more important characteristics of the Morrison Formation. In general the Lytle is characterized by a complex lateral heterogeneity, numerous erosional surfaces, and significant variations in grain size and sedimentary structures (Dolson, 1985). Sandstones exposed in the quarry are 66 ft (20.1 m) thick and composed of a basal quartz and clay clast conglomeratic sandstone that grades up section into cross-bedded sandstones. Cross-beds range from trough to planar, with troughs dominating the lower part of the section. Fractured zones and large-scale cut and fill structures are common in parts of the section and medium- to small-scale, fining-upward cycles are common. Interbedded siltstone to mudstone units, common at other localities, are not characteristic of the exposed Lytle in the quarry at Carter Lake. Along strike between Denver to the south and Boxelder Creek, tens of miles north of Fort Collins, the Lytle Sandstone is extremely variable in thickness (ranging from 50 to 135 ft [15.2 to 41.1 m] thick) and in the location and distribution of lithologies. North of Fort Collins the unit is characterized by a lower unit that grades from a conglomeratic sandstone with horizontal beds and trough cross beds to a sandstone characterized by planar cross beds and an upper unit that is composed of mudstone and lenticular trough cross bedded sandstones with lateral accretion surfaces. The units have been interpreted as low sinuosity (probably braided) deposits, and floodplain (coastal plain)/ high sinuosity (probably meandering) stream deposits respectively (Dolson, 1981 & 1985). To the south in the Denver area the Lytle is even more variable than it is north of Fort Collins. West of Denver some exposures are dominated by thick sandstone packages, others by mudstones with lenticular sandstones, and some contain both units. Also the mudstone/lenticular sandstone unit is not always at the top of the Lytle succession and may be sandwiched between thick sandstone units (Weimer et al, 1990). Significant relief on the lower Lytle boundary coupled with the high lateral variability along depositional strike, the upward transition into paralic deposits of the Plainveiw, and the disappearance of Lytle to the east in the subsurface all suggest that it was the result of deposition in large incised valleys along the western margin of the early Western Cretaceous Seaway.

Stop 4 — Highway 36, South of Hygiene Road Intersection

Good exposures of the Skull Creek Shale and the Fort Collins and Horsetooth members of the Muddy Sandstone are found at this road cut on Highway 36, south of Lyons, CO; Fig. 10; Sec. 32, T3N, R70W). Our purpose in stopping here is to compare and contrast the upper portion of the Dakota Group with that exposed at Stop 1 along the south-east sided of Horsetooth Reservoir. The Skull Creek Shale at this locality begins above the CS and consists of ripple cross-laminated, flaser bedded siltstones and interbedded shales that contain vertical, sand-filled burrow tubes. Trails are common on bedding-plane surfaces. The Skull Creek Shale grades upward into burrowed very fine-grained to fine-grained, clayey sandstones of the Fort Collins Member of the Muddy Sandstone. Trace fossils are abundant and include types similar to those at Stop 1, including *Teichichnus*, *Asterosoma*, and *Schanbcylindrichus (Terebelina)*. The Fort Collins Member is characterized by carbonaceous debris in the upper few feet and is capped by a rooted zone. The Horsetooth Member exposed at this stop is significantly different than that found at Horsetooth Reservoir. It is composed of a thin succession of interbedded carbonaceous sandstones and shales with small-scale cross beds and wavy bedding. The uppermost sandstone units contain *Diplocraterian* burrows and scattered chert pebbles. The thin Horsetooth section suggests a location near the margin of a paleovalley (Fig. 5) and a merging of the LSE at the base of the Horsetooth and the TSE at the base of the overlying Mowry Shale. Further north at several locations these two unconformity surfaces merge on inferred inter-valley divides (Fig. 5).

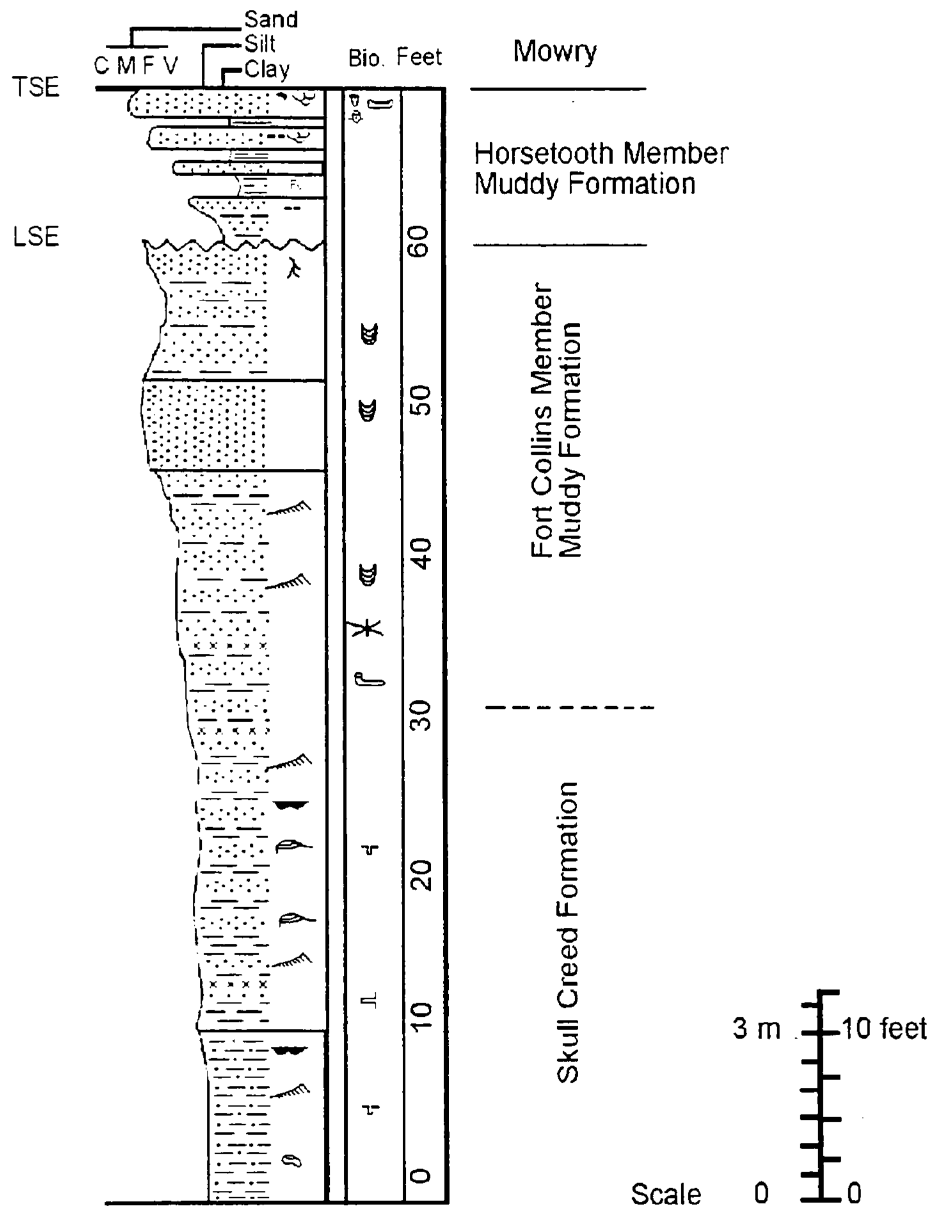


Figure 10. Stratigraphic column of the Skull Creek Shale, and Fort Collins and Horsetooth members of the Muddy Sandstone exposed along Highway 36 south of Hygiene road intersection. Column is modified from Clark (1978) and Weimer, et al. (1990).

Acknowledgments

The authors of day one acknowledge the support and help of C. Kent Chamberlain for trace fossil identification and Guy Plint for his understanding of gutter casts. We also thank these colleagues and John Dolson and Bob Weimer for many informative discussions on the rocks.

DAY 2: PUEBLO, COLORADO TO CLAYTON NEW MEXICO

John Holbrook, Southeast Missouri State University, Cape Girardeau, MO

Overview

Stops this day will be mixed in purpose. At the first stop, we will examine lithofacies architecture of Muddy valley-fill strata, and assess evidence supporting presence of a continuous sequence-bounding unconformity within these valley fill strata. We will then visit Capulin Mountain, one of the best preserved basaltic cinder cones in North America, to discuss Tertiary through Holocene volcanism in the High Plains of northeastern New Mexico. The day will end with a stop at the Clayton Lake dinosaur tracksite. Here, we will investigate the interrelationships between Lower Cretaceous sequence stratigraphy, Early Cretaceous dinosaur fauna, and track preservation potential on the "Dinosaur Freeway".

Regional Stratigraphic and Depositional Setting

The following discussion is extracted from work on Lower Cretaceous strata in southeastern Colorado and northeastern New Mexico by Holbrook (1992, 1996) and Holbrook and Wright Dunbar (1992) to establish a regional stratigraphic and depositional framework tieing Lower Cretaceous strata observed in the Front Range to that of southern High Plains exposures.

The sequence-bounding lowstand surface of erosion (LSE) observed at the base of Plainview strata in the Ft. Collins area (surface SB2; after Weimer and Sonnenberg, 1989) is continuous southward at least as far as east-central New Mexico. It regionally separates the Plainview equivalent Long Canyon bed (basal Glencairn Formation; southeastern Colorado and northeastern New Mexico) and Campana bed (basal Tucumcari Shale; east-central New Mexico) from underlying Morrison or Lytle strata (Fig. 11). Long Canyon and Campana strata are discontinuous, and, like the Plainview, represent local expression of valley filling preceding Kiowa-Skull Creek transgression (T-5 of Kauffman, 1977). Lytle strata is discontinuous beneath surface SB2 over most of the High Plains south of Colorado Springs, and is apparently absent south of northeastern New Mexico (Holbrook, et al, 1987).

The transgressive surface of erosion which separates Plainview from overlying Skull Creek strata in the Front Range is also continuous as far southward as east-central New Mexico, and separates underlying Long Canyon, Campana, Lytle, or Morrison strata from overlying off-shore marine equivalents of the Skull Creek Shale within the upper Glencairn (southeastern Colorado and northeastern New Mexico) and Tucumcari (east-central New Mexico) formations (Fig. 11). This surface represents regional ravinement preceding Kiowa-Skull Creek transgression, and is draped regionally by transgressive and regressive Skull Creek and Skull Creek equivalent offshore marine shale and shoreface sandstone.

Basal Muddy (southeast Colorado) and equivalent Mesa Rica (northeastern New Mexico) fluvial sandstone are separated from underlying Glencairn marine shale and sandstone by the 1992; Dryer, 1994; Allen, 1993). Lithofacies Sf is here interpreted to represent tidal redistribution of fluvially derived sediments into subtidal bars and sheets at the estuary head.

Subtidal bar/sheet strata interfinger laterally and vertically with thickly laminated-to-massive blue-gray silty mudstone. These deposits closely resemble the open estuarine mud deposits which lie directly seaward of subtidal bars in the Gironde estuary of western France (Allen, 1993; Allen and Posamentier, 1993), and are interpreted to reflect ancient analogs of these modern deposits. The rare sand stringers and minimal burrowing of lithofacies Fl are also consistent with Gironde estuarine mud deposits (Allen, 1993; Allen and Posamentier, 1993).

Estuarine mud (Fl) and subtidal bars/sheets (Sf) may be overlain or underlain by less common medium-bedded sand of lithofacies Sihs (Table 1). Lithofacies Sihs bears the tidally generated heterolithic features and upper shoreface marine ichnofauna typical of lithofacies Sf; however, Sihs strata are comparatively sandy and bear lateral accretion surfaces. Lithofacies Sihs represents what Thomas, et al (1987) termed inclined heterolithic strata. Such marine-influenced inclined heterolithic strata has been attributed to tidally influenced point-bar deposition by several authors

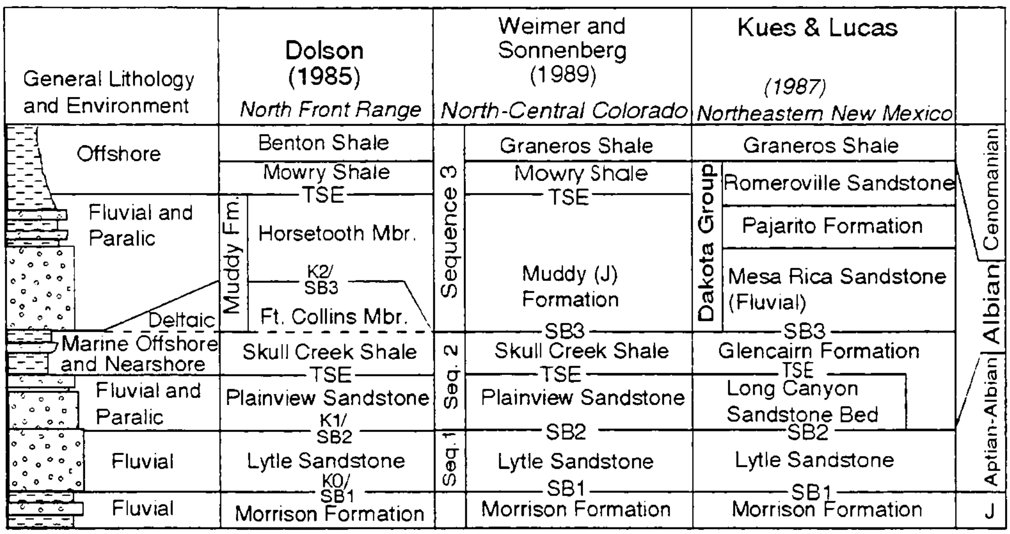


Figure 11. Correlation chart ogf major Lower Cretaceous formations and sequence stratigraphic b oundaries between the northern Front Range of Colorado and northeastern New Mexico.

Table 1. Lithofacies from Lower Cretaceous strata viewed on days two and three.

Code	Lithology	Characteristics	Biota	Environment
Stp	Fine-to-medium-grained sandstone	Medium-scale trough and planar cross bedding; channel scours locally with mud rip-up and pebble lags	Abundant plant fragment impressions; rare dinosaur tracks; no significant burrowing	Fluvial
Spr	Thick -to-very thick bedded fine-grained sandstone	Medium-scale planar cross bedded with subdominant current and oscillation ripple lamination; herringbone cross bedding common; ripple-bounded planar forests common; bound by shallow wide channel scours, and scours are amalgamated	Plant fragment impressions common; burrows rare, and mostly *Arenacolities*	Tidal channel
Stpr	Medium-to-very thick bedded fine-grained sandstone interbedded with blue-gray muddy siltstone	Sandstone - current and oscillation rippled and small-to-medium-scale planar and trough cross bedding; clay draped ripples rare but present locally; herringbone cross bedding and clay-draped planar cross-bed foresets in thickest beds Siltstone - rippled-to-thickly laminated	Abundant plant fragment impressions; local rooted horizons; abundant dinosaur tracks; burrows uncommon, but locally present and include *Teredolities*, *Planolities*, *Arenacolities*, and rare *Thalassinoides*	Fluvial/marine transitional
Sfr	Medium-to-thick bedded fine-to-medium-grained sandstone interbedded with thin-to-very thin siltstone beds	Sandstone - current rippled or small-scale planar cross bedded Siltstone - thickly laminated to rippled Exposures are bound and internally partitioned by channel scours	Abundant plant fragment impressions; no significant burrowing	Fluvial
Sihs	Medium-to-very thickly bedded fine-grained sandstone interbedded with thin-to-very thin bedded dark-gray silty mudstone	Sandstone - current and oscillation rippled or small-scale planar cross bedded; scours lined with clay rip-ups locally below sandstone beds; clay-draped ripples common Mudstone - thickly laminated-to-rippled Beds are parallel, and have depositional dip of approximately 10^0	Lignite fragments and plant fragment molds common; burrowing is minimal overall and comprises *Teredolities*, *Planolities*, *Arenacolities*, and rare *Thalassinoides*	Tidally influenced point bar

Sf	Thin-to-medium, tabular-to-slightly lenticular beds of fine-grained sandstone interbedded with thin-to-very thin beds of blue-to-dark-gray silty shale	Sandstone - mixed current and oscillation ripples grading laterally locally to small-scale planar cross bedding in thicker beds; ripple foresets are commonly clay draped; load casts common Silty shale - thickly laminated to rippled	Plant fragment and log impressions; rare bivalve molds; bioturbation minimal, but burrows and trails are common and include *Teredolities*, *Planolities*, *Arenacolities*, *Syphanities*, *Cruziana*, *Lockeia* and rare *Thalassinoides*	Subtidal bar/sheet
Fl	Blue-gray silty mudstone and muddy siltstone with rare widely dispersed very thin beds of very fine-grained sandstone	Mudstone/siltstone - thickly/ very thickly laminated Sandstone - current and oscillation rippled	Very minor burrowing	Open estuary
Fm		Medium to very thickly laminated	Dark blue-gray thick bedded lenticular mudstone gradational with lithofacies Sfr	Fluvial (abandoned channel fill)

(Thomas, et al, 1987; Shanley, et al, 1992; Dalrymple, et al, 1992). Lithofacies Sihs is here interpreted to record point-bar development in meandering tidal channels and/or strongly tidally influenced fluvial channels. southward continuation of the LSE (surface SB3; after Weimer and Sonnenberg, 1989) which separates Fort Collins and Horsetooth strata in the Colorado Front Range (Fig. 11). This surface is traceable southward into east-central New Mexico beneath deltaic Mesa Rica Sandstone (Fig. 1 and 11). This LSE records regional exposure and incision of Skull Creek and Skull Creek equivalent marine strata in eastern Colorado and northeastern New Mexico during Kiowa-Skull Creek lowstand (Fig. 11). Deltaic Mesa Rica strata in east-central New Mexico reflect shoreline progradation and lowstand wedge deposition at maximum regression (Fig. 1). Fluvial Mesa Rica and overlying basal Pajarito strata in northeastern New Mexico represent deposition of a coastal/alluvial plain contemporary with Mesa Rica lowstand deltaic deposition to the south.

Muddy (southeastern Colorado) and Pajarito (northeastern New Mexico) strata are equivalent to the Horsetooth Sandstone of the Front Range, and like the Horsetooth, represent coastal aggradation and valley filling associated with onset of the Greenhorn transgression and renewed flooding of the Western Interior. The existence of a transgressive surface of erosion in southeastern Colorado and northeastern New Mexico that is equivalent to the transgressive surface of erosion above Horsetooth strata is still unresolved.

Stop 1: Muddy Valley-fill Exposures in the Huerfano Canyon Area
Lithofacies of Muddy valley-fill strata

The most common rocks in Muddy strata are cross-bedded sandstone of lithofacies Stp (Table 1). Abundant channel scours, channel lags, amalgamated cross-bed sets, and lack of marine biota have led several authors to render a fluvial channel and bar interpretation for these strata (Long, 1966; Jacka and Brand, 1972; Holbrook, 1996). These strata are lateral to, and commonly engulf, less common rippled lenticular unfossiliferous sandstone units of lithofacies

Sfr (Table 1). Lithofacies Sfr strata have similarly been interpreted to represent channel deposits (Atalik, 1984; Holbrook, 1996). Lithofacies Stp and Sfr together constitute a cliff-forming sandstone unit which is consistently present at the base of Muddy strata. In most areas, these facies constitute a similar cliff former at the top of Muddy strata that Long (1966) referred to as the upper Dakota sandstone. These two cliff-forming sandstone units are typically separated by rocks of the lithofacies discussed below, but are locally amalgamated.

The next most abundant lithofacies is burrowed interbedded sandstone and shale of lithofacies Sf (Table 1). Abundant clay-draped ripples and shale partings in these ripple-dominated sandstone beds are typical of paralic rocks deposited under tidal influence (Visser, 1980; Nio and Yang, 1991; Shanley, et al, 1992). Likewise, the trace fossil assemblage of this lithofacies is characteristic of an upper shoreface environment (Seilacher, 1964; Ekdale, et al, 1984). Taylor (1984), quite reasonably, attributed nearby examples of this lithofacies to tidal-flat deposition. More extensive lateral examination, however, reveals that these strata are not dissected by tidal channels, and are more sand dominant than typical tidal flats. Likewise, these deposits show no signs of subaerial exposure (e.g., mudcracks). Lithofacies Sf more closely resembles low-energy versions of the subtidal bars and sheets observed in headward regions of modern mixed wave and tidally dominate estuaries (Nio and Yang, 1991; Dalrymple, et al, 1992; Dryer, 1994; Allen, 1993). Lithofacies Sf is here interpreted to represent tidal redistribution of fluvially derived sediments into subtidal bars and sheets at the estuary head.

Subtidal bar/sheet strata interfinger laterally and vertically with thickly laminated-to-massive blue-gray silty mudstone. These deposits closely resemble the open estuarine mud deposits which lie directly seaward of subtidal bars in the Gironde estuary of western France (Allen, 1993; Allen and Posamentier, 1993), and are interpreted to reflect ancient analogs of these modern deposits. The rare sand stringers and minimal burrowing of lithofacies Fl are also consistent with Gironde estuarine mud deposits (Allen, 1993; Allen and Posamentier, 1993).

Lithofacies Stpr caps fluvial deposits over most of the region and bears features of both underlying fluvial strata and overlying estuarine strata. Strata are sand rich and ripple, trough, or planar cross bedded. Locally, these strata exhibit marine tidal features, such as clay-draped foresets or herringbone cross bedding, and/or contain marine trace fossils. Root traces and abundant dinosaur tracks, however, infer that these strata were deposited in a largely emergent environment. These strata intertounge with both underlying fluvial and overlying estuarine strata, and are interpreted to represent the remains of coastal late-stage channel-fill and levee/splay complexes which were altered by tidal marine influence (c.f. Shanley, et al, 1992).

Several amalgamated shallow channel fills crop out at one location in the Huerfano Canyon in scoured contact with underlying basal Muddy fluvial strata. These sandy channel-fills contain abundant herringbone cross bedding and ripple-bound planar foresets, as well as the marine trace *Arenacolities*. These strata represent fills of small tidal channels.

Model for Muddy valley filling, and development of an intra-valley-fill sequence boundary

The lower two-thirds of the Muddy section fits well with the model for transgressive filling of a mixed wave and tidally influenced estuary proposed by Dalrymple, et al, (1992) and Allen (1993). As predicted by this model, transgression prompted increased meandering and marine flooding in streams of the estuarine coastal plain, prompting deposition of tidally influenced inclined heterolithic strata (Sihs) and other fluvial/marine transitional deposits (Stpr) directly above basal Muddy fluvial sandstone (Figs. 12b and 13). Overlying subtidal bar/sheet and open estuary deposits represent transgression of the open estuary over underlying channel-derived lithofacies (Figs. 12c and 13). Although tidally influenced point bar deposits (Sihs) are typically positioned between open estuary and fluvial deposits, they may locally occur above open estuary strata (e.g. Fig. 13). Such occurrences likely record episodes of local shoreline regression owing to locally increased sediment supply in an overall transgressing system.

The above model infers that open estuary deposits should be overlain by marine shoreface sandstone, or a more offshore deposit separated from underlying estuarine strata by a wave and/or tidal ravinement surface (Fig. 12c and d). This is not the case in the Huerfano Canyon area. Here, open estuary deposits are overlain by a sharp and regionally

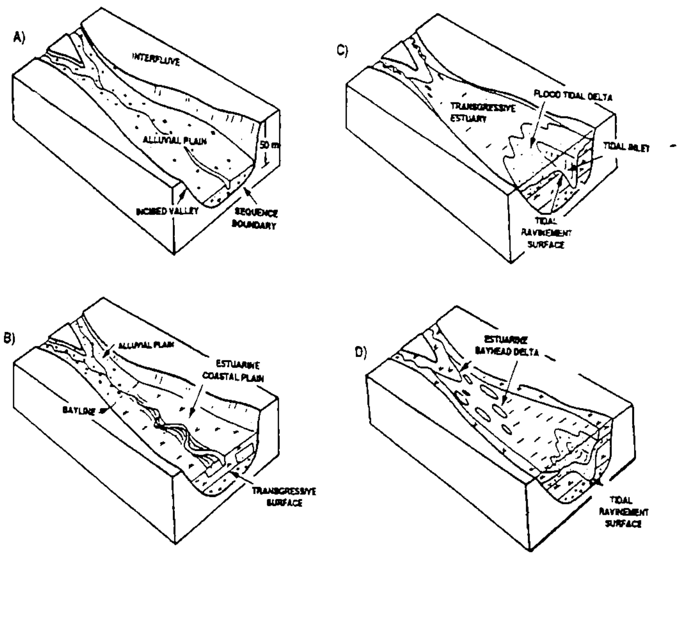


Figure 12. Evolution of the Gironde estuary in western France from a) Wisconsin sea level lowstand, to B) Initiation of Holocene transgression, to C) Maximum Holocene flooding, to D) Modern approximate sea level stillstand. (from Allen and Posamentier, 1993)

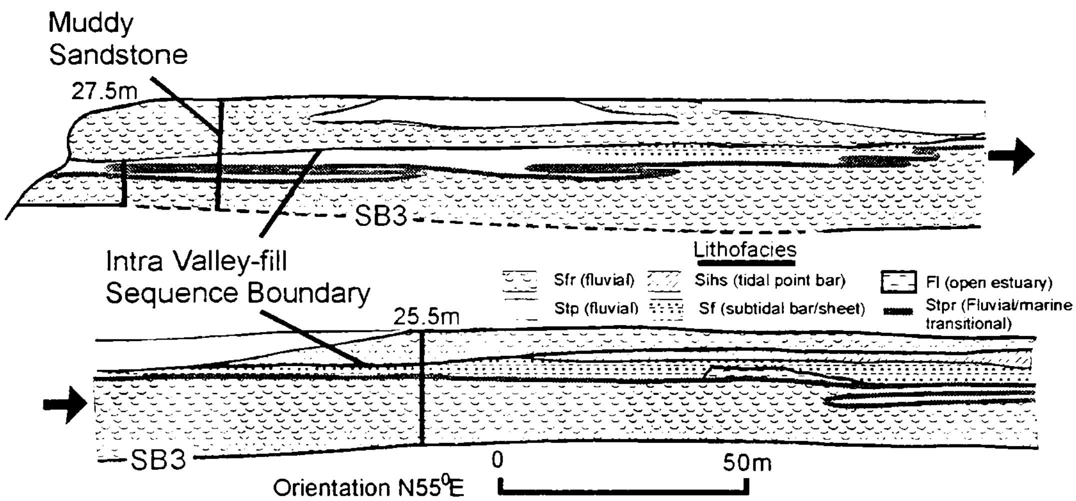


Figure 13. Sketch of facies distribution and sequence boundaries in exposure of the Muddy Formation at Stop 1, Day 2.

continuous subaerial erosion surface, above which lyes fluvial sandstone (Fig. 13). This erosional surface has been traced continuously over 16 kilometers of unbroken Huerfano Canyon exposure. The surface locally cuts through and removes estuarine deposits and basal Muddy fluvial strata. Nowhere are open marine deposits present between this erosional surface and underlying estuarine strata.

Transgression and Muddy valley filling was apparently interrupted by an episode of regression, which prompted scouring of existing estuarine fill and development of a lowstand surface of erosion above estuarine deposits. Deep levels of incision into underlying strata suggest that scouring of this surface was accompanied by relative sea-level fall. Any open marine strata deposited above estuarine fill was apparently removed during this incisional episode.

Reinitiation of transgression prompted fluvial deposition above this lowstand surface of erosion, resulting in the Stp and Sfr fluvial strata regionally at the top of the Muddy section (Fig. 13). These strata are capped by fluvial/marine transitional strata of lithofacies Stpr, which in turn are capped by offshore marine deposits of the Graneros Shale. The reason for this abrupt shift from marine-influenced fluvial to open-marine strata is unresolved, but a wave ravinement episode is suspected.

Previous workers made progress toward recognition of a sequence boundary within Muddy strata. Waage (1953) and Long (1966) both noted that upper Muddy fluvial sandstone deposits were locally incised into lower fluvial units, and intervening fines were removed at such locations. A sequence boundary was actually proposed at this stratigraphic level by Hamilton (1989) for Muddy equivalent fluvial strata of central Kansas. He based this on correlative association of abrupt upward change in fluvial style and landward pinchout of the marine Huntsman Shale. He further proposed a link with this inferred surface and the sequence-boundary at the base of the Lower Cretaceous D sequence of the Denver Basin. Lack of continuous exposure limited him to sparse point data. He was thus unable to laterally trace a single surface, that could be distinguished from a series of unrelated channel diastems.

Regionally traceable examples of intra-valley-fill sequence-bounding unconformities are rare, and have only been documented in a few cases (e.g. Aitken and Flint, 1994). Such sequence boundaries have been inferred by upward changes in fluvial architecture or abrupt transition from marine-influenced fluvial to fluvial deposition in a few other cases (e.g. Shanley and McCabe, 1991; Pattison and Walder, 1993). Muddy strata in the Huerfano Canyon area contain a rare and significant example of a traceable sequence boundary entirely within valley-fill strata. This boundary reflects the paralic/coastal plain expression of a sea-level-related sequence-bounding unconformity.

Features visible at stop 1 The Plainview Formation is not present at this location, and sequence boundary SB2 and the transgressive surface of erosion at the base of marine Glencairn strata exist as a single scour surface separating marine Glencairn shale from conglomeritic Lytle Sandstone (Fig. 13). Glencairn strata and the upper half of the Lytle section is largely covered here. Exposures are, however, apparent locally.

The basal fluvial, the medial estuarine, and the upper fluvial section of the Muddy Sandstone are exposed here. Each of the lithofacies discussed above lyes in its described stratigraphic position, except for lithofacies Sihs which is higher in the section than it normally occurs. The intra-valley-fill sequence boundary at the base of the upper Muddy fluvial sandstone is readily traceable here, however, exposures of fluvial/marine transitional strata at the top of the Muddy section are largely eroded. A site with five dinosaur tracks is located on the mesa rim in the northern half of the exposure.

Stop 2: Capulin Mountain National Monument, New Mexico
The Raton-Clayton volcanic field

The Raton-Clayton volcanic field (RCVF) covers the approximately 130 km stretch between the towns of Raton and Clayton, New Mexico (Fig. 14), and comprises the easternmost Cenozoic volcanic rocks in the western United States (Kudo, 1976). The RCVF contains rocks of basaltic, andesitic, and dacitic composition that have been historically subdivided into the Raton Basalt, Clayton Basalt, Red Mountain Dacite, and Capulin Basalt formations (Collins, 1949; Wood, et al, 1953; and Baldwin and Muehlberger, 1959). Not all of these formations are compositionally distinct, and the Raton and Clayton basalts contain rocks of more than one composition. Accordingly, definition of these formations has seen more recent revisions (Kudo,

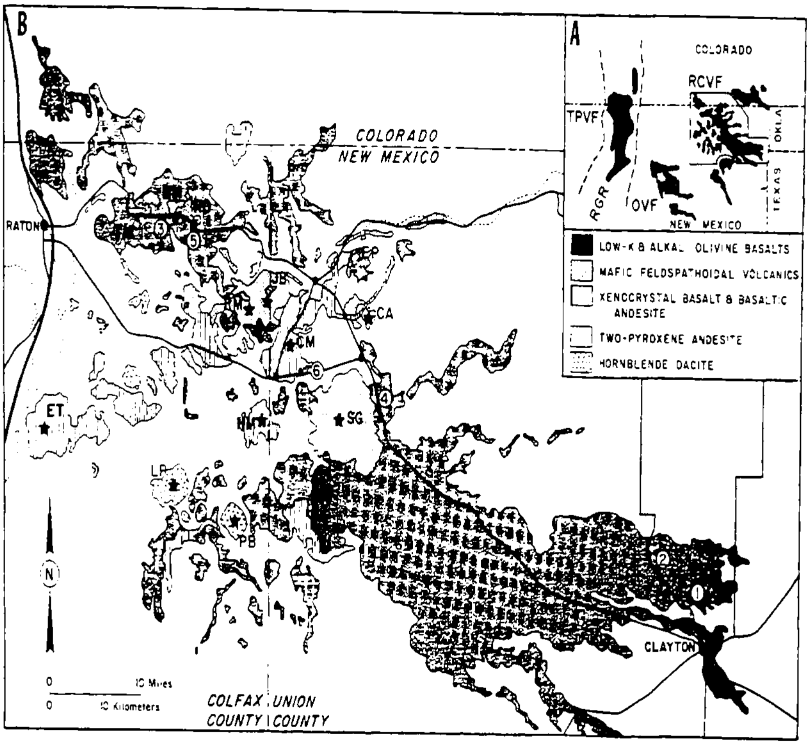


Figure 14. Map of volcanic units in the Raton-Clayton volcanic field. (from Stormer, 1987)

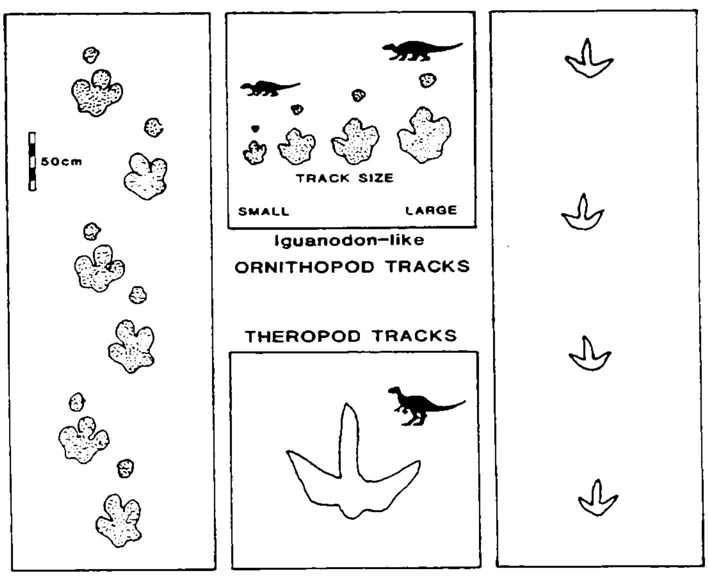


Figure 15. Comparison of ornithopod (*Caririchnium*) and theropod tracks characteristic of the "Dinosaur Freeway." (from Lockley, 1991).

1976; Stormer, 1972 and 1987). This section discusses rocks of the RCVF in the order in which they erupted, while placing these rocks in the formational framework used by Baldwin and Muehlberger (1959).

The first eruptive phase took place between 7.2 and 3.2 m.y. (Stormer, 1972), and covered much of the western part of the RCVF with low-K and alkali olivine basalts (Baldwin and Muehlberger, 1959; and Stormer, 1987). These basalts presently cap the high mesas (Johnson and Canyon mesas) in the western part of the RCVF, and are referred to as the Raton Basalts by Baldwin and Muehlberger (1959). Raton low-K basalts are mildly alkalic, olivine basalts similar to continental olivine tholeiites (Stormer, 1987). These rocks are interspersed with less common alkali olivine basalts which bare common olivine and clinopyroxene phenocrysts (Stormer, 1987).

An eruptive event along the southwestern margin of the RCVF about 2.7 m.y. produced the thick flows, domes, and plugs of the Red Mountain Dacite (Stormer, 1972). The Red Mountain Dacite is characterized by hornblende and plagioclase phenocrysts in a groundmass containing feldspar microlites and glass (Stormer, 1987).

A later phase of eruption between 2.5 and 2.2 m.y. (Stormer, 1972) flooded the RCVF with the extensive basalts which presently cap the low mesas between Capulin and Clayton, New Mexico (Fig. 14). These rocks are grouped into the Clayton Basalt by Baldwin and Muehlberger (1959) based on a topographic rather than compositional distinction. Compositionally, these rocks are similar to the Raton Basalt, and represent a continuation of mafic volcanism in the area.

Andesitic eruption about 1.9 m.y., produced the prominent Sierra Grande shield volcano (Stormer, 1972). These andesites are characterized by large Mg-rich orthopyroxene and smaller clinopyroxene and plagioclase phenocrysts, commonly in a glass-rich groundmass (Stormer, 1987). The Sierra Grande volcano is the only major expression of this event. Baldwin and Muehlberger (1959) lumped the Sierra Grande andesite into the Clayton Basalt; however, other workers (e.g., Kudo, 1976) consider these rocks separately.

Approximately 1.8 m.y. (Stormer, 1972), a series of feldspathoidal basaltic eruptions took place in the region near Capulin Mountain (Fig. 14). The resultant rocks are basanites and nephelinites with abundant phenocrysts of clinopyroxene and olivine (Stormer, 1987). Baldwin and Muehlberger (1959) lumped these rocks primarily into the Clayton Basalt.

The last eruptive phase in the RCVF produced the Capulin Basalt (18,000 - 4,500 years; Baldwin and Muehlberger, 1959). Capulin volcanics are xenocrystaline silicic alkalic basalts and basaltic andesites (Stormer, 1987). The most distinctive feature of these rocks is the local (especially in flows from Capulin Mountain) presence of large resorbed quartz and reverse-zoned plagioclase grains in direct association with abundant olivine phenocrysts (Stormer, 1987).

Capulin Mountain and environs Capulin Mountain is a roughly symmetrical cinder cone approximately 300 m tall that formed in the latest phases of Capulin eruption (Baldwin and Muehlberger, 1959). A spiral road leads to the top of the cone, and a loop trail approximately 1.6 km in length encircles the crater. Capulin Mountain is one of the best preserved examples of a basaltic cinder cone in North America, and exists entirely within the boundaries of Capulin Mountain National Monument.

Almost all of the Raton-Clayton volcanic field is visible from the Capulin loop trail. Visible from the loop trail in the distance are the Raton Basalt, capping Johnson Mesa to the northwest; the early Clayton Basalt flows and volcanos, capping low mesas to the southeast; the Sierra Grande shield volcano, to the southeast; and peaks and buttes dominated by the Red Mountain Dacite and feldspathoidal Clayton Basalt, to the west. In the area close to the cinder cone are several smaller splatter and cinder cones related to greater eruption of the Capulin Basalt. Flows from Capulin Mountain are also apparent around the base of the cone that display prominent squeeze-ups and pressure ridges. Labeled dioramas are posted on the loop trial to aid in location of the above volcanic features.

Stop 3: Clayton Lake State Park, New Mexico The Dakota Megatracksite/The "Dinosaur Freeway"

Lower Cretaceous strata of High Plains and Front Range exposures in Colorado and New Mexico are rich in dinosaur tracks. These tracks are confined almost entirely to the Pajarito Formation in northeastern New Mexico, and to Pajarito equivalents of the upper Muddy Sandstone in southeastern Colorado and the Colorado Front Range. Within these strata, Lockley, et al, (1992) document over 1300 tracks within 25 sites dispersed over an 80,000+ km^2 area between Boulder, Colorado and Mosquero, New Mexico. Such regional-scale and stratigraphically restricted track-bearing complexes are commonly referred to as "megatracksites" (Lockley, et al, 1988; Lockley and Pittman, 1989). The Dakota megatracksite is informally referred to as the "Dinosaur Freeway" (Jones, 1988; Lockley, 1988, 1990).

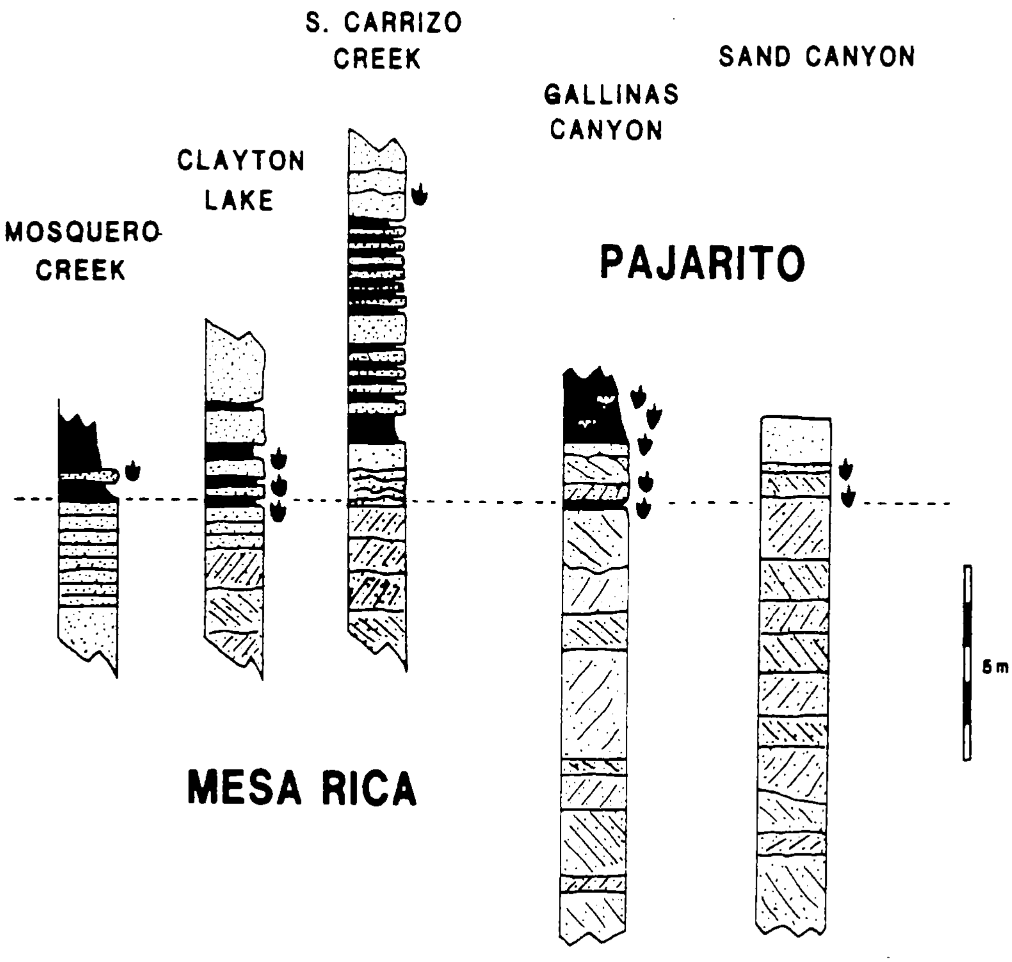
Most tracks in the Dakota megatracksite belong to the ichnogenra *Caririchnium* and *Amblydactylus* (Gillette and Thomas, 1985; Lockley, 1987; Lucas, et al, 1987). These ichnogenra are very similar. Their main distinction is the presence of a bilobate heel in the pes print and the association of a small manus print in *Caririchnium*; both features being normally absent in *Amblydactylus* (Leonardi, 1984; Currie and Sarjeant, 1979; Fig. 15). Both *Caririchnium* and *Amblydactylus* occur throughout the Dakota megatracksite, and represent tracks made by herbiferous ornithopods of iguanadontid taxa (Lockley, et al, 1992). Unclassified theropod tracks found in association with ornithopod tracks are characterized by slender toe impressions with wide digit divarication, and are presumably the tracks of gracile "coelurosaurians" (Lockley, et al, 1992; Fig. 15). Ornithopod tracks out-number theropod tracks by more than four-to-one throughout the Dakota megatracksite. Dinosaur tracks are locally associated with a few bird and/or crocodile tracks as well. Each of the track types above appear to be found in variable abundance throughout the Dakota megatracksite (Lockley, et al, 1992).

The regional abundance of ornithopod tracks in such a thin stratigraphic interval prompted some workers to speculate that the Dakota megatracksite records an ancient coastal migration route for herbiferous dinosaurs (Monastersky, 1988; Black, 1989; Boling, 1989). Indeed, many authors argue that large herbiferous dinosaurs like iguanadons would have been forced to migrate to avoid hunger as they locally outstripped their food supply (cf. Hotton, 1980; Calder, 1984). In examining these strata from a sequence stratigraphic viewpoint, Lockley, et al, (1992) determined that such an interpretation was overly simplistic. They noted that because Pajarito and equivalent strata predominantly represent coastal-plain aggradation and valley filling preceding up-dip (south-to-north) transgression (Holbrook and Wright Dunbar, 1992; Fig. 6), the Pajarito formation of the south is likely older than the stratigraphically equivalent track-bearing strata to the north. It is thus unlikely that northern and southern track-bearing strata were deposited concurrently, and that any single north/south migration path would be preserved. More likely, the Dakota megatracksite records northward stepping of a coastal dinosaur community with encroachment of the Western Interior sea, coupled with preferential preservation of tracks in the "preservation-friendly" coastal environments typical of Pajarito strata (Lockley, et al, 1992). Such and interpretation would mean that the abundance of tracks in the Dakota megatracksite only reflects a section of preferential preservation in the stratigraphic sequence, and neither supports or precludes the possibility that the fore mentioned coastal dinosaur community migrated.

The Clayton Lake Track Site The Clayton Lake tracksite covers an area of approximately 1/2 hectare within the floor of the overflow spillway of Clayton Lake, approximately 18 km north of Clayton, New Mexico. Nearly 500 tracks in excellent to poor condition are preserved here in three stratigraphic units which span the Mesa Rica/Pajarito boundary (Gillette and Thomas, 85; Fig. 16; a map of trackways is posted at the Clayton Lake site). Tracks are tightly spaced and difficult to distinguish locally, as is typical of such "dinoturbation" surfaces (Lockley, 1991). Tracks are best observed in the oblique light of early morning and late evening.

The lower-most track-bearing horizon is on the upper surface of the Mesa Rica Sandstone. The Mesa Rica Sandstone is a planar and trough cross-bedded cliff-forming fluvial sandstone (Lithofacies Stp; Table 1) 12.8 m thick at the site. Tracks on the upper Mesa Rica surface are associated with *Thalassinoides* burrows. The second track-bearing bed is on the top surface of a .3 m thick fine-grained rippled-to-massive quartzose sandstone bed, which is separated from the underlying Mesa Rica by only a .08 m thick siltstone layer. The third track-bearing layer is .9 m above the second, and is on top of a .5 m bed of very-fine-grained rippled-to-massive sandstone. The second and third layers are separated by thinly to very thinly interbedded sandstone and silty shale. Track-bearing beds two and

Figure 16. Stratigraphic sections from "Dinosaur Freeway" track sites at Clayton Lake State Park, and surrounding areas. (from Lockley, et al, 1992).



three are in the basal Pajarito Formation, and were deposited in the fluvial/marine transitional environments described above (lithofacies Sf; Table 1).

Tracks at the Clayton Lake site reflect ornithopod, theropod, and crocodillian track makers. Ornithopod tracks here are up to 50 cm long and 42 cm wide, and are identified by Gillette and Thomas (1985) as all belonging to the ichnogenous *Amblydactylus*. Gillette and Thomas (1985) and Lucas, et al (1986) contended that Clayton Lake tracks were made by hadrosaurs, whereas Lockley, et al, (1992) argue that such *Amblydactylus* prints throughout the Dakota megatracksite were made by iguanadonts. Most all theropod tracks at the Clayton Lake site are less than 28 cm long, and represent the slender-toed coelurosaur tracks typical of the Dakota megatracksite (Gillette and Thomas, 1985). Two larger, poorly preserved theropod tracks are up to 35 cm long with fatter toes and less digit divarication than the more typical coelurosaur tracks. Gillette and Thomas (1985) proposed that these might be the tracks of a carnosaur. An enigmatic diamond-shaped track type is common at the Clayton Lake site, but rare in the Dakota megatracksite overall. Gillette and Thomas (1985) proposed that this represented the track of a web-footed theropod; however, Lockley, et al (1992) contended that these tracks most likely represent a sediment-deformed ornithopod track. If the diamond-shaped tracks are truly theropod tracks, then theropod tracks are only slightly less abundant than ornithopod tracks; whereas, if these tracks record ornithopods, than theropods produced only about 20% of the trackways at the Clayton Lake site.

Approximately 50 trackways can be identified at the Clayton Lake site, including a few crocodillian trackways (Lockley, et al, 1992). Trackways do not appear to have a preferred orientation overall at Clayton Lake, although some trackways parallel each other (Gillette and Thomas, 1985). A tracksite just south near the town of Mosquero, New Mexico, however, does display 114 similar ornithopod tracks (mostly Caririchnium) in 31 trackways that are clearly bimodally oriented NW-SE and occur at the same stratigraphic level as tracks at Clayton Lake (Lucas, et al, 1987; Lockley, et al, 1992; Fig. 16).

DAY 3: DRY CIMARRON VALLEY OF NORTHEASTERN NEW MEXICO

John Holbrook, Southeast Missouri State University, Cape Girardeau, MO

Overview

All three stops this day will give us the opportunity to compare the interrelationships between sequence-boundary morphology and architecture of overlying strata for up-dip and down-dip areas in a sequence, namely, sequence 3 of Weimer and Sonnenberg (1989). Morphology of sequence boundary SB3 is smooth, and overlying fluvial Mesa Rica Sandstone is only one channel thick in Dry Cimarron exposures. This contrasts with equivalent strata seen up paleodepositional dip in the Ft Collins area on day one. There, sequence boundary SB3 had a valley-and-interfluve morphology, and fluvial Horsetooth Sandstone was confined to SB3 lows. We will discuss differences in the fluvial and erosional processes responsible for this down-dip shift in sequence structure.

Later in the day, at stops two and three, we will compare architecture of the Mesa Rica Sandstone over different segments of the Sierra Grande basement structure. We will discuss how subtle contemporaneous uplift on Sierra Grande structure may have influenced Mesa Rica deposition. For time's sake, we will probably not venture to the top of the mesa at stop 3, but rather will observe pertinent features from the valley floor.

Stop 1: Interrelationships between Mesa Rica Sandstone Architecture and Morphology of Underlying Sequence Boundary SB3 in the Dry Cimarron Valley

Architectural features of Mesa Rica Sandstone/basal Pajarito strata and morphology of sequence boundary SB3 Mesa Rica Sandstone in the Dry Cimarron valley is dominated by channel-fill and lateral-accretion elements, and is capped by overbank-fine, channel-fill, and sandy-bedform elements of the basal part of the Pajarito Formation. Other architectural elements are conspicuously absent.

Channel-fill elements are the dominant element in Mesa Rica strata throughout northeastern New Mexico, and are roughly symmetrical, with width/depth ratios of ≈ 9 - 15 (Figs. 17, 18, and 19). Channel fills mostly contain deposits of lithofacies Stp, which are interpreted to represent active channel filling (Holbrook, 1996; Fig. 17; Table 1). Some, however, are partly filled by massive dark blue-gray mudstone more appropriately attributed to abandoned channel-filling processes (Lithofacies Fm; Table 1). Most channels containing such abandoned channel fill comprise a secession of basal Stp and/or Sfr sandstone and upper massive mudstone (Fig. 18; Table 1).

Lateral-accretion elements are locally common, but rarely dominant, in Mesa Rica strata. Where present, they lie directly adjacent to channel-fill elements, and consist of lithofacies Stp strata (Fig. 18). They typically are 30% - 100% (averaging 65%) the width of adjacent channel elements. Paleocurrents from trough and planar cross beds in channel-fill and lateral-accretion elements yield generally south and southeastward vectors.

Interbedded sandstone and siltstone in the basal two meters of the Pajarito Formation are largely composed of lithofacies Stpr, and are considered to represent stacked sandy bedform and thin overbank-fine elements. These overbank-fine and sandy-bedform elements locally interfinger with and/or engulf small and large channel-fill elements of the basal Pajarito section (Fig. 17).

Physical correlation verifies that the Mesa Rica Sandstone overlies sequence boundary SB3 as a single continuous sandstone sheet throughout the entire length of the Dry Cimarron valley (Holbrook, 1996; Fig.: 20). Mesa Rica thickness also corresponds consistently with thickness of the larger channel-fill elements (Figs. 17, 18, and 19). The result is a widespread (> 87 km along strike) continuous sandstone sheet that is essentially one channel thick. Relief on sequence boundary SB3, relative to the transgressive surface of erosion above the underlying Plainview equivalent Long Canyon bed, is less than the thickness of overlying channel elements (Fig. 20). Relief on this surface is thus not attributed to major valley development, and sequence boundary SB3 is thus judged to be smooth (Holbrook, 1996).

Mesa Rica and basal Pajarito strata lie

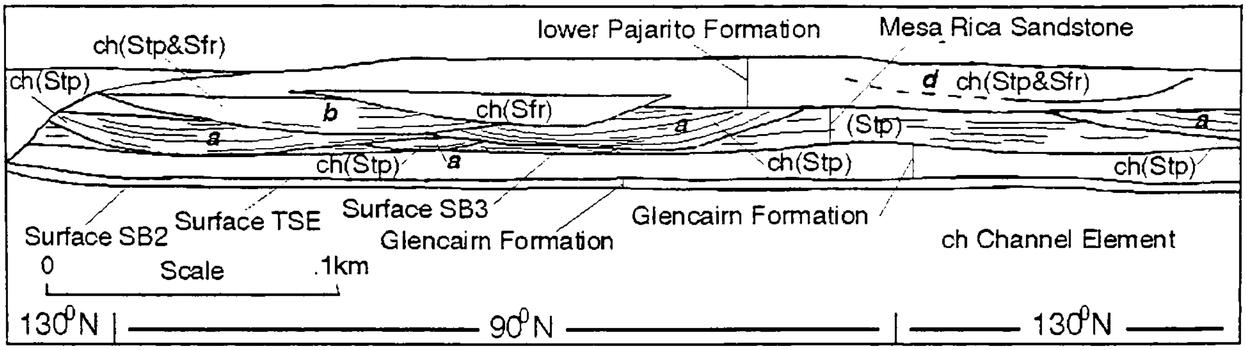


Figure 17. Lithofacies, stratigraphic units, architectural elements, and sequence stratigraphic surfaces at Stop 1, Day 3.

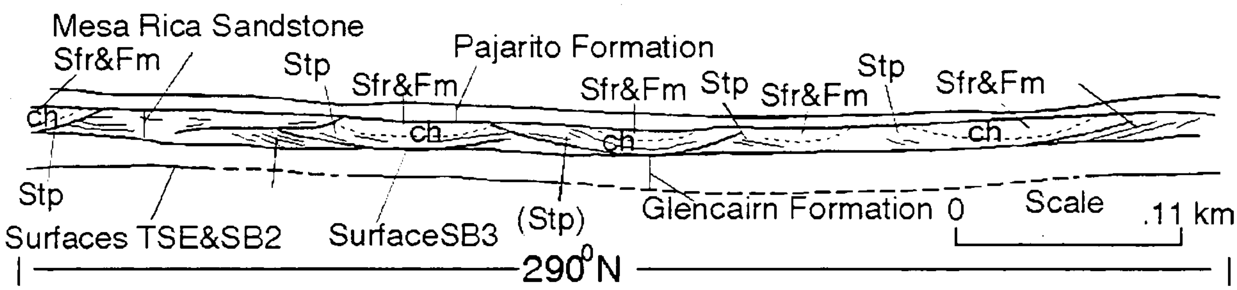


Figure 18. Lithofacies, stratigraphic units, architectural elements, and sequence stratigraphic surfaces at Stop 2, Day 3.

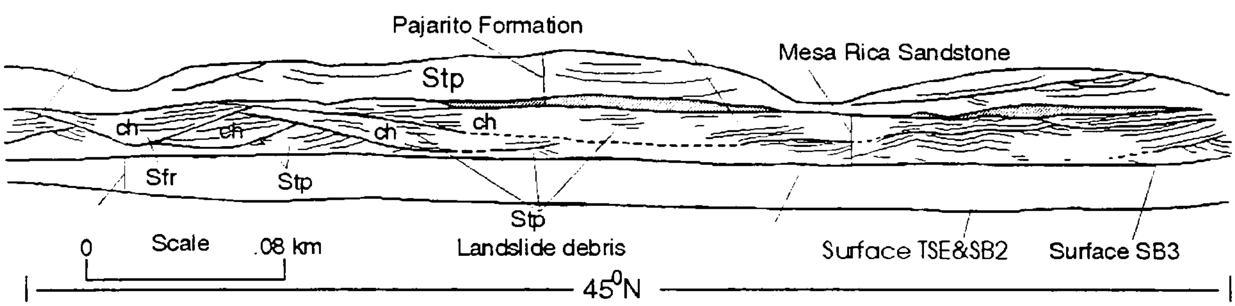


Figure 19. Lithofacies, stratigraphic units, architectural elements, and sequence stratigraphic surfaces at Stop 3, Day 3.

directly above the sequence boundary seen on day one at the base of the Horsetooth Sandstone, and represent the down-dip equivalents of these Horsetooth strata (Holbrook and Wright Dunbar, 1992). Association of a single-story sandstone sheet above a smooth sequence boundary in the Dry Cimarron valley, however, contrasts sharply with the discontinuous sandstone units confined to discrete valleys observed in equivalent Horsetooth strata of the Ft. Collins area.

Mesa Rica River Patterns Lithofacies and architectural features of the Mesa Rica Sandstone imply that these strata resulted from amalgamation of channel-derived deposits, which were generated by a complex of non-braided straight to low-sinuosity streams (Holbrook, 1996). Several lines of evidence are used by Holbrook (1996) to support this interpretation over a more meandering or braided model. These include preponderance of individually incised symmetrical to near symmetrical channel fills (c.f. Moody-Stuart 1966; Tyler and Ethridge 1983); highly subordinate role of lateral accretion elements in Mesa Rica architecture; close association of channels with levee/splay deposits, indicating channel confinement; low channel width/depth ratios; conspicuous lack of architectural elements typically associated with braided deposits (e.g., foreset macroforms; see Miall 1985); presence of abandoned channel-fill elements; and regional similarity in channel-element geometry and scale. Most importantly, photopans reveal that Mesa Rica channels aggraded from the Mesa Rica Sandstone sheet as independent channel bodies (Fig. 7). In contrast, minor braided-channel fills should have aggraded collectively, as part of a complex of amalgamated channel fills and bars within a larger, braided channel-fill element. Mesa Rica lateral-accretion elements represent preservation of narrow point bars where Mesa Rica streams ranged into slightly sinuous patterns.

Most abandoned channel fills comprise interbedded active-channel-fill and abandoned-channel-fill deposits, a feature typical of channel fills formed after abandonment by chute cutoff (Allen, 1965). Such fills may represent either abandonment of channels by chute cutoff in low-sinuosity streams, or abrupt abandonment of longer reaches of channel followed by episodic reoccupation during floods. Basal Pajarito strata directly atop Mesa Rica channel sandstone represent preservation of levee/splay complexes.

Model for Mesa Rica deposition and its sequence-stratigraphic significance Fluvial Mesa Rica sheet sandstone and basal Pajarito strata in the Dry Cimarron area comprise channel and floodplain deposits, respectively, of an extensive (> 87 km wide and ≈ 100 km long) coastal plain which developed during Kiowa-Skull Creek lowstand (Holbrook 1992; Holbrook and Wright Dunbar 1992). In contrast, equivalent fluvial/estuarine strata of the Horsetooth member farther up dip in central and southeastern Colorado are confined to discrete valleys, and represent mostly filling of valleys during transgression which followed Mesa Rica deposition (Weimer 1984; Dolson et al 1991; Holbrook 1992, 1993). Mesa Rica and basal Pajarito depositional history and sequence-stratigraphy are discussed at length in Holbrook (1996). The following discussion summarizes these conclusions.

During Kiowa-Skull Creek lowstand, Mesa Rica rivers delivered sediment from regions throughout the exposed mid-section of the Western Interior to a marine shoreline in northeastern and east-central New Mexico. Delivery of sediment under proposed stable relative sea level conditions at lowstand prompted rapid shoreline progradation. Coastal Mesa Rica rivers were forced to transport sediment progressively farther over near zero gradients to reach marine depocenters as progradation proceeded. Straightening and frequent avulsion of these coastal Mesa Rica rivers ensued as a complex fluvial response to the low gradients imposed by rapid progradation, much like in the case of the modern Yellow River of China (see Van Gelder, et al, 1994). Similar fluvial responses to low gradients during sea level lowstand are also predicted by conceptual (Posamentier, et al, 1992; Wescott, 1993; Schumm, 1993) and flume models (Koss, et al, 1994).

Proposed prolific avulsion of relatively straight Mesa Rica rivers throughout the coastal plain under these conditions of low accommodation space eventually resulted in deposition of a regionally continuous Mesa Rica fluvial sandstone sheet, and planation of underlying marine strata in coastal plain areas. This culminated in the distinctive genetic association of single-story fluvial sheet sandstone and smooth sequence-boundary morphology that is apparent in Mesa Rica Sandstone and underlying sequence boundary SB3 in the Dry Cimarron valley (Fig. 3). This contrasts markedly with the valley-fill scenario which addressed the discontinuous Horsetooth strata above a highly incised sequence boundary SB3 that was observed up paleodepositional dip near Ft. Collins on the first day. There, long-term exposure and significant base-level drop during Kiowa-Skull Creek lowstand prompted deep incision of local valleys that were filled during subsequent transgression. Colorado Front Range (Horsetooth) and New Mexico (Mesa Rica and Pajarito) sections provide an excellent example of large-scale down-dip shift in sequence-boundary morphology and architecture of overlying strata that can be attributed to contrasting response of lowstand rivers from erosional valley incision in the hinterland to lateral planation and sheet sandstone deposition near the lowstand shoreline.

Transgression and associated base-level rise that followed maximum Kiowa-Skull Creek regression prompted fluvial aggradation and burial of regressive Mesa Rica and basal Pajarito deposits beneath an extensive blanket of marine-influenced lower Pajarito coastal-plain strata.

Features visible at stop 1 The entire Lower Cretaceous section is visible here, excluding the upper half of the Pajarito Formation.

Sequence boundary SB2 (Fig. 20) separates 3-5 m of brown thoroughly bioturbated estuarine sandstone of the Plainview equivalent Long Canyon bed from underlying white cross-bedded fluvial sandstone (Fig. 17). Whether the white sandstone below SB2 is the Lytle Sandstone vs an upper Morrison sandstone is an enigma. This sandstone is certainly in the proper stratigraphic position for and resembles the Lytle section observed on Day one. Unlike the Lytle observed previously, however, this white sandstone is devoid of significant extraformational conglomerate. Such non-conglomeratic "Lytle" sandstone beds also resemble sandstone beds locally present in the underlying upper Morrison Formation (Holbrook, et al, 1987). Stratigraphically equivalent and similar white sandstone beds locally exposed in the Dry Cimarron valley are conglomeratic, and are easily interpreted as Lytle Sandstone. Kues and Lucas (1987) placed all white sandstone beds directly below surface SB2 within the Lytle Sandstone. Whether the white sandstone bed below surface SB2 at Stop 1 is a Lytle or upper Morrison exposure, however, is still a valid point of debate.

Long Canyon exposures are separated from overlying shelf and nearshore deposits of the upper Glencairn Formation by the local extension of the transgressive surface of erosion seen between Plainview and Skull Creek exposures on day one (Fig. 20). Skull Creek equivalent Glencairn deposits are largely covered at stop one, but small exposures of dark-gray shale and/or bioturbated sandstone can be found or excavated locally. These marine strata are sharply overlain by the local expression of sequence boundary SB3, which in turn is capped by fluvial Mesa Rica Sandstone.

Each of the Mesa Rica features described in the preceding section are visible at stop one, except for lateral-accretion elements which are present at stop two (Figs. 17 and 18). Mesa Rica Sandstone at stop one is composed of a sheet of amalgamated channel elements one channel thick (Fig. 17). Visible here as well is a series of channel-fills (channels b through d of Fig. 17) recording aggradation of Mesa Rica channels from the Mesa Rica sheet upward into the basal Pajarito section. These aggradational channels are flanked by basal Pajarito strata.

Stops 2 and 3: Subtle Tectonic Influence on Early Cretaceous Deposition in the Dry Cimarron Valley by the Sierra Grande Uplift

The Sierra Grande uplift The Sierra Grande uplift is identified by a northeast/southwest trending high in Precambrian basement of northeastern New Mexico, and has a southeast extension which is referred to as the Bravo Dome (Fig. 21). The Sierra Grande and Bravo Dome together constituted a major uplift within the late Paleozoic Ancestral Rockies (King, 1959; Baltz, 1965). Subsequent subtle reactivations (generating 10^1 m topographic relief) of Sierra Grande structure are argued to have occurred in Early Cretaceous (Holbrook and Wright Dunbar, 1992) Late Cretaceous (Hattin, 1986), and Tertiary (Baldwin and Muelberger, 1959) time.

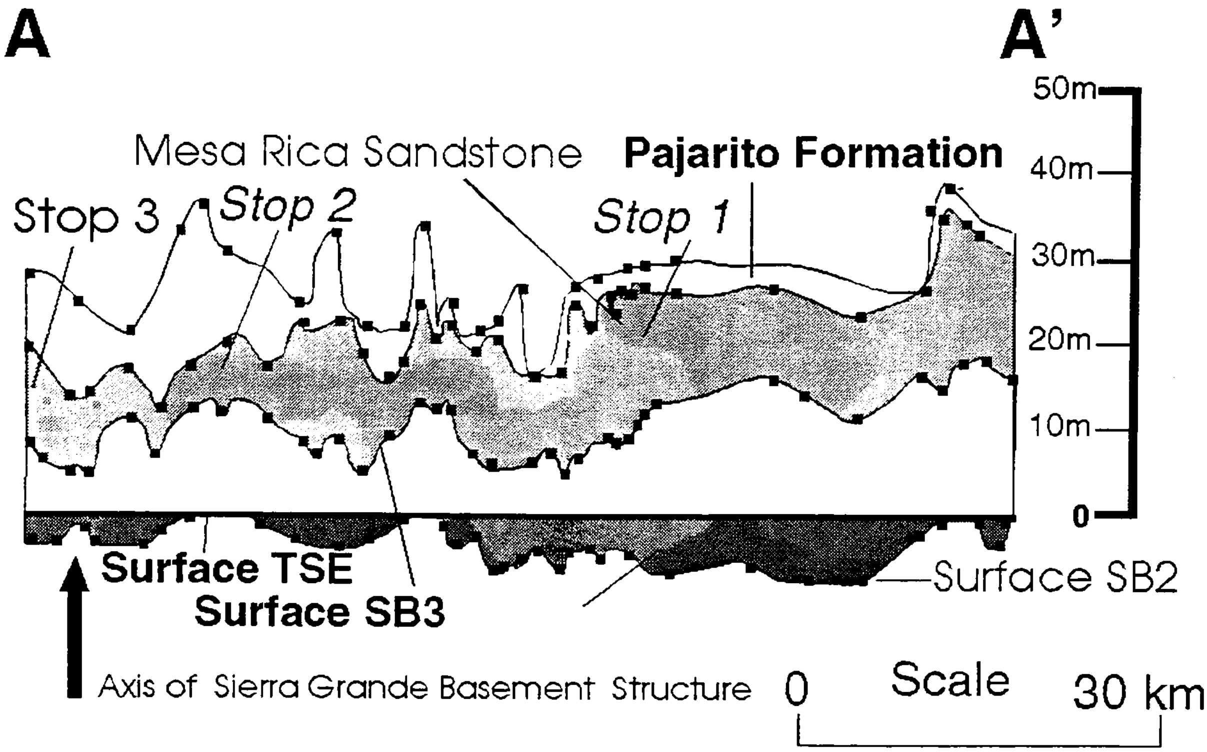


Figure 20. Cross section of Lower Cretaceous strata in the Dry Cimarron valley with Stops 1, 2, and 3, marked

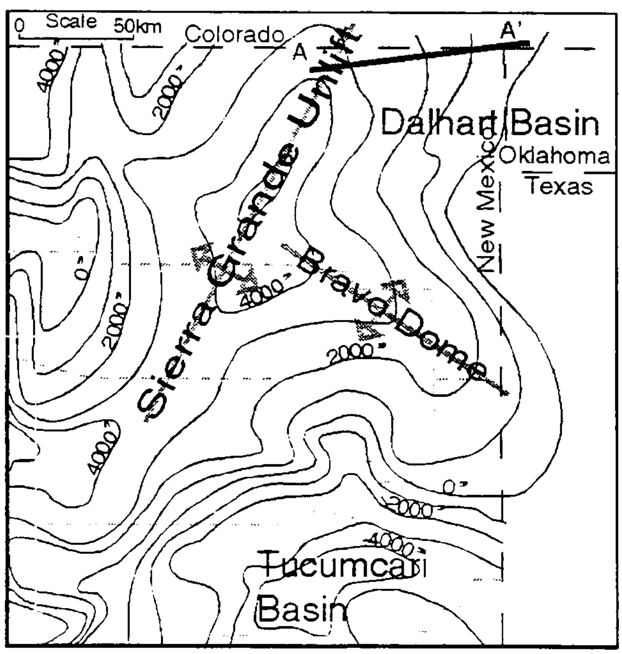


Figure 21. Contour map of precambrian basement in northeastern New Mexico. (modified from Suleiman and Keller, 1985)

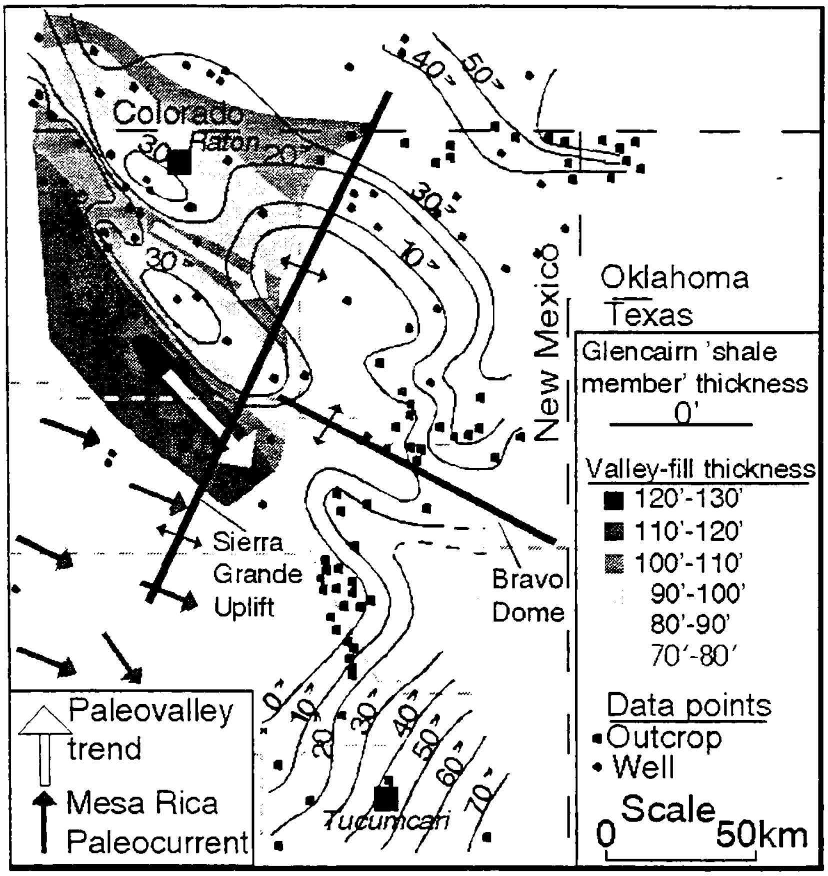


Figure 22. Isopach map of Glencairn strata, excluding the Long Canyon sandstone bed.

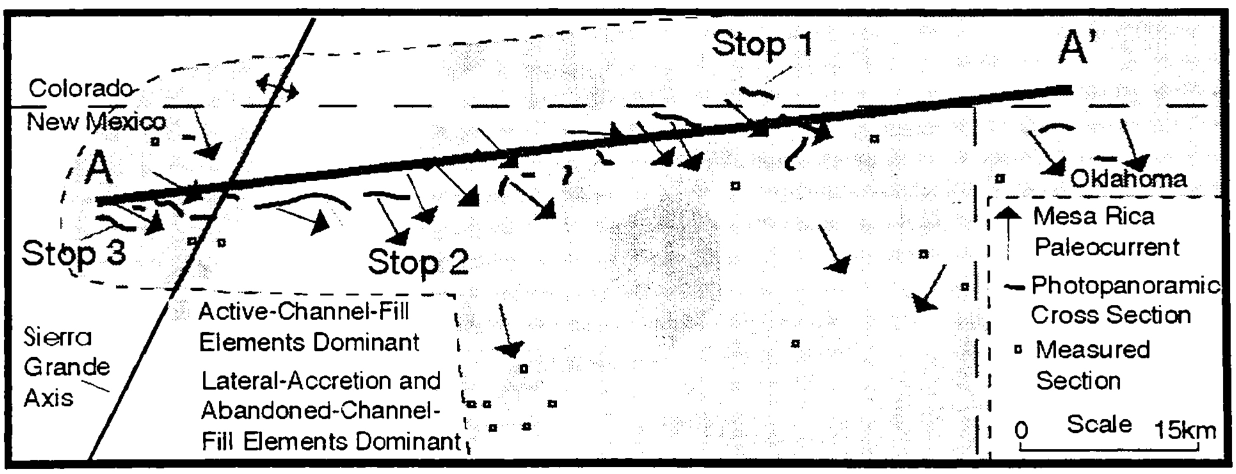


Figure 23. Architectural element distribution in the Dry Cimarron Valley area.

Tectonic influence on the Glencairn Formation Deflection of the marine Glencairn zero isopach contour, and parallel thickness contours, approximates the shape of Precambrian relief on the combined Sierra Grande and Bravo Dome basement structure (Figs. 21 and 22). Mesa Rica paleocurrents and thickness trends in Muddy equivalent valley fill strata are oriented perpendicular to the Sierra Grande axis for areas above and west/up depositional dip of Sierra Grande structure. Preferential thinning of Glencairn strata over Sierra Grande structure is thus not an artifact of valley development and incision of Glencairn strata parallel with the Sierra Grande crest.

Pinchout of marine Glencairn strata coincident with the eastern and northwestern flanks of the Sierra Grande uplift infers non-deposition of marine strata over an elevated Sierra Grande welt during Kiowa-Skull Creek marine flooding, and/or preferential erosion of previously deposited Kiowa-Skull Creek marine strata above a rising Sierra Grande welt during lowstand erosion of surface SB3. In either case, such close coincidence of basement structure and marine stratal thickness infers effects on marine Glencairn strata by topography generated above a Sierra Grande uplift which was rising either prior to, during, or shortly after Kiowa-Skull Creek marine flooding (Holbrook, 1992).

Tectonic influence on Mesa Rica Sandstone Down-dip continuation of Mesa Rica deposits over the Sierra Grande axis (Figs. 20, 22, and 23) infer that any topography above the Sierra Grande structure, coincident with Mesa Rica deposition, was insufficient to cause deflection of Mesa Rica streams and preferential valley development off the Sierra Grande flanks. Regional variations in Mesa Rica architecture, however, speak of extremely subtle influence on Mesa Rica fluvial deposition by contemporary uplift on Sierra Grande basement structure.

As discussed above, Mesa Rica Sandstone is composed of active-channel-fill, abandoned-channel-fill, and lateral-accretion elements throughout the Dry Cimarron valley; however, regional distribution of these three elements is not random. Mesa Rica strata in all Dry Cimarron exposures west and greater than 20 km east of the Sierra Grande axis are dominated by active-channel-fill elements, and abandoned-channel-fill and lateral-accretion elements are rare in these areas (Figs. 17, 19, and 23). The stretch of Mesa Rica exposure from the Sierra Grande axis eastward for 20 km is rich in abandoned-channel-fill and lateral-accretion elements. Active-channel-fill elements are common, but comparatively subordinate, in this area (Figs. 18 and 23). The observed increase in lateral-accretion element size and abundance reflects more extensive point bar growth locally, and abundance of abandoned-channel-fill elements infers a local increase in chute cutoff of stream meanders. This clear change in Mesa Rica architecture signifies a relative increase in sinuosity for Mesa Rica streams in reaches extending over the southeastern/downstream flank of the Sierra Grande uplift (Holbrook, 1992, 1994; Fig. 23). Maximum sinuosities calculated for these more sinuous streams from lateral-accretion sets is only 1.2 (see Leopold and Wolman, 1957), and is thus still very low (Holbrook, 1996).

Strong coincidence between increased Mesa Rica channel sinuosity and the Sierra Grande east flank is attributed to fluvial response to elevated gradients encountered by Mesa Rica rivers on the southeastern/downstream flank of a topographic welt rising penecontemporaneously above reactivated Sierra Grande basement structures (Holbrook, 1992, 1994). Such local increases in sinuosity owing to local elevation of gradient is well document in experimental flume studies (Friedkin, 1945; Schumm and Khan 1972; Ouchi, 1985; Schumm, et al, 1987). A modern example of the sinuosity effects proposed over the Sierra Grande uplift is seen on the modern Mississippi River of southeastern Missouri. As the river passes over the crest of the active Lake County uplift (30 feet topographic relief), it increases in sinuosity on the steepened downstream flank of this structurally generated topographic welt (Russ, 1982).

Features visible at stop 2 Neither the Plainview equivalent Long Canyon bed nor the Lytle Sandstone are present at this location, and sequence boundary SB2 and the transgressive surface of erosion at the base of marine Glencairn strata exist as a single scour surface separating marine Glencairn shale from underlying green and red mudstone of the Morrison Formation (Fig. 18). Glencairn strata is largely covered here, and exposures must be excavated.

Mesa Rica strata above sequence boundary SB3 at this location is dominated by abandoned-channel-fill elements. We will concentrate on a typical example of an abandoned channel fill which is located approximately 40 m west of the road passing up to the mesa top. This channel fill is floored by rocks of lithofacies Stp, which are in turn overlain by roughly equal proportions of lithofacies Sfr. The remaining quarter of this channel is filled by massive to thickly laminated blue-gray mudstone (Fig. 18). Mesa Rica Sandstone in the area is continuous, but high mud content, related to local abundance of abandoned-channel-fill elements, results in poor exposure.

Mesa Rica strata are capped by fluvial/marine transitional deposits of lithofacies Stpr, which are in turn capped conformably by mudstone of unknown origin that is similar to lithofacies Fl. These mudstone strata are capped by a second horizon of lithofacies Stpr strata. Laterally, these mudstone beds are separated from overlying Stpr strata by discontinuous lenses of lithofacies Stp fluvial strata. These Stp strata could possibly represent equivalents of the upper fluvial sandstone beds of the Muddy that were observed at stop one on day two.

Features visible at stop 3 Rainfall in this part of the Dry Cimarron valley is greater, resulting in poorer stratal exposure. Only the upper 3 m of a conglomeratic Lytle Sandstone are exposed here, and are overlain by conglomeritic bioturbated brown sandstone of the Long Canyon bed. These units are only locally exposed. The transgressive surface of erosion at the top of the Long Canyon bed is characterized by a thin lag of *Gryphea* shells at this location.

Mesa Rica Sandstone is composed almost entirely of active-channel-fill elements at this location, and more closely resembles exposures at stop one than those of stop two. A thin layer of fluvial/marine transitional strata (lithofacies Stpr) overlies Mesa Rica Sandstone which is in turn overlain in scoured contact by a cliff of fluvial Stp strata. Locally, these upper fluvial sandstone beds are incised into Mesa Rica Sandstone, and the intervening transitional strata are removed. This upper fluvial sandstone is likely an equivalent of the upper Muddy fluvial sandstone observed at stop one of day two.

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